MINUTES
OF THE TWENTY-FIRST EXPLOSIVES SAFETY SEMINAR
VOLUME I

Explosives Safety Board
DEPARTMENT OF DEFENSE

HYATT REGENCY HOTEL
HOUSTON, TX
28-30 AUGUST 1984

SPONSORED BY

DEPARTMENT OF DEFENSE EXPLOSIVES SAFETY BOARD

ALEXANDRIA, VA

MINUTES OF THE

TWENTY-FIRST EXPLOSIVES SAFETY SEMINAR

Volume I

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PREFACE

This Seminar is held as a medium by which there may be a free exchange of information regarding explosives safety. With this idea in mind, these minutes are being provided for your information. The presentations made at this Seminar do not imply indorsement of the ideas, accuracy of facts presented, or any product, by either the Department of Defense Explosives Safety Board or the Department of Defense.

O. M. BROOKS
Captain, USN
Chairman

These proceedings are published for information as an accomodation to the participants at the Seminar. The Department of Defense Explosives Safety Board cannot accept responsibility for the correctness of those papers which have been directly reporduced form copy furnished by the authors.

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By

Captain Otis M. Brooks
Chairman, Department of Defense
Explosives Safety Board

At

Twenty-First Department of Defense Explosives Safety Seminar
Houston, Texas
August 28, 1984

OPENING REMARKS

Dr. Korb, Brigadier Groom, Brigadier McKenzie-Orr, Distinguished guests, as the chairman, It is my sincere pleasure to welcome each of you to the Department of Defense Explosives Safety Board sponsored 21st Explosives Safety Seminar. The goal of this Seminar, as it has been since inception in 1959, is to improve the quality of explosives safety within our establishments through the exchange of state -of-the-art information. These periodic sessions provide the unique opportunity for those of us involved in the explosives safety business to compare notes and interact in pursuit of the awesome responsibilities that go with the territory. Lake Denmark, New Jersey (1926) which prompted the US Congress to form the DDESB: Port Chicago. California (1944); and more recently the munitions disaster at Severomorsh, Russia have to be constant reminders of catastrophies that have happened and can very easily be repreated. It is incumbent upon each of us involved with munitions throughout their life cycle, from cradle to grave, to be continually aware of the inherent hazards of the beast and concomitant necessary safe guards.

The presentations at this seminar cover a wide range of related material pertinent to the thrust of the conference and I'm sure that many sessions will be intense; however, I must remind you that this is an open forum and as such all information must be of an unclassified nature.

Its obvious that there is considerable interest in our business from the very fine representation we have here today and if numbers and diversity of people mean that we will have a successful seminar, this one is already assured of being an overwhelming success. I emplore each of you to make the most of this opportunity.

It is now my pleasure to introduce to you the current members of the Department of Defense Explosives Safety Board. From the Department of the Army, Colonel Robert Orton. Colonel Orton is on the Army staff at the Pentagon and is Chief of the Chemical and NBC Division, Deputy Chief of Staff, Operations and Plans. Also from the Department of the Army, the alternate board member, Mr. Peter Rutledge. Mr. Rutledge is the Technical Advisor to he DA Director of Safety. From the Department of the Navy, Captain Lawrence Masten, Captain Masten is Head of the Ordnance Material Management Branch in the office of Chief of Naval Operations. Also, in the Pentagon. Regrettably, Captain Masten could not be with us today. However, we do have with us, Mr. Carlo Ferraro, the alternate Navy board member. Mr. Ferraro is Head of the Explosives and Nuclear Weapons Safety Section, Office of Chief of Naval Operations, in the Pentagon. From the Department of the Air Force, Colonel William Gavitt. Colonel Gavitt is the Chief of Weapons Safety, Deputy Inspector General, HQAF at Norton Air Force Base, CA. Also from the Department of the Air Force, the alternate board member, Mr. Ken Shopher. Mr. Shopher is Chief of Explosives Safety, Deputy Inspector General, HQAF also at Norton.

I would now like to introduce the members of my Secretariat who are with us today:

COMBAT CAPABILITY ASSESSMENT

By

Dr. Lawrence Korb
Assistant Secretary of Defense
for Manpower, Installations, and Logistics

At

Twenty-First Department of Defense Explosives Safety Seminar
Houston, Texas
August 28, 1984

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Address to the 21st Explosives Safety Seminar
August 28, 1984

SUBJECT: Combat Capability Assessment

Introduction

I appreciate the opportunity to speak to you today at this 21st Explosives Safety Seminar. I am told that more than 600 of you will participate in its various technical sessions and that you reflect the interests and concerns of 18 sovereign nations. We welcome you all in this most worthy cause.

To achieve our defense readiness objectives within the constraints of available resources, we must prevent waste, regardless of its origin. Explosives accidents are an obvious and often tragic source of waste of human and material resources and must be prevented wherever possible. Affordability of preventive measures is of course a vital consideration. When properly conceived and administered, an explosives safety program not only is affordable, but in fact, reduces costs and conserves resources.

I would like to expand a bit from the announced topic of "Readiness of the Military Services" and discuss with you a subject of topical concern: "DoD's efforts to improve the combat capability of our forces."

As the principal advocate for readiness and sustainability in the Department, I am painfully aware of the many questions which have been raised recently concerning the sufficiency of our efforts in these areas.

While some of these questions seem to be purely the polemics of election year politics, most are motivated by a sincere concern to get the most for our defense dollar; most, that is, in terms of combat capability.

What I will do is:

First, describe the components of combat capability.

Second, discuss the methods used for evaluating combat capability -- the "capability curve," and how its components are measured.

Third, review some issues central to the ongoing debate as to the best approach to maximizing combat capability. I will cite several specific examples from a recent report we made to Senator Tower regarding our improvements in warfighting capability.

Fourth, describe a current issue on our tactical air force in Europe, which I believe best illustrates the trade-offs which need to be considered in any discussion of capability.

And finally, offer some personal observations on the nature of readiness and sustainability issues and their funding.

As we will see, military capability is a complex area. There is certainly plenty of room for legitimate debate, because we don't directly buy combat capability. What we do buy is contributors to capability, or components of capability that are themselves difficult to quantify.

Definitions

There are several ways that combat capability could be segmented into component. One framework we have used to evaluate the application of defense resources is the "four pillar" picture of combat capability:

we buy force structure - the number of air wings, battalions, and ships in the armed forces;

we buy modernization - to equip this force structure with more technically sophisticated and capable weaponry and facilities;

we buy readiness - the training, spare parts and maintenance to keep this force and its equipment prepared to deploy and fight;

and finally we buy sustainability - the inventories of munitions, spares, fuel and other items to keep this force fighting long enough to defeat the threat.

None of these "pillars" is sufficient by itself to achieve a desired level of combat capability -- we need measured and balanced progress in all four if we are to achieve a defense of sufficient size, armed with effective weapons, that is ready to respond and able to endure and succeed in defeating the threat it is deployed to meet.

The "questions" to which I referred earlier center primarily on a debate of the relative levels of defense resources devoted to each of these four pillars. Perhaps the most strident criticism is that we have neglected the readiness and sustainability pillars in favor of force structure and, particularly, modernization.

The Capability Curve

Before dissecting this debate, let me make a few observations regarding our overall objective in resource allocation -- namely, maximize combat capability.

There are generally three ways of assessing capability:

First, a scenario-dependent approach that uses a two-sided combat simulation to assess an "end-product" warfighting capability. In other words, a dynamic net assessment of how well our forces could be expected to perform in combat over time against a specified enemy force. This approach is used by the JCS in conducting its annual assessment of US warfighting capabilities, and is indispensable in this role. But because the basic assumptions such as forces, scenario, and threat change with each net assessment, it is less useful as resource allocation tool.

The second approach to assessing combat capability is the qualitative estimation of commanders in the field. The judgments and opinions of our commanders have been and will remain central in our evaluative process. These commander's assessments are often the only way to include intangible factors such as troop intelligence, morale, and experience in the overall capability assessment.

Finally, we can use a scenario-independent approach that combines static measures, against specific standards, of each component of combat capability into an overall assessment. Although this approach is most often used in our resource allocation decisions; I must tell you that we do not have the ability to synthesize into a single index the effects of changes in all the components of combat capability. Experience tells us that even if we could do this, it would certainly hide many important aspects of warfighting capability, and would not give a full and accurate picture.

The bottom line is that we have no single, direct, quantitative measure or index of combat capability. We cannot draw a single "capability curve" demonstrative of our achievement in improving our warfighting capability.

Measuring the Components of Capability

However, we can go one step deeper into the problem and rather than deal with capability directly consider the components of capability -- the four "pillars." As each component improves, we can justifiably conclude that our capability has improved, whether or not we can articulate a measure of combat capability.

Force Structure is measurable -- we can count the number of soldiers, planes, tanks, and ships. While an aggregate measure of structure is difficult, we at least have an intuitive understanding of the measure.

We can, with a little less certainty, measure sustainability by estimating the number of days of support that are provided by our stocks of munitions, spare parts, and fuel. Aggregate measures are difficult to develop, and a further complication is that "days of support" is a relative, rather than absolute measure. The munitions and spares we would consume in a combat situation is dependent on the forces being opposed -- more enemy planes requires more antiaircraft missiles, for example.

Readiness can be measured only with even greater uncertainty. We have had for several years a system by which most units in force report their readiness -- this is the (by now infamous) UNITREP system. Designed originally to provide a picture of unit status to operational commanders, each unit condenses information regarding personnel and equipment inventories, and training and equipment status, into a single "C-rating." Problems of both aggregation and relativity are magnified in readiness as measured through UNITREP. Moreover, the measurement is incomplete, in that it does not report such clearly important factors such as morale or leadership ability. For these reasons, while UNITREP is both a necessary and desirable report from an operational perspective, it is much less desirable as the basis for construction of a capability curve, especially one projected over time.

Finally, for modernization, the last of the four pillars, we have no direct measure at all. Although we certainly do extensive performance analysis on a weapons system basis, we have no measure of a unit, or force, modernization.

The conclusion is that it is not possible to completely quantify the capability curve. We need to realize that some measures exist for some components of capability, and not for others. We can describe, for example, specific quantitative improvement in aircraft force structure, but can only express in a qualitative sense the capability improvement which results from modernizing F-4 to F-16 squadrons.

The "Debate" Revisited

Given this brief look at what we can and cannot measure, let us return to the debate whose central issue is that readiness and sustainability have been sacrificed for force modernization.

Partially because of this debate, Senator Tower earlier this year asked Secretary Weinberger a series of detailed questions concerning our progress in improving the warfighting capability of our forces. The result of answering his questions was a 125-page report, detailing our progress in each of the four capability "pillars" over the past four years.

In brief, we reported that:

We have not significantly increased our force structure, except for a 10 percent increase in the number of combat ships and two additional Air Force airwing equivalents.

We have made significant progress in force readiness, particular in the personnel area. Our soldiers, sailors and airmen are better educated, better trained, and more experienced. Their equipment is in better shape.

While still short of our sustainability objectives, our investments in munitions and spare parts will result in considerable improvement when delivered.

And finally, our forces are considerably more modern: expanded production of F-16s, and full-scale production of F/A-18s and M-1 tanks lead the list of our major weapons systems modernization efforts.

In short, our report concluded that our warfighting capability had improved significantly over the past four years, although still short of our objectives. The report also noted several deficiencies which we will need to move to correct. Let me mention two of these:

Army Equipment Shortages

In the Army, the introduction of a more modern, more effective and more capable weapon system has in some cases been accompanied by a period of lower readiness for equipment fill during the period of transition when not all of the ancillary support equipment has been delivered and there are no suitable substitutes to offset the shortage. By way of illustration, here is a specific case history:

In January 1982 an Armor Battalion had an equipment on-hand readiness rating of C-1 fully combat capable. In March 1982 this battalion was modernized, and was authorized and received 58 M-1 tanks to replace their 54 M-60 tanks.

When this battalion received its new tanks, it was authorized additional ancillary equipment needed to support the new M-1 tanks. This ancillary equipment included additional cavalary fighting and command post vehicles, mortars, recovery and ammunition vehicles, and night vision, secure voice and chemical detection equipment. Lags in fielding these other newly authorized equipment resulted in this battalion reporting itself not combat ready (C-4) for 28 months, long after the battalion had learned to operate and maintain the new tanks. The point here is that when we modernize, we must also provide enough of the support equipment so that the unit can perform all of the missions for which it was designed. We will continue to pursue these efforts.

Before I move on to the second deficiency, I would like to digress a little to point out that the drop in this Armor Battalion's reported unit readiness did not reflect the overall increase in combat capability resulting from modernization. The M-1 tank is the Army's main offensive weapon. It can outperform any other tank on the battlefield. Tank gunners, while moving rapidly cross-country in the M-1, can routinely hit 5-foot targets from more than a mile away. The M-1s passive terminal imaging system allows target location at night and through dust and fog without disclosing the tank's position.

This battalion is now reporting a C-1 rating. This example, while showing where we need to improve, also illustrates the interdependence of the components of capability, and the confusion that can result when only one component of capability is measured. This battalion's combat capability had clearly increased as the result of modernizing its complement of tanks. Yet at the same time its reported readiness declined from the lag in delivery of additional equipment meant to further enhance their capability.

This points out two of the complexities of the capability curve:

First, a unit's combat capability may increase even while its reported readiness declines. In this example, the problem is that our reporting system, UNITREP, is only measuring the readiness component of capability. We have no quantitative report of the increase in combat capability resulting from modernization, which more than offset the decline in readiness.

And second, unit readiness depends as much on equipment procurement as operations and maintenance funding. In this case, readiness declined not because of lack of maintenance, spare parts or training, but because not all of the new equipment was available to fill the revised authorization. In our efforts to maintain the best balance among the components of capability, we must keep in mind that readiness can be as much as a function of procurement as operations and maintenance.

Sustainability Deficiencies

Now let me turn to another, more serious area of deficiency identified in our report to Senator Tower: our inadequate stocks of war reserve munitions and spare parts for sustainability.

Looking first at munitions, while we have seen more improvement, we are still significantly short of our objectives. At the end of this fiscal year, the Army will have less than 80 percent of its sustainability objective, the Marine Corps less than 50, and the Air Force and Navy 30 percent or less. This has obvious implications for our ability to maintain our combat capability over the course of a conflict.

The picture for war reserve spare parts is no brighter: None of the Services will have more than half of their objective by the end of this year; the Army and Air Force less than one-third. An important contribution to these depressed levels of war reserve spares is, of course, our modernization program. Spare parts once procured for war reserves become obsolete as the weapons systems they support are retired for a more modern replacement.

Although our funding for war reserves spares has grown considerably over the past four years, we must realize that even this pace needs to be accelerated. We have not only to make up current deficiencies, but we must also keep pace with our modernization program.

We should also keep in mind that, especially for munitions, our funding does not only buy sustainability, but is also an integral part of our force modernization process. We are continually replacing older, less effective munitions with newer more sophisticated ones: in the Air Force, for example, you know that the HARM and AMRAAM missiles are modernized replacements for SHRIKE and SPARROW, thereby increasing capability. In the case of the IIR Maverick missile, we are getting a new "launch and leave" capability.

I will return in a moment to this issue of modern munitions, but first let me first summarize what I believe our report to Senator Tower accomplished.

Effect of the Tower Report

Did our report fuel or help defuse the "modernization vs readiness" debate? Probably neither. What I hoped it helped to do was to put the debate in proper perspective.

Stressing the importance of definitions -- readiness is not capability, it is a component of capability.

Articulating what we can and cannot measure -- we cannot fall prey to the trap that that which is measurable is more important than that which cannot be quantified, and finally

Confirming our goal of maximizing capability, and by emphasizing that each of the four pillars is a necessary, but not sufficient, component of overall capability.

Highlighted our significant improvements in US warfighting capabilities over the past four years.

But recognized that there is still room for improvement.

Program Review

The debate is continuing within DoD through the program review and budget process.

We have reviewed the 5-year programs submitted by the Services and have raised many issues. Each of these has the objective of achieving a better balance in order to maximize our overall combat capability.

By way of background, you must realize that this Summer's program review has been particularly difficult in light of the President's promised reduction of $40 billion over the next three years, FY 85-87. The first increment of this reduction took place this past Spring when we submitted to the Congress $15B in proposed reductions to the FY 85 President's budget submitted in January. We are now getting ready to make the second and third installment payment of of this three year reduction. The fiscal guidance to the Services for FY 86-87 has been reduced significantly, and we are seeing the effects in the Services' POMs.

After a thorough review of the POMs, we raised issues on Army and Navy Materiel and Training Readiness, materiel sustainability for all of the Services, and the adequacy of Army equipment inventories. Many of these issues, some of which we won and some of which we lost, involved trade-offs between readiness and sustainability on the one hand and modernization and force structure on the other.

Obviously, these are complex issues with strong arguments for both sides. For example, sustainability funding in FY 86 was significantly reduced in the Air Force POM from the levels projected for FY 86 in the President's budget. Funds that we expected for significant improvements in both spare parts and modern munitions have been once again "bow-waved", or pushed to the out-years of the program. Aircraft procurement was also reduced, but even with these reductions, the Air Force's force structure is programmed to grow.

Our argument was that this reduction reduces the combat potential of the force. When the modern, preferred munitions are not available, the Air Force would have to load its expensive aircraft with less effective munitions. Not only would each sortie so affected be less effective in term of expected target kills, but the expected attrition of the aircraft would rise. Therefore, we suggested trading off aircraft procurement to procure more of these preferred munitions. We made the case that a reallocation of funds from aircraft procurement to the procurement of war reserves for munitions and spares would actually increased combat capability by more than 30 percent.

The arguments in opposition to this position were:

With fewer aircraft, our tactical options would be reduced. An aircraft can only be in one place at a time.

A larger force provides a more credible deterrent. This is, after all, the ultimate objective of Defense spending.

If, as we hope, we are successful in deterring any conflict in the near-term, the total cost may well be greater if we invest in munitions and spares which obsolesce more quickly than aircraft.

As it turned out, we lost this issue -- the DRB decided to accept the Air Force POM. However, I truly believe, as do my Air Force friends who were on the other side of this debate, that this is the kind of healthy discussion that is needed in the DRB. What all sides must appreciate is that there is no single, direct, quantitative solution. Qualitative judgments are a necessary part of the debate, even when some measurable data are available.

A second example involves Navy operations and maintenance shortfalls. Under reduced fiscal guidance, the Navy has proposed some significant backlogs in ship depot maintenance and reductions in operating tempo. Ship construction, however, continues its rapid pace.

A fundamental trade-off is involved here -- the operations and support of the ships we have versus the construction of new ones.

There are several aspects of this trade-off.

Deferral of maintenance on ships that we own may reduce their combat effectiveness. This is equivalent to reducing our inventory of combat ships while at the same time we are building ships to augment our inventory. It is more cost effective to take care of what we have.

On the other hand, the ships that we are building have more capability than the old ones already in the fleets. Thus, although the inventory argument may be correct, it is better to examine the trade-offs in the capability dimension.

Another factor is the fact that we own and operate some older ships of limited capability. Should these older ships consume resources that could be used for the newer sh..., in the fleets?

Our issue added funding to reduce the depot maintenance backlog. We won this one -- that funding is now in the Navy's program.

Readiness and Sustainability

As the DoD advocate for readiness and sustainability, I have to continue to press issues like this.

My objective is to make sure both our short- and long-range programs adequately balance these two pillars with force structure and modernization.

I believe we have been fairly successful in the past four years in achieving an adequate balance, but, to be candid, not without difficulty. And I do not foresee an easy road in the future.

The temptation is great for the Services to prefer hardware acquisition to readiness and sustainability. There are three basic reasons for this:

First, it is organizationally more appealing to invest in tangible assets. Readiness and sustainability are less appealing because they do not represent tangible assets; part their contribution to combat capability is more temporary. Especially in the readiness area, it is obvious that no matter how much we are willing to invest, for example, in training this year, its benefit will rapidly decay unless we continue to invest in subsequent years. Readiness is perishable.

Sustainability, on the other hand, is less perishable than readiness. For example, virtually all of the munitions we buy can be used by our modernized forces -- that is both the F-4s and F-16s can carry the new Maverick missile. However we still need to continue to update the war reserve spares inventories in support of modern weapons systems that replace the less capable tanks, ships and aircraft -- a spare for yesterday's F-4 aircraft will not necessarily be applicable to the new F-16.

The second handicap in readiness advocacy is the problem of linking readiness output to resource input: the "resource-to-readiness" problem. While we do measure some aspects of readiness, we have not been able to demonstrate, in all cases, the specific cause-and-effect relationship. For example, what will be the improvement in Air Force squadron readiness if we increase the flying hour program by 10 percent? What will be the impact on equipment readiness if we reduce spares funding by 10 percent?

Perhaps it is the fact that we do have some measures of readiness and sustainability that leaves one dissatisfied with our inability to completely equate resource inputs to these measurable outputs. While "resource-to-readiness" is a common question, one does not often hear of "resources-to-modernization." I submit this derives from a lack of measurement for modernization, not because the question is any less important.

Finally, there is the misperception that we can "fix" readiness and sustainability problems more quickly than the structure or modernization shortcomings. Those who hold to this point of view believe we should concentrate our near-term resources on what will take us longest to achieve.

It is true that most readiness and sustainability lead times are shorter than the 3-8 years required for fielding tanks, aircraft, and ships. The reality of the situation is, however, that even the shorter lead times to fix readiness and sustainability exceed the strategic warning times we are likely to get before a conflict. We will not have time to "get ready," much less "get sustainable."

Despite these three philosophical impediments to readiness and sustainability funding, I am convinced we have made significant progress. Our forces are clearly more ready today than they were four years ago, by any measure. Our progress in sustainability has been less dramatic and is, in my view, our most serious shortcoming and challenge to us during this and subsequent program reviews.

Conclusion

I have covered quite a broad topic in this address, and hope that you may find some of my observations useful in cutting through some of the confusion surrounding our collective assault on the capability curve.

I would like to conclude by stressing two points:

First, there is much more to the debate than numbers. Capability is a multidimensional commodity, and we have at best only imprecise measures of only some of its components. The debate must necessarily include qualitative assessments and arguments as well as quantitative analysis; to neglect this is to argue only part of the problem.

Second, readiness and sustainability characteristically take an organizational back seat to force structure and modernization, and require a strong external advocacy to remain in balance. I hope to continue to able to provide that.

ADDRESS
BY

BRIGADIER JIM GROOM
Ministry of Defence

Chairman Defence Explosives Safety Authority
Chairman Explosives Storage and Transport Committee
Vice President, Ordnance Board
London, Great Britain

at

Twenty First Department of Defense Explosives Safety Seminar

Houston, USA

28 August 1984

Explosives Storage and Transport Committee
Explosives and Ammunition Study

Good morning, ladies and Gentlemen:

I am indeed honoured to address this distinguished gathering of explosives safety experts here today. My thanks go therefore to the Department of Defense Explosives Safety Board and to Captain Otis Brooks for inviting me to speak.

At your last meeting my predecessor spoke to you on the implications of the United Kingdom 1974 Health and Safety at Work Act for the safe management of military explosives. He told you about our Ministry of Defence Explosive Safety and it relationship with a new joint Ministry of Defence and Ministry of Employment Committee called the Defence Explosives Safety Authority. This new Committee has responsibility to supervise within the Ministry of Defence the management and implications of explosives safety procedures and regulations to ensure that the safety of the general public is at all times being taken into account. He explained to you how the implications of all this are that the Ministry of Defence no longer has sole control at all times over military explosives other than in an operational situation.

I am presently the Chairman of this new Defence Explosive Safety Authority and am happy to say that many of the military's fears have been proved to be unfounded and that in no way has the civilian involvement impaired the Ministry of Defence in their day-to-day satisfactory and effective management of military explosives. Indeed the involvement of the civilian health and safety executive has in many instances been positively beneficial, and in particular where support for additional money or effort has been needed to improve safety.

The subject of my talk today is one of the problem areas that we have known about for some time, and which has really been brought to a head by this new concordat between the military and their civilian counterparts. It is the part that risk and hazard analysis has or may have in our management of the safe storage of military explosives.

Like most of you, the United Kingdom makes use of quantity distances criteria for the siting of explosives storage facilities. In past years with plenty of space and open fields this has not proven a problem. However, the recent increases in population within the UK and movement out of our major cities has brought about the encroachment of inhabited buildings around our explosive storage areas and we now find that in many instances a waiver or concession is necessary to in some way permit a breach of statutory quantity-distance criteria in order to enable the Ministry of Defence to continue effectively to store its explosive munitions. Our 1875 Explosives Act gave to our Secretary of State for Defence the right in law to make such concessions. However, as explained to you by my predecessor, our new 1974 Act removes that right. Our civilian health and safety executive accepts that in order to carry out its business, Ministry of Defence concessions already in force must temporary continue: However, they are insistant that any new explosive storage facilities should not required a concession and that the need for existing concessions be phased out as soon as possible. Indeed they look on concessions as being a breach of todays law albeit in the short term a necessary continuation of the old law.

To build new facilities is very expensive and not always possible. To discontinue the use of a store or to reduce the quantity of explosive in a particular store is not always militarily possible. We have to find a different but acceptable alternative.

The politicians argue that the military have not had a recent major explosive accident, have not killed anyone, and that as such our present quantity-distance criteria is too safe and thereby unnecessarily costing the tax payer too much money. For example we have a jetty used to load army munitions onto ships. The jetty is old and in need of replacement. The present jetty when built was in open countryside. Over the years the local council has allowed houses to be built near the jetty and today it operates under a concession. To replace the present jetty and continue the concession will cost 40m pounds, to build a new jetty free of concessions will cost 80m pounds. The big increase in cost being because of the new approach roads etc which will have to be built. The other side of the coin is that our quantity distances are such that if there is an explosive incident, there will only be minimal damage to buildings and a low probability of injury to people, i.e., that the government of the day will not be politically embarrassed other than by the actual explosion itself.

After much heart searching, the United Kingdom has accepted that perhaps total reliance on quantity-distance criteria may be unnecessarily demanding and that risk and hazard analysis could perhaps offer a less expensive approach. We accept taking account of sound design and of good storage and handling procedures the present quantity-distance criteria in some situations may be unnecessarily too safe. Looked at as a tax payer this may well be how the situation is seen: But looked at by someone whose house is close to the ammunition store, then rather different views may prevail. The problem now is to know what degree of risk and hazard is acceptable to the general public without degrading the level of safety we presently have with our quantity-distances.

Each location is going to pose a different scenario and require its own risk and hazard analysis to try and agree an arrangement whereby the military and the local population are happy that there is a safe situation. Let me explain what I mean.

Until our 1974 Act came into force, local government did not have to seek permission for giving local planning permission. A particular council gave authority for a sports centre to be built within the yellow line distance of a quayside where explosives were loaded onto a ship from a nearby explosives factory. The local council said the factory must stop loading explosives. The factory said that if they did that then the other alternatives for movement of explosives would be uneconomic and the factory must close. This was not at all what the council had in mind as it was many of the factory workers who would use the new sports centre, and if they lost their jobs would not be able to afford to continue to use it. It cost the council and the factory 700,000 pounds to carry out a risk and hazard analysis study to arrive at a mutually acceptable arrangement such that both the factory and the sports centre would continue to function. In no way could the British Ministry of Defence afford to pay 200,000 pounds, at each location where a risk and hazard analysis study may be considered necessary.

I would also draw to your attention that in the situation I have just described, both parties to the risk and hazard analysis study, the factory and the local council, were wanting a mutually acceptable arrangement. There is no guarantee that where a military explosive store is concerned, that the local population will be willing parties to a mutually agreed arrangement. I can well see the local civilians wanting the explosive store closed.

To address this problem and come up with a way ahead, the United Kingdom has decided a study is necessary. The study will be controlled and funded by the Ministry of Defence, whilst much of the work will be done under contract by civilian consultants in risk and hazard analysis. The results must be recognised as being free from military bias if they are to be accepted by the general public, and our civilian health and safety executive will be involved from the start. The study will take at least 3 years, probably 4 years, and is accepted as being unlikely to contribute to the solution of immediate storage problems.

It has taken eighteen months for senior management and politicians to agree to embark on such a study and which has included acceptance that, for a variety of reasons, the outcome may bring to light further as yet unforeseen problems. The terms of reference of the study are as on this slide:

a. To carry out a study into methods of hazard and risk analysis with a view to developing a basic methodology that could be applied to the storage, processing and handling of non-nuclear military explosive stores and munitions bearing in mind the interaction with operational and training environments.

b. To assess the transferability of the basic methodology from one situation to another.

c. To assess whether or not the complete methodology is necessary in every situation.

d. To prepare a manual describing the basic methodology.

e. To make recommendations on what is an acceptable risk for her majesty's government.

f. To undertake an audit of the quantity distance rules.

We want a basic risk and hazard methodology such that the study at each particular location will not cost us 700,000 pounds.

With regard to 5. this is interesting. It originally read 'To make recommendations on what is an acceptable risk to the general public'. It was changed by the politicians to its present wording and since democracy is the act of getting enough votes to win an election, I believe it is a better reflection of reality.

Management of the study is by a steering committee chaired by the principal of our royal military college of science. The composition of the steering committee is on this slide.

In addition there is an independent adviser who is a man of recognised national ability in the field of risk and hazard analysis. He will be a civilian, possibly an academic, and help to redress any military bias. His particular job is to advise the steering committee and to supervise and comment independently on its work and findings. He is not a member of the steering committee and reports directly to me as does the chairman of the steering committee. At various stages of the study I shall receive reports form the steering committee, together with the independent views of the independent adviser on the steering committee reports.

It is the job of the steering committee to think through how the study should be done and to make a plan. To make the necessary arrangements to have their plan implimented, to receive reports, resolve queries and to make decisions.

They will financially manage the study, and report to me at predetermined reporting stages. Nine million pounds is available upto 31 May 1986, and the steering committee are required to advise me what further monies they will require after 31 May 1986 to complete the study.

The United Kingdom has carried out similar studies in a number of risk areas, in particular the chemical, petrolchemical, and bulk liquid areas. The study I have described is recognised as a national study probably with implications also for civilian explosives. It may be that some of you will also be interested in it.

ESTC Explosives and Ammunition Study

Terms of Reference

1. To carry out a study into methods of hazard and risk analysis with a view to developing a basic methodology that could be applied to the storage, processing and handling of non-nuclear military explosive stores and munitions bearing in mind the interaction with operational and training environments.

2. To assess the transferability of the basic methodology from one situation to another.

3. To assess whether or not the complete methodology is necessary in every situation.

4. To prepare a manual describing the basic methodology.

5. To make recommendations on what is an acceptable risk for HMG.

6. To undertake an audit of the quantity distance rules.

ESTC Explosives and Ammunition Study

Steering Committee

Chairman - Principal of Royal Military College of Science/Cranfield

Members - Royal Navy (1)
Army (1)
Royal Air Force (1)
Procurement Executive (1)
Royal Ordnance plc (1)
Health and Safety Executive (2)

Independent Adviser

Recognised national authority on risk and hazard analysis

ADDRESS
BY

BRIGADIER M. H. McKENZIE-ORR
Ministry of Defence

President Australian Ordnance Council

at

Twenty-First Department of Defense Explosives Safety Seminar

Houston, USA

28 August 1984

THE PARADOX OF RISK ASSESSMENT

BY BRIGADIER M.H. MACKENZIE-ORR OBE GM

PRESIDENT AUSTRALIAN ORDNANCE COUNCIL

Introduction

1. Over the years a number of erudite papers have been presented to these seminars on the problems associated with the manufacture, transport, storage and use of explosives for and by Defence Forces. The famous 'American Table of Distances' published in 1909 and quoted by Hans A. Merz of Ernst Basler and Partners in his paper to the 20th Explosives Safety Seminar in 1982(1) introduced the basic assumption that beyond specified safe distances damage to personnel and structures resulting from explosives should be minimal. The philosophy behind this basic assumption still applies although a vast literature has been produced to attempt to define the elements of the philosophy and considerable experimentation to validate the assumptions inherent in it has occurred.

2. In Australia, with its vast land mass and small population of 15 million it may be thought that the provision of adequate safety distances between potential explosion sites and the public would present no great problem. Unfortunately the places selected by the Defence Forces for their activities in the early days of the Nation are now enveloped by the expansion of the public domain and the application of the quantity distances detailed in NATO Regulations is no longer a simple matter. Although something of a 'finger in the dyke' attempt to impose some control on encroachment the Australian Ordnance Council produced a Proceeding entitled "Safeguarding Guidelines" which laid down a method for producing safeguarding maps for all explosive sites as a preliminary to assessing non compliances with NATO Regulations(2). As expected, the production of the Safeguarding maps revealed a number of areas where compliance with NATO Regulations was impossible.

3. It is possible to overcome the problems of non compliance with regulations in many ways:

   a. We haven't had an explosion involving injury or damage to the public in living memory - the regulations are clearly wrong - change them.

   b. Move or modify the explosive site to comply with the regulations.

   c. Modify the site or the activities in which it engages to comply with the spirit if not the letter of the regulations.

   d. Move the public.

4. Each of these solutions has its proponents with a. and d. most favoured by the senior operational commanders, b. by the politicians (representatives of the public), c. by the pragmatists and none of these by the accountants. The most frequent questions asked are "What are the implications of not complying with the regulations (the penalties)? and, by the more discerning "What is the effect if we do (the benefits)?

5. In a paper given by LtCol Alan C. Graham Jr[3] at the 20th Seminar the statement was made "Eighteen months ago, the Air Force Safety Center decided that our conservative safety standards and our traditionally conservative interpretation of those standards prevented maximum or effective use of existing facilities and were a strongly negative influence on readiness and combat capabilities." This statement would be heartily endorsed by our Defence Force commanders who would obviously like to see their all too small budget allocations going towards improving the combat effectiveness of their forces and not towards reducing the effects of mishaps with the limited amount of weaponry available.

6. My paper aims to discuss the problems associated with the assessment of explosive risk and to provide some indication of the way in which we are tackling the problem in Australia.

7. In their treatise "Acceptable Risk",[4] Fischoff and others examined the possible approaches to making acceptable risk decisions. We all make decisions and take risks many times a day. In many instances the decisions are intuitive and their effects limited to the achievement or non achievement of personal goals. It is when the benefits or penalties begin to assume significant proportions that we tend to search for more objective methods of decision making and eschew the intuition which lands our wives with unworn and unwanted souvenirs of attendance at an overseas seminar. Fischoff et al make the point that there is never a single solution to acceptable risk problems and further that todays solution may be inappropriate or even irrelevant to tomorrows problem. This is particularly true of problems involving acceptable risks posed by Defence Force activities. In yesterdays and tomorrows wars, actions, which in times of deepest peace would be unthinkable, become commonplace. In the recent Falklands "war" the preparation of the British Armada, the ammunitioning of ships, the transport and storage of explosives and munitions probably involved major contraventions of NATO Regulations for the storage, transport and handling of explosives but in the circumstances the risks would have been deemed acceptable if indeed they were considered. When the horseless carriage first emerged it was deemed unsafe to allow it on the public roads without the man with the red flag preceeding it on foot. When one looks at modern automobile accident statistics one wonders if the Decision makers of the turn of the century were not correct.

8. In Northern Ireland where I once served as a bomb disposal officer (an example of voluntary risk) there are some 12,000 police and 17,000 military personnel mainly concerned with internal

security. A view of the statistics for deaths due to road accidents and those due to terrorist acts suggests that the majority should be traffic policemen. The point to be made is that it is not just the risk of injury or damage which determines its Acceptability - the nature of the event leading to the injury or damage is a factor of major significance.

9. In his paper presented to the 20th Seminar "Risk Analysis - Grasping the Nettle", R.R. Watson(5) of the UK HSE described the application of techniques of risk analysis to the problems of incompatible bedfellows in the UK, a busy explosive wharf and a large leisure centre. In this case the creation of the problem resulted from a decision to build a leisure centre by community leaders who were obviously unaware or uninfluenced by a very relevant local factor, or indeed of the Port Chicago disaster. In this case the nettle to be grasped is the endorsement of a proposal, which acknowledges a risk of serious casualties, by politicians or community leaders. They are quick to perceive benefits but rarely acknowledge penalties. The nettle must be grasped and it must be grasped by the representatives of the population exposed to the risk.

10. The next problem is that of precedents. I suppose that the representatives attending the seminar can congratulate themselves on the fact that there have been very few explosions involving Defence explosives which have led to injuries or damage to the public since WWII. In most cases such incidents can be attributed to tampering, breaches of safety procedures or human error and rarely to faults in the explosive or munitions. The emphasis on munitions development is on safety and survivability. The Bootlegging or statistical inference techniques for estimating the risk of mishaps which depend on an adequate and relevant data base are of limited help. The data base does not exist. In his paper to the 20th Seminar Lloyd L. Philipson(6) analysed the applicable risk estimation methodologies, their advantages and disadvantages. They are:

a. Statistical Inference;

b. Fault Tree Modelling;

c. Analytical/Simulation Modelling; and

d. Subjective Estimation of Risk Parameters.

There is no doubt that all are used (and abound) in the management of explosive risk. The financial, spatial, social and operational pressures on the personnel responsible for the management of explosive risks require them to develop the applications of such techniques for the successful discharge of their responsibilities.

<u>The Australian Approach</u>

11. Having adopted the UN Hazard Classification System and NATO Regulations for the storage, handling and transport of

explosives in 1981, the Australian Ordnance Council was charged with advising the Chief of the Defence Force on the implementation of the system. In common with many nations the Australian Defence Forces had attempted to comply with a variety of regulations of international, Federal, State and statutory body origin with varying degrees of success and with frequent recourse to waivers or concessions approved with varying degrees of formality. Following the adoption of the NATO Regulations the Safeguarding Guideline Proceeding was produced and all Defence Installations processing, storing, transporting or handling explosives were required to produce Safeguarding Maps. This process is continuing with considerable complexity where more than one independent Defence Installation shares a site with overlapping quantity distances from explosive facilities developed independently. In the case of single Service installations the problems in producing safeguarding maps are less complex although the implementation of the regulations is often far from simple. As the complexities were revealed it was decided to deal first with the public risk and then with the internal or Defence community risk. In the case of public risk approval of waivers or concessions will be the responsibility of the Minister and for internal risks of senior service delegates nominated by the Minister. In all cases applications for waivers will be supported by risk assessments which may be independently evaluated by the Australian Ordnance Council before Ministerial approval for a fixed term is granted.

12. As an example of the way in which the problem is being tackled I propose to describe the Naval system for ammunitioning ships in Sydney Harbour.

13. Sydney was first settled in the 18th Century, following the American war of independence, as a penal colony because the new United States of America declined to further accept the overflow of felons from British jails. Law and order in Sydney was initially established by the Royal Navy and enforced by Royal Marines. The history of Naval activity in Sydney's waterways thus predates the foundation of the city itself. As the city grew to its present position as Australia's largest population centre (about 4 million people), Naval activity increased proportionally and the city has always been the home port of the Australian fleet. The harbour also developed into the largest maritime complex in Australia as well as becoming a major leisure centre for the people of Sydney. There is now the situation where the Australian fleet's major wharf, engineering, maintenance and supply facilities are literally centered in the main commercial and leisure centre of a large metropolis.

14. After the introduction of the NATO Safety Principles, the AOC was asked to examine RAN ammunition logistic activities and advice the effect of these activities on the safety of the public. A summary of these activities is now appropriate. Munitions are transported by road from inland storage depots, through the city's suburbs to an upriver storage and wharf area situated amidst residential, industrial and recreational facilities.

The munitions may be then unpacked, or inspected and then loaded across the wharf into lighters for transhipment dwon river to the harbour. During this trip, it was possible for the lighters to be left at a holding point in the actual harbour for some months. The lighters then moved to ammunitioning buoys in the main harbour to ammunition ships of war. De-ammunitioning is a reverse of this process.

15. Our study was developed in two phases conducted concurrently. Phase 1 was a study of regulations and procedures controlling the activity and Phase 2 was a traditional risk assessment of activity stages. The Phase 1 study showed where regulations and procedures were considered deficient and provided remedial advice. The second phase proved more difficult. Using conventional statistical and hazard analysis techniques the various stages of the logistic chain were examined. Currently used techniques were only appropriate for land transport activities. A lack of maritime accident data made it impossible to quantify the risk to the public. Estimates could only be made using purely subjective data. This lead to a third phase of the study where we decided paradoxically that though we couldn't determine the risk to the public we would reduce it. Again each stage of the logistic chain was re-examined and procedures to lessen or contain to some degree the effects of an untoward event were recommended. The study thus utilized the four methodologies mentioned earlier ie:

a. Statistical Inference;

b. Fault Tree Modelling;

c. Analytical/Simulation Modelling; and

d. Subjective Estimation of Risk Parameters.

The residual risk to the inhabitants of Sydney is deemed acceptable but is to be reviewed annually.

Conclusions

16. The strict application of the United Nations Hazard Classifications and NATO Regulations for the storage, handling and transport of explosive ordnance has been made impossible in some cases due to:

a. Increasing encroachment of public facilities into areas which affect quantity distances.

b. Increasing quantities of more energetic materials in modern explosive ordnance.

c. The need for higher combat readiness and efficiency.

17. Whilst the application of regulations will continue to be the aim the use of hazard and risk analysis to achieve an acceptable balance between safety and combat efficiency will be increasingly utilized in the next decade.

18. Paradoxically, having devoted a great deal of effort to establish the Regulations which are an attempt to limit the risk to the public from Defence Force EO, we are now devoting even greater efforts to avoid having to strictly implement the regulations we have designed.

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2. Australian Ordnance Council Proceeding 8/83 - "GUIDELINES ON SAFEGUARDING FOR EXPLOSIVES AND MUNITIONS FACILITIES".

3. "RISK ANALYSIS FOR EXPLOSIVES OPERATIONS" - LtCol Alan C. Graham, Jr HQ Air Force Inspection and Safety Center. Presented to 20th DDESB Explosives Safety Seminar 24-26 Aug 82.

4. "ACCEPTABLE RISK" By B. Fischoff, S. Lichtenstein, P. Slovic, S.L. Derby, and R.L. Keeney. Published by Cambrigde University Press NY 1981.

5. "RISK ANALYSIS - GRASPING THE NETTLE" - R.R. Watson Presented at 20th DDESB Explosives Safety Seminar 24-26 Aug 82.

6. "GENERAL RISK ANALYSIS METHODOLOGICAL IMPLICATIONS TO EXPLOSIVES RISK MANAGEMENT SYSTEMS" by Lloyd L. Philipson. Presented to 20th DDESB Explosives Safety Seminar 24-26 Aug 82.

DEPARTMENT OF THE ARMY
FACILITY SYSTEM SAFETY (FASS)
PROGRAM

BY
ROBERT D. DEMPSEY

US ARMY CORPS OF ENGINEERS
HUNTSVILLE, ALABAMA

The Department of the Army is in the process of implementing a new approach to safety in the design of military facilities. This new program, the Facility System Safety (FASS) program, is designed to apply system safety engineering and management principles to identify hazards and reduce risks associated with new facilities to a level consistent with mission requirements.

The requirements for establishing this new program have been evolving since 1976 in a number of DOD and DA publications. The initial requirements just tacked the facilities requirement onto the existing systems safety requirements for new weapons systems without recognizing the differences between the life cycles and procurement methods. The FASS Program requirements are currently established in four publications:

1. DODI 5000.36, Systems Safety Engineering and Management.
2. MIL-STD-882, Systems Safety.
3. AR 385-10, Army Safety Program.
4. AR 385-16, Systems Safety Engineering and Management.

The DODI establishes two policy goals for the FASS Program. The first goal is to utilize system safety programs to ensure the highest possible degree of safety and occupational health consistent with mission requirements is designed into DOD facilities. The second directive is to place primary emphasis on the identification, evaluation and control of hazards prior to the construction of facilities. These policy goals have been implemented by the Department of the Army in the form of responsibility assignments to the Corps of Engineers (USACE).

Initial efforts to establish the FASS Program began within the Headquarters of the Corps in FY83. The situation facing this new program appeared pretty bleak indeed. In too many cases, poor communication between user installations and Corps districts regarding facility safety requirements was causing expensive retrofits of newly completed facilities. Other problems were being caused by a lack of understanding of the Military Construction process by the users. Within the Corps, there was poor accountability for facility design and construction changes affecting safety. Overall within the Department of the Army there appeared to be both a poor allocation of the existing safety resources and inadequate staffing to properly address facility system safety.

The FASS Program still has not received any manpower allocations, but work has begun to implement the program on a test basis. The first phases of this program are being directed by the Headquarters, USACE with technical support from the Huntsville Division. The Huntsville Division is one of 14 Divisions within the Corps of Engineers. Unlike the other Corps Divisions, Huntsville has no subordinate districts and no geographic boundaries. Huntsville serves as a special purpose agency working on programs that involve high technology and that are national and international in scope. The technical support for the FASS program was placed in Huntsville to take advantage of the safety engineering expertise and systems safety experience that our Division has gained from working on NASA Test Facilities, Army Chemical Demilitarization

Facilities, DOE Coal Gasification Plants, and other complex facilities that have had system safety requirements in their design and construction.

The FASS Program is being planned to work as closely as possible within the existing military construction program. The scope and requirements for the FASS Program will be initiated by the user during the programming cycle for each project. By changing the emphasis of the safety efforts to the earlier stages of a facility's life cycle a number of benefits are foreseen. The highlights of the program are shown here.

I feel sure that most of you have at least some familiarity with the safety cycle for military construction projects. I wonder however, how many of you are aware of how this safety cycle relates to the major steps in the MCA facility life cycle.

During the Programming and Requirements Development phase of a project the user is responsible for:

1. Making safety input to the DD FORM 1391. Once the FASS Program is fully operational Corps planning for system safety actions will be prompted by the insertion by the user of requirements in the DD 1391.

2. Developing and keeping updated the Preliminary Hazard Analysis for the facility.

3. Making the initial decision on the scope of the facility system safety program. This decision is to be based upon the outcome of the PHA and the overall complexity and estimated cost of the project.

4. Preparing the Safety Site Plan for projects involving ammunition or explosives.

5. Generating a list of special safety requirements that are applicable to the design of the facility.

6. Making the safety input to the Project Development Brochure (PDB). The PDB will continue to be the most important document in the design phases of the facility life cycle. The safety information generated by the earlier action in the Programming and Requirements Development phase must be properly incorporated into the PDB if the facility is to meet the expectation and requirements of the user.

I would like to point out to you that the special safety requirements list should include any documents that are not a a part of the Corps' basic design guides. You will notice that this list does not include any safety regulations. Regulations such as AR 385-64 or DARCOMR 385-100 which may provide vital requirements for the design must be specifically identified in the PDB. Requirements for such things as grounding, safety chutes, lightning protection, barricades, and quantity distance must be clearly established. The Corps of Engineers is available to work with the user on a cost reimbursable basis in developing requirements and criteria during this user controlled phase of the project life cycle.

The major responsibility for management of an MCA project shifts from the user to the Corps at the beginning of the Concept Design phase. This shift also occurs in the safety responsibilities for the project. The user maintains a responsibility to review the Corps actions and for submission of the Safety Site Plan. It is critical that the user submit the Safety Site Plan as early in the cycle as possible using the PDB drawings and sketches. Approval of this document must be received prior to entering the Final Design Phase. Another early action in Concept Design that the user may also participate in is the selection of the design A/E.

The Corps maintains the lead role for design safety during the Final Design Phase with the user primarily in the role of critical reviewer. One of the biggest potential stumbling blocks in this phase of the facility life cycle is the preparation and submission of the Safety Submission by the user. It is imperative that this submission be made no later than the 60% final design submission so that the impact of any MACOM or DDESB required changes can be minimized.

The final design drawings and specifications form the basis for the construction contract. If a safety requirement is not included in these documents most likely it will not be in the completed facility. While the Corps is responsible for all safety aspects of Army construction, the working relationships established during the design phases and the involvement of user safety personnel will be continued during the construction phase. The user will need to review carefully the contract and any changes to it that affect the design. For complex and high dollar value projects a formal configuration control procedure may be necessary to assure proper coordination. On-site safety audits to assure that the construction matches the contract and meets regulatory requirements will also be planned for these complex projects at approximately 60% completion. This action will allow time for any necessary changes to be made prior to construction close-out without adversely affecting the beneficial occupancy date, BOD.

At BOD, the Corps hands the responsibility for safety and the facility back over to the user. The Corps is not out of the facility life cycle however since the disposal of facilities and real estate is a Corps function. For facilities that handle toxic or hazardous materials, the user will need to establish and maintain good records of operations, accidents, and decontamination.

The proper integration of system safety engineering and management actions into the MCA facility life cycle is essential to reduce the level of risk in new Army facilities. As you have seen in the FASS Program the user will be most heavily involved in the early stages of facility development. The Corps becomes heavily involved in the middle stages of design and construction of the facility life cycle. With proper coordination of user and Corps safety efforts a safe facility can be designed and constructed.

Once the FASS Program is fully operational it is expected to provide the Army with a number of benefits.

1. Better allocation of safety resources. Currently too much of our financial and manpower resources are tied up in the very last days of the construction phase and the early days of the use and operation phase. With

the implementation of FASS we expect to change these profiles considerably to the benefit of the Army.

2. Lower cost of facilities due to less retrofit actions.

3. Fewer delays and change orders.

4. Fewer modifications after occupancy due to noncompliance with safety requirements.

5. Safer operation after occupancy.

6. And overall a more "Mission Responsive" facility.

The Corps has completed a number of actions and has others underway.

1. A contract clause for facility system safety has been written and approved.

2. A technical support center for facility system safety has been established within the Huntsville Division.

3. A FASS Program support contract has been awarded by the Huntsville Division to JRB Associates. Under this contract JRB Associates will develop the overall FASS program guidance manual, survey existing system safety training, develop a training plan, and conduct a field test of the proposed system. This field test will have JRB actually performing systems safety assessments and evaluations of three high hazard facilities currently being designed for construction at Aberdeen Proving Grounds, Maryland.

Actions planned for the near term for the FASS Program are:

1. Development of tailored data item descriptions for items such as System Safety Assessments, System Safety Engineering Reports, and Hazard Analyses that more nearly represent the facility design requirements than those prepared for weapon system development.

2. Establishment of an open-end contract to support system safety and hazard analyses on future military facility design projects.

3. Survey of existing hazard tracking file techniques and automated lessons-learned data bases.

4. Revision of Army regulations in the 385 and 415 series to more clearly define FASS Program requirements.

Our long term actions that are anticipated include:

1. Establishment of the capability within the Corps to perform FASS Program requirements for all user identified projects.

2. Establishment of an automated hazard tracking file and lessons-learned system.

3. Establishment of a FASS training program that is available to user, Corps, and contractor personnel.

US Army Corps
of Engineers
Huntsville Division

Department of the Army Facility System Safety (FASS) Program

US Army Corps
of Engineers
Huntsville Division

FASS Program Requirements

- DODI 5000.36
- MIL-STD 882B
- AR 385-10
- AR 385-16

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DoD Policy Statement

1. System safety programs shall be used to ensure the highest possible degree of safety and occupational health consistent with mission requirements is designed into DoD facilities.

2. Primary emphasis will be placed on the identification, evaluation, and control of hazards prior to the construction of facilities.

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USACE Facility System Safety Responsibilities From AR 385-10 & AR 385-16

AR 385-10

1. All Safety Aspects of Fire Prevention/Protection
2. Safety in all Army Construction
3. Compliance with OSH Standards in Design, Construction, and Renovation of Facilities

AR 385-16

1. Control or Eliminate Hazards in Facilities Prior to Construction Phase
2. Insure that a Hazard Assessment is a Part of all Facility Design Reviews

Problem Areas

- Poor Communication Between Users and USACE Regarding Facility Safety Requirements
- Lack of Understanding of MCA Process by Users
- Poor Accountability for Facility Design & Construction Changes Affecting Safety
- Poor Allocation of Existing Safety Resources
- Inadequate Staffing or Expertise to Properly Address Facility Safety.

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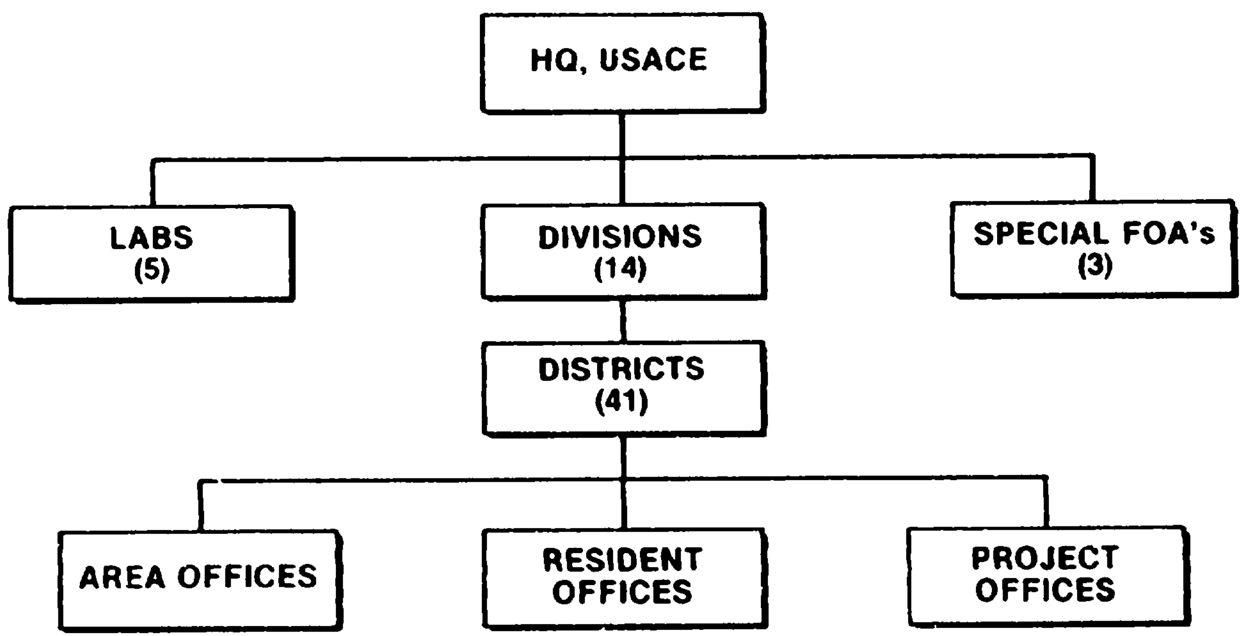
USACE Organization



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Highlights of the FASS Program

- Works Within Existing MCA Framework
- User Initiated
- Changes Safety Emphasis to Earlier Stages of MCA Facility Life Cycle
- Provides for Accountability & Tracking of Hazard Resolution
- Integrates Safety Efforts of User & USACE
- Improves Safety Communications Between User & USACE

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Safety Cycle For MCA Projects

Safety Site Plan

Safety Submission

Supplemental Safety Submission

Pre-Operational Surveys

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Major Steps in MCA Facility Life Cycle

- Programming & Requirement Development
- Concept Design
- Final Design
- Construction
- Use & Operations
- Disposal

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Programming & Requirements Development

- Safety Input to DD 1391
- PHA Developed & Updated
- Initial Decision on Scope of Facility System Safety Program
- Safety Site Plan Prepared
- Safety Requirements List Generated
- Safety Input to PDB

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USACE
Basic Design Guides

1. DoD 4270.1M, DoD Construction Criteria Manual
2. DA Technical Manuals 5-800 thru 5-899 Series
3. USACE Engineer Technical Letters
4. Division/District Design Manual
5. USACE Standard Designs

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Concept Design

- Safety Site Plan Submission
- Incorporate Safety Requirements in Contract
- Select Designer
- Develop Facility System Safety Plan
- Perform Hazard Analysis
- Develop Concept Design Plans & Analyses

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Final Design

- Follow Thru on Facility System Safety Plan
- Develop Final Design
- Prepare & Submit Safety Submission

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Construction

- Incorporate Safety Requirements in Contract
- Conduct Safety Audits & Evaluations
- Manage Changes to Contract
- Provide User With Unresolved Hazards List

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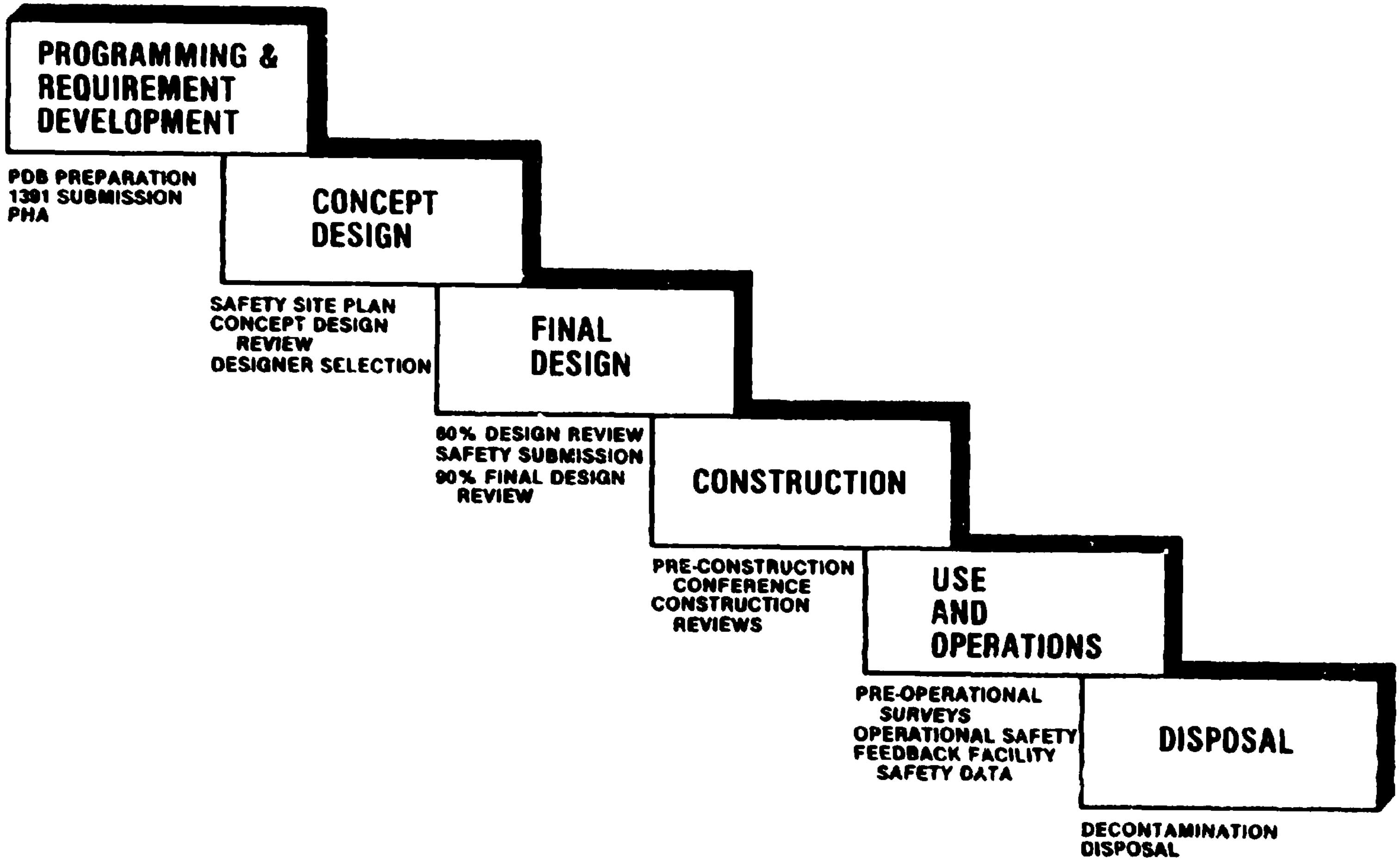
Use & Operations

- Survey Facility to Determine Residual Hazards
- Develop SOPs
- Develop and Conduct Training Programs
- Conduct Inspections and Evaluations
- Collect, Compile and Analyze Statistics
- Feedback Facility Safety Data

MCA Facility Life Cycle



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User Most Heavily Involved in Early Stages

- PHA
- Define Scope of Facility System Safety Program
- Safety Requirements Development
- Programming and Planning
- Early Design Reviews

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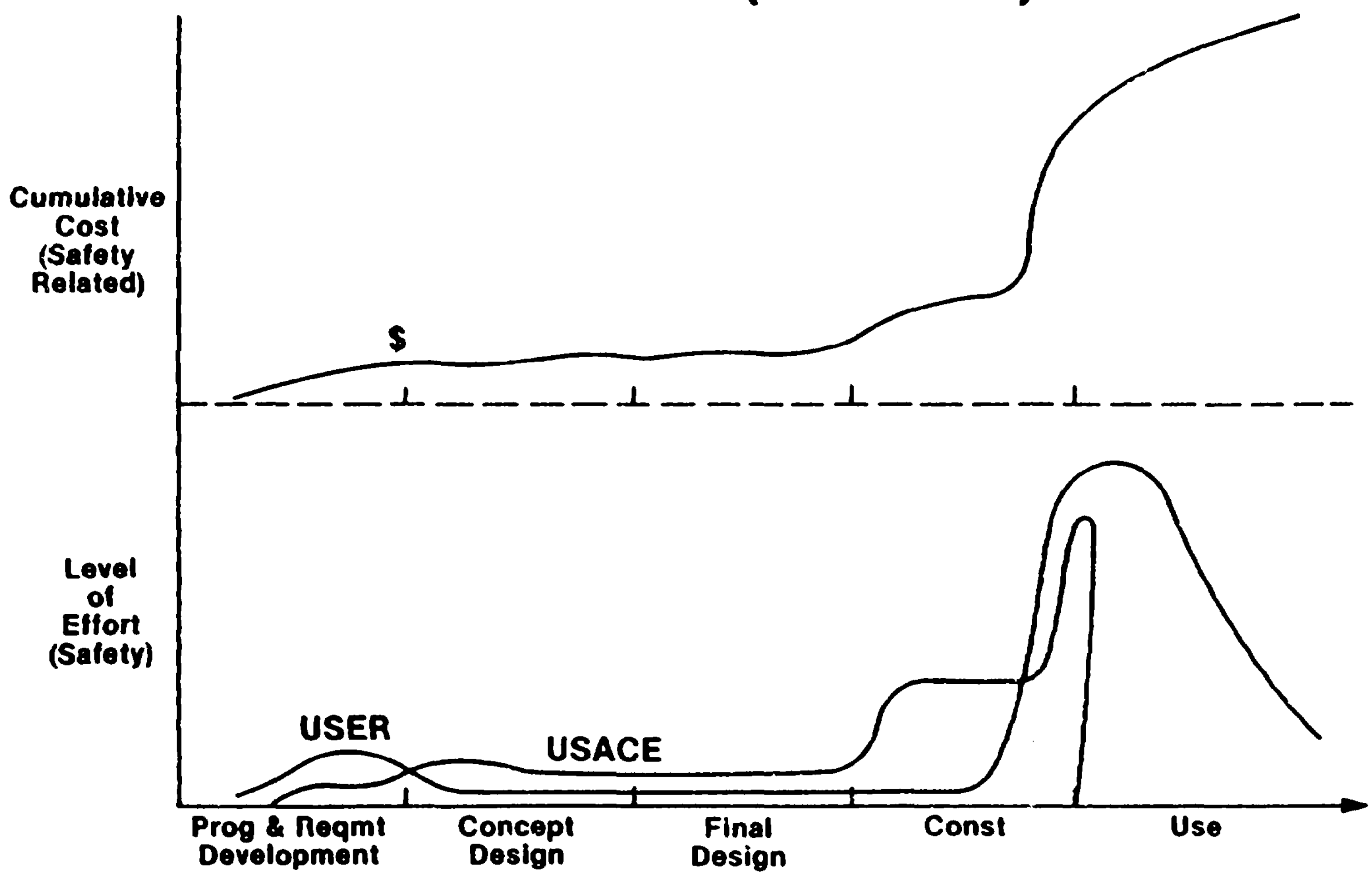
USACE Most Heavily Involved in Middle Stages

- Incorporate Safety Requirements in Design and Construction Contracts
- Review & Monitor Contractor Safety Effort
- Design and Change Order Reviews
- Conduct Audits for Facility Safety Features

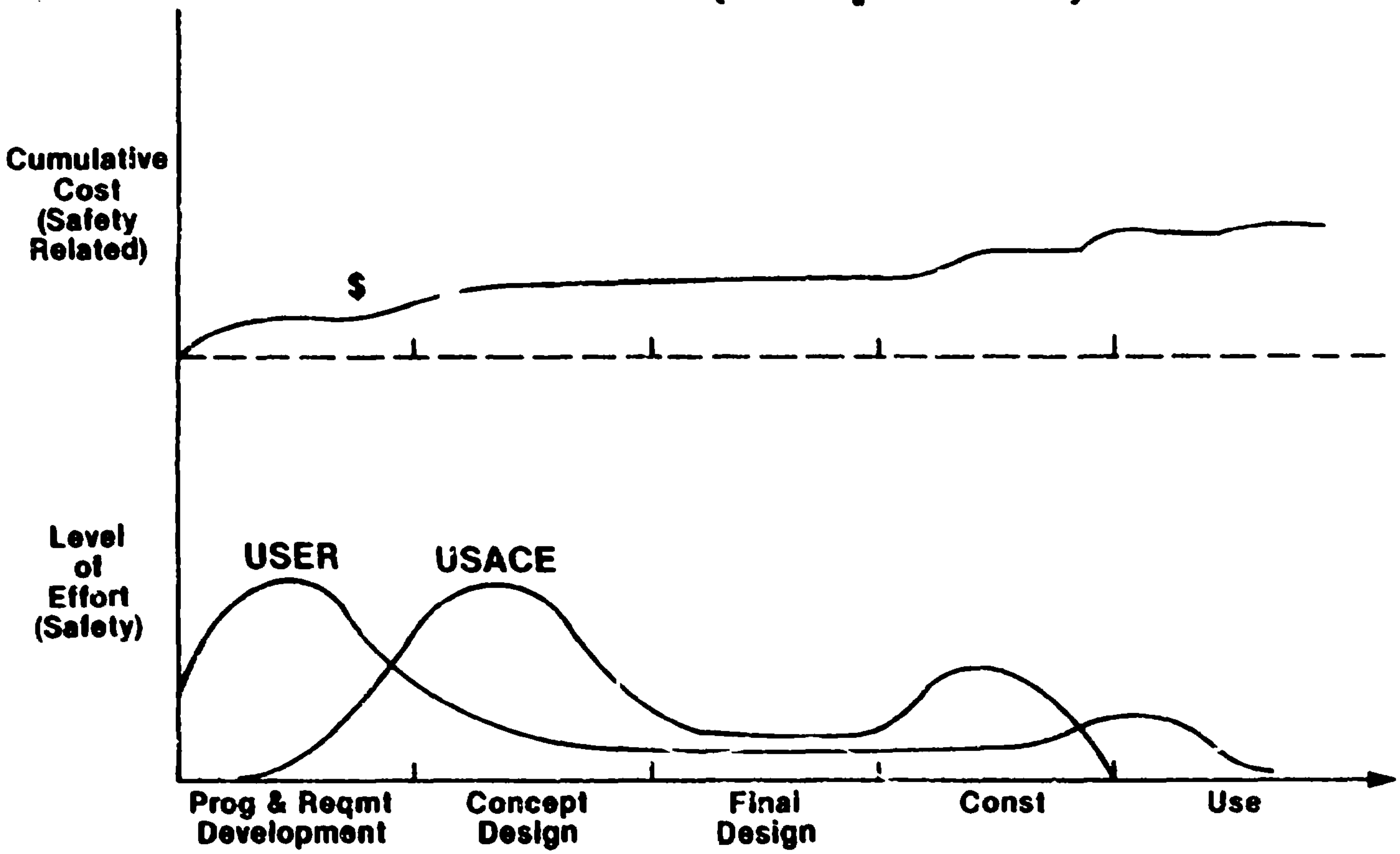
Benefits

- Better Allocation of Safety Resources
- Lower Cost (Less Retrofit)
- Fewer Delays
- Fewer Change Orders
- Fewer Modifications After Occupancy
- Safer Operation After Occupancy
- A More "Mission Responsive" Facility

Breakdown of Work Effort vs. Cost (Current)



Breakdown of Work Effort vs. Cost (Proposed)



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FASS Program Completed Actions

- Facility System Safety Clause Established
- Technical Support Center Established
- Support Contract Awarded

7-XXX System Safety Requirements

(c) Insert the Following Clause In Contracts for the Design of Facilities.

("The Contractor Shall Provide and Maintain a System Safety Program (SSP) Tailored to the Design Effort Required by this Contract. The SSP Shall Be Guided by the Principles of MIL-STD-882 and its Output Will Be Documented by the Submission of Safety and Health Assessment Reports of a Type and Frequency Determined by the Government in the Technical Provisions of the Contract. During Design of the Facility, the Contractor Shall Notify the Government of Any Safety and Health Hazards Identified Either Through Analyses or Historical Data, and of Any Procedures or Safeguards That Are Required to Control the Identified Hazard(s). The Contractor Shall Also Document Any Assumptions and Limitations Upon Which Safety of the Design is Dependent.)

END OF CLAUSE

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Contractor Support
For
Facility System Safety Program

- Develop Overall Program Guidance
- Survey Existing System Safety Training Courses
- Develop a Training Plan
- Conduct a Field Test of the Proposed System

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Aberdeen Proving Grounds Field Test Projects

- Chemical/Biological Defense Laboratory
- Material Evaluation Facility
- Vibration Test Facility

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Near Term Planned Actions

- Development of Tailored Data Item Descriptions for FASS
- Establishment of Open-End Support Contract
- Survey of Hazard Tracking Techniques and Automated Lessons Learned Data Bases
- Revision of AR's in 385 & 415 Series

US Army Corps
of Engineers
Huntsville Division

Long Term Actions

- Establishment of Full Fledged FASS Capability Within the Corps
- Establishment of Automated Hazard Tracking File and Lessons Learned System
- Establishment of a FASS Training Program

THE DEVELOPMENT AND IMPLEMENTATION OF

FACILITY SYSTEM SAFETY PROGRAM

AT THE

CHEMICAL RESEARCH AND DEVELOPMENT CENTER

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Introduction

A systems approach to hazard identification, elimination and control has historically been applied primarily to the development of equipment. The Safety Office of the Chemical Research and Development Center (CRDC) has reviewed and evaluated the current facility safety posture to determine regulatory compliance and good engineering practices. Based on this evaluation it was determined that the present method of facility design and construction review had to be modified to better address the Command's interests. To augment the effectiveness of facility design and construction review, a new systematic approach for early hazard identification, assessment, elimination and control for facilities was developed and implemented to alleviate these shortcomings in the future.

The formal systematic approach to facility design and construction at CRDC had the following major goals.

1. Reduce the intrinsic hazardous conditions of the facility.

2. Reduce the overall cost of the facility.

3. Reduce the delays in occupancy of the facility, reduce mission downtime, and reduce number of idle workers and equipment.

4. Provide a more mission responsive facility.

5. Reduce repeat design/construction deficiencies in future facilities.

WHAT IS FACILITY SYSTEM SAFETY

To establish a uniform understanding of terms used in this report, the following definitions are provided:

SYSTEM: A composite (at any level of complexity) of personnel, materials, tools, equipment, facilities, and software. The elements of this composite entity are used together in the intended operation to perform its required mission.

FACILITY: Land and land improvement, buildings, structures, utilities, and associated processes.

SAFETY: Freedom from those conditions that can cause death, injury, occupational illness, or damge to or loss of equipment or property.

SYSTEM SAFETY: The optimum degree of safety (within the constraints of operational effectiveness, time, and cost) attained through specific application of management and engineering principles whereby hazards are identified and risks minimized throughout all phases of the system life cycle.

FACILITY SYSTEM SAFETY: The systems approach to safety in the design and construction of facilities.

The CRDC FACILITY SYSTEM SAFETY PROGRAM

A plan of action was established to implement the FSSP. This plan of action had eight elements.

1. Develop an understanding of the Military Construction, Army (MCA) lifecycle process. Review AR 415-15, Military Construction, Army Program Development, 1 Dec 83;AR 415-20, Project Development and Design Approval, Draft; and MIL STD 882A, System Safety Program Requirements, 30 Mar 84.

2. Develop a CRDC MCA safety lifecycle chart for facilities. Review all applicable regulations and develop a lifecycle chart. This chart should identify all safety tasks and milestone dates for completion.

3. Develop procedures to ensure that all hazards are identified early in design. Hazard Analysis (i.e. PHA) techniques maybe employed.

4. Develop safety design criteria for the facility based on known hazards of the facility and user requirements.

5. Provide the safety design criteria to the CRDC Configuration Control Board (CCB) for each MCA project. The CCB controls the design and construction activities for CRDC and provides a unified position on all matters concerning the project to the Corps of Engineers (CE). The CCB consists of a representative from Developmental Support Division (DSD), Safety Office, User (Division), Security, and any other activity deemed appropriate based on the scope of work of the project.

6. Review the design effort at various stages (35%, 60% and 90%) and provide feedback to the CCB on foreseen problems and status of hazard abatements.

7. Track hazards from identification to resolution. This provides an audit trail of the resolution of hazards, risk assessment/acceptance, and configuration of proper safety equipment installation and testing.

8. Develop a data base of safety lessons learned.

All appropriate regulations describing the MCA process were reviewed. As a result, a CRDC MCA lifecycle chart was developed showing tasks and major milestones. This chart is attached as Appendix A. The MCA process can be broken down into five (5) major phases.

1. Project Development

2. Concept Design

3. Final Design

4. Construction

5. Post Construction

It is essential that safety input be provided in each of these phases. The project development phase is the most important phase for the user because the criteria established at this point is the foundation for all other MCA activities. If this criteria is inadequate problems may develop and may be amplified as the lifecycle of the facility progresses.

Attached at Appendix B is a detailed outline of activities that take place at CRDC to implement our facility system safety program. This outline should be used in conjunction with the CRDC MCA lifecycle chart at Appendix A. As you work through this process you should keep in mind that this MCA program has been tailored to fit CRDC's needs.

Facility System Safety Engineering Tasks

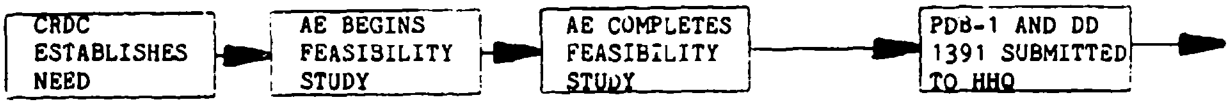
This whole MCA process has been reviewed and tailored to identify safety engineering tasks that must be performed during each phase of the lifecycle. The discussion on the CRDC MCA Lifecycle Program provides a detailed overview of the entire process and discusses some of the activities of other important organizations besides CRDC Safety. The specific safety engineering tasks that should be performed during each phase of the MCA lifecycle are shown in Appendix C.

APPENDIX A

MCA LIFECYCLE

1. Project Development Phase.
2. Concept Design.
3. Final Design.
4. Construction
5. Post Construction

PROJECT DEVELOPMENT PHASE



CRDC SAFETY OFFICE DEVELOPS

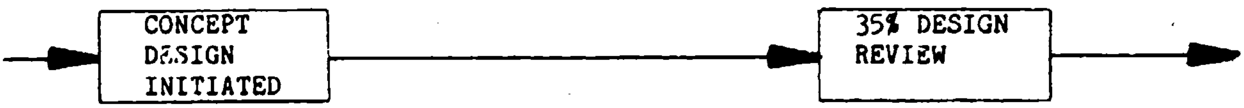
- Facility System Safety Data File
- Facility System Safety Program Plan

CRDC SAFETY OFFICE AND A/E DEVELOP

- Preliminary Hazard List
- Preliminary Hazard Analysis
- CRDC Safety Office Prepares Ssafety Site Plan

SAFETY SITE PLAN SUBMITTED TO HHQ FOR APPROVAL

CONCEPT DESIGN PHASE



CRDC Safety Office Provides:

- Preliminary hazard analysis
- Pertinent Safety requirements
- System Safety task requirements
- Prepares Safety Submission

CRDC Safety Office will:

- Review and update System Safety tasks
- Review design
- Provide additional safety criteria
- Update and submit Safety Submission to HHQ.

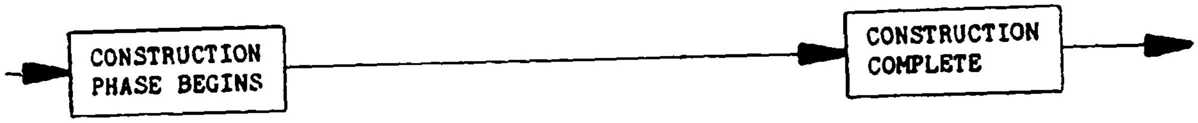
FINAL DESIGN PHASE

→ FINAL DESIGN INITIATED → 60 % DESIGN REVIEW → 90% DESIGN REVIEW → FINAL DESIGN APPROVAL →

* Approval of safety site plan required before final design begins.

Safety Office provides:	Safety Office will:	Safety Office will:
	Review design	Review design
. Pertinent safety requirements	. Review & update System Safety tasks	. Review and update System Safety tasks
. System safety task requirements	. Update safety criteria	. Update safety criteria
. Copies of hazards analysis	. Update safety submission	. Update safety submission

CONSTRUCTION PHASE



* Approval of safety submission required before construction begins.

Safety Office will:

. Participate during 30%, 60%, 90%, site inspections.

. Safety Office will review appropriate change orders.

Safety Office will:

. Participate in certifications/ acceptance testing of safety systems/ equipment.

. Assist in beneficial occupancy inspection.

POST CONSTRUCTION

APPENDIX B

CRDC MCA LIFECYCLE PROGRAM

1. Project Development Phase.

a. Need established by user.

b. Work order submitted by CRDC to Directorate of Engineering and Housing (DEH) for Initial Study Report (ISR).

c. CRDC Safety Office creates a Facility System Safety Data File (FSSDF).

d. Configuration Control Board (CCB) Meets.

e. Scope of work is developed for ISR.

(1) CRDC Safety Office develops a Facility System Safety Program Plan (FSSPP). The FSSPP shall describe the implementation of MIL-STD-882B and shall:

(a) Identify safety milestones to permit evaluation of the effectiveness of the system safety effort at critical safety check points such as preliminary and critical design reviews.

(b) Provide a program schedule of safety tasks showing start and completion dates, reports, and reviews which shall be kept current with other program milestones.

(c) Identify integrated system activities (i.e., design analyses, tests, and demonstrations) applicable to the system safety program but specified in other engineering studies to preclude duplication.

(2) CRDC Safety Office develops and provides all pertinent safety regulations and safety design requirements.

f. CRDC Safety Office developed a Preliminary Hazard List (PHL) based on Scope of Work.

g. Contractor develops an ISR with a PHL based on his knowledge.

h. PHA developed using both PHL's.

i. Additional safety design criteria is developed based on the PHA. This criteria will supplement/refine previous criteria provided in Scope of Work.

j. Project Development Brochure (PDB) is completed by DEH.

k. DD Form 1391, Military Construction Project Data, is completed by DEH and CRDC. CRDC Safety Office will include a safety requirements statement in Section D-5, Criteria for Proposed Construction, on DD Form 1391.

l. CRDC Safety Office prepares safety site plan.

m. DEH submits to HQDA for approval.

(1) Form 1391.

(2) Final PDB.

(3) Cost Estimate.

(4) Sketch of CE site plan.

n. CRDC Safety Office submits the safety site plan through the chain of command to DDESB for approval.

2. Concept Design (0-35% of total design).

a. Develop A/E requirements. CRDC CCB develops scope of work.

(1) CRDC Safety Office will provide, to the CCB:

(a) Updated safety design requirements package.

(b) Pertinent safety regulations.

(c) PHA.

(d) FSSPP.

(e) System Safety Task requirements (if any).

(f) Facility System Safety Data File.

(2) CCB submits scope of work to DEH.

b. CCB participates with CE in AE selection.

c. CRDC Safety Office will prepare safety submission.

d. 5% design review (if required, by CE contract).

(1) Review and update system safety tasks (CRDC).

(2) Review design (DEH and CRDC).

(3) Provide any additional safety design criteria, if necessary.

e. 35% design review.

(1) Review and update system safety tasks (CRDC).

(2) Review design (DEH and CRDC).

(3) Provide any additional safety criteria, if necessary.

f. CRDC Safety Office submits safety submission to DDESB for approval.

g. Safety site plan approved required before final design phase begins.

3. Final Design (60% - 100% of total design).

a. 60% review.

(1) Review and update system safety tasks (CRDC.)

(2) Review design (DEH and CRDC).

b. 90% review.

(1) Review and update system safety tasks (CRDC).

(2) Review design (DEH and CRDC).

c. Submit changes to safety submission, if necessary.

d. Safety submission approval required before construction begins.

4. Construction.

a. CE develops construction contract requirements. CCB provided input if requested (if required).

b. CCB establishes joint CCB/CE engineering surveys and checklists (if required).

c. CCB inspects to verify (joint inspection CCB/CE on 30, 60 and 90 percent reviews).

(1) Work completed complies with contract package/design.

(2) No material substitutions.

(3) Contractor certifies systems/subsystems.

(4) On schedule.

d. CRDC CCB reviews and approves all safety related change orders.

e. Construction complete.

5. Post construction.

a. CE conducts pre-occupancy inspection.

b. Contract violations identified and corrected by CE.

c. CCB conducts Beneficiary Occupancy Inspection (BOI).

d. Contract/non-contract violations identified and corrected by CE or in-house forces.

e. Facility accepted by CCB.

f. DARCOM Safety conducts pre-operation inspection for chemical agent facilities.

g. DARCOM Safety approval.

h. Occupancy.

APPENDIX C

FACILITY SYSTEMS SAFETY ENGINEERING

PROJECT DEVELOPMENT →	CONCEPT DESIGN →	FINAL DESIGN →	CONSTRUCTION →	POST CONSTRUCTION
Develop Facility System Safety Program Plan (FSSPP)	Update Safety Design requirements in AE contract.	Review designs at 60% and 90% stage.	Insert safety requirements in contract specs.	Conduct beneficiary occupancy inspection.
				Update FSSDF.
Create Facility System Safety Data	Insert Systems Safety tasks in AE contract.	Update Safety Design requirements.	Participate in 30%, 60%, and 90% site inspection.	Conduct DARCOM Pre-op inspection.
Insert Safety Design requirements in scope of work.	Insert PHA in AE contract.	Review system safety tasks.	Assist in safety system/subsystem certification.	Receive DARCOM approval
				Occupy building.
Develop PHL & PHA with AE.	Conducts 5% and 35% design review.	Update FSSDF.	Update FSSDF.	
Insert Safety Design Clause in DD Form 1391.	Review System Safety Tasks.	Finalize System Safety Tasks.	Review engineer change orders.	
Prepare Safety Site Plan (SSP)	Receive SSP approval.	Update Safety Submission approval.		
	Prepare Safety Submission & submit to HHQ.	Receive Safety Submission approval.		
	Update FSSDF.	Update FSSDF.		

KEY

Facility System Safety Program Plan (FSSPP)
Facility System Safety Data File (FSSDF)
Preliminary Hazard List (PHL)
Preliminary Hazard Analysis (PHA)
Safety Site Plan (SSP)
Safety Submission (SS)
Hazard Analysis (HA)
Initial Study Report (ISR)
Architect Engineer (AE)

SAFETY AND HEALTH CRITERIA FOR THE DESIGN OF A

RESEARCH AND DEVELOPMENT

FACILITY

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PREFACE

This document was prepared to provide the safety engineering support to a Chemical Research and Development Center (CRDC) research and development facility. The criteria was developed during the early stages of the project and represents the minium requirements tailored specifically for this facility.

The use of trade names in this report does not constitute an official endorsement or approval of the use of such commercial hardware or materials. This report may not be cited for purposes of advertisement.

A. Introduction. Chemical Research and Development Center (CRDC) has recently received poorly designed/constructed facilities. The problems have resulted in cost overruns and delays in occupancy which resulted in an inability to meet mission requirements in a timely fashion. In response to these problems, the CRDC Safety Office has established a Facility System Safety Program (FSSP) for Military Construction, Army (MCA) projects. The principle objective of this program is to ensure safety and health criteria are included throughout the lifecycle of a facility. One of the major milestones in the FSSP is to establish functional safety and health requirements to be used in the design of the facility.

This report outlines the major functional safety and health criteria that were assembled during the design of a new research and development facility. The report is the result of an extensive safety and health evaluation of all proposed operations in the facility. The report was generated by first identifying the materials and processes to be used in this facility. This information was obtained through interviews with operators and on-site field investigations. Once this information was acquired, applicable safety and health criteria documents (standards, regulations, criteria documents) were reviewed to determine criteria for the materials and processes to be used in the facility. The criteria was then provided to the design Architectural Engineering firm for incorporation into the design of the facility. After the criteria was included in the early design stages, subsequent design reviews by the using installation safety office ensured safety and health criteria was included in the engineering design criteria.

B. Facility Description. The safety and health criteria was developed for a facility that will have the following materials and processes:

Biological Defense Research: Laboratories and chambers will be provided to conduct Class I and Class II defensive microbiological research. These materials range from micro-organisms not known to cause disease in healthy adult humans or not known to colonize in humans to micro-organisms of moderate risk present in the community and associated with human disease in varying severity. Work with any of these materials will be conducted under proper engineering controls and in accordance with safety provisions contained in section C-3.

General Chemistry Research: Laboratories will be provided for work with a variety of chemical compounds ranging from non-toxic chemicals to highly toxic chemical carcinogens. Engineering controls (i.e., exhaust ventilation systems) will be required as a means to protect laboratory workers from the harmful effects of these chemical materials.

Filter Research: Facilities will be provided for filter filling (charcoal) and testing. The major process hazard with the charcoal filter filling operations is with the inhalation of charcoal dust. Exhaust ventilation systems capable of removing harmful concentrations of charcoal dust will be installed. These systems will include filter systems capable of removing charcoal dust from the effluent air stream.

Laser Research: Facilities will be provided for work with lasers ranging from Class I to Class IV. Primary hazards resulting from lasers include fire, skin, and eye burns. Various types of engineering controls will be used to reduce exposure to operating personnel to a minimum. These include door interlock systems, warning lights and shielding.

General Facility Safety: Overall facility safety is covered throughout the criteria section. This criteria is grouped into several sections including: Mechanical and Utility Design, Fire Protection, Compressed Gas Storage, Electrical Installations, and General Design Requirements.

C. Safety and Health Criteria. The following safety and health criteria was extracted from Army, Federal, state and local Aberdeen Proving Ground regulations that impact on the design of a chemical research and development facility.

1. GENERAL DESIGN CONSIDERATIONS

1.1 Laboratory Furniture.

Laboratory casework and hoods shall be constructed of non-combustible materials.

Working surfaces within the facility will be constructed of materials for which test results indicate the surface treatment is resistant to contaminant retention.

Laboratory bench tops shall be a resin impregnated material impervious to water and resistant to acids, alkalis, organic solvents, and moderate heat.

Permanent office areas (i.e., desks) shall not be provided within the laboratory room (good housekeeping practice).

Furniture and equipment in laboratory work areas shall be arranged so that means of access to an exit may be reached easily from any point.

Solvent storage cabinet(s) shall be provided in each laboratory using flammable and combustible liquids. It should be located underneath the laboratory hood. The cabinet must comply with NFPA and OSHA requirements.

1.2 Lifting Devices (Hoists)

Hoists.

All lifting devices shall be inspected and tested IAW Technical Bulletin 43-0142. The following test procedures must be initiated prior to acceptance of lifting devices.

(1) The test load to be used will be determined by multiplying the desired load rating (not to exceed manufacturer's rated load) by 110% for hoists. Tests loads for all types of hoists may take the form of a calibrated load indicator, a calibrated dynamometer, weights that may be locally fabricated, or any available item of proper weight. All load testing devices shall have a valid calibration label affixed in a conspicuous place. All locally fabricated weights and available items used for load testing must be verified for proper weight by the use of a calibrated scale.

(2) Upon successful completion of the load test, the lifting device will be assigned a load rating.

Load capacity shall be plainly marked on each piece of equipment (DARCOMR 385-100, Chapter 9-6).

Electric and air hoists shall be provided with a limit stop to prevent the hoist block from over-travel in case the operating handle is not released in time (DARCOMR 385-100, Chapter 9-6).

Stops shall be provided at all switches and turnouts on monorail systems to prevent the trolley from running off if the switch is left in the open position and prevent accidental collision of equipment with adjacent walls (DARCOMR 385-100, Chapter 9-6).

Safety latches shall be provided on all hooks (DARCOMR 385-100, Chapter 9-6).

Cranes.

The control board and all exposed wiring and switches should be guarded (DARCOMR 385-100, para 9-5b).

Traveling cranes should be equipped with a signal warning device to be sounded intermittently while the crane is in motion (DARCOMR 385-100, para 9-5b).

Access ladders for electrically driven overhead cranes should be located so that the operator does not pass within reach of electrical conductors while approaching the controls of the crane. Where needed, an adequate rope ladder or other suitable device should be provided for the escape of the operator in an emergency (DARCOMR 385-100, para 9-5).

1.3 Illumination.

The following minimum levels of illumination shall be used:

Areas	Foot Candles
Office areas	70
Corridors/Elevators/Stairways	20
Laboratories	100
Aerosol Chamber	Variable 50 - 100
High Bay Chambers	Variable 50 - 100
Storage Rooms	10
Rest Rooms	20

Taken from Illuminating Engineering Society Lighting Handbook

Ceiling lights shall have vapor and dust tight covers in laboratories and chambers.

1.4 Interstitial Space Requirements

-Interstitial space above the laboratories and office spaces shall be designed to minimized tripping hazards IAW OSHA 1910.144.

-In interstitial spaces, all open sided floors, four feet or more above adjacent floor or ground level, shall be guarded by a standard railing. A standard railing shall consist of a top rail, intermediate rail and posts, and shall have a vertical height of 42 inches nominal from the upper surface of the top rail to floor, platform, runway, or ramp. The railing shall be provided with a toeboard wherever, beneath the open sides:

A person can pass.

There is moving machinery, or

There is equipment with which falling materials could create a hazard.

-In interstitial spaces, all railings shall be provided with a clearance of not less than 3 inches between the railing and any other object (OSHA 1910.23).

-All Interstitial space platforms and runways with floor openings shall be designed with a standard floor hole cover which can be closed when openings are not in use (OSHA 1910.23).

1.5 Egress.

Laboratory buildings shall comply with the means of egress requirements of Chapter 28, Industrial Occupancies, of NFPA 101, Life Safety Code (NFPA 45, para 3-3).

Exits and Exit markings shall be IAW OSHA 1910.37.

Exits must be sufficient in size and number to permit rapid evacuation of all personnel in the event of fire, explosions, or spills (DARCOMR 385-102, para 6-4).

Each operating room (or building) containing materials which constitute a serious hazard to operating personnel shall be provided with at least two exits (DARCOMR 385-100, para 5-7).

Laboratories require two exits located remotely from each other and arranged to minimize any possibility that both may be blocked by any fire or emergency condition.

The required exit doors of all laboratory work areas within Class A or Class B laboratory units (as defined by the NFPA) shall swing in the direction of exit travel (NFPA 45, para 3-3.3).

Swing and Force to Open. Any door in a means of egress shall be of the side-hinged swinging type.

During its swing, any door in a means of egress shall not reduce the effective width of an aisle, passageway, stair or stair landing to less than one-half its required width. When fully open, the door shall not project more than 3 1/2 inches (8.89 cm) into the required width of a stair or stair landing nor more than 7 inches (17.78 cm) into the required width of an aisle or passageway.

The force required to fully open any door in the means of egress shall not exceed 50 lb (222N) applied to the latch side.

1.6 Miscellaneous Requirements

Interior walls, partitions and ceilings shall be painted with one coat of primer material and one finish coat of lead free polyamide epoxy. Primer and finish coat shall be a compatible system.

Floors shall be painted with one coat of primer material and one finish coat of lead free polyamide epoxy coating containing a skid resistant additive. Primer and finish coat shall be a compatible system.

Junction of floors and walls or casework and floors shall be rounded; and the corner formed by two intersecting walls and the floor or intersecting casework and the floor shall also be rounded.

Floor surfaces will be treated and seams sealed to contain and control contamination and facilitate cleanup.

Water outlets with hose cocks into laboratory sinks shall be provided with vacuum breakers to prevent backflow of water into the service lines (DOD 5154.4S, Chapter 14).

Laboratory layout should provide for visual observation of virtually all work spaces from the corridor (i.e., windows in all doorways to laboratories) (DOD 5154.4S, Chapter 14).

Laboratories will be totally isolated units with no possibility of contamination between adjacent laboratories or corridors (DOD 5154.4S, Chapter 14).

Building air flow will be from the clean areas (i.e., offices, mechanical rooms) toward areas of greater hazard (i.e., chemistry laboratories, chambers).

The building design will provide clearly defined and separate areas (by walls, physical barriers, or other positive means) for segregating clean and hazardous areas (DARCOMR 385-102, para 6-3c(2)).

With the supply air to a laboratory, the vertical sash of the hoods open to their maximum position, and the exhaust system operating, the noise level, at any point in the laboratory 5 1/2 feet above the floor, shall not exceed 55dB(A).

Loading Docks. Adequate bumper rails should be installed parallel to loading docks, at distances which permit trucks and trailers to back in without striking the dock (DARCOMR 385-100, para 9-4).

Storage of Chemicals. Each laboratory building should have a storage room (s) for bulk chemicals and one for laboratory equipment and apparatus. Bulk chemicals must be stored in this room and are not permitted to be stored in operating areas (DARCOMR 385-100, para 4-2).

Sequenced starting of emergency power supply shall be used to avoid excessive voltage fluctuations in the building power system.

The laboratory or individual rooms must be capable of being locked during non-work periods (DARCOMR 385-102, para 8-5d).

2. Mechanical and Utility Design Requirements.

Mechanical and Utility Design

Electrical wiring and equipment and their installation shall be IAW the National Electrical Code, OSHA, and DARCOMR 385-100, and shall be approved for the particular hazards present (DARCOMR 385-100, para 4-9).

Safety showers of the deluge type and eyewash fountains shall be provided at locations where personnel are exposed to hazardous chemicals, and located so that a worker will have immediate access in case of emergencies (DARCOMR 385-100, para 4-5b).

There will be a method of coordinating activity in the laboratory area with those in the administration area. This may be an electronic communication system, a system of observation windows, or other equivalent methods (DARCOMR 385-102, para 6-4).

This facility should have a master alarm and control panel which will permit functional verification of the exhaust blowers, air conditioning units, fire control systems, waste treatment and exhaust filters. Keyed to this master alarm panel will be visual and audible alert alarms to instantly indicate failure of exhaust blowers, fire alarms, and other emergency systems (DOD 5154.4S, Chapter 14).

Electrical control panels, hot water heater, and vacuum pump will be located in a utility area. The waste liquid treatment area and the emergency auxiliary power will be located in the facility complex. Appropriate access to all plumbing, electrical conduits and relays, refrigeration equipment and air handling equipment will be incorporated (DOD 5154.4S, Chapter 14).

The electrical system will be designed so that major pieces of equipment can be operated either directly or remotely. An auxiliary electrical power source or a fail safe system will be used, so that a power outage will not give rise to a hazardous situation (DARCOMR 385-102, para 6-4).

Compressed gas cylinders which are not necessary for current laboratory requirements shall be stored in a safely arranged location outside the laboratory (DARCOMR 385-102, para 8-5g).

Facility should be designed so an area is provided in each laboratory using compressed gas cylinders to secure the cylinder(s). This area must not be in front of a ventilation hood.

All pipelines and compressed gas cylinders shall be color coded IAW MIL STD 101B.

Lines from the house vacuum system shall be connected to an exhaust ventilating system with a pre-filter, HEPA filter, and charcoal adsorber filter, in this order, capable of removing carcinogenic materials from the airstream.

The filter housing and motor-blower for this vacuum exhaust system should not be located inside the building.

3. Specialized Laboratory.

3.1 Specific Biological Laboratory Requirements

Laboratory bench tops shall be a resin impregnated material impervious to water and resistant to acids, alkalis, organic solvents, Class I and II biologicals, and moderate heat (Proposed Biosafety Guidelines for Microbiological and Biomedical Laboratories).

Laboratory furniture shall be sturdy, and spaces between benches, cabinets, and equipment shall be accessible for cleaning.

Each laboratory shall contain an elbow operated handwashing sink (Proposed Biosafety Guidelines for Microbiological and Biomedical Laboratories).

An autoclave for decontamination of infectious laboratory wastes shall be readily available to each laboratory (Proposed Biosafety Guidelines for Microbiological and Biomedical Laboratories).

All biological laboratories shall be insect and rodent proof (Proposed Biosafety Guidelines for Microbiological and Biomedical Laboratories).

All vacuum lines in biological laboratories shall be protected with high efficienty particulate air (HEPA) filters and liquid traps as close to the outlet as possible (Proposed Biosafety Guidelines for Microbiological and Biomedical Laboratories).

The biological safety cabinets provided shall be Class II, vertical laminar-flow or Class III totally enclosed cabinets. The Class II cabinet shall be an open-fronted, ventilated cabinet with an average inward face velocity at the work opening of at least 100 feet per minute. This cabinet shall provide a HEPA-filtered, recirculated mass airflow within the work space. The exhaust air from the cabinet is also filtered by HEPA filters. Specific guidance on the design and construction for Class II cabinets is available from the National Sanitation Foundation Standard 49. (Class II (Laminar Flow) Biohazard Cabinetry Ann Arbor, Michigan, 1976) (Proposed Biosafety Guidelines for Microbiological and Biomedical Laboratories).

The Class III cabinet provides the highest level of personnel and product protection. This protection is provided by the physical isolation of the space in which the infectious agent is maintained. Pressure within this cabinet will be a minimum of 0.25 inches of water gauge below that of surrounding areas (Proposed Biosafety Guidelines for Microbiological and Biomedical Laboratories).

Exhaust ventilation systems from biological areas shall be filtered through a high efficiency particulate air (HEPA) filter (Proposed Biosafety Guidelines for Microbiological and Biomedical Laboratories).

All ventilated enclosures shall be equipped with audible and visual alarms which will initiate in the event of a ventilation system failure.

3.2 Special Radiation Lab Requirements.

-Laboratory rooms will have stainless steel countertops.

-Laboratory hoods will be stainless steel and approved for radioisotope work.

-All laboratories will have two exits.

-Utilities (gas, air and vacuum) will have wall mounted outlets. The continuity of the stainless steel countertops cannot be broken.

-The maximum hazardous range is approximately 50 meters.

Special Laser Room Requirements.

-The 500 meter laser range shall be directed in the northeastern direction.

-The most powerful laser used will not exceed the maximum permissible exposure to the eye at 100 meters. This distance is less than the nearest building.

-A laser in-use light will be at the entrance to the room.

-An interlock system, to prevent entrance of unauthorized personnel into the room during normal laser operation, shall be installed at all entrances.

-Removable sliding glass doors shall have a railing designed and installed IAW OSHA 1910.23.

4. Emergency Showers and Eye/Face Wash Fountains.

Emergency showers and eye/face wash fountains shall be provided in every room in which hazardous chemicals may be used. The emergency showers and eye/face wash fountains shall conform to the following:

4.1 Emergency Showers

Performance of Shower Heads. Emergency shower heads shall be designed so that a water column is provided that is not less than 208.3 cm (82 inches) nor more than 243.8 cm (96 inches) in height from the surface on which the user stands. The spray pattern shall have a minimum diameter of 50.8 cm (20 inches) at 152.4 cm (60 inches) above the surface on which the user stands, and the center of the spray pattern shall be located at least 40.6 cm (16 inches) from any obstruction. Emergency shower heads should be capable of delivering a minimum of 113.6 liters per minute (30 gallons per minute) of water, which shall be substantially dispersed throughout the pattern.

All dimensions in this section are based on Woodson, W.E., and Conover, D.W., Human Engineering guide to Equipment Design, Army, Navy, Air Force Steering Committee, United States Government, 1972; and on Human Engineering Guide for Equipment Designers, University of California Press, 1964, 2nd ed. In a combination unit, the eyewash is not considered an obstruction for the purpose of determining the distance of the center of the spray patter. The water pressure required at the inlet is enough to achieve the water column specified. Shower head designers usually use 113.6 liters per minute (30 gallons per minute) at 0.207 megapascal (30 pounds per square inch). A flow of 75.7 liters per minute (20 gallons per minute) can achieve the same water column under the right conditions, in which case this pressure is acceptable.

Performance of Control Valve. The valve shall be designed so that the water flow remains on without requiring the use of the operator's hands. The valve shall be designed to remain activated until intentionally shut off. The valve shall be simple to operate and shall go from "off" to "on" in one second or less. The valve shall be resistant to corrosion from potable water.

Performance of Valve Actuator. Manual or automatic actuators shall be easy to locate and readily accessible to the user.

In the interests of safety, the valve's remaining open is most desirable.

Manual actuators should be located not more than 175.3 cm (69 inches) above the surface on which the user stands.

Manufacturer's Performance Testing Procedures. The manufacturer shall test emergency shower heads as follows:

a. Connect a flowmeter to the shower to be tested, or provide other means of measuring water flow.

b. Attach the shower to a water supply with a minimum iron pipe size of 1 inch. The shower head's height shall be 213.4 cm (84 inches) from the surface on which the user stands. The water supply shall have a control valve or pump system that can be adjusted.

c. Open the valve on the emergency shower and verify that it opens in one second and stays open.

d. Adjust the control valve on the water supply to deliver a minimum of 113.6 liters per minute (30 gallons per minute), and determine that water is substantially dispersed throughout the pattern. Measure the diameter of the water pattern 152.4 cm (60 inches) above the surface on which the user stands. Visually record the diameter of the spread. This shall be a minimum of 50.8 cm (20 inches).

Installation

Emergency showers shall be in accessible locations that require no more than 10 seconds to reach and should be within a travel distance no greater than 30.5 meters (100 feet) from the hazard. The unit should be located as close to the hazard as possible without physically causing a hazard itself, such as protruding fittings. The maximum time required to reach the shower should be determined by the potential effect of the chemical. For example, exposure to a highly corrosive chemical might require showers to be installed within 3 to 6 meters (10 to 20 feet) from the hazard. Installation procedures should be IAW proper plumbing practices, with supply piping sized adequately to meet flow requirements.

Each emergency shower location shall be identified with a highly visible sign. The area under the emergency shower shall be painted a bright green and white color and shall be well lighted.

The emergency shower shall be assembled in accordance with the manufacturer's instructions.

The unit shall be connected to a supply of potable water capable of deliverying sufficient volume to produce the required water column by the method shown in the manufacturer's instructions. If shut-off valves are installed in the shower line for maintenance purposes, provisions should be made to prevent unauthorized shutoff.

When the shower is installed, it shall be tested IAW the follow procedures:

a. With the unit correctly connected to the water source and the valve(s) closed, visually check the piping connections for leaks.

b. Open the valve to the full open position. The valve shall remain open without requiring further use of the operator's hands.

c. Measure the shower. The face of the shower head shall be not less than 208.3 cm (82 inches) nor more than 243.8 (96 inches) fro the surface on which the user stands.

d. With the valve in the "full on" position, measure the diameter of the spray pattern. It shall be a minimum of 50.8 cm (20 inches) at 152.4 cm (60 inches) above the standing surface. The center of the spray shall be at least 40.6 cm (16 inches) from any obstructions.

4.2 Eye/Face Wash Equipment

Performance of Eye/Face Wash Units.

A means shall be provided to ensure that a controlled flow of potable water or its equivalent is provided to both eyes simultaneously at a velocity low enough not to be injurious to the user, and to wash the face simultaneously.

There shall be no sharp projections anywhere in the operating area of the unit.

Nozzles shall be protected from airborne contaminants. Whatever means is used to affort such protection, its removal shall not require a separate motion by the operator when activating the unit.

Emergency eye/face wash equipment shall be capable of delivering to the eyes and face not less than 11.4 liters per minute (3.0 gallons per minute) for 15 minutes. A flow 11.4 liters per minute (3.0 gallons pr minute) is required so that the entire surface of the face may be covered. In addition to having enough force to purge the contaminants, the stream will also target the face area.

The unit shall be designed to provide enough room to allow the eyelids to be held open with the hands while the eyes are in the stream of water.

Performance of Control Valve. The valve shall be designed in such a manner that the water flow remains on without requiring the use of the operator's hands. The valve shall be designed to remain activated until intentionally shut off. The valve shall be simple to operate and shall go from "off" to "on" in one second or less. The valve shall be resistant to corrosion from potable water. The valve actuator shall be large enough to be easily located and operated by the user.

Manufacturer's Performance Testing Procedures. The manufacturer shall test eye/face wash units as follows:

Connect a flowmeter to the eye/face wash to be tested, or provide other means of measuring water flow.

Attach the eye/face wash unit to a 1.3 cm (1/2 inch) water supply line at 0.207 megapascal (30 pounds per square inch) of flow pressure.

Open the valve on the eye/face wash unit and verify that it opens in one second and stays open.

Using the flowmeter or other means, determine that the rate is at least 11.4 liters per minute (3.0 gallons per minute), that the flushing streams rise to approximately equal heights, and that the water will wash the eyes and face at a velocity low enough not to be injurious to the user.

Installation. All dimensions in this section are based on Woodson, W.E., and Conover, D.W., Human Engineering Guide to Equipment Design, Army, Navy, Air Force Steering Committee, United States Government 1972; and on Human Engineering Guide for Equipment Designers, University of California Press, 1964, 2nd ed.

The unit shall be positioned with the water nozzles 83.8 cm (33 inches) to 114.3 cm (45 inches) from the floor.

Eye/face wash units shall deliver potable water or the equivalent. The supply line shall provide an uninterruptible supply of water at 0.207 megapascal (30 pounds per square inch) of flow pressure. Units shall be installed IAW manufacturer's instructions and acceptable plumbing practices.

When the unit is installed, the valve shall be operated to determine that both eyes will be washed simultaneously at a velocity low enough not to be injurious to the user.

Eye/face wash units shall be in accessible locations that require no more than 10 seconds to reach and should be within a travel distance no greater than 30.5 meters (100 feet) from the hazard. The unit should be located as close to the hazard as possible, and on the same level. The maximum time required to reach the eye/face wash should be determined by the potential effect of the chemical. For a strong acid or strong caustic, the eye/face wash should be immediately adjacent to or within 3 meters (10 feet) of the hazard.

Each eye/face wash location shall be identified with a highly visible sign. The area under the eye/face wash shall be painted a bright green and white color and shall be well lighted.

Emergency showers shall be located with eye/face wash fountains.

Delivered water temperature should not be at extremes that might be expected to discourage the units effective use under emergency conditions. A comfortable range is between 60°F - 75°F.

5 Exhaust Ventilation.

5.1 Basic Requirements.

Except as supplemented by the requirements of this chapter, duct systems for laboratory heating and ventilating, including warm air heating systems, general environmental ventilating systems, air conditioning systems, laboratory exhaust systems and laboratory hood exhaust systems, shall comply with applicable requirements of NFPA 90A, Standard for the Installation of Air Conditioning and Ventilating Systems, and NFPA 91, Standard for the Installation of Blower and Exhaust Systems for Dust, Stock and Vapor Removal (NFPA 45, para 6-2).

Laboratory hoods normally are not designed or intended to provide explosion protection (NFPA 45, para 6-2).

The location of fresh air intakes shall be chosen to avoid drawing in hazardous chemicals or products of combustion coming either from the laboratory building itself or from other structures and devices (NFPA 45, para 6-4).

Laboratory units and laboratory work areas in which hazardous chemical are being used shall be maintained at an air pressure that is negative relative to the corridors or adjacent nonlaboratory areas (NFPA 45, para 6-4.2).

Exception No.1. Where operations such as those requiring clean rooms preclude a negative pressure relative to surrounding areas, special precautions shall be taken to prevent escape of the atmosphere in the laboratroy work area or unit to the surrounding spaces.

Care shall be exercised in the selection and placement of air supply diffusion devices to avoid air currents that would adversely affect the performance of laboratory hoods, exhaust systems, and fire detection or extinguishing systems (NFPA 45, para 6-4.3).

Air supplied to laboratories.

-Sidewall registers and conventional ceiling difussers shall not be used for laboratory air supply.

-Perforated panels shall be located so that the distribution of supply air is three feet minimum from the face of the hood.

-The exhaust velocity from the perforated panels shall be no greater than 35 fpm.

5.2 Ventilation

Laboratory ventilation systems must be adequate to maintain a comfortable temperature level. They must have sufficient capacities to properly condition make-up air required for exhaust hoods (DARCOMR 385-100, para 4-6).

With supply air to a laboratory and the exhaust ventilating system operating, a negative pressure of .10 to .15 inches of water relative to the main corridor, service corridor or change rooms shall be maintained.

5.3 Laboratory Hood Fire Protection.

Automatic fire protection systems shall not be required in laboratory hoods (NFPA 45, para 6-11).

Exception No. 1: Under conditions of extraordinary hazard automatic fire protection may be required for hoods having interiors with a flame spread index of 25 or less.

Automatic fire protection systems, when provided, shall comply with the following standards, as applicable.

a. NFPA 12, Standard on Carbon Dioxide Extinguishing Systems.

b. NFPA 12A, Standard on Halon 1301 Fire Extinguishing Systems.

c. NFPA 12B, Standard on Halon 1211 Fire Extinguishing Systems.

d. NFPA 13, Standard for the Installation of Sprinkler Systems.

e. NFPA 15, Standard for Water Spray Fixed Systems for Fire Protection.

f. NFPA 17, Standard for Dry Chemical Extinguishing Systems.

5.4 Fire Protection

The fire extinguishing system shall be suitable to extinguish within the laboratory hood under the anticipated conditions of use (NFPA 45, para 6-11.2.1).

Automatic fire dampers shall not be used in laboratory hood exhaust systems. Fire detection and alarm systems shall not be interlocked to automatically shut down laboratory hood exhaust fans unless required by special extinguishing systems (See 4-2.3) (NFPA 45, para 3-11.3).

5.5 Laboratory Hood Location.

Laboratory hoods shall be located in areas of minimum air turbulence (NFPA 45, para 6-10).

For new installations, laboratory hoods shall not be located adjacent to a single means of access to an exit or high traffic areas (NFPA 45, para 6-10.2).

In the design of new hood systems, hoods should be located away from heavy traffic aisles, doorways, corners, and supply grilles (Letter, DRDAR-CLM, 30 Jun 83, subject: DA Standard for Chemical Laboratory Hoods).

5.6 Perchloric Acid Hoods.

When perchloric acid is evaporated in a laboratory hood, the following requirements shall apply.

If perchloric acid is heated above ambient temperature and vapors are not trapped or scrubbed before entering the laboratory hood or its exhaust system, a separate hood, designed for use with perchloric acid and labeled "For Perchloric Acid Use Only," shall be provided (see also 9-1.2.4). (NFPA 45, para 6-12).

If a laboratory hood or exhaust system has been exposed to perchloric acid heat above ambient temperature, tests shall be conducted for explosive perchlorates before any inspections, cleaning, maintenance, or any other work is done on any part of the exhaust system or hood interior (NFPA 45, para 6-12).

Perchloric acid hoods and exhaust duct work shall be constructed of materials that are acid resistant, nonreactive, and impervious to perchloric acid (NFPA 45, para 6-12).

The exhaust fan shall be acid resistant and nonsparking. The exhaust fan motor shall not be located within the duct work. Drive belts shall be conductive and shall not be located within the duct work (NFPA 45, para 6-12).

Ductwork for perchloric acid hoods and exhaust systems shall take the shortest and straightest path to the outside of the building and shall not be manifolded with other exhaust systems. Horizontal runs shall be as short as possible, with no sharp turns or bends. The duct work shall provide a positive drainage slope back into the hood. Duct work shall consist of sealed sections. Flexible connectors shall not be used (NFPA 45, para 6-12).

Sealants, gaskets, and lubricants used with perchloric acid hoods, duct work, and exhaust systems shall be acid resistant and nonreactive with perchloric acid (NFPA 45, para 6-12).

A water spray system shall be provided for washing down the hood interior behind the baffle and the entire exhaust system. The hood work surface shall be watertight with a minimum depression of 1/2 in (12.7 mm) at the front and sides. An integral trough shall be provided at the rear of the hood to collect wash down water (NFPA 45, para 6-12).

The hood baffle shall be removable for inspection and cleaning (NFPA 45, para 6-12).

5.7 Laboratory Hoods.

For new installations controls for laboratory hood services (gas, air, water, etc.) shall be located external to the hood and within easy reach (NFPA 45, para 6-9.5.1).

Hood ventilation systems will be equipped with both visible and audible alarm devices which will give a warning should the ventilation system fail because of power failure or mechanical malfunction, or if the average face velocity falls below the minimum requirement. (DARCOMR 385-102, para 8-2b(5)).

Visible alarms must be located so they can be readily seen by personnel while working at the exhaust hood. For all hoods, the visual alarm should be visible from outside the room containing the hoods. (DARCOMR 385-102, para 8-2b(5)).

Where ventilation is the sole or prime method of personnel protection, back up emergency power or other fail safe systems shall be installed to prevent exposure in the event of an unplanned power outage (DARCOMR 385-102, para 8-2 (7)).

A test switch must be installed on all light and sound alarms which will permit the operator to verify that the light has not burned out and the sound alarm will make noise without having to shut the ventilation system down.

Materials of construction used for the interiors of new laboratory hoods shall have a flame spread index of 25 or less when tested according to NFPA 255, Method of Test Surface Burning Characteristics of Building Materials (NFPA 45, para 6-9.1.1).

Baffles shall be constructed so that they may not be adjusted to materially restrict the volume of air exhausted through the laboratory hood (NFPA 45, para 6-9.1.2).

Laboratory hoods shall be provided with a means of containing minor spills (NFPA 45, para 6-9.1.3).

The sash shall be glazed with material which will provide protection to the operator or the environment against the hazards normally associated with the use of the hood (NFPA 45. para 6-9.2).

The bypass opening shall be shielded by a grill or solid panel to impede or deflect flying glass or flaming debris in case of a runaway reaction within the hood (NFPA 45, para 6-9.3).

For new installations or modifications of existing installations, fixed electrical services and their controls shall be located external to the hood and within easy reach (NFPA 45, para 6-9.4).

Hood lighting shall be provided by fixtures external to the hood or, if located within the hood interior, the fixtures shall meet the requirements of Article 501 of NFPA 70, National Electrical Code (NFPA 45, para 6-9.4.3).

Laboratory hoods in which radioactive materials are handled shall be identified with the radiation hazard symbol (NFPA 45, para 6-13.1).

A sign shall be affixed to each hood containing the following information from the last inspection:

a. Inspection interval.

b. Last inspection date.

c. Average face velocity.

d. Location of fan which serves hood.

e. Inspector's name.

Exception: In lieu of a sign, a properly maintained log of all hoods giving the above information shall be deemed acceptable (NFPA 45, para 6-13.2).

Laboratory hoods and special local exhaust systems shall be labeled to indicate intended use (NFPA 45, para 6-14).

Laboratory hoods and other ventilated enclosures shall be located such that crossdrafts do not exceed 20 percent of the inward face velocity.

Laboratory hoods should be designed as deep and low in height as practical, and the presence of rough wall surfaces and recesses in walls and work surfaces should be avoided. The location of sash tracks and location of and number of baffles and slots provided within the hood must also be considered when evaluating a hood design (1st ind, DASH-PSP, undated, to letter, DRDAR-CLM, 30 Jun 83, subject: DA Standard for Chemical Laboratory Hoods.)

The chemical fume hood lining, baffles, work surface, exhaust stack, sash track, and the sash frame shall be 300 series stainless steel with all joints being welded.

Chemical fume hoods shall have an entrance air foil at the table top and beveled entrances at the sides and top. The work surface shall be water tight with a minimum of 1/2" dished front and sides and integral trough at the rear to collect wash down water.

The sash shall be counter balanced for vertical type designs and the panel shall be 1/4" thick laminated safety glass.

Laboratory hoods shall have an average inward face velocity (for open face hoods) of 0.5 meters per second (100 lfpm) ± 10% with the velocity at any point not deviating from the average face velocity by more than 20%.

Ducts shall be of adequate strength and rigidity to meet the conditions of service and installation requirements and shall be protected against mechanical damage (NFPA 45, para 6-6.4).

Vibration isolation connectors shall comply with NFPA 255 (NFPA 45, para 6-6.5).

5.8 Exhaust Air Discharge.

Air exhausted from laboratory hoods and other special local exhaust systems shall not be recirculated (NFPA 45, para 6-5).

If energy conservation devices are used, they shall not recirculate laboratory exhaust air or otherwise compromise the safety of the labortory hood (NFPA 45, para 6-5).

Air containing hazardous chemicals shall be discharged through duct systems maintained at a negative pressure relative to the pressure of normally occupied areas of the building (NFPA 45, para 6-5).

Air exhausted from laboratory work areas shall not pass unducted through other areas (NFPA 45, para 6-5.3).

Ductwork shall be designed to facilitate dismantling and to minimize the release of contamintion to adjacent areas with the use of bagging or other approved means.

Ductwork shall be round, all welded with flange connection.

The air carrying system, e.g., ductwork, stacks, blower housing, will be sealed to preclude leakage or entrapment of chemical vapors exceeding PEL's (DOD 5154.4S, Ch 11).

Ducts from laboratory hoods and from local exhaust systems shall be constructed entirely of noncombustible materials (NFPA 45, para 6-6).

Flexible connectors containing pockets in which conveyed material may collect shall not be used in any concealed space, or where strong oxidizing chemicals are used (e.g., perchloric acid) (NFPA 45, para 6-6.6).

Controls and dampers, where required for balancing or control of the exhaust system, shall be of a type that, in event of failure, will fail open to assure continuous draft (NFPA 45, para 6-6.7).

Hand holes installed for damper, sprinkler, or fusible link inspection or resetting and for residue clean-out purposes shall be equipped with tight-fitting covers provided with substantial fasteners (NFPA 45, para 6-6.8).

Duct velocities of laboratory exhaust systems shall be high enough to minimize the deposition of materials in the exhaust systems (NFPA 45, para 6-7).

5.9 Exhausters (Fans), Controls, Velocities, and Discharge.

Fans shall be selected to meet fire, explosion and corrosion requirements (NFPA 45, para 6-8.1).

Fans conveying both corrosive and flammable or combustible materials may be lined with or constructed of corrosion-resistant materials meeting the requirements of NFPA 255 (NFPA 45, para 6-8.2).

Fans shall be located and arranged so as to affort ready access for repairs, cleaning, inspection, and maintenance (NFPA 45, para 6-8.3).

When flammable vapors or combustible dusts are passed through the fans, the rotating element shall be constructed of nonferrous or nonsparking material. Alternatively, the casing shall be constructed of or lined with such material. Where there is the possibility of solid material passing through the fan that would product a spark, both the rotating element and the casing shall be constructed of such material. Nonferrous or nonsparking materials shall meet the requirements NFPA 255 (NFPA 45, para 6-8.4).

Motors and their controls shall be located outside the location where flammable or combustible vapors or combustible dusts are generated or conveyed unless specifically approved for the location and use (NFPA 45, para 6-8.5).

Fans shall be labeled with an arrow or other means to indicate proper direction of rotation, and with the location of laboratory hoods and exhaust sytems served (NFPA 45, para 6-8.6).

Air exhausted from laboratory hoods and special exhaust systems shall be discharged above the roof at a height and velocity sufficient to prevent re-entry of hazardous chemicals (NFPA 45, para 6-8.7).

Exhaust ducts from each laboratory unit shall be separately ducted to a point outside the building, to a mechanical space, or to a shaft (NFPA 45, para 6-6.9).

5.10 Laboratory - Materials of Construction.

Materials of construction for ducts, piping, and vessels shall be compatible with materials to be transferred or handled (NFPA 45, para 7-2.2.2).

5.11 Exhaust Stacks

There are no safety requirements for minimum exhaust stack height. The recommended practice is to provide at least a short straight exhaust stack on all ventilating systems. The purpose of installing an exhaust stack on a ventilation system is to help disperse contaminants, in the exhaust stream, by discharging the exhausted air above roof level; and to improve fan performance since the uneven velocity distribution at the fan outlet causes a high velocity pressure at the outlet. This higher velocity pressure can result in higher discharge losses if the system has no stack. A stack to change high, uneven velocity patterns into a uniform flow. This results in a more efficient fan performance.

The minimum stack height required to provide for maximum fan efficiency and adequate dispersion of contaminants should be determined using the Industrial Ventilation, A Manual of Recommended Practice, ACGIH, 17 ed.

Exhaust stacks shall be located to ensure good dispersion of exhaust air to the atmosphere thereby preventing recirculation to work areas and adjacent buildings.

5.12 Gloveboxes.

Pressure within gloveboxes will be a minimum of 1/4 inch of water gauge below that of surrounding areas (DARCOMR 385-102, para 8-2c).

Make up air should be allowed into the glovebox to prevent stagnation and build up of hazardous vapor contamination. The make-up air sources will be protected by filters, back flow dampers, or other means (DARCOMR 385-102, para 8-2c).

Openings into a glovebox must maintain an inward flow of at least 100 lfpm.

6. Laboratory Hood Qualification Procedures

General Chemistry.

6.1 Laboratory Hood Qualification Testing - General Requirements:

a. The laboratory hood shall be free of backdrafts along the bottom and sides of the hood, and shall contain and carry away vapors generated within the hood when tested under operating conditions as described herein. When the hood is operated under the selected entrainment test conditions as described, the hood shall capture at least 95% of the auxiliary air. When operated under the imbalance test conditions described the hood loss shall not exceed 0.05%. The hood sash shall operate smoothly and freely. Compliance to these performance requirements shall be demonstrated by conducting the series of tests as described hereinafter. The user and/or his designated representative shall view the tests and successful compliance results are contingent upon concurrence by the user and/or his representative. All tests shall be conducted prior to acceptance.

b. A Test Room of similar design to rooms located in the facility, as well as the actual test demonstration shall be provided by the manufacturer at his own expense.

c. The facilities required shall include:

(1) A typical laboratory hood as specified (but without auxiliary air plenum attached) shall be set up in a test room of sufficient size so that minimum of 5 feet of clear space is available in front of and on both sides of the hood for viewing of performance tests.

(2) The test room shall have adequate heating and/or or air conditioning provided so that room air temperatures can be maintained within range of 70° to 80°F.

(3) Room air currents and personal movement in front of the test hood shall be properly controlled so that air velocities shall not exceed 25 FPM in the test viewing area.

(4) A hood exhaust system, properly calibrated so that known exhaust air volumes can be easily attained, shall be provided.

(5) An auxiliary air plenum complete with an inlet duct stub shall be available for installation as required in performance test procedure.

(6) An auxiliary air system capable of supplying air through the auxiliary air plenum in volumes of up to 70% of the hood exhaust volume shall be provided. This auxiliary air system shall also be properly calibrated so that airflows can be easily and accurately attained. The auxiliary air system should have a heating unit capable of maintaining the supply air temperature at any specified temperature up to 95°F.

d. The materials instrumentation and equipment required shall include:

11 - #40 Devilbiss Nebulizers

2 - Liter of 5% sodium carbonate solution

50 - cc of 5 to 10% uranine in 5% sodium carbonate solution

3 - Gelman 47 mm filter holders (closed) or equivalent.

1 - Box Gelman 47 mm glass fiber filters Type A or equivalent

3 - Glass proves (for sampling in exhaust duct)

1 - Vacuum Pump (Gelman Little Giant model or equivalent)

1 - Source of compressed air

1 - Mercury Manometer (0-25" Hg)

1 - Flowmeter (Rotameter) for flow rates of 2-10 liters/minutes

3 - Settling Flasks (5 liter capacity or larger).

1 - Filter Flask (aspirator type)

3 - Limiting Orifices for sampling lines (6 liter/minute) suggested

3 - Filter Funnels.

1 - Box Whatman #41 filter paper (11 cm size)

1 - Turner fluorimeter or equivalent with proper filters and curvettes.

1 - 50 cc stoppered shaking flasks.

9 - Beakers - Clamps

5 - Ring stands

12 - One minute smoke bombs

1 - Bottle Titanium Tetrachloride

1 - Box cotton swabs

1 - Pitot tube and include manometer (0-2"0)

1 - Alnor Thermoanemometer - type 8500 or equivalent with recent calibration sheet.

1 - Alnor Velometer - type 3002 or equivalent with recent calibration sheet

All necessary and associated glassware, rubber tubing and miscellaneous items.

6.2 Performance Test Procedures.

a. Before any hood tests are conducted, or air systems for the hood are turned on, demonstrate that no cross drafts exist in the test area which exceed 25 FPM. Use the Alnor thermoanemometer (or equivalent) for this check.

b. Turn the exhaust fan on. Set the exhaust air volume to provide an average face velocity of 100 FPM. The exhaust volume shall be determined by taking proper pitot tube traverses.

c. The uniformity of the face air velocity shall be determined by taking velocity readings in the center of a grid made up of three sections across the middle third of the hood face across the top third of the hood face. Readings shall not vary more than plus or minus 10 FPM from average face velocity with the hood sash fully raised.

d. Using a swab dipped in titanium tetrachloride, traverse the hood face to show flow patterns of air entering the hood. No back flows shall be permitted

e. Discharge a one-minute smoke bomb within the hood chamber at workbench level. Proper and quick removal of smoke must be demonstrated.

f. Lower the sash to a point six inches above the work surface. Velocity as measured at three points across the reduced face opening shall be less than three times the design face velocity when the sash was fully raised.

g. With the sash still at the lowered position, the exhaust air volume (as indicated by the calibrated flow device) shall be essentially the same as when the sash is fully raised. Now lower sash to fully closed position. Total exhaust flow shall be essentially as measured previously with different sash opening positions.

h. Install the auxiliary air plenum and connect it to the supply air system. The installation shall indicate relative ease of adapting unit to the basic hood. No cutting or removal of exhaust duct work shall be allowed.

i. Raise the hood sash and verify that the sash does not enter the auxiliary chamber and that there is no appreciable opening or means by which auxiliary air can enter hood either behind the sash or through the bypass until the sash is lowered to the point of bypass opening.

j. With the exhaust system off, turn on auxiliary air system and adjust the supply air volume to 70% of the exhaust air volume. The supply air volume shall be measured by a calibrated flow device.

k. Under conditions as outlined in para j above, meausre the air velocity along a line 3" out from the face of the hood and at a height equal to the bottom of the sash when the sash is in a fully raised position. The velocity should not exceed 200 FPM along this line.

l. Turn on the exhaust system and operate as described in paragraph b; maintain supply air operation as outlined in paragraph j. This will provide a 70-30 ratio of auxiliary air to room air being exhausted by the hood.

m. Again traverse the hood face (sash fully raised) with a swab dipped in titanium tetrachloride. The smoke pattern shall show air flowing into the hood and that no back flow exists.

n. Paint a strip of titanium tetrachloride along the sides and working surface 6" back from the hood face. All air flow shall be towards rear of hood with no back flow permitted.

o. Introduce a one-minute smoke bomb into the auxiliary air system prior to the point that air enters the plenum and observe the air pattern. Smoke must indicate a smooth uniform air pattern leaving the auxiliary air discharge and smoke must be efficiently entrained and exhausted by the hood when the sash is fully raised.

p. Repeat smoke bomb test as in para o, but with the sash in fully closed position. Smoke must be efficiently captured by air entering the bypass.

q. Demonstrate that under the condition 70% auxiliary air supply that capture of auxiliary air is at least 95% efficent. Use the uranine dye test. Details of the test described in paragraph 6.3.

r. Demonstrate that, under conditions wherein exhaust and supply air volumes are equal, the loss of contaminated air from hood is less than 0.05%. Test shall be as prescribed in paragraph 6.3.

s. Repeat tests in paragraphs q and r but with auxiliary air temperature maintained at 20°F higher than the room air temperature.

6.3 Uranine Dye Test for Entrainment.

a. Generation of Fine Uranine Aerosol

(1) Place approximately 8 cc of 5 to 10% uranine solution into each of two nebulizers.

(2) Set up the two nebulizers in parallel; connect air hose from compressed air source and provide access for the mercury manometer in the air line (for pressure reading).

(3) Have both nebulizers discharge into the first of the three settling flasks. Arrange for the aerosol to leave the first flask and enter the second flask and then to the third. (Flasks arranged in series). Each flask to be equipped with a tight fitting, two-hole stopper having one long

glass tube that extends close to the bottom of the flask and one which is short and extends just into the flask. The aerosol path should be from the nebulizers into each consecutive flask using the long tube and exiting each flask by the short tube.

(4) The exit tube of the last settling should be connected by use of tubing to the point where the aerosol is to be introduced into the supply air system. This point must be upstream of the auxiliary air chamber and preferably at the inlet to the supply air fan.

(5) After checking all joints for rightness, aerosol generation will be started by turning on compressed air and maintaining an 18" to 20" reading on the mercury manometer.

b. Air Sampling Procedure.

(1) Place a three-holed rubber stopper in the filter flask and connect the vacuum pump to the aspirator leg of the flask.

(2) Place glass fiber filters in the filter holders (check for tightness).

(3) Place limiting orifices on outlet side of the filter holders and connect them to holes in the stopper of the filter flask. (Now all samples are manifolded and will sample simultaneously when pump is turned on).

(4) Turn pump on and check airflow through each sampler using the rotameter. All flows must be identical (Actual flow not critical provided each sampler has same flow rate).

(5) Locate samplers in position for tests as described later.

(6) Turn on aerosol generator.

(7) Turn on sampling pump.

(8) Sample for five minutes. Then shut off aerosol generator and sampling pump.

(9) Place exactly 50 ml of sodium carbonate solution in the stoppered shaking flasks.

(10) Remove filters from the holders using tweezers, and using caution to prevent contamination, place each filter in a numbered shaking flask.

(11) Stopper flask and shake vigorously for three minutes.

(12) Filter a portion of the solution from each flask through separate Whatman #41 filter papers and read fluorescence in the fluorimeter.

(13) Make the necessary calculations.

c. Check for Uniform Dispersal of Aerosol in Supply Air. Three simultaneous air samples shall be taken at points across the auxiliary air discharge and these samples when analyzed must indicate that the uranine aerosol is uniformly distributed in the auxiliary air.

d. Check for Uniform Dispersion of Aerosol in Exhaust Air. Three air samples shall then be taken in the exhaust duct at a point as close to the hood exhaust collar as possible (not more than 4 feet from hood). These discharge samples shall also be taken simultaneously with the sampler inlets located in the same plane and at the center of equal areas in the cross sectional area of the exhaust duct. These samples when taken and analyzed must indicate the uniform mixing of auxiliary air and room air.

e. Actual Test for Percent Entrainment. When it has been proven that the uranine is properly dispersed throughout the auxiliary air and that the auxiliary air and room air are thoroughly mixed at the exhaust sampling point, the performance test shall be performed. For this test two samplers, one at the point of discharge of auxiliary air from the supply system and one at the enterline of the hood exhaust duct at the point previously checked shall be taken simultaneously. These samples when analyzed must indicate that at least 95% of the auxiliary air supplied is entrained and exhausted. Test to be conducted with sash in fully raised position.

6.4 Hood Loss Test Under Imbalance Conditions.

a. General. The imbalance test is a simulation of a possible field condition which can be experienced when the exhaust system for an auxiliary air hood exhausts less than the proper amount of air. The reason for such reduced exhaust could be fan belt slippage, fan blade corrosion, and other such commonly encountered problems. To assure adequate and safe performance, the following test requires that the auxiliary air hood when operated so that the exhaust air volume has been reduced to equal the supply air volume, the loss does not exceed 0.05% of the hood concentration.

b. Test Procedure.

(1) Set auxiliary air volume (using calibrated flow device) to 70% of the exhaust air volume required to provide an average face velocity of 100 FPM.

(2) Set auxiliary air temperature so that it is essentially equal to room air temperature.

(3) Set exhaust air volume (using calibrated flow device) the same as the auxiliary air volume in (1) above. This provides condition of essentially 100% supply.

(4) Generate heavy concentration of uranine aerosol within the hood work area by setting up at least 9 of the #40 De-Vilbliss Nebulizers filled with 10% uranine and each connected to a source of compressed air. Each of the nebulizers should be provided with a goose-neck attachment which deflects and impinges the aerosol generated onto the bottom of an adjacent beaker. All nebulizers and beakers should be located in a plan 6" back from the hood sash opening, and equally sapced in that plane.

(5) Using the manifolded sampling technique as described in 6-3(b) obtain the following three samples simulaneously. Sample No. 1 taken at the centerline of the hood exhaust duct (represents hood concentration). Samples No. 2 and 3 taken 6" in from each side of opening, 12" out from plane of sash opening and 6" below level of work surface. The sampling time to be at least sixty minutes in durations.

(6) The samples shall then be extracted and fluorescence determined as described in para 6-3(b), steps 9 through 13.

(7) Calculations must indicate that the hood loss under imbalance conditions does not exceed 0.05% of the hood concentration.

7. In Place Laboratory Hood Acceptance Test Plan

In-Place General Chemistry Laboratory Hood Acceptance Test Plan

7.1 Laboratory hood air flow and alarm controls.

7.1.1 General requirements.

a. These procedures test the dynamic response of the local controls of the bench type laboratory hood.

b. The bench hood, in order to satisfactorily pass this Acceptance Test Plan, shall satisfactorily pass each test procedure set forth in paragraph 7.1.2.

c. The laboratory room air temperature must be maintained within a range of 70°F to 80°F prior to any tests.

d. Personnel movement in front of the fume hood being tested shall be avoided whenever possible.

7.1.2 Acceptance Test Procedures.

a. Laboratory hood test. This laboratory hood test shall consist of multiple airflow measurements as the laboratory hood sash operates in a continuous uninterrupted manner from a fully closed to a fully open position and vice versa. Average air flow measurements (in CFM) shall be taken with a CFM gage. The laboratory hood test measurements shall be taken when the laboratory hood sash travels through the following positions - fully closed, one third (1/3) open, two thirds (2/3) open, fully open, and vice versa. Average air velocity is found by dividing the average airflow measurement at a particular sash position. This test shall consist of eight (8) average airlow measurements.

b. Execution of tests.

(1) A sequence of laboratory hood test procedures shall be executed as described below:

(a) Activate the supply - exhaust system through the "System On-Off" switch. All system fans shall start and airflow controls shall be operating.

(b) Close the laboratory hood sash.

(c) Operate the laboratory hood sash and conduct a test as described in paragraph 7.1.2.a. To satisfactorily pass this test procedure, all average air velocity measurements made through the free area of the laboratory hood and slot shall be not less than 90 FPM (sash full open). Average air velocity measurements made through the free area of the laboratory hood and slot shall not be greater than 110 FPM (sash full open). Record appropriate airflow measurements (in CFM), calculated average laboratory hood velocities (in FPM), and satisfactory or unsatisfactory performance of each velocity.

7.2 A sequence of laboratory hood alarm test procedures shall be executed as described below:

a. Activate the supply - exhaust system through the "System On-Off" switch. All system fans shall start and airflow controls shall be operating.

b. Automatically open the laboratory sash.

c. Disconnect the damper operator from the damper.

d. By hand, gradually close the damper.

e. To satisfactorily pass this test procedure, the following test conditions shall be performed.

(1) Audible alarm shall sound.

(2) When the audible alarms are initated, the average face air velocity of the laboratory hood shall be 90 $\pm$ 5 FPM (sash full open). Average air velocity is found by dividing an average airflow measurement (in CFM) at the particular sash position, by the open hood and slot area for that particular sash position.

(3) Visual lights shall come on. Record the average face air velocity when the audible alarm sounds, and satisfactory or unsatisfactory performance of each of the above conditions.

f. Silence the audible alarm light at the fume hood control panel with the "Active Silence" switch. To satisfactorily pass this test procedure, the following conditions shall be performed:

(1) Audible alarm shall turn off.

(2) Alarm light shall blink.

Record satisfactory or unsatisfactory performance of each of the above conditions.

g. By hand, gradually open the damper.

h. To satisfactorily pass this test procedure, the following test conditions shall be performed:

(1) The visual light shall turn off.

(2) When the visual alarms turns off, the average face velocity of the laboratory hood shall be 90 $\pm$ 5 FPM (sash full open). Average air velocity is found by dividing an average airflow measurement (in CFM) at the particular sash position, by the open hood and slot area for that particular sash position.

Record the average face air velocity when the visual light turns off, and satisfactory or unsatisfactory performance of each of the above conditions.

i. Re-connect the damper to the damper operator.

j. Automatically lower the hood sash and then manually close the hood sash to override the sash positioner. To satisfactorily pass this test procedure, the hood sash shall manually close in a smooth and continuous fashion. Record satisfactory or unsatisfactory test procedure.

k. Automatically raise the hood sash. As the sash passes the two thirds (2/3) position, manually override the sash positioner to a fully closed position. To satisfactorily pass this test procedure, the hood sash shall manually close in a smooth and continuous fashion. Record a satisfactory or unsatisfactory test procedure.

7.3 A performance specification must be written to perform an in-place leak test of the HEPA filters, adsorber filters, ducts and filter housings. ANSI/ASME N510-1980, Testing of Nuclear Air Cleaning Systems, and ANSI/ASME N509 Nuclear Power Plant Air Cleaning Units and Components can be used as a guide. This performance test must be completed prior to acceptance of the exhaust ventilation system.

8. Fire Protection.

Automatic Fire Extinguishing Systems.

General. An automatic fire extinguishing system may be required in a laboratory unit, depending on the construction of the building, the hazard class of the laboratory unit, the construction of the laboratory unit enclosure and its area, and the activity within the laboratory unit (NFPA 45, para 4-2).

The discharge of an automatic fire extinguishing system shall activate an audible fire alarm system on the premises (NFPA 45, para 4-2).

Automatic sprinklers for Class A laboratory units shall be designed for extra hazard occupancies or shall be hydraulically designed for Ordinary Hazard Group 3, as specified in NFPA 13, Standard for the Installation of Sprinkler Systems (NFPA 45, para 4-2).

Automatic sprinklers for Class B laboratory units shall be designed for ordinary hazard occupancies or shall be hydraulically designed for Ordinary Hazard Group 2, as specified in NFPA 13, Standard for the Installation of Sprinkler Systems (NFPA 45, para 4-2).

Automatic sprinklers for Class C laboratory units shall be designed for ordinary hazard occupancies or shall be hydraulically designed for Ordinary Hazard Group 1, as specified in NFPA 13, Standard for the Installation of Sprinkler Systems (NFPA 45, para 4-2).

Other Automatic Extinguishing Systems. Where required or used in place of automatic sprinklers, special hazard extinguishing systems and nonwater automatic extinguishing systems shall be designed, installed, and maintained IAW the following standards, as applicable (NFPA 45, pra 4-2.3):

a. NFPA 11, Standard for Foam Extinguishing Systems.

b. NFPA 11A, Standard for High Expansion Foam Systems.

c. NFPA 11B, Standard on Synthetic Foam and Combined Agent Systems.

d. NFPA 12, Standard on Carbon Dioxide Extinguishing Systems.

e. NFPA 12A, Standard on Halon 1301 Fire Extinguishing Agent Systems.

f. NFPA 12B, Standard on Halon 1211 Fire Extinguishing Agent Systems.

g. NFPA 15, Standard for Water Spray Fixed Systems for Fire Protection.

h. NFPA 17, Standard for Dry Chemical Extinguishing Systems.

i. NFPA 69, Standard on Explosion Prevention systems.

The discharge of an automatic fire extinguishing system shall activate an audible alarm system on the premises.

Metal cabinets constructed in the following manner are acceptable. The bottom, top, door and sides of cabinet shall be at least No. 18 gage sheet steel and double walled with 1 1/2 inch (38.1 mm) air space. Joints shall be riveted, welded or made tight by some equally effective means. The door shall be provided with a three-point latch arrangement and the door sill shall be raised at least 2 inches (50.8 mm) above the bottom of the cabinet to retain spilled liquid within the cabinet (NFPA 30, 1981, para 4-3.2.1).

Flammable storage cabinets shall not be vented. The cabinets shall be designed, constructed and installed IAW NFPA 30.

Indoor Storage - Basic Conditions.

The storage of any liquids shall not physically obstruct a means of egress. Class 1 liquids in other than separate inside storage areas or warehouses shall be so placed that a fire in the liquid storage would not preclude egress from the area (NFPA 30, 1981, para 4-5.1.1).

Protection Requirements for Protected Storage of Liquids.

Containers and portable tanks storing flammable and combustible liquids may be stored in the quantities and arrangements specified in Tables 4-6.1(a) and 4-6.1(b) from NFPA 30 provided the storage is protected IAW 4-6.2 and 4-6.5 of NFPA 30, as applicable (NFPA 30, 1981, para 4-6).

Other quantities and arrangements may be used where suitably protected and approved by the authority having jurisdiction (NFPA 30-1981, para 4-6).

Where automatic sprinklers are used, they shall be installed IAW NFPA 13, Standard for the Installation of Sprinkler Systems, and approved by the authority having jurisdiction (NFPA 30-1981, para 4-6).

Other systems such as automatic foam-water systems, automatic water-spray systems, or other combinations of systems may be considered acceptable if approved by the authority having jurisdiction (NFPA 30-1981, para 4-6).

Racks storing Class 1 or Class II liquids shall be either single-row or double-row as described in NFPA 231C, Rack Storage of Materials (NFPA 30-1981, para 4-6).

Ordinary combustibles other than those used for packaging the liquids shall not be stored in the same rack section as liquids, and shall be separated a minimum of 8 ft (2.4m) horizontally, by aisles or open racks, from liquids stored in racks.

In-rack sprinklers shall be installed IAW the provisions of NFPA 231C, Rack of Storage of Materials, except as modified by para 4-6.2. Alternate lines of in-rack sprinklers shall be staggered. Multiple levels of in-rack sprinkler heads shall be provided with water shields unless otherwise separated by horizontal barriers, or unless the sprinkler heads are listed for such installations (NFPA 30, para 4-6.4).

Portable Fire Extinquishers. Portable fire extinguishers shall be installed, located and maintained IAW NFPA 10, Standard for the Installation of Portable Fire Extinguishers. For purposes of fire extinguisher placement, Class A laboratory units shall be graded as extra hazard and Class B and C laboratory units as ordinary hazard (NFPA 45, para 4-4).

Facility should be designed so an area is available for placement of these fire extinguishers (NFPA 45, para 4-4).

A manual fire alarm system shall be installed in a laboratory building if a fire may not, of itself, provide adequate warning to building occupants.

Fire alarm systems and fire detection systems, where required, shall be installed and maintained IAW the following standards, as applicable (NFPA 45, para 4-5):

a. NFPA 71, Standard for the Installation, Maintenance, and Use of Central Station Signaling Systems.

b. NFPA 72A, Standard for the Installation, Maintenance, and Use of Local Protective Signaling Systems for Guard's Tour, Fire Alarm and Supervisory Service.

c. NFPA 72B, Standard for the Installation, Maintenance, and Use of Remote Station Protective Signaling Systems for Fire Alarm Service.

d. NFPA 72C, Standard for the Installation, Maintenance, and Use of Remote Station Protective Signaling Systems.

e. NFPA 72D, Standard for the Installation, Maintenance, and Use of Proprietary Protective Signaling Systems.

f. NFPA 72E, Standard for the Installation, Maintenance, and Use of Automatic Fire Detection Systems.

Signal transmission for alarms designed to activate signals at more than one location shall be verified at each location during each inspection of the alarm system.

The fire alarm system, where required, shall be so designed that all personnel endangered by the fire condition or a contingent condition shall be alerted.

The fire alarm system shall alert a local fire brigade or public fire department.

9. Flammable and Combustible Liquid Storage

Storage of industrial and educational laboratory work shall comply with NFPA 45, Standard on Fire Protection for Laboratories Using Chemicals (NFPA 30-1981, para 4-5.4).

Storage drums and containers not exceeding 60 gallons.

This section shall apply to the storage of liquids, including flammable aerosols, in drums or other containers not exceeding 60 gallons individual capacity and limited transfers incidental thereto (NFPA 30, para 4.1.1).

Each portable tank shall be provided with one or more devices installed in the top with sufficient emergency venting capacity to limit internal pressure under fire exposure conditions to 10 psig (68.95 kPa)., or 30 percent of the bursting pressure of the tank, whichever is greater. The total venting capacity shall be not less than that specified in 2-2.5.4 or 2-2.5.6 of NFPA 45. At least one pressure-actuated vent having a minimum capacity of 6,000 cu ft (169.92m^3) of free air per hour (14.7 psia (101.3 kPa) and 60^oF (15.6^oC) shall be used. It shall be set to open not less than 5 psig (34.48 kPa). If fusible vents are used, they shall be actuated by elements that operate at a temperature not exceeding 300^oF (148.9^oC). When used for paints, drying oils and similar materials where plugging of the pressure actuated vent can occur, fusible vents or vents of the type that soften to failue at a maximum of 300^oF (148.9^oC) under fire exposure may be used for the entire emergency venting requirement (NFPA 30, 1981, para 4-2.2).

Containers and portable tanks for liquids shall conform to Table 4-2.3 from NFPA 30 except as provided below:

Class 1A and Class 1B liquids may be stored in glass containers of not more than one gallon capacity if the required liquid purity (such as ACS analytical reagent grade or higher) would be affected by storage in metal containers or if the liquid would cause excessive corrosion of the metal container (NFPA 30, 1981, para 4-2.3, 4-2.3.1, 4-2.3.3).

Not more than 120 gallons of Class 1, Class II, and Class IIIA liquids may be stored in a storage cabinet. Of this total, not more than 60 gallons may be of Class 1 and Class II liquids and not moe than three (3) such cabinets may be located in a single fire area, except that, in an industrial occupancy, additional cabinets may be located in the same fire area if the additional cabinet, or group of not more than three (3) cabinets, is separated from other cabinets by at least 100 ft (NFPA 30, 1981, para 4-3.1).

Storage cabinets shall be designed and constructed to limit the internal temperature at the center, 1 in. (25.40 mm) from the top to not more than 325^oF) (162.^oC) when subjected to a 10-minute fire test with burners simulating a room fire exposure using the standard time-temperature curve as given in ASTM E152-72. All joints and seams shall remain tight and the door shall remain securely closed during the fire test. Cabinets shall be labeled in conspicuous lettering "FLAMMABLE - KEEP FIRE AWAY" (NFPA 30, 1981, para 4-3.2).

Storage - Fire Control

Suitable fire extinguishers or preconnected hose lines, either 1 1/2 in (38.1 mm) lines or 1 in (25.4 mm) hard rubber, shall be provided where liquids are stored. Where 1 1/2 in (38.1 mm) fire hose is used it shall be installed IAW NFPA 14, Standard for the Installation of Standpipe and Hose Systems (NFPA 30, 1981, para 4-7.1).

At least one portable fire extinguisher having a rating of not less than 20-B shall be located outside of, but not more than 10 ft (3m) from, the door opening into any separate inside storage area (NFPA 30, 1981, para 4-7.1).

At least one portable fire extinguisher having a rating of not less than 20-B shall be located not less than 10 ft (3m) nor more than 50 ft (15.2m) from any Class I or Class II liquid storage area located outside of a separate inside storage area (NFPA 30, 1981, para 4-7.1).

In protected general purpose and liquid warehouses, hand hose lines shall be provided in sufficient number to reach all liquid storage areas (NFPA 30, 1981, para 4-7.1).

The water supply shall be sufficient to meet the fixed fire protection demand, plus a total of at least 500 gal (1892.5 L) per minute for inside and outside hose lines (See C-4-6.2) (NFPA 30, 1981, para 4-7.1).

Control of Ignition Sources. Precautions shall be taken to prevent the ignition of flammable vapors. Sources of ignition include but are not limited to open flames, lightning, smoking, cutting, and welding, hot surfaces, frictional heat, static, electrical and mechanical sparks, spontaneous ignition, including heat-productng chemical reactions, and radiant heat (NFPA 30, 1981, para 4-7.1).

Storage - Drums Outside

Outdoor storage of liquids in containers and portable tanks shall be IAW Table 4-8, as qualified by 4-8.1.1 through 4-8.1.4 and 4-8.2, 4-8.3, and 4-8.4 of NFPA 30 (NFPA 30, 1981, para 4-8.1).

When two or more classes of materials are stored in a single pile the maximum gallonage in that pile shall be the smallest of the two or more separate gallonages (NFPA 30, 1981, para 4-8.1).

No container or portable tank in a pile shall be more than 200 ft (60.9 m) from a 12 ft (3.65 m) wide access way to permit approach of fire control apparatus under all weather conditions (NFPA 30, 1981, para 4-8.1).

The distances listed in Table 4-8 apply to properties that have protection for exposures as defined. If there are exposures, and such protection for exposures does not exist, the distances in column 4 shall be doubled. (NFPA 30, 1981, para 4-8.1).

When total quantity stored does not exceed 50 percent of maximum per pile, the distances in columns 4 and 5 may be reduced 50 percent, but to not less than 3 ft (0.91m) (NFPA 30, 1981, para 4-8.1).

A maximum of 1,100 gal (4163.5L) of liquids in closed containers and portable tanks may be stored adjacent to a building located on the same premises and under the same mangement provided that (NFPA 30, 1981, para 4-8.1).

a. The building is limited to a one-story building of fire-resistive or noncombustible construction and is devoted principally to the storage and handling of liquids, or

b. The building has an exterior wall with a fire resistance rating of not less than 2 hr and having no opening to above grade areas within 10 ft (3.05m) horizontally of such storage and no openings to below grade areas within 50 ft (15.24m) horizontally of such storage.

The quantity of liquids adjacent to a building protected IAW 4-8.2(b) (NFPA 30) may exceed that permitted in 4-8.2 (NFPA 30) provided the maximum quantity per pile does not exceed 1,100 gal (4163.5L) and each pile is separated by a 10 ft (3.05 m) minimum clear space along the common wall (NFPA 30, 1981, para 4-8).

Where the quantity stored exceeds the 1,100 gal (4163.5L) permitted adjacent to the building given in 4-8.2(a) (NFPA 30) or the provisions of 4-8.2(b) (NFPA 30) cannot be met, a minimum distance IAW column 4 of Table 4 shall be maintained between buildings and nearest container or portable tank (NFPA 30, 1981, para 4-8).

The storage area shall be graded in a manner to divert possible spills away from buildings or other exposures or shall be surrounded by a curb at least 6 inches (152.4mm) high. When curbs are used, provisions shall be made for draining of accumulations of ground or rain water or spills of liquids. Drains shall terminate at a safe location and shall be accessible to operation under fire conditions (NFPA 30, 1981, para 4-8).

Storage area shall be protected against tampering or trespassers where necessary and shall be kept free of weeds, debris and other combustible materials not necessary to the storage (NFPA 30, 1981, para 4-8).

Laboratory Units

Laboratory units shall be classified as Class A, B, or C, according to the quantities of flammable and combustible liquids specified in Table 2.2 (NFPA 45, para 2-2.1).

Laboratory Unit Enclosure.

The required construction of laboratory units depends on the laboratory unit fire hazard classification, the area of the laboratory unit, and the protection to be provided (NFPA 45, para 3-1).

The construction requirements are the minimum permitted and do not exclude the use of construction with greater fire resistance (NFPA 45, para 3-1).

Laboratory units shall be separated from nonlaboratory areas by construction equal to or greater than the fire resistance requirements shown in Table 3-1 (NFPA 45, para 3-1).

Laboratory units shall be separated from other laboratory units of equal or lower hazard by construction equal to or greater than the fire resistance requirements shown in Table 3-1 (NFPA 45, para 3-1).

Penetrations of fire-rated floor/ceiling and wall assemblies shall be protected so as to retain the required fire resistance rating and to prevent the passage of smoke, fire, or vapors between floors or through walls (See 6-11.3) (NFPA 45, para 3-1).

All floor openings shall be sealed or curbed to prevent liquid leakage to lower floors (NFPA 45, para 3-1).

The maximum area of a laboratory unit shall be determined by the fire hazard classification, the construction of the laboratory unit, and the fire protection provided, as shown in Table 3-1 ((NFPA 45, para 3-1).

10. Compressed Gases, Compressed Gas Cylinders, and Industrial Gases.

10.1 Storage Compressed Gases.

Compressed gas cylinders will be stored and handled IAW AR 700-68 (DARCOMR 385-100, para 13-21).

Cylinders which are not necessary for current laboratory requirements shall be stored in a safe location outside the laboratory work area (NFPA 45, para 8-2.3).

General purpose warehouse space is preferred for storage of filled and empty cylinders that require no repair or maintenance, with shed space being the second choice (AR 700-68, para 5-2a).

Cylinders will be protected from dampness, and filled cylinders must be protected against excessive rise in temperature from direct rays of the sun or from other sources of heat not to exceed 130°F (AR 700-68, para 5-2a).

All cylinders, both inside and outside the facility, shall be adequately secured against accidental displacement. Facility should be designed to provide areas for all cylinders to be secured (DARCOMR 385-100, para 13-21a).

Cylinder storage facilities should be designed so that filled and empty cylinders can be stored separately (AR 700-68, para 5-2c).

When filled cylinders are stored in the same location, the cylinder storage facility should be designed so the cylinders can be grouped according to the gases that are contained, and segregated according to the type classification, e.g., flammable, toxic, oxidizing, or physically hazardous (AR 700-68, para 5-2c).

Ventilation must be provided under outside storage covers to carry off gas leakage. An airspace of at least 18 inches shall be provided between the cover and the cylinder to keep the temperature of cylinders below 125°F (DARCOMR 385-100, para 13-21a).

Oxidizing gases must never be stored within 50 feet of flammable gases or flammable liquids (AR 700-68, para 5-2c).

Smoking is prohibited within 50 feet of compressed gas cylinder storage and "No Smoking" signs shall be conspicuously posted (DARCOMR 385-100, para 13-21).

When cylinders of flammable gases or oxygen are stored out of doors, a separate storage facility shall be provided (DARCOMR 385-100).

Storage facilities of over 6000 cubic feet total capacity shall be at least 25 feet from any important building (DARCOMR 385-100, Letter, DRCSF-E, 11 Jun 82, subject: Storage of Compressed Gas Cylinders.

Facilities with a capacity in excess of 15000 cubic feet shall be at least 50 feet from any important building (DARCOMR 385-100, Letter, DRCSF-E, 11 Jun 82, subject: Storage of Compressed Gas Cylinders.

Cylinder storage should be designed so cylinders can be stored in groups as small in area and height as is practicable, with aisles between groups to minimize the spread of fire (DARCOMR 385-100, para 13-21a).

Cylinder storage should be designed to permit inspection at periodic intervals (DARCOMR 385-100, para 13-21a).

10.2 Manifolded Compressed Gases.

Method of storage and piping systems for compressed gases and liquefied gases shall comply with the requirements of applicable NFPA and American National Standards Institute (ANSI) standards, including the following (NFPA 45, para 8-1):

a. NFPA 50, Standard for Bulk Oxygen Systems at Consumer Sites.

b. NFPA 50A, Standard for Gaseous Hydrogen Systems at Consumer Sites.

c. NFPA 50B, Liquefied Hydrogen Systems at Consumer Sites.

d. NFPA 51, Standard for Oxygen-Fuel Gas Systems for Cutting and Welding.

e. NFPA 54, National Fuel Gas Code.

f. NFPA 58, Standard for the Storage and Handling of Liquefied Petroleum Gases.

g. ANSI B31.1.0, Power Piping (including Addenda B31.1.0a, B31.1.1.0b, B31.1.1.1.0c, and B31.1.1.0d).

h. ANSI B31.2, Fuel Gas Piping.

i. ANSI B31.3, Petroluem Refinery Piping.

Frequently used compressed gases shall be supplied to the facility from gas bottle manifolds (DOD 5154.4S, Chapter 14).

Manifolds must be of substantial construction and of a design and material suitable for the particular gas and service for which they are to be used.

Manual shut-off valves shall be provided at all points of supply and at all points of use (NFPA 45, para 8-1.3).

Exception No. 1. If the containers supplying the piping system are equipped with shut-off valves, a separate valve on the piping system is not required.

Exception No. 2. A valve at the point of use is not required if there is a supply shut-off valve within immediate reach of the point of use.

Each and every portion of a piping system shall have uninterruptible pressure relief. Any part of the system than can be isolated from the rest of the system shall have adequate pressure relief (NFPA 45, para 8-1.4).

Exception: Piping systems designed with a working pressure greater than the maximum allowable working pressure developed at ambient temperature.

Pressure relief systems shall be designed to provide a discharge rate sufficient to avoid further pressure increase and shall vent to a safe location (NFPA 45, para 8-1.4).

Permanent piping shall be identified at the supply point and at each discharge point with the name of the material to be piped (NFPA 45, para 8-1.5).

Piping systems, including regulators, shall not be used for gases, other than those for which they are designed and identified (NFPA 45, para 8-1.6).

11. ELECTRICAL INSTALLATIONS

11.1 General Requirements. All electrical installations, including wiring and appurtenances, apparatus, lighting, signal systems, alarm systems, remote control systems, or parts thereof, shall comply with NFPA 70, National Electrical Code (NFPA 45, para 3-5).

Electrical receptacles, switches and controls shall be located so as not to be subject to liquid spills (NFPA 45, para 3-5).

Laboratory work areas and laboratory units shall be considered as unclassified electrically with respect to Article 500 of NFPA 70, National Electrical Code (NFPA 45, para 3-5).

Exception: Under some conditions of extraordinary hazard, it may be necessary to classify a laboratory work area, or a part thereof, as a hazardous location, for the purpose of designating suitable electrical installations.

11.2 Electrical Requirements for Charcoal Room. All electrical equipment in the charcoal room must be approved for use in Class I, Div I, Group F. Locations as defined in Articles 500 through 503, National Electrical Code. Standard electrical apparatus considered safe for ordinary application is obviously unfit for installation in locations where flammable gases, vapors, dusts, and other easily ignitable materials are present.

Articles 500 through 503 cover the requirements for electrical equipment and wiring for all voltages in locations where fire or explosion hazards may exist due to flammable gases or vapors, flammable liquids, combustible dust, or ignitible fibers or flyings (NFPA 70, Article 500 through 503).

Locations are classified depending on the properties of the flammable vapors, liquids or gases, or combustible dusts or fibers which may be present and the likelihood that a flammable or combustible concentration or quantity is present (NFPA 70, Article 500 through 503).

Each room, section, or area shall be considered individually in determining its classification (NFPA 70, Article 500 through 503).

11.3 Class II Requirements. Articles 500 through 503 require a form of construction of equipment and of installation that will ensure safe performance under conditions of proper use and maintenance (NFPA 70, Article 500).

It is important that inspection authorities and users exercise more than ordinary care with regard to installation and maintenance (NFPA 70, Article 500).

For Class II locations, Groups E, F, and G, the classification involves the tightness of the joints of assembly and shaft openings, to prevent entrance of dust in the dust-ignition-proof enclosure, the blanketing effect of layers of dust on the equipment that may cause overheating, electrical conductivity of the dust, and the ignition temperature of the dust. It is necessary, therefore, that equipment be approved not only for the class, but also for the specific group of the gas, vapor, or dust that will be present (NFPA 70, Article 500).

Group F: Atmospheres containing carbon black, charcoal, coal or coke dusts which have more than 8 percent total volatile material (carbon black per ASTM D1620, charcoal, coal, and coke dusts per ASTM D271) or atmospheres containing these dusts sensitized by other materials so that they present an explosion hazard, and having resistivity greater than 10 ohm-centimeter but equal to or less than 10 ohm centimeter (NFPA 70, Article 500).

11.4 Class II Locations. Class II locations are those that are hazardous because of the presence of combustible dust. Class II locations shall include those specified in (a) and (b) below (NFPA 70, Article 500).

a. Class II, Division 1. A Class II, Division 1 location is a location: (1) in which combustible dust is in the air under normal operating conditions in quantities sufficient to produce explosive or ignitible mixtures; or (2) where mechanical failure or abnormal operation of machinery or equipment might cause such explosive or ignitible mixtures to be produced, and might also provide a source of ignition through simultaneous failure of electric equipment, operation of protection devices, or from other causes; or (3) in which combustible dusts of an electically conductive nature may be present (NFPA 70, Article 500).

Combustible dusts which are electrically nonconductive include dusts produced in the handling and processing of grain and grain products, pulverized sugar and cocoa, dried egg and milk powders, pulverized spices, starch and pastes, potato and woodflour, oil meal from beans and seed, dried hay, and other organic materials which may produce combustible dusts when processed or handled. Electrically conductive dusts are dusts with a resistivity less than 10 ohm-centimeter. Dusts containing magnesium or aluminum are particularly hazardous and the use of extreme precaution will be necessary to avoid ignition and explosion (NFPA 70, Article 500).

b. Class II, Division 2. A Class II, Division 2 location is a location in which (1) combustible dust will not normally be in suspension in the air in quantities sufficient to produce explosive or ignitible mixtures, and dust accumulations are normally insufficient to interfere with the normal operation of electrical equipment or other apparatus, or (2) dust may be in suspension in the air as a result of infrequent malfunctioning of handling or processing equipment, and dust accumulations resulting therefrom may be ignitible by abnormal operation or failure of electrical equipment or other apparatus (NFPA 70, Article 500).

12. Acceptance Test Plan.

An acceptance test plan for the following s stems must be developed:

- Heating and Ventilating System.
- Laboratory Hood Air Flow and Alarms
  - General chemistry hoods.
  - Radioisotope hoods.
  - Level II and III biological safety cabinets.
  - California hoods.
  - Canopy hoods.
  - Slot hood for charcoal room.
- Emergency showers and eye/face wash fountains
- Supply-exhaust system interlock and air balance controls
- Emergency power supply
- Fire protection system
- Exhaust filtration system/in-place testing.

13. Disposal of Waste.

Disposal of chemical wastes shall be IAW good safety practices and applicable government regulations (NFPA 45, para 7-3.3).

Disposal and storage for disposal are also dictated by established installation waste management procedures to insure compliance with environmental regulations. Coordinate with the Installation Environmental Coordinator (DARCOMR 385-100, para 4-10).

All drains will be provided with liquid seals (traps).

Drains should be designed to keep the liquid in the trap from evaporating or to keep the liquid level in the trap adequate to prevent air from leaking through the trap (DARCOMR 385-102, para 6-4g/6-4h).

The building shall have a chemical waste drain and holding system connected to all sinks in laboratories, hoods and eyewash/emergency shower drains.

The chemical waste drain and holding system shall be equipped with a means of sampling the effluent and a means to add required decontaminate/neutralizing chemicals to the holding tank and a means to release the waste when authorized.

The neutralization system shall be designed to neutralize waste to an acceptable pH of 6 to 8 by the addition of acids or bases. This neutralization system must be capable of permitting release of the sanitary sewer or containerization of waste.

Storage tanks should have overflow lines from the top and have flow detectors and alarms to give a warning prior to overflowing. Tanks should be equipped with an external guage to show the quantity of material in the tank (DARCOMR 385-100, para 13-3).

D. Conclusions. This report provides safety and health criteria for the design of a research and development facility. This report can serve as a guideline for the development of safety and health criteria for similar facilities.

21st DoD EXPLOSIVES SAFETY SEMINAR
28-30 AUGUST 1984, HOUSTON, TEXAS (USA)

WINDOW PANES LOADED BY EXPLOSIONS

by

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1. INTRODUCTION

The Prins Maurits Laboratory TNO is interested in window-pane fracture by explosions for two reasons:

- Window-panes are the most vulnerable parts of buildings. So, for the safe distance to potential explosive sources the lower limit of window-pane fracture is very important.
- Because of their relative low breakage pressure window-panes often have a function as vents for a possible internal gas or dust explosion. In these situations the upper limit of the breakage pressure is important.

It is generally known that the pressures at which windows break vary widely and are difficult to predict.
This is partly because it is difficult to calculate the maximum stresses in a window-pane loaded by an explosion.
These mechanical problems fall into three groups:

- The dynamic response calculation.
  Often only the first normal mode of the pane is taken into account, but may be higher modes play an important part.
- The edge conditions.
  Normally panes are schematized as simply supported plates, but if the edges are not free to rotate some amount of clamping has to be taken into account.
- Membrane action.
  Especially for thin panes the behaviour is dominated by membrane action.

However, even if the stresses were known it is still difficult to predict the breakage pressure because the strength of the material glass is influenced by many quantities:

- Inhomogenities in the glass
- Scratches on the surface
- Age of the pane
- Single- or double-pane windows
- Thickness of the pane
- Duration of the loading
- Temperature of the glass
- Humidity of the surroundings.

To gain more insight into the mechanical problems strain-measurements have been performed on blast loaded windows. With the help of these measurements a calculation model for the maximum stresses has been developed. Besides, lots of tests have been carried out in order to determine the breakage pressure of panes with various dimensions. These tests provided the opportunity to verify the calculation model and to quantify the effect of thickness and area of the pane on its strength.

2. DETERMINATION OF STRAINS

The strain measurements were carried out on a square pane, with dimensions 420 × 420 × 5 mm. Strain gauges were cemented on both sides, perpendicular and parallel to both the diagonal and the mediane. The positions are sketched in Figure 1.

The pane was loaded by a shock wave with the help of the small PML 40 × 40 cm^2 square cross-section blast simulator. In order to gain more insight into the membrane action also tests were carried out on a pane made of some polycarbonate.

This material is much stronger and more flexible than glass, so the displacements of this pane were more than those of the glass-pane and therefore membrane action was more pronounced.

For comparison the strains were also calculated, assuming a simply supported Kirchoff-plate (without membrane action).

The plate with the axes of the coordinates used is sketched in Figure 2.

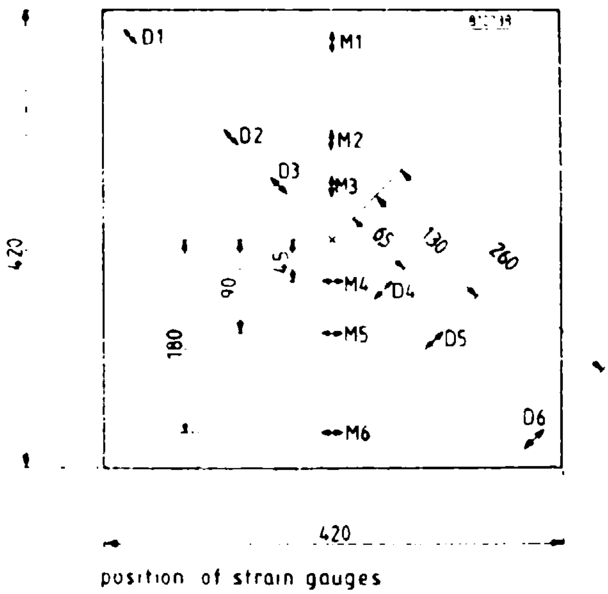


Figure 1.

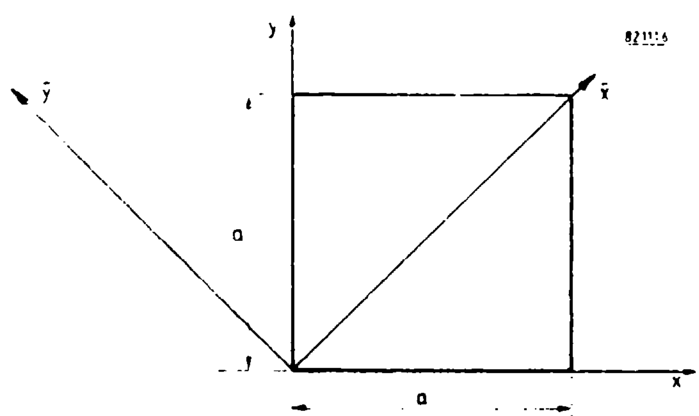


Figure 2. Plate with axes of coordinates.

The maximum displacements $\hat{z}$ under an even distributed static loading q is given by (ref. (1)):

$$\hat{z} = 0.00406 \frac{q a^4}{D} \quad (1)$$

where D is the stiffness of the plate. To obtain the displacement under dynamic loading it had to be multiplied by a dynamic load factor (DLF) which is dependent on the duration t_+ of the shock wave and the first natural frequency ω of the plate.
This frequency is given by (ref. (2)):

$$\omega = \frac{2 \pi^2}{a^2} \sqrt{\frac{D}{\rho h}} \quad (2)$$

where h is the plate thickness and ρ the density of the plate material.
The DLF, as a function of ωt_+, is given in Figure 3.

If it is assumed that only the first mode of the plate is important the displacement is given by:

$$z = \hat{z} \sin \frac{\pi x}{a} \cdot \sin \frac{\pi y}{b} \quad (3)$$

Now the bending moments can be found (ref. (1)):

$$M_x = M_y = \hat{z} \cdot D (1 + \nu) \frac{\pi^2}{a^2} \sin \frac{\pi x}{a} \cdot \sin \frac{\pi y}{b} \quad (4)$$

$$M_{xy} = \hat{z} \cdot D (1 - \nu) \frac{\pi^2}{a^2} \cos \frac{\pi x}{a} \cdot \cos \frac{\pi y}{b} \quad (5)$$

$$M_{\bar{x}} = M_x - M_{xy} \quad (6)$$

$$M_{\bar{y}} = M_x + M_{xy} \quad (7)$$

In these equations ν is Poisson's ratio.

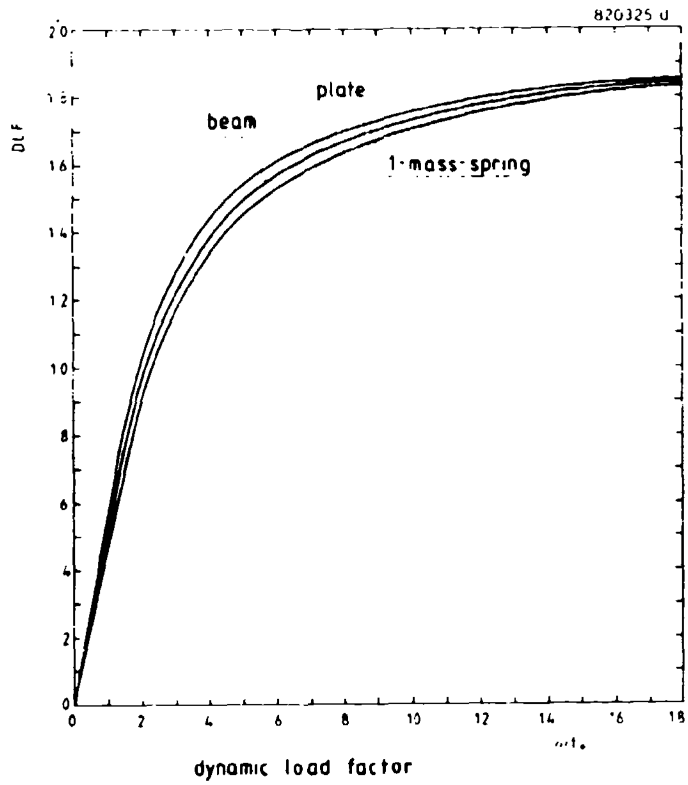


Figure 3.

Finally the strain ε follows from

$$\varepsilon = \frac{M}{1/6\ h^2 E} \qquad (8)$$

In Figures 4 to 7 the calculated strain divided by the peak overpressure of the loading is compared with the measured maximum strains for the window-pane.

All the strains measured on the loaded side of the pane are multiplied by -1, so, if there is only bending, the strains measured on both sides should coincide.

From these Figures the following conclusions can be drawn:

- The assumption of a simply-supported plate is correct; Figures 4 and 5 show that there are no bending moments along the edges.
- Although the data are insufficient for the evaluation of the influence of higher modes it is clear that the first mode dominates the response.

- The effect of membrane action is obvious in the Figures: most of the strains measured on both sides do not coincide and are below the calculated strains.
  These phenomena tend to increase with increasing loading: because of the non-linear behaviour of membrane action the part of the loading carried by membrane action increases with increasing displacements.

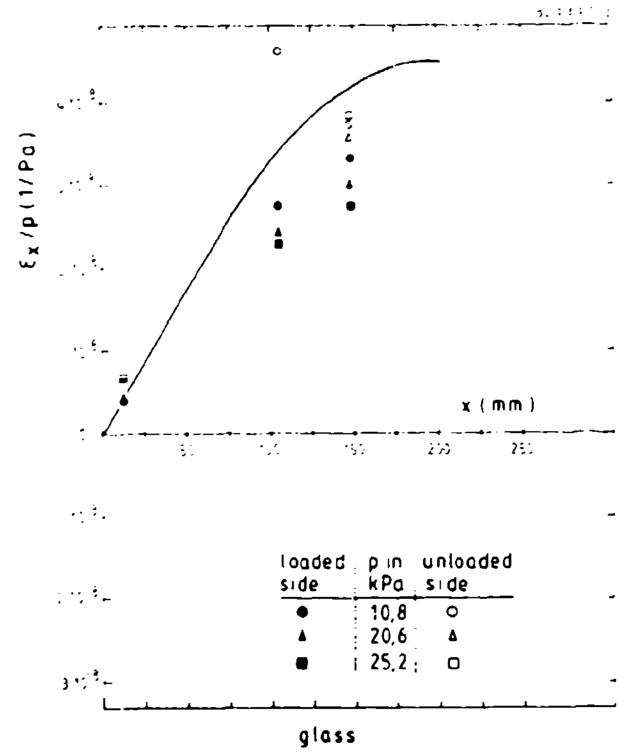


Figure 4. Strain parallel to the mediane.

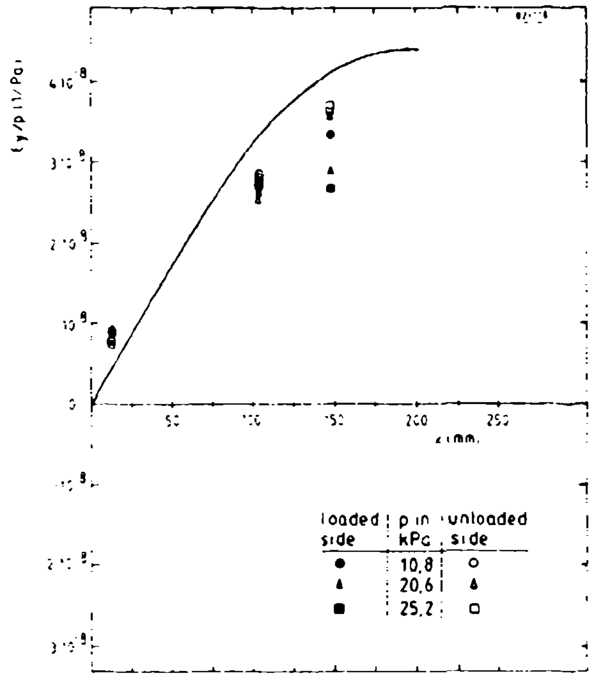


Figure 5. Strain perpendicular to the mediane.

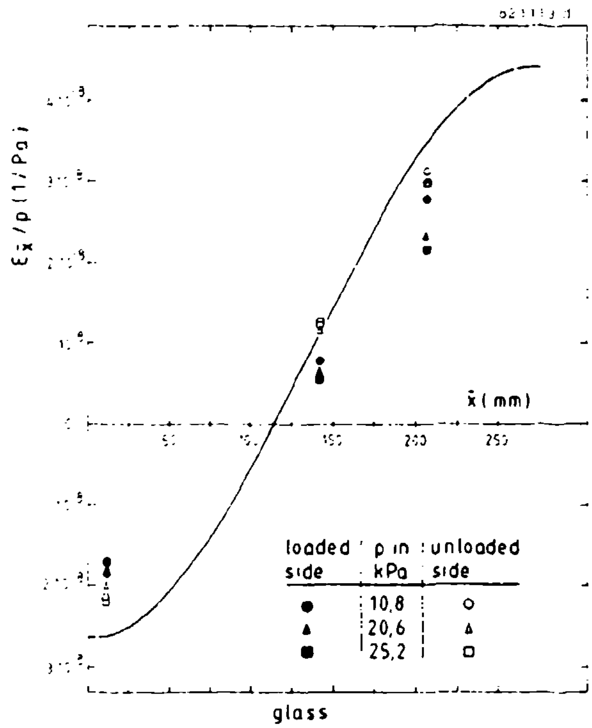


Figure 6. Strain parallel to the diagonal.

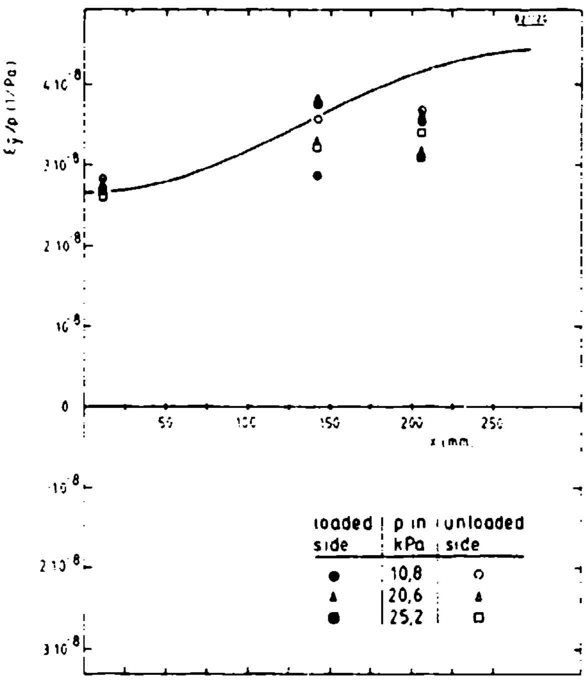


Figure 7. Strain perpendicular to the diagonal.

Figures 8-11 represent the strains for the polycarbonate in the first three loading steps. The conclusions are the same as for glass, but the influence of membrane action is even more pronounced.

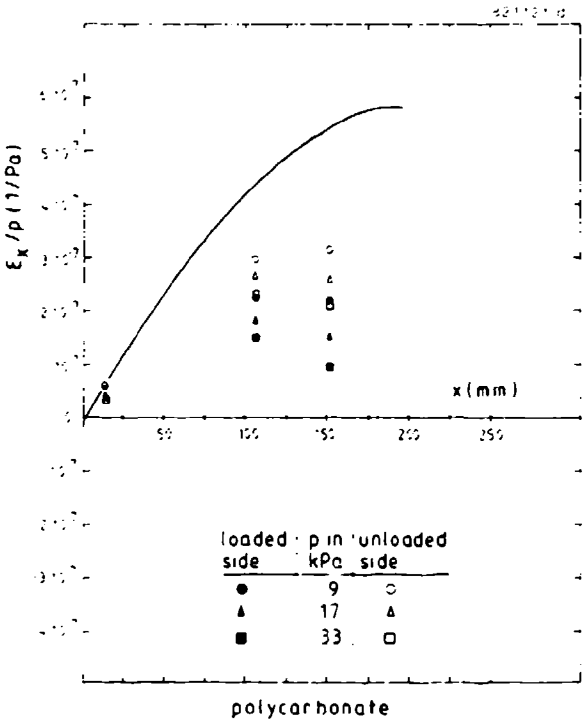


Figure 8. Strain parallel to the mediane.

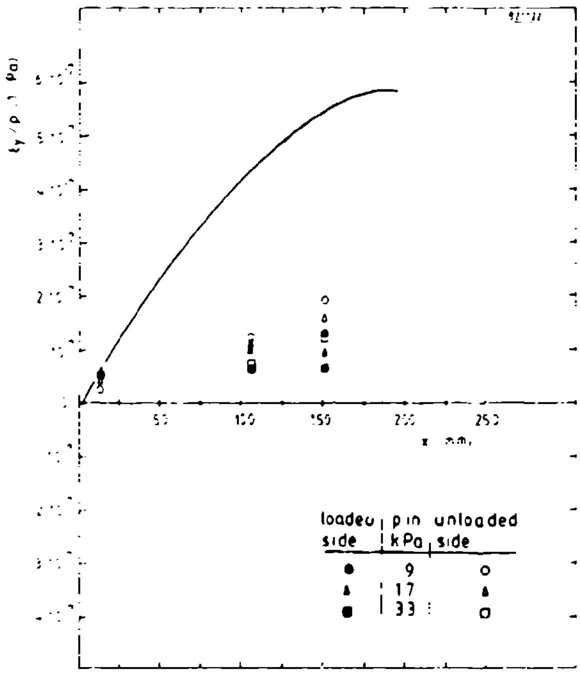


Figure 9. Strain perpendicular to the mediane.

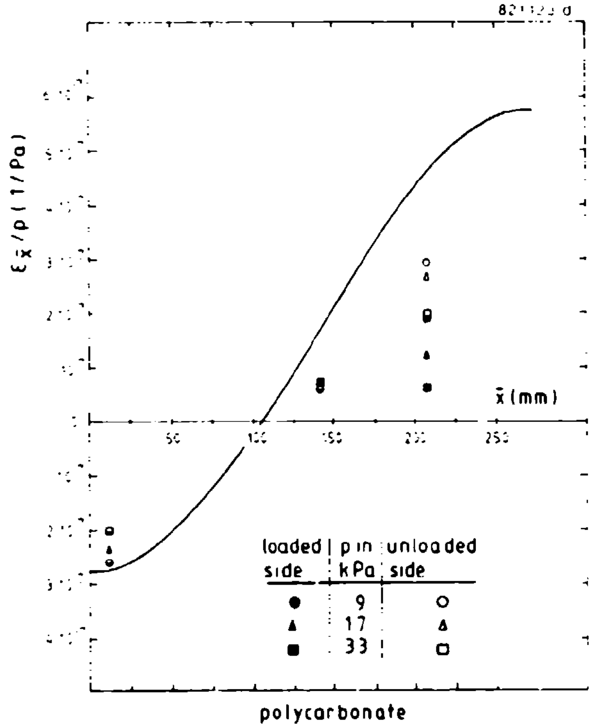


Figure 10. Strain parallel to the diagonal.

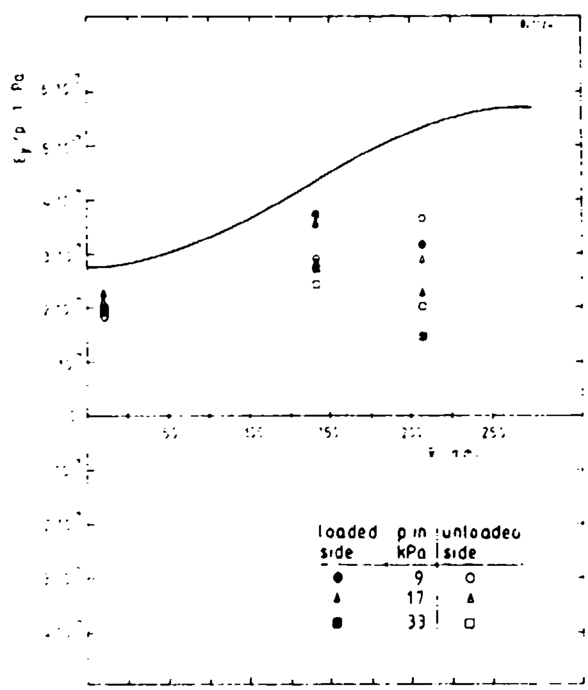


Figure 11. Strain perpendicular to the diagonal.

3. DERIVATION OF CALCULATION MODEL

From the strain measurements it is clear that by neglecting membrane action the strains are greatly overestimated.

It is very well possible to calculate the strains in a square (or rectangular) membrane that is fixed along the edges (ref. (1)).

Although the combination of bending and membrane action is much more complicated some investigators have developed approximate formulae that take into account both bending and membrane action (ref. (3) and (4)) by assuming fixed edges.

However, the strain measurements clearly show that there are no membrane stresses perpendicular to the edges (Figs. 4 and 8). This means that these edges are free to translate inward and that the assumption of fixed edges will give an overestimate of the membrane action.

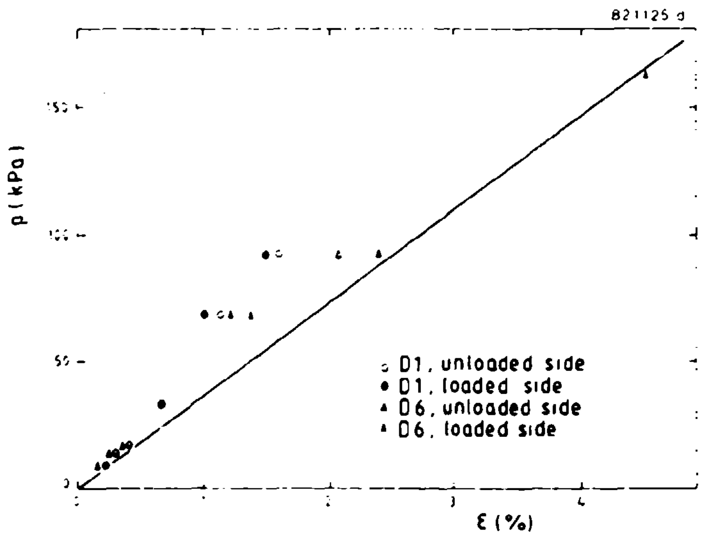
Unfortunately it is impossible to give an analytic solution of membrane action in rectangular plates with edges that are free to move. There is a possibility however to obtain results in each specific situation with the help of finite-element-methods.

For the drafting of a new Dutch Building code on window-panes lots of finite-element-calculations have been performed. One of the conclusions that could be drawn from the results is, that the point in which the stresses are maximal, moves from the centre of the pane, along the diagonal, to the corners. This is in agreement with the strain measurements: the relative strains in the corners remain about constant under uncreasing loading, while all the other relative strains decrease. Figs. 6, 7, 10 and 11 with $\bar{x} = \bar{y} = o$).

Therefore it is rational that these strains will finally become decisive.

In order to check whether the relative strains in the corners also remain constant under very high deformation and are thus not influenced by membrane action, in Figure 12 the relation is given between these strains and the peak overpressure of the loading for the polycarbonate.

In the plot also the theretical relationship is drawn.



relation between overpressure and strains near the corner of a pane

Figure 12.

For very high loadings there appears to be some influence of membrane action, but it is clear that by assuming a simply-supported Kirchoff-plate the maximum strains in the corners can be predicted quite accurately.
Although the measurements have been carried out on a square plate, it is to be expected that rectangular plates will behave in the same way.
So, for rectangular plates the maximum stresses are the bending stresses in the corners if the deflections are big enough.
These stresses are given by:

$$\sigma = 51 \cdot \alpha \frac{q}{h^2} \cdot \frac{a^3}{b} \tag{9}$$

where b is the greater span and α a coefficient dependent on the b/a ratio. Numerical values for α are given in Table 1 (ref. (1)).

TABLE I. Numerical values for α.

b/a	$\alpha(\times 10^{-3})$	b/a	$\alpha(\times 10^{-3})$
1,0	4,06	1,6	8,30
1,1	4,85	1,7	8,83
1,2	5,64	1,8	9,31
1,3	6,38	1,9	9,74
1,4	7,05	2,0	10,13
1,5	7,72	3,0	12,23

It appears that α is more or less directly proportional to b/a, so eq. (9) can be approximated by:

$$\sigma = 0{,}225\, q\, \frac{a^2}{h^2} \tag{10}$$

4. VALIDITY OF THE MODEL

Eq. (10) is only valid if the deflections are big enough. So, it is necessary to determine whether the equation may be used. From ref. (1) it can be derived that, as an approximation, the influence of membrane action relative to bending is determined by the factor $C \cdot \frac{\hat{z}^2}{h^2}$.

Coefficient C generally depends on the edge conditions, Poisson's ratio and the length-to-width ratio b/a of the plate.

The edge conditions are the same for all panes. From the strain measurements it can be found that for both the glass and the polycarbonate pane the strains in the corners become decisive at about $\hat{z}/h = 6$.

So, only the effect of b/a on C has to be quantified. Increasing the b/a ratio has two aspects:

(a) The effect of membrane action decrease: for large b/a ratios there is no membrane action.

(b) The bending stresses near the centre increase much more than those near the corners.

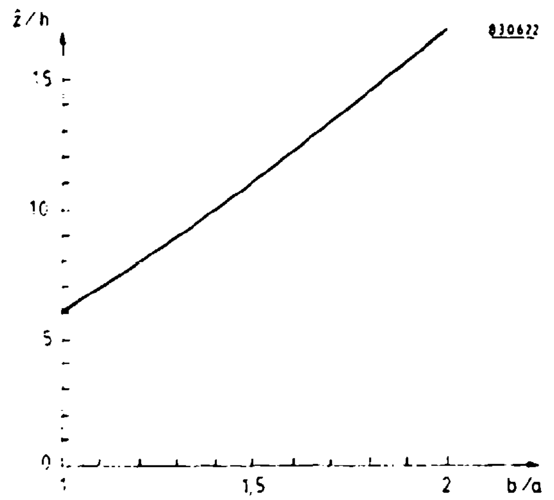
Both aspects will result in an increase in the critical $\hat{z}/h$ ratio.

The influence can be quantified as follows:

(a) A formula in ref. (5) suggests that C is about proportional to $(a/b)^2$, so the critical $\hat{z}/h$ would be proportional to b/a.

(b) As the stresses in the centre are almost proportional to b/a, while those in the corners are almost constant, the critical $\hat{z}/h$ would be proportional to $(b/a)^{1/2}$.

On aggretate the critical value of $\hat{z}/h$ will be proportional to $(b/a)^{3/2}$. This is visualised in Figure 13.



critical value of max displacement as a function of length-width ratio

Figure 13.

The displacement $\hat{z}$ for rectangular plates follows from:

$$\hat{z} = \alpha \cdot \frac{q\,a^4}{D} \tag{11}$$

Because of the uncertainties in the reasoning for the critical value of $\hat{z}/h$ it is advisable to use the result only for b/a ratios up to 2.

In those situations where $\hat{z}/h$ is smaller than the above given critical value, eq. (10) may not be used, but membrane action may already be considerable. Therefore it is advisable to interpolate linearly between the normal bending stress in the centre of the pane and the stress given by eg. (10).

This leads to:

$$\sigma = f \cdot 0{,}225 \cdot q \frac{a^2}{h^2} \qquad (12)$$

and the correction factor f follows from:

$$f = 1 + 1/9\,[\,(\hat{z}/h)_{cr} - \hat{z}/h\,] \qquad (13)$$

where $(\hat{z}/h)_{cr}$ is the critical value given by Figure 13.

5. EVALUATION OF BREAKAGE TESTS

The breakage pressures found for 220 panes have been analysed with the calculation model derived earlier.

Attention has been given to the influence of:

(a) length-to-width ratio

(b) thickness of the pane

(c) area of the pane

(d) application of double panes.

(a) The panes in the tests had length-to-width ratios from 1, 1,5 or 2. Application of the model compared favourably with the actual results.

(b) The thicknesses of the panes tested ranged from 1,3 to 6,5 mm; in all there were 8 different thicknesses.
From the properties of glass it can be explained that the strength will increase with decreasing thickness (ref. (6)). When the strength of a pane with a thickness of 6 mm is assumed to be one, the relative strength of other thicknesses are given in Figure 14.

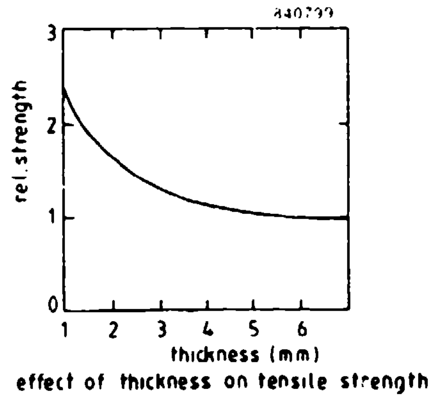


Figure 14.

(c) The panes tested had areas of 0,16, 0,18, 0,32 and 1,8 m^2. The later were tested in the 2-m blast simulator, Figure 15.

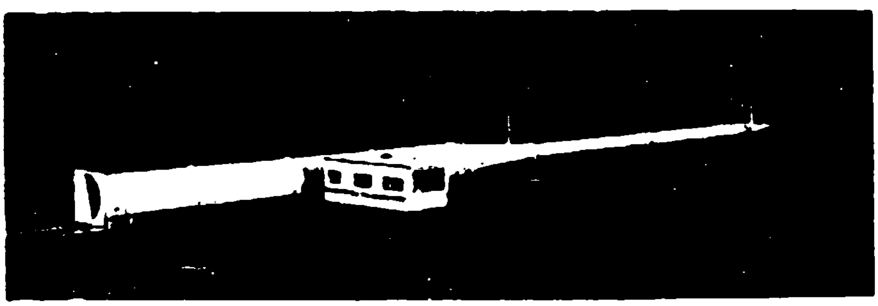


Figure 15. Overview of the 2-m PML blast simulator.

Since with increasing area also the chance of a severe scratch being present increases, the strength will decrease with increasing area. Ref. (7) states on the basis on statistics that by increasing the area by a factor of 10, the strength will be reduced by one third. This is in agreement with the tests.

(d) The breakage pressure of double panes can be calculated by assuming that both panes always move together. So, when both panes have equal thickness, the breakage pressure will be double that of a single pane. However, the strength will reduce by 10 percent, for the same reasons as under (c).

The strength of a pane with a surface area of about 2 m^2 and a thickness of 6 mm, loaded by an explosion, is about 65 MPa with a standard deviation of 20 percent.

6. CONCLUSIONS

It is possible to calculate the maximum stresses in blast-loaded, rectangular window-panes, with the help of the stresses in the corner of a simply supported plate under pure bending.
A value for the strength of glass has been established that may be adjusted for changes in pane area and thickness.

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DESIGN CRITERIA AND PRELIMINARY ACCEPTANCE TEST SPECIFICATIONS FOR BLAST RESISTANT WINDOWS

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ABSTRACT

Preliminary design criteria for blast resistant windows exposed to blast overpressures up to 25 psi are recommended. Design procedures and design curves for fully tempered glass are presented and parametized according to glass thickness, glass dimensions, glass aspect ratio, peak blast overpressures, and effective blast duration. Curves for annealed glass are also presented for the purpose of analyzing the safety of existing structures. Design criteria for frames and a test certification procedure are also discussed. Additionally, design examples are presented.

1. INTRODUCTION

Historical records of explosion effects demonstrate that airborne glass fragments from failed windows are a major cause of injuries from accidental explosions. This risk to life is heightened in modern facilities, which often have large areas of glass for aesthetic reasons.

Guidelines are presented for both the design, evaluation, and certification of windows to safely survive a prescribed blast environment described by a triangular-shaped pressure-time curve. Window designs using tempered glass based on these guidelines can be expected to provide a probability of failure at least equivalent to that provided by current safety standards for safely resisting wind loads.

The guidelines, which apply for peak blast overpressures less than about 25 psi, are presented in the form of load criteria for the design of both the glass panes and framing system for the window. The criteria account for both bending and membrane stresses and their effect on maximum principal stresses and the nonlinear behavior of glass panes. The criteria cover a broad range of design parameters for rectangular-shaped glass panes: a pane aspect ratio $1.00 \leq a/b \leq 2.00$, pane area $1.0 \leq ab \leq 25$ ft^2, and nominal glass thickness $1/8 \leq t \leq 1/2$ inch. Most of the criteria are for blast resistant windows with fully heat-treated, tempered glass. However, criteria are also presented for annealed glass in order to assess the safety of existing windows that were not designed to resist blast overpressures.

2. DESIGN CRITERIA FOR GLAZING

2.1 Glazing Materials

The design criteria cover two types of glass: annealed glass and fully tempered glass. Both glazings are required to meet the requirements of Federal Specifications DD-G-1403B and DD-G-451d. Tempered glass is also required to meet the requirements of ANSI Z97.1-1975.

Annealed glass is the most common form of glass available today. Depending upon manufacturing techniques, it is also known as plate, float or sheet glass. During manufacture, it is cooled slowly. The process results in very little, if any, residual compressive surface stress. Consequently, annealed glass is of relatively low strength when compared to tempered glass. Furthermore, it has large variations in strength and fractures into dagger-shaped, razor-sharp fragments. For these reasons, annealed glass is not recommended for use in blast resistant windows. It is included in the design criteria only for safety analysis of existing facilities.

Heat-treated, tempered glass is the most readily available tempered glass on the market. It is manufactured from annealed glass by heating to a high uniform temperature and then applying controlled rapid cooling. As the internal temperature profile relaxes towards uniformity, internal stresses are created. The outer layers, which cool and contract first, are set in compression, while internal layers are set in tension. As it is rare for flaws, which act as stress magnifiers, to exist in the interior of tempered glass sheets, the internal tensile stress is of relatively minimal consequence. As failure originates from tensile stresses exciting surface flaws in the glass, precompression permits a larger load to be carried before the net tensile strength of the tempered glass pane is exceeded. Tempered glass is typically four to five times stronger than annealed glass.

The fracture characteristics of tempered glass are superior to annealed glass. Due to the high strain energy stored by the prestress, tempered glass will eventually fracture into small cube-shaped fragments instead of the razor-sharp and dagger-shaped fragments associated with fracture of annealed glass. Breakage patterns of side and rear windows in American automobiles are a good example of the failure mode of heat-treated tempered glass.

Semi-tempered glass is often marketed as safety or heat-treated glass. However, it exhibits neither the dicing characteristic upon breakage nor the higher tensile strength associated with fully tempered glass. Semi-tempered glass is not recommended for blast resistant windows unless it is laminated or backed by a fragment retention film.

Another common glazing material is wire glass, annealed glass with an embedded layer of wire mesh. Wire glass has the fracture characteristics of annealed glass and although the wire binds fragments, it presents metal fragments as an additional hazard. Wire glass is not recommended for blast resistant windows.

The design of blast resistant windows is restricted to heat-treated fully-tempered glass meeting both Federal Specification DD-G-1403B and ANSI Z97.1-1975. Tempered glass meeting only DD-G-1403B may possess a surface precompression of only 10,000 psi. At this level of precompression, the fracture pattern is similar to annealed and semi-tempered glass. Tempered glass meeting ANSI Z97.1-1975 has a higher surface precompression level and tensile strength which improves the capacity of blast resistant windows. Additionally, failure results in smaller cubical-shaped fragments. To assure reliable performance of blast resistant glazing, it is required that heat-treated tempered glass fully conform to ANSI Z97.1-1975.

Although heat-treated tempered glass exhibits the safest failure mode, failure under blast loading still presents a significant health hazard. Results from blast tests reveal that upon fracture, tempered glass fragments may be propelled in cohesive clumps that only fragment upon impact into smaller rock-salt type fragments. Even if the tempered glass breaks up initially into small fragments, the blast pressure will propel the fragments at a high velocity which constitutes a hazard. Adding fragment retention film (discussed in Section 2.5) to the inside face of heat-treated tempered glass will significantly improve safety.

2.2 Design Stresses

The design stress is the maximum principal tensile stress allowed for the glazing. The design stress was derived for a prescribed probability of failure, using a statistical failure prediction model under development by the ASTM. Thus, failure of the glazing is assumed to occur when the maximum principal tensile stress exceeds a design stress associated with a prescribed probability of failure. The model accounts for the area of glazing (as it effects the size, number and distribution of surface flaws), stress intensity duration, thickness and aspect ratio of glazing (as it affects the ratio of maximum to minimum principle stresses in the glazing), degree of glass temper (as it affects the precompression stress in the glazing), strength degradation due to exposure, and the maximum probability of failure required of the glazing. For the full range of design parameters ($1.0 \leq ab \leq 25$ ft^2, $1.00 \leq a/b \leq 2.00$ and $1/8 \leq t \leq 1/2$ inches), and a stress intensity duration of 1,000 msec, the model predicted a design stress for tempered glass ranging between 16,950 and 20,270 psi based on a probability of failure $P(F) \leq 0.001$. Because analysis indicates that significant stress intensity durations are less than 1,000 msec, even for pressure durations of 1,000 msec, a design stress equal to 17,000 psi was selected for tempered glass. The model also predicted an allowable stress for annealed glass ranging between 3,990 and 6,039 psi, based on $P(F) \leq 0.008$, which is conventional for annealed glass. Based on these results, an allowable stress of 4,000 psi was selected for the analysis of annealed glass.

These design stresses for blast resistant glazing are higher than those commonly used in the design for one-minute wind loads. However, these higher design stresses are justified on the basis of the relatively short stress intensity duration (always considerably less than one second) produced by blast loads.

2.3 Dynamic Response to Blast Load.

An analytical model was used to predict the blast load capacity of annealed and tempered glazings. Characteristic parameters of the model are illustrated in Figure 1.

The glazing is a rectangular glass plate having a long dimension, a, short dimension, b, thickness, t, poisson ratio, $\nu = 0.22$, and elastic modulus, E = 10,000,000 psi. The plate is simply supported along all four edges, with no in-plane and rotational restraints at the edges. The relative bending stiffness of the support members is assumed to be infinite relative to the pane. The failure or design stress, f_u, was assumed to be 17,000 psi for tempered glass and 4,000 psi for annealed glass.

The blast pressure loading is described by a peak triangular-shaped pressure-time curve as shown in Figure 1b. The blast pressure rises instantaneously to a peak blast pressure, B, and then decays with a blast pressure duration, T. The pressure is uniformly distributed over the surface of the plate and applied normal to the plate.

The resistance function (static uniform load, r, versus center deflection, X) for the plate accounts for both bending and membrane stresses. The effects of membrane stresses produce nonlinear stiffening of the resistance function as illustrated in Figure 1c. The failure deflection, X_u, is defined as the center deflection where the maximum principle tensile stress at any point in the glass first reaches the design stress, f_u.

The model used a single degree of freedom system to simulate the dynamic response of the plate, as shown in Figure 1d. Damping of the window pane is assumed to be 5% of critical damping . The applied load, P(t), is shown in Figure 1b. The resistance function, r(x), is shown in Figure 1d. Given the design parameters for the glazing, the design or failure stress, f_u, and the blast load duration, T, the model calculated the peak blast pressure, B, required to fail the glazing by exceeding the prescribed probability of failure, P(F). The model also assumed failure to occur if the center deflection exceeded ten times the glazing thickness. This restricts solutions to the valid range of the Von Karmen plate equations used to develop the resistance function for the glazing.

2.4 Design Charts

Charts are presented in Figures 2 to 16 for both the design and evaluation of glazing to safely survive a prescribed blast loading. The charts were developed using the analytical model described in Section 2.3. The charts relate the peak blast pressure capacity, B, of both tempered and annealed glazing to all combinations of the following design parameters: a/b = 1.00, 1.25, 1.50, 1.75 and 2.00; $1.00 \leq ab \leq 25$ ft^2; $12 \leq b \leq 60$ inches; $2 \leq T \leq 1{,}000$ msec; and t = 1/8, 3/16, 1/4, 3/8 and 1/2 inch (nominal) for tempered glass and t = 1/8 and 1/4 inch (nominal) for annealed glass.

Each chart has a series of curves. Each curve corresponds to the value of b (short dimension of pane) shown to the right of the curve. Adjacent to each posted value of b is the value of B (peak blast pressure capacity) corresponding to T = 1,000 msec. The posted value of B is intended to reduce errors when interpolating between curves.

Figures 2 to 11 apply for heat-treated tempered glass meeting Federal Specification DD-G-1403B and ANSI Z97.1-1975. The value of B is the peak blast capacity of the glazing based on failure defined as f_u = 17,000 psi. This value corresponds to a probability of failure, $P(F) \leq 0.001$.

Figures 12 to 16 apply for annealed (float, plate or sheet) glass. Due to the variation in the mechanical properties and fragment hazard of annealed glass, Figures 12 to 16 are not intended for design, but for safety evaluation of existing glazing. The value of B is the peak blast pressure capacity of the glazing based on f_u = 4,000 psi. This value corresponds to $P(F) \leq 0.008$, the common architectural standard for annealed glass.

The charts are based on the minimum thickness of fabricated glass allowed by Federal Specification DD-G-451d. However, the nominal thickness should always be used in conjunction with the charts, i.e., t = 1/8 inch instead of the possible minimum thickness of 0.115 inch.

In a few cases, the charts show a pane to be slightly stronger than the preceding smaller size. This anomaly stems from dynamic effects and the migration of maximum principal stresses from the center to the corner region of the window pane. In such cases, interpolation should be between the two curves that bound the desired value.

2.5 Fragment Retention Film

Many injuries in explosions are caused by glass fragments propelled by the blast wave when a window is shattered. Commercial products have been developed which offer a relatively inexpensive method to improve the shatter resistance of window glass and decrease the energy and destructive capability of glass fragments. The product is a clear plastic (polyester) film which is glued to the inside surface of window panes. The film is used primarily for retrofitting previously installed windows. Typical films are about 0.002 to 0.004 inch thick polyester with a self-adhesive face. The film is often commercially referred to as shatter resistant film, safety film, or security film.

The film increases safety by providing a strong plastic type backing. The film will hold the glass in position even though the glass is shattered. If a complete pane of film reinforced glass is blown away from its frame by a higher than design blast wave, it will travel as a single piece while adhering to the film. In this configuration, tests indicate that it will travel a shorter distance and the individual fragments will be less hazardous because of the shielding effect of the film. If a strong structural member or crossbar, which can be decorative, is secured across the opening, the glass will tend to wrap around the crossbar in a manner similar to a wet blanket and will be prevented from being propelled across a room. Additionally, if a projectile strikes the film reinforced glass with sufficient force to pass through it, the glass immediately around the hole will ordinarily adhere to the film. The result is that any fragments broken free by the impact will be few in number and lower in energy content. Results from explosives tests demonstrate that the film is highly effective in reducing the number of airborne glass fragments.

There are additional benefits from fragment retention film. The film can be tinted to improve the heat balance of the structure. Also, the film affords benefits in terms of physical security. Additionally, the film also protects the inner tensile surface of the glazing from scratches and humidity, thus reducing strength degradation of the glazing with time. Finally, in the event of a multiple blast explosion where the glass will be progressively weakened by the effects of ceramic fatigue, fragment retention film can provide a critical factor of safety.

3. DESIGN CRITERIA FOR FRAME

3.1 Sealants and Gaskets

The sealant and gasket design should be consistent with industry standards and also account for special requirements for blast resistant windows. The gasket should be continuous around the perimeter of the glass pane and its stiffness should be at least 10,000 psi (pounds/linear inch of frame/inch of gasket deflection). Analysis indicates that the employment of a gasket stiffness below 10,000 psi will increase the failure rate of the window pane. The gasket should provide adequate grip as the glass pane flexes under the applied blast loading.

3.2 Frame Loads

The window frame must develop the static design strength of the glass pane, r_u, given in Table 1. Otherwise, the design is inconsistent with frame assumptions and the peak blast pressure capacity of the window pane predicted from Figures 2 to 16 will produce a failure rate in excess of the prescribed failure rate. This results because frame deflections induce higher principal tensile stresses in the pane, thus reducing the strain energy capacity available to safely resist the blast loading.

In addition to the load transferred to the frame by the glass, frame members must also resist a uniform line load, r_u, applied to all exposed members. Until criteria are developed to account for the interaction of the frame and glass panes, the frame, mullions, fasteners, and gaskets should satisfy the following design criteria:

1. Deflection: No frame member should have a relative displacement exceeding 1/264 of its span or 1/8 inch, whichever is less.

2. Stress: The maximum stress in any member should not exceed $f_y/1.65$, where f_y = yield stress of the members material.

3. Fasteners: The maximum stress in any fastener should not exceed $f_y/2.00$.

4. Gaskets: The stiffness of gaskets should be at least 10,000 psi (pounds/linear inch of frame/inch of gasket deflection).

The design loads for the glazing are based on large deflection theory, but the resulting transferred design loads for the frame are based on an approximate solution of small deflection theory for laterally loaded plates. Analysis indicates this approach to be considerably simpler and more conservative than using the frame loading based exclusively on large deflection membrane behavior, characteristic of window panes. According to the assumed plate theory, the design load, r_u, produces a line shear, V_x, applied by the long side, a, of the pane equal to:

$$V_x = C_x r_u b \sin(\pi x/a) \qquad (1)$$

The design load, r_u, produces a line shear, V_y, applied by the short side, b, of the pane equal to:

$$V_y = C_y r_u b \sin(\pi y/b) \qquad (2)$$

The design load, r_u, produces a corner concentrated load, R, tending to uplift the corners of the window pane equal to:

$$R = -C_R r_u b^2 \qquad (3)$$

Distribution of these forces, as loads acting on the window frame, is shown in Figure 17. Table 2 presents the design coefficients, C_x, C_y, and C_R for practical aspect ratios of the window pane. Linear interpolation can be used for aspect ratios not presented. The loads given by Equations 1, 2, 3 and the load caused by a uniform line load, r_u, should be used to check the frame mullions and fasteners for compliance with the deflection and stress criteria stated above. It is important to note that the design load for mullions is twice the load given by Equations 1 to 3, in order to account for effects of two panes being supported by a common mullion.

3.3 Rebound Stresses

Under a short duration blast load, the window will rebound with a negative (outward) deflection. The stresses produced by the negative deflection must be safely resisted by the window while positive pressures act on the window. Otherwise, the window which safely resists stresses induced by positive (inward) displacements will later fail in rebound while positive pressure still acts. This will propel glass fragments into the interior of the structure. However, if the window fails in rebound during the negative (suction) phase of the blast loading, glass fragments will be drawn away from the structure.

Rebound criteria are currently not available for predicting the equivalent static uniform negative load (resistance), r_u^-, that the window must safely resist for various blast load durations. However, analysis indicates that for $T \geq 400$ msec, significant rebound does not occur during the positive blast pressure phase for the range of design parameters given in Figures 2 to 16. Therefore, rebound can be neglected as a design consideration for $T \geq 400$ msec. For $T < 400$ msec, it is recommended that the rebound charts in Volume 3 of NAVFAC P-397 be used to estimate r_u^-.

4. CERTIFICATION TESTS

Certification tests of the entire window assembly are required unless analysis demonstrates that the window design is consistent with assumptions used to develop the design criteria presented in Figures 2 to 16. The certification tests consist of applying static uniform loads on at least two sample window assemblies until failure occurs in either the tempered glass or frame. Although at least two static uniform load tests until sample failure are required, the acceptance criteria presented below encourages a larger number of test samples. The number of samples, beyond two, is left up to the vendor. Results from all tests shall be recorded in the calculations. All testing shall be performed by an independent and certified testing laboratory.

A probability of failure under testing of less than 0.025 with a confidence level of 90% is considered sufficient proof for acceptance. This should substantiate a design probability of failure, P(F), under the design blast load of 0.001.

4.1 Test Procedure - Window Assembly Test

The test windows (glass panes plus support frames) shall be identical in type, size, sealant, and construction to those furnished by the window manufacturer. The frame assembly in the test setup shall be secured by boundary conditions that simulate the adjoining walls. Using either a vacuum or a liquid-filled bladder, an increasing uniform load shall be applied to the entire window assembly (glass and frame) until failure occurs in either the glass or frame. Failure shall be defined as either breaking of glass or loss of frame resistance. The failure load, $\hat{r}$, shall be recorded to three significant figures. The load should be applied at a rate of 0.5 r_u per minute which corresponds to approximately one minute of significant tensile stress duration until failure. Table 1 presents the static ultimate resistance, r_u, for new tempered glass correlated with a probability of failure, P(F), = 0.001 and a static load duration of 1 minute. Because the effects of utilizing new glass and a longer duration tend to offset each other, r_u also closely corresponds to the equivalent static load induced by the design blast.

4.2 Acceptance Criteria

The window assembly (frame and glazing) are considered acceptable when the arithmetic mean of all the samples tested, $\bar{r}$, is such that:

$$\bar{r} \geq r_u + s\,\alpha \tag{4}$$

where: r_u = ultimate static load capacity of the glass pane

s = sample standard deviation

α = acceptance coefficient

For n test samples, $\bar{r}$ is defined as:

$$\bar{r} = \frac{\sum_{i=1}^{n} \hat{r}_i}{n} \tag{5}$$

where $\hat{r}_i$ is the recorded failure load of the i^{th} test sample. The standard sample deviation, s, is defined as:

$$s = \sqrt{\frac{\sum_{i=1}^{n} (\hat{r}_i - \bar{r})^2}{(n - 1)}} \tag{6}$$

Convenience in calculation often can be obtained by employing an alternative but equal ᶠ.ᵢm of Equation 6.

$$s = \sqrt{\frac{\sum_{i=1}^{n} \hat{r}_i^2 - \left(\frac{\sum_{i=1}^{n} \hat{r}_i}{n}\right)^2}{(n - 1)}} \tag{7}$$

The minimum value of the sample standard deviation, s, permitted to be employed in Equation 4 is:

$$s_{min} = 0.145\ r_u \qquad (8)$$

This assures a sample standard deviation no better than ideal tempered glass in ideal frames.

The acceptance coeffieient, α, is tabulated in Table 3 for the number of samples, n, tested.

As an aid to the tester, the following informational equation is presented to aid in determining if additional test samples are justified. If:

$$\bar{r} \leq r_u + s\ \beta \qquad (9)$$

then with 90% confidence, the design will not prove to be adequate with additional testing. The frame should be redesigned or thicker tempered glass used. The rejection coefficient, β, is obtained from Table 3.

If the glass assembly is upgraded with thicker tempered glass than required by the design charts (Figures 2 through 12) to resist a design blast load, it is not required to develop the higher ultimate static load capacity of the thicker glass. Instead, a static load equal to twice the design peak blast overpressure, B, shall be resisted by the window assembly. Thus the window assembly with thicker than required tempered glass shall be acceptable when:

$$\bar{r} \geq 2\ B + s\ \alpha \qquad (10)$$

If Equation 10 is not satisfied, and:

$$\bar{r} \leq 2\ B + s\ \beta \qquad (11)$$

then with 90% confidence continued testing will not raise the arithmetic mean of the failure load of the window assembly, $\bar{r}$, to the point of acceptance.

4.3 Rebound Tests

The window that passes the window assembly test is an acceptable design if the window assembly design is symmetrical about the plane of the glass or if the design blast load duration, T, exceeds 400 msec. Otherwise, the window design must pass a rebound load test to prove that the window assembly can develop the necessary strength to resist failure during the rebound phase of response. The rebound tests shall be conducted using a procedure similar to the window assembly tests, except r_u^- shall be substituted for r_u in Equations 4, 8 and 9 and the uniform load shall be applied on the inside surface of the window assembly. The loading rate shall be 0.5 r_u per minute.

4.4 Installation Inspection

A survey of past glazing failures indicates that improper installation of setting blocks, gaskets or lateral shims, or poor edge bite is a significant cause of failure because of the resultant unconservative support conditions. In order to prevent premature glass failure, a strenuous quality control program is required.

5. SAMPLE PROBLEMS

The following examples demonstrate the application of the design criteria in the design and evaluatior of windows to safely survive blast overpressures from explosions.

5.1 Problem 1 -- Design of Tempered Glass Panes

Given: A nonoperable window having a single pane of glass. Glazing: heat-treated tempered glass meeting Federal Specification DDG-G-1403B and ANSI Z97.1-1975. Dimensions of pane: a = 54 in., b = 36 in. Blast loading: B = 5.0 psi, T = 500 msec.

Find: Minimum thickness of glazing required for $P(F) \leq 0.001$.

Solution: Step 1: Tabulate the design parameters needed to enter Figure 2 to 16.

Glazing = tempered glass

a/b = 54/36 = 1.50

b = 36 in.

B = 5.0 psi

T = 500 msec

Step 2: Enter Figures 2 to 16 with the design parameters from Step 1 and find the minimum glazing thickness.

Figures 6 and 7 apply for the given design parameters. Enter Figure 6 and find the minimum glazing thickness required for B = 5.0 psi and T = 500 msec is:

t = 3/8 in. ANS

The asterisk adjacent to b = 36 inches indicates that the strength of the glazing is limited by principle stresses in corner regions of the pane.

5.2 Problem 2 -- Safety Evaluation of Existing Windows

Given: Multi-pane windows in an existing building. Dimensions of each pane: a = 36 in., b = 36 in. Glazing: float glass. Glazing thickness: t = 1/4 in. nominal. Blast loading: B = 0.60 psi, T = 100 msec.

Find: Safety of windows, based on $P(F) \leq 0.008$

Solution: Step 1: Tabulate the design parameters needed to enter Figures 2 to 16.

Glazing = annealed glass

a/b = 36/36 = 1.00

B = 0.60 psi

T = 100 msec

t = 1/4 in.

Step 2: Enter Figures 12 to 16 with the design parameters from Step 1 and find the peak blast pressure capacity.

From Figure 12, the peak blast pressure capacity of the glazing is:

B = 0.53 psi

Step 3: Determine the safety of the glazing.

The applied peak blast pressure, B = 0.60 psi, exceeds the capacity, B = 0.53 psi. Therefore, the glazing will fail at an average rate exceeding eight per thousand panes. ANS

5.3 Problem 3 -- Design Loads for Window Frame

Given: A nonoperable window has a single pane of glass. Glazing: heat-treated tempered glass meeting Federal Specification DD-G-1403B and ANSI Z97.1-1975. Dimensions of the pane: a = 50 in., b = 40 in. Blast loading: B = 1.3 psi, T = 1,000 msec.

Find: Thickness of glazing required for $P(F) \leq 0.001$ and design loading for window frame.

Solution: <u>Step 1</u>: Tabulate the design parameters needed to enter Figures 2 to 16.

Glazing = tempered glass

$a/b = 50/40 = 1.25$

$b = 40$ in.

$B = 1.3$ psi

$T = 1,000$ msec

<u>Step 2</u>: Select the minimum glazing thickness.

Enter Figures 4 and 5 which apply for the given design parameters. From Figure 5 find the minimum glazing thickness required is:

$t = 3/16$ in. nominal <u>ANS</u>

<u>Step 3</u>: Calculate the static ultimate uniform load that produces the same maximum frame load as the blast load.

Enter Table 1 for tempered glass with $b = 40$ in., $a/b = 1.25$ and $t = 3/16$ in., and find the static ultimate uniform load capacity of the glazing is:

$r_u = 2.31$ psi

Thus, the window frame must be designed to safely support, without undue deflection, a static uniform load equal to 2.31 psi applied normal to the glazing.

<u>Step 4</u>: Calculate the design loading for the window frame.

Enter Table 2 with $a/b = 1.25$, and find by interpolation the design coefficients for the frame loading are:

$C_R = 0.077$

$C_x = 0.545$

$C_y = 0.543$

From Equation 3, the concentrated load in each corner of the pane is:

$$R \text{ (corners)} = -0.077\,(2.31)(40)^2 = -285 \text{ lb}$$ ANS

From Equation 1, the design loading for the frame in the long direction (a) is:

$$V_x = 0.545\,(2.31)(40) \sin(\pi x/50)$$

$$V_x = 50.4 \sin(\pi x/50) \text{ lb/in.}$$ ANS

From Equation 2, the design loading for the frame in the short direction (b) is:

$$V_y = 0.543\,(2.31)(40) \sin(\pi y/40)$$

$$V_y = 50.2 \sin(\pi y/40) \text{ lb/in.}$$ ANS

Distribution of the design load on the frame is shown in Figure 17.

5.4 Problem 4 -- Design Loads for Multi-pane Frame

Given: A nonoperable window consists of four equal size panes of glass. Glazing: heat-treated tempered glass meeting Federal Specification DD-G-1403B and ANSI Z97.1-1975. Dimensions of the panes: a = 22.5 in., b = 18 in. Blast loading: B = 5.0 psi, T = 500 msec.

Find: Minimum thickness of glazing required for $P(F) \leq 0.001$ and the design loads for the framing system.

Solution: Step 1: Tabulate the design parameters needed to enter Figures 2 to 11.

Glazing = tempered glass

$a/b = 22.5/18 = 1.25$

$b = 18$ in.

$B = 5.0$ psi

$T = 500$ msec

Step 2: Select the minimum glazing thickness.

Enter Figures 4 and 5 which apply for the given design parameters. From Figure 5, find the minimum glazing thickness required is:

$t = 3/16$ in. nominal **ANS**

Step 3: Calculate the static ultimate uniform load that produces the same maximum reactions on the window frame as the blast load.

Enter Table 1 with b = 18 in., a/b = 1.25 and t = 3/16 in., and find the static ultimate uniform load capacity of the glazing is:

$r_u = 9.18$ psi

The window frame must be designed to safely support, without undue deflections, a static uniform load equal to 9.18 psi applied normal to the glazing.

Step 4: Calculate the design loading for the window frame.

Enter Table 2 with a/b = 1.25. With interpolation, the design coefficients for the frame loading are:

C_R = 0.077

C_x = 0.545

C_y = 0.543

From Equation 3, the concentrated loads in the corners of each pane are:

$R \text{ (corners)} = -0.077\ (9.18)(18)^2 = -229 \text{ lb}$ ANS

From Equation 1, the design loading for the long spans of the frame and mullions are:

$V_x = 0.545\ (9.18)(18) \sin(\pi x/22.5)$

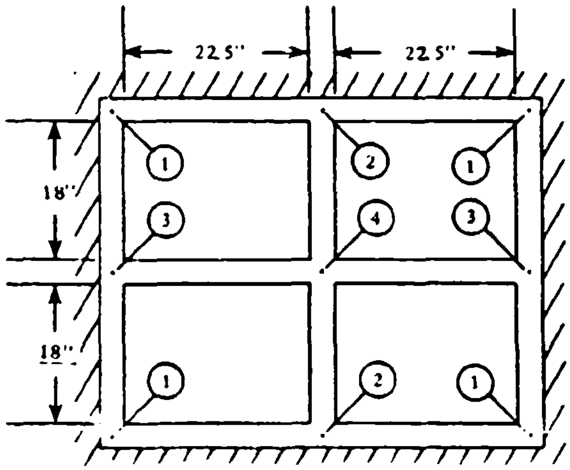
$= 90.1 \sin(\pi x/22.5) \text{ lb/in.}$ ANS

From Equation 2, the design loading for the short spans of the frame and mullions are:

$V_y = 0.543\ (9.18)(18) \sin(\pi y/18)$

$= 89.7 \sin(\pi y/18) \text{ lb/in.}$ ANS

The design loads for the window frame are shown in the following figure and table and are illustrated below.



Locations	Design Load
(1)	R
(2) (3)	2R
(4)	4R
(1)–(2)	V_x
(1)–(3)	V_y
(2)–(4)	$2\,V_y$
(3)–(4)	$2\,V_x$

5.5 Problem 5 -- Design Acceptance Based upon Certification Test Results

Given: A window 30 x 30 x 1/4-inch with a single pane of tempered glass is designed to safely resist a blast load, B, of 4.0 psi with an effective blast duration, T, of 200 msec. Certification testing involved testing three window assemblies (n = 3) to failure. Failure loads, $\hat{r}_i$, were recorded at 8.84, 9.51, and 10.8 psi.

Find: Determine if the window design is acceptable based on results from the certification tests.

Solution: Step 1: Tabulate the design parameters needed to enter Table 1:

b = 30 in.

a/b = 30/30 = 1.00

t = 1/4 in. nominal

Step 2: Employing Table 1, select the static ultimate load, r_u, corresponding to the pane geometry.

$$r_u = 6.59 \text{ psi}$$

Step 3: Calculate the arithmetic mean, $\bar{r}$, of all the samples tested.

Using Equation 5:

$$\bar{r} = \frac{\sum_{i=1}^{n} \hat{r}_i}{n} = \frac{(8.84 + 9.51 + 10.8)}{3} = 9.72 \text{ psi}$$

Step 4: Using either Equation 6 or 7, calculate the sample standard deviation, s.

The sample standard deviation, s, is calculated using Equation 6 as,

$$s = \sqrt{\frac{\sum_{i=1}^{n} (\hat{r}_i - \bar{r})^2}{(n - 1)}}$$

$$= \sqrt{\frac{(8.84 - 9.72)^2 + (9.51 - 9.72)^2 + (10.8 - 9.72)^2}{(3 - 1)}}$$

$$= 1.01 \text{ psi}$$

Step 5: Verify that the sample standard deviation, s, is larger than the minimum value, s_{min}, prescribed in Equation 8.

$$s = 1.01 \text{ psi} > s_{min} = 0.145\, r_u = 0.145\,(6.59) = 0.956 \text{ psi}$$

Thus, s = 1.01 psi is the appropriate value to use in subsequent calculations.

Step 6: Using Table 3, select the acceptance coefficient, α, that correlates with the three samples tested.

Entering Table 3, with n = 3, find:

$\alpha = 3.05$

Step 7: Verify that the window and frame passed the certification tests by meeting the conditions of Equation 4:

$$\bar{r} = 9.72 \text{ psi} > r_u + s\,\alpha = 6.59 + 1.01\,(3.04) = 9.67 \text{ psi}$$

Therefore, the window assembly design is considered safe for the prescribed blast loading.

5.6 Problem 6 -- Design Rejection Based upon Certification Test Results

Given: A window 30 x 30 x 1/4 inch with a single pane of tempered glass is designed to safely resist a blast load, B, of 4.0 psi with an effective blast duration, T, of 200 msec. Certification testing involved testing three window assemblies (n = 3) to failure. Failure loads, $\hat{r}_i$, were 6.39, 7.49, and 8.47 psi.

Find: Determine if the window design is acceptable based upon results from the certification tests

Solution: Step 1: Tabulate the design parameters needed to enter Table 1.

b = 30 in.
a/b = 30/30 = 1.00
t = 1/4 in.

Step 2: Employing Table 1 select the static ultimate load, r_u, corresponding to the pane geometry.

$r_u = 6.59$ psi

Step 3: Calculate the arithmetic mean, $\bar{r}$, of all the samples tested:

$$\bar{r} = \frac{\sum_{i=1}^{n} \hat{r}_i}{n} = \frac{(6.39 + 7.49 + 8.47)}{3} = 7.45 \text{ psi}$$

Step 4: Employing either Equation 6 or 7, calculate the sample standard deviation, s.

The sample standard deviation, s, is calculated using Equation 6 as:

$$s = \sqrt{\sum_{i=1}^{n} \frac{\hat{r}_i - \bar{r}^{\,2}}{(n - 1)}} =$$

$$\sqrt{\frac{(6.39 - 7.45)^2 + (7.49 - 7.45)^2 + (8.47 - 7.45)^2}{(3 - 1)}}$$

$$= 1.04 \text{ psi}$$

Step 5: Verify that the sample deviation, s, is larger than the minimum value, s_{min}, prescribed in Equation 8.

$$s = 1.04 \text{ psi} > s_{min} = 0.145\ r_u = 0.145\ (6.59) = 0.956 \text{ psi}$$

Thus, s = 1.04 psi is the appropriate value to use in subsequent calculations.

Step 6: Using Table 3, select the acceptance coefficient, α, and the rejection coefficient, β, for n = 3. Entering Table 3 with n = 3, find,

$\alpha = 3.05$

$\beta = 0.871$

Step 7: Verify if the window and frame passed the certification tests by meeting the conditions of Equation 4:

$$\bar{r} = 7.45 \text{ psi} < r_u + s\,\alpha = 6.59 + 1.04\,(3.04) = 9.75 \text{ psi}$$

Therefore, the window assembly design does not satisfy Equation 4 and is considered unsafe for the prescribed design blast loading.

Step 8: Determine if the window design should be abandoned or of additional testing is justified. From Equation 9,

$$\bar{r} = 7.45 \text{ psi} < r_u + 5\,\beta = 6.59 + 1.04\,(0.871) = 7.50 \text{ psi}$$

Therefore, with a level of confidence of 90%, additional testing will not lead to acceptance of the window design. A new design should be chosen and certified.

6. LIST OF SYMBOLS

a	Long dimension of glass pane, in.
B	Peak blast overpressure, psi
b	Short dimension of glass pane, in.
C	Shear coefficient for load passed from glass pane to its support frame
D	Modulus of rigidity of glass pane, in-lb
E	Modulus of elasticity, psi
f_u	Design stress and allowable principal tensile stress in glass pane for prescribed P(F), psi
f_y	Yield stress of frame members and fasteners, psi
I	Moment of inertia of window frame, $in.^4$
n	Number of window assemblies tested

M_e	Effective total mass ($lb\text{-}ms^2/in.$)
P	Blast overpressure at any time, psi
P(F)	Probability of failure of glass pane
R	Uplifting nodal force applied by glass pane to corners of frame, lb
r	Resistance, psi
$\hat{r}$	Test load at failure of frame or glass during certification tests, psi
$\bar{r}$	Mean failure load of n samples, psi
r_u	Uniform static load capacity of the glass pane, psi
$\bar{r}_u$	Uniform static negative load capacity of the window assembly, psi
s	Sample standard deviation, psi
T	Effective duration of blast load, msec
t	Nominal thickness of glass pane, in.; elapsed time, msec
V_x	Static load applied by glass pane to long edge of frame, lb/in.
V_y	Static load applied by glass pane to short edge of frame, lb/in.
x	Distance from corner measured along long edge of glass pane, in.
X	Center deflection of pane, in.
X_u	Center deflection of pane at r_u, in.
α	Acceptance coefficient
β	Rejection coefficient
ν	Poisson's ratio

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8. ACKNOWLEDGMENTS

The authors wish to express their appreciation and gratitude to all the following dedicated scientists, engineers and professionals who made this study possible. We thank Dr. Lynn Beason and Dr. James Morgan of Texas A&M University for their pioneering and high quality work on maximum allowable stress levels in glass. We also thank Mr. Donald Moore of the Jet Propulsion Laboratory for his work on the load, stress, and deflection relationships of glass panes. Additionally, we thank Dr. J. Minor and Dr. C.V.G. Vallabhan of Texas Technical University for their unselfish and excellent advice.

Table 1. Static Ultimate Loads, r_u, (psi) for Testing Certification of Tempered Glass

b (in.)	a/b = 1.00*				a/b = 1.25				a/b = 1.50			
	t=1/2 in.	t=3/8 in.	t=1/4 in.	t=3/16 in.	t=1/2 in.	t=3/8 in.	t=1/4 in.	t=3/16 in.	t=1/2 in.	t=3/8 in.	t=1/4 in.	t=3/16 in.
12	106.0	60.7	22.6	16.9	80.8	46.7	19.3	13.0	64.5	38.5	13.7	11.3
14	76.7	39.8	17.5	16.2	58.8	33.7	13.5	12.1	46.9	27.5	11.4	10.1
16	58.1	30.5	15.6	13.7	44.7	25.9	11.8	11.2	36.8	20.6	9.95	9.08
18	43.5	24.3	15.3	10.9	34.8	20.9	11.7	9.18	28.5	16.7	9.49	8.09
20	33.2	20.6	12.4	9.38	28.0	17.5	10.5	7.71	22.7	12.5	9.15	6.76
22	27.8	17.4	10.6	8.12	23.4	13.3	8.93	6.62	18.5	11.0	7.88	5.57
24	23.8	15.3	9.35	7.04	20.0	11.9	7.74	5.55	15.9	10.2	6.79	4.73
26	20.7	14.6	8.33	5.57	17.4	11.0	6.80	4.90	13.9	9.34	5.77	4.18
28	18.2	14.5	7.39	4.96	15.5	10.8	6.02	4.34	11.2	9.07	5.03	3.73
30	16.1	14.0	6.59	4.47	12.5	10.7	5.21	3.87	10.4	8.81	4.42	3.32
32	14.7	12.6	5.37	4.05	11.4	10.3	4.71	3.47	9.83	8.54	4.02	2.96
34	14.2	10.9	4.88	3.69	10.7	9.30	4.27	3.13	9.17	8.20	3.67	2.65
36	13.8	9.97	4.47	3.39	10.4	8.42	3.88	2.84	8.79	7.43	3.33	2.34
38	13.7	9.16	4.12	3.12	10.4	7.70	3.54	2.59	8.71	6.78	3.04	2.12
40	13.5	8.55	3.81	2.88	10.3	7.07	3.25	2.31	8.36	6.20	2.77	1.94
42	12.5	7.99	3.54	2.67	10.2	6.53	2.99	2.12	8.23	5.68	2.53	1.79
44	11.0	7.41	3.29	2.45	9.42	6.05	2.76	1.97	8.19	5.11	2.27	1.57
46	10.3	6.90	3.08	2.28	8.72	5.61	2.56	1.83	7.70	4.70	2.10	1.31
48	9.58	6.43	2.88	2.14	8.10	5.06	2.32	1.65	7.16	4.34	1.95	1.11
50	8.97	5.99	2.71	2.01	7.57	4.76	2.16	1.40				
52	8.50	5.58	2.54	1.89	7.09	4.48	2.02	1.20				
54	8.07	4.82	2.37	[illegible]								
56	7.68	4.55	2.24	1.45								
58	7.25	4.31	2.12	1.26								
60	6.87	4.09	2.01	1.10								

b (in.)	a/b = 1.75				a/b = 2.00			
	t=1/2 in.	t=3/8 in.	t=1/4 in.	t=3/16 in.	t=1/2 in.	t=3/4 in.	t=1/4 in.	t=3/16 in.
12	57.9	32.7	13.0	9.98	51.1	29.4	11.6	8.57
14	42.2	23.6	10.3	6.85	37.1	21.3	8.94	5.83
16	31.3	17.8	8.58	6.79	28.1	16.2	7.26	5.24
18	24.4	13.9	7.62	6.69	22.0	12.9	5.37	5.15
20	19.5	11.8	7.01	5.84	17.7	10.5	5.07	5.00
22	15.9	10.1	6.73	4.95	14.6	8.86	4.99	4.48
24	13.3	9.03	5.83	4.28	12.3	7.77	4.87	3.85
26	11.8	8.10	5.12	3.76	10.5	6.87	4.64	3.38
28	10.4	7.34	4.50	3.37	9.11	5.34	4.07	2.99
30	9.39	7.08	4.02	3.00	8.20	5.08	3.62	2.66
32	8.66	6.82	3.62	2.63	7.44	4.97	3.26	2.35
34	7.99	6.56	3.31	2.36	6.78	4.86	2.94	2.10
36	7.37	6.30	3.01	2.13	6.21	4.74	2.66	1.88
38	6.93	6.02	2.73	1.94	5.05	4.60	2.42	1.61
40	6.60	5.37	2.46	1.73	4.78	4.53	2.20	1.31
42	6.26	4.94	2.25	1.42	4.60	4.49	2.00	1.08
44	5.93	4.55	2.08	1.18				

*a = longest side of window; b = shortest side of window; t = nominal thickness of window.

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Table 2. Coefficients for Frame Loading

a/b	C_R	C_x	C_y
1.00	0.065	0.495	0.495
1.10	0.070	0.516	0.516
1.20	0.074	0.535	0.533
1.30	0.079	0.554	0.551
1.40	0.083	0.570	0.562
1.50	0.085	0.581	0.574
1.60	0.086	0.590	0.583
1.70	0.088	0.600	0.591
1.80	0.090	0.609	0.600
1.90	0.091	0.616	0.607
2.00	0.092	0.623	0.614

Table 3. Statistical Acceptance and Rejection Coefficients

Number of Window Assemblies	Acceptance Coefficient	Rejection Coefficient
n	α	β
2	4.14	.546
3	3.05	.871
4	2.78	1.14
5	2.65	1.27
6	2.56	1.36
7	2.50	1.42
8	2.46	1.48
9	2.42	1.49
10	2.39	1.52
11	2.37	1.54
12	2.35	1.57
13	2.33	1.58
14	2.32	1.60
15	2.31	1.61
16	2.30	1.62
17	2.28	1.64
18	2.27	1.65
19	2.27	1.65
20	2.26	1.66
21	2.25	1.67
22	2.24	1.68
23	2.24	1.68
24	2.23	1.69
25	2.22	1.70
30	2.19	1.72
40	2.17	1.75
50	2.14	1.77

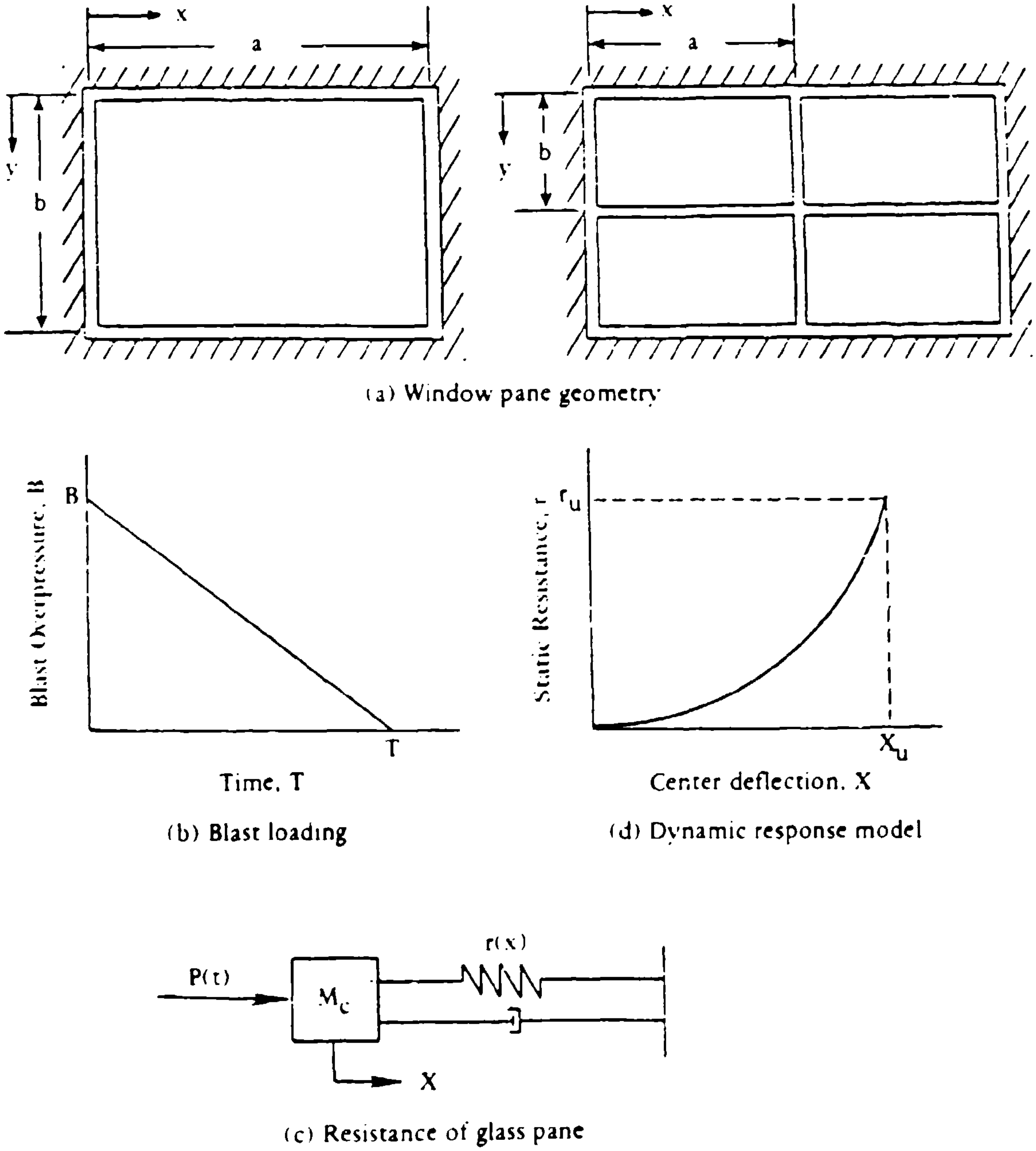

Figure 1. Characteristic parameters for glass pane, blast loading, resistance function and response model.

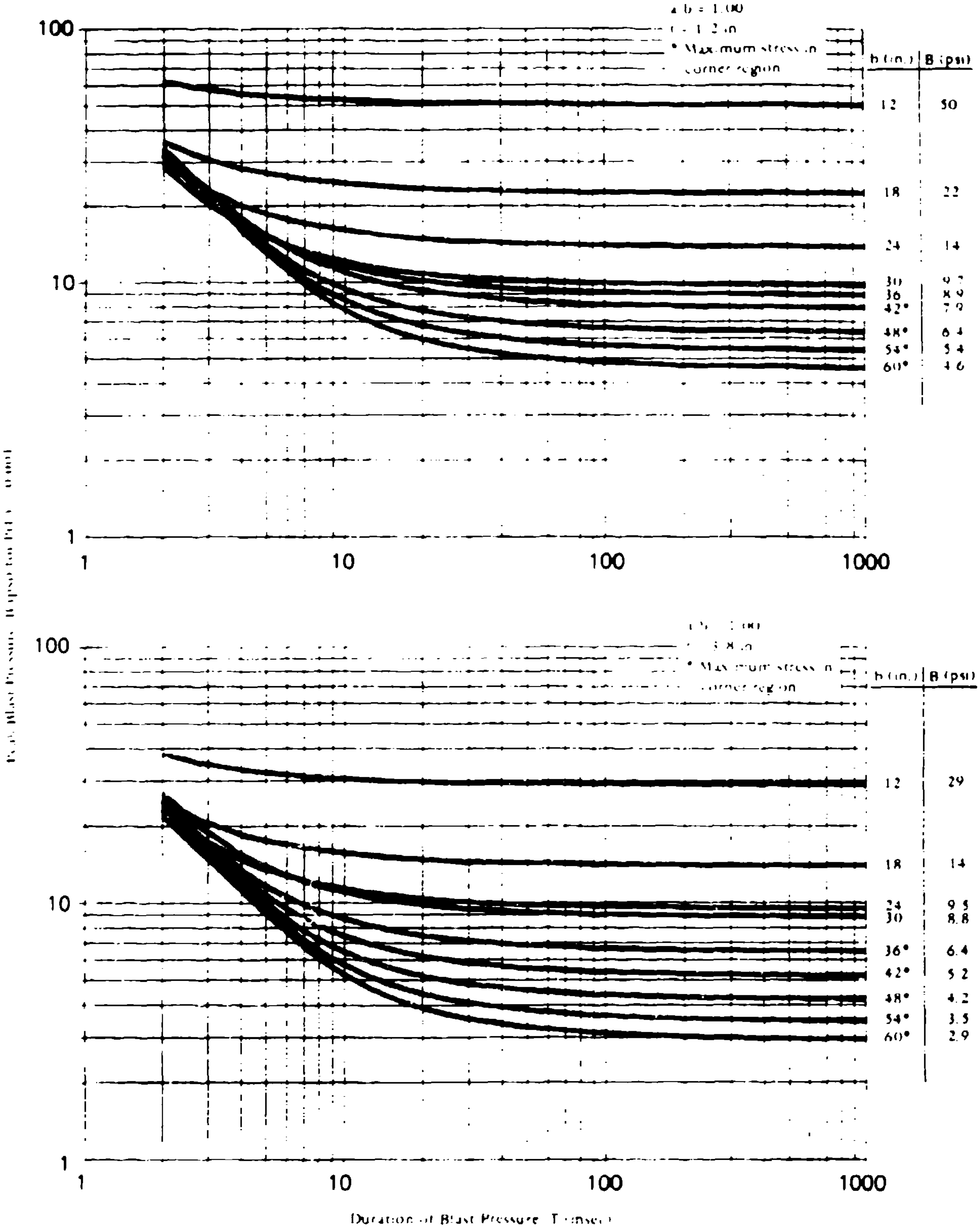

Figure 2. Peak blast pressure capacity for tempered glass panes (a/b = 1.00, t = 1/2 and 3/8 in.)

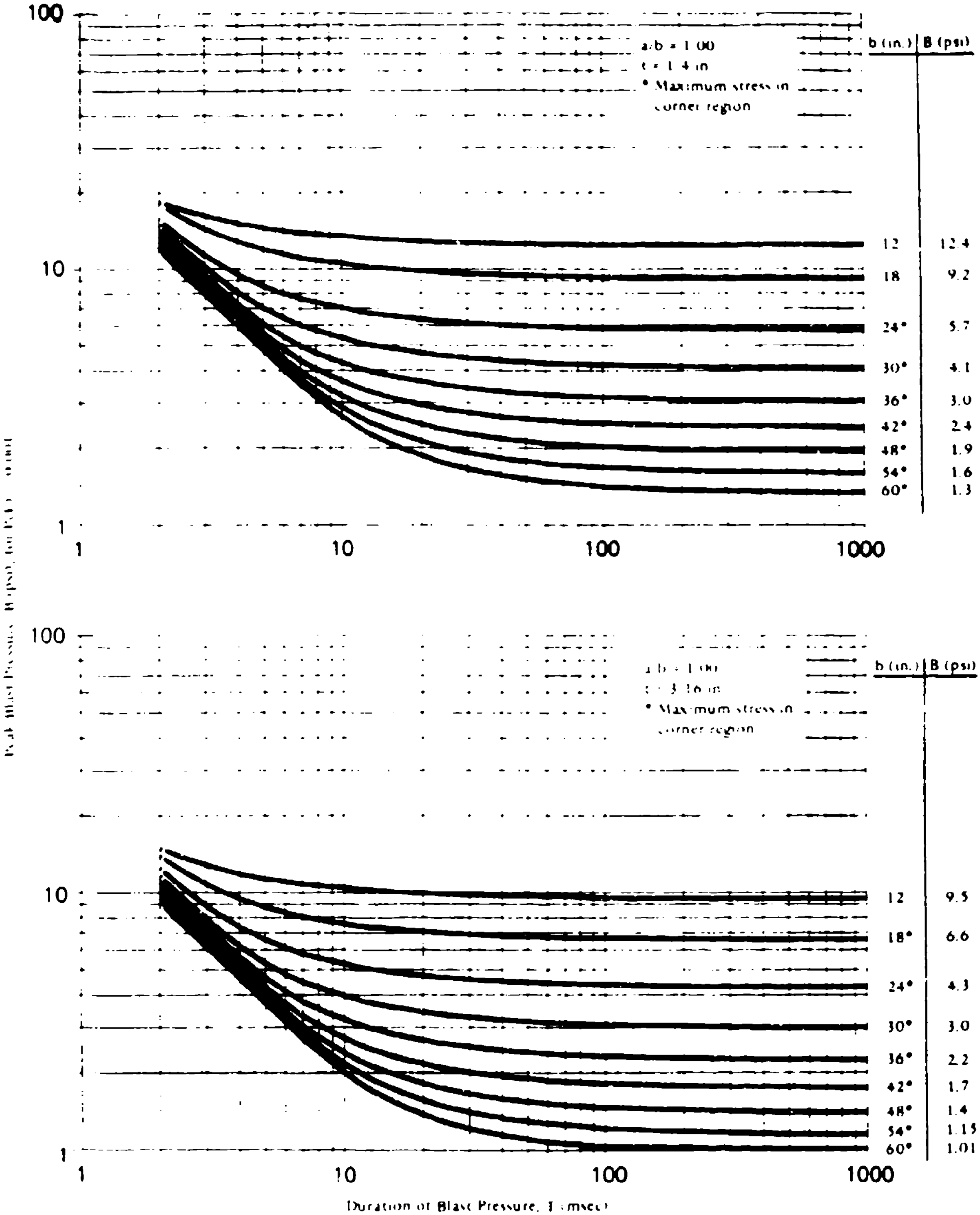

Figure 3. Peak blast pressure capacity for tempered glass panes a/b = 1.00, t = 1/4 and 3/16 in

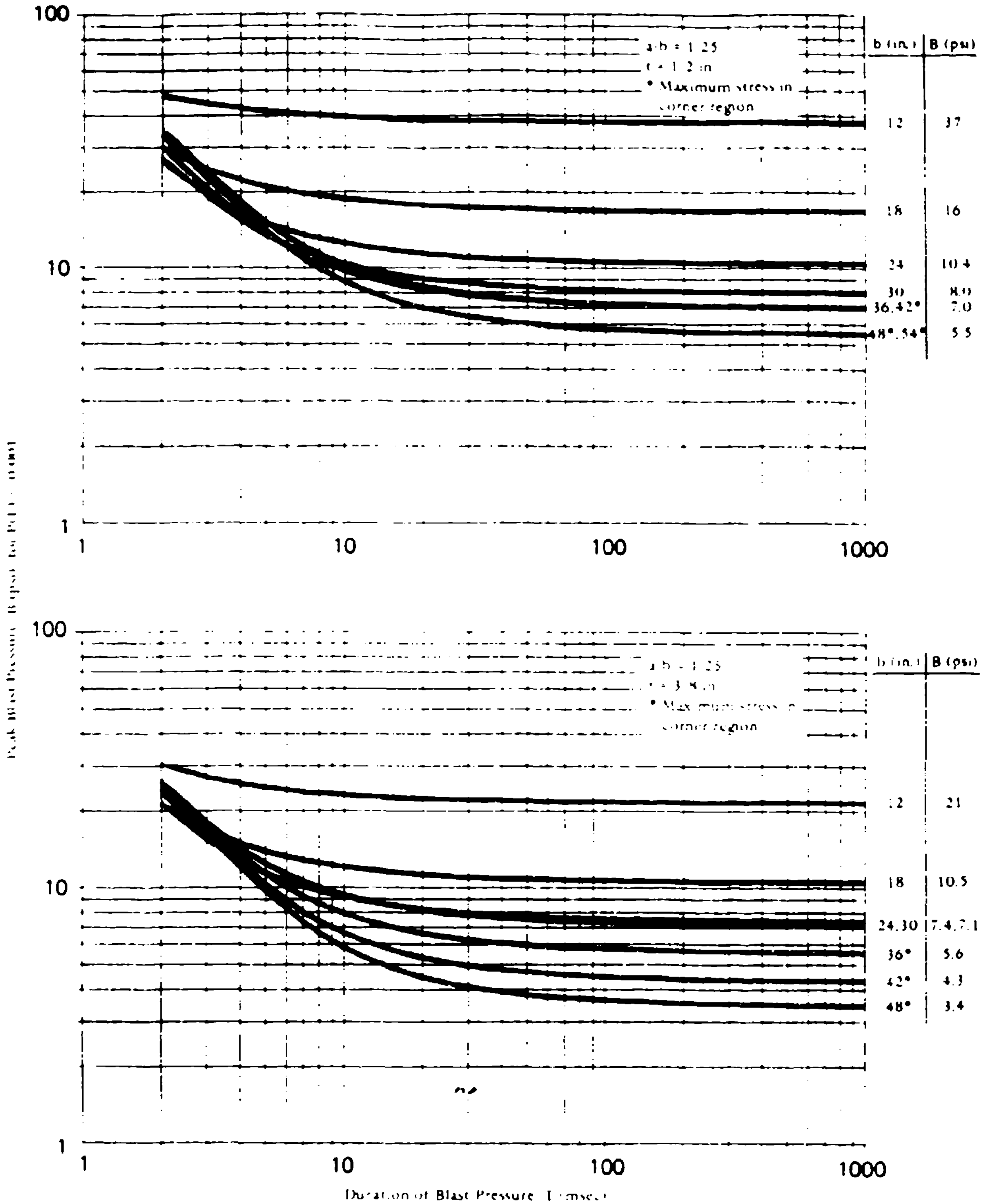

Figure 4. Peak blast pressure capacity for tempered glass panes (a/b = 1.25; t = 1/2 and 3/8 in.)

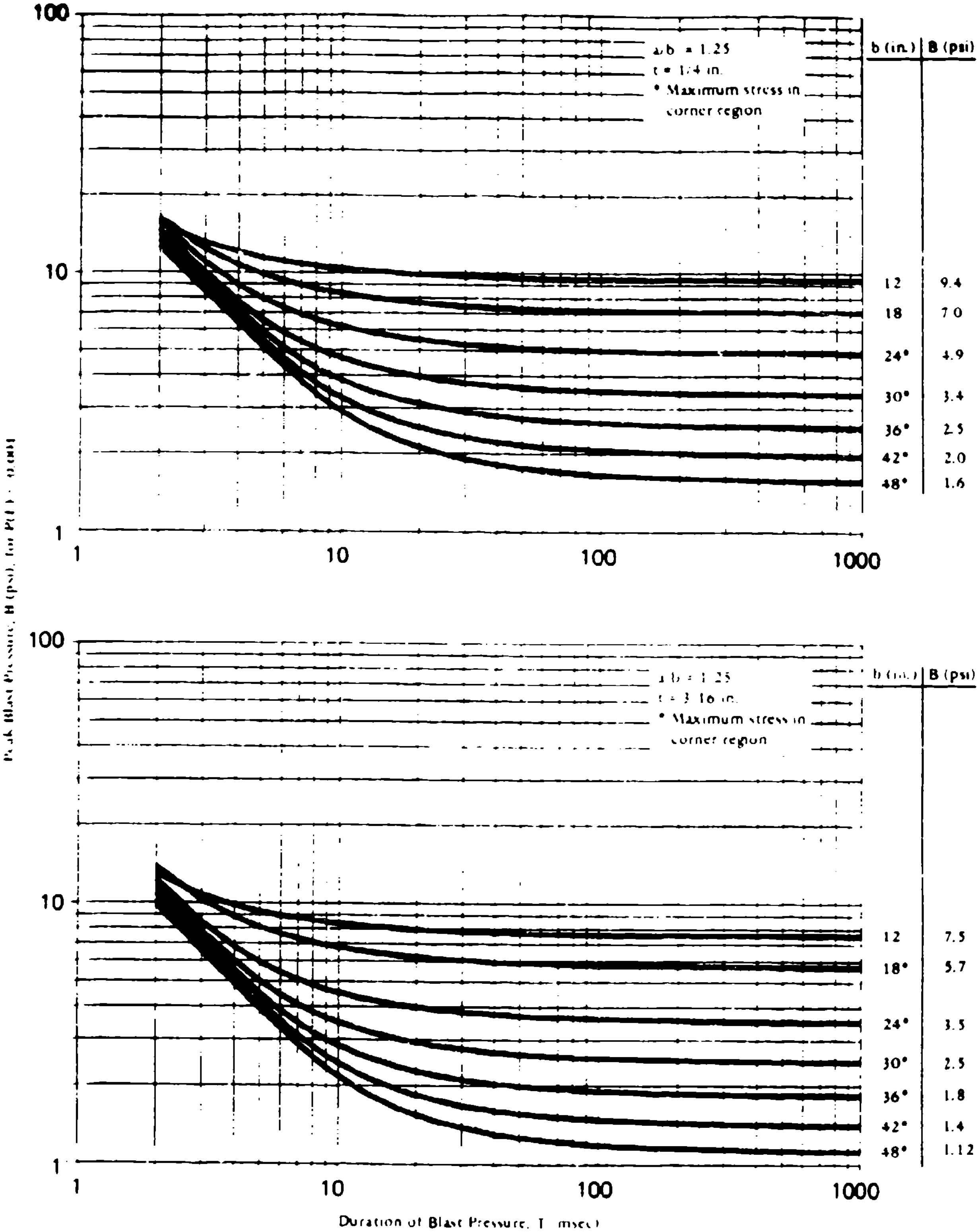

Figure 5 Peak blast pressure capacity for tempered glass panes a/b = 1.25, t = 1/4 and 3/16 in

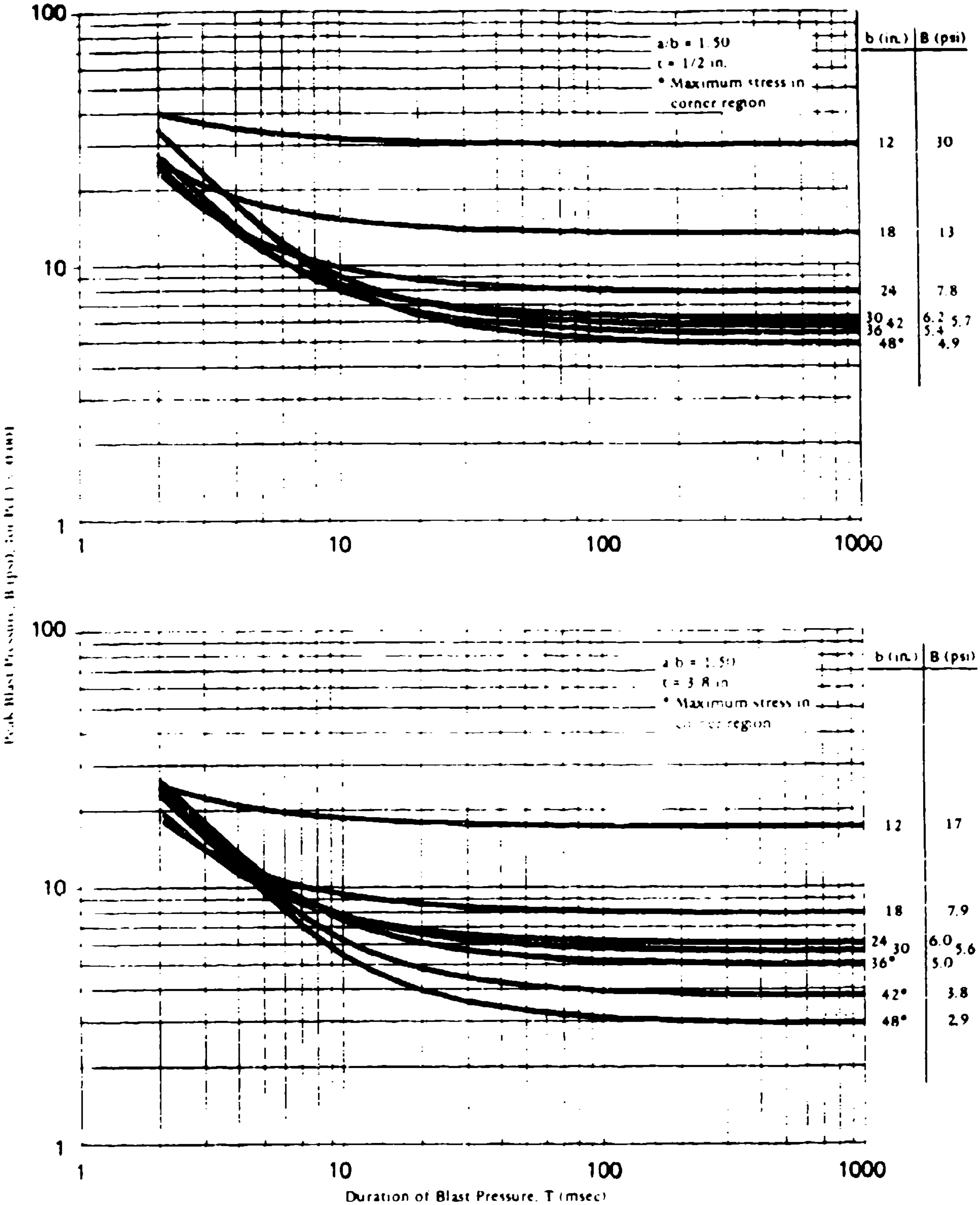

Figure 6 Peak blast pressure capacity for tempered glass panes a/b = 1.50, t = 1/2 and 3/8 in

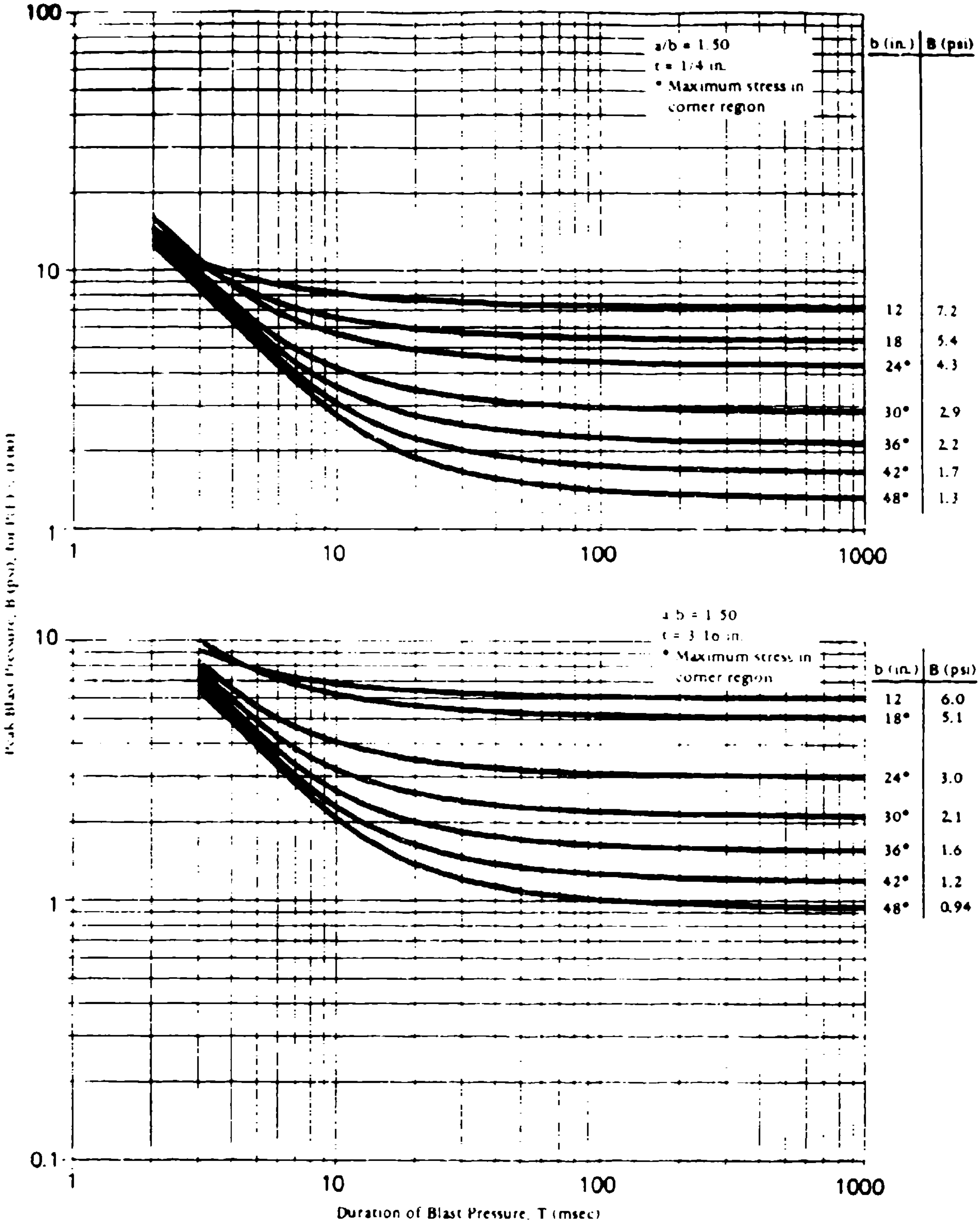

Figure 7. Peak blast pressure capacity for tempered glass panes, a/b = 1.50, t = 1/4 and 3/16 in.

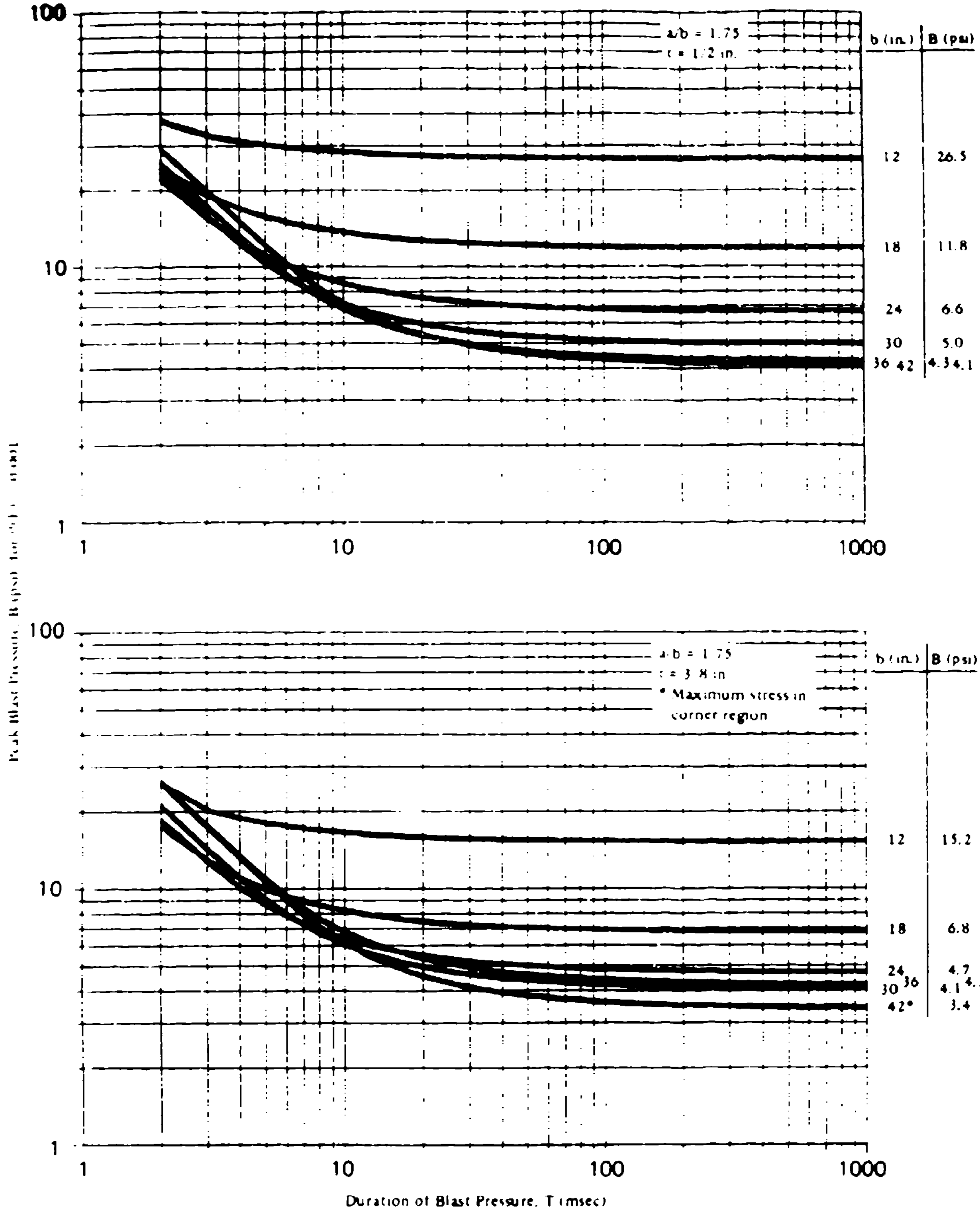

Figure 8 Peak blast pressure capacity for tempered glass panes a/b = 1.75, t = 1/2 and 3/8 in.

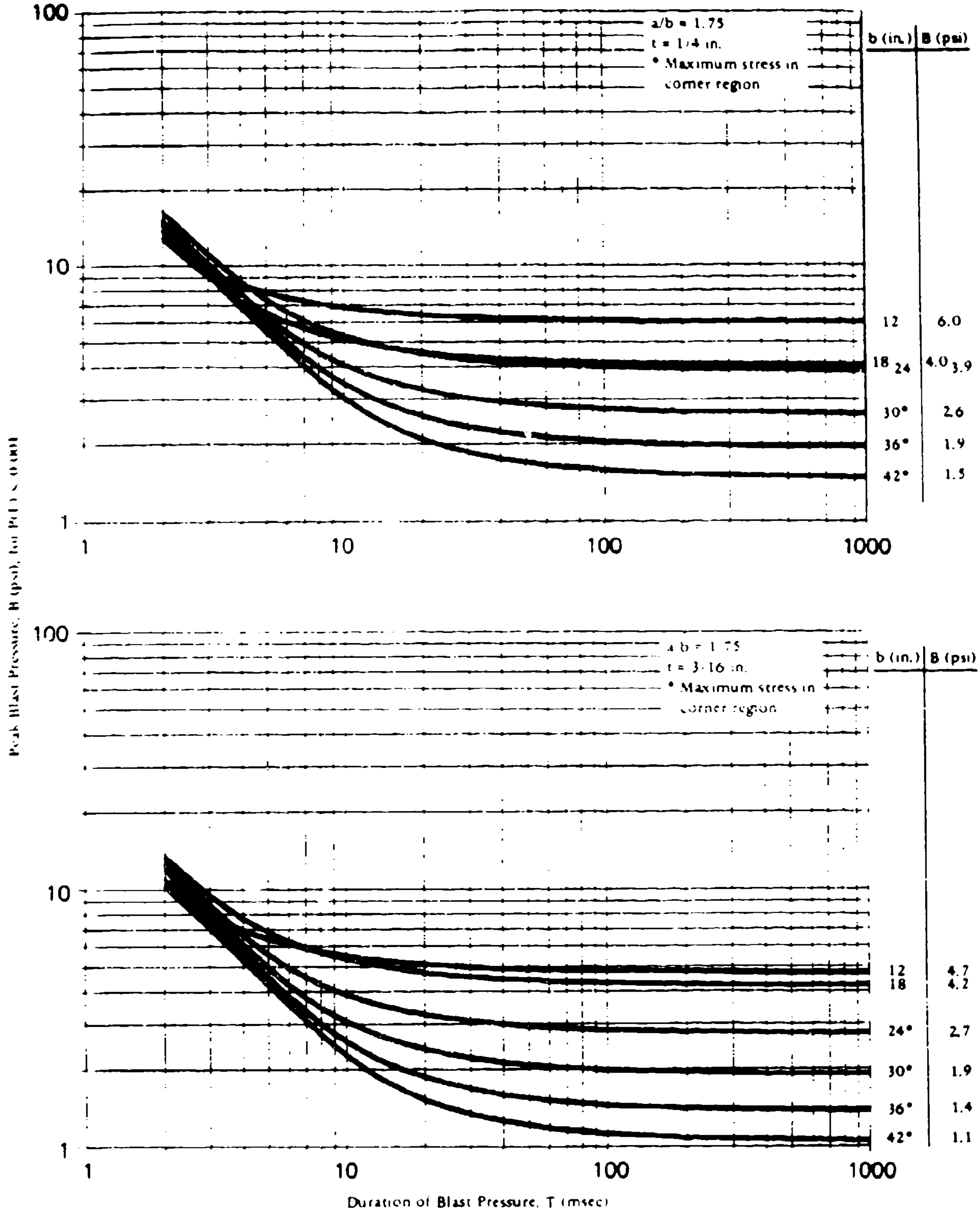

Figure 9 Peak blast pressure capacity for tempered glass panes a/b = 1.75, t = 1/4 and 3/16 in.

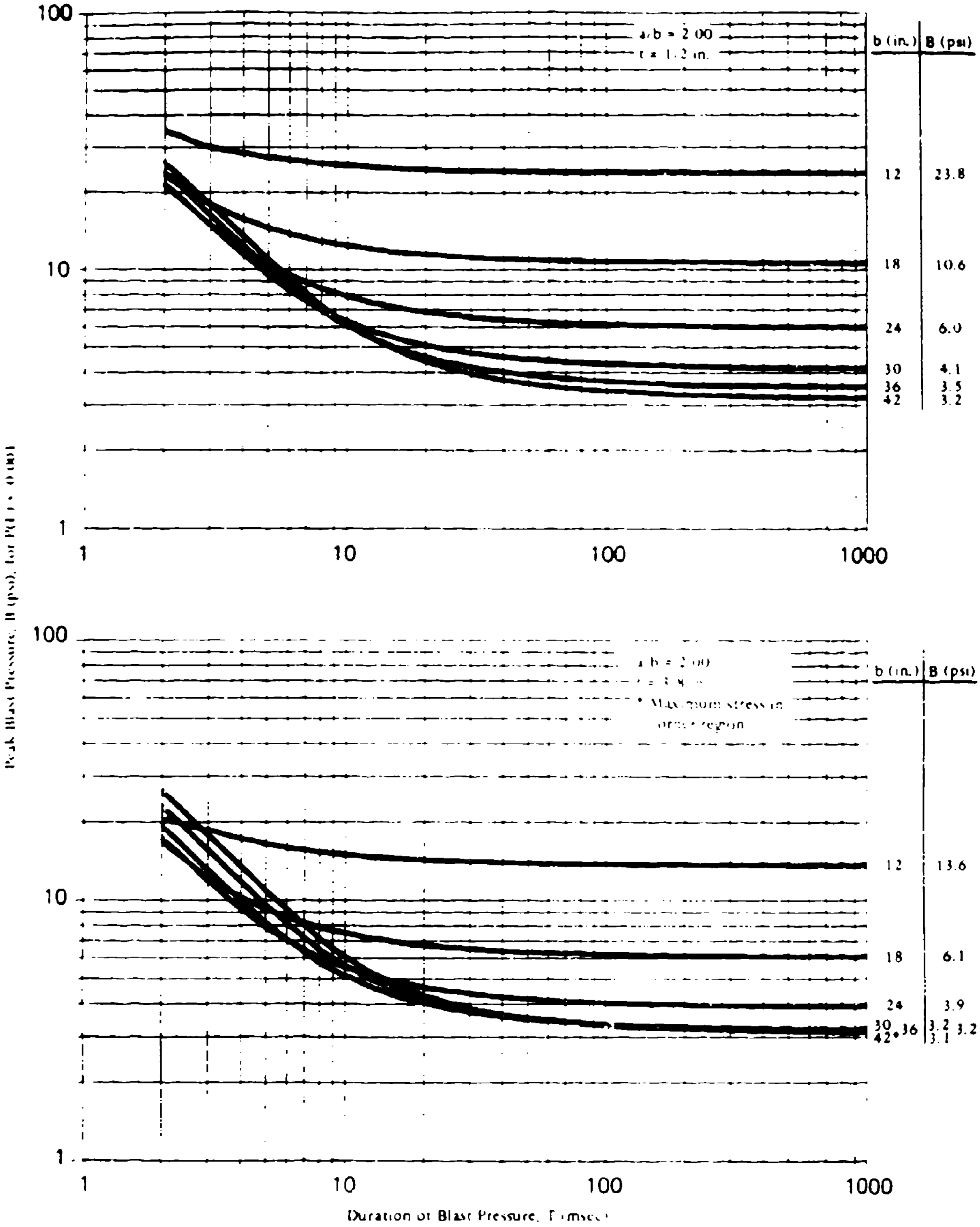

Figure 10. Peak blast pressure capacity for tempered glass panes (a/b = 2.00, t = 1/2 and 3/8 in.)

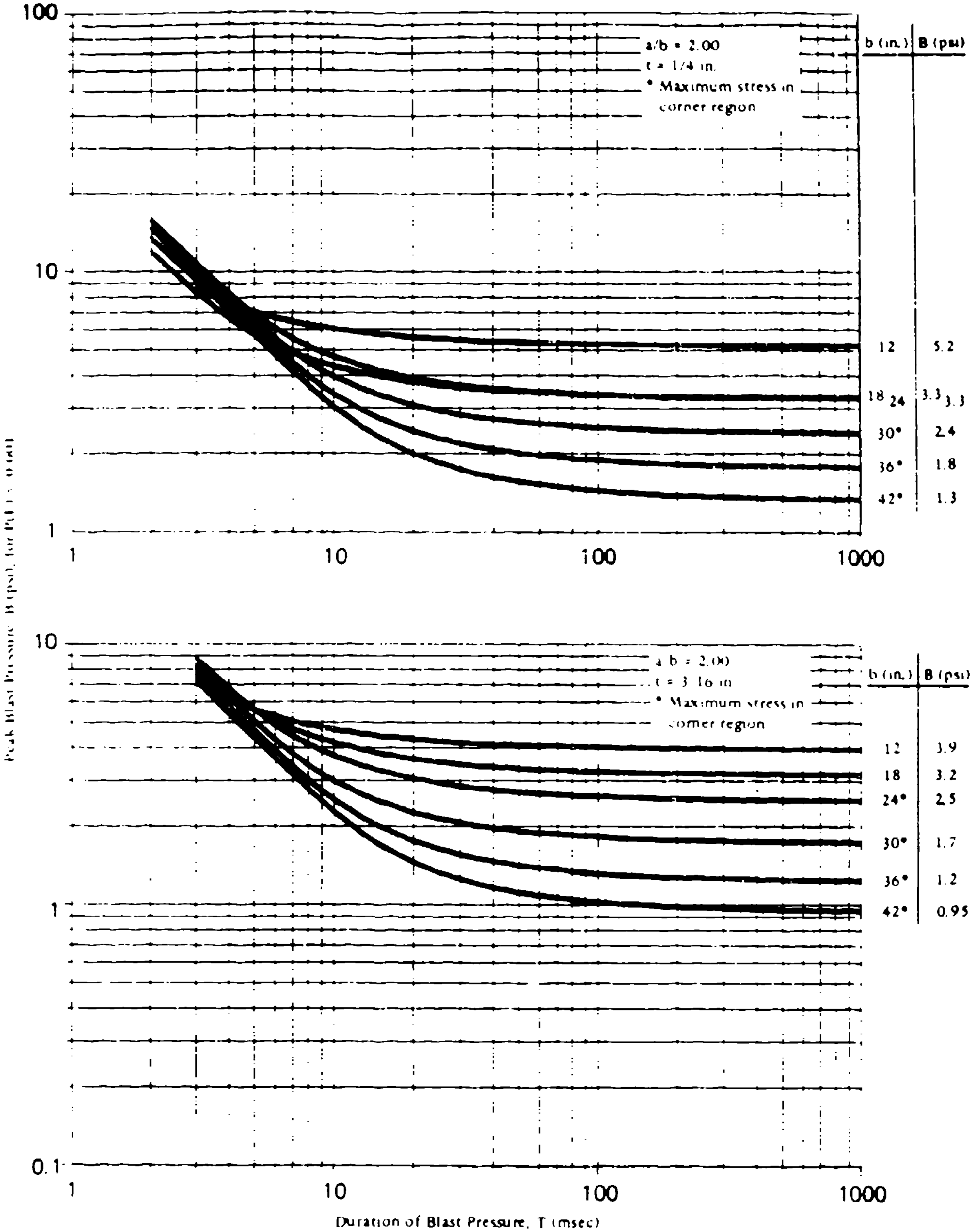

Figure 11 Peak blast pressure capacity for tempered glass panes a b = 2.00, t = 1 4 and 3 16 in.

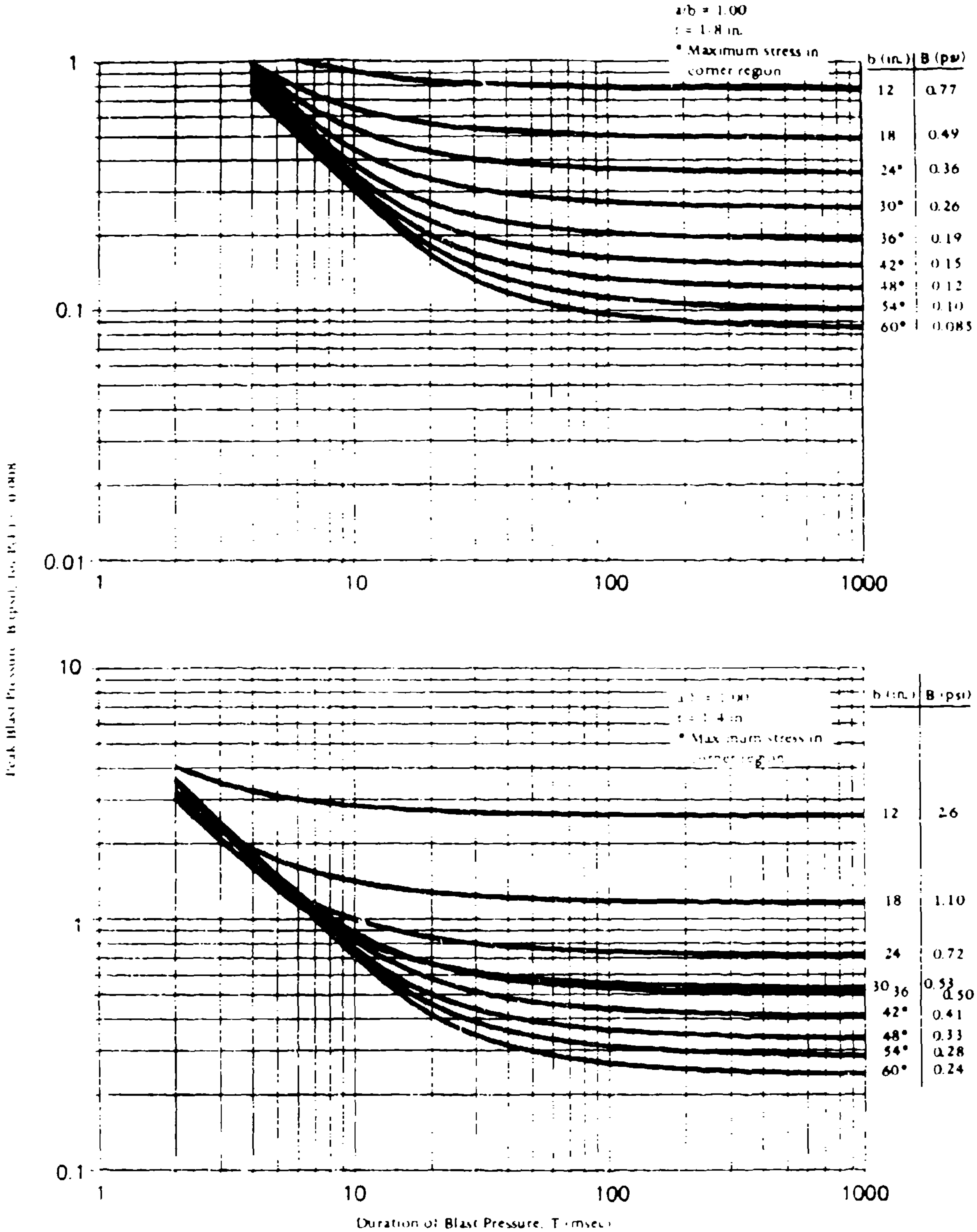

Figure 12. Peak blast pressure capacity for annealed glass panes (a/b = 1.00, t = 1/8 and 1/4 in.)

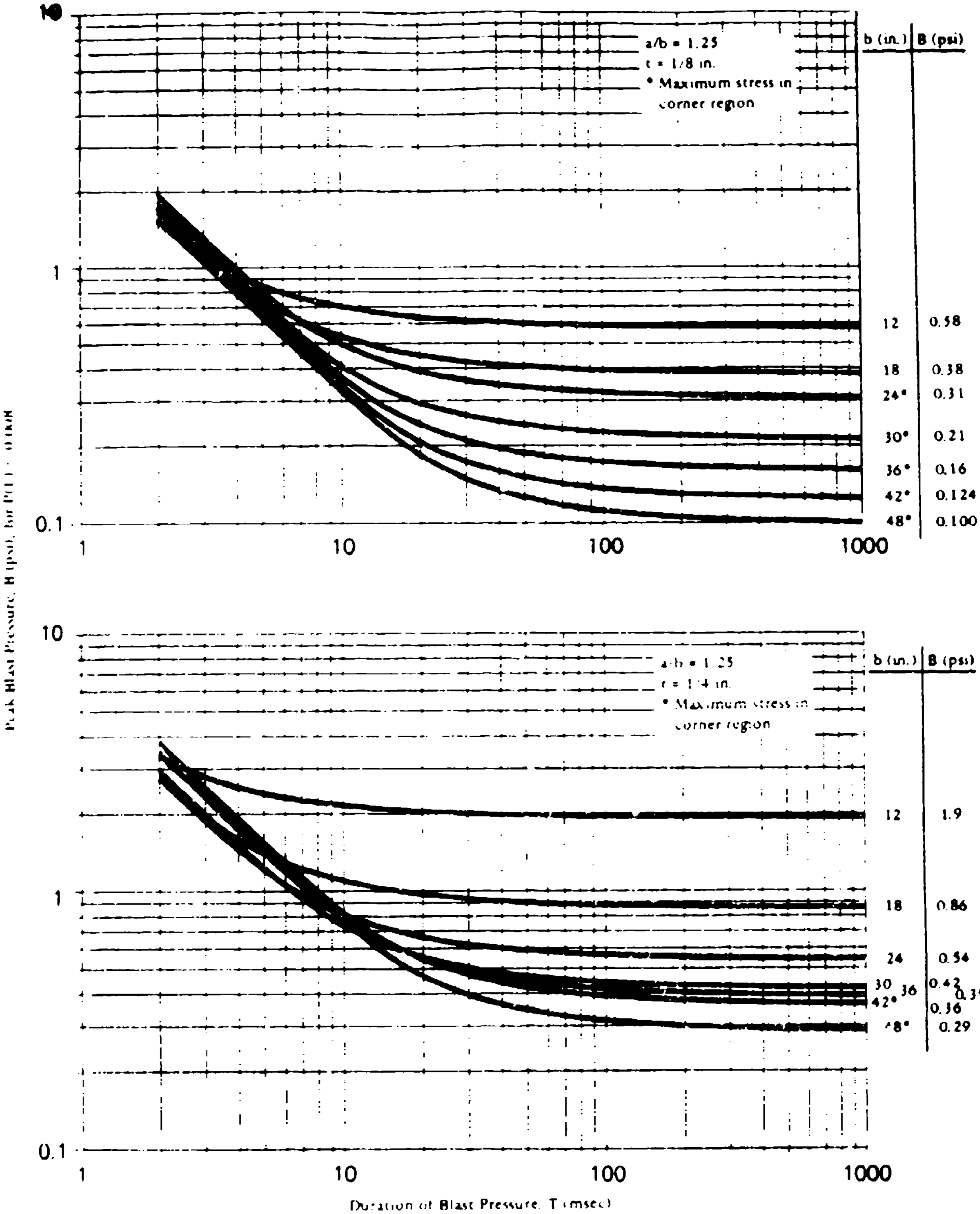

Figure 13. Peak blast pressure capacity for annealed glass panes a/b = 1.25, t = 1/8 and 1/4 in.

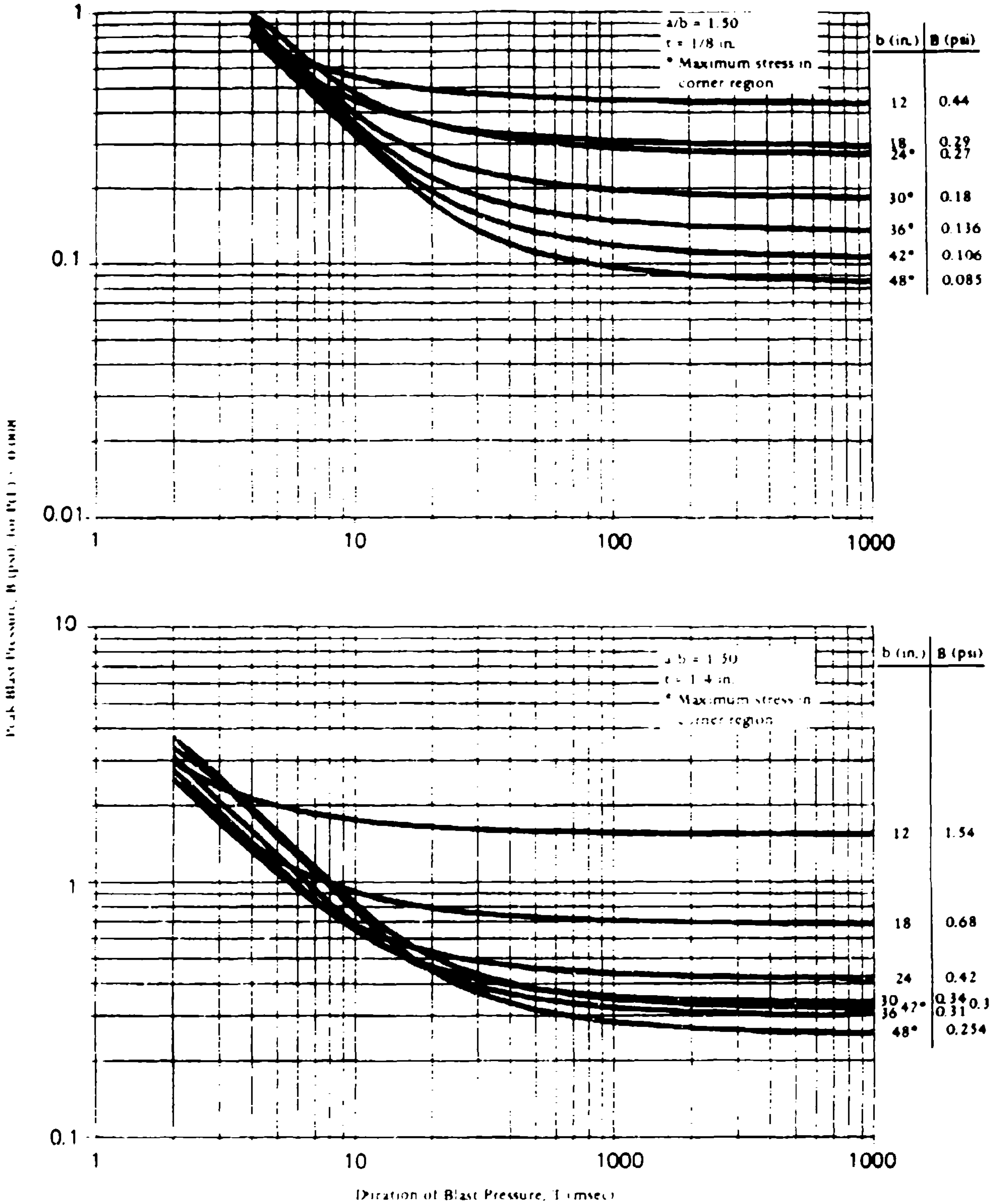

Figure 14 Peak blast pressure capacity for annealed glass panes a/b = 1.50, t = 1/8 and 1/4 in

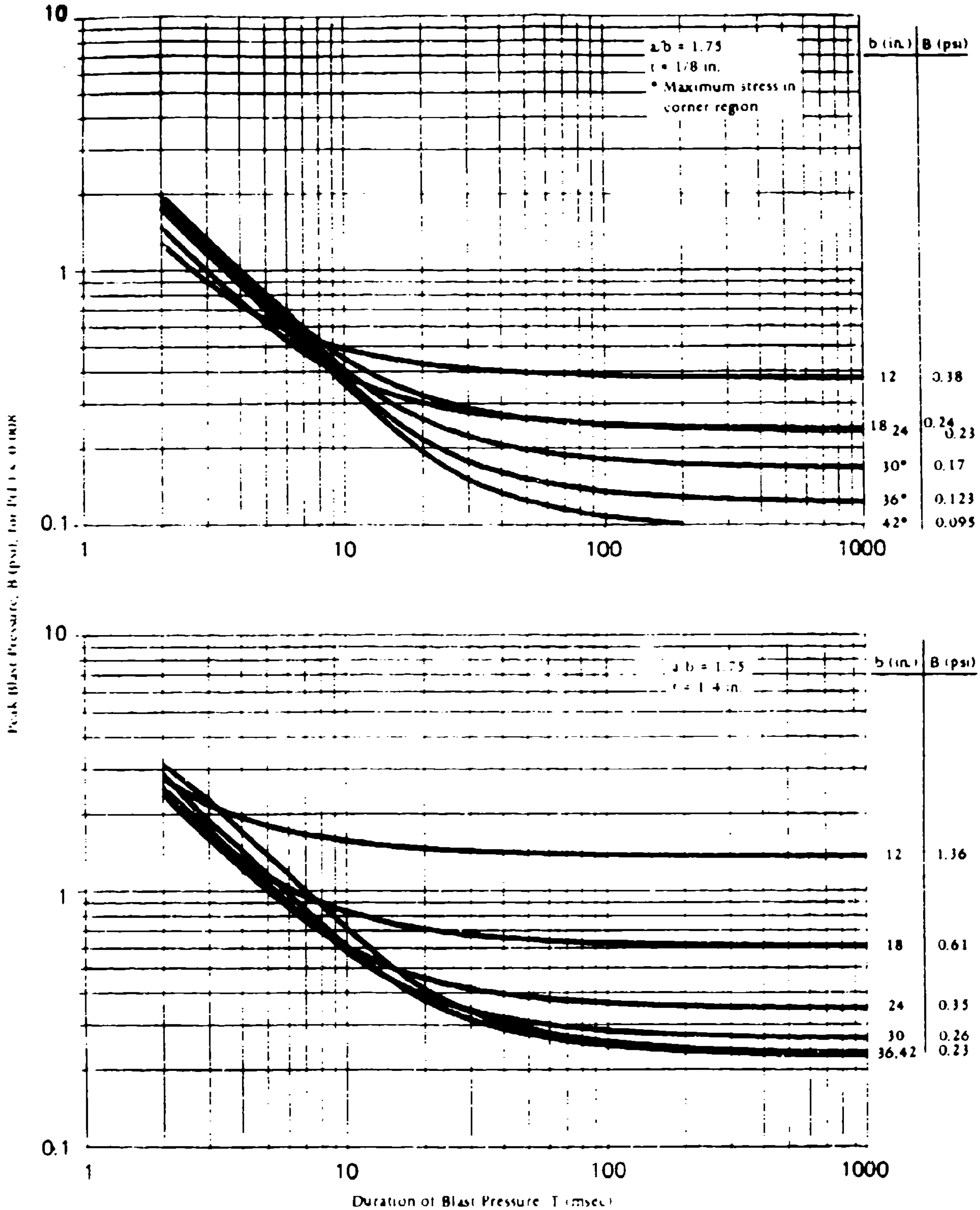

Figure 15. Peak blast pressure capacity for annealed glass panes (a/b = 1.75, t = 1/8 and 1/4 in.)

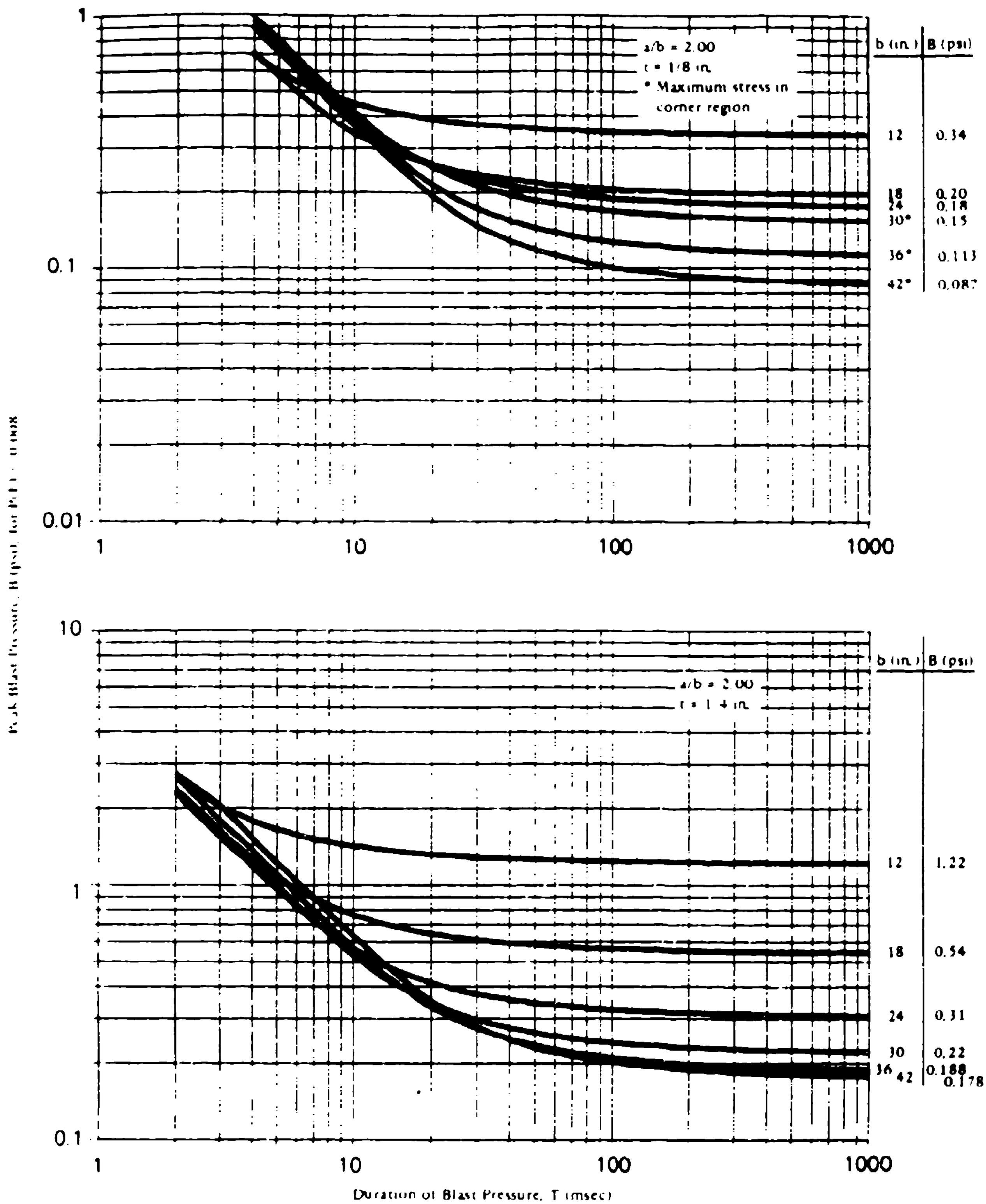

Figure 16 Peak blast pressure capacity for annealed glass panes a b = 2 00, t = 1 8 and 1 4 in.

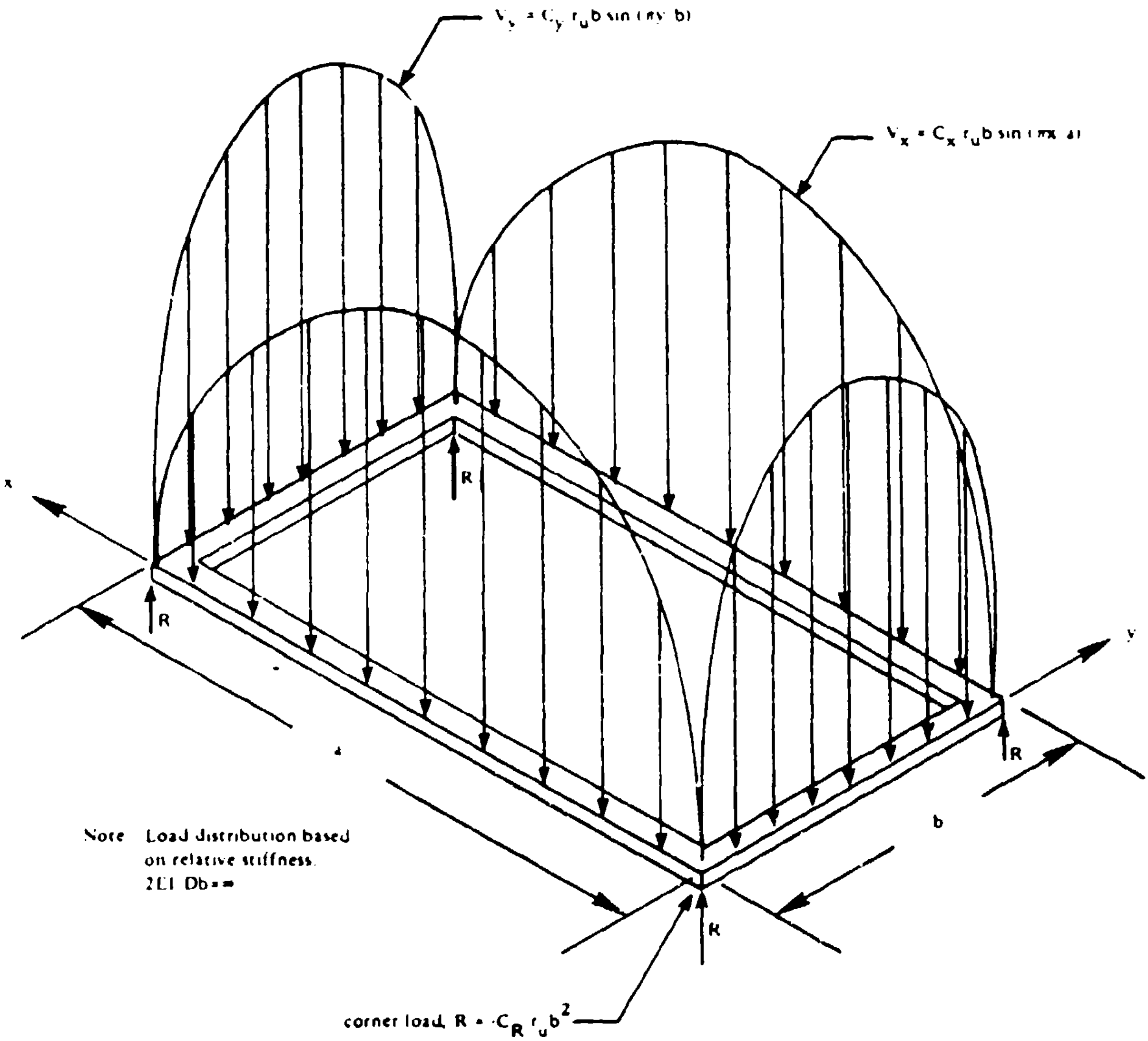

Figure 17 Distribution of lateral load transmitted by glass pane to the window frame.

Appendix A

COMMENTARY ON

DESIGN CRITERIA FOR BLAST RESISTANT WINDOWS

by

G. E. Meyers

INTRODUCTION

Presently, an adequate data base for the evaluation and validation of blast resistant window design criteria has yet to be developed. However, the proposed blast resistant window design criteria appear to be conservative when compared to the existing static uniform load and blast load data.

In FY85, the Naval Civil Engineering Laboratory (NCEL) plans static load validation tests on blast resistant windows. Blast load validation tests are also scheduled during FY85.

Static Ultimate Resistance

The resistance function utilized for the modeling blast capacity of windows is based upon a finite element solution of glass plates with realistic boundary conditions subjected to static uniform loads and large deflections. The relationship between the non-dimensional stress, non-dimensional center deflection and non-dimensional load are presented in Figures 1 and 2. The computer model developed to develop the blast resistant window design criteria digitized the resulting curves within its internal data base.

Table 1 presents a comparison between the measured and predicted capacities of glass panes tested. As a large sample of data is necessary for a meaningful comparison, the test data from ARRADCOM (Ref 2) should only be used for the purpose of orientation. For tests with a sufficient sample size, the mean failure load is reported. A Student's t distribution estimate of a probability of failure, P(F), of 0.001 for Wilson's tempered glass test is reported in parentheses. A probability of failure P(F) of 0.001 is assumed by the design criteria in predicting ultimate static uniform load strength of tempered glass. The Student's t distribution estimates of probability of failure, P(F), of 0.008 for the

Bowles and Sugarman (Ref 3) annealed glass tests are also reported in parenthesis in Table 1. A probability of failure, P(F), of 0.008 is assumed by the design criteria in predicting static uniform load strength of annealed glass. Both series of tests indicate that the predicted static design load, r_u, is reasonably conservative. The one exception, the 0.250-inch annealed glass plates tested by Bowles and Sugarman, exhibited a bimodal ultimate static load distribution instead of a bell-shaped distribution. It is reasonable to assume that this particular sample batch was not representative of the true population of glass.

The following considerations must be taken into account when analyzing Table 1. A maximum principle tensile stress level of 4,000 psi for annealed glass and 17,000 psi for tempered glass is assumed by the design criteria. These values lower bound the maximum stresses derived from a failure prediction model developed by Beason and Morgan (Ref 4). Environmental degradation of load-carrying ability from regular in-service use is assumed by the prediction model. In contrast to the prediction model, all the tested glass was probably new. Ratios of ultimate static uniform loads for new annealed glass, which has not yet accumulated an equivalent amount of weakening surface flaws, to in-service glass can be as high as two. Ratios of new to in-service tempered glass strength are not as well known, but are estimated to be closer to unity.

The predicted static uniform load also assumes the minimum thickness specified by Federal Specification DD-G-451d. The ARRADCOM and Wilson data in Table 1 are reported in nominal thickness. Most likely, the glass was of a thinner thickness within the prescribed tolerance. Thicknesses of 0.115, 0.219, and 0.355 (nominally 1/8, 1/4, and 3/8) inch were assumed for the purpose of prediction, respectively. As actual mean thicknesses were reported by Bowles and Sugarman, they were included in static uniform load prediction model.

Additionally, the predicted uniform static load assumes an approximation of an infinitely stiff simple support. Frame deformations can induce premature failures as evidenced in the ARRADCOM static load tests nos. 9, 10, and 11.

The design criteria assume a relatively short stress intensity duration of less than one second. As less ceramic fatigue is induced, a higher allowable maximum principle tensile stress for a given probability of failure can be assumed than for the standard one minute static load. However according to the glass industry (Ref 5), a maximum stress of 4,000 to 4,400 psi correlates with typical mean breaking stresses for annealed glass under a static load of one minute duration. As this is a similar magnitude of stress intensity duration as the static tests of Table 1, a rough equivalence of static load capacity should exist between the Bowles and Sugarman mean breaking loads and the predicted breaking loads correlated with a probability of failure, P(F), of 0.008. If a reduction by a factor of two is applied to the Bowles and Sugarman data to account for environmental degradation, the predicted load values are all conservative.

The predicted value of the ultimate static uniform load for the tempered glass samples tested by Wilson (Ref 1) is limited to the uniform static load associated with a center deflection of ten times the glass thickness. This condition is imposed by the accuracy limits of the equations implicit in the finite element modeling. With this limit imposed, the maximum stress induced in the 48 inch by 48 inch by 1/4-inch tempered glass plates by 0.97 psi of static uniform load is 15,920 psi. If the deflection limit was relaxed and the failure stress, f_u, of 17,000 psi was allowed to govern, the predicted load capacity would be 1.05 psi with a center deflection of 1.29 inch which is 10.3 times the glass thickness.

Blast Load Capacity

The design criteria are compared to data from explosive load tests of both tempered and annealed glass in Table 2. As a large data base does not exist, the data should only be used for orientation. With this perspective in mind, no evidence of invalidation of the design criteria is apparent. As with the static uniform load tests, frame distortion will induce premature failure.

Blast load design predictions are also based upon a probability of failure, P(F) of 0.001 for tempered glass and 0.008 for the analysis of annealed glass. Allowable maximum principle tensile stresses associated with the probability of failure are 17,000 psi for tempered glass and 4,000 for annealed glass. In-service strength degradation is assumed. In tests where the thickness is presented as a fraction, minimum thickness within prescribed federal tolerance is used for the design prediction. Where thickness is specified, interpolated results from the design charts or special computer runs of the design program are used to obtain predictions.

The blast load capacity design criteria assume that the glass has not been exposed to more than one explosive load. Because each large stress experience resulting from an explosive load will expand the microscopic flaw network or flaw web in the glass, the glass, in a probabilistic sense, will be weaker after each explosive episode. As most of the explosive glass tests in Table 2 are repeated until failure, an unspecified reduction in the survivable blast load is most likely exhibited by the test results.

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Table 1. Measured and Predicted Strength of Windows Subjected to a Static Uniform Load to Failure

Window					Samples Tested	Ultimate Strength, r_u			Comment
a (in.)	b (in.)	a/b	t (in.)	Glass Type[a]		Measured (psi)	Predicted[b] (psi)	$\frac{r_u}{\bar{r}_u}$ $\frac{(measured)}{(predicted)}$	
43.25	28.375	1.52	1/4[c]	annealed	1	0.65	0.57	1.14	ARRADCOM static test no. 8. Glass breakage occurs in a wooden frame.
43.25	28.375	1.52	1/4[c]	tempered	1	8.58	4.56	1.88	ARRADCOM static test no. 6. Glass breakage occurs in a wooden frame.
43.25	28.375	1.52	1/4[c]	tempered	1	8.30	4.56	1.82	ARRADCOM static test no. 7. Glass breakage occurs in a wooden frame.
43.25	28.375	1.52	1/4[c]	tempered	1	1.02	4.56	0.22	ARRADCOM static test no. 9. Frame bead failure induced premature failure.
43.25	28.375	1.52	1/4[c]	tempered	1	2.23	4.56	0.49	ARRADCOM static test no. 10. Failure occurs due to deformation of strengthened aluminum frame.

continued

Table 1. Continued

Window					Samples Tested	Ultimate Strength, r_u			Comment
a (in.)	b (in.)	a/b	t (in.)	Glass Type[a]		Measured (psi)	Predicted[b] (psi)	$\frac{r_u \text{(measured)}}{r_u \text{(predicted)}}$	
43.25	28.375	1.52	1/4[c]	tempered	1	4.43	4.56	0.97	ARRADCOM static test no. 11. Failure due to deformation of strengthened aluminum frame.
48	48	1	1/8[c]	tempered	8	1.765 (1.21)[d]	0.97	1.82 (1.25)[e]	Wilson static load tests. Prediction is limited to test capacity of center deflection = 10 t.
40	40	1	0.122	annealed	40	0.754 (0.41)[d]	0.24	3.14 (1.71)[e]	Static testing by Bowles and Sugarman.
40	40	1	0.197	annealed	30	1.412 (0.77)[d]	0.54	2.61 (1.42)[e]	
40	40	1	0.250	annealed	30	1.811 (0.64)[d]	0.78	2.32 (0.82)[e]	
40	40	1	0.373	annealed	30	3.625 (1.45)[d]	1.27	2.85 (1.14)[e]	

[a] All glass tested is new.

[b] Based on P(F) = 0.001 for tempered glass at f_u = 17,000 psi and P(F) = 0.008 for annealed glass at f_u = 4,000 psi.

[c] Thickness reported in fractions are nominal thicknesses.

[d] Statistical estimate of design probability of failure based on a Student's t distribution of test sample P(F) = 0.001 for tempered glass and P(F) = 0.008 for annealed glass.

[e] Ratio of statistical estimate of the design probability of failure of the test sample to the predicted strength.

Table 2. Measured and Predicted Dynamic Strength of Windows Subjected to Dynamic Blast Loads

Window					Blast Parameters		Design Prediction		Comments
a (in.)	c (in.)	a/b	t (in.)[a]	Glass Type	B (psi)	T (msec)	B (psi)	T (msec)	
43.25	28.375	1.52	1/4	tempered	4.4	45	3.6	45	ARRADCOM dynamic test no. 5, Series I. Glass fails after repeated loadings (Ref 2).
62.75	47.00	1.34	1/4	tempered	4.4	45	1.7	45	ARRADCOM dynamic test no. 5, Series I. Glass survived.
43.25	28.375	1.52	1/4	tempered	4.4	45	3.6	45	ARRADCOM dynamic test no. 5, Series I. Glass survived.
43.25	28.375	1.52	3/8	tempered	4.4	45	6.1	45	ARRADCOM dynamic test no. 5, Series I. Glass survived.
62.75	47.00	1.34	1/4	tempered	4.4	45	1.7	45	ARRADCOM dynamic test no. 5, Series I. Glass survived.
62.75	47.00	1.34	3/8	tempered	4.4	45	3.8	45	ARRADCOM dynamic test no. 5, Series I. Glass survived.
43.25	28.375	1.52	1/4	tempered	1.0	48	3.5	48	ARRADCOM test no. 1, Series II. Tempered glass in aluminum frame survived.
43.25	28.375	1.52	1/4	tempered	1.2	50	3.5	50	ARRADCOM test no. 2, Series II. Failure occurred due to frame distortion.
43.25	28.375	1.52	1/4	tempered	2.3	50	3.5	50	ARRADCOM test no. 3, Series II. Glass survived.

continued

Table 2. Continued

Window					Blast Parameters		Design Prediction		Comments
a (in.)	c (in.)	a/b	t (in.)[a]	Glass Type	B (psi)	T (msec)	B (psi)	T (msec)	
43.25	28.375	1.52	1/4	tempered	3.1	50	3.5	50	ARRADCOM test no. 4, Series II. Glass fails due to frame distortion.
43.25	28.375	1.52	1/4	annealed	0.78	44	0.42	44	ARRADCOM test no. 3, Series II. Glass survived.
62.75	47.00	1.34	1/4	annealed	0.78	44	0.36	44	ARRADCOM test no. 3, Series II. Glass failed.
62.75	47.00	1.34	1/4	annealed	0.31	43	0.36	43	ARRADCOM test no. 2, Series II. Glass survived.
35.85	35.85	1.00	1/8	annealed	0.58	60	0.21	60	DNA 5593T. Glass failed in a shock tube test (Ref 7).
48.00	34.00	1.40	0.236	annealed	1.00	250	0.37	250	ESKIMO III tests. Window survived (Ref 8).
45.00	45.00	1.00	0.232	annealed	1.00	260	0.37	260	ESKIMO III tests. Window failed.
42.00	20.00	2.10	0.124	annealed	1.00	260	0.47	260	ESKIMO III tests. Window failed.
53.54	37.80	1.41	0.157	annealed	2.9	10	0.56	10	Fortification directorate. Window survived (Ref 9).
53.54	37.80	1.41	0.157	annealed	5.0	10	0.56	10	Fortification directorate. Window failed.

[a]Thicknesses in fraction format are nominal inches.

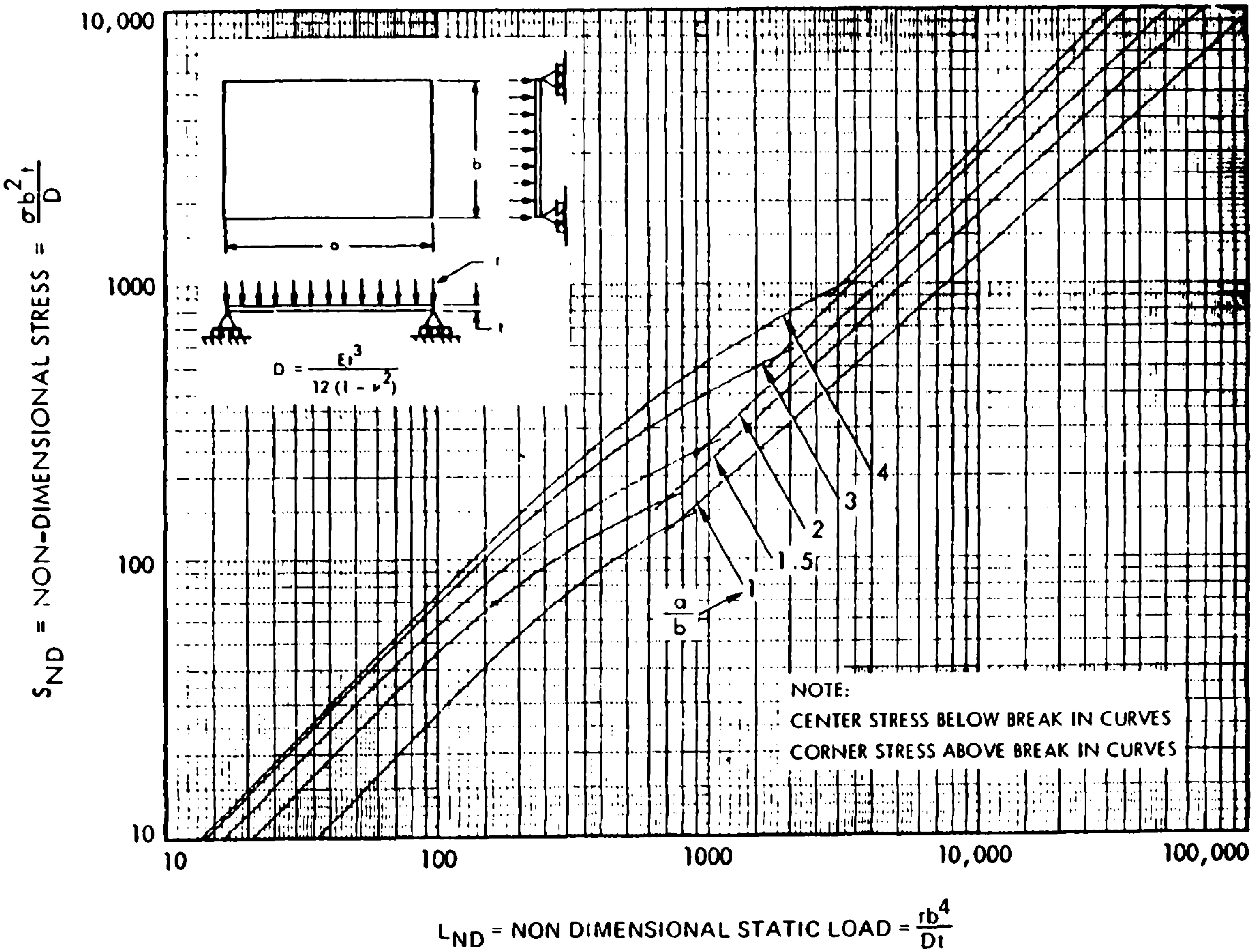

Figure 1. Non dimensional static load stress relationships for simply supported plates

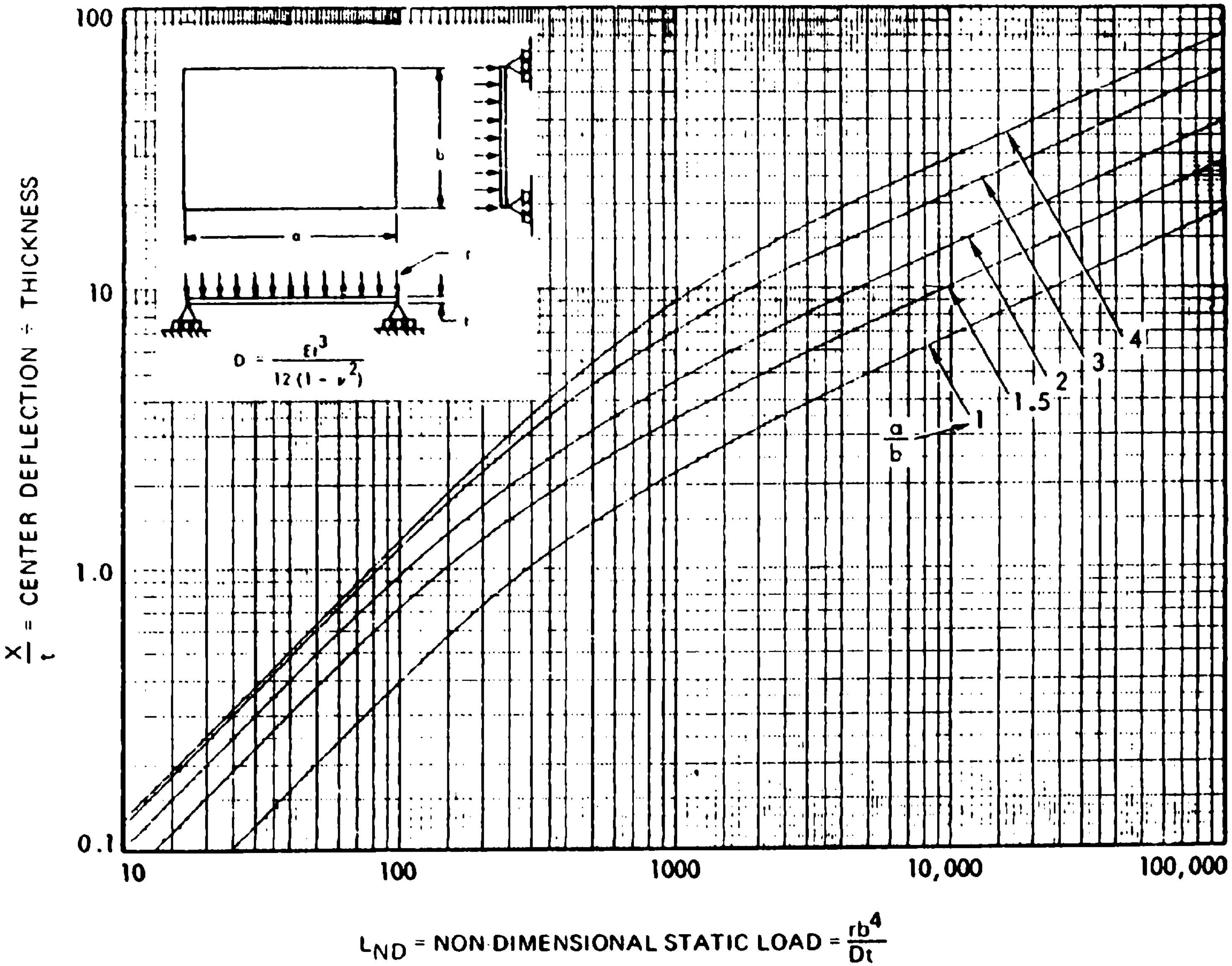

Figure 2. Non dimensional static load crater deflection relationships for simply supported plates

VEHICLE OVERTURNING VULNERABILITY FROM AIR BLAST LOADS

R.R. Robinson*, H. Napadensky* and A. Longinow**

Introduction

The overturning response of a vehicle to air blast loads derived from a nuclear blast environment is presented herein. The vehicle considered is representative of an armored personnel carrier (APC). The orientation of the vehicle is side-on to the air blast shock front. It is assumed that either there is sufficient friction at the vehicle/ground surface interface or that the downwind wheels are chocked so that there is no translation at the downwind wheels, i.e., the roll over point. In addition, the vehicle is assumed to behave as a rigid body. That is, the suspension systems is taken as rigid, so that the wheels and axles rotate in unison with the body. It can be shown that this assumption slightly overestimates the overturning resistance of vehicles with suspension systems. For a stiff suspension system, such as that of the APC, the rigid body behavior assumption is justified.

The air blast loads are obtained by considering the diffraction and drag forces, acting on a series of interconnected rectangular blocks positioned in space which represent the aerodynamic model of the vehicle. The separate block loads at any time step are summed-up to obtain the total load history acting on the rigid body, single degree of freedom dynamic model. The only motion possible for this analysis is rotation about the rollover point. The effect of overturning restraint systems has been included in the analysis by incorporating a perfectly plastic vehicle to ground connection on the upwind side of the vehicle. The results presented give the threshold nuclear environment that just causes overturning. The threshold environment is given in terms of a peak overpressure corresponding to a weapon yield. Results are presented for a range of weapon yields from 1KT to 1MT.

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Method of Analysis

A computer program (OVRTRN) was used to numerically determine the overturning potential of an airblast load applied to a vehicle. The program incorporates the recently developed Ballistic Research Laboratory BLOP program to obtain the airblast loading on the vehicle.

The OVRTRN code can be used to evaluate both the reflected pressure loading and the drag loading that occurs from the dynamic pressure. The reflected pressure loading can be optionally included as an impulse load which imparts an initial velocity to the vehicle. It is also possible to evaluate the influence of nonlevel terrain since an initial angle (from the horizontal) of the ground surface can be specified by the user. In addition, the effect of a moving vehicle can be approximated by the application of a lateral load to the center of mass to simulate the centrifugal loading of the vehicle traveling around a curve. This feature can also be used to study the effect of perfectly plastic restraints connected between the vehicle and the ground. The overturning resistance provided by the restraint or tie downs can be easily related to a centrifugal force applied to the center of mass toward ground zero.

The numerical integration solution procedure of the equations of motion employed in the OVRTRN program is an explicit, central difference technique. The solution is automatically terminated if the vehicle rotation exceeds the instability rotation angle. Instability is assumed to occur when the center of mass rotates to a point directly over the rollover point. It is noted that for the case where restraints are included or there is a centrifugal force toward ground zero that larger rotations can occur before tipover. For this case, it is necessary to continue the solution further to establish whether tipover occurs.

The technique used to analyze the vehicle for overturning was to assume that the complete system is a single rigid body incapable of sliding motion. This assumes that the coefficient of friction between the wheels and the ground surface is sufficiently high and that any lifting forces acting on the vehicle are negligible compared to its weight. This latter assumption assures that there will be a nontensile vertical interface force (reaction) between the vehicle and the ground surface.

Figure 1 illustrates an APC subjected to side-on blast loading and the only degree-of-freedom possible, which is the rotation (Θ) about the downwind track/ground surface interface, Point A. The time dependent blast load resultant lateral force is denoted by F(t). The height or point of application of the blast load, h(t), is also time dependent since some of the smaller components parts (e.g., wheels) which are modeled as rectangular boxes in the BLOP code will have shorter duration diffraction phase loading than other components. However, after the diffraction phase loading is over, the point of application of the resultant blast load will not appreciably change. The angle, Θ, represents the rotation of the rigid body vehicle model from its initial position Θ_0. If the vehicle is on level ground, then Θ_0 = 0.0. It is also assumed that the rigid body is initially at rest ($\dot{\Theta}_0 = 0$); however, there is an option to provide for both nonzero initial values of Θ_0 and $\dot{\Theta}_0$. An initial nonzero Θ_0 would represent a rigid body on nonlevel ground and nonzero $\dot{\Theta}_0$ can be used to represent the short duration reflected pressure and/or diffraction phase loading impulse. An initial value of $\Theta_0 > o$ indicates that the ground slopes away from ground zero and this would increase the vulnerability of the vehicle to overturning.

The effect of centrifugal loading to simulate vehicle travel at constant velocity around a curve or the equivalent overturning resistance offered by a perfectly plastic restraint is modelled by the application of a horizontal force resultant, γW, applied laterally to the center of mass as indicated in Figure 1.

The equation of motion that governs the time dependent rotation of the rigid body is

$$I_A \ddot{\theta} + M_R(\theta) = M_F(t,\theta) \qquad (1)$$

where I_A = second moment of mass of the rigid body about point A

$M_R(\theta)$ = restoring moment = $Wx(\theta) + \gamma Wy(\theta)$ (2)

$M_F(t,\theta)$ = $F(t) \cdot H(t,\theta)$ = air blast overturning moment (3)

$x(\theta)$ = rotational dependent horizontal distance from point A to the center of mass

$y(\theta)$ = rotational dependent vertical distance from point A to center of mass

W = total weight of rigid body

F(t) = time dependent horizontal force acting on rigid body

$H\{t,\theta\}$ = time and rotation dependent vertical location of $F\{t\}$ from point A.

The parameter $H\{t,\theta\}$ can be used to compute the overturning moment, M_F, rather than merely the BLOP code computed $h\{t\}$ for the following reason. As the rigid body rotates, it is reasonable to assume that the BLOP code computed overturning moment (which is the lateral force times to height to its point of action) will be increased from at least two sources: (1) lift forces will be produced on the underside of the rigid body, and (2) the drag area will be increased (at least for the initial rotations). In order to approximately account for the rotational increase to the overturning moment, it can be assumed that the $h\{t\}$ variable should be modified to produce $H\{t,\theta\}$ which is used in Equation (3) to compute the overturning moment. The procedure used assumes that the location of the center-of-pressure (C.P.) is a function of the rotation (θ), viz,

$$H\{t,\theta\} = h\{t\} \cos\theta + \sin\theta \qquad (4)$$

The restoring moment is the first moment of the vehicle weight gravitational vector, W, and the horizontal force, γW, about point A. Initially, the location of the W and γW vectors for level ground is $x = x_o$ and $y = y_o$, respectively. The distance from point A to the center of mass is

$$R = x_o^2 + y_o^2 \qquad (5)$$

The second moment of mass is computed from

$$I_A = I_o + Wr^2/g \qquad (6)$$

where I_o = moment of inertia about center of mass = Wr^2/g

r = radius of gyration

Armored Personnel Carrier Analysis

The basic parameters used in the overturning analysis of an APC are

W = 24,000 lb (weight)

r = 37.54 in. (Radius of Gyration)

x_o = 50 in.

y_o = 39 in.

$w = 100$ in.

The critical instability angle, θ_c, which is the angle at which the center of gravity is directly above point A, is given by

$$\theta_c = \tan^{-1}(x_o/y_o)$$
$$= 52 \text{ deg.}$$

Even though the OVRTRN program has the capability to increase with rotation (θ) the BLOP code computed vertical location of the center of pressure, this option has not been used for this analysis. A total of 16 different blocks were used to define the aerodynamic model of the APC as shown in Figure 2. The majority of these blocks were used to model the ten (10) track wheels. The hull was modeled with five (5) blocks and one (1) additional block for the gun and hatch at the top of the vehicle.

The typical angular response of the vehicle is shown in Figure 3. These results are for a weapon yield of 10 KT. The critical overpressure for this yield for the case where there is no tie-down restraint is $p_o = 14.4$ psi. The response for slightly higher (14.5 psi) and lower (14.3 psi) overpressures is also shown in Figure 3. For the higher overpressure level, the critical angular rotation of $\theta_c = 52$ degrees is reached at $t = 1.44$ sec and the angular velocity is 13.9 degrees/sec. The solution was terminated at this time; however, the angular displacement and rotation would increase rapidly after this time since the gravity vector also contributes to the overturning moment.

The vulnerability curve for the APC is shown in Figure 4. Four curves are shown therein representing the overturning vulnerability for the case where there is no external tie-down restraint ($\gamma = 0$) and also three (3) magnitudes of restraint, i.e., $\gamma = 0.1$, 0.25 and 0.50. It is seen that for high weapon yields, the restraint is not as effective at increasing the overturning hardness as it is at lower weapon yields. If the tie-down system was oriented at 45 degrees with the ground surface and located at a point near the top of the hull (70 inches above the ground), the required total tie-down force of the restraint system would be

$$F = \frac{\sqrt{2}\ (39)}{100 + 70} \gamma W$$
$$= 7785\ \gamma$$

Thus for a restraint parameter of $\gamma = 0.5$, the tie-down system would have to supply a plastic resistance force of 3,893 lbs. This is not an unreasonable value that could be obtained from a rapidly deployed light gage cable and anchor system.

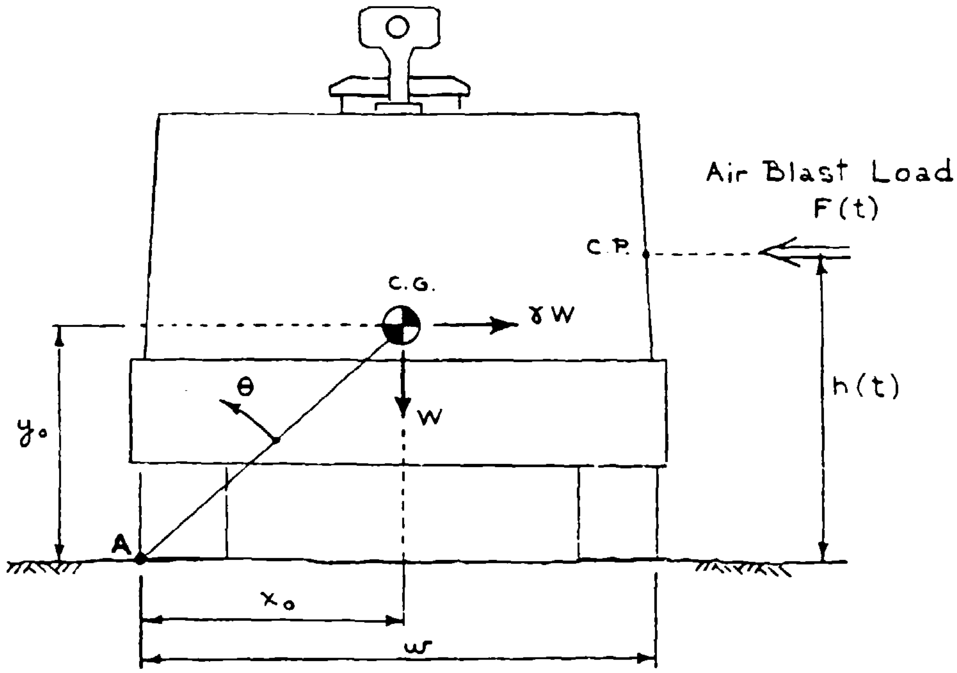
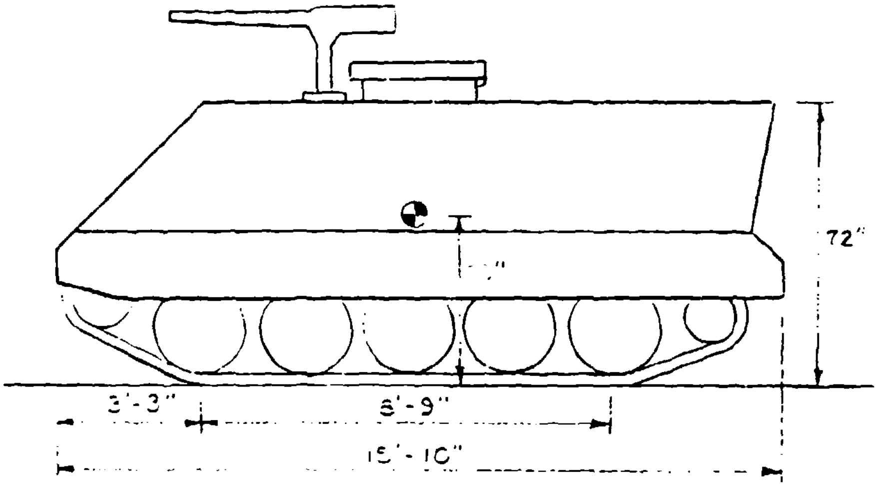
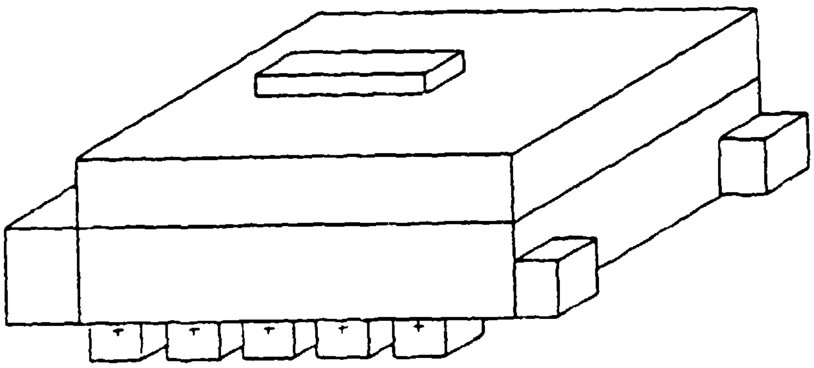


Figure 1. Rigid Body Overturning Model



Side View



Aerodynamic Model

Figure 2. Armored Personnel Carrier

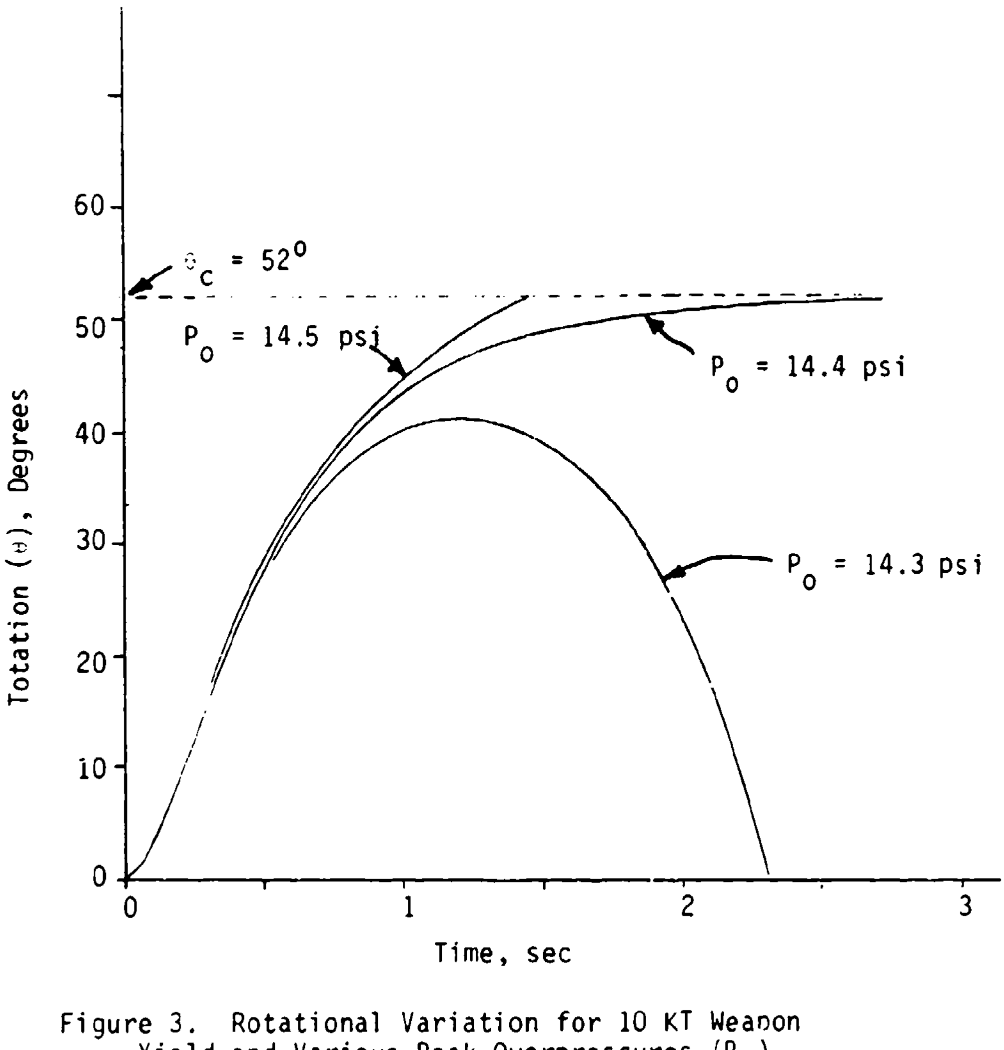


Figure 3. Rotational Variation for 10 KT Weapon Yield and Various Peak Overpressures (P_o)

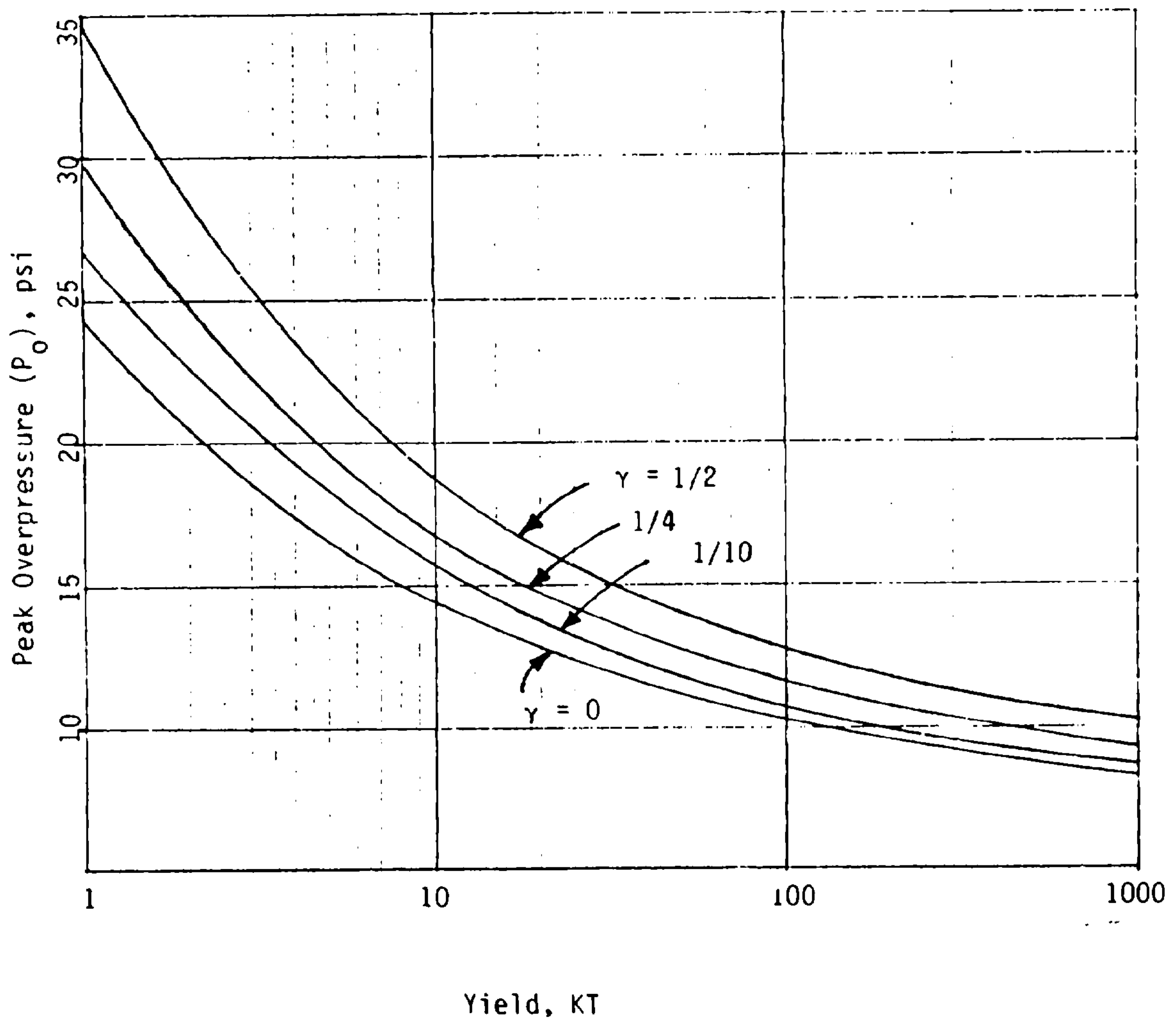


Figure 4. APC Overturning Vulnerability for Various Restraint Parameters (γ)

Sensitivity of High Explosives Against Hot Fragments

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Abstract:

A procedure has been developed for testing the reaction of high explosive to the heat of hot fragments.
Fragments are heated up to 1000°C and injected into HE and the reaction noted. Results will be presented.

FRAGMENT SCISSORS

Introduction

At the shooting against an anti-ship warhead developped by MBB with Phalanx ammunition the reaction of the explosive charge as shown in the following pictures occured. The furmulation of the charge was TNT/RDX/Wax 49/50/1, this is conform to composition B with reduced RDX content.
In fig. 1 you see the warhead ready for the test.

fig. 1

On fig. 2, the additional parts for the simulation of the aerodynamic device and the sensors are already added.

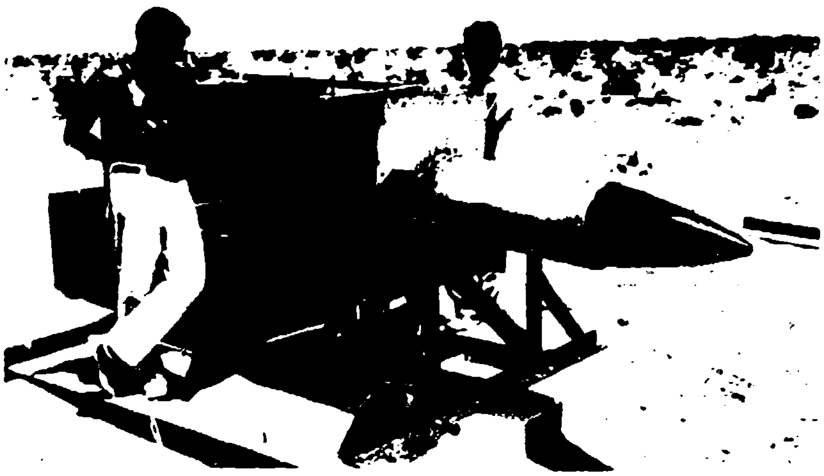


fig. 2

Fig. 3 shows the gun line with the possibility for single and multiple firing. The test results are shown on the next pictures.

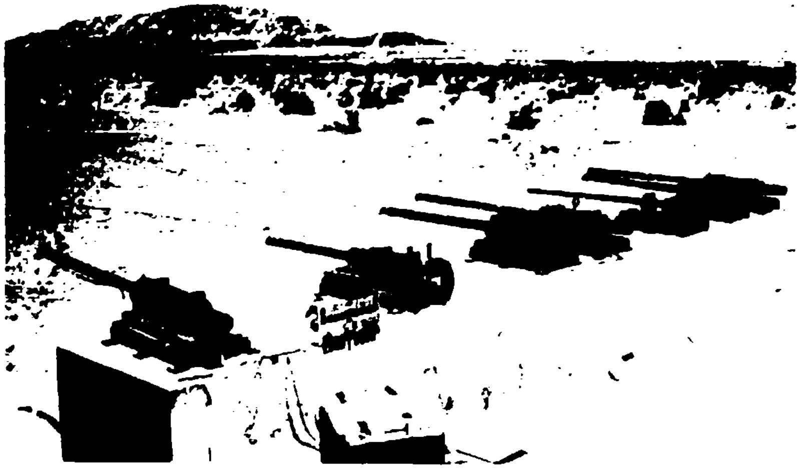


fig. 3

Fig. [illegible] : the reaction flash

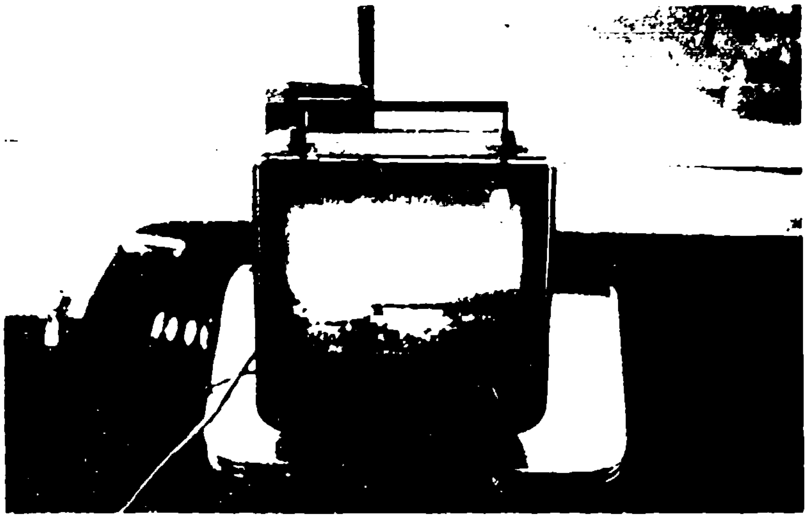
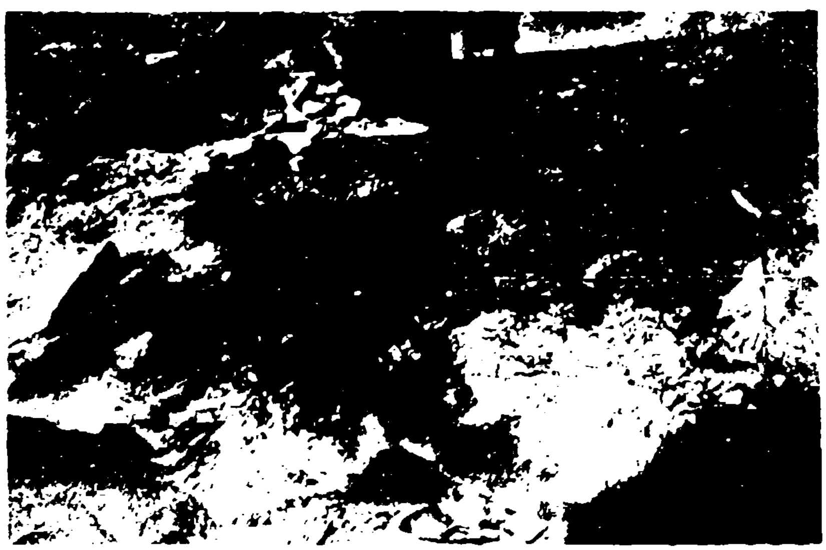


Fig. [illegible] : the same flash by TV observation

figures 6 and 7 : recovered parts of the fuze well sleeve and of the test equipment



Explosive remainders were not found.
These results prove an at least partial deflagration of the charge.

The so observed reaction of the explosive charge in a warhead can in principle occur through two different mechanisms:

- influence of shock load
- influence of hot fragments

To decide which one of these two mechanisms is responsible or more responsible for the reaction, the shooting test is not useful, because always both influences occur simultaneously.
For the evaluation of the prevailing one of the two mechanisms we separated them and measured the sensitivity against shock load by means of a gap test and the sensitivity against hot fragments by means of fragment scissors.
To analyse the influence of hot fragments on an explosive charge as it occurs during shooting, this means that fundamental experiments should not be carried out in a tight system with more or less inifinite heat capacity, if one wants to achieve realistic results in this point of view.
This makes the situation different from very good theoretical affirmation of the behaviour of HE charges depending on the temperature as this has been realized by LLNL with their device (lit. 1).
Phenomenologically it has to be assumed that the reaction probability of the HE charge is a function of fragment temperature and its heat capacity, that is function of the fragment mass.
For this reason, a measuring device has been designed which allows variation of these two important influences. On this topic, some previous results were already published.
(lit. 2, 3).

Measuring device:

We called the measuring device " Splitterzange " (fragment scissors or fragment nippers). It allows to bring into close contact fragments of different size, i.e. heat capacity and different temperature with HE charges of different composition, so that the influence of a hot fragment that penetrates a HE charge and remains there can be simulated well.
Fig. 8 gives the test equipment " Fragment Scissors " in a perspective drawing.

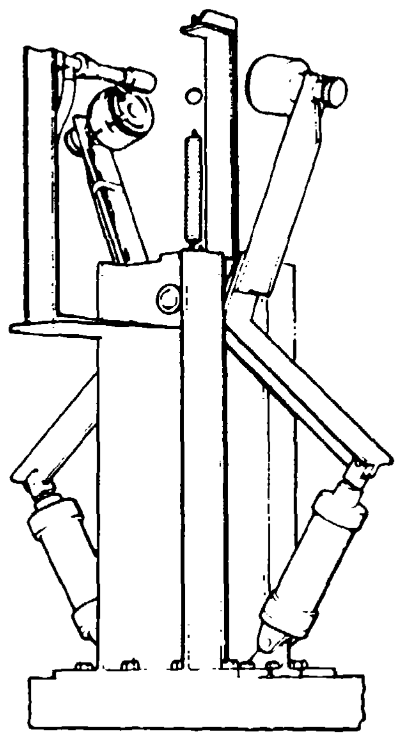


fig. 8

As fragments, steel spheres of different diameters have been used. They were heated to a maximum temperature of 1000 °C resp.1800F by means of a welding burner.

The temperature of the fragment was measured by means of a thermocouple.
After heating the fragments, the two halves of HE charge with hemispherical cavities for a good contact with the hot fragments were pressed on it by means of pneumatic cylinders.
This equipment can be seen from figs. 9 and 10.

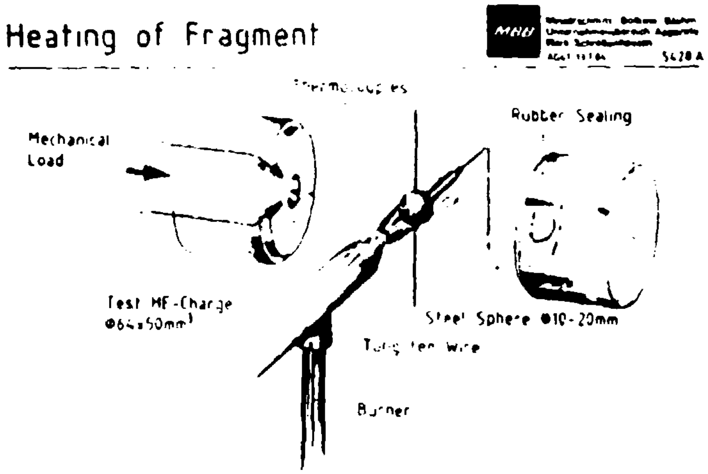


fig. 9

fig. 10

This device allows a maximum pressing force of 4000 N.
At the application of such a high pressure, the HE charge is likely to break if the cavities are not fitted perfectly into the fragment.
In spite of the pressing on of the HE charge to the fragment, an air gap remains at the separation line. At some tests it was left open, at others it was insulated with a very soft sealing material - foam rubber - so that the air could not circulate. The device is designed in a way that even at violent reaction only the clamps for the HE charges will be damaged or destroyed but not the complete set-up..
As the design is similar to that of the scissors it was called " Fragment Scissors ".
By means of the pneumatic cylinders, the HE charges are pressed on the heated fragment with a closing velocity per lever arm of 0,5 to 1 m/sec.
The temperature of the fragment was registered by means of a thermocouple by an XY recorder. Thus, the exact temperature of the fragment at the closing of the two HE charge halves around the heated sphere could be determined.
Furthermore it has been tried to measure the temperature within the HE charge by means of thermocouples in 5 and 10 mm distance from the sphere surface. These measurements however, cannot be regarded as being representative as the heat dissipation of the thermocouples was greater than the heat conductivity of the HE charge itself.
The sphere shaped fragment was held by wires and a spring in the space between the HE charges and thus was apt to center itself within the bore of the HE charge.
Before starting the experiment, the HE charges were installed adjustably in the cylindrical support at the two holders and were oriented towards each other, going out at the sphere fragment.

The heating and turning off of the burner, resp. the closing the HE charge was done under remote control.
In principle it is also possible to test confined charges by using suitable gasket rings and a stronger case whereby the torque of the cylinder determines the maximum possible tightness. At our experiments we only used non-confined charges, i.e. the HE charge overtops the casing by 5 mm.
For the experiments described herein, two types of HE charges were tested:

- TNT, casted
- TNT/RDX/Wax, casted, with a ratio of 49:50:1

Results:

Closing Force:

As described above, the device allows a maximum pressing force of 4000 N. To evaluate the influence of the mechanical load of the HE charge, we first checked the behaviour of the charge under increasing pressure force. The HE charge was TNT/RDX/Wax - 49/50/1, the steel sphere had a diameter of 10 mm on 4,8 grs. and the pressing force was increased from 2000 N to 3000 N and 4000 N. The test was conducted at ambient temperature.
Fig. 11 shows the result.

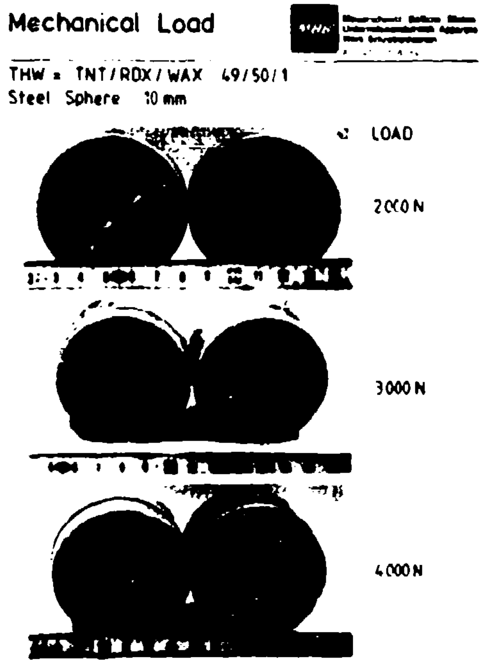


fig. 11

With 2000 N pressure force, there occured no crack formation whilst at 3000 and, more severely, at 4000 N cracks split up the charges into different pieces.
As the closure of the two halves of the charges was tight enough with 2000 N, we applied this pressure force in all further experiments.
In the following presentation, the results we obtained depending on the various, changed parameters, are given.

1. <u>Increased Temperature</u>

First test series show influence of increasing temperature. The HE charge was TNT/RDX/Wax - 49/50/1. The mechanical load was 2000 N and the steel sphere diameter was 10mm. We cautiously started with a low temperature of 100°C and also at a temperature of 200°C (fig. 12) no reaction was noticed.

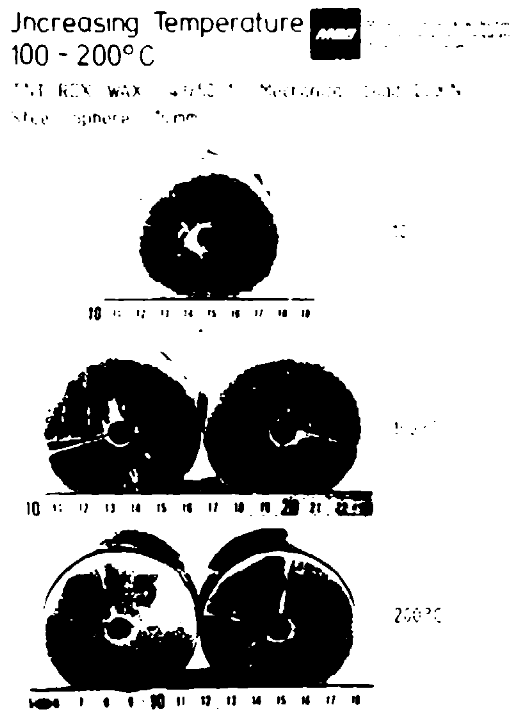


fig. 12

Only melting traces occured at the contact area between fragment and HE charge. Between 300°C and 500°C (fig. 13) reaction with burning traces was observed.

2. Reproducibility

To check the reproducibility of the test results, we subjected the same charge twice to rather similar testing conditions. These were:

- mechanical load : 2000 N
- steel sphere : 10 mm
- fragment temperature: about 700°C (measured temperature was 690°C and 720°C)

The charge was casted TNT (fig. 14).

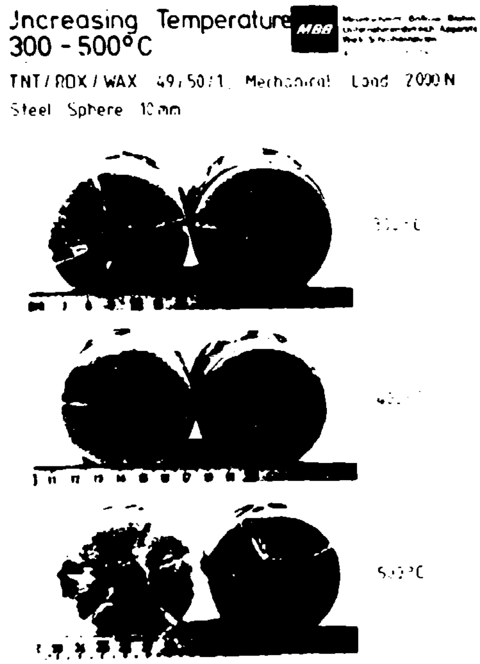


fig. 13

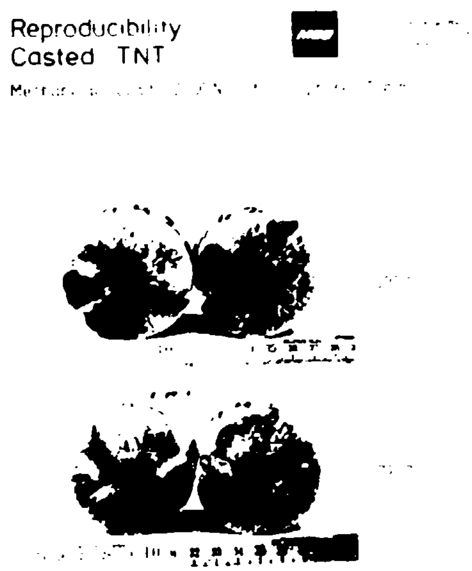


fig. 14

On TNT we obtained similar results compared against TNT/RDX/Wax however at comparably higher temperatures. As shown in fig. 14, the reproducibility of the test results seems to be sufficient. There is no principle difference in the behaviour of the two charges. Melting traces occured in the contact area and smoke generation and burning were observed, but only after 30 - 70 sec.

3. Sealed Charges

The time till reaction was somewhat varying within the test series. We correlated this to the more or less appearing air circulation through the gap between the two halves of the HE charges. So for a part of the experiments we sealed the gap with foam rubber to prevent the air from passing through.
Test conditions were:

- HE charge: casted TNT; steel fragment of 15 mm diameter and increasing temperature from 700 to 900 °C (fig. 15).

With these tests we observed only smoke generation and after the opening of the fragment scissors, melting traces. No burning was observed even up to a temperature of 900°C.

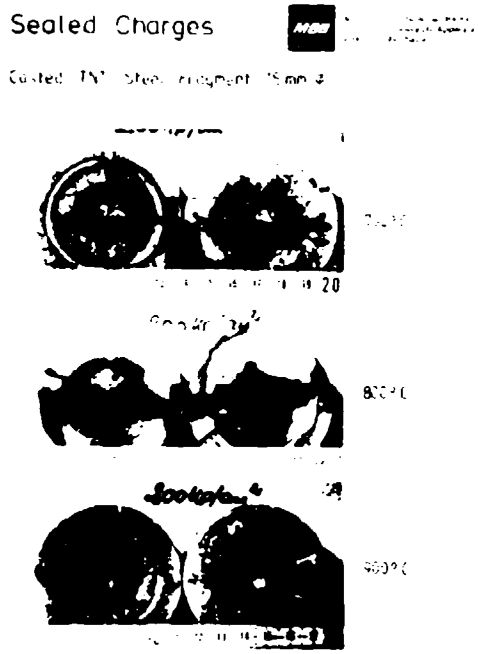


Fig. 15

4. Increased Fragment Diameter

Test conditions:

- HE charge, casted TNT, fragment temperature about 600 - 700°C, fragment diameter varying from 10 - 20 mm (fig. 16).

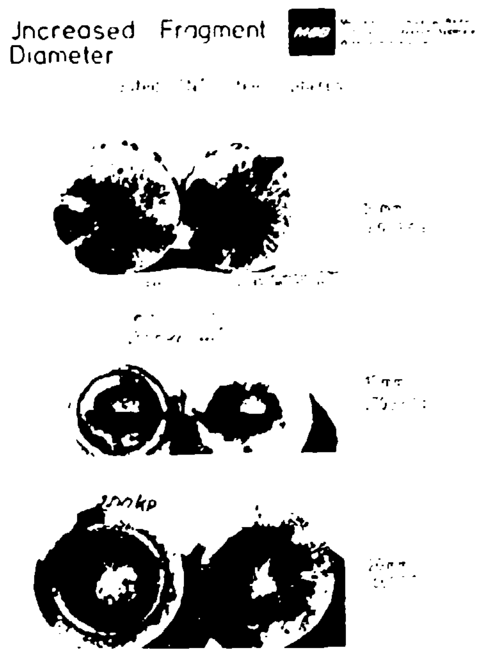


Fig.16

Since we observed no burning of the charges during test on item 3 with 10 mm fragments even at high temperatures, we increased the frament diameter to 15 and 20 mm for a higher heat capacity. In addition, the air gap between the two HE charge halves was sealed with foam rubber.
But there was no difference to results with smaller fragments. Only melting occured. So we can state that for pure TNT charges this test equipment is too insensitive.

5. Increased Fragment Diameter With TNT/RDX/Wax

Test conditions:

- HE charge TNT/RDX/Wax, 49/50/1, fragment temperature 600°C, fragment diameter 10 and 20 mm. The charges for the 10 mm fragment were unsealed, the charges for 20 mm fragments were sealed with foam rubber (fig. 17).

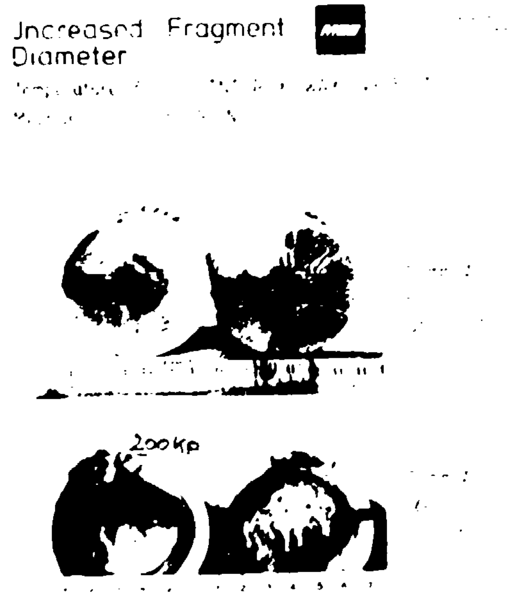


fig. 17

To evaluate the influence of fragment diameter, we did some test on fragments with 10 and 20 mm diameter, for here we found already burning of the TNT/RDX/Wax charge at 600°C with fragments of 10 mm.
Simultaneously we wanted to check the influence of the foam rubber sealing.
At this test we could determine the influence of the foam rubbersealing. With the 10 mm fragment, immediately after closing of the fragment scissors, we observed smoke generation and after 30 sec. burning.
With the 20 mm fragment and sealed charges no burning occured after opening of the fragment scissors, the fragment hole was only eroded by melting of the HE charge.

6. Increased Fragment Diameter at 1000°C

Test conditions:

- HE charge TNT/RDX/Wax, 49/50/1, fragment temperature 1000°C, fragment diameter 15 and 20 mm (fig. 18)

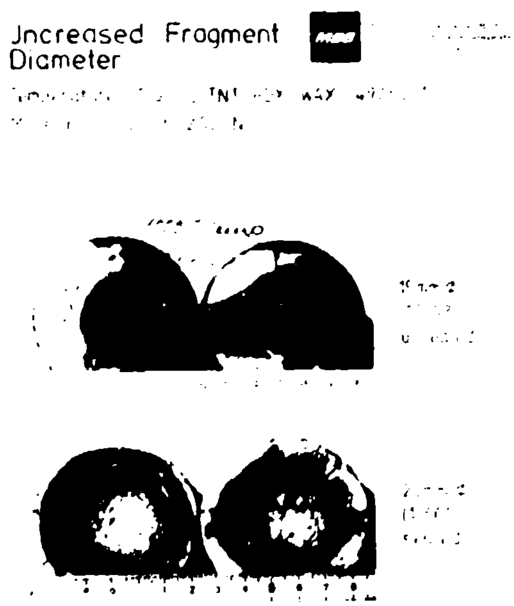


fig. 18

Even with a fragment temperature of 1000°C we found no fast reaction or deflagration. Since the foam rubber sealing prevented the air from passing through the gap between the explosive charges, no burning occured even with a 20 mm fragment of 1000°C. Under unsealed conditions the 15 mm fragment induced burning after about 50 sec.

7. Increased Temperature

Test conditions:

- HE charge TNT/RDX/Wax, 49/50/1, fragment diameter 15 mm, fragment temperature 700 - 1000°C
  The charges were not sealed (fig. 19).

In this test series all charges were burning after a time of 30sec. to 4 minutes.

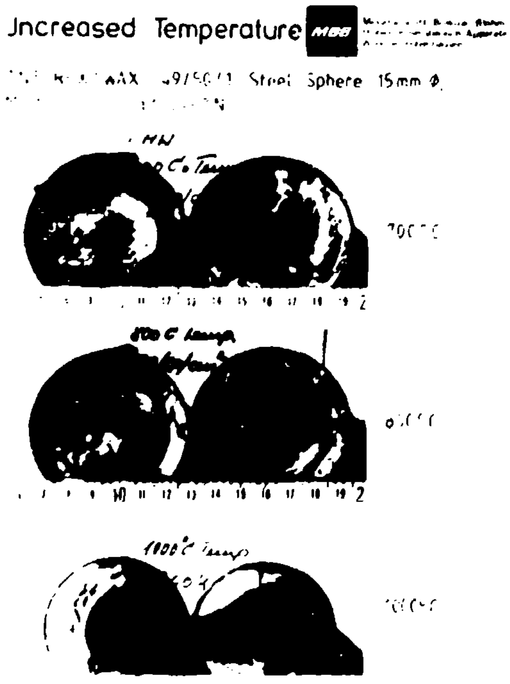


Fig. 19

8. Increased Temperature, 20 mm Fragment

Test conditions:

- HE charge TNT/RDX/Wax, 49/50/1, fragment diameter 20 mm, fragment temperature 600 - 1000°C

The HE charges' halves were sealed with foam rubber (fig. 20). Under these test conditions we did not observe any burning from 600°C even up to 1000°C. The explosive was only molten and so the cavity was eroded.

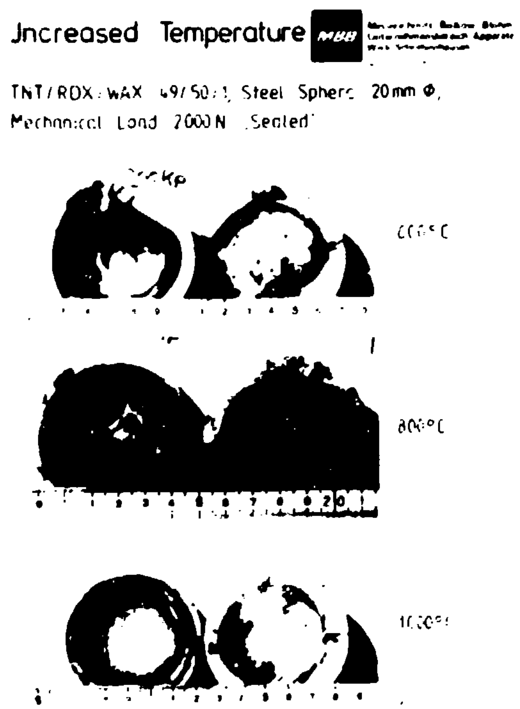


fig. 20

Summarized Results:

Reactions:

First results and observations are listed in fig. 21.

Summary

Charge	Sealing	Fragment Temperatures	Reaction
TNT	NO and YES	600°C - 900°C	Quick Smoke Reaction Cave NO Burning
TNT/RDX /WAX	NO	100°C - 200°C	Only Melting
	NO	300°C - 500°C	Smoke Cook off Traces
		> 600°C	Burning
	YES TYP A	700°C - 1000°C	Quick Smoke Burning
	YES TYP B	600°C - 1000°C	Reaction Cave NO Burning

Steel Sphere between 10 - 20mm Ø
Mechanical Load 2000 N

fig. 21

TNT charges at a fragment temperature from 700 - 900°C show quick smoke generation and melting of the explosive in the cavity.
The TNT charges never started to burn unrelated to a sealing with foam rubber.

As expected, TNT/RDX/Wax charges show a more sensitive behaviour.
Up to 200°C only melting occurs.
Between 300 and 500°C smoke is generated and the charges show cook-off traces.

At temperatures higher than 600°C burning occurs.
This is valid for unsealed charges.
With sealed charges burning starts at least at higher temperatures (700°C) but depends on sealing conditions, so also at 1000°C no burning occured.
So the influence of the foam rubber sealing on the reaction is not clear. The experiments do not allow to decide whether the charges combust by themselves without oxygen from outside or whether burning, that is reaction of the molten and vaporating HE charges, occurs with oxygen from the air.
The author tends to believe that the film recordings and the evaluation of the pictures rather point to a combustion, i.e. reaction of the HE charge by itself at least without an important part of oxygen from the air. This opinion is also underlined by the more sensitive behaviour of the TNT/RDX/Wax charge under these test conditions compared against the TNT, which complies with the normal behaviour of these two types of HE.
But of course, the results depend somehow on the test conditions, especially if air can enter or not.

Testing Equipment:

The testing equipment even in the first construction turned out to be entirely sufficient for the expected purpose. The bearings for the long lever arms eventually could be more precise, so that the steel fragment fits better to the cavity. During the tests conducted by us with our fragment scissors, however a self-adjusting occured in the prepared cavities.

The most doubtful point is the reaction of the explosive with the external oxygen resp. the reaction of outflowing explosive. May be, the test conditions could be defined more precisely if channels were prepared in the charge corresponding with the shooting channel.

9. Conclusion:

(Fig. 22):
The most surprising result was that at all tests performed on this device with steel spheres of 10 and 20 mm diameter even up to temperatures of 1000°C, neither a fast reaction nor deflagration, nor even a detonation occured.

Conclusion

- no High Order Reaction
  = still with 1000° C
  = from 20mm Steel Spheres
  = in TNT Based HE-CHARGES

- With Sealing
  = no External Oxygen
  = no Burning
  = Only internal Erosion (Reaction Caves)

- Would the Fragment Scissors be a useful Test?

fig. 22

If the entrance of external oxygen was prevented by sealing the charges, no fire but only internal erosion or reaction in the cavities occured. The question arises, why the HE charge does not explode, even as the temperature of the fragment is much higher than the self ignition point of the tested HE.

There are three potential reasons possible (e.g. besides others) or to be discussed:

1. The HE is not powdered as it is in the self-ignition test. Therefore, flame propagation does not occur.

2. The solid TNT based charge will firstly melt. This absorbed most of the heat capacity of the contacting surface. So the critical value for self ignition will not be reached.

3. Maybe the self ignition of the HE charge starts but in the solid HE the reaction is only smooth because the pressure in the special test set up is more or less the ambient pressure. This reaction is maybe what we called the erosion reaction so I would like to ask the audience if the fragment scissors would be:

- a useful test to answer the proposed question on the sensitivity of HE charges against hot fragments.

- in general a useful test to evaluate the sensitivity of HE charges against heat, because it allows the application of defined heat quantities.

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(2) M. Held, D. Vollrath, K. Hollenbach

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MBB report TN-AF24-378/1978

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Sensitivity of High Explosive Charges at the Influence of Defined Heat Quantities

Paper held on DEA-AF-F-G-7304 Meeting, Schrobenhausen 1979.

ATEX - A CASTABLE INSENSITIVE HIGH EXPLOSIVE

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ABSTRACT

This paper describes a new castable IHE explosive, ATEX, developed by the Aerojet Tactical Systems Company. The Interim Qualification testing conducted successfully according to NAVord OD44811 is reviewed and the processing characteristics and physical properties of the explosive are discussed. ATEX was the first composition to be tested to the new IHE standards established by the DOD Ammunition and Explosives Safety Standards, DOD 5154.45, Interim Change 4. These tests conducted by the TERA Group of the New Mexico Institute of Mining and Technology were all passed successfully and are reviewed and discussed in the paper.

INTRODUCTION

There is a real need for less hazardous explosives for use by the Military. Events such as occurred on the Forrestal and Enterprise, as well as others, have served to emphasize the problem. Not only is there a concern for the loss of life and equipment, there are severe limitations on transport, loading, and storage facilities with current high explosives. Recognizing this need for low hazard explosives led the Aerojet Tactical Systems Company into undertaking a program to develop a new insensitive high explosive.

Aerojet's background in the development of composite castable propellant, as well as castable PBX's, was the basis for formulation of a castable insensitive explosive which has been designated "ATEX". The work was completed in a little over one year and has produced a composition which meets all of the requirements established by the Department of Defense Explosives Safety Board for an "Insensitive High Explosive" (IHE).

ATEX is a proprietary composite castable explosive. It has excellent processing and physical properties and meets all of the criteria established to define an IHE explosive. Its properties are reviewed below.

TECHNICAL DISCUSSION

Processing of the ATEX explosive is done in vertical mixers using techniques similar to those for other plastic bonded explosives and composite propellants. To date, batches have been prepared in 1, 30, and 300-gallon sizes. The uncured explosive has excellent viscosity and potlife as shown in Figure 1. This demonstrated low viscosity permits ATEX to be cast in complex shapes without voids and lowers production costs by reducing mix energy requirements.

The cured material is an elastomeric solid with excellent mechanical properties over the temperature range of -65 to +160°F. Typical properties are tabulated below.

Test Temp, °F	Tensile σ_m, psi	Elongation ϵ_m, %	ϵ_b, %	Modulus E_o, psi
+160	90	51	51	280
77	126	56	57	388
-65	536	47	56	4450

These properties can be easily altered within the range of approximately 200-1000 psi modulus at 77°F depending on requirements. The properties exceed those of almost all of the current PBX's.

The detonation velocity has been determined to be 7.35 mm/μsec. This performance is very satisfactory for general purpose munitions and compares favorably with other main charge explosives as shown below.

Charge	Density g/cc	Detonation Velocity mm/μsec
ATEX	1.49	7.35
TNT	1.61	6.90
Tritonal	1.72	6.70
Comp. B	1.66	7.80

The testing to qualify the explosive according to OD44811 is described below.

A. Interim Qualification Testing

Small-Scale Testing

Testing of small scale samples for Interim Qualification were conducted on the Aerojet Tactical Systems Facility in Sacramento. These tests included impact, friction, vacuum stability, NOL, deflagration to detonation, thermal stability, spark sensitivity, and the #8 blasting cap, and were all passed successfully. The results of these tests are first summarized and then the individual tests are reviewed.

SUMMARY OF ATEX INTERIM QUALIFICATION TESTS

	Test	Pass/Fail Criteria	ATEX Result
1.	Impact Sensitivity	Comp. B equivalence (109 cm)	Pass - 20/20 no fires at 320 cm
2.	NOL Card Gap	≥Tetryl	Pass - 50% point 29 cards
3.	Friction	250 lbf 8 ft/sec	Pass - 20/20 no fires
4.	Electrostatic Sensitivity	0.25 Joules	Pass - 20/20 no fires
5.	Vacuum Thermal Stability	<2.0 ml/g/48 hours at 100°C	Pass - 0.11 ml/g/48 hours at 100°C
6.	Irreversible Growth	1.0 Vol. % after 30 cycles	Pass - 0.2 Vol. %
7.	Exudation	0.1 wt%	Pass - no exudate
8.	Self Heating	180°F	Pass - critical temp. 347°F
9.	#8 Cap Test	No reaction	Pass - no reaction
10.	2-Inch Cube Burn	No violent reaction	Pass - burn only
11.	4 each 2-in. Cubes	No violent reaction	Pass - burn only

Impact Testing

This test was done on a Bureau of Mines apparatus which uses a 2 kg weight and has a maximum drop height of 100 cm. Twenty trials were performed on the ATEX explosive using the apparatus at the maximum height and all were negative. On this machine the 50% fire point of RDX Type 11 Class 1 is 30-33 cm.

Because a greater impact shock capability was desired, additional impact tests were run at Los Alamos National Laboratory on an apparatus with a drop height of 320 cm. Los Alamos National Laboratory uses two different surfaces. Type 12B tooling uses bare, sandblasted tool-steel surfaces, while Type 12 tooling uses garnet paper to introduce the effect of grit on the sensitivity of the explosive. This machine uses a 2.5 kg weight. The ATEX was tested at the maximum drop height under conditions of both bare anvil and with garnet paper. All trials were negative. In contrast RDX on the Type 12 tool gives a 50% point of 28 cm, and on the Type 12B, 32 cm.

Sliding Friction

Sliding friction testing was conducted using the Aerojet machine which is patterned after the ABL device. The test was run at 250 lbf at 8 ft/sec with negative results.

Comparative measurements for calibration standard, PETN, on this apparatus showed the following results.

Anvil Velocity, ft/sec	Pressure, lbf normal
8	100
6	200
3	700

The pressure is the maximum that yields twenty consecutive negative results at a given anvil velocity.

Electrostatic Sensitivity

The relative sensitivity of ATEX to spark discharge was measured. A total of 20 trials were conducted at 0.25 Joules and all were negative.

Vacuum Stability

The vacuum stability test was run to determine the volume of gas given off from a small sample of explosive after heating under vacuum at 100°C for 48 hours. Test results for ATEX showed a gas evolution of 0.107 ml/g after 48 hours at 100°C, considerably below the required limit of 2 ml/g.

Growth

To determine the effect of temperature cycling on the irreversible growth of the ATEX explosive, samples were cycled 30 times from -65°F to +140°F. After cycling the samples were visually inspected, then weighed and measured. No evidence of exudation was found and the volumetric change was only 0.02%.

Thermal Stability Tests

One 2-inch cube was placed in a constant temperature explosion proof oven and the temperature raised to 75°C and the sample held for 48 hours. There was no visible change in the cube after the test.

Time-to-Explosion Test (Modified Henkin Test)

This test to define the critical temperature for catastrophic self-heating was conducted by Dr. Ray Rogers at LASL. The results for ATEX are shown graphically in Figure 2, indicating a critical temperature of 175°C, well above the required 82°C.

Ignition and Unconfined Burning

This small scale test of the susceptibility of the explosive to detonation by fire was passed successfully. There was no evidence of deflagration to detonation in either the single 2-inch cube nor in the combined four 2-inch cube tests. The test specimens burned quietly for about 200 seconds. Burning was so mild that it was difficult to distinguish from the kerosene-soaked sawdust burning.

Detonation Test

A 2-inch cube of ATEX was placed on a lead cylinder and a No. 8 blasting cap was placed on the sample surface. After the cap was detonated, the cylinder was inspected for deformation (mushrooming). Any deformation was considered evidence of detonation. For ATEX, five tests were conducted. The force of the explosion punched a hole approximately 1/4" into the cube and scorched the surface, but all tests were negative.

NOL Card Gap (Large Scale Gap Test)

This test to define sensitivity to detonation by a pentolite donor charge was passed successfully. With a requirement of 0.70 inch attenuation as a maximum to prevent detonation the 50% point was found to be only 0.30 inch.

B. IHE Qualification Tests

The IHE Qualification testing required samples too large to be tested at Aerojet. Because of this requirement the work was contracted to the New Mexico Institute of Mining Technology, TERA, Socorro, New Mexico.

The screening tests and the qualification test results are first summarized and then reviewed individually. All of the tests were passed successfully.

SUMMARY OF ATEX IHE SCREENING TESTS[1]

Test	Pass/Fail Criteria	ATEX Result
1. Impact	$\geq$254 cm	Pass - 320 cm
2. Friction	Same as Interim Qual	Pass
3. Small Burn	Same as Interim Qual	Pass
4. Spark	Same as Interim Qual	Pass
5. DTA	No Exotherm at 250°C	Exotherm at 195°C

1 Failure to achieve required results in a single tests is not regarded as disqualifying.

SUMMARY OF QUALIFICATION TESTS

1. Critical Diameter	N/A N/A	>3.3 <4.00 in. - Unconfined 1.1 in. - Confined
2. Detonation Vel.		7.3 mm/μsec
3. Cap Sensitivity	No Reaction	Pass - No Reaction
4. Fast Cookoff	No Violent Reaction	Pass - Burn Only
5. Slow Cookoff	No Reaction No Reaction to 300°F	Pass - Burn Only, 286-294°F
6. Card Gap	<70 Cards Equiv.	Pass
7. Bullet Impact	No Violent Reaction	Pass - Samples only Smoldered
8. Susan Test	Less than 10% of TNT Reaction	Pass - 9% of TNT

The differential analysis peak temperature of 195°C was less than the desired goal of 250°C, however, one screening test failure is allowed by Interim Change 4.

Unconfined Critical Diameter

The unconfined critical diameter was determined to be between 3.33 and 4.00 inches based on perforation of a 0.5 inch thick steel witness plate. The individual test results are tabulated below.

Diameter	Results
3.00	No-Go
3.00	No-Go
3.00	No-Go
3.33	No-Go
3.33	No-Go
4.00	Go
4.50	Go

Continuous Detonation Velocity

The detonation velocity measured in a 5 x 25" confined test was 7.30 mm/μsec. The results of the tests are tabulated below with the interval measurements made as shown. The spread in the data was minimal and the average value was slightly higher than had been predicted by the Kamlet method. The recorded times and associated velocity estimates are presented.

Interval	(mm)	(μsec)	Velocity (mm/μsec)
1	25.4	3.50	7.26
2	25.4	3.50	7.26
3	25.4	3.45	7.36
4	50.8	7.95	7.31
1-4	127.0	17.40	7.30

Extra Large Scale Gap Tests

These tests conducted with 2.94 x 11.25 inch specimens in steel sleeves were passed successfully with a 50% point at 0.95-1.0 inch attenuation. The test was introduced late in the development as a result of the Interim Change 4. Before the test could be conducted it was necessary to establish the size of the booster charge. This was established by Price at NSWC to be a 3.5 x 3.5 inch charge of pentolite. The test results are summarized below.

EXTRA LARGE SCALE GAP TESTS

Gap, in.	No. of Tests	Results
0.95	5	Go
1.00	5	No-Go
1.00	2	Go
1.05	1	No-Go
1.20	3	No-Go

No. 8 Cap Test

The test was run with both a 3 inch and 6.7 inch diameter sample and all tests were negative. Three 6.7 x 6.7 inch and five 3 x 12 inch cylindrical samples were tested. There was no visible reaction, only a slight cratering.

The larger samples were tested to be certain that the test specimen exceeded the critical diameter. The tested specimens were inverted and detonated high order by a pentolite booster.

Slow Cook-Off

Three slow cook-off tests were conducted successfully with 5 in. dia. x 20 in. long specimens with no evidence of violent reaction. In this test the specimen is heated from 100°F at a rate of 6°F per hour until reaction or a temperature of 300°F is reached. A typical temperature vs time curve is shown in Figure 3.

The measured temperatures at time of reaction were measured as tabulated below.

SLOW COOK-OFF TEST

Temperatures at Reaction

Internal Temperature	Skin Temperature
277°F	386°F
288	289
284	294

In no case was there a violent reaction.

Fast Cook-Off

Three external fire fast cook-off tests were conducted and all were successful. The cast iron end caps failed after about 3 minutes and the explosive burned vigorously for approximately 30 seconds. There was no violent reaction in any of the tests. The wood-kerosene fire had a measured temperature ranging from 800 to 1500°F.

Bullet Impact

Six bullet impact tests were conducted using 5 inch x 20 inch samples encased in capped steel sleeves. All tests were negative. Three tests were with 50 caliber armor piercing bullets fired into the side of the sample and three were end shots.

In the side-on tests, the bullets passed completely through the sample and out the far side of the pipe. In two of the end-on tests, the bullet was trapped inside the sample, while in the third test the bullet traveled approximately 12" into the sample and then exited through the side of the pipe.

In all six tests the sample smoldered for thirty to forty minutes following the bullet impact. Subsequent inspection indicated the presence of black residue in the sample pipes. There was no violent reaction, no fragmentation hazard of any sort, in any of the six tests.

Susan Tests

A series of five SUSAN tests was performed with the ATEX explosive and an additional two SUSAN tests were performed with cast TNT as a control. The nominal striking velocity for the first three ATEX samples was 1000 fps, and this was increased to 1089 fps for the last two ATEX samples and for the TNT tests. The test results are tabulated below.

Explosive Type	Velocity, fps	P_1, psi	P_2, psi	P_3, psi
ATEX	971	0.8	0.8	0.9
ATEX	997	2.5	2.5	2.5
ATEX	885	1.3	1.5	2.0
ATEX	1067	0.80	0.81	0.83
ATEX	1116	0.80	0.84	0.93
TNT	1078	5.5	6.1	6.6
TNT	1071	5.5	5.0	5.8

CONCLUSIONS

The results from all of these prescribed tests show that the ATEX explosive is indeed an insensitive high explosive and meets the criteria for IHE as defined in DOD 5154.45 Interim Change 4. Its properties are such that with adoption and use by DOD, a significant new level of safety can be attained in the handling, storage and use of explosives.

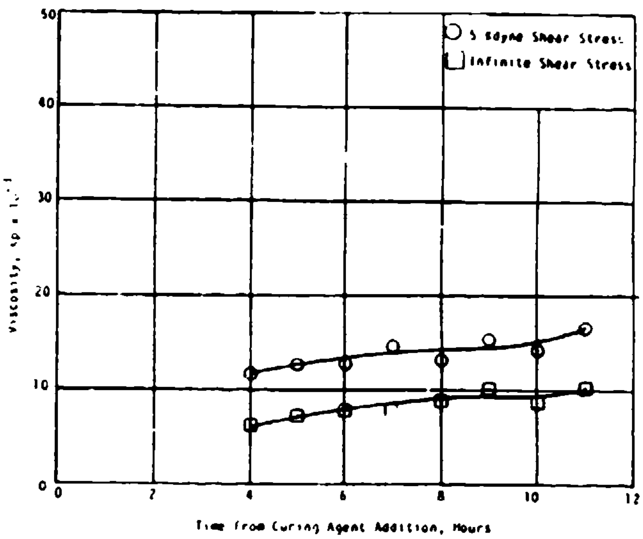

Fig. 1 Viscosity Buildup of ATEX Explosive, 120°F

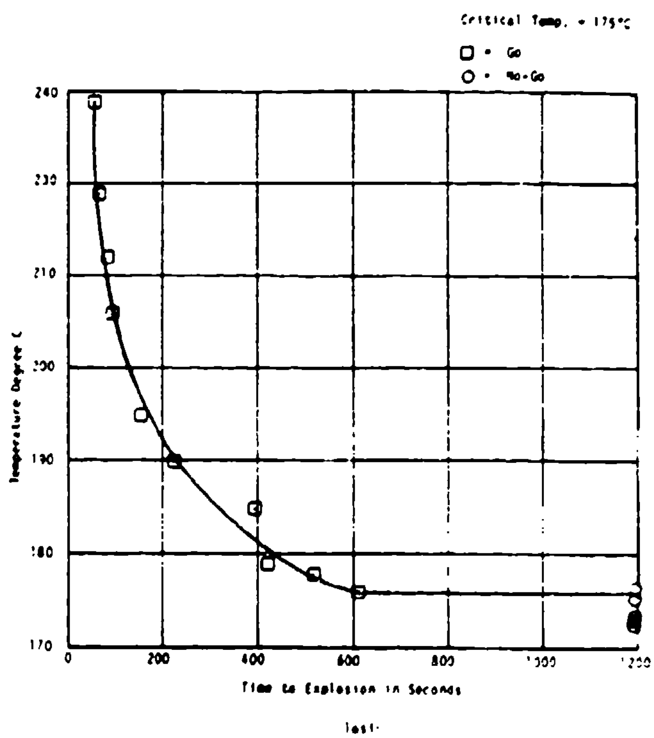

Fig. 2 Time to Explosion Curve for ATEX

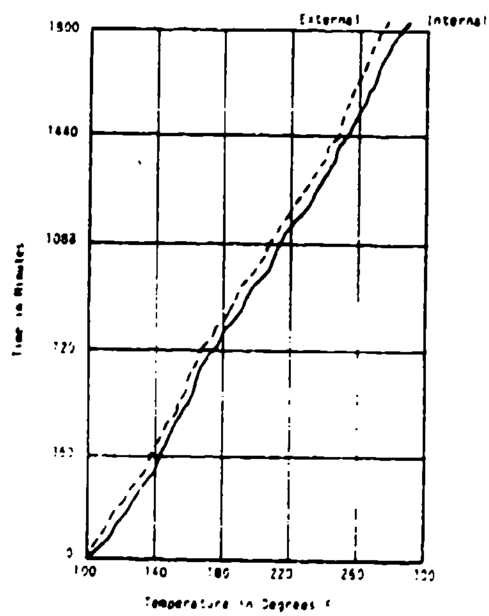

Fig. 3 Typical Slow Cookoff Temperature Buildup for ATEX Explosive

METHOD OF PREDICTION OF THE EXPLOSIVE BEHAVIOR OF HIGHLY CONFINED PBXs SUBMITTED TO BULLET IMPACT

Presented to :

21st Department of Defense
Explosive Safety Seminar

August 28, 1984
to
August 30, 1984

by

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METHOD OF PREDICTION OF THE EXPLOSIVE BEHAVIOR OF HIGHLY CONFINED PBXs SUBMITTED TO BULLET IMPACT.

Author : P. MONTEAGUDO , SNPE , FRANCE

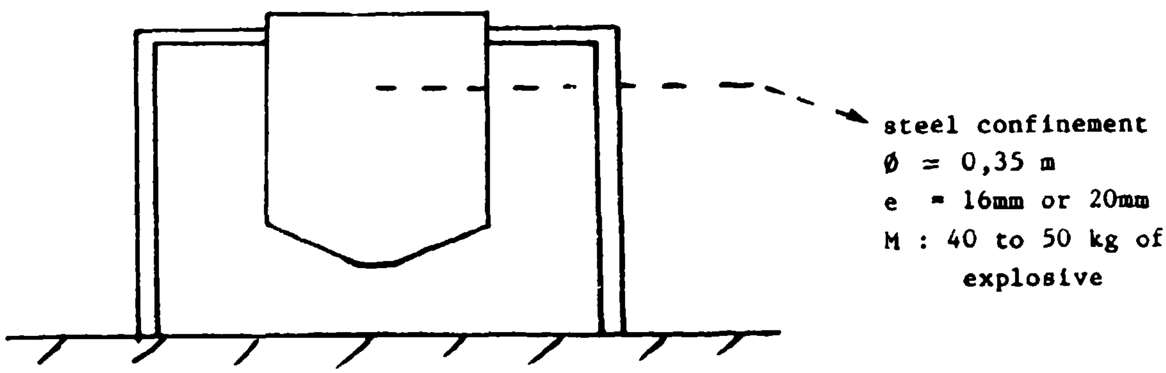
Abstract : We describe the mechanisms which govern the bullet impact reactivity of strongly confined castable plastic bonded high explosives. We point out the parameters which drive the reaction. This one is a deflagration to detonation transition, in the studied cases.

We succeed in elaborating a first practical model, able to forecast the explosive behavior of castable plastic bonded high explosives (based on the fragmentability of the explosive material) and strongly confined.

1. ORIGIN OF THE NEED AND STAKE.

Since 1973, the need expressed by French Navy to have bullet insensitive military warheads, has led to realize large scale experiments on warheads charged with PBXs.

The experiment configuration was as follows :



The PBX of the charge was made up of 14 % of polyurethane binder and of 86 % of octogen.

The stress was the following :

- bullet : caliber 13,2 P
- velocities : 700 to 825 m/s

The results obtained could be listed as follows :

- nothing (no reaction)
- combustion
- deflagration
- extremely violent reaction occuring after varying lapses of time and lasting sometimes several minutes.

In order to get a better understanding of the situation we have undertaken a study with the aim to identify the reactive mechanisms, so that we could improve the behavior of warheads to bullet impact.

The stake is very important because the results of this work may allow :

- to foresee a priori the behavior of a military warhead to the bullet impact.
- to define some compositions of confined explosives that would be less sensitive or insensitive to this impact.

This study consists of two main lines :

1. - a theoretical line : to realize a numerical modelling of the behavior of a body composed of steel and of explosive to the bullet impact .
2. - an experimental line : to research a configuration on a small scale allowing to reproduce the results obtained on a large scale.
   - to identify the parameters that govern the reaction.

2. NUMERICAL MODELLING.

2.1. Hypothesis of calculation and modelling.

In order to bring the actual problem to a configuration that could be dealt with by the HEMP code (three dimensions with axial symmetry) we have given a cylindrical geometry to the target and we have made the trajectory of the bullet meet the axis of symmetry of the device.

We were also led to simplify the form and the composition of the bullet.

The planes and grooves have not been taken into account and the bullet has been given a geometrically sharp form (figure 1). From its actual components we kept only the steel, wich volumic mass was modified (7,85 g/cm3) in order to obtain an identity of the masses (45 g).

The velocity of the bullet is of 833 m/s.

The target is 16 mm thick and its radius is 100 mm. Its mass is of 3946 g.

The explosive is 30 mm thick for a radius of 100 mm.

The axis of the bullet must always meet the axis of symmetry of the target.

It is also considered that the coating and the explosive must slip on the bullet without having the possibility to create a vaccuum or a punching.

These two materials are supposed to be strictly interdependent at the level of their interface (hypothesis of a perfect stricking).

The explosive (14% of polyurethane binder and 86% of octogen) is supposed to behave in a hydrodynamic way on account of the strong stresses that we can expect. It is also supposed that the minimal pressure withstood in traction is equal to zero.

The state equation is a form of the HUGONIOT equation :

$$P = \rho_0 \frac{a^2 (y - 1)}{[y - b (y - 1)]^2}$$

where P is expressed in Megabars and y is the reverse of the relative volume $\frac{V}{V_o}$, and with :

ρ_o = 1.71 g/cm3
a = 0.2071 cm/s
b = 2.309 (without dimension).

The steels of the bullet and of the protective coating are described by a perfect elastoplastic behavior. No rupture criterion was used during the modelling.

- Characteristics of the coating :
  It is a tempered steel :
  elastic limit Y = 9500 bars,
  modulus of shearing off G = 0.815 Megabar
  modulus of compressibility K = 1.65 Megabar
  volumic mass ρ_o = 7.85 g/cm3,

- Characteristics of the projectile :
  They are identical to those of the coating, except for the elastic limit : Y = 9000 bars.

The state equation selected for these two materials is the following :

$$P = 1.65\ (y - 1) + 1.87\ (y - 1)^2$$

where P is expressed in Megabar and where y is the reverse of the relative volume.

The velocity of the elastic waves, calculated with the above data, is :

A = 5904 m/s.

2.1. The results.

The calculations have been made from the impact, taken as the zero hour, up to 54 μs, at which moment the bullet started to penetrate the explosive.

Figures 2 to 5, given in appendices,describe the history of the pressure in various places of the target, or show the aspects of the meshing during the calculation.

2.3. Description of the effects of the penetration.

The important fact resulting from the modelling is the oscillatory character of the pressures and of the stresses in all points of the target and of the projectile.

The first peak pressure (figure 4) corresponds to the initial shock due to the impact and expands on the axis of symmetry of the device in the neighbourhood of the bullet head, in the coating.

This shock, of a significant amplitude (120 kbar), will be very quickly absorbed, on the one hand because of the proximity of the free surfaces that provoke releases in the steel, and on the other hand by a natural divergence during its propagation.

The following oscillations are much more difficult to interpret. Actually several phenomena are working nearly simultaneously :

- the numerous reflections of pressure waves on the free surfaces and on the interfaces may explain the early appearance (5 to 6 μs) of tractions in the coating (of the HOPKINSON effect type);

- similar occurrences take place in the projectile but at different times and with different amplitudes ;

- the projectile penetrates and is distorted in a surrounding that never offers the same resistance, depending upon the spatial localization and the stresses occuring on the place;

- the interfaces and the free surfaces can be distorted or are moving from one another thus complicating the propagation and the reflection of the waves.

These facts, as well as the results obtained, lead to suppose that an effect of pulsation is associated to the penetrating of the bullet, besides this has been noticed by some authors.

2.4. Behavior of the explosive.

Hypothetically the explosive is interdependent of the coating at the interface level. Therefore it is going to undergo the wave train previously created in the steel and absorbed when crossing the line by disadaptation of acoustic impedance.

Figure 5 shows the succession of compressions and tractions modifying the explosive in some points that were initially near the axis and the interface.

It is noted that the maximal amplitude of the pressures is of 10 kbar and that it occurs in the neighborhood of the bullet head when it starts penetrating the explosive.

Previously the pressure never exceeded the value of 4 kbar and this shows that the coating has a function of screening.

2.5. Conclusions.

The comparison of the pressure profiles, calculated with the experimental curve of squibbing by a calibrated shock wave, shows that the direct squibbing of the explosive by a shock wave is most unlikely (figure 6). Indeed, this threshold curve is built with rectangular shocks varying in amplitude between 75 and 25 kbar, whereas the calculated pressures remain at definitely lower levels.

Actually, there remains an uncertainty with regard to the duration of application of the shocks. The calculated intervals of times sometimes clearly exceed the field of validity of the experimental curve, however its asymptotic appearance allows to overlook this uncertainty.

3. EXPERIMENTAL STUDY.

3.1. Search for a configuration.

We have searched for an experimental configuration on a small scale allowing to reproduce the results obtained on a large scale. After some experiments we arrived at the model shown in figure 7.

The model can be defined along the following lines :

- we kept :
  - the nature of the steel of the military warhead
  - the thickness of the steel of the military warhead
  - the static pressure of bursting of the military warhead, this leading us to create planes on the model.

- the mass effect of the explosive is modelled by an anvil placed on the model. The firings showed that the same effects could be observed for the same velocities of the bullet as on a large scale if the mass of this anvil was of 500 kg. The same effects are observed but at higher velocities of the bullet if the mass of the anvil was 250 kg. It is the latter that has been selected because it is easier to implement.

3.2. identifying the parameters that govern the reaction.

The analysis of the experiments realized on a large scale as well as the results obtained after the numerical modelling led us to the conclusion that the reactive mechanism by shock to detonation transition was most unlikely in the configuration in question.

We have therefore worked out a reactive scenario implementing a mechanism of Deflagration to Detonation Transition. This scenario is described in appendix 1. It implies a mechanism of fragmentation of the explosive.

This fragmentation can be of two kinds :

. mechanical : when resulting of the crossing of the bullet

. by cracking combustion : the explosive is fragmented by its own combustion, thus creating favourable conditions for a Deflagration to Detonation Transition.

We have formulated a number of compositions in order to check our reactive scenario.

These compositions are as follows :

Compositions / Components	A	B	C	D	E
HMX coarse	50 %	50 %	-	76%	-
HMX medium	10 %	11 %	76%	-	-
HMX fine	26 %	27 %	-	-	76%
global content	86 %	88 %	76%	76%	76%
binder	Polyurethane	Polybutadiene	Polyurethane	Polyurethane	Polyurethane

We have characterized them, as regards the mechanical fragmentation, by the test of the "shot gun".

Figure 8 shows the diagram of this test.

The summary of the method is given in appendixes 2 and 3.

The curves of figure 9 describe the obtained results.

They show that :

- all the compositions have not the same behavior to the mechanical fragmentation evaluated by the shot gun test.
- the "coarse" Octogen makes the compositions fragile
- the finer the Octogen, the better the mechanical behavior evaluated by the shot gun test
- the polybutadiene binder improves the behavior of the compositions; it even weakens the harmful effect of the "coarse" Octogen.

These compositions have also been characterized as regards the cracking combustion by the test of burning in high pressure closed vessel (8000 bar). It is observed in that case whether the sample is fragmenting or not by its own combustion and in this way the cracking pressure of the explosive is noted.

The results are summarized in the following table :

Composition	Fragmentation	P Fragmentation (MPa)	dP/dt max. (MPa/ms)
A	yes	170	≃ 1400
B	no	-	≃ 50
C	no	-	≃ 20
D	yes	≃ 250	≃ 530
E	no	-	≃ 13

The compositions that are fragmenting contain "coarse" Octogen.

It appears that the polybutadiene binder weakens the part played by the "coarse" Octogen since the latter enters in the composition B which is not fragmenting.

The diagram of figure 10 gives an example of curves obtained in coordinates V = f (P) on a composition which is fragmenting and on one which is not.

3.3. Firings on models with a 12.7 perforating bullet.

The previously evaluated compositions have been fired in the models defined at par.3.1. The procedure of the firing was as follows :

500 m/s; 740 m/s; 850 m/s; 930 m/s; 1145 m/s with an anvil of 250 kg placed on the model.

The following results were obtained :

Composition → / Impact velocity ↓ (m/s)	A	B	C	D	E
550	nothing to report	nothing to report	nothing to report	noting to report	nothing to report
740	explosion material remaining	opening not much material missin^	"	explosion	"
850	id	id	opening not much material missing	id	"
930	stronger explosion	id	id	id	"
1140 250kg	DDT	id	DDT	DDT	"

The compositions that are fragmenting when burning in high pressure vessel and/or that have not as good a behavior as the composition called B to the mechanical fragmentation estimated by the test of the shot gun, lead to a Deflagration to Detonation Transition during the test of firing with a 12.7 P bullet.

The other compositions do not lead to deflagration to detonation transitions. We must point out the particular behavior of the composition E which was not even ignited during the firings with a bullet.

3. PRACTICAL MODEL OF PREDICTION.

This work allowed us to arrive at a first practical model of prediction of the pyrotechnic behavior of a higly confined PBX submitted to a 12.7 P bullet impact.

These will be a high probability of Deflagration to Detonation Transition of a PBX when :

- during the test of burning under high pressure, the composition is fragmenting
- during the test of the shot gun, the composition is showing a curve of evolution of the dP/dt according to the impact velocit, situated above a reference curve that we regard at present as being the composition called "B".
- during the tests of impact on models with a 12.7 P bullet, for velocities from 550 to 1140 m/s, a deflagration to detonation transition is observed.

This practical model of prediction has been worked out from the 5 compositions that are presented here and from the experiments on a large scale that were made until now.

It has furthermore been checked on some other compositions of PBX.

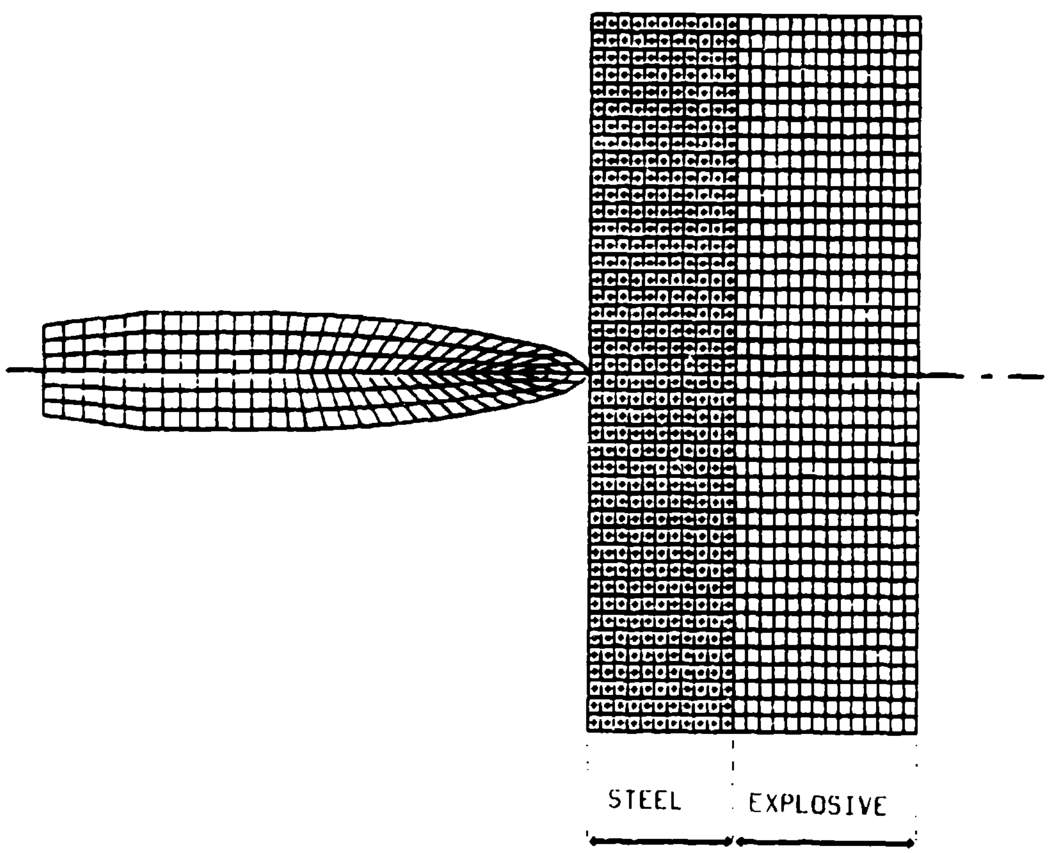
3.4. Conclusion.

This study has led to the realisation of a reactive scenario and we have tried to demonstrate its validity.

We could also develop a first practical model of prediction.

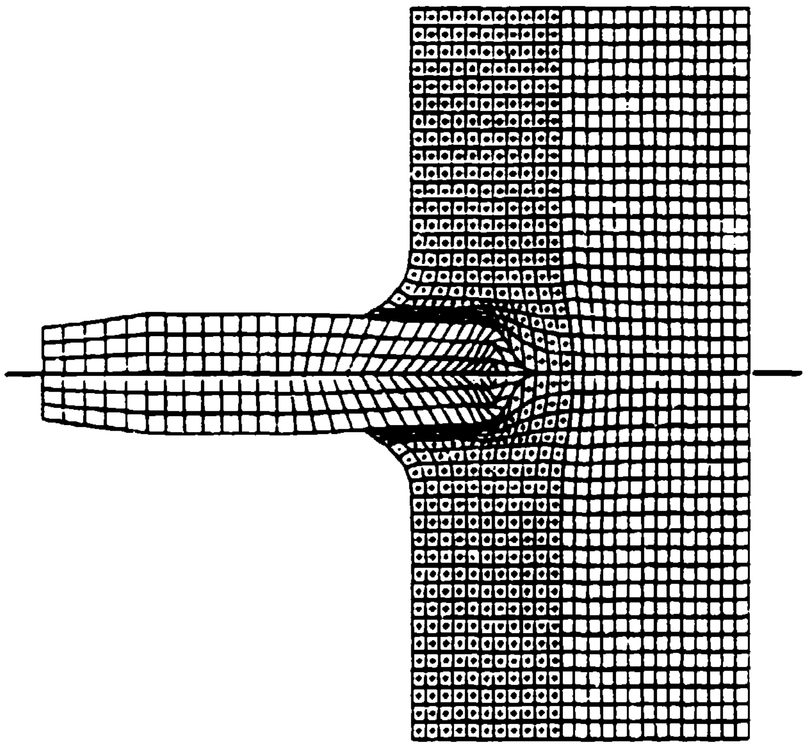
Nevertheless, a considerable work remains to do in order to polish our reactive scenario, to broaden its field of application and to study the directions of research that we can foresee to improve the formulations as regards the stress from the bullet.

- FIGURE 1 -



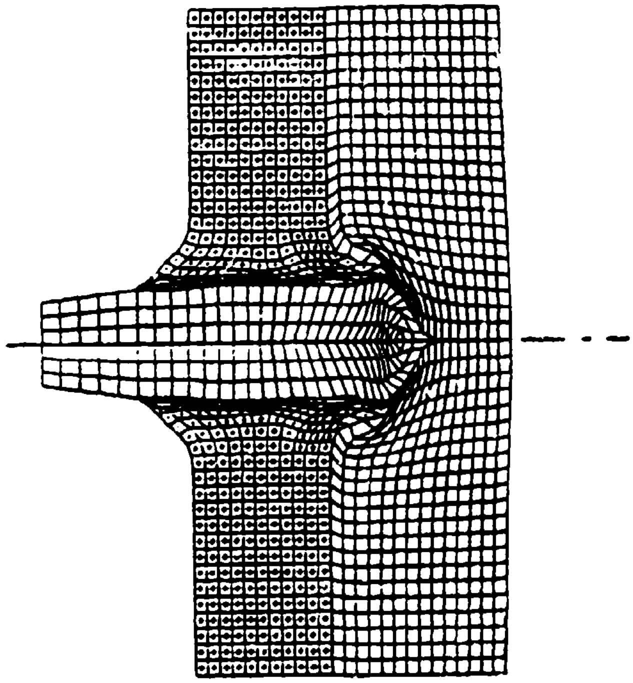
- FIGURE 2 -

PARTIAL VIEW OF THE MESHING AT T = 25 μs



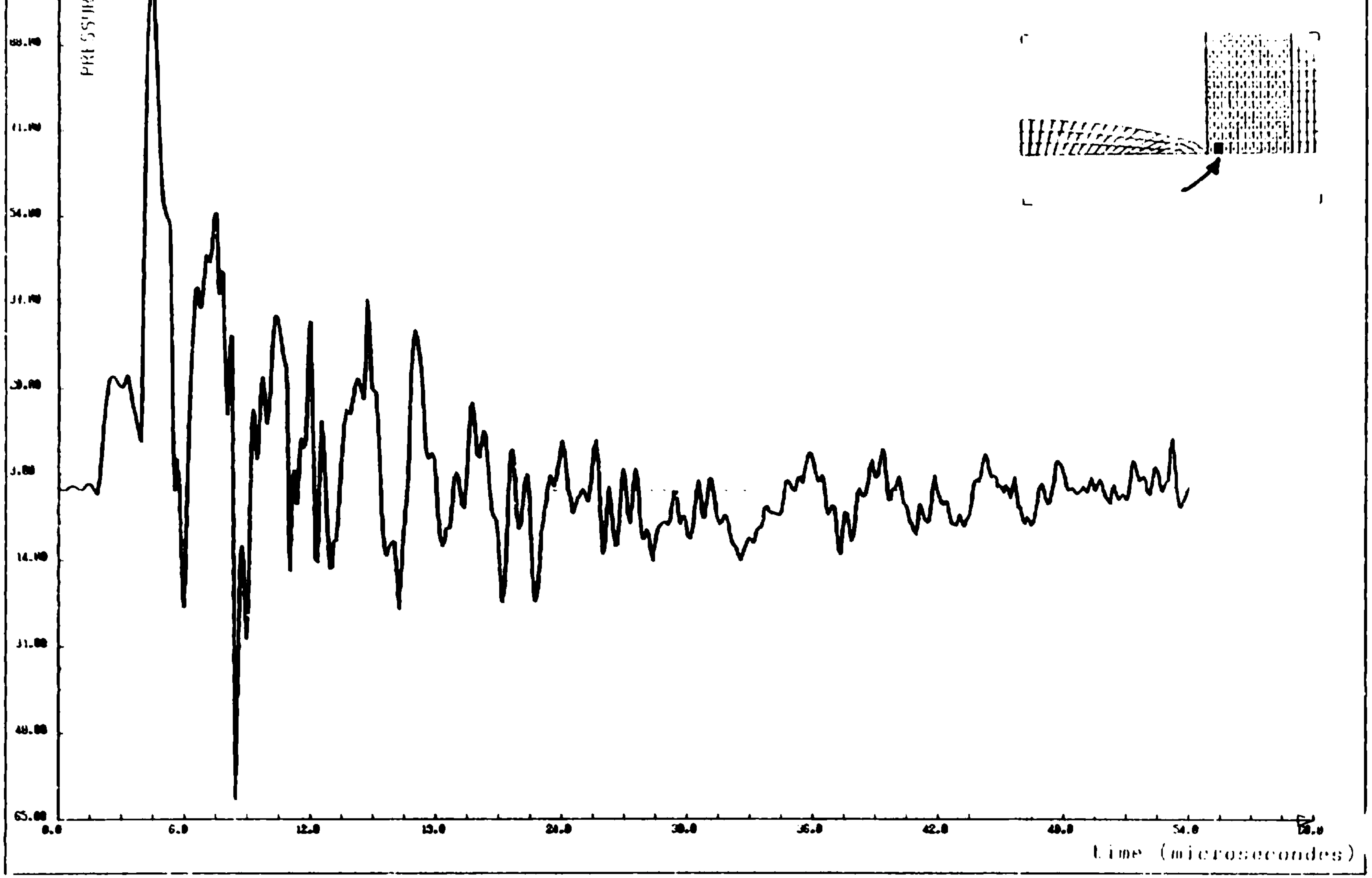
- FIGURE 3 -

PARTIAL VIEW OF THE MESHING : T = 54 μs



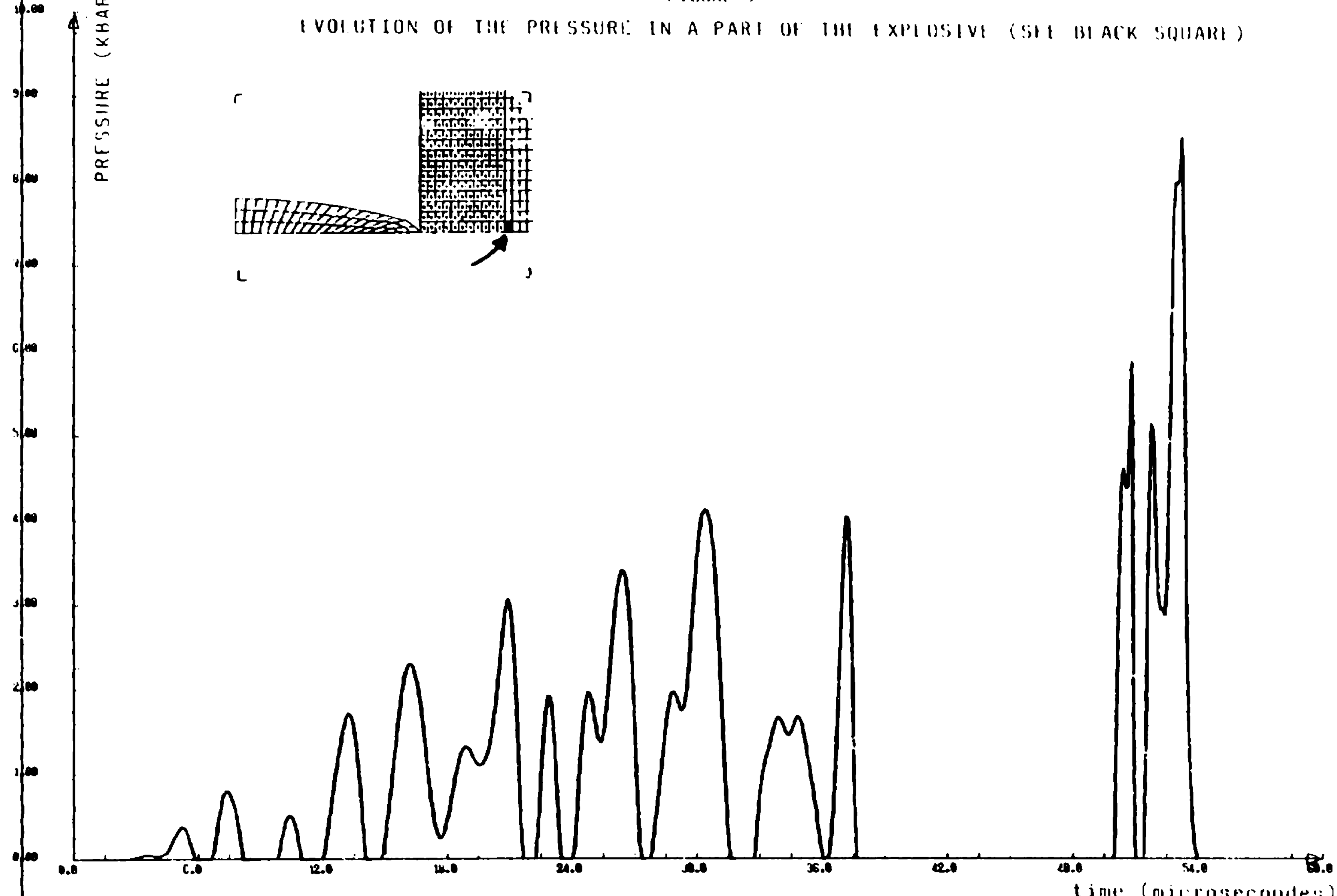
- FIGURE 4 -

EVOLUTION OF THE PRESSURE IN THE MESH MARKED BY THE BLACK SQUARE



- FIGURE 5 -

EVOLUTION OF THE PRESSURE IN A PART OF THE EXPLOSIVE (SEE BLACK SQUARE)



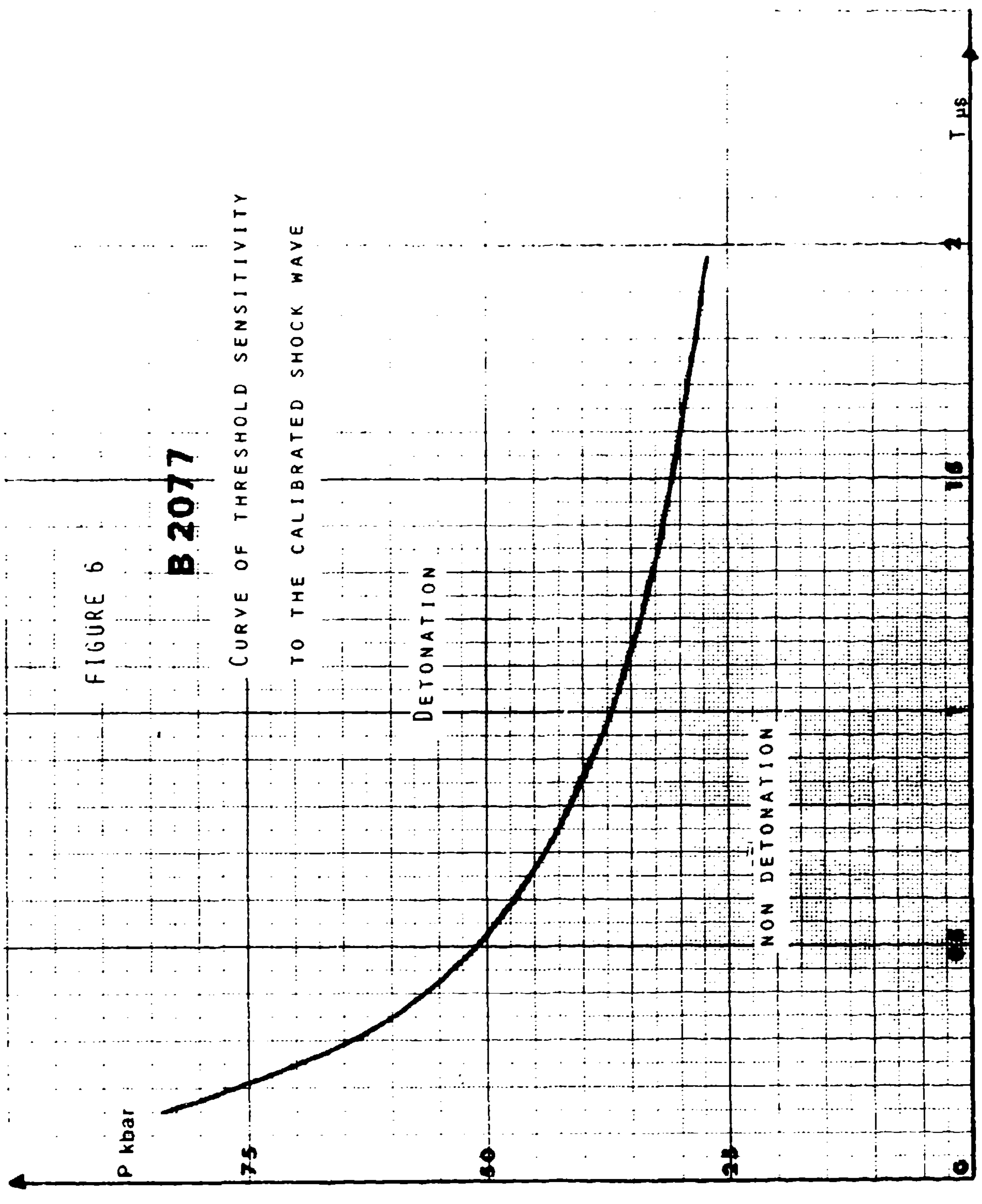


FIGURE 6
B 2077
CURVE OF THRESHOLD SENSITIVITY
TO THE CALIBRATED SHOCK WAVE
DETONATION
NON DETONATION
P kbar
75
T µs
1
2

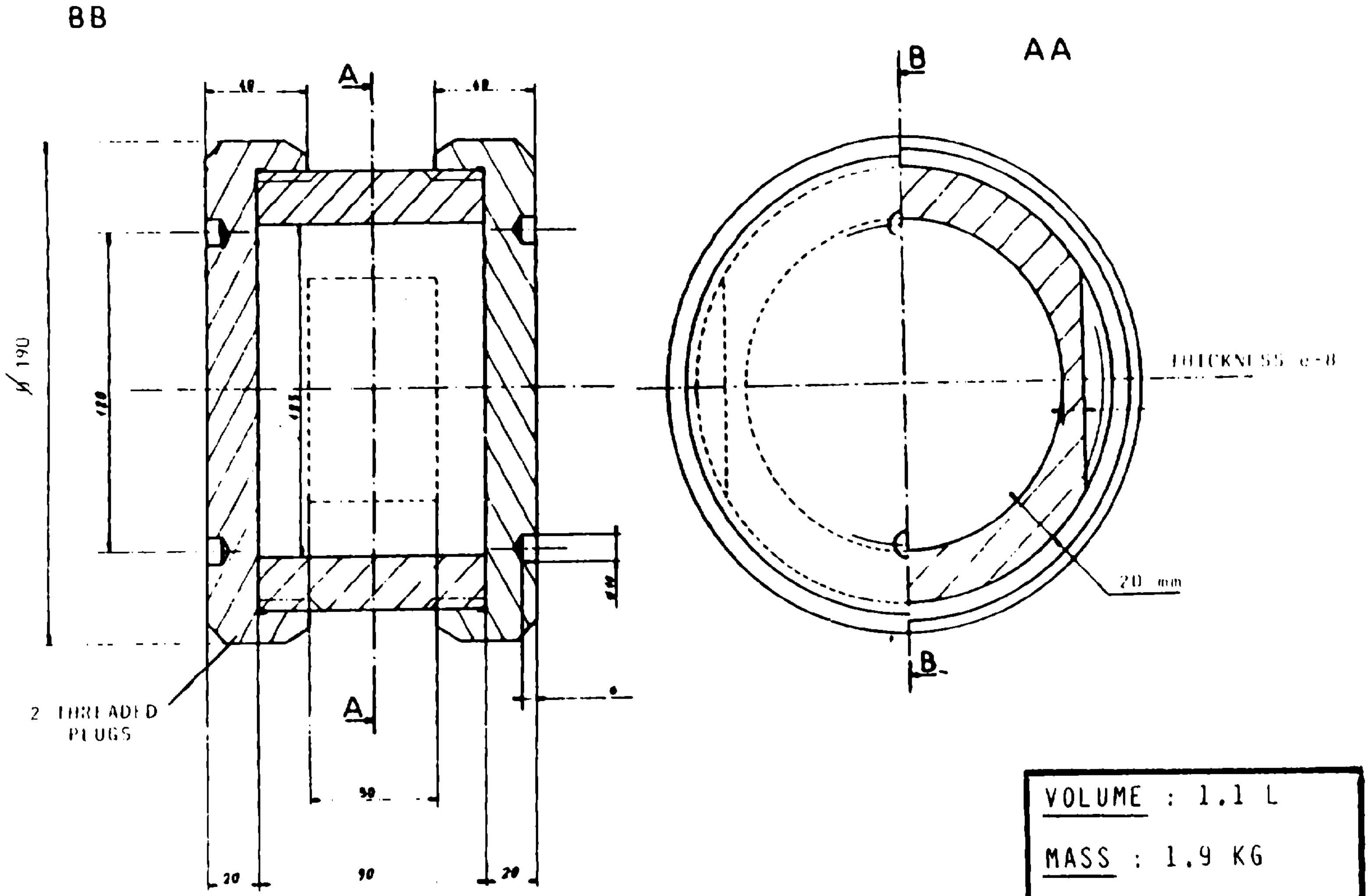


FIGURE 7

VOLUME : 1.1 L

MASS : 1.9 KG

STATIC BURSTING

PRESSURE : 130 MPA

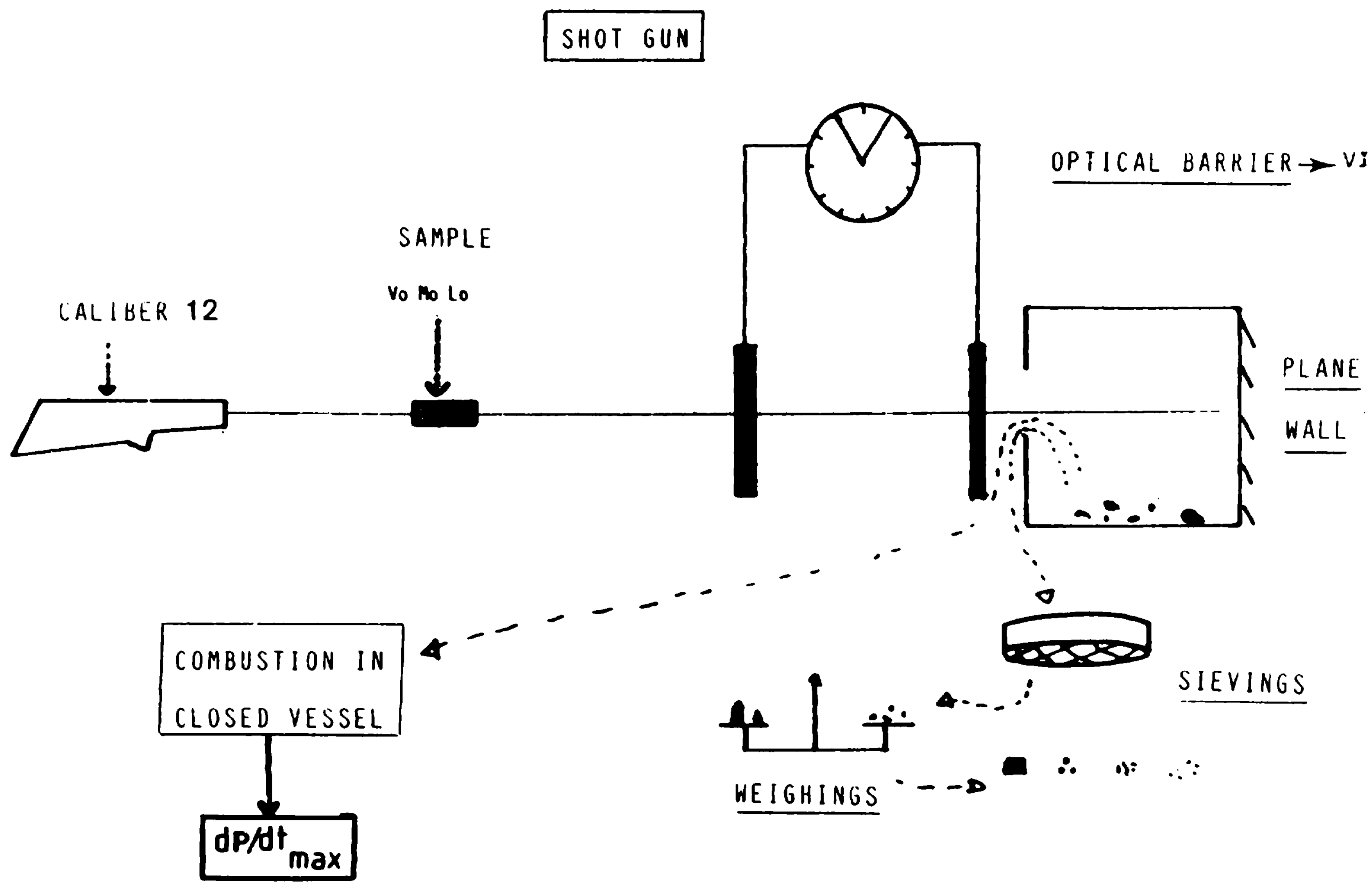

SHOT GUN
OPTICAL BARRIER → VI
SAMPLE
Vo Mo Lo
CALIBER 12
PLANE
WALL
COMBUSTION IN
CLOSED VESSEL
dP/dt max
SIEVINGS
WEIGHINGS

FIGURE 8

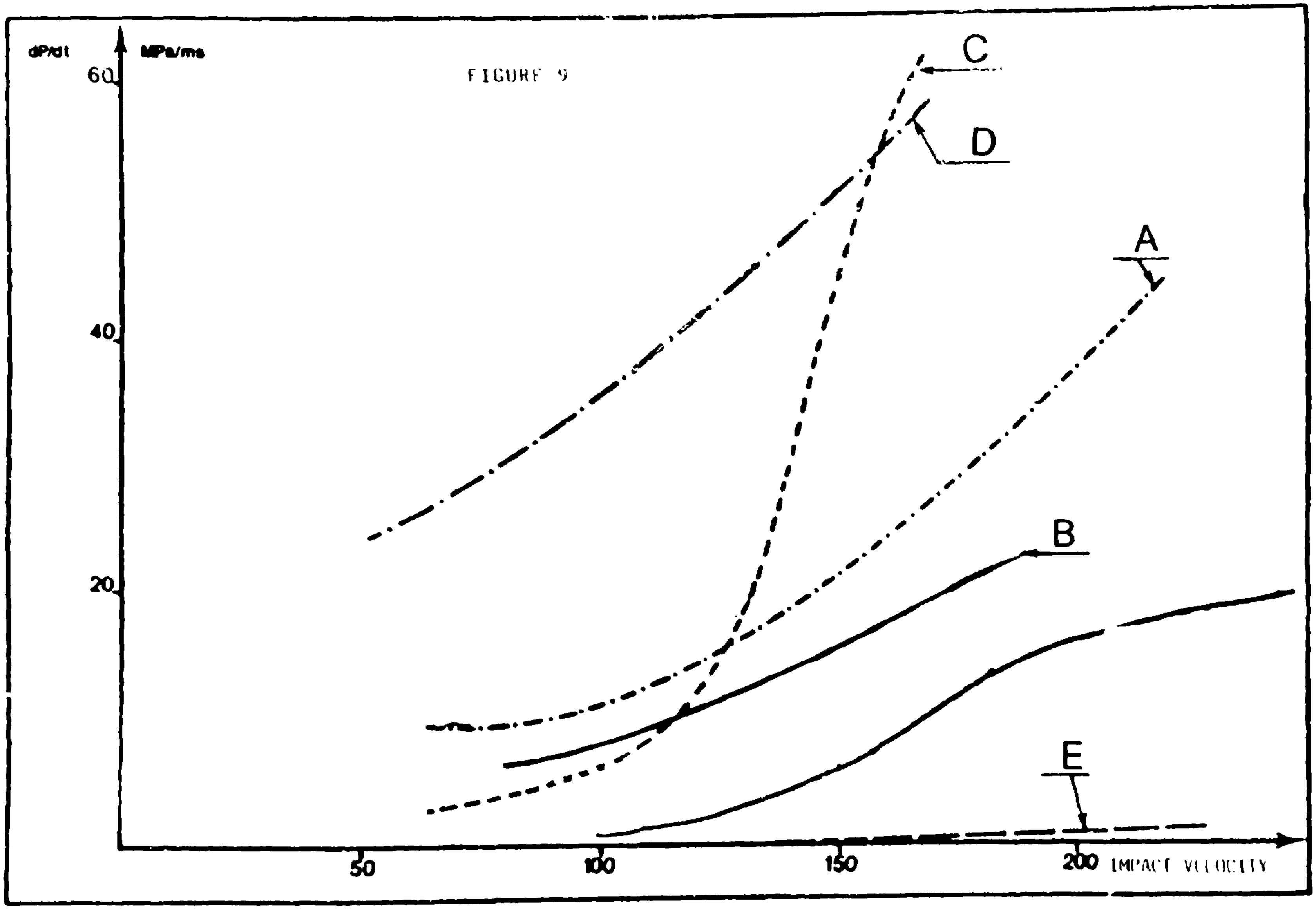
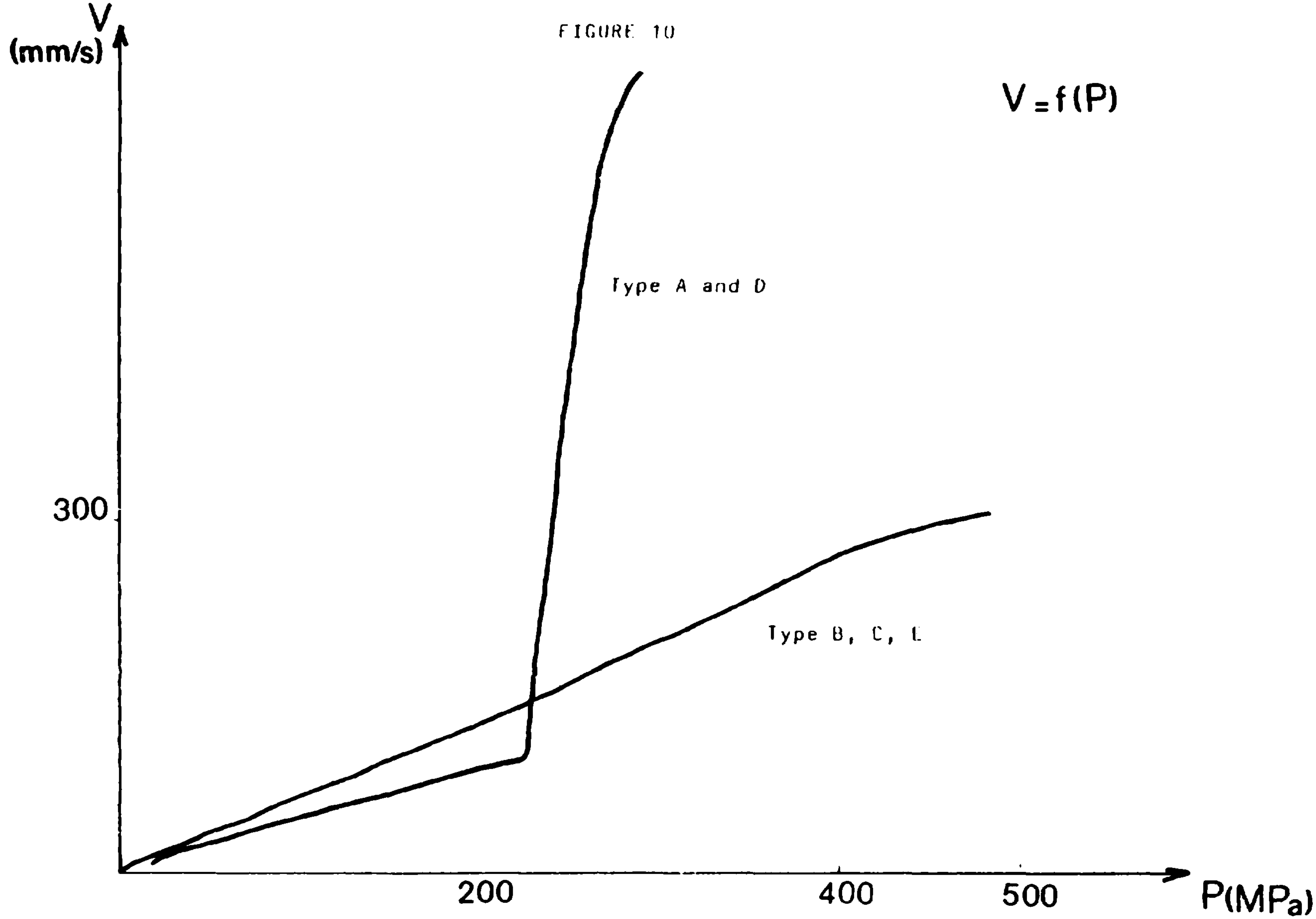
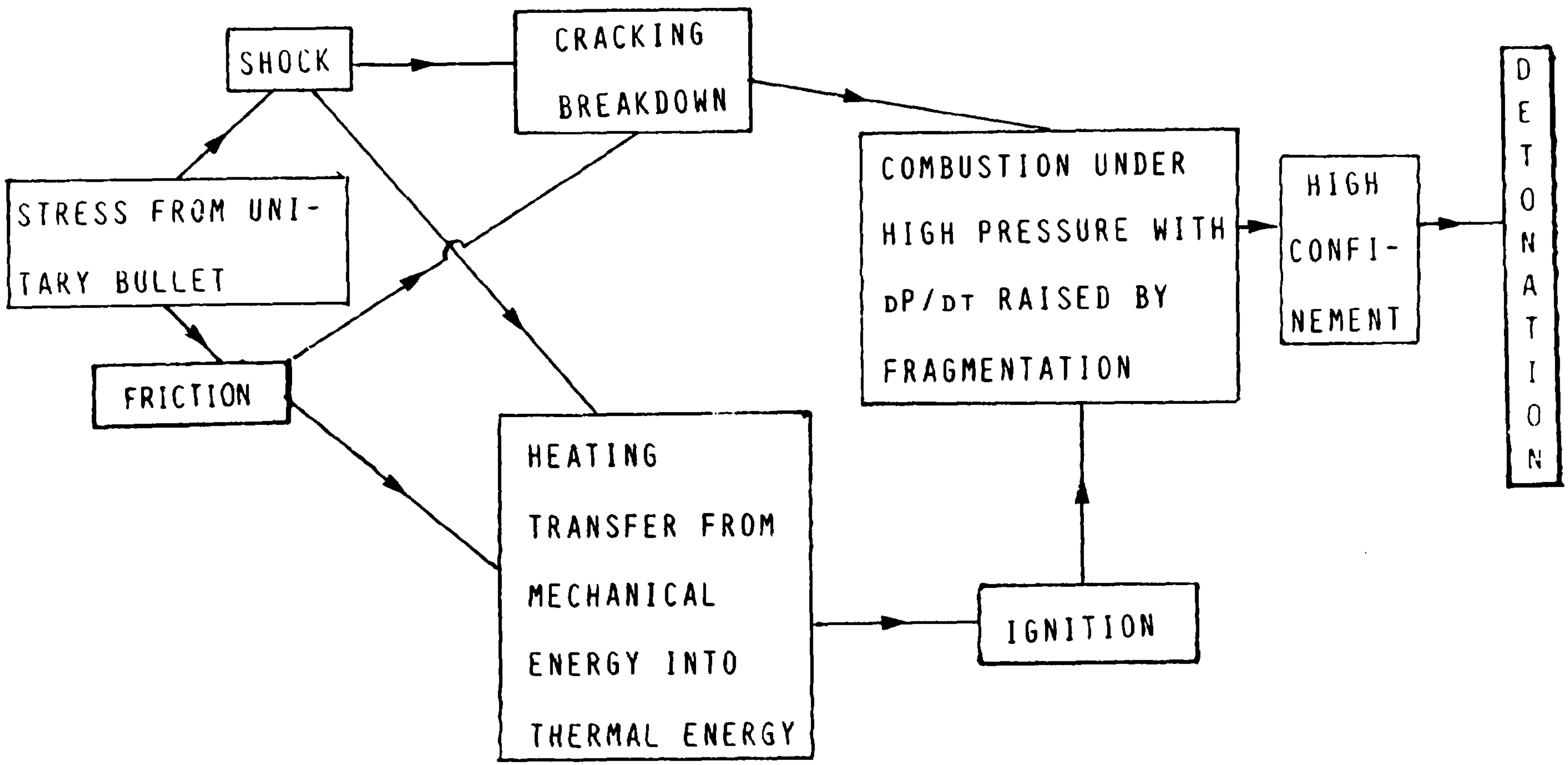


FIGURE 9

FIGURE 10



REACTIVE SCENARIO



EXPERIMENTS NETWORK Test n°82-01/01	PROJECTION OF A FREE BLOCK ON A PLANE WALL	SNPE/CRB Service TB January 1983

FAMILY OF THE MATERIALS : PBXs.

PRINCIPLE.

A sample of explosive, in the form of a small cylinder, is thrown on a steel (plane) wall.

The degree of fragmentation of the material or, as the case may be, the type of reaction from the moment of the impact, is observed according to the velocity of projection of the cylinder.

THE ESSENTIAL POINTS OF THE TEST.

The cylinders of explosive are 18 mm in diameter; their length is adjusted when manufactured so that a mass of 9 grams is obtained.

The test cylinder is placed at the front of a cartridge charged in order to obtain the value of the desired impact velocity.

For a given material and for a conditioning temperature, various samples are thrown in order to have :
a) either the velocity under which there is no pyrotechnic occurence (confirmed by 3 negative tests)
b) or the evolution of the decohesion.

The characterization of the decohesion level can be made either with the codified test n°49 "combustion of fragments in closed vessel" or with a granulometric analysis of the collected fragments.

CODIFIED RESULTS.

Reference of the PBX	Temperature of the sample in C°	Impact velocity of pyrotechnic non-reaction	Type of reaction observed at higher velocity	Reference of the test sheet

SHORT TITLE OF THE TEST : IMPACT ON A PLANE WALL.

EXPERIMENTS NETWORK Test n°49-01/01	COMBUSTION OF FRAGMENTS IN CLOSED VESSEL	SNPE/CRB Service TB January 1983

FAMILY OF THE MATERIALS : PBXs.

PRINCIPLE.

A certain amount of PBX in a fragmented form is burnt in a pressure resistant vessel, of constant volume.

The evolution of the pressure inside the vessel according to the time is recorded. The maximal value of dP/dt is researched.

THE ESSENTIAL POINTS OF THE TEST.

The vessel has a volume of 90 cm3 and is used at a density of charge of : $\Delta = 0,1$ g/cm3.

The ignition is made with a hot wire and a relay bag of black powder of 0,5 g.

The recording of the pressure is obtained with a piezo electric sensor and an associated numerical recording chain. P = f (t) and dP/dt = f (P/Pmax) is recorded as well as ti (time taken by the pressure to go from 0 to 30 bar) ans tc (time taken by the pressure to go from 30 bar to Pmax).

CODIFIED RESULTS.

Reference of the PBX	Method for obtaining the product	Temperature of the sample before the impact if necessary	$\frac{dP}{dt}$ max	Reference of the test sheet.

SHORT TITLE OF THE TEST : COMBUSTION IN CLOSED VESSEL.

THE UNITED NATIONS MANUAL OF TESTS FOR CLASSIFICATION OF EXPLOSIVES

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SUMMARY

1. The United Nations Committee of Experts on the Transport of Dangerous Goods has prescribed a regime of test methods in chapter 4 of its recommendations on the transport of dangerous goods, commonly known as "The Orange Book". The UN Group of Experts on Explosives has just completed a manual of tests which will enable national competent authorities to harmonize their techniques and criteria for acceptance of explosives into Class 1 and the assignment of explosives to appropriate hazard divisions, thereby promoting the international recognition of one another's classifications. The paper describes the test manual in broad terms, the difficulties in harmonizing test methods and the future programme of work by the UN in this field.

INTRODUCTION

2. There are a number of organisations in the world today which are concerned with the reduction and eventual elimination of technical barriers to trade. The United States Inter-state Commerce Commission played an important part in the development of uniform classifications of explosives. The UN Economic and Social Council, which is the organisation behind the Committee of Experts on the Transport of Dangerous Goods, produced recommendations many years ago to serve as a general framework t which national and international regulations could be adapted. It is expected that barriers to trade will diminish as the numerous regulations concerned with the transport of explosives become more uniform in respect of the classification codes used, the marking and labelling of packages, the shipping documentation and the placarding of transport units.

3. In March 1967 the Group of Experts on Explosives first introduced the concept of an explosion test in its recommendations. It introduced what is commonly known as the bonfire test to determine the reaction of an explosive article or a package of explosives in the sort of fire which could occur in transport. The criterion was whether or not mass explosion occurred. Since then a whole regime of tests has been developed and is now set out in chapter 4 of the Orange Book. A flow chart has been developed to indicate the inter-relationship of the various tests and the criteria. This is shown in the accompanying 2 figures. Basically there are two parts to the testing regime. The first is a procedure for acceptance into Class 1; the second is a procedure for assignment of an appropriate hazard division for those products which are accepted into Class 1. It is important to note that it is possible for a substance which is provisionally accepted into Class 1 to be excluded from the class after completion of the tests for assignment of hazard division.

A PLETHORA OF TESTS

4. The testing of explosives is a topic which has been under lively consideration for over a century. A measure of the lack of agreement is given in the Encyclopaedia of Explosives and Related Items where no less than 43 heat tests are listed. In such a plethora of methods, each with its dedicated protagonists, it is difficult to pick one's way. Some participants in this seminar may have been involved in the development of a manual of sensitiveness tests by a Technical Cooperation Programme in 1966. Many participants will be familiar with the Department of Defense Explosives Hazards Classification Procedures (TB700 - 2).

5. Against this background it is not surprising that the UN Group of Experts on Explosives has taken 6 years to secure an international consensus for its first edition of a manual of test methods to be used in conjunction with the Orange Book. At this stage it has not been possible to secure international recognition for one definitive test method for each type of test. For each test series (numbered 1 to 6) there are one or more

parameters or characteristics of the explosive product which are to be determined. A short list of suitable test methods or test types is given for each parameter or characteristic. It is hoped that after a period of perhaps 5 years it will be possible for nations to converge on a small number of definitive test methods, in the light of practical experience with one and another's preferred tests.

A TESTING REGIME - MASTER OR SERVANT?

6. For several decades the UN has classified dangerous substances and articles for transport on the basis of a consensus in the Committee taking due cognizance of test data submitted with each application for classification. On occasion, certain inconsistencies have been apparent. This has led to requests to develop precise definitions and criteria for the 9 classes and various divisions into which dangerous goods are classified. In turn this has led to requests for definitive test methods associated with the criteria.

7. The UN Group of Experts on Explosives has always emphasised that its recommendations for classification of explosives represent a corporate judgement, fully informed by - but not dictated by - test data. However tidy and satisfying to the scientific mind it may be to construct flow charts and specify test criteria, there will always be anomalous results. For this reason the experts have always stressed that "the assessment must be carried out at an adequately equipped explosives laboratory by trained scientists under the direction of an experienced explosives expert who must have discretion to vary the details of the tests where he considers this necessary in the interests of obtaining a reliable assessment". This doctrine is particularly important when it comes to the possibility of excluding from Class 1 a substance which exhibits some explosive properties but is not manufactured with a view to producing a practical effect by explosion. It is essential therefore that the manual of test methods and the flow chart which guides national competent authorities in the assessment of potentially explosive products should be regarded as a useful guide or

tool, and should not be followed slavishly. The manual is the servant not the master of the classifying authority.

RECENT DIFFICULTIES AND FUTURE PROGRAMME OF WORK

8. Adoption of an international system of classification has not solved all the problems at a stroke. Indeed,it has served to highlight certain inconsistencies between nations which hitherto remained latent. Mr Duckworth of the UK Explosives Inspectorate will shortly describe some of the practical problems encountered by his Inspectorate. Dr Connor of UK Ministry of Defence will suggest that slavish adherence to the manual of tests and the flow chart may result in unrealistic classifications of certain military explosives. He will offer some suggestions for further development of the UN scheme so as to achieve more realistic classifications for some types of explosive substances.

9. The UN Group of Experts on Explosives is very conscious of the controversial nature of some of its classifications in the past. Some of the participants at this seminar will be aware that industrial nitrocellulose, used in the manufacture of paints and lacquers, is classified as an explosive in some countries but as a flammable solid in other countries. This is basically a commercial or political decision taken in full awareness of the test results on this substance. Therefore argument over test criteria is unlikely to alter the policy decision as to whether or not it is 'safe' to permit industrial nitrocellulose to be conveyed as a flammable material rather than a material of Class 1.

10. Division 1.5 was developed to cater for blasting agents such as NCN, certain slurry explosives which are not cap-sensitive, and certain emulsion explosives. Consideration is now being given to the extension of this division to cater for articles containing very insensitive explosive substances which are nevertheless capable of mass explosion. This requires the development of an associated set of test methods and test criteria

together with an appropriate modification to the flow chart procedure for assignment of the hazard division.

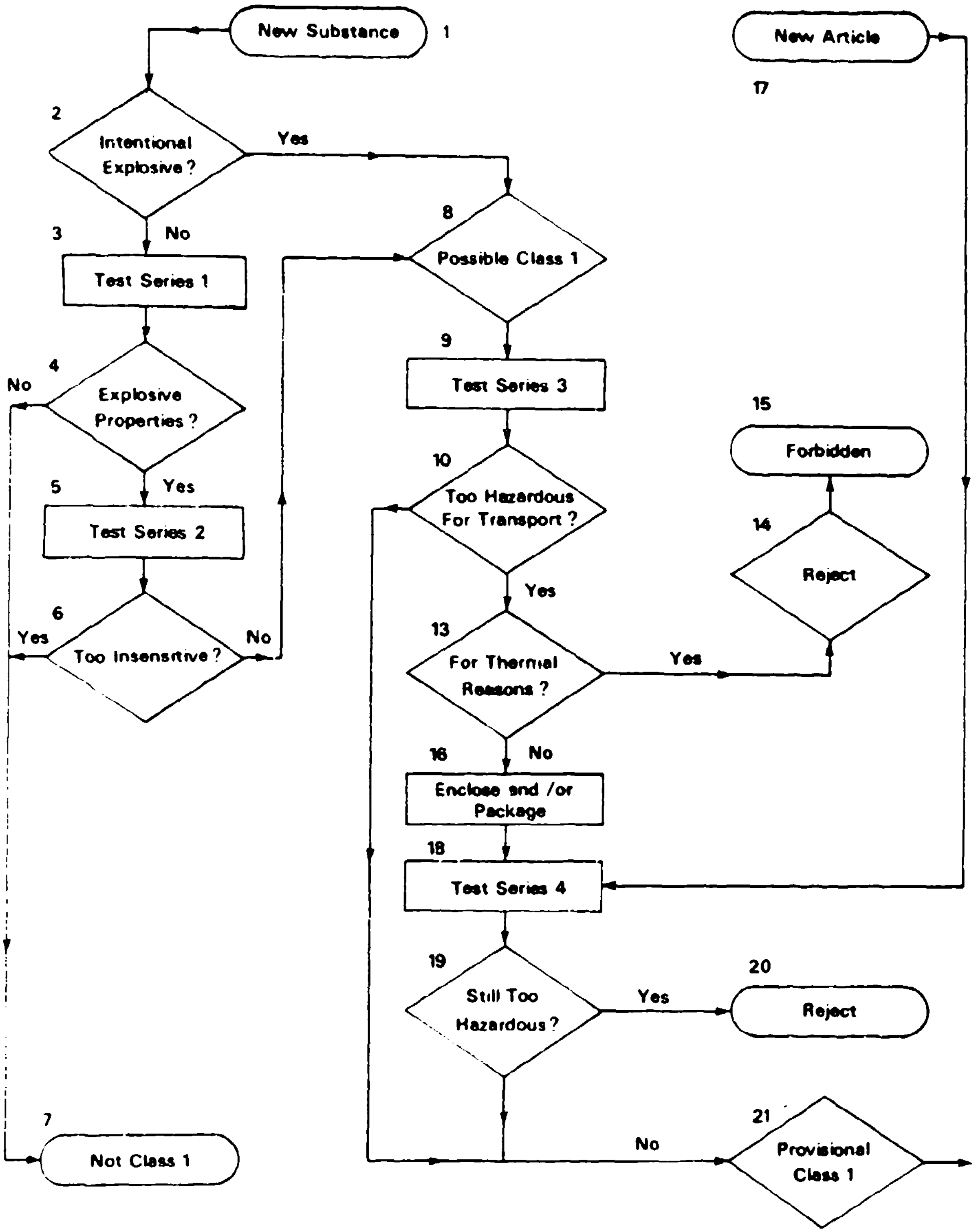
11. Another field which requires further work in the future by the Group of Experts on Explosives concerns the assessment of small explosive articles to determine whether or not they should be assigned to Division 1.4. The basic definition of Division 1.4, and particularly the associated Compatibility Group S, implies that an article classified as 1.4 (or 1.4 S) should be tested to ensure that it would present only a small hazard in the event of ignition or initiation during transport. It has been suggested that the existing tests in Series 6 do not give sufficiently explicit guidance on what type of stimulus to use during such testing. The classification of shaped charges, used in the North Sea oil rigs, which are alleged to be 1.4 S highlights the problem that different national competent authorities may interpret differently the test methods in the manual and the choice of stimulus for the tests in Series 6.

CONCLUSIONS

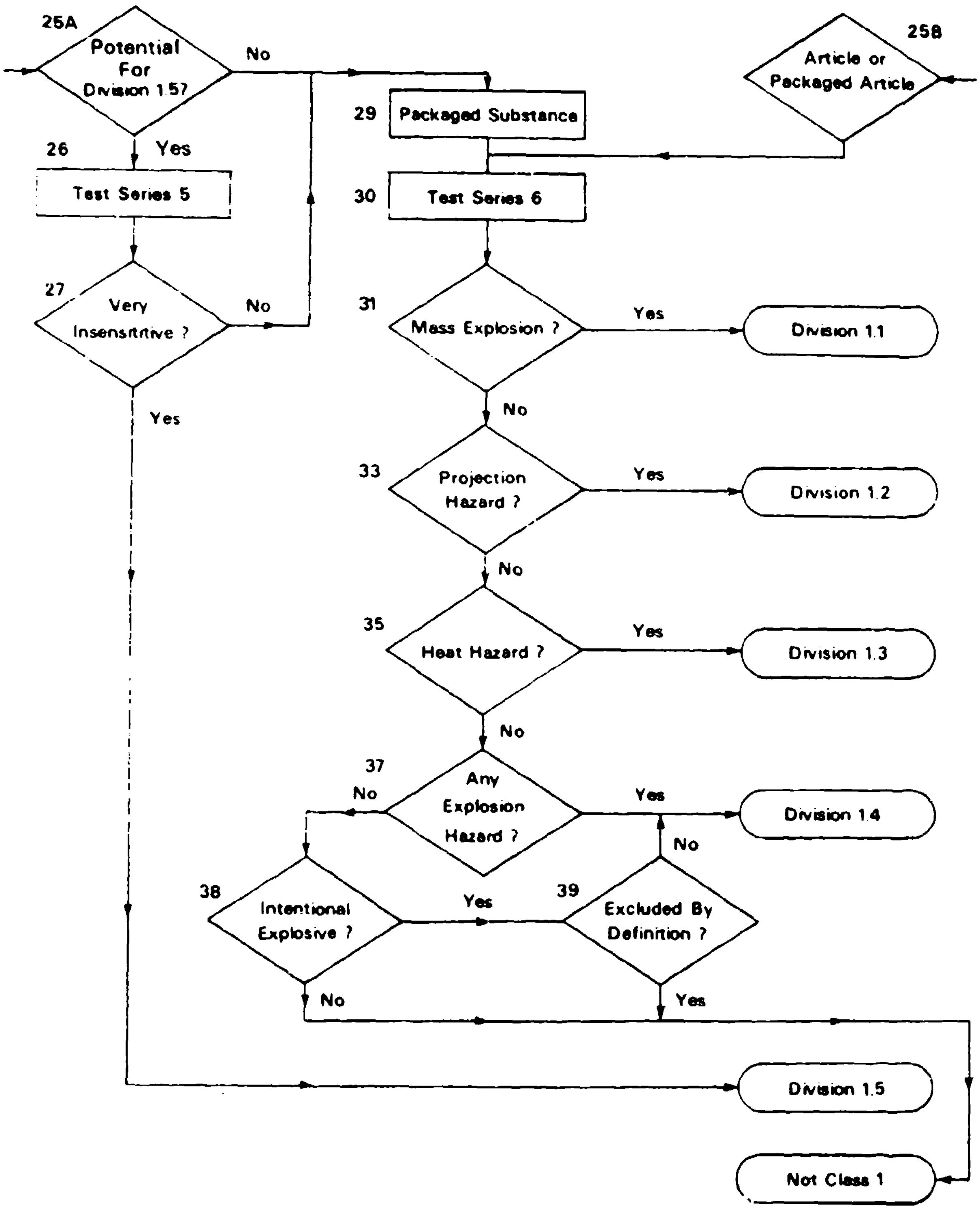
12. It is submitted that the publication of a manual of test methods by the United Nations will be a very significant step in the long-term strategy to harmonise international methods for classifying explosives. It will not solve all the problems at a stroke; indeed it will create some by highlighting latent discrepancies. Nations will be invited to use one or more of the recommended test methods in order to gain practical experience with them and to report their experience to the UN Group of Experts on Explosives in the years to come. In the light of this practical experience the Group of Experts will then be in a position to prune the test manual so as to converge on a small number of definitive test methods. Some of the test criteria for assessing results may also require refinement in the light of practical experience.

13. It is confidently expected that the United States Department of Defense and Industry will play an important role in this future work of the UN Group of Experts on Explosives. The communication of difficulties and apparent anomalies revealed during the practical application of the recommended tests is to be encouraged.

PROCEDURE FOR ACCEPTANCE INTO CLASS 1



PROCEDURE FOR ASSIGNMENT OF HAZARD DIVISION



TWENTY FIRST UNITED STATES DoD EXPLOSIVES SAFETY SEMINAR

CLASSIFICATION REQUIREMENTS FOR THE IMPORTATION OF EXPLOSIVES INTO THE UNITED KINGDOM

Author: A R Duckworth
United Kingdom
Health and Safety Executive

1 INTRODUCTION

All commercial explosives imported into the United Kingdom, other than gunpowder and safety ammunition, are required by legislation to have an importation licence. Applications for licences have grown considerably during recent years, particularly for articles used in oil operations in the North Sea. At the same time as this increase, there have also been changes internationally in the classification of explosives, with most countries adopting the United Nations system.

The UK authority has found it necessary on many occasions to question the classifications which have been claimed by the importers for products and often to change them. This has led to delays in processing the licences, and various other problems for the importers.

It is intended in this paper to present the UK position on the classification of commercial explosives, describe some of the problems encountered, and propose an approach for the international acceptance of explosives classified in other countries which the UK has recently adopted. The description commercial explosives in this paper refers to all types other than military explosives under the control of the Ministry of Defence.

2 CLASSIFICATION OF EXPLOSIVES IN THE UK

Recently the Classification and Labelling of Explosives Regulations 1983 came into operation in the UK, which require explosives to be classified by the UN scheme - although a transition period (of 5 years) to allow the phasing out of the Explosives Act 1875 scheme is included in the Regulations.

The assignment of a hazard division to many explosives can be relatively straightforward. It can be assessed by, for example, correlation with other explosives previously tested, or generally known performance, without the need for carrying out the UN Class 1, Series 6 test scheme. Quite clearly to apply this test series to all explosives before assigning a hazard division would be enormously time consuming and expensive.

There are, however, a number of articles and substances in the UN Class 1 list which have more than one possible serial number and hazard division which could be allocated to them. The UK authorities' view is that in these circumstances the items ought to be placed in the highest risk hazard division applicable unless proven by tests, or valid analogy with previous data, to warrant a lower risk hazard division. For example, blasting caps (detonators) electric would be considered to be UN No 0030 1.1B not UN No 0255 1.4B unless tests proved otherwise.

The tests to be carried out are those described in the UN "Orange Book", Transport of Dangerous Goods 1984 for Class 1 articles and substances. The general descriptions of the types of tests to be carried out on packaged items have been known for several years, and the UN Group of Experts recently agreed to the acceptance of a test manual for explosives in Geneva, 6-10 August 1984.

In the UK all explosives imported, manufactured and distributed are required to be authorised by the national competent authority - which for commercial explosives is HM Explosives Inspectorate within the Health and Safety Executive. It is realised that this may not be the case in other countries where individual companies may be allowed to classify explosives in accordance with their own interpretation of the UN classification system. Under this latter arrangement there is clearly an incentive for companies to select a lower risk classification particularly with the difficulties in transporting high risk explosives - for example, the International Civil Aviation Organisation (ICAO) forbids the transport of hazard division 1.1 explosives by passenger or cargo aircraft.

3 EXAMPLES OF PROBLEMS EXPERIENCED

Following the above comments, three examples are quoted to illustrate differences of opinion that have arisen recently between ourselves and manufacturers or other national competent authorities on the subject of the classification of explosives.

3.1 Explosives for oil-well operations:

Many importation requests in the last year have claimed classifications of 1.4D or 1.4S for such items as shaped charges, detonators and detonating cord.

These articles would in the UK view be expected to be placed in the highest risk hazard division (1.1) until proven by tests to be otherwise. The UK Inspectors of Explosives followed the practice of re-classifying them as 1.1 until supporting evidence from UN Series 6 tests proved that they merited the lower risk hazard division claimed. This practice inevitably led to difficulties for importers because of restrictions on the handling of hazard division 1.1 explosives at airports and on both passenger and cargo aircraft.

When information has been supplied by the manufacturers invariably it has been based on tests that did not comply with the requirements of UN Series 6. The possibility of shaped charges being accorded a 1.4S classification depends largely on the method of initiation used. If it is in accordance with the mode in which the articles are meant to function (ie by initiation using a detonator) as decided by the UN Group of Experts in Geneva in September 1983, then it is difficult to imagine how shaped charges could satisfy the criteria required for a 1.4S classification. The UK opinion is that the means of initiation ought to be that which the articles would be likely to encounter during transportation (credible accident stimulus) and that a suitable preliminary impact test could be used to determine whether an igniter as opposed to a detonator or detonative stimulus should be applied.

3.2 Classification of Propellant:

Smokeless propellant powders are normally classified in the UK as being of hazard division 1.1 unless proved otherwise. This led to problems for one particular importer of French propellant. The port he wished to use to import the propellant had been assessed for explosive limits and a relatively low limit of 1100 Kg was set for 1.1 substances and articles.

The importer requested that the propellant be re-classified as 1.3 and supplied data of tests carried out by the manufacturers to support his application. Again the original tests, whilst following the UN Series 6 in some respects, did not comply with all the UN stack test or single package test requirements. These latter tests are considered by ourselves to be particularly important since when assessing the behaviour of propellants the degree of confinement is very significant.

As a result, the propellant was re-tested in France in accordance with the UN Series 6 tests that were current at the time. The propellant is transported in fibreboard drums and it was considered that the confinement used could be provided by the drums used in transport filled with dry earth. The results of the tests were that the propellant deflagrated and could be re-classified as hazard division 1.3. An illustration of the drums after the tests is shown in Figure 1.

In a further single package test carried out in the UK, using a greater confinement of 0.5 metre of sand bags around the drum, a detonation occurred on the second test. This is illustrated in Figures 2 and 3. The methods to be used for confining packages are still under discussion with the UN Group of Experts but the UK view is that it is reasonable to confine packages by similar packages as would be expected to occur during transport.

3.3 <u>Classification of Practice Grenades and Line Throwing Rockets</u>:

For every UN serial number there is both a proper shipping name for the article or substances and a classification code (hazard division and compatibility group). In the opinion of the UK authorities the most important consideration when allocating a UN classification is that the correct hazard division and compatibility group are given.

In 1979 a UK manufacturer applied for re-classification of their practice grenades and line throwing rockets from hazard division 1.3 to 1.4. After tests were carried out it was considered that these articles merited the 1.4G classification. It was discovered, however, that there was no UN number of either articles corresponding to 1.4G. To obtain a new UN number takes considerable time and therefore the articles were given a UN number for 'Fireworks Type D' which have a hazard division of 1.4. The UN number for 'Articles Pyrotechnic 1.4G' was not in existence at the time and it was considered reasonable by the UK authorities to allow a slightly different description which gave the correct hazard division and compatibility group. The articles were, however, labelled on the packages as training grenades and line throwing rockets not as manufactured 'Fireworks'.

Recently, during the export of these articles from the UK through the Netherlands, the Dutch authorities during an inspection examination, expressed serious concern over the placing of them in a UN number which gave the incorrect title for them. In their opinion, articles must be placed in a number which gives the correct title and the hazard division follows from that. The UK has now submitted an application to the UN for a new number for both items which will have a classification of 1.4G. However, it is the UK view that the UN hazard classification takes precedence over the UN number and we are putting a case to the UN on this basis.

4 ACCEPTANCE OF THE CLASSIFICATION OF IMPORTED EXPLOSIVES

Following recent experiences, some of which have been described above, the UK has decided on a procedure which will allow goods classified by foreign national competent authorities to be imported without undue delay.

The system is that in cases of doubt on the classification of products to be imported, when importers claim a lower risk than would normally be accorded by the UK authorities, the claim will only be accepted and the lower risk classification granted when the importer supplies either reports of the UN tests carried out by an independent testing authority to prove his claim, or the approval of those products to be the lower risk classification by the national competent authority in the country of manufacture. The products referred to will have to be the specific named ones requested for importation as packaged not just a reference to a general acceptance of, for example, "Charges, Shaped, Commercial, UN No 0441 1.4S" as has occurred in some instances.

The UK will normally accept in good faith the classifications given by other authorities. It may, however, wish to make contact with the approving authority in certain instances to obtain more details of the evidence on which the approval was given, and in cases of disagreement reserves the right to require the classification for importation to be that which the UK considers to be correct.

It is hoped that a reciprocal approach to the classification of imported explosives will be taken by other countries. If all national competent authorities take the same approach to classification tests and base them on the UN Test Series 6 methods then in time, it should remove many of the problems so far experienced.

By presenting this paper at this international seminar it is further hoped that manufacturers will be aware of the UK system of approach and therefore be able to anticipate problems and prevent them from arising.

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FIGURE 3 - CRATER PRODUCED AFTER IGNITION
OF DRUM SHOWN IN FIGURE 2

Classification of Energetic Materials for Transport

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Summary

The United Nations recommendations on the Transport of Dangerous Goods give guidelines for the procedures to be followed in order to determine whether materials should be classified as explosives and, if they should, to which hazard division they should be assigned. This report details studies of two materials, a demolition explosive and an energetic plasticiser, designed to determine their hazard classifications. Comments are made on the UN scheme and on its interpretation.

1 INTRODUCTION

The UN Recommendations on the Transport of Dangerous Goods give guidelines for the procedures to be followed to determine whether materials should be classified as explosives and, if they should, to which hazard division they should be assigned. Although intended primarily to cover hazards in transport, the UN classifications are also widely used to control storage and other aspects of the processing of energetic materials and munitions. Over-classification of energetic materials or munitions can, as a result, lead to very severe cost penalties due, for example, to storage restrictions over the lifetime of the substances and/or articles involved. Because of the expected long service life of military stores, this is a particular problem for defence agencies. On the other hand, under-classification is also to be avoided since this can lead to hazardous situations with potentially disastrous consequences.

This paper details studies of two materials, a demolition explosive and an energetic plasticiser, designed to determine their hazard classifications. In the light of the experience gained during this study, suggestions are made for the further development of the UN scheme so as to achieve more realistic classifications for some types of substances.

2 MATERIALS

Two materials were tested in these trials; K10, an energetic plasticiser, and PE4, an RDX based demolition explosive. K10 liquid, a eutectic mixture of 34.7% trinitroethylbenzene and 65.3% dinitro-ethylbenzene, is used to plasticise plastic bonded propellants and explosives. UK defence authorities provisionally assigned this material to UN hazard division 1.1. compatibility group D(HD1.1D) on the basis of its proposed applications. This assignment was generally felt to be extremely conservative, erring very much on the side of safety. While compositions containing K10 liquid were subjects for research only, the classification of K10 had few consequencies. However, as efforts to introduce such compositions into service have been made, the classification has become increasingly onerous since it severely restricts production batch sizes and quantities which can be stored. Our studies were carried out in an attempt to justify a relaxation of the classification which would lead to a substantial saving in production costs with no significant loss of safety.

PE4, a dough-like material consisting of 88% RDX in an inert grease matrix, is used as a demolition explosive. It is specifically designed to be cap sensitive but, because of the efficient grease coating, it displays low sensitiveness to mechanical impact and, because of its resistance to cracking and propagation of burning reactions, it also displays low explosiveness. It is currently assigned to HD1.1D and, as a consequence new UK regulations on transportation of explosives would have the effect of severely limiting quantities which could be carried in military vehicles, potentially causing a substantial disruption to the training of engineer units. Our trials were intended to investigate the realism of the 1.1D classification and to demonstrate that even if this classification were valid, PE4 could be regarded as a low hazard explosive and hence exempted from the most stringent application of the regulations.

3 UN TEST SERIES 1-4

3.1 K10 Liquid

Since K10 liquid is not manufactured with the intent of producing an explosive or pyrotechnic effect, it must be subjected to UN Test Series 1 and 2 to determine if it has explosive properties and is not so insensitive as to be removed from the explosives class. Series 3 tests may also be applied to determine that it is not too hazardous for transport.

Relevant test data are given in Table 1. Clearly K10 does possess some explosive properties, being, for example, more sensitive than nitromethane in the liquid impact test. However, it is extremely insensitive to detonative shock, failing to propagate detonation even at zero gap width in the Large Scale Gap Test. Arguably, K10 liquid could be removed from the explosives class on the basis of this data along but in view of the significance attached to this study, it was decided to proceed with the large scale tests which will be described below.

3.2 PE4

PE4 is manufactured with the intent of producing an explosive effect and is therefore a member of UN Class 1 by definition. As a result, no small scale testing is required for classification. However, small scale powder and charge hazard data is reproduced in Tables 2 and 3 since these data support the description of PE4 as a low hazard explosive.

Powder tests indicate a low level of sensitiveness, comparable to that of RDX/Wax compositions with similar nitramine contents, while the charge tests indicate low explosiveness. Of particular interest in this respect are the Susan and Spigot Intrusion test results which demonstrate that very severe mechanical impacts lead to little or no response. PE4 can be ignited only by mechanical shocks of sufficient intensity to cause prompt shock initiation of detonation and, in our view, such shocks are not attainable in any realistic transport accident scenario.

Small scale fuel fire tests have resulted in detonation of PE4. However, in this test the explosive is subjected to rapid heating to temperatures well above its ignition temperature while under heavy confinement. Every nitramine/TNT based explosive we have tested has given detonations in this test which we regard as being too severe to realistically reproduce hazards of substances during transport. The test does, of course, have direct relevance to hazards of explosive stores, particularly shell,and it is noteworthy that many PBXs give a very mild response in this test.

4 UN TEST SERIES 6

4.1 K10 Liquid

To carry out the tests of UN Series 6 and related trials, K10 liquid as supplied in 10 litre polyethylene bottles was overpacked in robust metal drums with plastic linings and spring clip fixed lids. Such a package provides substantial confinement and represents an overtest as compared to the normal transport container.

Preliminary tests showed that the liquid was not cap sensitive and, on this basis, classification could have been made on the basis of bonfire trials only. However, it was decided to investigate more fully the sensitiveness of K10 to detonative and ignition stimuli.

In two trials attempts were made to initiate K10 liquid from a 250g charge of PE4 suspended in the liquid and protected from it by polyethylene. In one trial there was no reaction and unburnt K10 liquid was scattered around the range. In the second trial a severe explosion occurred which, on the basis of blast pressure measurements, was judged to have been a detonation. It is concluded that the shock sensitivity of K10 liquid is very low and certainly insufficient to allow explosion of K10 as a result of mechanical shocks received in credible accident situations. However, K10 could explode if involved in an accident which brought other materials carried close to it to detonation.

Several attempts were made to ignite K10 liquid using igniters or igniter/ballistite charges but without success. Flame from a burning cordite train also failed to produce ignition. Ignition was finally achieved by removing the lid of the metal outer drum and scattering copious quantities of broken cordite inside the drum. The K10 burnt for $>$15 minutes with a flame ~1m in length, producing thick black smoke. Since reaction could not be propagated through K10 liquid from an igniter, no attempt was made to carry out stack tests to assess package to package propagation.

When K10 liquid was subjected to bonfire tests, packages were ignited after 10 to 15 minutes and burnt quietly. No drum lid was thrown more than 2 to 3m from the fire and most lids were in place and had simply buckled to allow venting. Other than from the amounts of thick black smoke produced, it was difficult to detect when K10 was burning.

4.2 PE4

PE4 is cap sensitive and, when tested according to the current UN prescriptions for the single package and stack tests 6a and 6b, detonation of the total explosive contents inevitably occurs. As a result, PE4 must, on the present recommendations, be assigned to HD1.1. However, in an attempt to demonstrate the low hazard of PE4 when subjected to less severe and more realistic stimuli, further tests were carried out.

The explosive was tested in two forms, either in 20lb packages containing 40x8oz sticks or in 25kg packages of bulk material. In both forms the material could be ignited from an igniter/ballistite charge but it burnt quietly over a period of 15 minutes even when heavily confined under 0.5m of sand. In view of this mild response no studies of package to package propagation of explosion were attempted.

Bonfire trials were carried out on 5x20lb packages and on 5x25kg packages. The explosive ignited after ~8 minutes and burnt steadily with little or no increase in the intensity of the fire. No explosive events were observed.

5 DISCUSSION

5.1 K10 Liquid

From the results presented here, K10 liquid is clearly not a member of UN Class 1. It is not manufactured with the intent of producting an explosive effect and, from the small scale tests of Series 1 and 2, it does not possess explosive properties such that it should nevertheless be included in Class 1. On this basis alone it could be excluded from the class. However, as further confirmation, the large scale tests of Series 6 have been carried. These indicate that in transport accident scenarios, K10 liquid would response in a very mild manner, scarcely distinguishable from an inert liquid.

As a result of these trials, we have recommended that K10 liquid be removed from Class 1. This has immediate practical and economic benefits. As a consequence of reclassification, K10 can be manufactured in increased batch sizes, improving production rates and releasing plant for other processes, storage in specialised facilities is no longer required and transport requirements are greatly simplified. There is no doubt that this is a case where the costs of carrying out large scale classification testing are trivial compared to the cost benefits of reclassification.

5.2 PE4

The case of PE4 is more complex than that of K10 liquid. As has been pointed out earlier, since PE4 is cap sensitive it must, under present UN prescriptions, fall into HD1.1. This follows from a recent addition to the UN scheme proposed by the US Department of Transport which specifies that the choice of an initiation or ignition stimulus in the Series 6 tests should be made on the basis of the intended use of the substance or article under test. Thus products intended to function by detonation should be tested using a standard deotnator while products intended to function by burning should be tested with an ignitor. However, the aim of the UN test procedures is to produce classifications based on realistic assessments of transport hazards. It is our view that the current method of determining whether an initiation or ignition stimulus should be employed in Series 6 is in conflict with this aim since it implies classification by end use rather than by hazard.

Test Series 6 is intended to reproduce the response of the product under test in realistic accident scenarios. Since secondary explosives are not transported in contact with detonators, the use of a detonator as initiation stimulus is credible only if accidental stimuli can lead directly to detonation. This is not the case with PE4 where even such a severe mechanical shock as projectile impact at velocities of 1200ms^{-1} on charges confined in steel cases leads only to a relatively mild reaction.

The use of a detonative stimulus in the Series 6 testing of secondary explosives can not only lead to over-classification of cap sensitive but low hazard substances but, perhaps more seriously, it can also lead to under-classification of non-cap sensitive explosives. Many secondary explosives are transported in powder or granular form. Such materials may be sufficiently insensitive to detonative shocks that they give no response in package and stack trials when initiated from a standard detonator. However, if ignited from a small propellant charge they may, under the confinement provided in these tests, burn to detonation. Such behaviour is unlikely to be observed in bonfire trials where the explosive is less severely confined. The end results may be that materials which could, in accident situations, burn to detonation will not be classified as members of HD1.1, giving a quite false and dangerous impression to emergency services.

Other problems follow from the present method of UN classification testing. It is not difficult to imagine secondary explosive and propellant compositions which are chemically and physically virtually identical but which receive quite different classifications because the former are tested with a detonator while the latter are tested with an igniter. The present situation is illogical and rationalisation is urgently required.

One way out of these difficulties would be to base the decision on the use of detonation or ignition stimulus on test data not on proposed end use of the product under test. If the product were subjected to a very severe mechanical stimulus such as that produced in a rifle bullet impact test, then the response to that stimulus could be employed as the determining factor and only if detonation were observed in the impact test would a detonative stimulus be employed in the package and stack tests.

If a detonative stimulus is employed in these tests and no explosion of total contents results then the debris from the test should be examined carefully to ensure that at least ignition of the product did occur but that reaction failed to propagate. If there is no evidence of ignition having occurred, which may well be the case with shock insensitive explosives, retesting with an ignition stimulus should be considered since the UN Series 6 tests are essentially tests of explosiveness, the response of the explosive to accidental stimuli, rather than sensitiveness, the probability of such a response occurring.

One further point should be made, if the UN scheme were to be changed in the way outlined above, the classification of PE4 would still cause some problems. Insensitive high explosives should fall in hazard division 1.5 but, because materials of 1.5 must be cap insensitive, PE4 does not qualify for this classification. However, test results with ignition stimuli and the bonfire tests would then support an assignment to HD1.4 which is less strictly controlled than HD1.5. It seems to me to be illogical that PE4 should be handled with fewer controls than is, for example, TATB, and it would suggest that the requirement for cap insensitivity be removed from the requirements for HD1.5 so that this classification could include all low hazard secondary explosives. Such a step would again be justified by the fact that the shock output from a detonator is not a credible accident stimulus and should not therefore be employed to determine hazard classifications.

6 CONCLUSIONS

6.1 K10 liquid should be removed from the UN explosives class since test results demonstrate such a classification to be unrealistically severe.

6.2 Under the present UN scheme, PE4 is correctly assigned to HD1.1D. However, PE4 is a low sensitiveness, low explosiveness material and this assignment is believed to be unnecessarily severe.

6.3 The choice of ignition or initiation stimulus in the package and stack tests of UN Series 6 should be based on a test of the product employing a severe mechanical shock such as bullet impact rather than on the proposed end use of the product.

6.4 The requirement for cap insensitivity should be removed from UN HD1.5 so as to allow the inclusion in that hazard division of low hazard but cap sensitive materials such as PE4.

TABLE 1 K10 Liquid: Small Scale Test Data

Test	Result
Liquid Impact Test	19cm (Nitroglycerine 4cm; (Nitromethane 80cm)
Mallet Friction Test	No ignitions
Temperature of Ignition	244°C
Ignition by Flash	Failed to ignite
Behaviour on Inflammation	Failed to ignite
Large Scale Gap Test	No reaction at zero gap
Chemical Stability	Satisfactory

TABLE 2 PE4 Powder Test Data

Test	Result
Rotter Impact	Figure of Insensitiveness = 140 (cf RDX=80, TNT=150)
Friction	No ignitions with wooden mallets on wood or stone anvils. No ignitions with steel mallets on steel, aluminium bronze or brass anvils.
Temperature of Ignition	218°C
Ignition by Flash	No ignition in five trials
Behaviour on Inflammation	Ignites, burns steadily
Ignition by Electrical Spark	No ignition at 4.5J

TABLE 3 PE4 Charge Test Data

Test	Result
RARDE Small Scale Burning Tube Test	2 fragments, 90% of explosive recovered
Small Scale Fuel Fire Test	Detonation
Large Scale Gap Test	50% gap = 45.9mm ρ = 1.58Mg m^{-3}
RARDE Fragment Attack Test	1265m s^{-1}, 20% of explosive consumed, septum detached
Spigot Intrusion Test 40m drop, 1.5mm air gap	No reaction
Susan Test	Response equivalent to 35g TNT at impact velocity of 300m s^{-1}.

CLASSIFICATION OF EXPLOSIVES IN ACCORDANCE WITH INTERNATIONAL SYSTEM

BY

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INTRODUCTION

1. The only justification for going to the considerable trouble of classifying explosive substances and articles is to minimise the deleterious effects should they be involved in an accident or fire. The International ('United Nations') scheme of classification of dangerous goods, places explosives in Class 1 and is solely concerned with transport. It is, however, widely agreed that the principles used in the scheme are generally applicable to the task of minimising the effects of an accident in storage etc.

2. The classification procedure recommended by the UN takes the form of a logical sequence of questions and specified physical tests. Test series 1 to 4 inclusive address the problem as to whether the substance or article is an 'explosive' (ie suitable for Class 1) and, if so, whether it is suitably safe for transport. (The term 'explosive' will be used to represent both substances and articles.) I shall assume that the substance or article is an 'explosive' and is not unduly sensitive or unstable. This, in fact, is the typical situation in the field of ammunition and military explosives where 'new' explosives are usually simply rearrangements of familiar explosive substances possibly using a slightly modified containment to produce a 'new' article. My understanding is that the situation in the field of civilian explosives is similar and is not confined to the United Kingdom. Excepting some types of military explosives where operational requirements call for protection, packaging is likely to differ more from previous traditional types, unfortunately from the view point of safety, too often in the direction of lighter, cheaper designs affording less protection against communication.

3. UN Test Series 5 addresses the question as to whether the substance is suitable for inclusion in Hazard Division 1.5 (or possible article, too, if the concept of HD 1.5 articles is accepted by UN). I propose to ignore the HD 1.5 problem for the present. Test Series 6 addresses the question as to whether Hazard Division 1, 2, 3 or 4 is appropriate. (It is now accepted practice to quote the UN Class number for explosives (i.e.1) in front of the hazard division number as in HD 1.1 etc in spite of its illogicality). The tests in Series 6 comprise the familiar confined stack detonation etc tests

and the bonfire tests. There seems to be no dispute that such tests on the packaged substance or article are relevant and that the results are useful to indicate the accidental mode of behaviour in determining the hazard division. The tests are, however, expensive, time consuming and usually require the use of large arenas in remote areas.

4. Where purpose designed explosive resistant buildings are planned, trials on scale model structures are often used successfully and modelling has been proposed for the classification testing of large rockets etc. Although concrete building models have been shown to effectively represent full scale structural behaviour, when submitted to scaled HE detonating charges, the response there under investigation is the comparatively straightforward deflection of inert structural elements. The susceptibility of a packaged explosive to communication of explosion is much more complex and, in my opinion, subject to a 'fail dangerous' effect as model dimensions are reduced.

5. Lists of classified explosives are published by many countries (the UK military explosives permanent list alone exceeds 2000 items at the present time) and rather more than 1 per cent of these classification decisions are based on a specific test series 6 investigation. It must be presumed that decisions as to the classifications of the others were based on analogies with substances or articles actually submitted to test series 6 or the logical assessment of physical parameters of the packaged explosive offered for classification. I do not anticipate that the proportion of individually tested items will significntly increase in the future and I therefore offer some thoughts on the principles involved in the assessment of explosives classification based on judgement.

PRINCIPLES FOR DECIDING THE HAZARD DIVISION CLASSIFICATION

6. If the explosive be assumed to have functioned accidentally, an assessment of the nature of the predominant effect on the surroundings allows Class 1 to be divided into Hazard Divisions (written HD 1.1, 1.2, 1.3 and 1.4) in descending order of effect.(Fig. 1) Although, when considering the classification of an explosive much attention is understandably given to possible mass explosion (HD1.1) behaviour, logically the initial question to be asked should be "Is the explosive suitable for HD 1.4"? This hazard division comprises explosives of 'no significant hazard' which I interpret as having an effect on the surroundings no more deleterious than that associated with common articles of commerce widely held to display an acceptable risk and hazard. If a fire occurs in a storehouse holding HD 1.4 explosives it should present no greater hazard to the public and the fire fighters than that produced in a hardware store holding a similar quantity of aerosol cans of paint etc. It should be noted that this hazard may not be negligible, but is assumed to be acceptable by society. An advantage of initially addressing hazard division 1.4 when classifying a new explosive is that it avoids the error of using HD 1.4 as a sink into which, by default, difficult types of explosive may be dumped. The allocation of an HD 1.4 classfication to an explosive should be considered an accolade recognising its comparative safety viz a viz explosives generally.

7. Having decided that the explosive does display significant explosive qualities such as blast, dangerous projections or a fire hazard or any combination; the decision as to what is the predominant hazard is not always obvious. Clearly a risk of mass explosion requires the decision to be HD 1.1 but the effects are not always restricted to those produced by the blast wave. HD 1.1 explosives may carry any degree of projection and/or fire hazard in addition to the blast produced by the mass explosion. The apparently obvious point is sometimes overlooked. When considering the classification of an explosive for which data is not available the option to accept a more restrictive classification is offered. It may often be easier to opt for Hazard Division 1.1 decision rather than waste effort to establish a less onerous classification. An important implication is that some published classifications, issued by a fully competent authority will be greatly pesimistic and misleading if analogies are to be drawn.

8. A comparison of the behaviour of HD 1.2 and 1.3 explosives seems to cause some difficulty but if the problem is considered from the view point of the stand-off radii this should resolve the ambiguity. Where no mass explosion occurs and an explosive shows both a fire hazard and a serious projection hazard, it appears logical to opt for that hazard division which requires the greatest stand-off distance. If, for example, one considers the NATO Quantity Distances (Q-Ds) to Inhabited Buildings for the storage of an NEQ of, say, 5000 kg of explosives, these distances are:-

HD 1.1	HD 1.2	HD 1.3	HD 1.4
380 metres	320 metres	110 metres	No distance specified.

As an aside it may be that the actual radius of 320m for HD 1.2 explosives appears somewhat out of proportion to those quoted for the other hazard divsions, being much too high in comparison with 380m for HD 1.1. One bears in mind the relative effects of the mass explosion of e.g a High explosive (HE) shell compared to HD 1.2 HE shell in a fire causing intermittent explosions each involving only a few shell spread over perhaps half an hour in time.

9. Consider an article which exhibits both a high velocity projection hazard and a significant fire hazard (assuming there is no mass explosion hazard) such as a rocket with an HE war head. It is known that HE and propellant substances typically have similar energy contents per kg, it appears to be a reasonable assumption that one can relate relative hazard to relative energy content, i.e. mass of the active substances. This approach has the attraction of being apparently based on thermodynamic principles using logical scientific reasoning but, in fact, would lead to an unfortunate classification decision. To be specific, a one kg net explosive content (NEC) detonating warhead fitted to a 10 kg NEC rocket motor would typically require a classification of HD 1.2 in spite of the overwhelming proportion of propellent in the complete missile.

10. A typical HD 1.2 explosive could be a shell or mortar bomb filled with high explosive. In an accident which caused detonation, the high velocity fragments from the steel case would reach some hundreds of metres. It is not essential, however, for metal projections to have such heroic velocities and range for the projection hazard to predominate over radiant heat

effects. The possibility of a round (i.e. cartridge) of gun ammunition, containing propellant only, justifying a classification of HD 1.2 has obviously been envisaged in the UN scheme of classification (e.g Cartridge for Weapon with Inert Projectile, UN No. 0328, HD 1.2C). Since the definiion of HD 1.3 permits only a minor projection hazard, any practice round in which the inert projectile or metal cartridge case, or both, are projected more than say 50 metres could be said to display a projection hazard which predominates over the fire hazard from the propellant. This takes account of the relative masses of cartridge cases or projectiles and that of the propelling charge which may be only 10-20 per cent of the total mass of the cartridge or round.

PRINCIPLES FOR DECIDING THE COMPATIBILITY GROUP CLASSIFICATION

11. The definition of some of the compatibility groups are so specific that allocation or otherwise of the explosive to the group is effectively unambiguous. These are A, C, G, H, J and K. Some groups apply to articles only and group A applies to substances only. (Fig.2).

It is proposed that the allocation of compatibility group is considered in the following order:-

S - any hazardous effect is confined to the package unless this has been degraded by fire. If so degraded the hazardous effects must be trivial and very limited in range (see below).

The following groups are broadly in descending order of risk and hazard, i.e. groups C,D and E carry the least hazard.

L - comprising explosives which present a special risk and which additionally need isolation of each type of Group L explosive.

The next three groups (H, J, and K) may be considered together:-

H - article containing an explosive substance and white phosphorus.

J - article containing an explosive substance and a flammable liquid or gel.

K - article containing an explosive substance and a toxic chemical agent.

A - primary explosive substance (i.e. Lead Azide etc)

B - article containing a primary explosive substance without effective isolating features (see below).

F - article containing a secondary detonating explosive substance with its means of intiation (i.e. Group B).

G - pyrotechnic explosive substance or article containing same.

E - article containing a secondary detonating explosive substance without its means of initiation (i.e. not Group B) with propellant (not group J or hypergolic) (see below).

C - propellant explosive substance or article containing same.

D - secondary detonating explosive substance (or black powder) or article containing same without its means of initiation (i.e. not Group B) without propellant. (see below).

For all groups other than L it is taken for granted that mixing of differing explosives having the same compatibility group letters is allowed. There may be a penalty if one mixes explosives of differing hazard divisions, e.g. HD 1.1C explosives mixed with HD 1.2C explosives may need to be treated as if the total explosive mass were all HD 1.1 for quantity distance purposes. Group L contains explosives which are e.g. pyrophoric (i.e. spontaneously igniting), water activated, contain hypergolic liquids (i.e. when the liquids are mixed they spontaneously ignite) or have other special properties.

12. Group B comprises articles which contain a primary explosive substance such as detonators and fuzes. This may be the only explosive present or there may also be a secondary explosive. Since the mass of secondary explosive would normally far exceed that of the primary explosive it would be beneficial if they could be isolated. In practice the isolating barriers need only resist the effect of explosion of the primary explosive, which is assumed to be the more likely to initiate on rough handling, heating etc of the system. If isolation can be successfuly accomplished the fuze etc could be assigned Group D. If there is doubt about the isolation of the primary explosive substance from secondary explosive substance, or if only primary explosive is present then compatibility Group B is called for. Should the package be sufficiently robust to contain the effect of functioning of the item then compatibility Group S would be appropriate. Group D includes secondary (i.e. less sensitive than primary) detonating explosive substances (or gunpowder) or an article containing such alone. It also includes articles which contain a primary explosive provided this is effectivly isolated from the, assumed much greater mass, of secondary explosive. It must not contain propellant.

13. Group E comprises articles containing propellant (other than a flammable or hypergolic liquid) and an article otherwise suitable for Group D. Since propellants, or articles containing propellants, are in Group C we can make the equation:-

Group E = Group C + Group D

Group F comprises articles containing a secondary detonating explosive not effectively isolated from a primary explosive. It may or may not contain propellant. If it does not the definition overlaps that for Group B. Group B is confined to articles containing only limited quantities of secondary detonating explosives used to initiate larger charges, e.g. fuzes, primers, boosters with detonator fitted etc. Group F includes HE bombs, rocket and torpedo warheads etc fitted with their own (non isolated) means of initiation. Again we can make the equations:-

Group F = Group B + Group D

or Group F = Group B + Group C + Group D.

CLASSIFICATION CODES

14. The combination of hazard division and compatibility group (with the prefix of the UN dangerous goods class i.e. ´1´) e.g. 1.3G, is known as the "Classification Code´ although this term is not widely used. Generally one addresses the Classification Code by the strict misnomer ´hazard division´ as in ´HD 1.3C´. Not all combinations are permitted. (Fig. 3). Group A is confined to HD 1.1 and hazard division 1.5 is confined to Group D. Most other combinations are permitted but HD 1.4 (no significant hazard) is incompatible with groups H, J, K, and L in Addition to A. A particularly restricted compatibility group is S which is confined to hazard division 1.4. There is, in fact, general interaction between hazard division and compatibility group although their formal definiions imply complete independance. Classification Code 1.4S is restricted to those explosives whose effect would be confined within the package (unless degraded by fire). Even then the effects should be effectively trivial and localised.

15. Apart from such articles as small cable cutters which are intrinsically ´safe´ it is possible, if often expensive, to package quite formidable explosive devices to conform to HD 1.4S. If it is assumed that the article is e.g. a detonating fuze too hazardous on its own to be of trivial effect in the open this would require a fire proof outer container of e.g steel. If the internal packaging were such as to isolate each article from its neighbour to preclude communication then the only requirement would be that the outer steel case could contain the effects of detonation of one device. In my opinion this is an example where the decision to classify as HD 1.4S would either rest on a specific test or on a very closely drawn analogy with an article/package combination which has been tested. An explosive content per article of 20g in a heavy steel bolted lid case would, in my experience, be the practical limit.

INTERACTION OF HAZARD DIVISION, COMPATIBILITY GROUP AND QUANTITY OF EXPLOSIVE

16 The risk and hazard associated with the transport, handling or storage of a quantity of explosive clearly depends on its mode of action, i.e. is it liable to mass explode or simply burn fiercely? The mode of action is identified by the hazard division. Another basic element in assessing the risk and hazard is the probability that an accident will occur which is associated with the sensitivity of the packaged explosive to the mechanical environment or temperatures experienced. This probability is broadly represented by the compatibility group, (leaving aside articles in groups H, J and K which classifications draw attention to the presence in the explosive article of dangerous substances of UN classes 4.2, 3 and 6.1 respectively). The magnitude of the accidental event is clearly an essential factor in the perceived risk and hazard and depends on the quantity of explosives.

17. The perceived overall risk and hazard depends on the three basic factors:- Probability, Magnitude and Mode of action which operate simultaneously and Fig. 4 is an attempt at illustrating their interaction by plotting the factors along three axes. With the exception of magnitude the weight to be placed on the differenT Hazard Divisions and Compatibility Groups must be arbitrary. It will be noted that the origin represents an unacceptable situation and the distance of a point in three dimensional space from the origin is a measure of 'Unacceptability'.

REFERENCE

"Orange Book" Transport of Dangerous Goods.
Recommendations of the Committee of Experts on the Transport of Dangerous Goods.
3rd Revised Edition ST/SG/AC.10/1/Rev.3
United Nations.

Figure 1

DEFINITION OF HAZARD DIVISIONS

Class 1 is divided into five divisions:

Division 1.1 Substances and articles which have a mass explosion hazard
(A mass explosion is one which affects almost the entire load virtually instantaneously.)

Division 1.2 Substances and articles which have a projection hazard but not a mass explosion hazard

Division 1.3 Substances and articles which have a fire hazard and either a minor blast hazard or a minor projection hazard or both, but not a mass explosion hazard

This division comprises substances and articles:
(a) which give rise to considerable radiant heat, or
(b) which burn one after another, producing minor blast or projection effects or both.

Division 1.4 Substances and articles which present no significant hazard

This division comprises substances and articles which present only a small hazard in the event of ignition or initiation during transport. The effects are largely confined to the package and no projection of fragments of appreciable size or range is to be expected. An external fire must not cause virtually instantaneous explosion of almost the entire contents of the package.

Division 1.5 Very insensitive substances which have a mass explosion hazard

This division comprises explosive substances which are so insensitive that there is very little probability of initiation or of transition from burning to detonation under normal conditions of transport. As a minimum requirement they must not explode in the external fire test.

Class 1 is unique in that the type of packaging frequently has a decisive effect on the hazard and therefore on the assignment to a particular division.

DEFINITION OF COMPATIBILITY GROUPS

Description of substance or article to be classified	*Compatibility Group*
Primary explosive substance	A
Article containing a primary explosive substance and not containing two or more independent safety features	B
Propellant explosive substance or other deflagrating explosive substance or article containing such explosive substance	C
Secondary detonating explosive substance or black powder or article containing a secondary detonating explosive substance, in each case without means of initiation and without a propelling charge, or article containing a primary explosive substance and containing two or more independent safety features	D
Article containing a secondary detonating explosive substance, without means of initiation, with a propelling charge (other than one containing an inflammable or hypergolic liquid)	E
Article containing a secondary detonating explosive substance with its own means of initiation, with a propelling charge (other than one containing an inflammable or hypergolic liquid) or without a propelling charge	F
Pyrotechnic substance, or article containing a pyrotechnic substance, or article containing both an explosive substance and an illuminating, incendiary, lachrymatory or smoke-producing substance (other than a water-activated article or one containing white phosphorus, phosphide or an inflammable liquid or gel)	G
Article containing both an explosive substance and white phosphorus	H
Article containing both an explosive substance and an inflammable liquid or gel	J
Article containing both an explosive substance and a toxic chemical agent	K
Explosive substance or article containing an explosive substance and presenting a special risk needing isolation of each type	L
Substance or article so packed or designed that any hazardous effects arising from accidental functioning are confined within the package unless the package has been degraded by fire, in which case all blast or projection effects are limited to the extent that they do not significantly hinder or prohibit fire fighting or other emergency response efforts in the immediate vicinity of the package	S

Figure 3

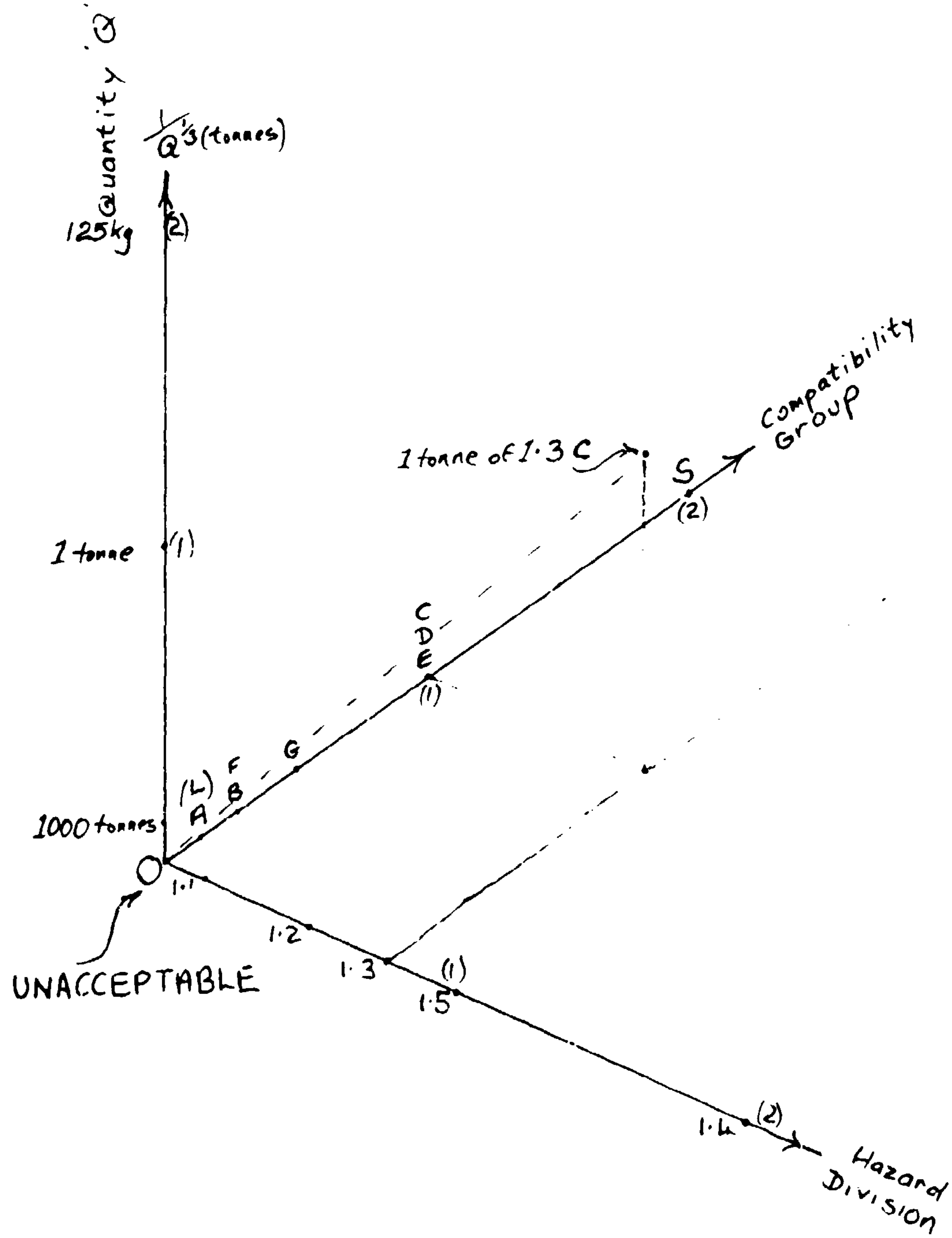
COMBINATION OF THE HAZARD DIVISION WITH THE COMPATIBILITY GROUP

Hazard Division	Compatibility group											
	A	B	C	D	E	F	G	H	J	K	L	S
1.1	1.1 A	1.1 B	1.1 C	1.1 D	1.1 E	1.1 F	1.1 G		1.1 J		1.1 L	
1.2		1.2 B	1.2 C	1.2 D	1.2 E	1.2 F	1.2 G	1.2 H	1.2 J	1.2 K	1.2 L	
1.3			1.3 C			1.3 F	1.3 G	1.3 H	1.3 J	1.3 K	1.3 L	
1.4		1.4 B	1.4 C	1.4 D	1.4 E	1.4 F	1.4 G					1.4 S
1.5				1.5 D								

Figure 4

ACCEPTABILITY OF EXPLOSIVE RISK AND HAZARD

Interaction of Hazard Division, Compatibility Group and the quantity of explosives involved



REFLECTED OVERPRESSURE IMPULSE ON A FINITE STRUCTURE

by
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ABSTRACT

The effect of angle of incidence of the shock front on reflected impulse loading on a finite structure is presented in this paper. Impulse reflection factors have been developed for angles of incidence from zero to ninety degrees. Reflected impulse on a finite structure is much less than reflected impulse on an infinite plane because of the unloading due to rarefaction waves propagating from the sides of the structure which lowers the reflected overpressure.

I. INTRODUCTION

A. Background

During one of the meetings of the Blast Technology Subcommittee for the Revision of the Protective Structures Manual[1] it was pointed out that there was a data gap with regard to the effect of angle of incidence on reflected impulse impinging on finite structures. The effect of angle of incidence of the shock wave striking an infinite plane on peak reflected pressure and reflected impulse has been documented in many height of burst studies. The latest of these was conducted in Canada and reported in References 2 and 3. After a literature survey there appeared to be little information on the effect of angle of incidence on reflected impulse loading of isolated structures.

B. Objective

The objective of this study is to determine experimentally the effect of angle of incidence of the shock front on the reflected impulse loading on an isolated structure. The experiment was conducted with 1/50 scaled non-responding models of a single structure.

II. TEST PROCEDURES

This section will describe the procedure followed in conducting an experimental program to meet the stated objective.

A. Design of Model

The model was designed to represent a structure 15.24 metres wide by 15.24 metres long by 22.86 metres high (50 ft x 50 ft x 75 ft). A 1/50th scale produced a model 0.305 m x 0.305 m x 0.457 m (1 ft x 1 ft x 1.5 ft). The model was constructed of a 2.54 cm thick steel plate. A sketch of the model is presented in Figure 1. The four upright walls were welded together with the top bolted on to allow access to the pressure gages. A reinforced concrete mount with an anchor bolt imbeded (as shown in Figure 2) was used to secure the model. The pressure transducers were then installed and the top plate was bolted in place. An exploded view of the model, mount, and pressure transducers is shown in Figure 3. The model was held in place by tightening the large nut down against top plate. By loosening the nut, the model

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1 *Department of the Army, the Navy, and the Air Force, "Structures to Resist the Effects of Accidental Explosions," June 1969, TM5-1300, NAVFAC P-397, AFM 88-22.*

2 *R.E. Reisler, B. Pettit and L. Kennedy, "Air Blast Data from Height of Burst Studies in Canada, Vol I: HOB 5.4 to 71.9 Feet," BRL Report No. 1950, December 1976 (AD#B016344L).*

3 *R.E. Reisler, B. Pettit and L. Kennedy, "Air Blast Data from Height of Burst Studies in Canada, Vol. II, HOB 4.6 to 144.5 Feet," BRL Report No. 1990, May 1977.*

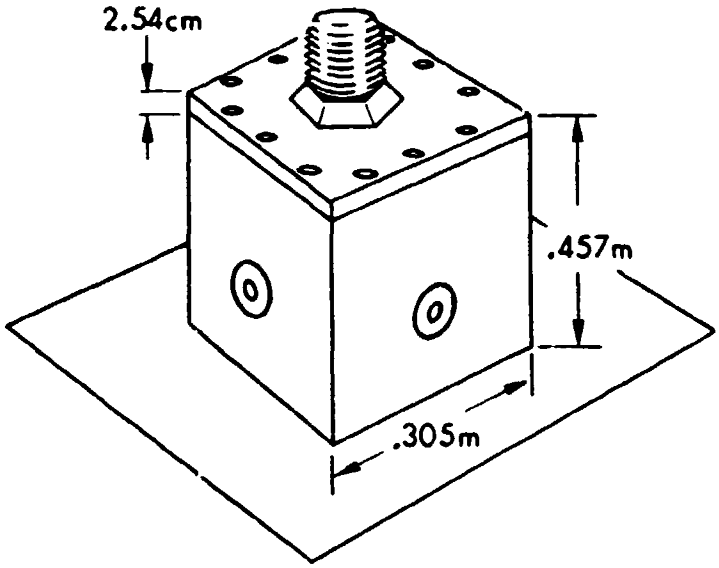

Figure 1. The 1/50th Scale Steel Structure Model.

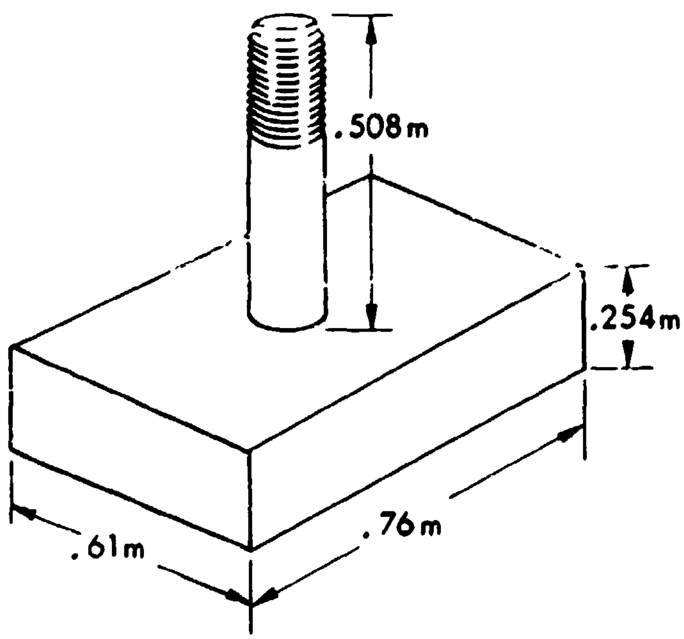

Figure 2. Concrete Mount with Anchor Bolt.

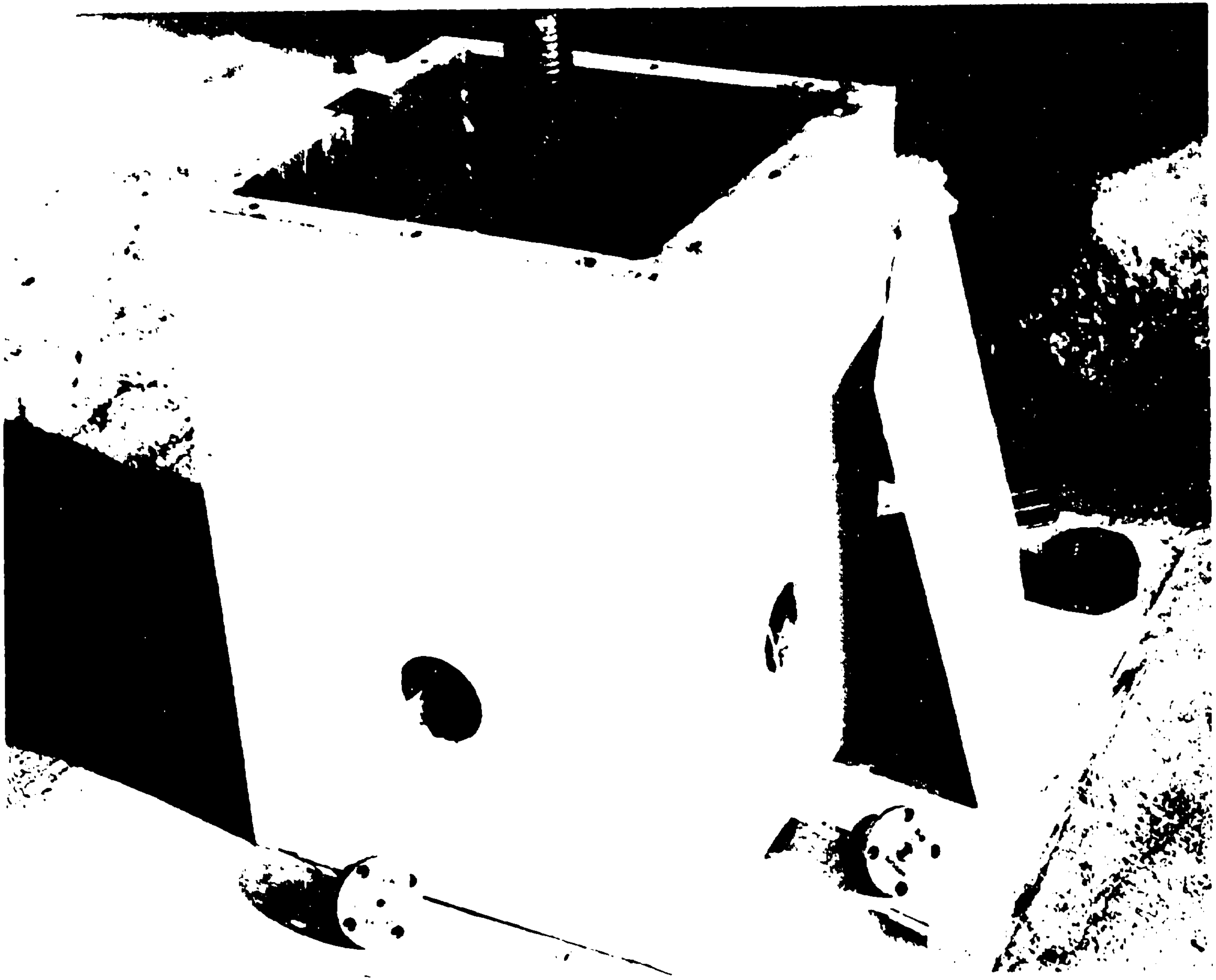

Figure 3. Exploded View of the Model, Mount, and Pressure Transducers.

orientation could be changed for each test and then retightened. A total of eight models was constructed. The pressure transducers were placed on the center line of a front and side wall at a height of 0.152 m. The model was rotated to change the angle of incidence of the shock front with the model walls.

B. Test Charges

The test charges were cast Pentolite (50 PETN, 50 TNT). The shape was hemispherical and the point of detonation was at the center of the flat side which was placed on the ground surface. The full size charge yield selected for simulation was 125000 kilograms. Therefore a 1/50 scale model would require (according to cube root scaling) a one kilogram charge. One kilogram cast Pentolite charges were used on all of the fifteen tests conducted.

C. Test Instrumentation

The instrumentation for this test series consisted of pressure transducers, magnetic tape recorder/playback, and a data reduction system. A block diagram is shown in Figure 4.

1. Pressure Transducers. Piezo-electric pressure transducers were used for this series of tests. The PCB Electronics Inc., models 112A22, 113A24, and 113A28, with quartz sensing elements and built-in source followers were used extensively.

2. Tape Recorder System. The tape recorder consisted of three basic units, the power supply and voltage calibrator, the amplifiers, and the FM recorder. The FM tape recorder was a Honeywell 7600 having a frequency response of 80 kHz. Once the signal was recorded on the magnetic tape it was played back and recorded on a Honeywell Visicorder. This oscillograph has 5 kHz frequency response and the overpressure versus time recorded at the individual stations can be read directly from the playback records for preliminary data analysis.

3. Data Reduction System. For the final data output, the tape signals were processed through an analog-to-digital converter, to a digital recorder-reproducer, and then to a computer. The computer (TEKTRONIX 4051) was programmed to apply the calibration values and present the data in the proper units for analysis. From the computer, the data is put on a digital tape from which the final form can be plotted or tabulated. The digital tape can be also stored for future analysis.

D. Test Layout

The test layout was planned to acquire the maximum amount of data for each test conducted. A total of eight peak overpressure levels was selected and therefore eight models were constructed. Twenty-one angles of incidence were selected with eleven bunched between 37.5 and 62.5 degrees in order to document the transition between regular reflection and Mach reflection. The test layout is shown in Figure 5. The peak overpressure range of interest for this project was from 345 kPa down to 6.89 kPa. The distances selected to

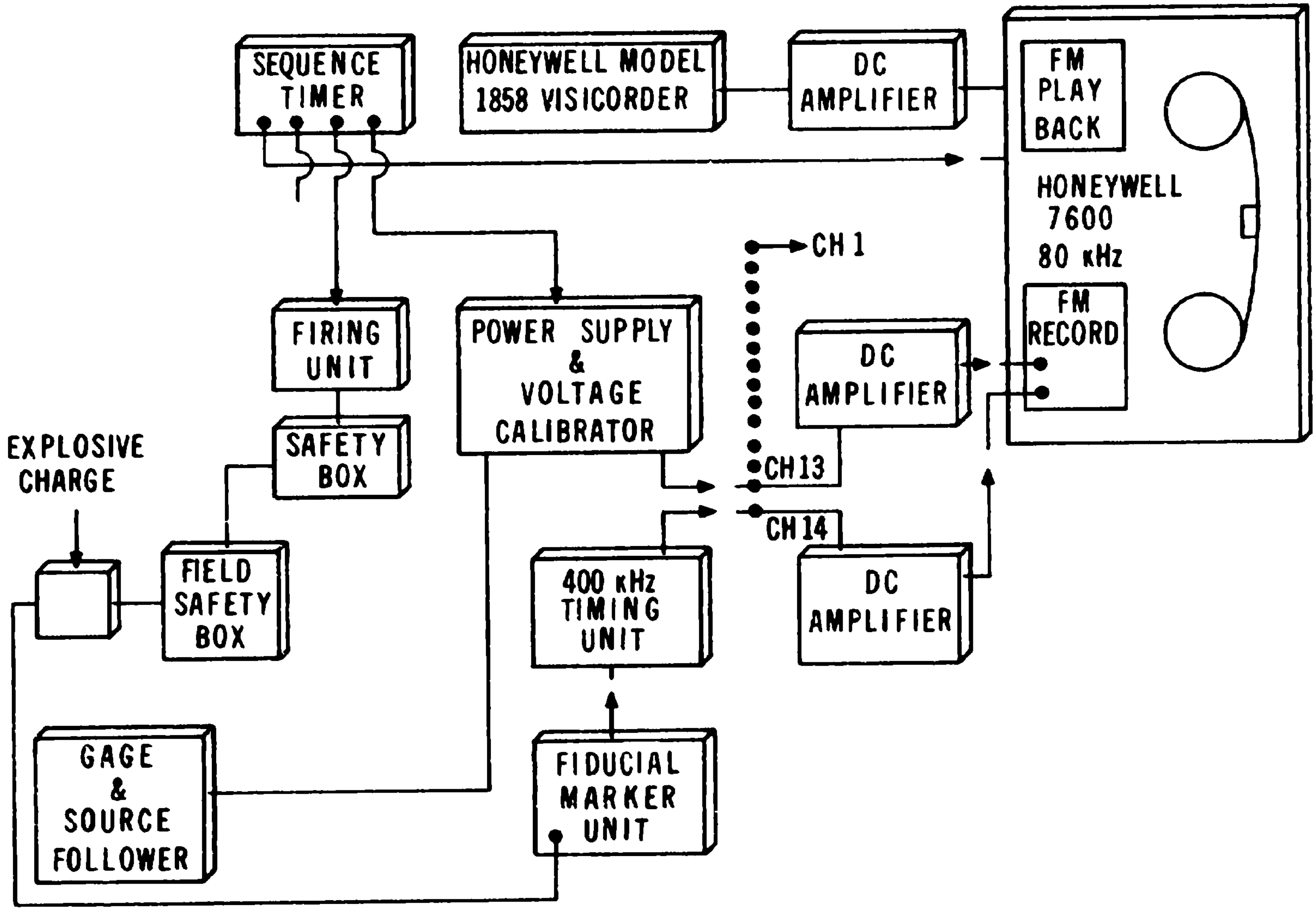

Figure 4. Instrumentation Block Diagram.

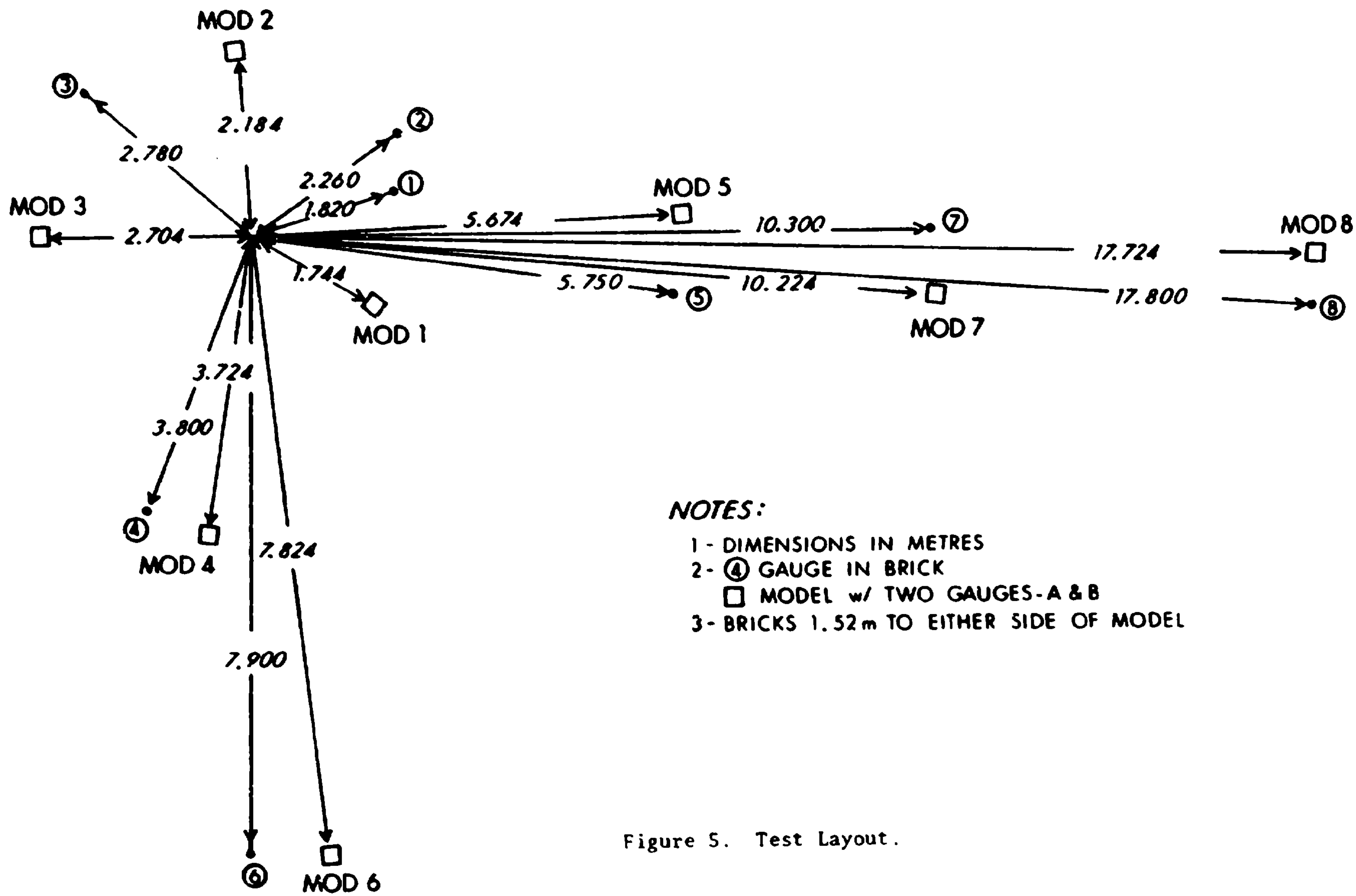

Figure 5. Test Layout.

meet the required pressure range were based on the standard TNT hemispherical surface burst curve.[4] The free-field incident peak overpressure was measured near each structure to provide the input blast parameters. Nomenclature used to identify the gage locations at each station is as follows: Station 1 is the free-field gage, Station 1A is in the front of the model wtih orientation from 0 to 45 degrees, and Station B is in the side of the model with orientation from 90 to 45 degrees. On Test 1, Station A on all models was at an angle of 0 degrees or normal reflection while Station B on all models was at an angle of 90 degrees or a side-on measurement. The station locations, predicted peak overpressures, and impulses are listed in Table 1 for Test Number 1. The locations of the free-field stations remained the same on all 15 tests. The radial distances for the Stations A and B changed on each shot. A photograph showing Structures 2 (foreground), 1, 4, and 6 for 0 degree and 90 degree orientation with a 1 kg charge in place is presented in Figure 6.

E. Test Matrix

Eight model structures were placed at the distances shown in Table 1 to receive the predicted input pressure and impulse. After each test, each model was rotated the same number of degrees in order that the shock front would strike each set of structure walls at the same angles of incidence. The angle of incidence for each test (1-12) is listed in Table 2. On Tests 13, 14, and 15 the structure models were exposed at different angles and at different pressure levels. These exposures are listed in Table 3.

F. Predictive Approach

There are many references in which the enhancement of peak overpressure as a function of angle of incidence is reported. One of the more complete treatments is given in Reference 5. Normal reflection or head-on reflection can be predicted for the range of incident overpressures of interest in these tests using the following equation:

$$P_r = 2 P_s \left(\frac{7 P_0 + 4 P_s}{7 P_0 + P_s} \right) \qquad (1)$$

where P_0 = Ambient atmospheric pressure,
P_r = Normal reflected overpressure, and
P_s = Side-on incident overpressure.

This is valid where the ratio of specific heat (γ) for air is a constant 1.4. The equation is good only for predicting the reflected pressure when the models are in the 0-degree orientation, face-on.

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[4] C.N. Kingery, "Air Blast Parameters versus Distance for Hemispherical Surface Bursts," BRL Report 1344, September 1966 (AD#811673).

[5] "Nuclear Weapons Blast Phenomena, Volume II, Blast Wave Interaction," DASA 1200-II, 1 December 1970 (Confidential RD).

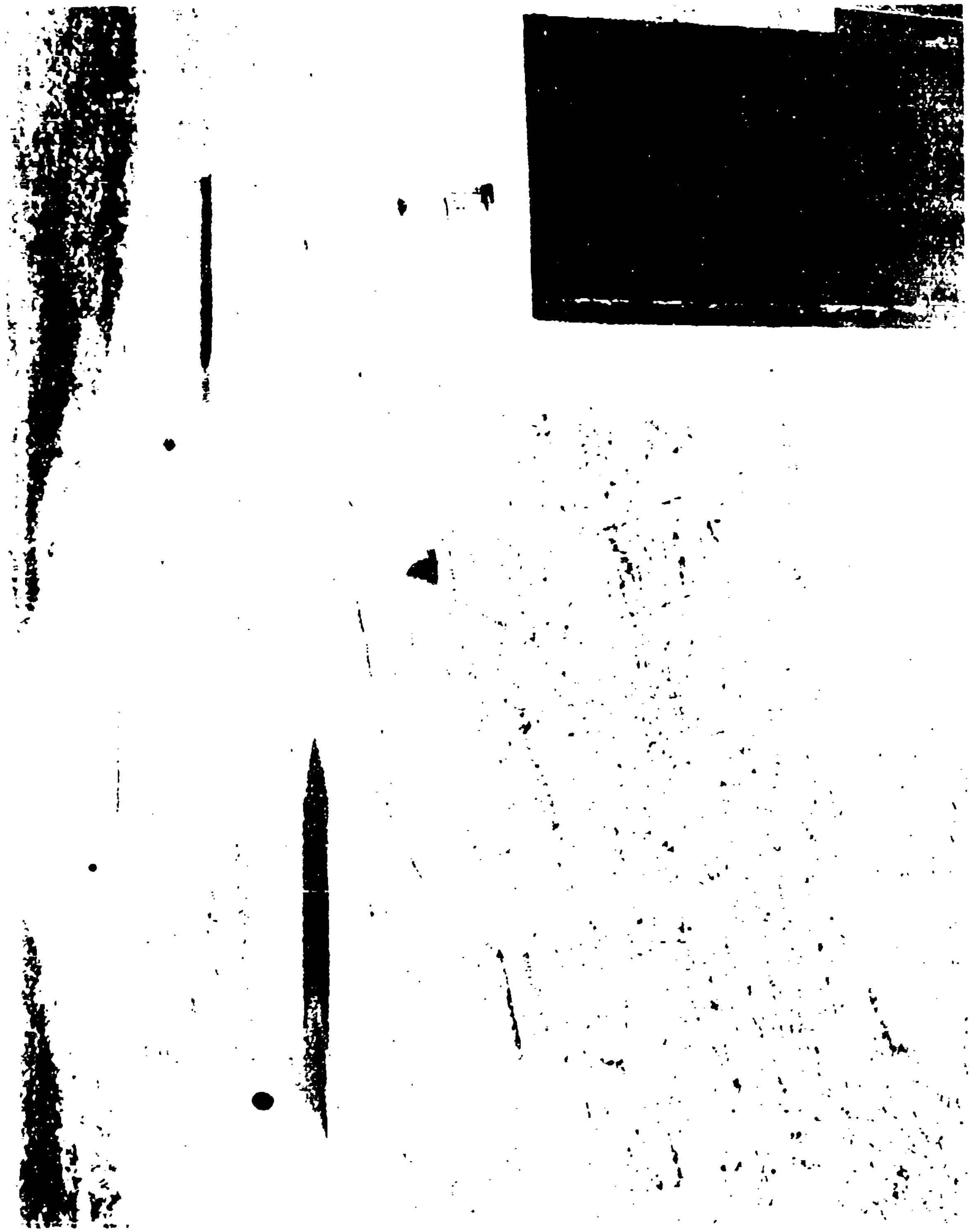

TABLE 1. PREDICTED PEAK PRESSURES AND IMPULSES FOR TEST 1

Station	Distance m	Pressure kPa	Impulse kPa-ms	Station	Distance m	Pressure kPa	Impulse kPa-ms
1	1.82	345	145	5	5.75	34.5	51
1A	1.74	1361	430	5A	5.67	78.7	110
1B	1.90	340	140	5B	5.83	33.9	50
2	2.26	207	120	6	7.90	20.7	39
2A	2.18	695	320	6A	7.82	44.9	80
2B	2.34	190	112	6B	7.98	20.8	38
3	2.78	138	98	7	10.30	13.8	30
3A	2.70	408	250	7A	10.22	29.1	59
3B	2.86	130	96	7B	10.38	13.7	30
4	3.80	68.9	74	8	17.80	6.89	18
4A	3.72	164	170	8A	17.72	14.7	32
4B	3.88	66.0	72	8B	17.88	6.89	18

TABLE 2. MODEL ORIENTATION. TESTS 1-12

Test No.*	Angle of Incidence A	Angle of Incidence B	Test No.	Angle of Incidence A	Angle of Incidence B
1	0	90	7	37.5	52.5
2	10	80	8	40.5	49.5
3	16	74	9	42.5	47.5
4	21	69	10	43.5	46.5
5	27.5	62.5	11	45	45
6	34	56	12	0	90

*Tests 1 through 12 all models had same orientation

TABLE 3. MODEL ORIENTATION, TESTS 13-15

Station**	1		2		3		4		5		6		7		8	
Test	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
13	34	56	34	56	40.5	49.5	40.5	49.5	37.5	52.5	37.5	52.5	37.5	52.5	37.5	52.5
14	37.5	52.5	40.5	49.5	46.5	43.5	42.5	47.5	40.5	49.5	43.5	46.5	0	90	40.5	49.5
15	43.5	46.5	16	74	16	74	21	69	16	74	45	45	21	69	16	74

**On Tests 13, 14, and 15 models were oriented for repeat exposure at selected angles and pressure levels.

A second source used for predicting the reflected pressure in the regular reflection region for different angles of incidence is Reference 6. This report is based on a theoretical treatment by J. Von Newman. It considers the shock wave reflecting on an infinite plane as in a height of burst study. The reference does not treat impulse.

A newer source, Reference 7, treats both the enhancement of pressure in the regular reflection on rising slopes as well as the enhancement in the Mach reflection region on rising slopes. The reflected pressure versus incident pressure undergoing regular reflection for various rising slopes (Figure 12 from Reference 7) is presented as Figure 7. The reflected pressure versus incident pressure undergoing Mach reflection for various rising slopes (Figure 5 from Reference 7) is presented as Figure 8.

A family of curves from Reference 8 showing the reflection factor or pressure ratio P_r/P_s for selected input pressures (P_s) versus angle of incidence are presented in Figure 9. They were used in predicting the reflected pressure, P_r, expected to load the model. These curves and the other predictive methods will be compared with the field measurements.

III. RESULTS

As mentioned in the introduction, the primary objective of this project is to determine the enhancement of overpressure impulse as a function of the angle of incidence of the shock front striking an isolated structure. Presented in Section F of Test Procedures, are predictive approaches for determining the peak reflected pressure but there is a lack of information on predicting the reflected impulse other than normal or head-on. Information that is available, is from various height of burst studies, where the reflection process is on an infinite plane.

The results will be presented in the form of reflected pressure compared to side-on pressure or reflected pressure ratios (P_r/P_s). This comparison will also be done for impulse where ratios of I_r/I_s will be developed for angle of incidence and a variety of side-on or free-field impulses.

A. Side-on Overpressure and Impulse Measurements

In order to determine the pressure reflection and impulse reflection ratios, the side-on or incident overpressures and impulses must be established. Eight pressure transducers were placed at the distances and locations shown in Figure 5 to record the incident overpressure versus time of the blast wave. Records were obtained on each test and the incident peak

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[6] *C.N. Kingery and B.F. Pannill, "Parametric Analysis of Regular Reflection of Air Blast," BRL Report 1249, June 1964 (AD#444997).*

[7] *Kenneth Kaplan, "Effects of Terrain on Blast Propagation Methods and Prediction," BRL Contract Report ARBRL-CR-00355, January 1978 (AD#A051350).*

[8] *Brode, H.L., "Height of Burst Effects at High Overpressures," The Rand Corporation, RM-6301, DASA 2506, July 1970.*

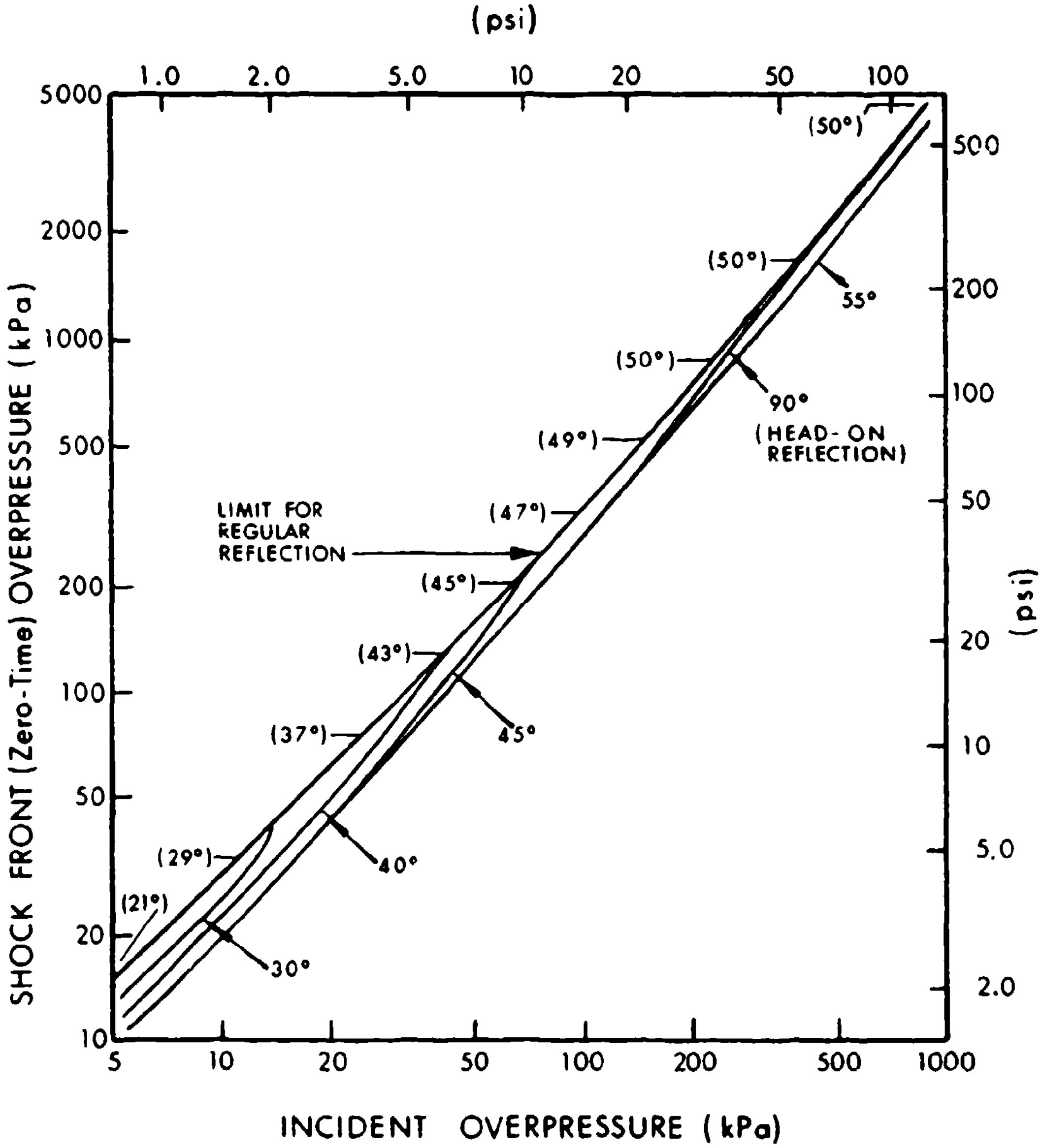

Figure 7. Reflected Pressure versus Incident Overpressure for a Shock Wave Undergoing Regular Reflection on a Rising Slope.

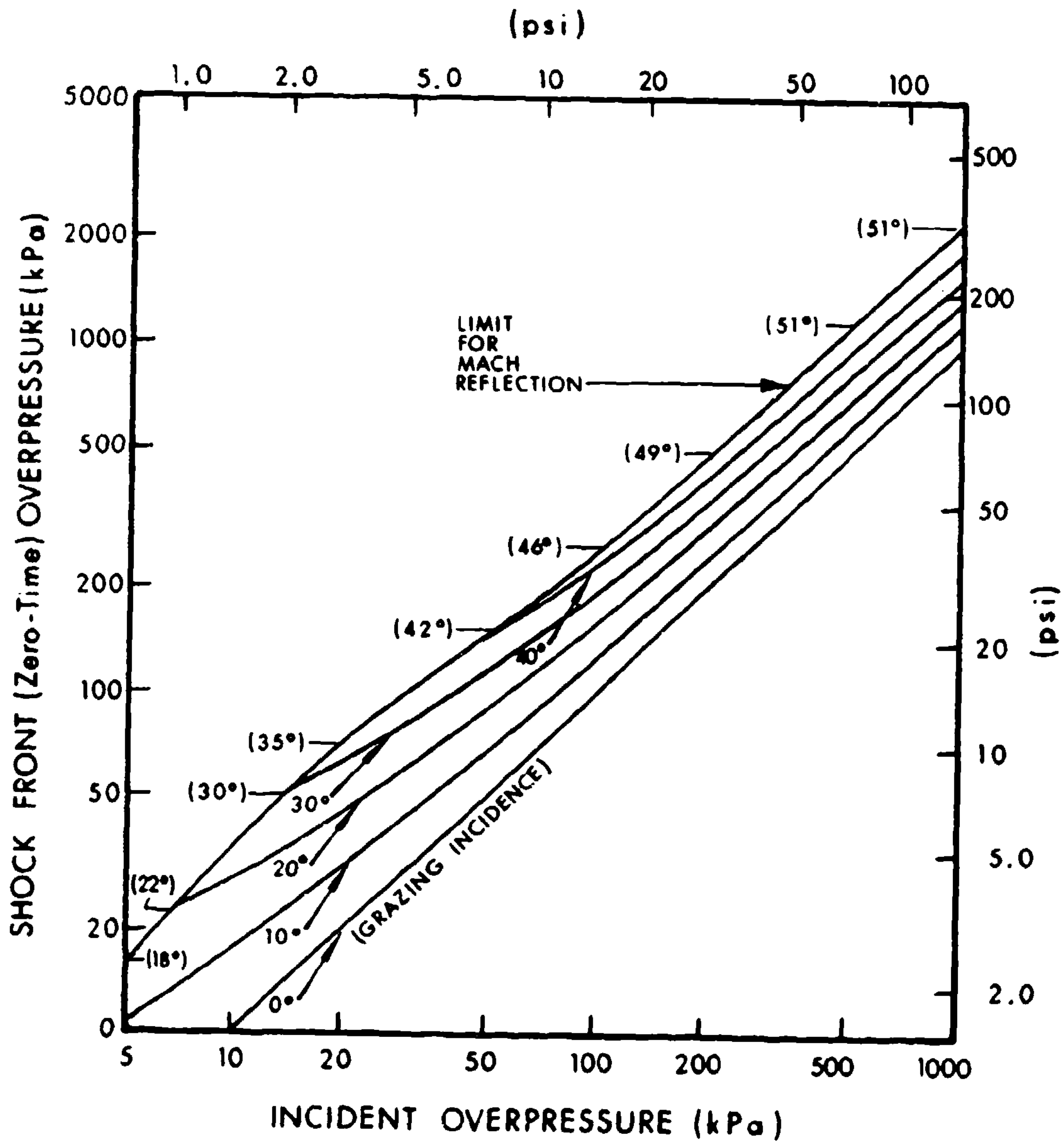

Figure 8. Reflected Pressure versus Incident Overpressure for Shock Waves Undergoing Mach Reflection on a Rising Slope.

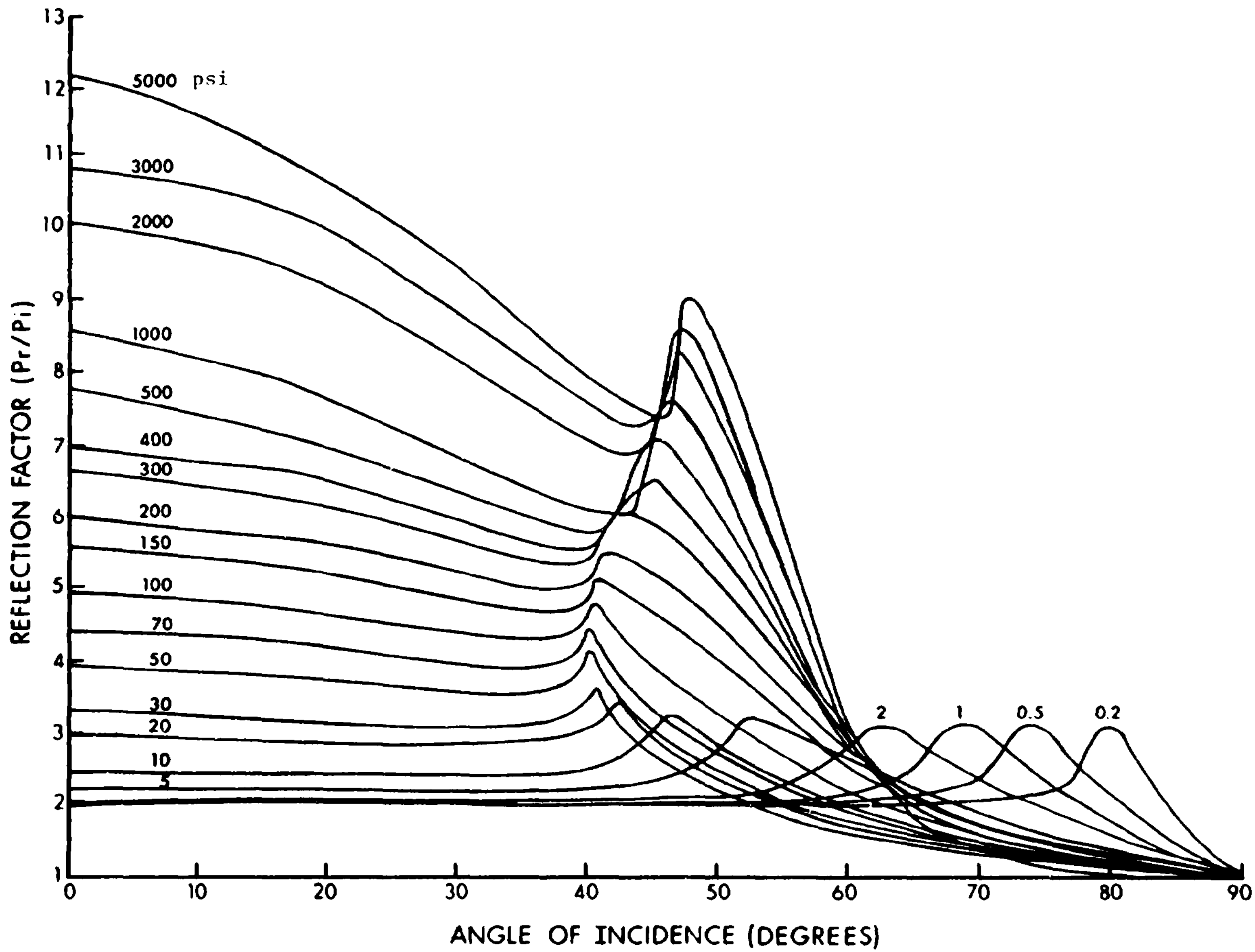

Figure 9. Reflection Factors versus Angle of Incidence for Selected Incident Overpressures.

overpressure and incident overpressure impulses are listed in Table 4 for each station. An average value from the fifteen tests was used to plot a peak overpressure versus distance for a 1 kg hemispherical Pentolite surface burst. Over ninety percent of the values of both pressure and impulse fell within a ±5 percent of the average value established at each station. The average peak incident overpressure (P_s) versus horizontal distances are plotted in Figure 10. The solid lines in Figures 10 and 11 were established from data presented in Reference 9. The average incident impulses (I_s) versus horizontal distances from Table 4 are plotted in Figure 11.

B. Reflected Peak Overpressure and Impulse versus Angle of Incidence

The reflected peak overpressure versus angle of incidence is a direct measurement made on the front and side wall of the model. The reflected impulse is obtained from the integration of the overpressure versus time recorded from Stations A and B located on the model.

The reflected pressure recorded on Stations 1A and 1B through 8A and 8B are plotted versus angle of incidence in Figure 12. The lines through the data points are visual fits and were used to establish the values of reflected pressure listed in Table 5.

The reflected impulses versus angle of incidence recorded at Stations 1A and 1B through 8A and 8B are plotted in Figure 13. The solid lines are visual fits of the data points and were used to determine the values of reflected impulse listed in Table 5.

C. Reflected Pressure and Impulse Ratios versus Angle of Incidence

Both the reflected pressure (P_r) and the reflected impulse (I_r) will be presented as a function of side-on pressure (P_s) and side-on impulse (I_s) in the form of ratios. That is P_r/P_s and I_r/I_s will be presented versus angle of incidence.

The reflected pressure ratios P_r/P_s were calculated for each angle of incidence at each station and are listed in Table 5. It was noted in the Test Layout Section that Station A and Station B are located at different radial distances (ΔR) but this ΔR becomes less as the model is rotated and $\Delta R = 0$ at 45 degrees angle of incidence. In Table 5 the side-on pressure (P_s) for a θ of 0 degrees is listed for Station A and the P_s for 90 degrees is listed for Station B. The P_s for each radial distance from $\theta = 0$ degrees through $\theta = 90$ degrees was calculated to insure that the correct P_s for each angle was used in determining the ratio P_r/P_s. The values listed in Table 5 are plotted in Figures 14 and 15.

The reflected impulse ratios listed in Table 5 are based on the reflected impulse curves plotted in Figure 13 and the side-on impulse listed in Table 4 adjusted for the R distance between Station A and B. The range of side-on impulses is listed for each station in Table 5. The values of reflected impulse I_r divided by the side-on impulse I_s listed in Table 5 are plotted in Figure 16.

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[9] *Charles Kingery and George Coulter, "TNT Equivalency of Pentolite Hemispheres," ARBRL-TR-02456, December 1982 (AD#A123340).*

TABLE 4. INCIDENT OVERPRESSURE AND IMPULSE AT FREE-FIELD STATIONS

Test No.	Station 1 Distance 1.82		Station 2 Distance 2.26		Station 3 Distance 2.78		Station 4 Distance 3.80	
	P_s kPa	I_s kPa-ms	P_s kPa	I_s kPa-ms	P_s kPa	I_s kPa-ms	P_s kPa	I_s kPa-ms
1	327	110	169*	103	121*	85	66	68
2	335	116	227	105	134	88	70	70
3	332	117	220	100	135	87	69	69
4	303	113	209	103	127	88	66	66
5	308	116	196	103	129	86	74	70
6	307	113	195	102	127	84	71	67
7	340	117	206	104	129	84	68	68
8	302	112	201	102	135	84	69	67
9	N-1	N-1	208	99	131	86	66	69
10	N-1	N-1	172*	106*	138	83	68	66
11	321	115	208	100	135	87	86*	286*
12	380*	116	190*	105	139	89	68	63*
13	315	121	215	99	139	85	71	67
14	324	114	206	108	131	91	72	69
15	292	120	212	104	140	91	69	71
AVG	317	115.4	208.6	102.6	133.5	86.5	69.1	68.2

*Questionable value
N-1 - Not instrumented

TABLE 4. INCIDENT OVERPRESSURE AND IMPULSE AT FREE-FIELD STATIONS (CONT)

Test	Station 5		Station 6		Station 7		Station 8	
	Distance 5.75		Distance 7.90		Distance 10.3		Distance 17.8	
No.	P_s kPa	I_s kPa-ms	P_s kPa	I_s kPa -ms	P_s kPa	I_s kPa-ms	P_s kPa	I_s kPa-ms
1	39	45	25	34	13.9	24.4	6.1	15.0
2	40	43	26	35	14.5	25.3	5.9	15.1
3	42	45	26	36	14.1	25.3	6.2	15.1
4	41	49	25	35	13.1	25.3	7.4	15.4
5	41	46	25	35	13.7	25.6	5.8	14.8
6	39	45	25	35	13.6	25.1	5.7	14.9
7	39	47	25	35	13.9	25.6	6.7	15.2
8	39	47	25	35	13.5	25.9	5.2	15.5
9	40	47	24	34	14.4	24.4	N-1	N-1
10	38	46	25	35	13.6	24.8	N-1	N-1
11	40	47	24	36	14.2	25.5	5.9	15.2
12	41	49	25	35	14.6	26.1	6.1	15.8
13	39	47	25	36	14.0	26.0	5.9	15.5
14	41	47	24	36	14.7	26.7	6.9	16.2
15	41	47	24	36	14.9	25.9	6.7	16.1
AVG	40.0	46.5	24.9	35.2	14.1	25.4	6.27	15.4

N-1 - Not instrumented

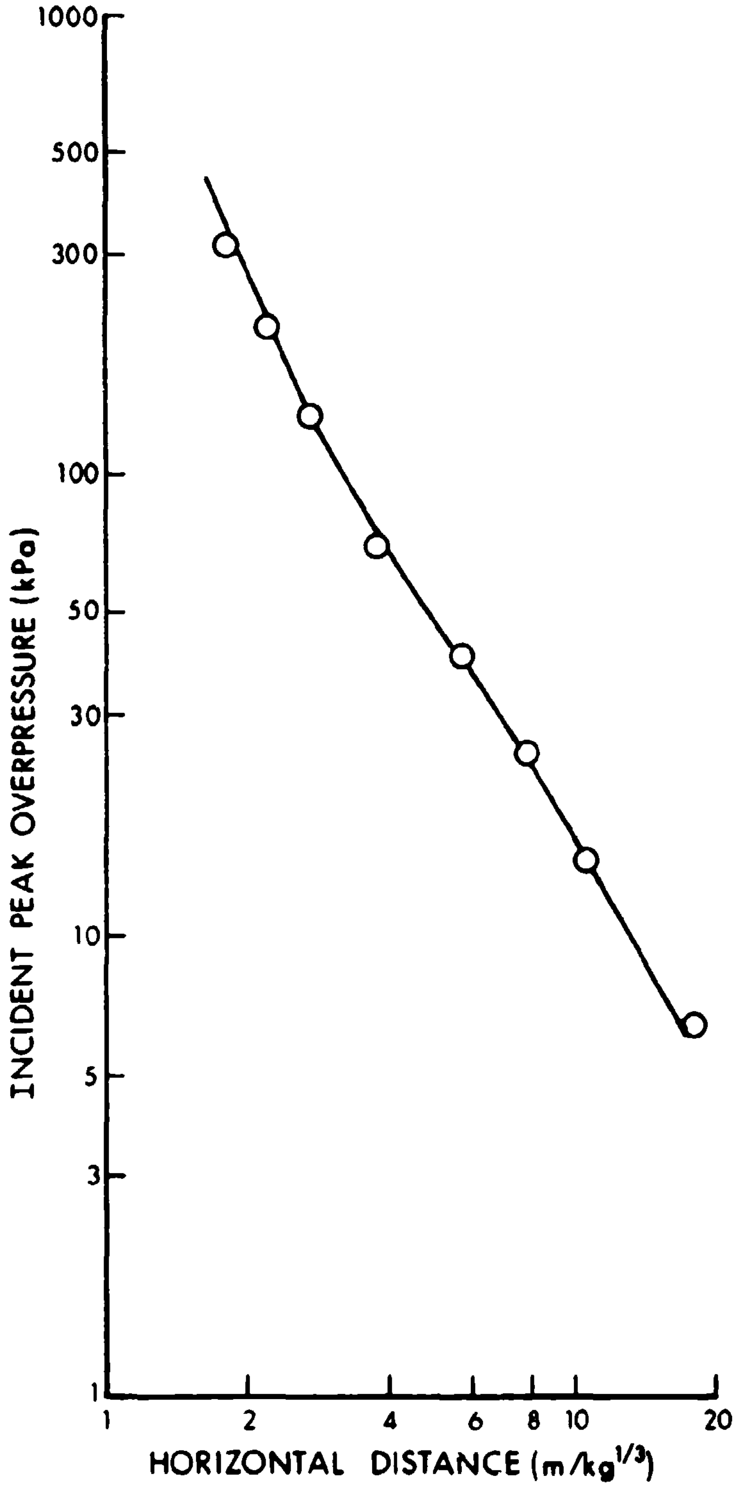

Figure 10. Peak Incident Overpressure versus Scaled Distance for a 1 kg Hemispherical Surface Burst.

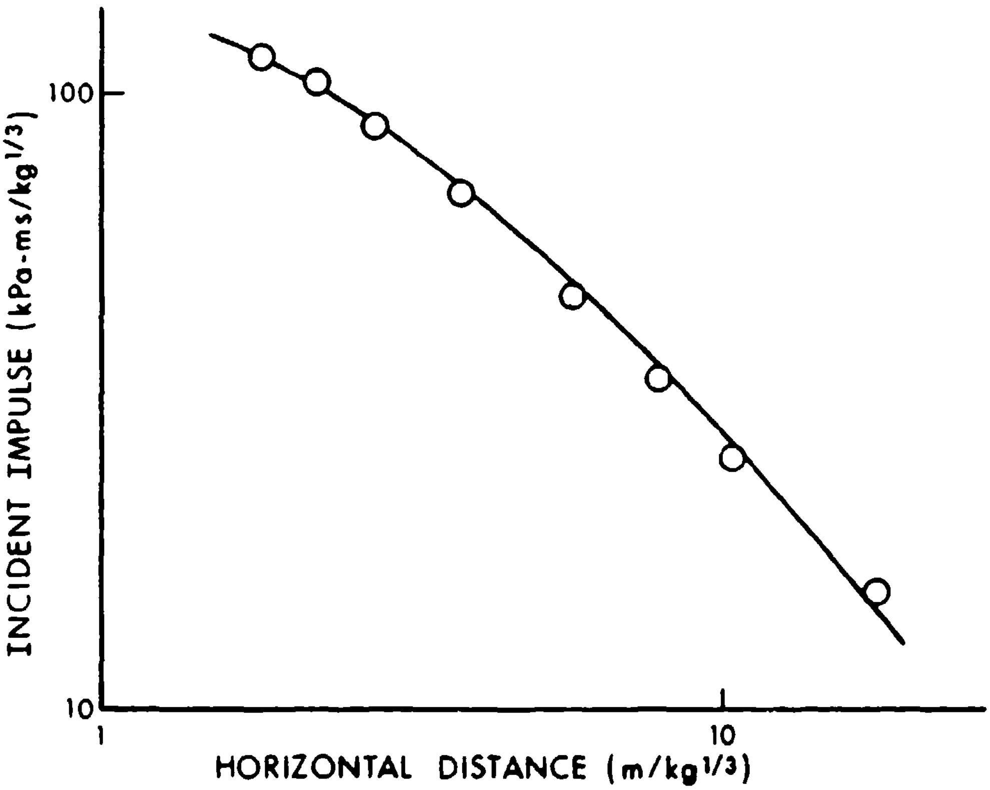

Figure 11. Incident Scaled Impulse versus Scaled Distance for a 1 kg Hemispherical Surface Burst.

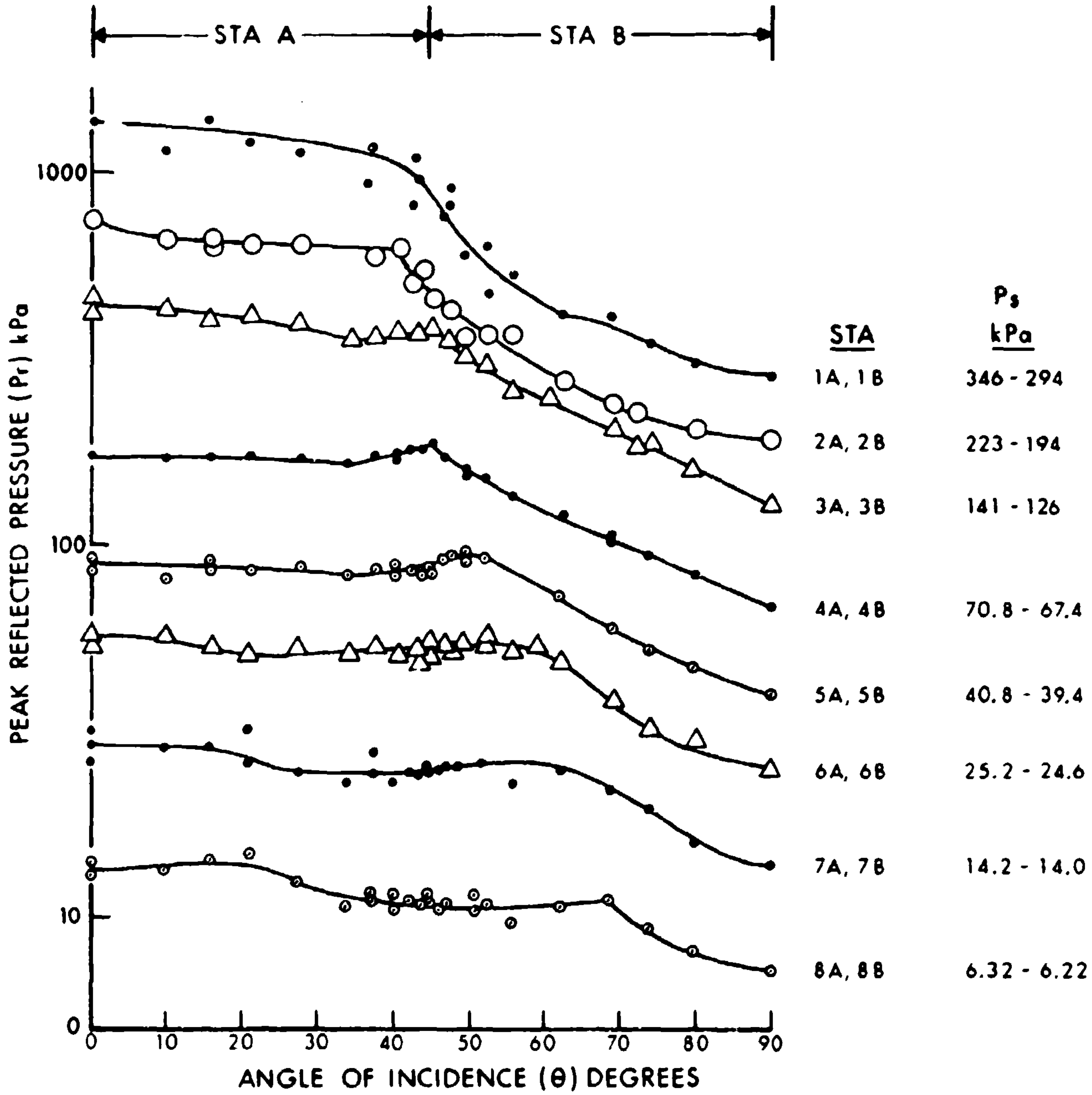

Figure 12. Peak Reflected Pressure versus Angle of Incidence for Stations 1 through 8.

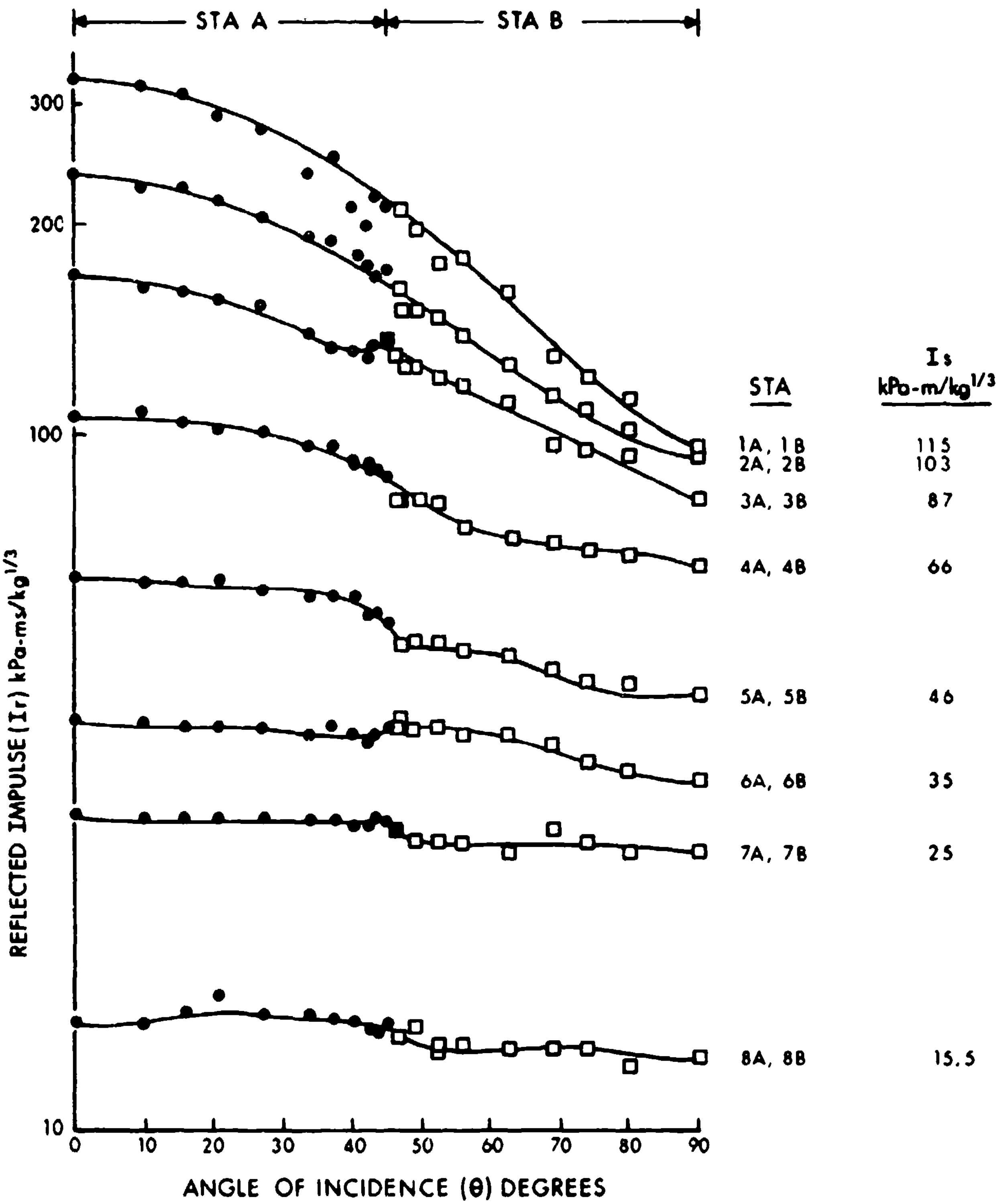

Figure 13. Scaled Reflected Impulse versus Angle of Incidence for Stations 1 through 8.

TABLE 5. REFLECTED PRESSURE AND IMPULSE RATIOS VERSUS ANGLE OF INCIDENCE

Station 1A, $P_s^* = 346$, $I_s^* = 118$					Station 1B, $P_s = 294$, $I_s = 113$				
Angle of Incidence degrees	REFL PRESS P_r kPa	PRESS REFL FACTOR P_r/P_s	REFL IMP I_r kPa-ms/kg$^{1/3}$	IMP REFL FACTOR I_r/I_s	Angle of Incidence degrees	REFL PRESS P_r kPa	PRESS REFL FACTOR P_r/P_s	REFL IMP I_r kPa-ms/kg$^{1/3}$	IMP REFL FACTOR I_r/I_s
0	1367	3.95	331	2.81	90	294	1.00	97	0.86
10	1310	3.81	325	2.75	80	310	1.06	114	1.01
16	1300	3.79	315	2.67	74	350	1.14	122	1.07
21	1280	3.74	291	2.47	69	390	1.25	130	1.14
27.5	1240	3.66	279	2.38	62.5	440	1.39	162	1.41
34	1200	3.57	237	2.03	56	500	1.56	180	1.55
37.5	1130	3.39	256	2.19	52.5	570	1.76	177	1.53
40.5	1050	3.16	213	1.82	49.5	650	1.99	200	1.72
42.5	950	2.88	201	1.72	47.5	750	2.29	211	1.82
43.5	900	2.73	221	1.89	46.5	812	2.48	212	1.83
45	850	2.58	215	1.85	45	850	2.58	215	1.85

*P_s unit - kPa
I_s unit = kPa-ms

TABLE 5. REFLECTED PRESSURE AND IMPULSE RATIOS VERSUS ANGLE OF INCIDENCE (CONT)

Station 2A, P_s = 223, I_s = 105					Station 2B, P_s = 194, I_s = 100				
Angle of Incidence degrees	REFL PRESS P_r kPa	PRESS REFL FACTOR P_r/P_s	REFL IMP I_r kPa-ms/kg$^{1/3}$	IMP REFL FACTOR I_r/I_s	Angle of Incidence degrees	REFL PRESS P_r kPa	PRESS REFL FACTOR P_r/P_s	REFL IMP I_r kPa-ms/kg$^{1/3}$	IMP REFL FACTOR I_r/I_s
0	760	3.41	240	2.29	90	194	1.00	94	0.94
10	690	3.09	232	2.21	80	205	1.03	104	1.03
16	650	2.93	230	2.19	74	224	1.11	110	1.09
21	650	2.94	220	2.10	69	240	1.18	116	1.14
27.5	650	2.95	210	2.02	62.5	277	1.34	129	1.26
34	640	2.94	195	1.88	56	325	1.55	140	1.36
37.5	620	2.86	192	1.85	52.5	370	1.75	149	1.45
40.5	510	2.59	183	1.76	49.5	410	1.93	152	1.48
42.5	520	2.42	175	1.68	47.5	430	2.02	151	1.47
43.5	520	2.33	170	1.65	46.5	460	2.16	164	1.59
45	480	2.25	173	1.68	45	480	2.25	173	1.68

TABLE 5. REFLECTED PRESSURE AND IMPULSE RATIOS VERSUS ANGLE OF INCIDENCE (CONT)

Station 3A, P_s = 141, I_s = 88					Station 3B, P_s = 126, I_s = 84				
Angle of Incidence degrees	REFL PRESS P_r kPa	PRESS REFL FACTOR P_r/P_s	REFL IMP I_r kPa-ms/kg$^{1/3}$	IMP REFL FACTOR I_r/I_s	Angle of Incidence degrees	REFL PRESS P_r kPa	PRESS REFL FACTOR P_r/P_s	REFL IMP I_r kPa-ms/kg$^{1/3}$	IMP REFL FACTOR I_r/I_s
0	433	3.07	172	1.95	90	126	1.00	81	0.96
10	431	3.06	165	1.88	80	160	1.25	94	1.11
16	420	2.98	163	1.85	74	184	1.40	96	1.13
21	405	2.89	159	1.81	69	206	1.57	97	1.13
27.5	390	2.81	155	1.76	62.5	235	1.77	112	1.30
34	360	2.61	140	1.59	56	275	2.05	118	1.36
37.5	365	2.64	134	1.52	52.5	305	2.26	123	1.41
40.5	380	2.77	134	1.54	49.5	330	2.43	127	1.46
42.5	380	2.77	131	1.51	47.5	348	2.56	127	1.46
43.5	385	2.81	136	1.56	46.5	362	2.66	131	1.51
45	390	2.87	138	1.59	45	390	2.87	138	1.59

TABLE 5. REFLECTED PRESSURE AND IMPULSE RATIOS VERSUS ANGLE OF INCIDENCE (CONT)

Station 4A, P_s = 70.8, I_s = 69					Station 4B, P_s = 67.4, I_s = 67				
Angle of Incidence degrees	REFL PRESS P_r kPa	PRESS REFL FACTOR P_r/P_s	REFL IMP I_r kPa-ms/kg$^{1/3}$	IMP REFL FACTOR I_r/I_s	Angle of Incidence degrees	REFL PRESS P_r kPa	PRESS REFL FACTOR P_r/P_s	REFL IMP I_r kPa-ms/kg$^{1/3}$	IMP REFL FACTOR I_r/I_s
0	177	2.50	107	1.55	90	69	1.02	64	0.96
10	175	2.48	109	1.58	80	84	1.25	67	1.00
16	178	2.52	106	1.54	74	92	1.35	68	1.00
21	178	2.52	103	1.49	69	103	1.50	70	1.03
27.5	172	2.44	101	1.46	62.5	122	1.77	72	1.06
34	161	2.38	96	1.39	56	138	1.99	74	1.07
37.5	176	2.52	97	1.41	52.5	157	2.26	82	1.21
40.5	178	2.55	92	1.33	49.5	164	2.36	82	1.19
42.5	183	2.61	91	1.32	47.5	172	2.47	80	1.16
43.5	183	2.61	90	1.30	46.5	173	2.48	81	1.17
45	189	2.71	89	1.29	45	189	2.71	89,	1.29

TABLE 5. REFLECTED PRESSURE AND IMPULSE RATIOS VERSUS ANGLE OF INCIDENCE (CONT)

Station 5A, P_s = 40.8, I_s = 47					Station 5B, P_s = 39.4, I_s = 46				
Angle of Incidence degrees	REFL PRESS P_r kPa	PRESS REFL FACTOR P_r/P_s	REFL IMP I_r kPa-ms/kg$^{1/3}$	IMP REFL FACTOR I_r/I_s	Angle of Incidence degrees	REFL PRESS P_r kPa	PRESS REFL FACTOR P_r/P_s	REFL IMP I_r kPa-ms/kg$^{1/3}$	IMP REFL FACTOR I_r/I_s
0	93	2.28	63	1.34	90	40	1.02	42	0.91
10	89	2.18	62	1.32	80	48	1.21	44	0.96
16	88	2.16	62	1.32	74	52	1.31	44	0.96
21	87	2.14	62	1.32	69	60	1.50	41	1.00
27.5	88	2.16	60	1.28	62.5	73	1.83	48	1.04
34	84	2.07	59	1.25	56	83	2.06	49	1.04
37.5	85	2.10	59	1.25	52.5	91	2.26	50	1.06
40.5	87	2.15	59	1.25	49.5	94	2.34	50	1.06
42.5	86	2.13	55	1.17	47.5	93	2.31	49	1.04
43.5	85	2.10	56	1.19	46.5	91	2.25	50	1.06
45	88	2.18	54	1.15	45	88	2.18	54	1.15

TABLE 5. REFLECTED PRESSURE AND IMPULSE RATIOS VERSUS ANGLE OF INCIDENCE (CONT)

Station 6A, P_s = 25.2, I_s = 35					Station 6B, P_s = 24.6, I_s = 35				
Angle of Incidence degrees	REFL PRESS P_r kPa	PRESS REFL FACTOR P_r/P_s	REFL IMP I_r kPa-ms/kg$^{1/3}$	IMP REFL FACTOR I_r/I_s	Angle of Incidence degrees	REFL PRESS P_r kPa	PRESS REFL FACTOR P_r/P_s	REFL IMP I_r kPa-ms/kg$^{1/3}$	IMP REFL FACTOR I_r/I_s
0	56	2.22	39	1.11	90	25	1.02	32	0.91
10	56	2.22	39	1.11	80	29	1.17	33	0.94
16	52	2.06	38	1.09	74	32	1.30	34	0.97
21	50	1.98	38	1.09	69	38	1.53	36	1.03
27.5	52	2.07	38	1.09	62.5	48	1.93	37	1.06
34	51	2.03	37	1.06	56	52	2.09	37	1.06
37.5	52	2.07	38	1.09	52.5	54	2.17	38	1.09
40.5	50	2.00	37	1.06	49.5	53	2.12	38	1.09
42.5	50	2.00	36	1.03	47.5	51	2.04	39	1.11
43.5	50	2.00	36	1.03	46.5	52	2.08	38	1.09
45	52	2.08	38	1.09	45	52	2.08	38	1.09

TABLE 5. REFLECTED PRESSURE AND IMPULSE RATIOS VERSUS ANGLE OF INCIDENCE (CONT)

Station 7A, P_s = 14.2, I_s = 25					Station 7B, P_s = 14.0, I_s = 25				
Angle of Incidence degrees	REFL PRESS P_r kPa	PRESS REFL FACTOR P_r/P_s	REFL IMP I_r kPa-ms/kg$^{1/3}$	IMP REFL FACTOR I_r/I_s	Angle of Incidence degrees	REFL PRESS P_r kPa	PRESS REFL FACTOR P_r/P_s	REFL IMP I_r kPa-ms/kg$^{1/3}$	IMP REFL FACTOR I_r/I_s
0	30	2.11	28.7	1.15	90	14	1.00	25.0	1.00
10	29	2.04	28.0	1.12	80	16	1.14	25.0	1.00
16	29	2.04	28.0	1.12	74	20	1.43	26.0	1.04
21	29	2.04	28.0	1.12	69	22	1.57	27.0	1.08
27.5	26	1.83	28.0	1.12	62.5	25	1.79	25.0	1.00
34	25	1.77	28.0	1.12	56	26	1.84	26.0	1.04
37.5	26	1.84	28.0	1.12	52.5	26	1.84	26.0	1.04
40.5	25	1.77	27.5	1.10	49.5	26	1.84	26.0	1.04
42.5	25	1.77	27.5	1.10	47.5	26	1.84	26.0	1.04
43.5	25	1.77	28.0	1.12	46.5	25	1.80	27.0	1.08
45	25	1.80	28.0	1.12	45	25	1.80	28.0	1.12

TABLE 5. REFLECTED PRESSURE AND IMPULSE RATIOS VERSUS ANGLE OF INCIDENCE (CONT)

Station 8A, $P_s = 6.32$, $I_s = 15.5$					Station 8B, $P_s = 6.22$, $I_s = 15.4$				
Angle of Incidence degrees	REFL PRESS P_r kPa	PRESS REFL FACTOR P_r/P_s	REFL IMP I_r kPa-ms/kg$^{1/3}$	IMP REFL FACTOR I_r/I_s	Angle of Incidence degrees	REFL PRESS P_r kPa	PRESS REFL FACTOR P_r/P_s	REFL IMP I_r kPa-ms/kg$^{1/3}$	IMP REFL FACTOR I_r/I_s
0	13.2	2.09	14.2	0.92	90	7.2	1.16	12.6	0.82
10	13.5	2.14	14.2	0.92	80	8.2	1.31	12.2	0.79
16	14.0	2.21	14.8	0.95	74	9.9	1.58	13.2	0.86
21	14.0	2.21	15.6	1.01	69	11.0	1.76	13.1	0.85
27.5	12.4	1.97	14.6	0.94	62.5	10.9	1.74	13.1	0.85
34	11.2	1.77	14.5	0.94	56	10.5	1.67	13.1	0.85
37.5	11.3	1.79	14.5	0.94	52.5	10.9	1.74	13.0	0.84
40.5	11.3	1.79	14.4	0.93	49.5	11.0	1.75	14.0	0.91
42.5	11.1	1.76	13.9	0.90	47.5	11.0	1.75	13.5	0.88
43.5	10.8	1.72	13.8	0.89	46.5	11.0	1.75	13.5	0.88
45	11.4	1.81	14.3	0.93	45	11.4	1.81	14.3	0.93

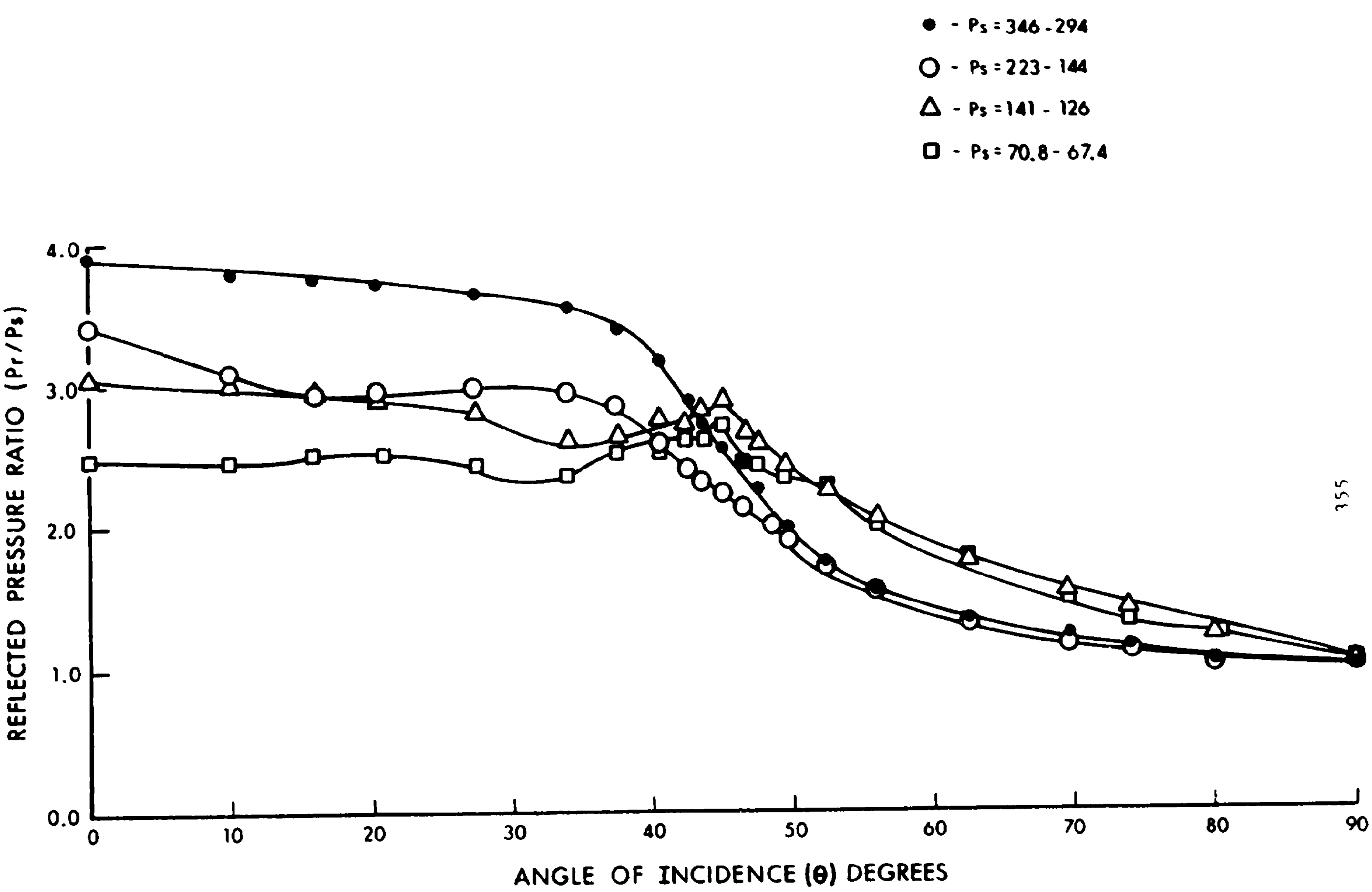

Figure 14. Reflected Pressure Ratios (P_r/P_s) versus Angle of Incidence for P_s from 346 kPa to 67.4 kPa.

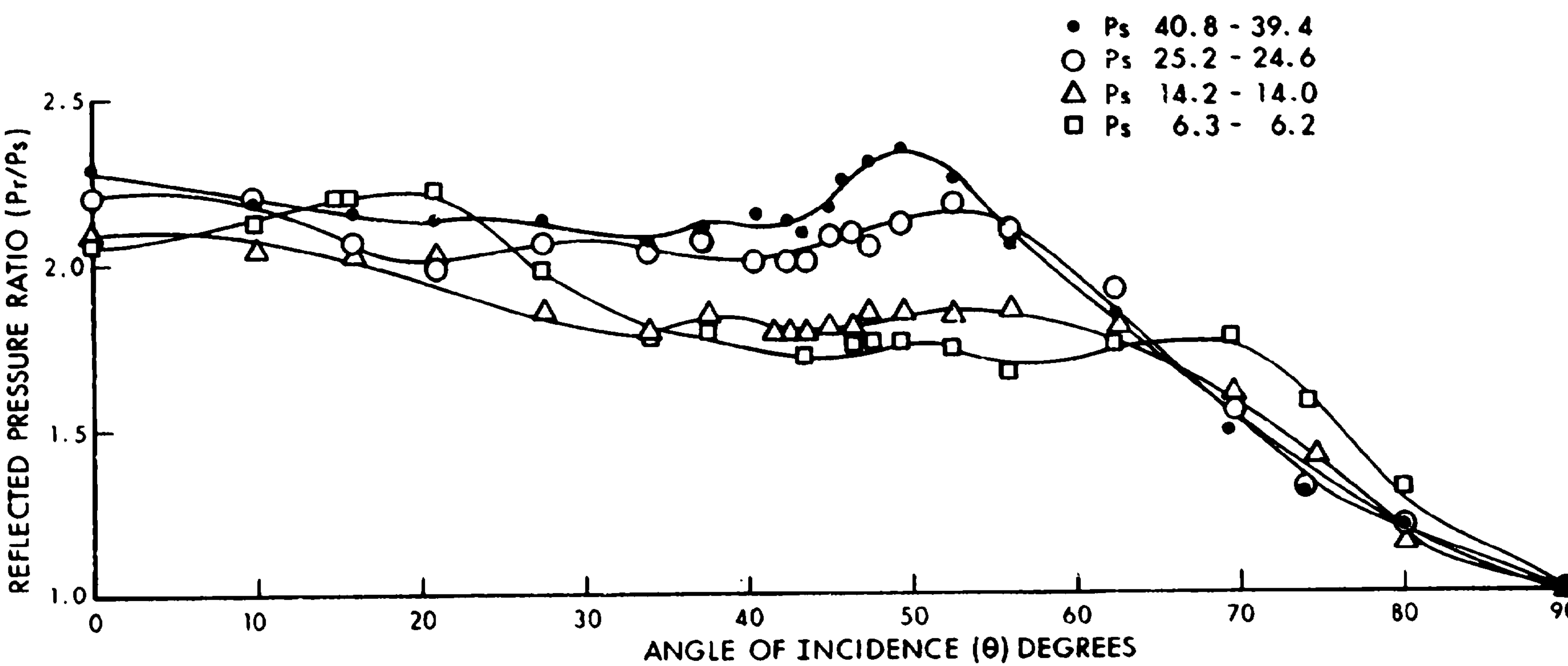

Figure 15. Reflected Pressure Ratios (P_r/P_s) versus Angle of Incidence for P_s from 40.8 kPa to 6.2 kPa.

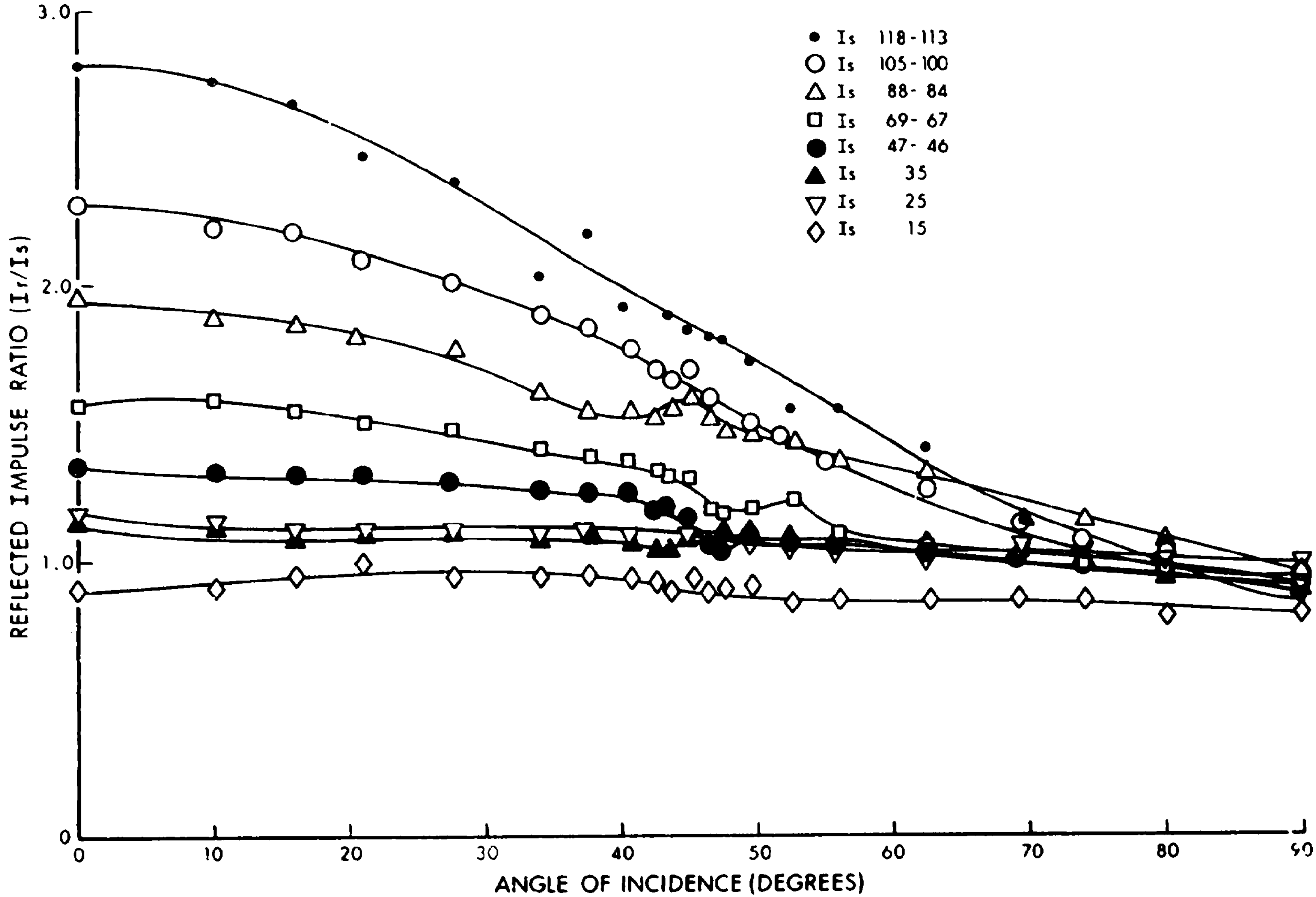

Figure 16. Reflected Impulse Ratios (I_r/I_s) versus Angle of Incidence.

IV. DISCUSSION

The data tables and plotted curves presented in the Results Section show trends of the effects on reflected pressure and impulse, of the angle of incidence of the shock front striking an isolated structure. Some of these trends follow theory and predictions as presented in the Predictive Approach of the Test Procedures Section while other results are different.

A. Reflected Pressure in the Regular and Mach Reflection Region

The curve showing reflective pressure (P_r) as a function of incident pressure (P_s) for all angles of incidence in the regular reflection region is shown in Figure 17. This curve is quite similar to the family of curves presented in Figure 7. Note in Figure 7 the slope angles are identified rather than the angle of incidence. The spread of data is indicated by the band at each station location. This means that when a particular station receives the same incident pressure (P_s) and as the model is rotated to change the angle of incidence the reflected pressure (P_r) does not change greatly in the regular reflection region. This is shown graphically in Figure 12.

The family of curves presented in Figure 18 show a trend similar to that presented in Figure 8, for pressure enhancement in the Mach reflection region. The quantitative values are higher in Figure 8, than measured experimentally in Figure 18. This difference is because the measured values from this series did not record the enhancement at the transition zone from the regular reflection region to the Mach reflection region as shown in Figure 9. The enhancement shown in Figure 9 is of very short duration and would have little effect on impulse in the blast wave.

B. Reflected Impulse in the Regular and Mach Reflection Regions

The reflected impulse versus incident impulse and angle of incidence is presented in Figure 13. A variation of this presentation is made in Figure 19 where the data is plotted for reflected impulse I_r, as a function of incident impulse (I_s) in the regular reflection region. The two solid lines show the variation in reflected impulse measured on an isolated structure when the angle of incidence is in the regular reflection region.

The dashed line presented in Figure 19 is to show the difference in the zero degree or head-on reflected impulse on an infinite plane and that recorded on a finite model. The lower values recorded on the model are because of the arrival of the rarefaction waves from the sides of the structure causes an increase in the rate of decay of the reflected pressure which produces a lower reflected impulse.

The reflected impulse recorded in the Mach reflection region is plotted in Figure 13 and presented in a different manner in Figure 20. In this figure the enhancement of reflected impulse becomes less as the angle of incidence approaches 90 degrees, or side-on conditions. The vortex from the front corner of the structure causes a lowering of the overpressure during the passage of the blast wave and the reflected impulse becomes less than the side-on impulse at an angle of incidence of 90 degrees. This is also true at some of the values measured at an 80 degree angle of incidence.

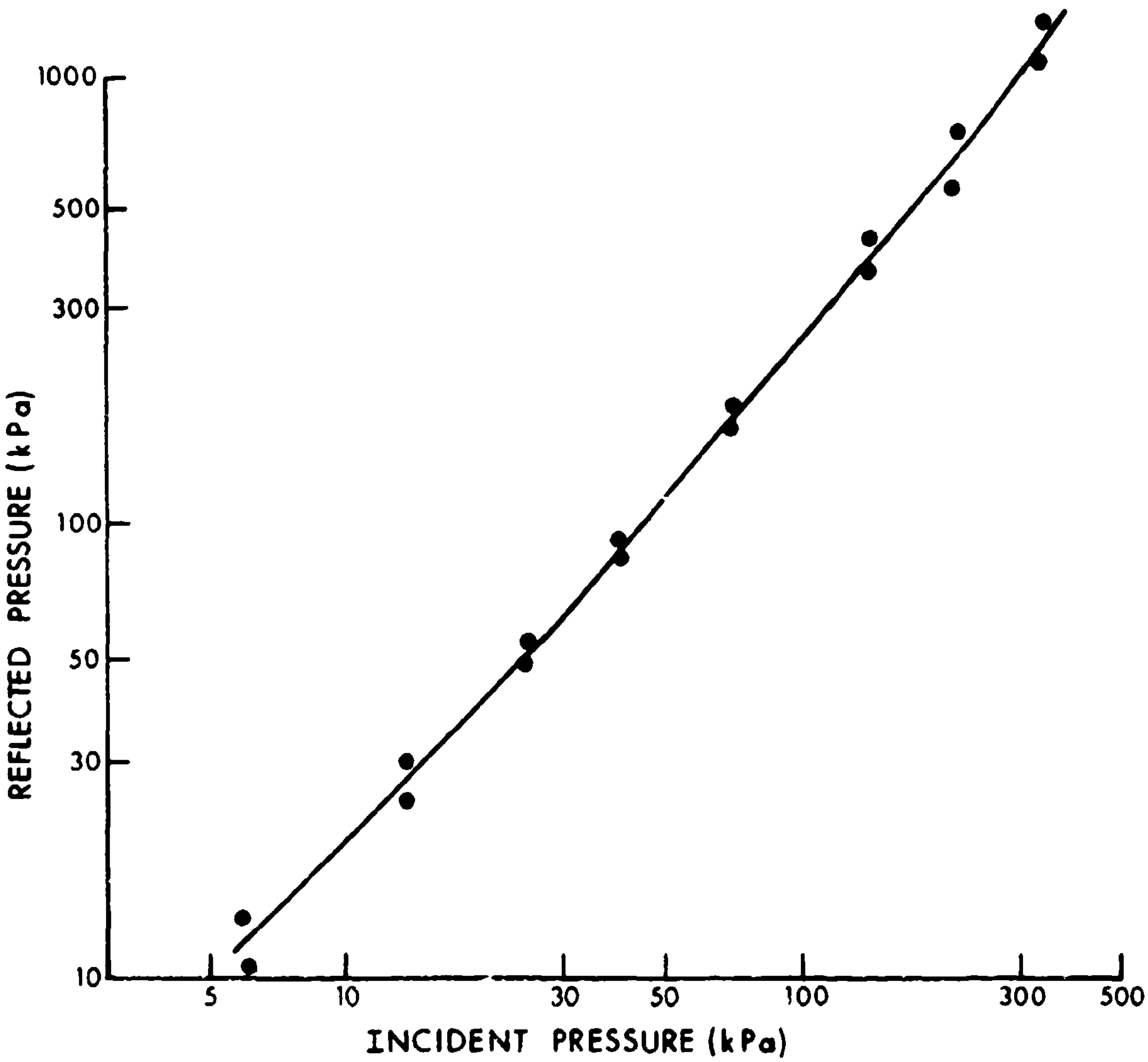

Figure 17. Reflected Pressure versus Incident Pressure in the Regular Reflection Region.

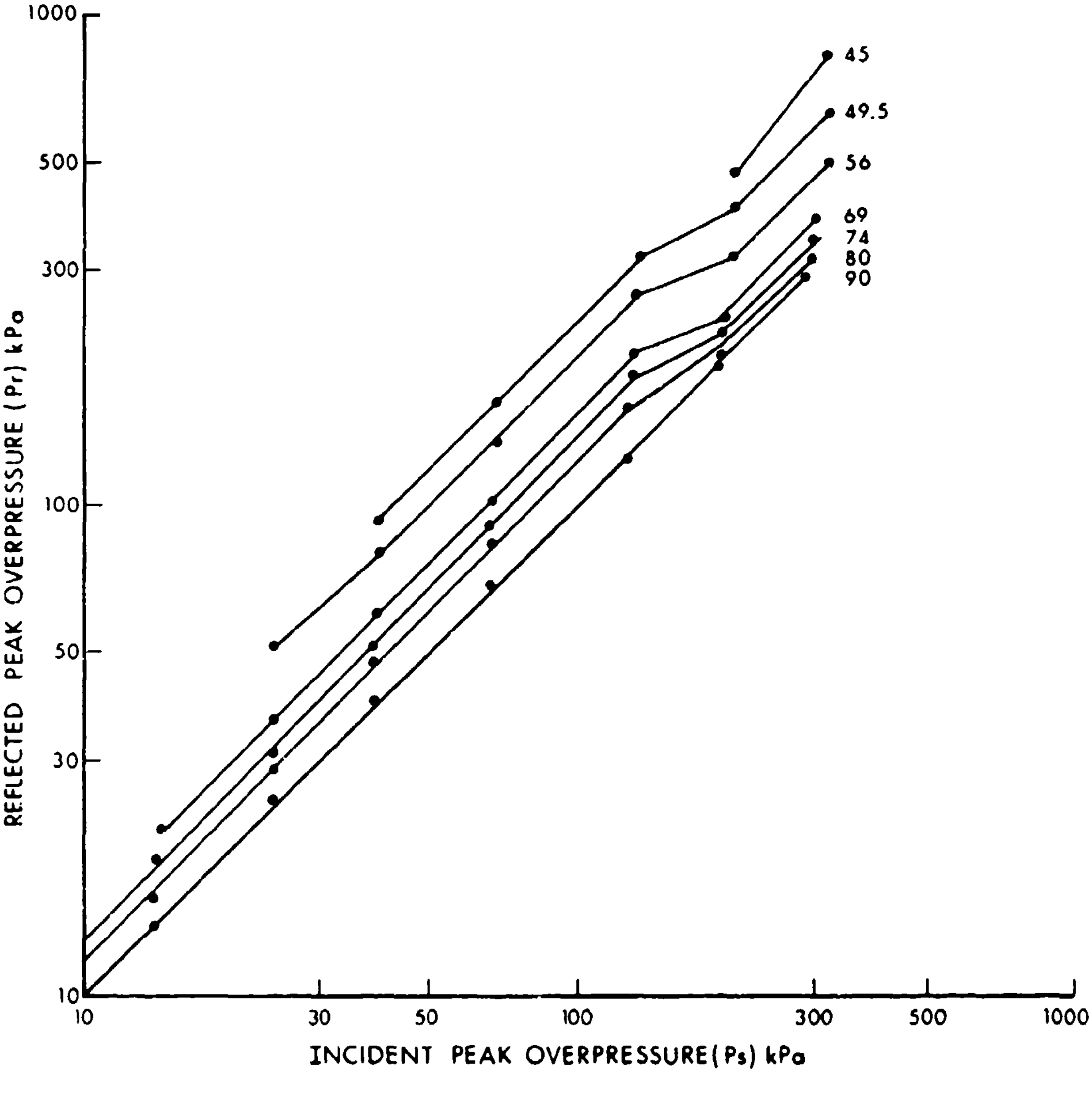

Figure 18. Reflected Pressure (P_r) versus Incident Pressure (P_s) in the Mach Reflection Region as a Function of Angle of Incidence.

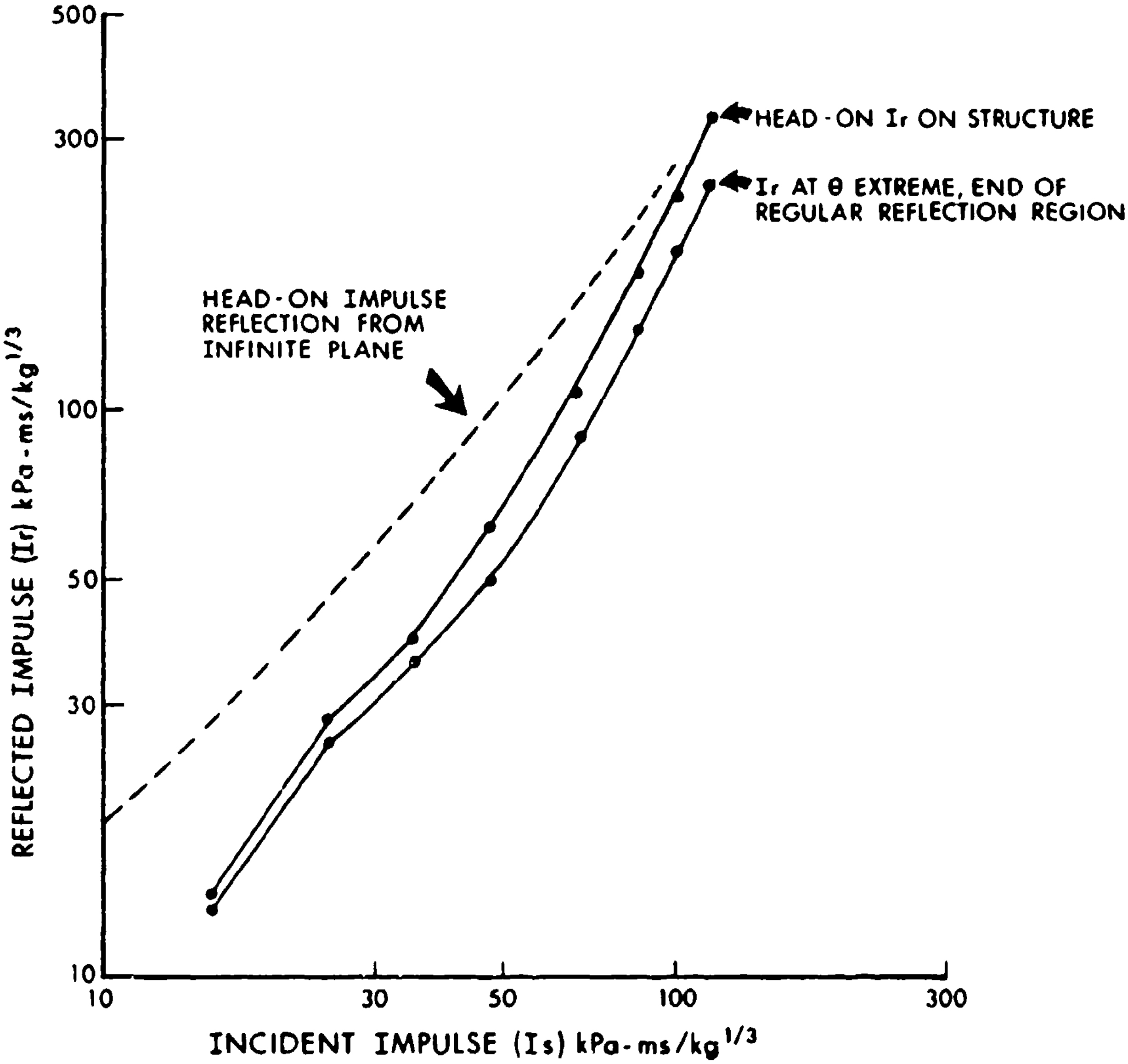

Figure 19. Scaled Reflected Impulse (I_r) versus Scaled Incident Impulse (I_s) in the Regular Reflection Region.

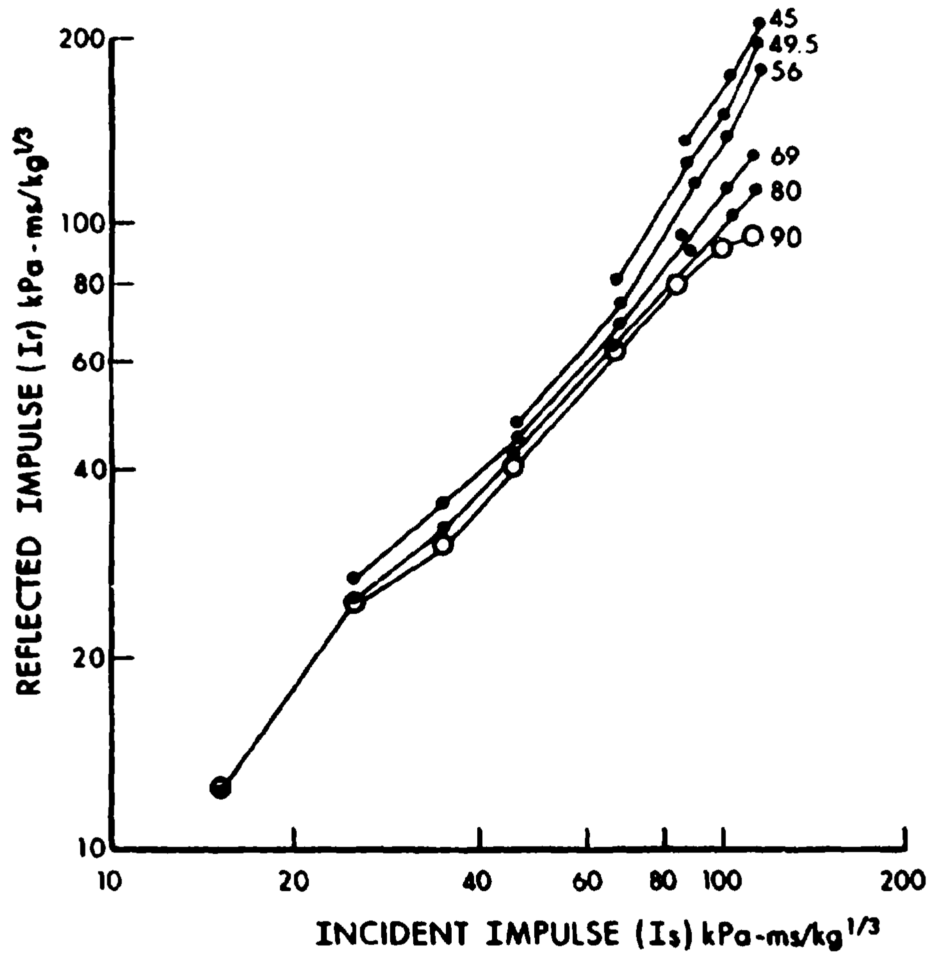

Figure 20. Scaled Reflected Impulse (I_r) versus Scaled Incident Impulse (I_s) in the Mach Reflection Region as a Function of Angle of Incidence.

V. CONCLUSIONS

The results presented in this report are based on one size structure and one charge mass. Therefore they cannot be applied in general to all size structures and all charge masses. The model was 0.3048m x 0.3048m x 0.4572m exposed to a 1 kg charge mass. This means the results could be applied to structures where the size is increased by the cube root of the charge mass. For example, a 1000 kg charge mass and a 3.048 metre structure or a 125000 kg charge and a 15.24 metre structure or a 512000 kg charge mass and a 24.38 metre structure 36.58 metres high. Care would have to be exercised in applying the results to other combinations of charge mass and structure dimensions. If a charge mass is held constant and the structure size increased, the reflected impulse values in the regular reflection region would approach the infinite plane case.

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The authors also wish to acknowledge the work of Mr. K. Holbrook, technician and explosives handles for the excellent job done in site preparation, blast line installation, and model instrumentation and placement.

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Effect of Frangible Panels on Internal Gas Pressures

by

J.E. Tancreto and E.S. Helseth

1.0 INTRODUCTION

A frangible panel in a structure is an exterior surface designed to break loose and blow away quickly enough to limit effects from an explosion inside the structure. Typical frangible panels are lightweight, compared to other surfaces of the structure. Panel connections are designed to offer little resistance to motion from internal loads. Frangible panels may be located in any surface of the structure.

Frangible panels are used primarily to limit the internal blast environment, reduce the debris hazard to personnel and property outside the structure, and vent effects of explosions inside hardened structures in prescribed directions away from the structure. Typical uses of frangible panels are illustrated in Figures 1 and 2.

An ideal frangible panel is one that does not increase the internal blast environment. This requires a massless panel that is a nonreflecting surface for shock waves. Since any panel will have mass, frangible panels must be designed on a case-by-case basis and their effects on the internal blast environment accounted for in the design of the structure.

The design of a frangible panel and prediction of the internal blast environment must account for several parameters related to the characteristics of the structure, frangible panel, and explosive. Important parameters of the structure are the volume of the structure,

$V(ft^3)$, and the area of the frangible opening, $A(ft^2)$. Important parameters of the frangible panel are the mass of the panel, γ (lb/ft^2), and the initial distance, X_o, that the panel must displace before gases can begin venting through the frangible opening. Important parameters of the explosive are the net weight of explosive, W (lb TNT equivalent), and location of the charge relative to the frangible panel, expressed in terms of the reflected shock impulse on the frangible panel, i_r (psi-msec). The following sections develop theory and present charts that account for effects of these parameters on the internal blast environment and the design of frangible panels.

2.0 GAS PRESSURE LOADING

2.1 Fixed Vent Area

Consider the structures shown in Figures 1 and 2 with the frangible panels removed. Assume the mass and strain energy capacity of the structure are such that the only path for internal gases to escape from the structure is through the opening provided by removal of the frangible panel. Thus, the structure has a constant vent area, A, and constant structure volume, V. If the explosive is not TNT it must be converted into a TNT equivalent weight for gas pressure calculations. See Section 4.0 for the calculation procedure.

Given detonation of the equivalent TNT explosive weight, W, the resulting peak gas pressure, P_g, gas duration, t_g', and total gas impulse, i_g, inside the structure are:

$$P_g = f(W/V), \text{ Figure 3} \tag{1}$$

$$\frac{A}{V^{2/3}} \le 0.10 :$$

$$\frac{t_g'}{W^{1/3}} = 2.26 \left(\frac{A}{V^{2/3}}\right)^{-0.86} \left(\frac{W}{V}\right)^{-0.29} \tag{2}$$

$$\frac{i_g}{W^{1/3}} = a\left(\frac{A}{V^{2/3}}\right)^{-0.77}\left(\frac{W}{V}\right)^{b} \qquad (3)$$

$$\frac{A}{V^{2/3}} > 0.10 :$$

$$\frac{t_g'}{W^{1/3}} = \left(\frac{W}{V}\right)^{-.29} \exp\left[\frac{1}{0.01237\ \ell n \frac{A}{V^{2/3}} - 0.09825} + 10.6864\right] \qquad (2a)$$

$$\frac{i_g}{W^{1/3}} = a\left(\frac{W}{V}\right)^{b} \exp\left[\frac{1}{0.02061\ \ell n \frac{A}{V^{2/3}} - 0.11614} + c\right] \qquad (3a)$$

Table 1. Constants in Gas Pressure-Time Equations 2 and 3

W/V	a	b	c
W/V < 0.015	1,855	0.36	15.41135
0.015 ≦ W/V ≦ 0.15	409	0	13.89943
W/V > 0.15	643	0.24	14.35186

Equations 1 through 3 are empirical relationships derived from the gas pressure history measured inside a structure with A, V and W held constant in each test but varied between tests.

Given the time constant, α, describing the rate of exponential decay of gas pressure inside the structure, the gas pressure, P_g, inside the structure at any time, t, is:

$$P_g(t) = P_g\left(1 - \frac{t}{t_g}\right) e^{-\alpha(t/t_g')} \qquad (4)$$

and the corresponding total gas impulse, i_g, is:

$$\frac{i_g}{W^{1/3}} = P_g \int_0^{t_g'} (1 - \frac{t}{t_g'}) e^{-\alpha(t/t_g')} dt \qquad (5)$$

By combining Equations 1, 2, 3 and 5 it is possible to derive an explicit expression for the time constant, α. Note that α is a constant value for fixed values of A, V and W. However, in the case of an opening covered with a frangible panel, the vent area is not fixed but variable.

2.2 Variable Vent Area

In practice, a frangible panel covers the opening in a structure. Given an explosion inside the structure, the combined shock and gas pressures will force the frangible panel to move away from the opening. This motion results in a variable vent area for escaping gases. Initially, the vent area is zero. The vent area increases with time and eventually reaches a maximum value equal to the area of the frangible opening, A', as illustrated in Figure 4. Because of the variable vent area, the value of α varies with time and calculation of the gas pressure history inside the structure requires an iterative process.

The iterative process involves dividing the problem into time increments, Δt, as shown in Figure 4. At time t = 0, the reflected shock impulse applied to the frangible panel is assumed to be finite duration. Thus, the initial velocity of the panel is:

$$\dot{X}_o = \frac{144 \ g \ i_r}{Y} \qquad (6)$$

Further, the gas pressure inside the structure is assumed to reach P_g, given in Figure 3, at the end of the shock impulse. Thus, the gas pressure rises to P_g at t = 0 and then begins to decay as increasing displacement of the frangible panel provides an increasing opening for gases to vent from the structure.

Calculation of the gas pressure history involves a trial and error process. Referring to Figure 4, at time, t_i, the gas pressure, P_i, and the acceleration, velocity and displacement, X_i, of the panel, acting as a rigid plate, are known values. At time, t_{i+1}, the gas pressure, P_{i+1}, is estimated and used to calculate the displacement, X_{i+1}. During the time interval, Δt, the average panel displacement is $(X_i + X_{i+1})/2$. For an opening with a perimeter, s, the average vent area, $\bar{A}_{i+1}$, available for gases to escape from the structure is $X_i + X_{i+1})s/2$. Considering $\bar{A}_{i+1}$ to be a fixed vent area during time interval, Δt, the gas impulse, i_g, is calculated from Equation 3, the gas pressure duration, t'_g, from Equation 2, and the time constant, α_{i+1}, from Equation 5. Knowing α_{i+1}, the gas pressure, P_{i+1}, at t_{i+1} is calculated from Equation 4. The calculated value of P_{i+1} becomes the new estimated value of P_{i+1} and the above process is repeated until the difference between the estimated and computed values of P_{i+1} is within a prescribed error limit. Given agreement, time is incremented by Δt and the entire process is repeated for the next time step. If during this process $\bar{A}$ becomes equal to the area of the opening, then the effective vent area is fixed and $\bar{A} = A$ for all succeeding time intervals. The above computational process was used to generate a series of charts for a broad range of design parameters.

3.0 DESIGN LOADING

Charts are presented in Figures 5 through 16 for designing a frangible panel and predicting the gas impulse inside a structure with a frangible panel. The charts are based on the theory described in Section 2.2. The charts express the scaled gas impulse inside the structure, $i_g/W^{1/3}$, as a function of the charge density inside the structure, W/V, scaled impulse of reflected shock pressures on the frangible panel, $i_r/W^{1/3}$, scaled effective area of the frangible opening, $A/V^{2/3}$, and scaled mass of the frangible panel, $\gamma/W^{1/3}$. Table 2 lists the range of parameters and recommends the procedure for interpolating between parameters and the limits for extrapolating beyond the range of the charts.

Table 2. Range, Interpolation Procedure, and Extrapolation Limits for Chart Parameters

Parameter	Range of Charts	Interpolation Procedure	Extrapolation Limits[a]
$\frac{W}{V}\ \frac{lb}{ft^3}$	0.002 to 1.0	$Log\left(\frac{W}{V}\right)-Log\left(\frac{i_g}{W^{1/3}}\right)$	0.001 to 2.0
$\frac{i_r}{W^{1/3}}\ \frac{psi\text{-}msec}{lb^{1/3}}$	20 to 600[b]	$Log\left(\frac{i_r}{W^{1/3}}\right)-Log\left(\frac{i_g}{W^{1/3}}\right)$	10 to 2000
$\frac{\gamma}{W^{1/3}}\ \frac{lb/ft^2}{lb^{1/3}}$	0.30 to 100	$Log\left(\frac{\gamma}{W^{1/3}}\right)-Log\left(\frac{i_g}{W^{1/3}}\right)$	0.10 to 300[c]

[a] Extrapolation beyond these limits may underestimate $i_g/W^{1/3}$

[b] Range is 100 to 2,000 for charts with W/V = 1.0

[c] For $\gamma/W^{1/3} < 0.10$ use value of $i_g/W^{1/3}$ at $\gamma/W^{1/3} = 0.10$

3.1 Shock Impulse on Panel

The value of $i_r/W^{1/3}$ posted in each chart is the scaled reflected shock impulse acting on the frangible panel The value of $i_r/W^{1/3}$ should account for the mass of the frangib panel which, in most cases, does not produce full reflection of striking shock waves. Thus, the reflected shock impulse based on an infinite mass, i_r' calculated from Equation 7a, should be reduced by the shock reflection factor, f_r, and the charts entered with the value from Equation 7:

$$\frac{i_r}{W^{1/3}} = f_r\left(\frac{i_r'}{W^{1/3}}\right) \quad (7)$$

$$\frac{i_r'}{W^{1/3}} = \left(\frac{88 + 133\ Z^{1.16}}{Z^{2.22}}\right) \quad (7a)$$

$$f_r = (0.5)^{0.1424^{\log_{10}(Y/Y_{50})}} \quad (7b)$$

$$Y_{50} = W^{1/6} (i_r'/W^{1/3})^{1/2} /20 \quad (7c)$$

Equation 7b is plotted in Figure 17 to facilitate evaluation of the shock reflection factor, f_r. In Equations 7 through 7c, use W equal to the TNT equivalent design charge weight for shock impulse.

3.2 Design Loading

The combined shock and gas pressure - time loading can be idealized by overlapping the shock and gas pressure triangular loadings as shown in Figure 18. The relationships for determining P_r, and t_g, given P_g, i_g, i_r, and t_r, are:

$$P_r = 2\, i_r/t_r \quad (8)$$

$$t_g = 2\, i_g/P_g \quad (9)$$

3.3 Strain Energy of Frangible Panel

The reflected shock impulse imparts kenetic energy to the frangible panel. Some of this energy is dissipated by work done to fail the panel or its connections. The work done is equal to the strain energy capacity of the frangible panel, S.E. The balance of the energy is dissipated by work done in moving the panel away from the opening. Thus, the greater the strain energy capacity of the panel, the slower the panel moves away from the opening. The net result is slower venting of gases and more gas impulse inside the structure.

The strain energy capacity of a typical frangible panel is insignificant, compared to the kinetic energy imparted to the panel by the reflected shock impulse. In such cases, the strain energy capacity of the panel, S.E., can be ignored and Figures 5 to 16 entered with the value of $i_r/W^{1/3}$ given by Equation 7. However, if S.E. is significant, it can be accounted for by entering Figures 5 to 16 with an adjusted value of $i_r/W^{1/3}$ equal to:

$$i_r/W^{1/3} = (i_r' - i_E)/W^{1/3} \qquad (10)$$

where i_r = net impulse available to move the panel away from the opening, psi-msec

i_r' = reflected shock impulse for a panel of infinite mass, psi-msec

i_E = $2\, m_c$ (S.E.) , psi-msec

S.E. = total area under the ultimate resistance-deflection diagram for the panel, psi-in.

m_e = effective mass of the panel, psi-msec^2/in.

The strain energy capacity of the panel effects the shock reflection factor, f_r. For a fixed mass of the frangible panel, γ, the value of f_r approaches 1.0 with increasing value of S.E. For this reason, the shock reflection factor is neglected in Equation 10. It is recommended that the values of $i_r/W^{1/3}$ be calculated from Equations 7 and 10 and the lesser value used to enter Figures 5 to 16.

In the design of frangible panels, an objective is to minimize the value of S.E. in order to maximize the energy available to move the panel away from the opening. An effective scheme to accomplish this objective is to design the panel connections to fail before the ultimate flexural resistance of the panel can be developed.

3.4 Recessed Panels

If the frangible panel is recessed a distance X_o from the outside edge of the adjacent wall, then it must displace the distance X_o before venting can begin. During the time t_x that it takes the panel to move X_o, the gas pressure will be constant and equal to P_g (see Figure 3). The clearing time, t_x, can be calculated using the initial shock impulse, i_r (Equation 7), the peak gas pressure, P_g, and the unit weight of the panel, γ. The shock impulse imparts an initial velocity (see Equation 6) to the panel and P_g accelerates the panel. The clearing time is calculated from Equation 11 or 12.

$$t_x = [(i_r/P_g)^2 + (432\ \gamma\ X_o/P_g)]^{1/2} - i_r/P_g \qquad (11)$$

$$\frac{t_x}{W^{1/3}} = \left[\left(\frac{i_r/W^{1/3}}{P_g}\right)^2 + \frac{432(\gamma/W^{1/3})(X_o/W^{1/3})}{P_g}\right]^{1/2} - \frac{i_r/W^{1/3}}{P_g} \qquad (12)$$

The gas impulse developed during time t_x is:

$$i_x = P_g\ t_x \qquad (13)$$

The gas impulse, i_g, that is produced after venting begins is calculated from the impulse charts in Figures 5 to 16 using the total impulse, i_{rt}, for i_r in the charts. This impulse is used because it has produced the panel velocity at the time venting (and i_g calculation) begins.

$$i_{rt} = i_r + P_g\ t_x \qquad (14)$$

The gas impulse is the sum of those developed before and after venting begins:

$$i_{gt} = i_x + i_g \qquad (15)$$

It will usually be adequate to assume a triangular gas pressure-time history with a duration of:

$$t_g = 2\ i_{gt}/P_g \qquad (16)$$

If i_x is greater than i_g, the use of a triangular gas pressure loading function may be unconservative (since the gas pressure is constant for time t_x). Other functions should then be considered including a constant (square) P_g versus t load history with $t_g = i_{gt}/P_g$.

When P_g is determined from Figure 3, the average structure volume, during time t_x, should be used if X_o is large relative to the total length dimension. The total structure volume should be used when calculating the scaled vent area, $A/V^{2/3}$.

3.5 Effective Vent Area

The initial vent area for escaping gases is equal to the perimeter of the frangible opening multiplied by the displacement of the frangible panel, but is never greater than the area of the frangible opening, A. The design charts in Figures 5 to 16 are based on a single square opening with a perimeter equal to $4A^{1/2}$. If the design opening is not square, then the charts will be conservative if the perimeter of the opening is greater than that for a square area (e.g., a rectangle) and slightly unconservative if the perimeter of the opening is less than that for a square area (e.g., a circle). This effect will only be significant if highly elongated vent areas are used. For example, if the aspect ratio of a rectangular vent area is less than about 5, the results would be conservative by less than 10%. Multiple openings can be analyzed by summing areas and using the total area to determine gas impulse.

Since the vent perimeter is only a factor when the venting around the panel is less than the vent area, A, the effect becomes negligible if the scaled vent area is less than about 0.1 (the time for the frangible panel to displace and allow full venting through A is relatively short compared to the gas pressure duration). If $A/V^{2/3}$ is greater than 0.1 and the square of the perimeter of the opening divided by $16 \cdot (S^2/16)$ exceeds 2 times A, then errors could be more than 10%, but they would be conservative.

3.6 Frangibility Criteria

The frangibility of a panel depends on its effect on the blast environment inside the structure. Since this effect is a function of many parameters (γ, W, V, A, i_r, X_o, and S.E.), it is difficult to define frangibility in terms of physical parameters. However, frangibility can be defined in terms of performance criteria. For example, the less the panel increases the total gas impulse inside the structure, the greater the frangibility of the panel. A fully frangible panel could be defined as a panel for which the gas impulse inside the structure is increased no more than 5% over the gas impulse without a panel. This definition can only be satisfied at small scaled vent areas where the mass of the panel does not greatly affect the loads but where large gas impulses occur in any case.

In practice, there are no fully frangible panels. However, they are used to either reduce the design blast loads on hardened surfaces of a structure or to reduce the maximum strike range of debris missiles from an unhardened structure (by limiting the total impulse on interior surfaces and thereby limiting the maximum launch velocity of debris). In such cases, the effects of the panel are accounted for in the design process and the definition of frangibility is irrelevant in the design process.

4.0 EQUIVALENT WEIGHT OF TNT

Southwest Research Institute gives the following procedure for determining the equivalent TNT weight of an explosive for gas pressure calculations.

The data used by SwRI to prepare Figure 3 are for $0 \leq A/V^{2/3} \leq 0.022$ and for TNT charges only. To use Figures 3 and 5 through 16 for an explosive type other than TNT, the charge weight must be converted to an equivalent TNT charge weight W for the gas loading phase as follows:

$$W = \frac{\phi \left[H_C^{\,C} - H_D^{\,C} \right] + H_D^{\,C}}{\phi \left[H_C^{\,TNT} - H_D^{\,TNT} \right] + H_D^{\,TNT}} W_C \qquad (17)$$

where ϕ is the TNT conversion factor, W is the equivalent TNT charge weight for gas loading phase, W_C is the weight of the explosive, H_C^{TNT} is the heat of combustion of TNT, H_C^{C} is the heat of combustion of the charge, H_D^{TNT} is the heat of detonation of TNT, and H_D^{C} is the heat of detonation of the charge. The value of ϕ is determined using Figure 19.

5.0 LIST OF SYMBOLS

A'	Area of the opening without the frangible panel, ft^2
A	Effective area of a square opening and pseudo area of a nonsquare opening, ft^2
a,b,c	Constants in Equations 2 and 3
f_r	Fraction of reflected shock impulse on frangible panel
f_s	Shock reflection factor that accounts for mass effects
g	Gravity = 32.2×10^{-6}, $ft/msec^2$
H_C	Heat of combustion
H_D	Heat of detonation
i_g	Total gas impulse, psi-msec
i'_r	Total reflected-shock impulse on stationary surface, psi-msec
i_r	Reduced reflected shock impulse on frangible panel, psi-msec
i_x	Gas impulse developed during t_x for recessed panel.
i_T	Total impulse; sum of reflected-shock plus gas impulses, psi-msec
l	Length of frangible opening, ft
P(t)	Pressure at time t, psi
P_g	Peak gas pressure extrapolated to time t = 0, psi
$P_g(t)$	Gas pressure at any time t, psi
P_r	Peak reflected-shock pressure, psi
$P_r(t)$	Reflected-shock pressure at any time t, psi

R	Distance from center of explosive to frangible panel, ft
s	Perimeter of the opening providing escape path for gases, ft
t_g	$2i_g/P_g$ = Effective duration of the gas pressure based on a linear time decay, msec
t_g'	Predicted actual gas pressure duration
t	Elapsed time after detonation, msec
t_1	Time when reflected pressure equals the gas pressure, msec
t_r	$2i_r/B_r$ = Effective duration of the reflected shock pressure based on a linear time decay, msec
t_x	Duration for recessed frangible panel to displace X_o
V	Volume of structure containing the explosion, ft^3
w	Width of frangible opening, ft
W	Net weight of explosive, lb (TNT equivalent for gas pressure)
W_s	Net weight of explosive, lb (TNT equivalent for shock pressure)
Xs	Effective vent area at displacement X and time t, ft^2
X	Displacement at any time t, ft
X_o	Initial recess of frangible panel, ft. (Panel must displace X_o feet before venting begins.)
$\dot{X}_o$	Initial velocity of frangible panel, ft/msec
α	Exponential decay constant for $P_g(t)$, $msec^{-1}$
γ	Mass of frangible panel per unit surface area, lb/ft^2
γ_{50}	Mass of frangible panel which would reflect 50% of i_r, lb/ft^2
ϕ	TNT conversion factor

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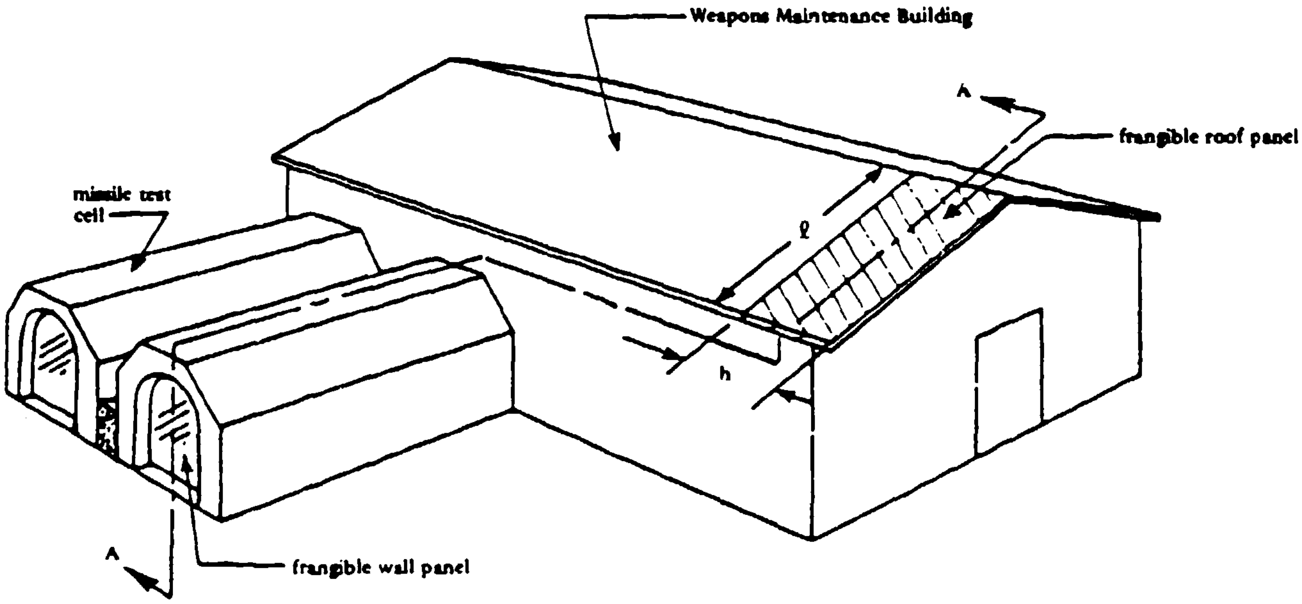

Figure 1. Frangible panels in Weapons Maintenance Facility.

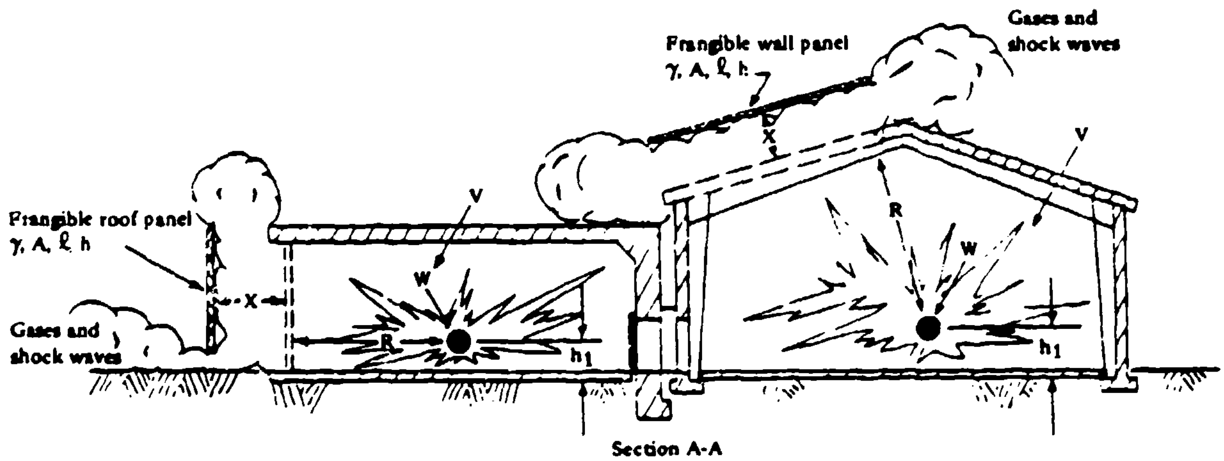

Figure 2. Design parameters for frangible panels.

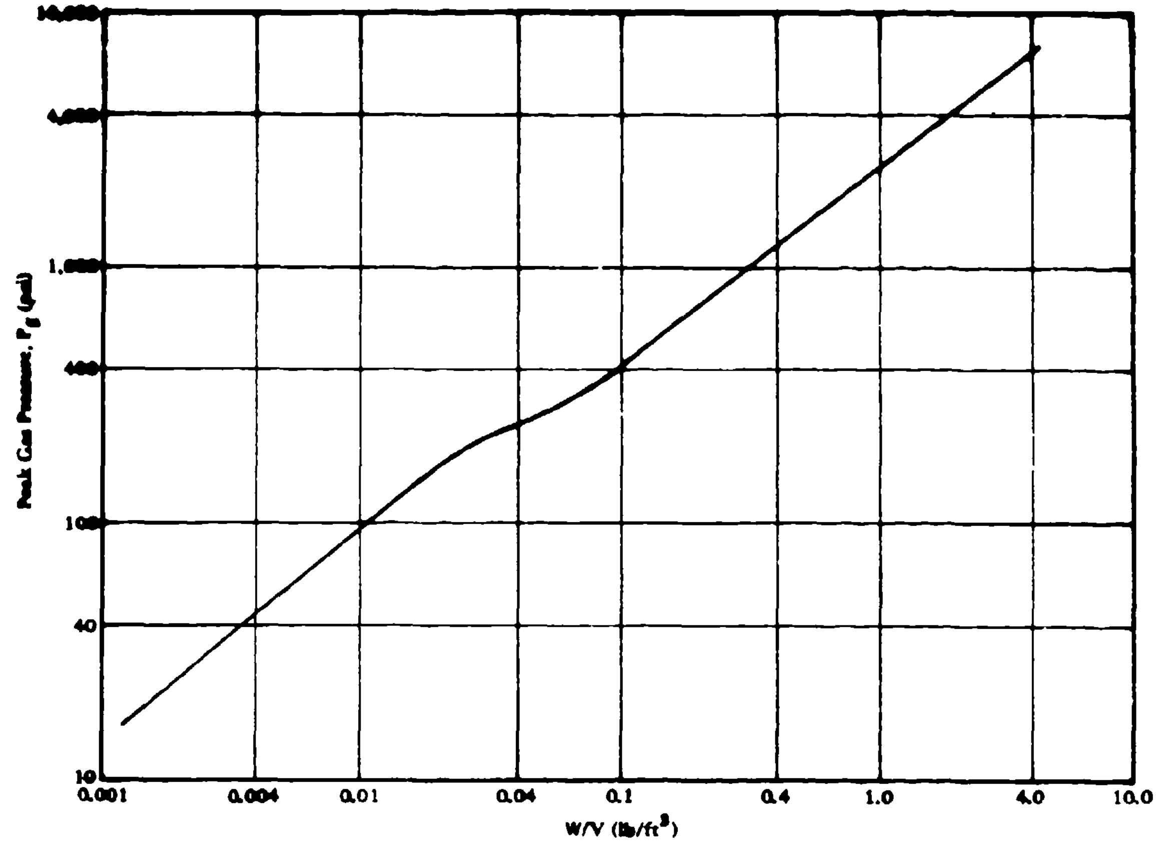

Figure 3. Peak gas pressure in relation to charge weight to free room volume ratio for TNT equivalent charges.

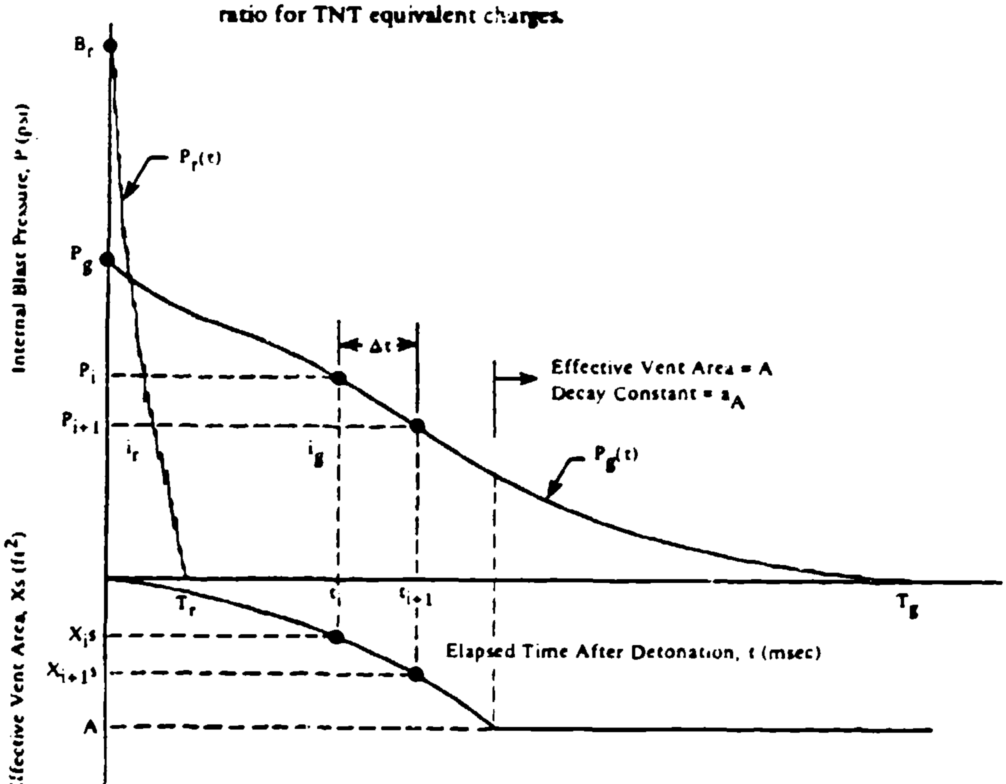

Figure 4. Blast loading inside structure with frangible panel.

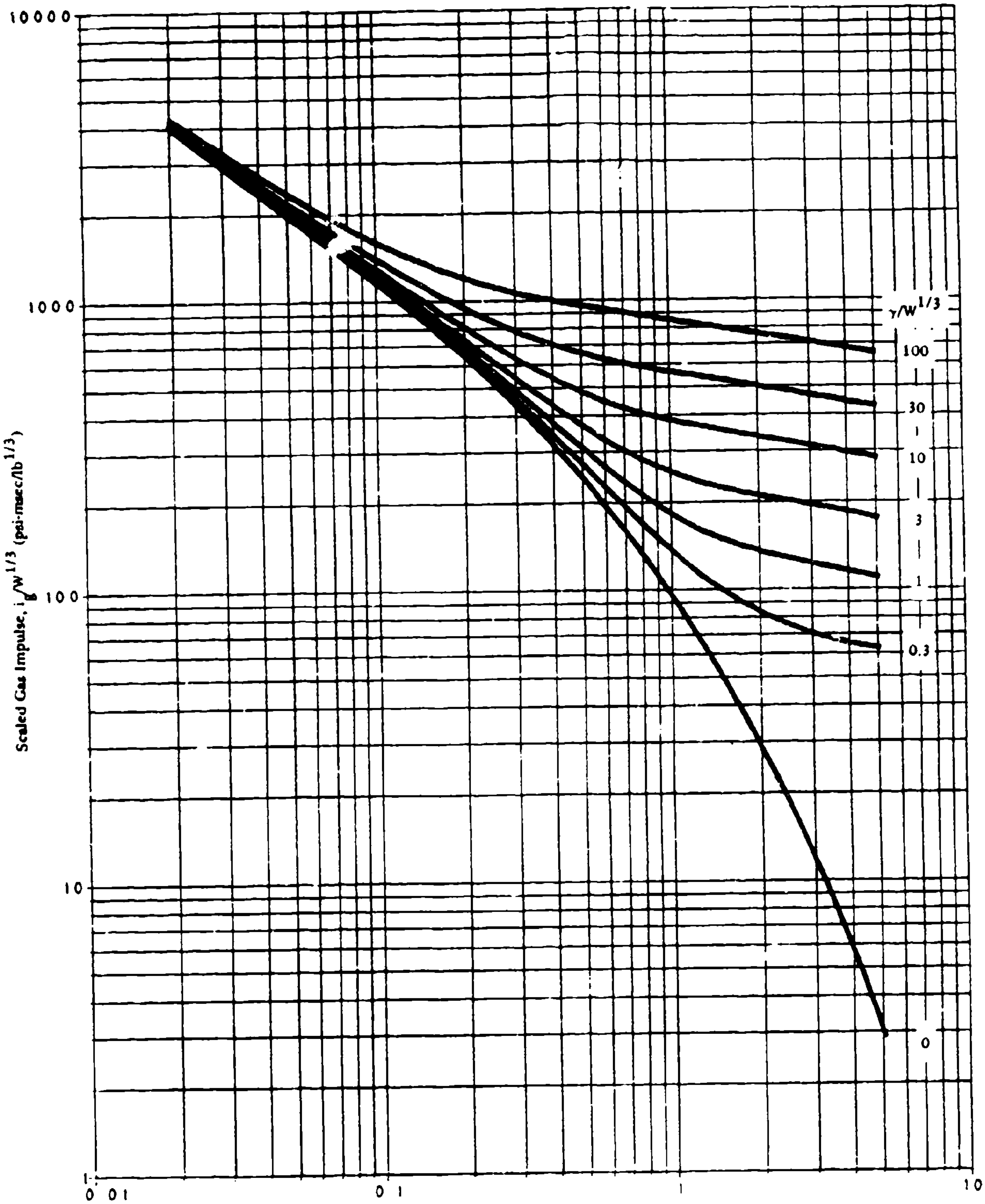

Figure 5. Gas impulse inside structure with frangible panel ($W/V = 0.002$, $i_r/W^{1/3} = 20$).

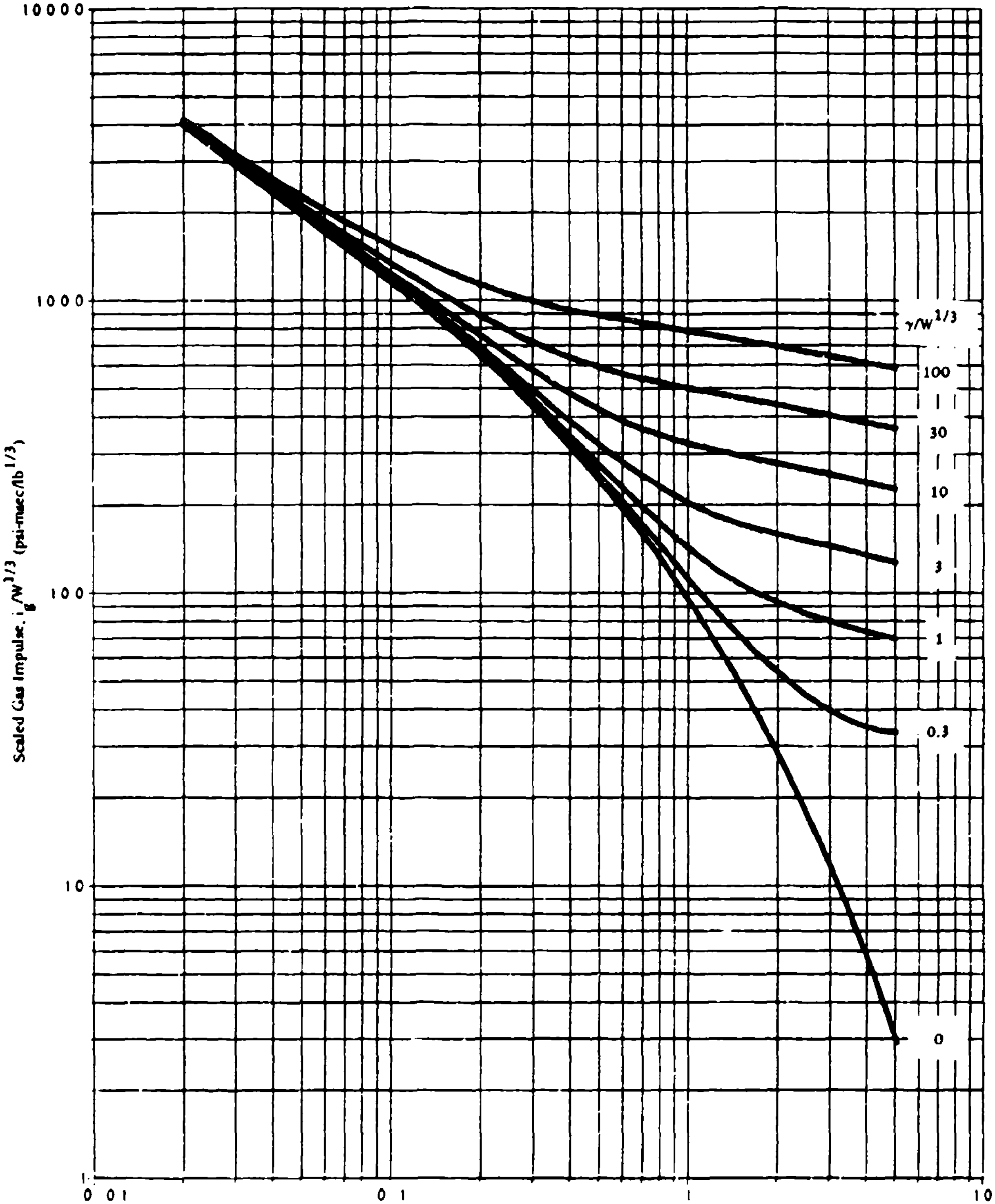

Figure 6. Gas impulse inside structure with frangible panel ($W/V = 0.002$, $i_r/W^{1/3} = 100$).

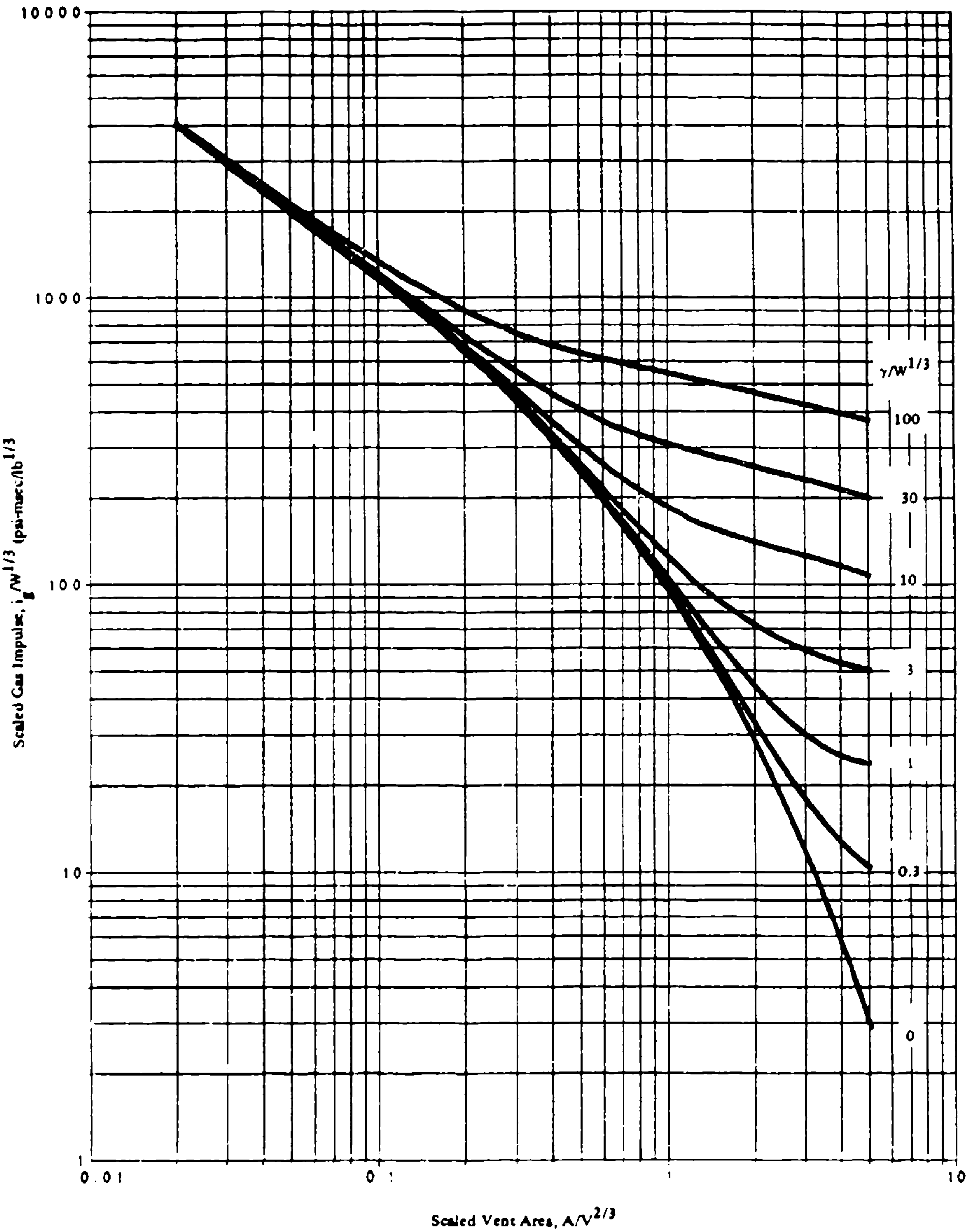

Figure 7. Gas impulse inside structure with frangible panel ($W/V = 0.002$, $i_r/W^{1/3} = 600$).

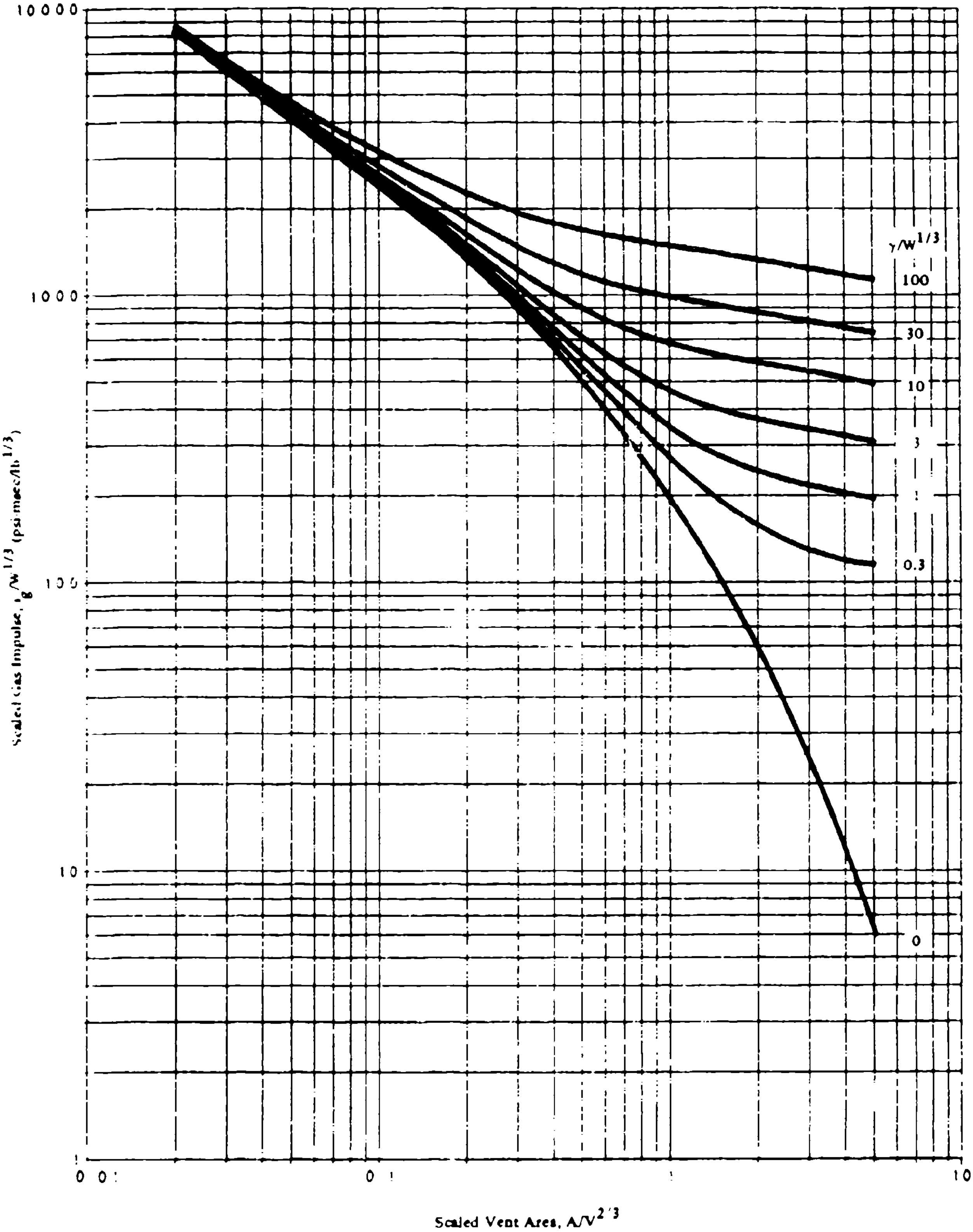

Figure 8. Gas impulse inside structure with frangible panel ($W/V = 0.015$, $i_r/W^{1/3} = 20$).

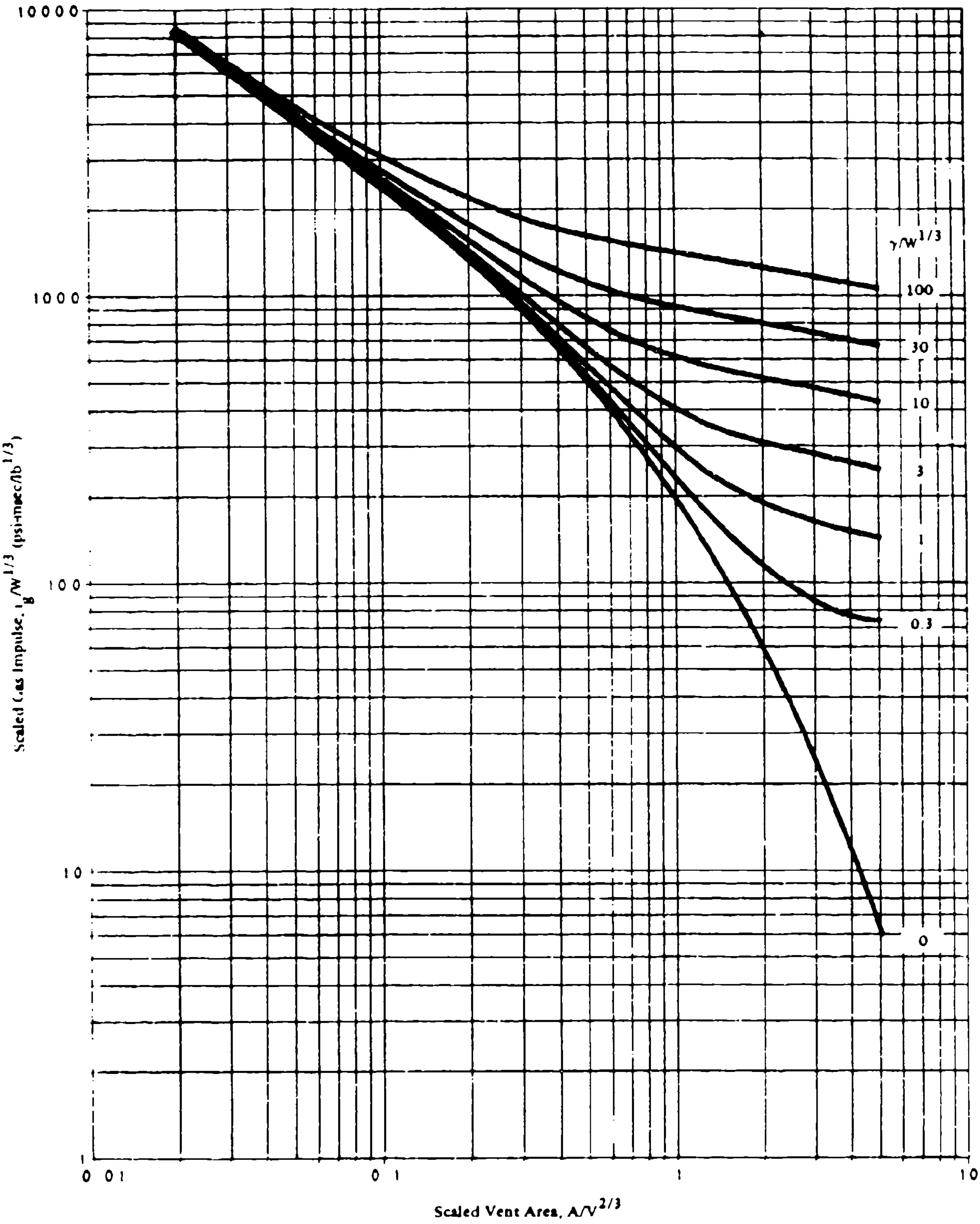

Figure 9. Gas impulse inside structure with frangible panel ($W/V = 0.015$, $i_r/W^{1/3} = 100$).

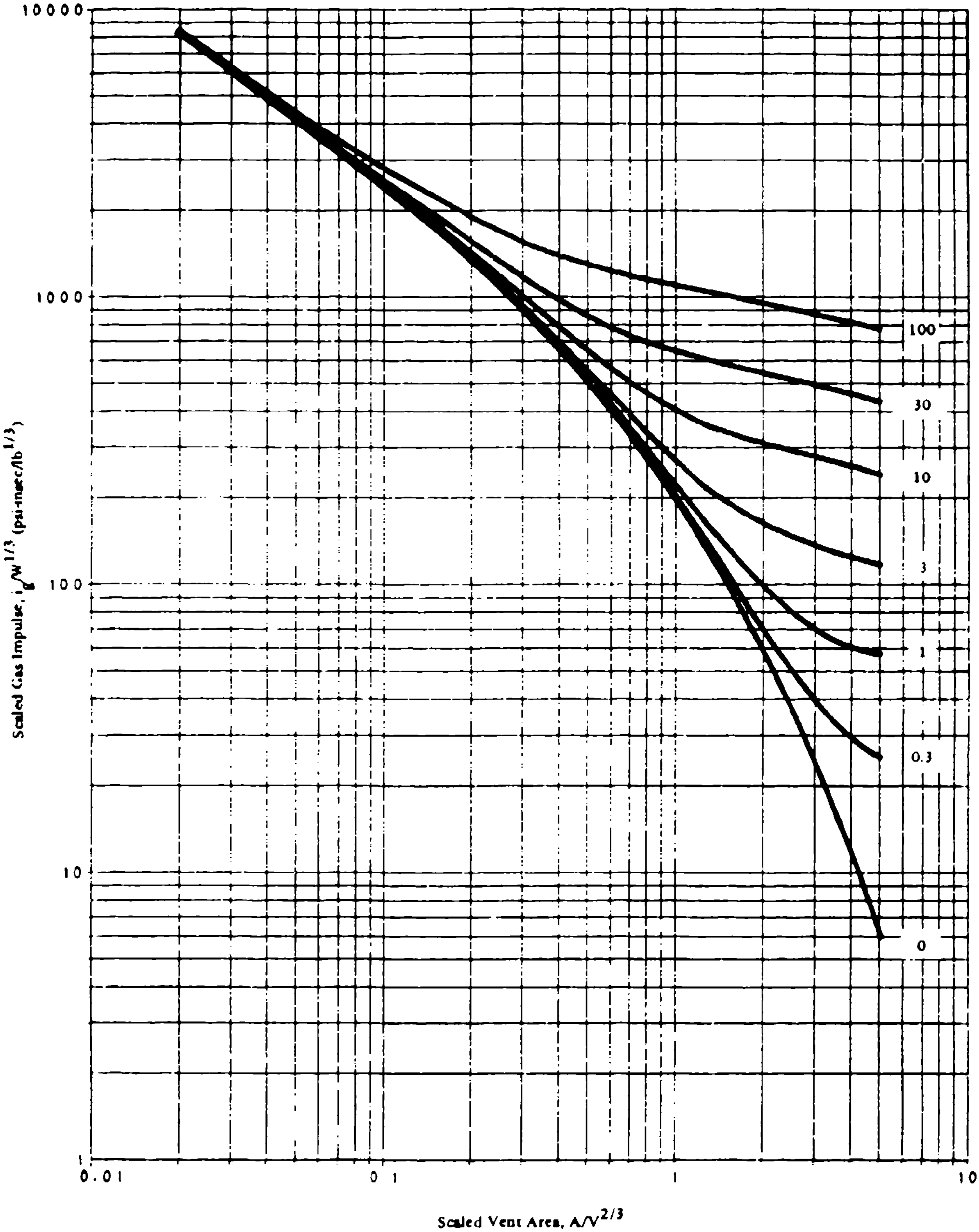

Figure 10. Gas impulse inside structure with frangible panel ($W/V = 0.015$, $i_r/W^{1/3} = 600$).

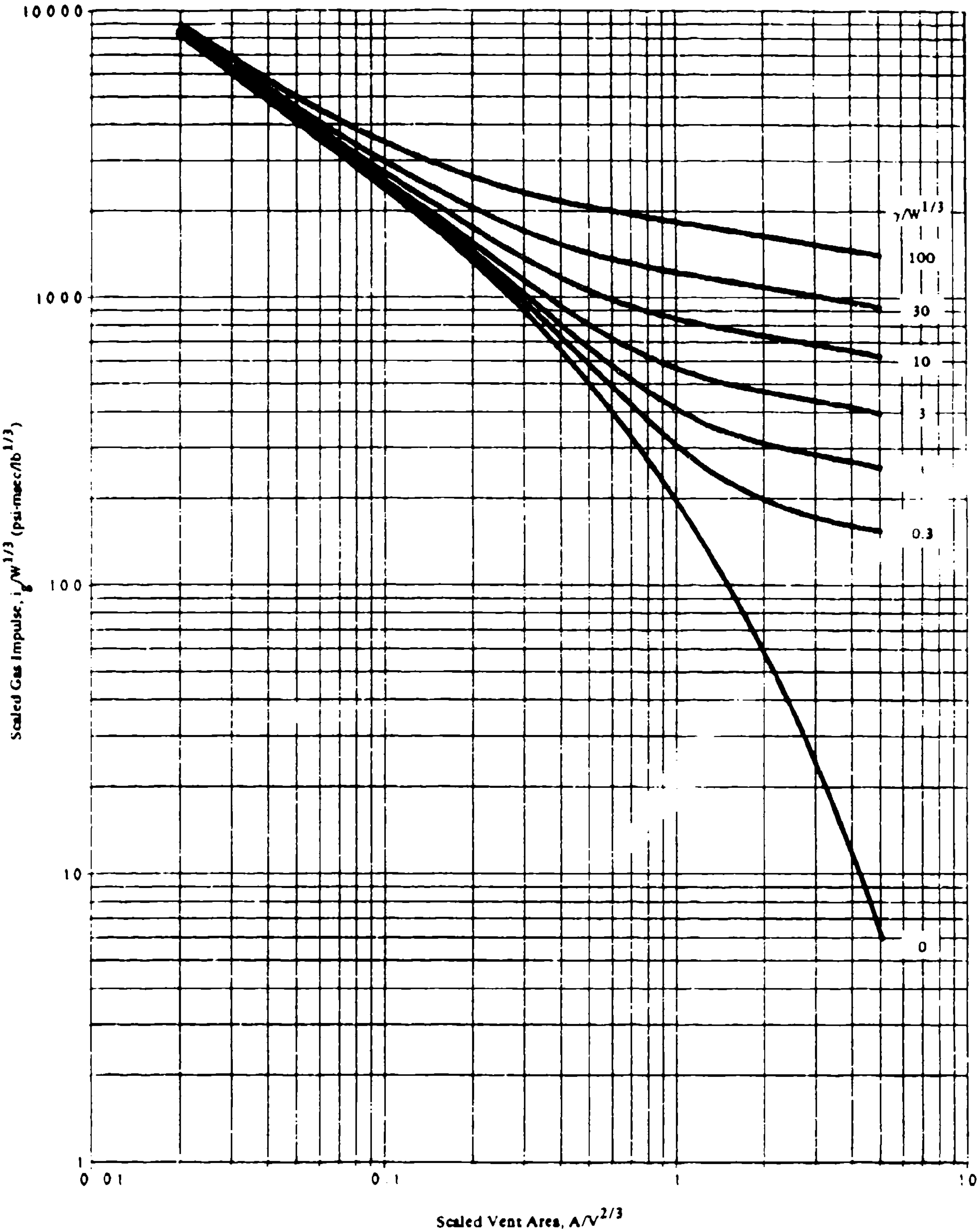

Figure 11. Gas impulse inside structure with frangible panel
($W/V = 0.15$, $i_r/W^{1/3} = 20$).

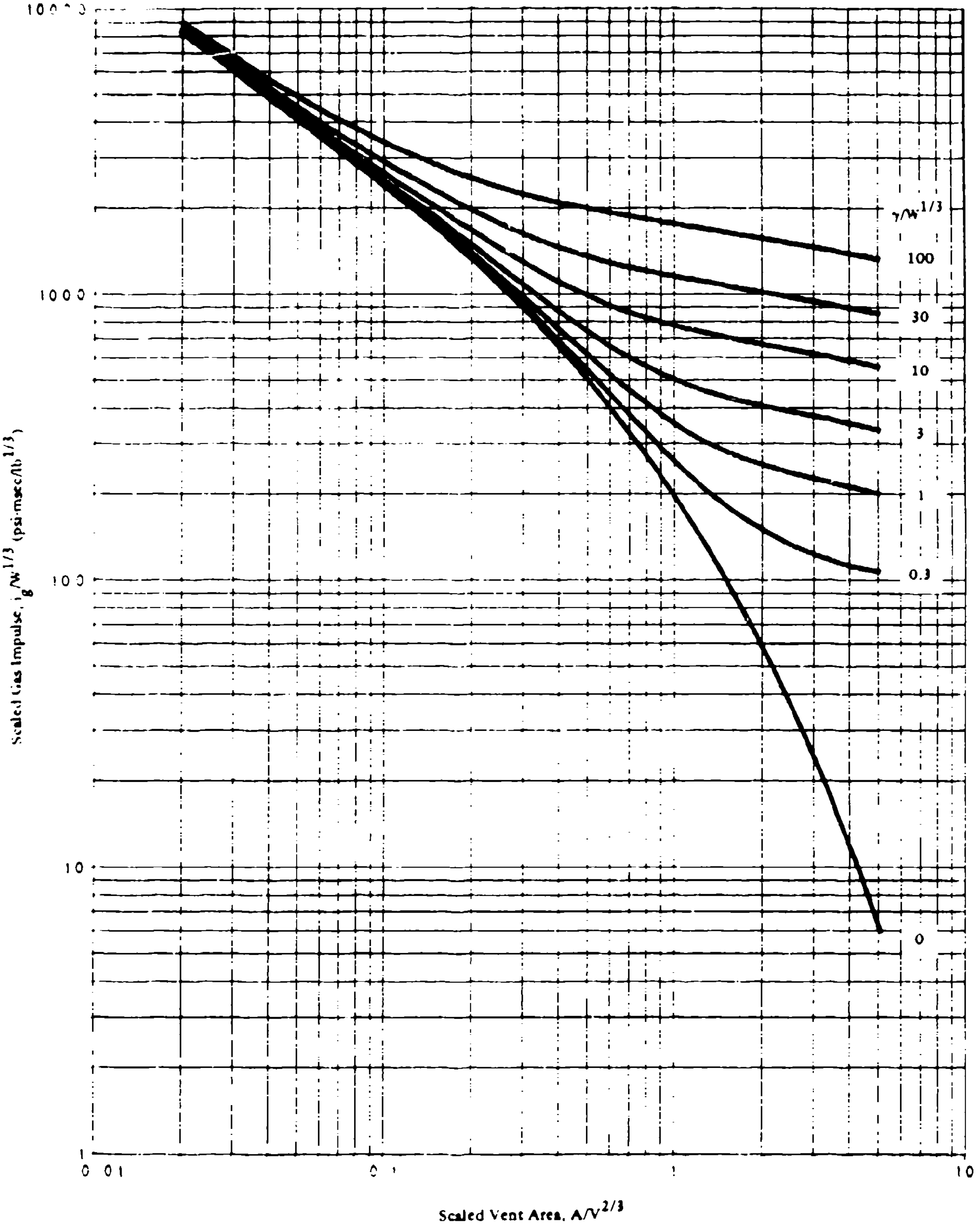

Figure 12 Gas impulse inside structure with frangible panel ($W/V = 0.15$, $i_r/W^{1/3} = 100$)

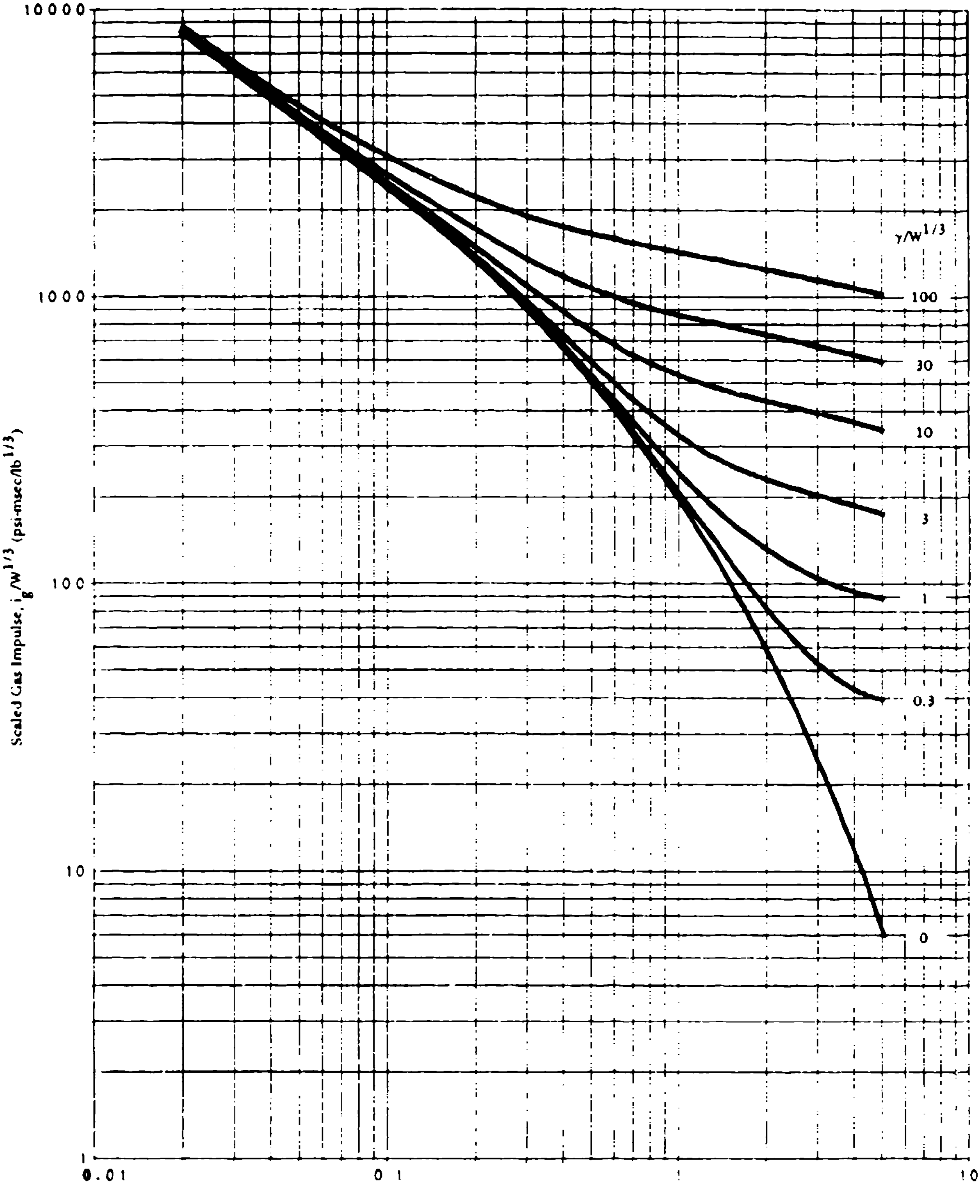

Figure 13. Gas impulse inside structure with frangible panel
($W/V = 0.15$, $i_r/W^{1/3} = 600$).

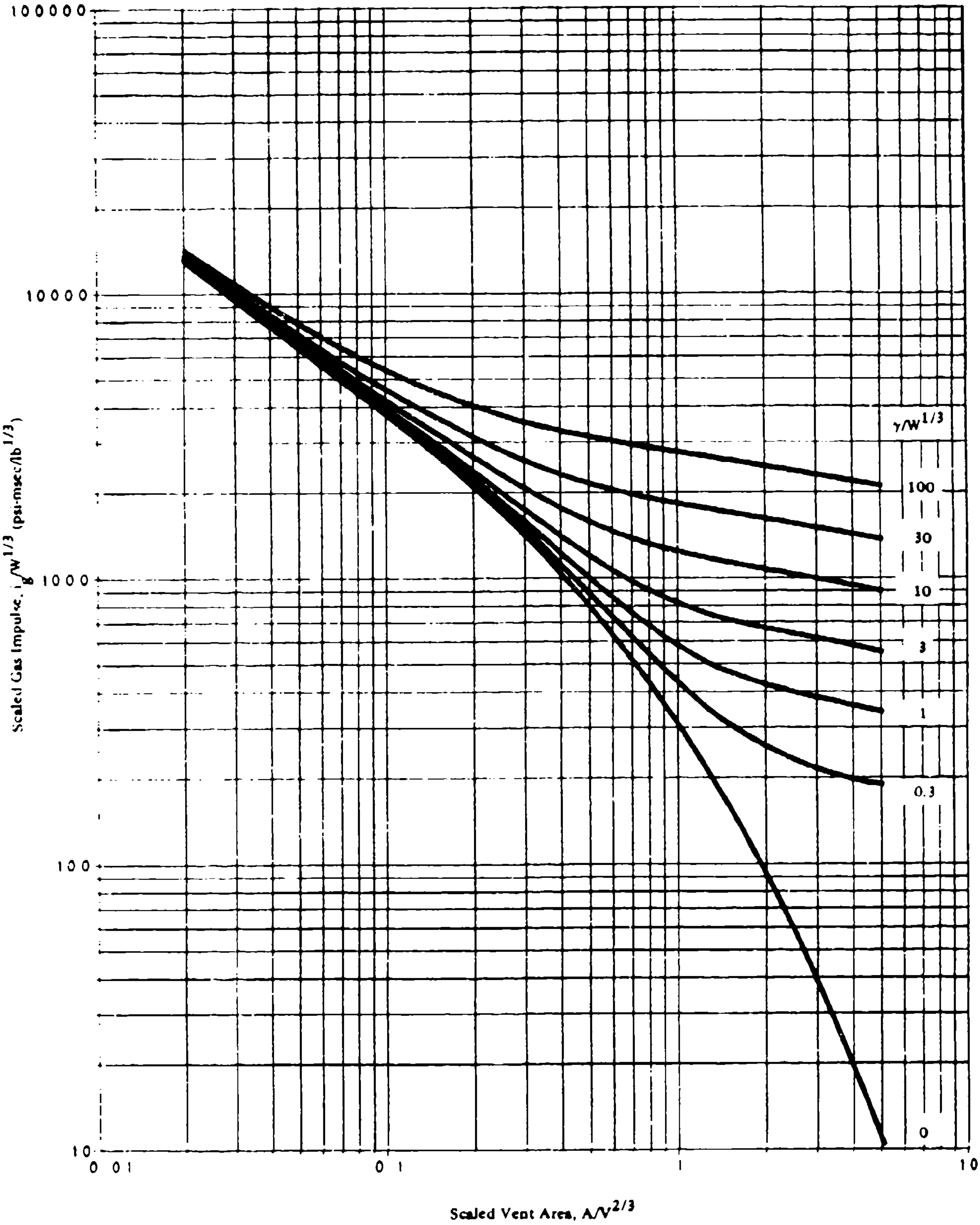

Figure 14. Gas impulse inside structure with frangible panel (W/V = 1.0, $i_r/W^{1/3}$ = 100).

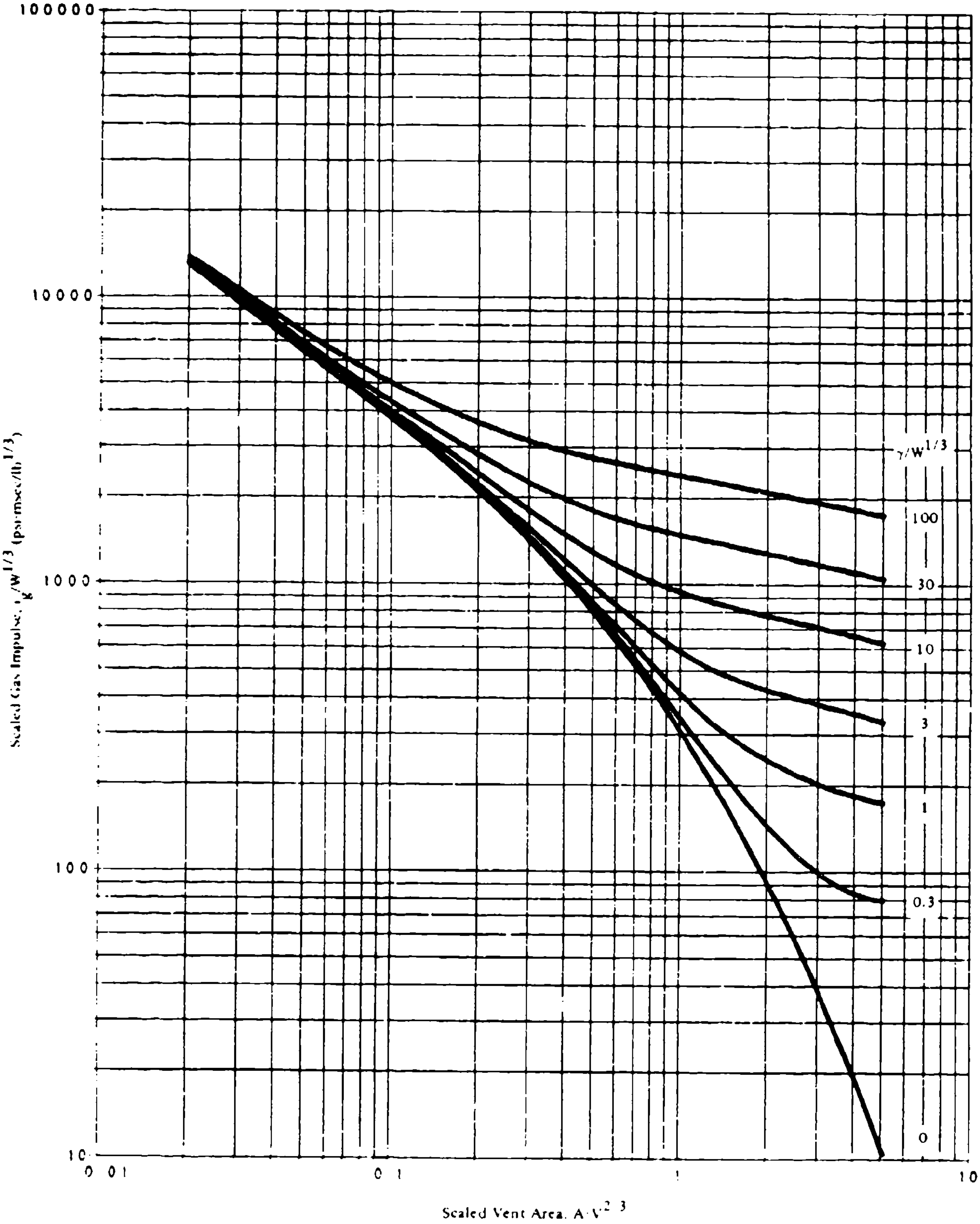

Figure 15. Gas impulse inside structure with frangible panel ($W/V = 1.0$, $i_r/W^{1/3} = 600$).

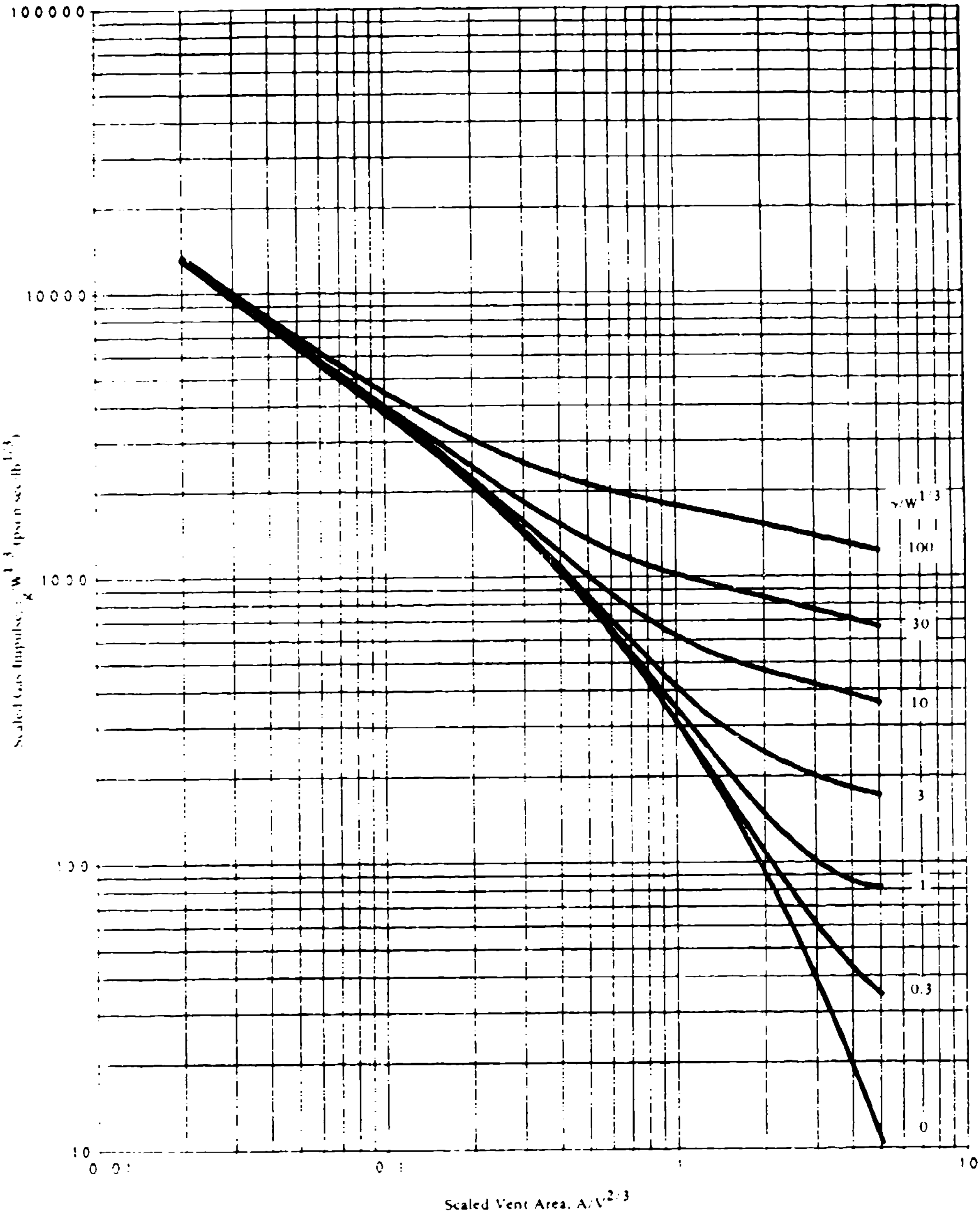

Figure 16. Gas impulse inside structure with frangible panel ($W/V = 1.0$, $i_r/W^{1/3} = 2,000$).

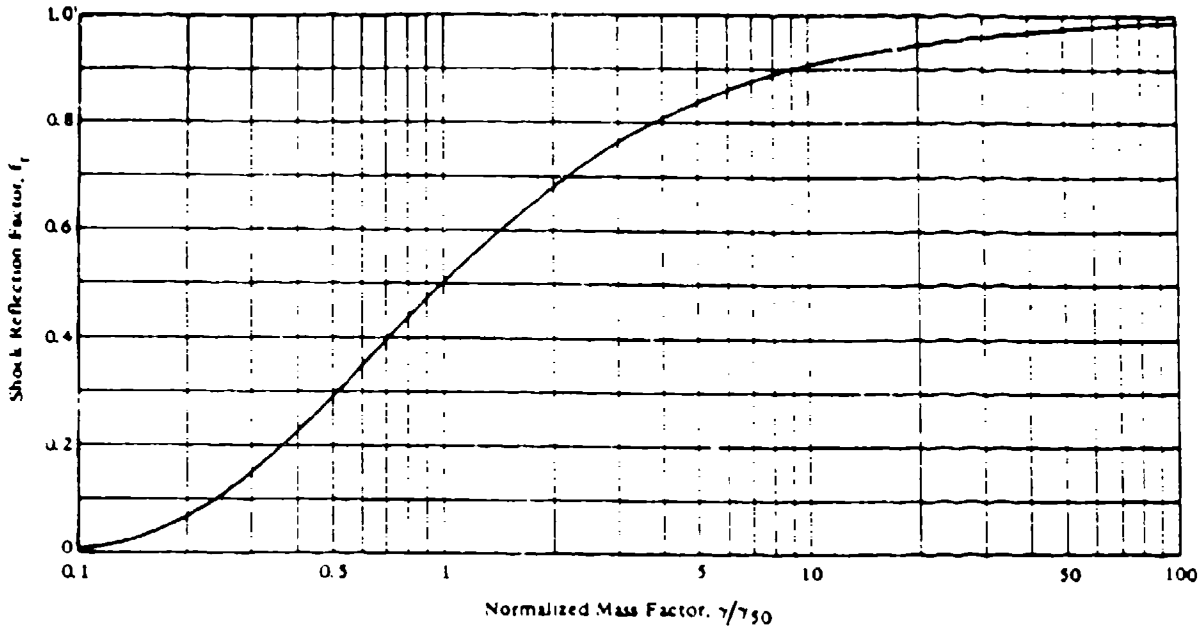

Figure 17. Shock reflection factor for frangible panels.

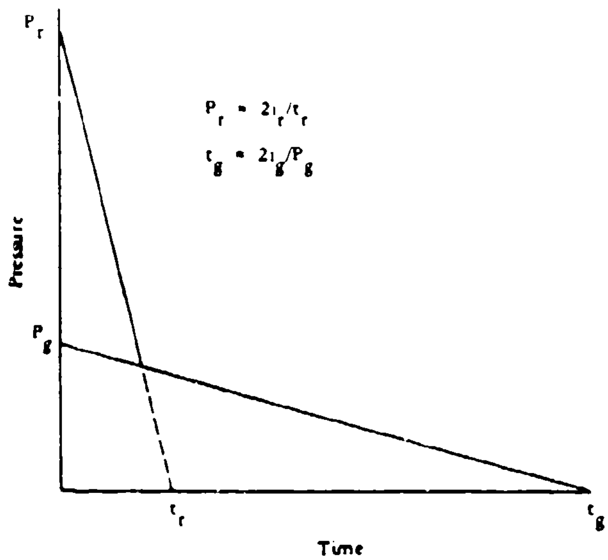

Figure 18. Design loading for combined shock and gas pressures on interior surfaces of structures.

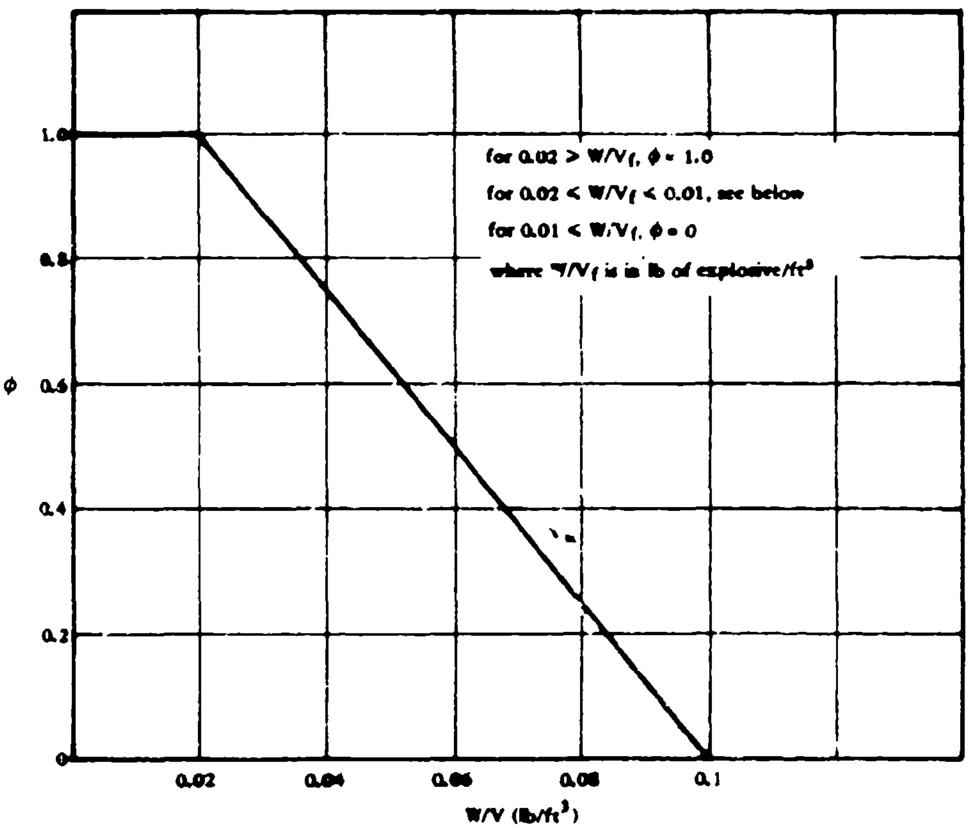

Figure 19. TNT conversion factor for charges, φ (for use with Equation 17).

EFFECTS OF COMBUSTIBLES ON INTERNAL QUASI-STATIC LOADS

by

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ABSTRACT

The effects of placing solid and liquid combustible materials near detonating explosives on internal blast loading was measured during tests conducted in a one-eighth scale model of a containment structure. In many cases, dramatic increases in gas pressures resulted. The paper will summarize data and present conclusions regarding the effects of combustibles on internal blast loads.

INTRODUCTION

For explosions in enclosures involving high explosives or combustible materials in contact with high explosives, the long-duration gas pressures caused by confinement of the products of the explosives can be the dominant loads causing structural failure. These quasi-static pressures are determined by the total heat energy in the explosive and/or combustible source, the volume of the enclosure, the vent area and vent panel configuration, the mass per unit area of vent covers, the amount of oxygen in the enclosure, and the initial ambient conditions.

Previous analytic work, similitude analysis, and numerous experiments have addressed several aspects of this problem and provided a good data base for more general predictions. Reference 1 collates much of this information for gas pressure parameters from bare high explosive detonations in enclosures with open vents, while Reference 2 includes analytic predictions of these parameters for similar explosions with covered vents with various masses per unit area.

More recently, test data for gas pressures in sealed structures from high explosives surrounded by combustible liquids and solids has been obtained (Reference 3). This series of experiments was conducted with combustible materials placed in varying degrees of contact with high explosive charges. The explosion tests were conducted in a one-eighth scale model of the Pantex Damaged Weapons Facility. The program, conducted by SwRI, was sponsored by DOE and monitored by Mason & Hanger, Silas-Mason Co., Inc., Pantex Plant. The object of the tests was to determine whether the combustible materials could contribute to the quasi-static pressure development, within a sealed enclosure. In this paper, the authors will summarize conclusions of these experiments regarding the effects of combustibles on internal blast loads.

EXPERIMENTAL PROGRAM

The combustible materials of interest to the sponsor which were investigated in this effort are listed in Table 1. Six series of tests were conducted with each series having a different combustible configuration. In every case, the high explosive was 0.992 lb of PBX-9404. The only parameter not held constant was the combustible configuration. Figures 1 through 6 illustrate each of the test configurations described in Table 1.

Series 1 and 2 tests, conducted in an earlier phase of this experimental program, (Reference 5) used bare and cased cylindrical explosive charges. These tests produced higher quasi-static pressures than expected. based on previous tests (See Reference 4 and 5) with equal weight, bare spherical charges of the same PBX-9404 explosive. To explain this discrepancy, it was noted that the cylindrical charges had combustible solids in intimate contact, while the spherical charges did not. It was postulated that rapid burning of all or part of those materials caused greater pressure rises than for explosives alone. This phenomenon can be quite important in predicting quasi-static pressures in blast containment structures when solid or liquid combustible materials are in intimate contact with or are near detonating high explosives. The Phase IV tests, Series 3 through 6 were intended to obtain more data on the effects of such combustibles on blast and gas pressure loads in containment structures.

Figure 7 shows the one-eighth scale model of the Damaged Weapons Facility used to determine the effects of the combustible materials in contact with or near explosive charges. The enclosed volume of the structure remained constant throughout the experiments at 145.3 ft^3. Six blast and six gas pressure transducers were located at various points throughout the model. Figure 8 shows a floor plan of the model indicating the position of the explosive charge throughout the experiments. The floor plan also shows the transducer positions at which pressure measurements were recorded.

EXPERIMENTAL RESULTS

Results of the experimental program are presented in this section. Table 2 shows the peak quasi-static pressure associated with each of the six configurations. From previous tests with bare PBX-9404 charges, the quasi-static pressure value is known to be 48.7 psi. It is this value which was used as a baseline to compare measurements for all combustible configurations. The excess quasi-static pressure column contains the difference between the measured pressure and the baseline. In every case, the addition of combustible materials in near contact with the HE charge increased the quasi-static pressure, in some cases dramatically.

To illustrate the pressure enhancement caused by the different combustible materials actual data records will be examined. Figures 9-11 show the pressure histories measured at location 26 with three different combustible configurations. Figure 9 represents a pressure history resulting from a bare, spherical PBX-9404 charge. This figure shows a maximum pressure amplitude just under 50 psi. Figure 10 shows a pressure history obtained when a spherical charge is in contact with two polycarbonate lenses, Series 4. The quasi-static pressure is now read about 58 psi, indicating an increase in pressure over the bare charge. Figure 11 represents a pressure history measured in Series 6, where the four-sided polyethylene box surrounded the charge. The quasi-static pressure of 85 psi shows a dramatic increase over the bare charge configuration.

The degree of quasi-static pressure enhancement produced by a combustible is related to the heat energy content of the material. This is shown in Figure 12 where the excess P_{qs} (the P_{qs} produced by the combustible plus the HE, less the P_{qs} produced by the HE alone) is plotted as a function of the combustible energy content (See Table 2). The combustible energy content is defined as the mass of combustible times the appropriate heat of combustion from Table 3. As seen in Figure 12, the enhancement in the quasi-static pressure increases uniformly with increasing combustible energy, as long as the combustible is in intimate contact with the charge. The only point not following the general trend of the data corresponds to the series of tests in which the combustible fluid was dispersed a large distance from the charge (Series 5).

SUMMARY

The phenomenon of quasi-static pressure enhancement produced when combustible materials are placed near HE sources has only been recently discovered. The principal conclusions of this study are:

- Combustible materials near explosives can markedly increase gas pressures in enclosed structures.
- There is a lack of data on HE-combustible combinations.
- Quasi-static loading calculations should include estimates of contributions from the burning of combustible materials whenever such materials are expected to be in intimate contact with HE sources.
- Effects of combustibles should be investigated further to determine methods for prediction. Variations in charge to combustible mass, charge type, structure volume, degree of venting and degree of contact between HE and combustible should be studied.

FIGURES AND TABLES

Table 1. Combustible Materials and Configurations Tested*

Series	Material	Configuration
1	Polycarbonate	A 67.7 gm polycarbonate disk was attached to the end of a cylindrical (ℓ/d=1) charge.
2	Polycarbonate and Aluminum	A 135 gm aluminum casing surrounding the side of a cylindrical charge. A polycarbonate disk covered one end of the charge.
3	50/50 Mix of DMF** and Acetone	A spherical charge was submerged in 5 oz of the fluid.
4	Polycarbonate	Two polycarbonate hemispheres were attached to opposite poles of the charge. The total polycarbonate weight was 48.25 gm.
5	50/50 Mix of DMF and Acetone	Five 1 oz containers of the fluid were equally spaced on a circle 36 in. in diameter around the charge.
6	Low density Polyethylene	Polyethylene beads suspended in an epoxy base, and formed into a four-sided box, centered on the charge. The weight of the box was 273 gm.

*The explosive was 0.992 lb of PBX-9404. Test Series 1 and 2 utilized cylindrical charges, while the remaining tests utilized spherical charges. The charge location was the same in all experiments.

**Dimethyl Formamide

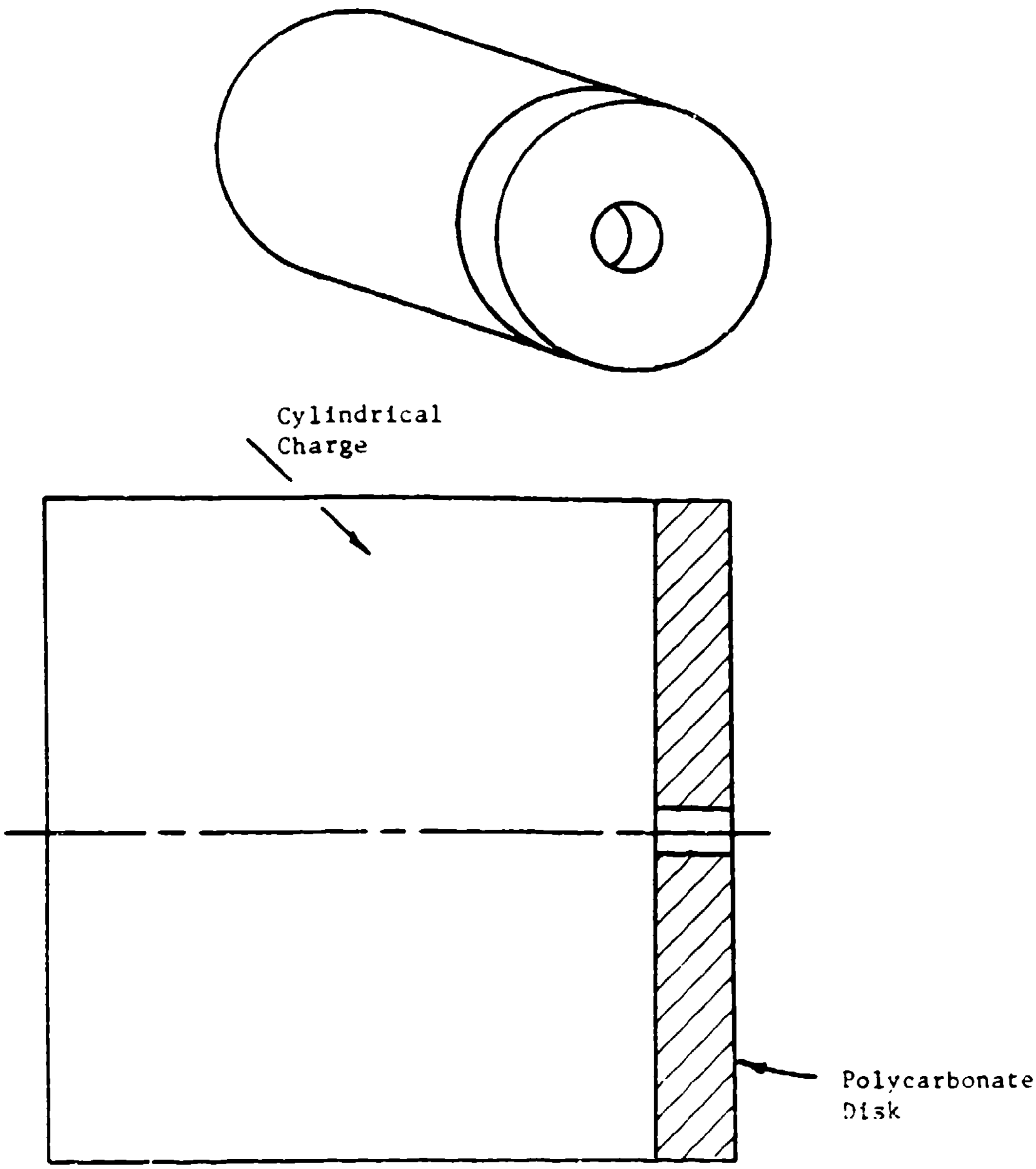


Figure 1. Series 1 Configuration

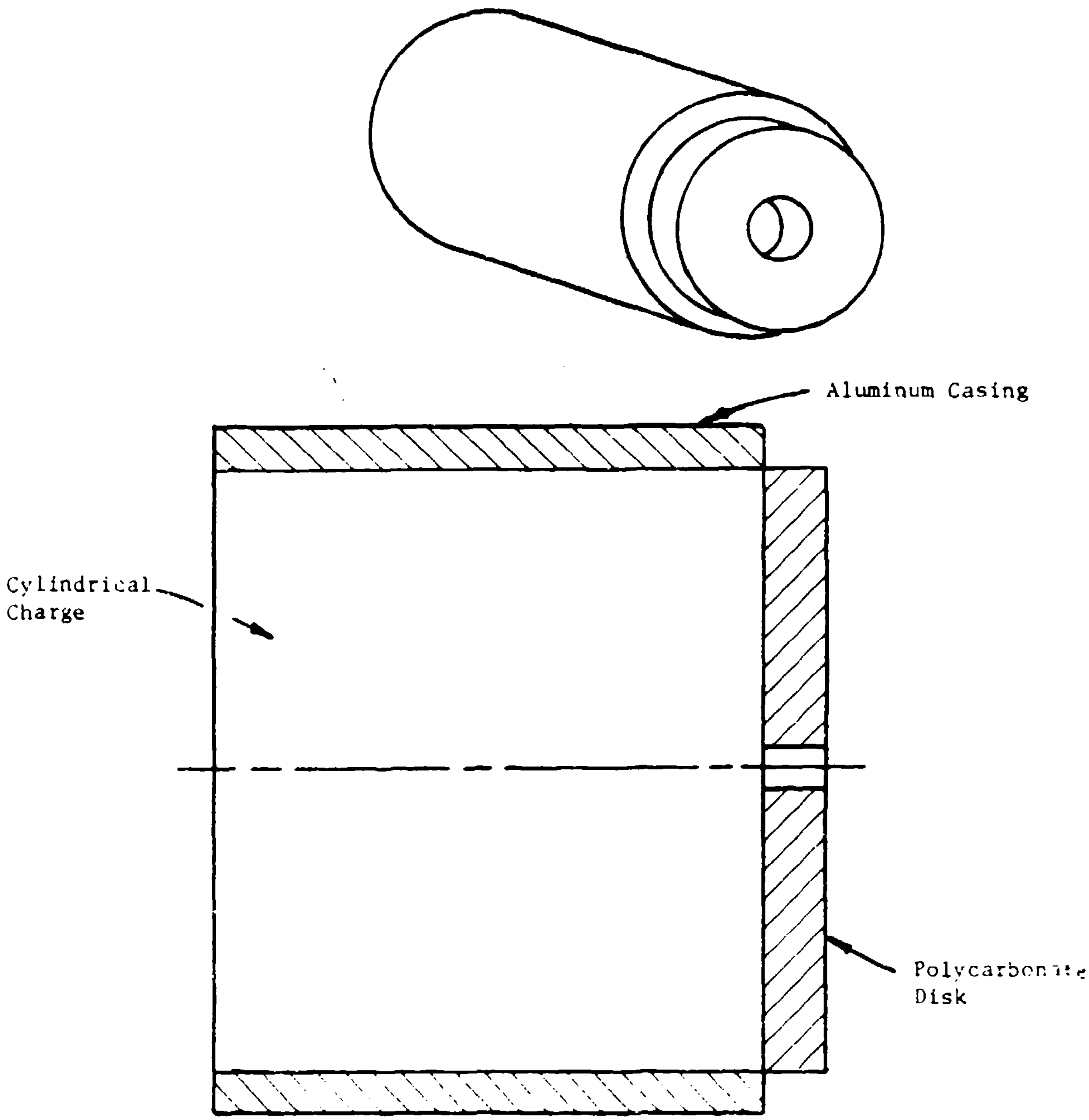


Figure 2. Series 2 Configuration

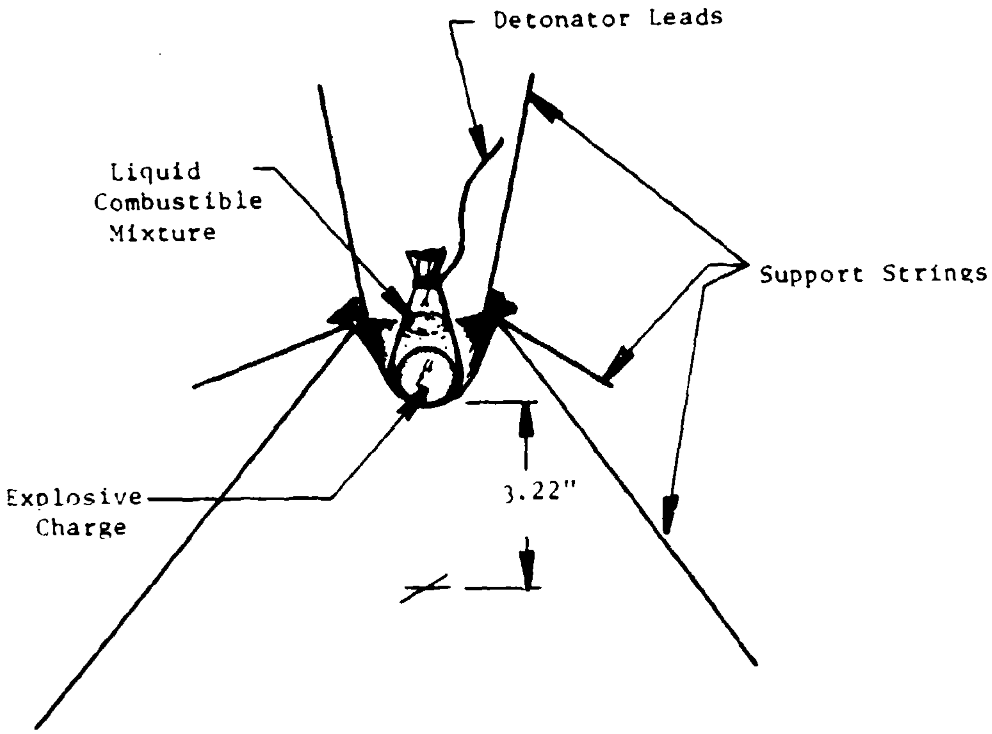


Figure 3. Series 3 Configuration

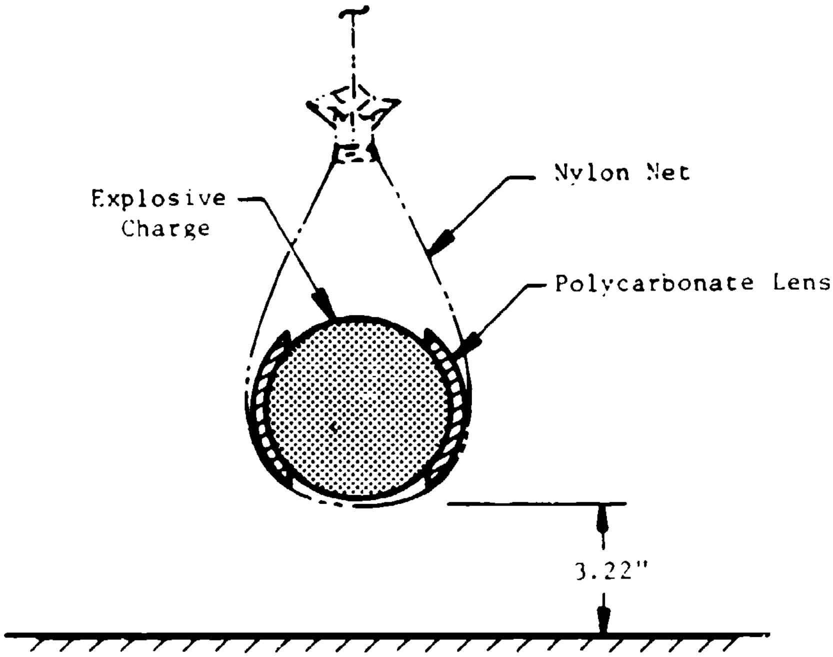


Figure 4. Series 4 Configuration

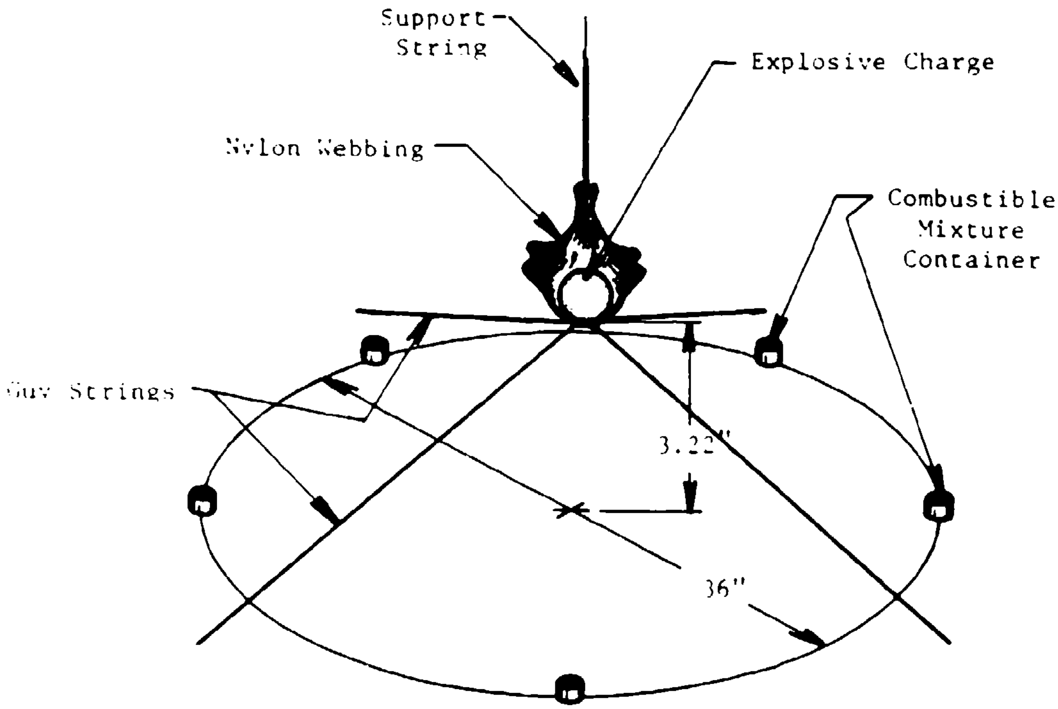


Figure 5. Series 5 Configuration

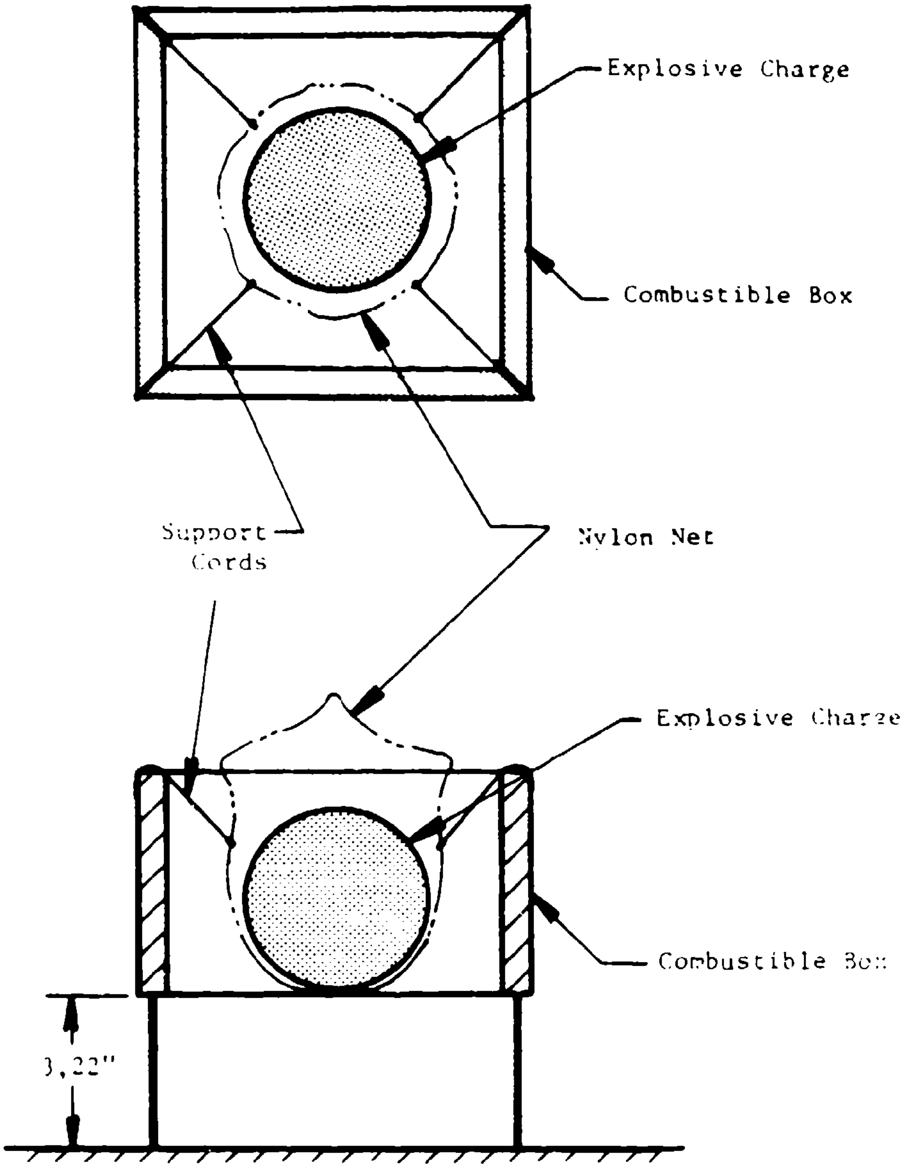


Figure 6. Series 6 Configuration

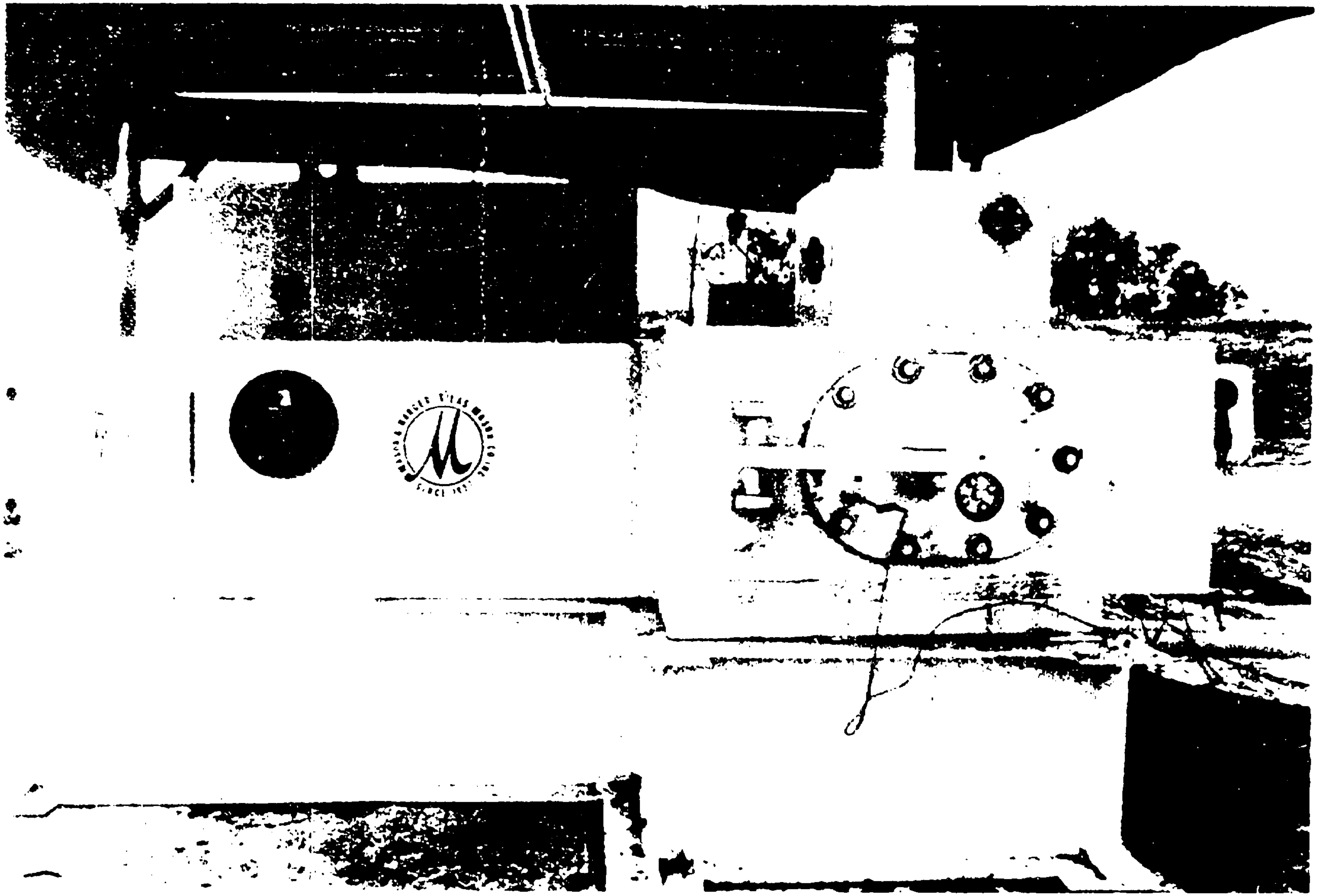
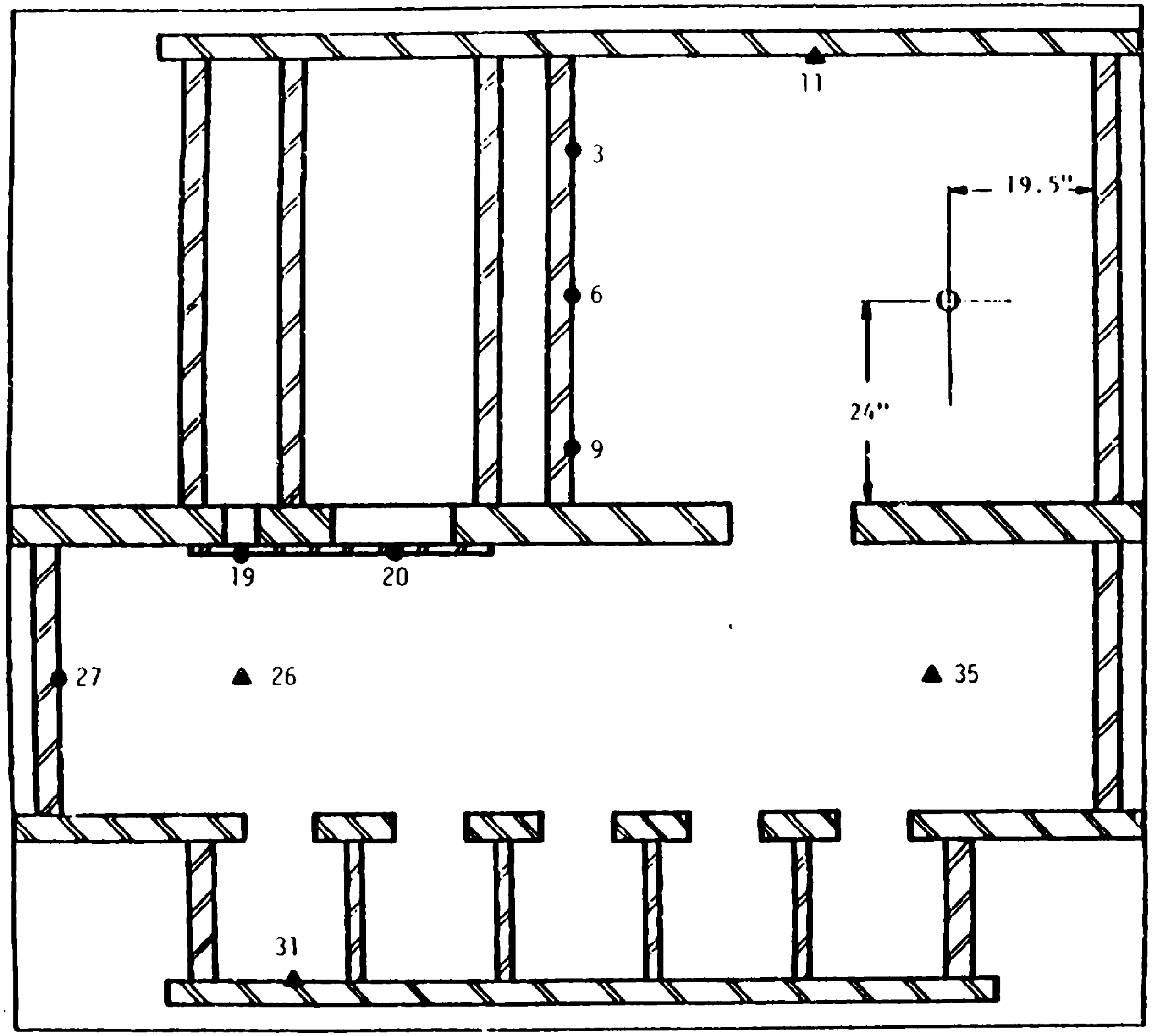


Figure 7. Scale Model Of The Pantex Damaged Weapons Facility



● Blast pressure

▲ Gas Pressure

Figure 8. Charge and Transducer Locations

Table 2
Summary of P_{QS} Enhancement

Series	Combustible	P_{QS} (psi)	ΔP_{QS} Excess Quasi-Static Pressure (psi)	Combustible Energy (Mcal)
Previous tests	HE only	48.7	0	0
1	Polycarbonate (cylindrical)	62.1	13.4	0.488
2	Polycarbonate + Aluminum (cased cylindrical)	76.0	27.3	1.487
3	DMF/Acetone in contact	68.6	19.9	0.367
4	Polycarbonate Hemispheres	56.4	7.7	0.348
5	DMF/Acetone at Distance	60.3	11.6	0.374
6	Polyethylene	85.4	36.7	4.37

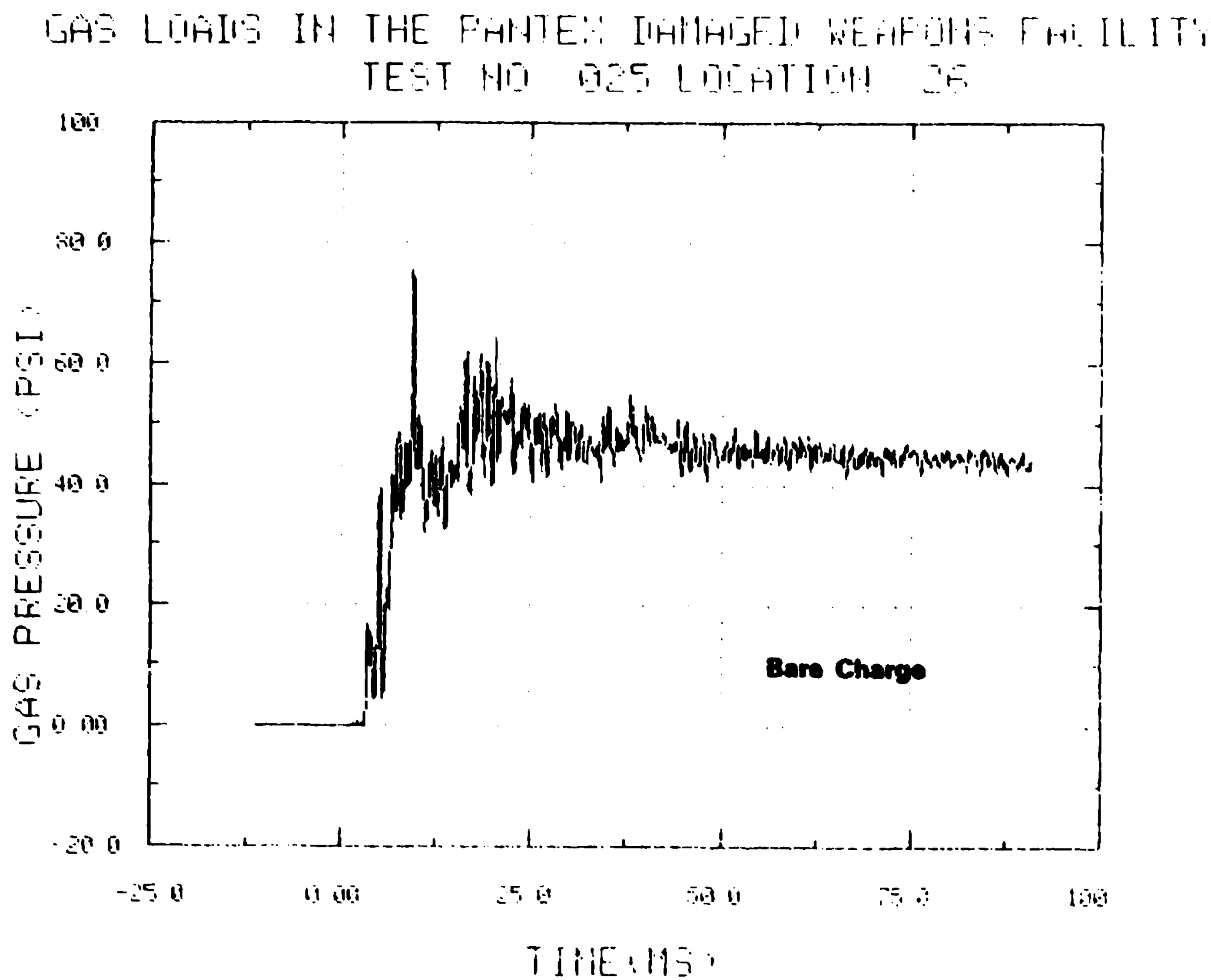


Figure [illegible]. Pressure History From Bare PBX-9404 Charge

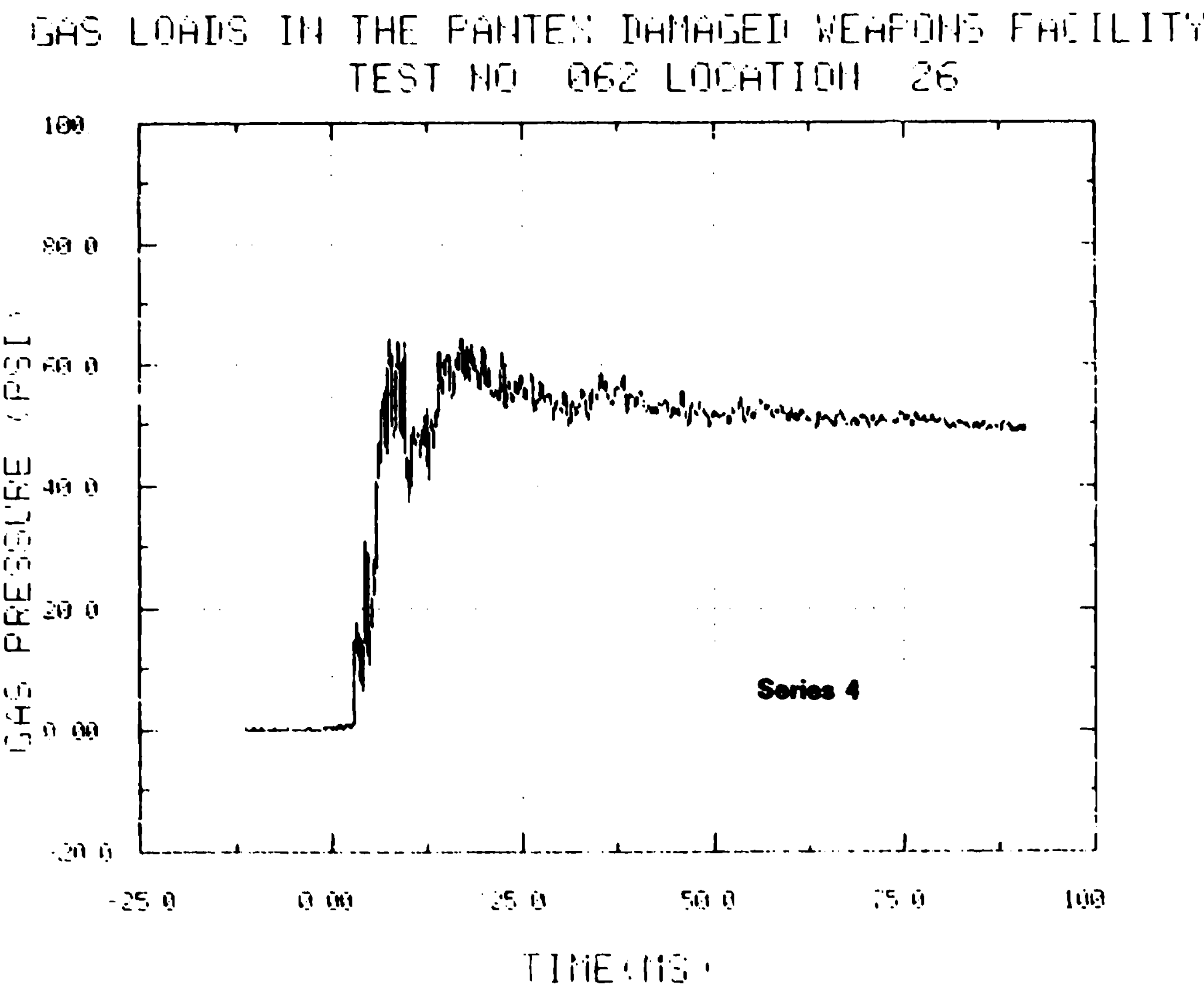


Figure 10. Pressure History From Charge With Attached Polycarbonate Lenses

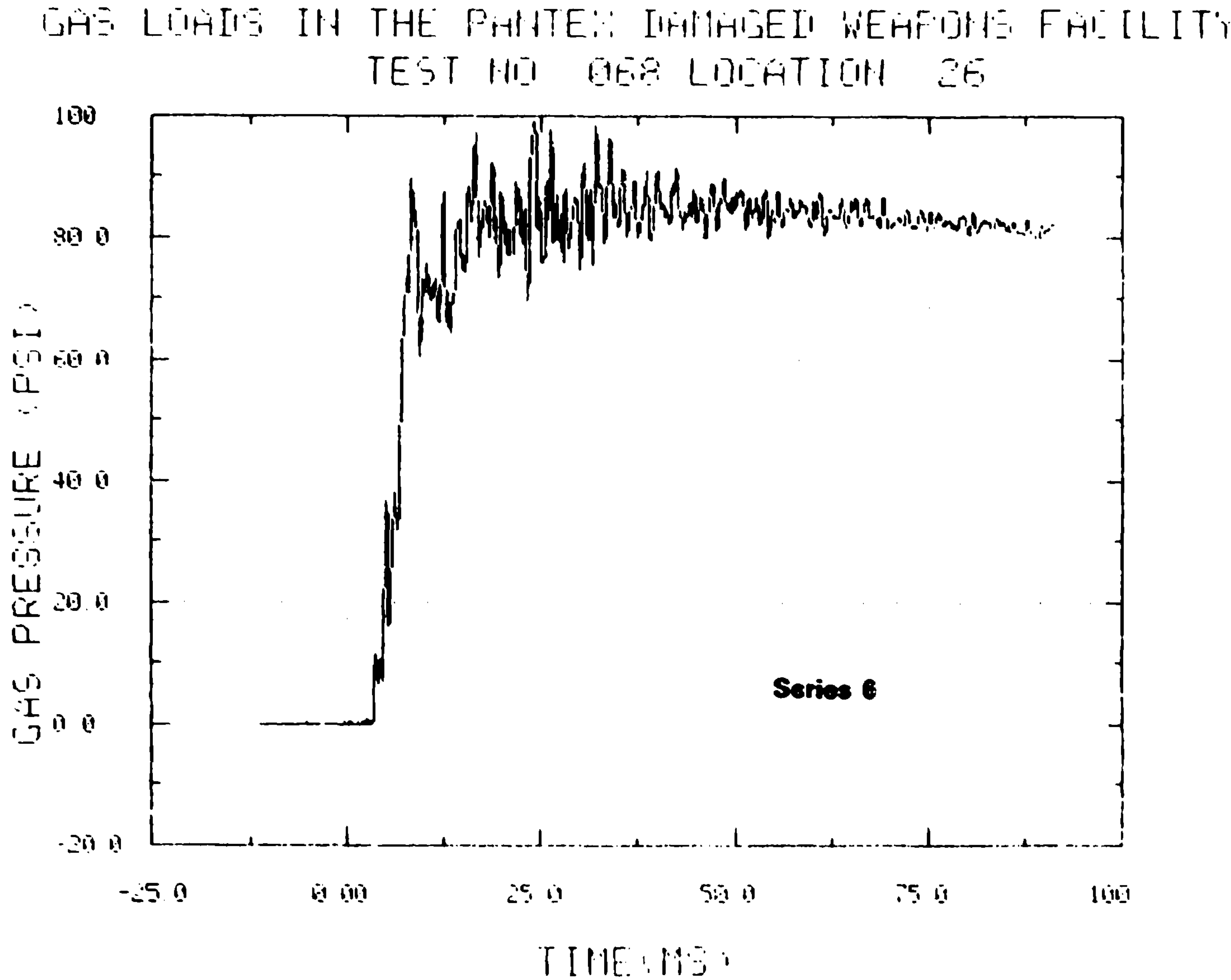


Figure 11. Pressure History From Charge Surrounded By Polyethylene Box

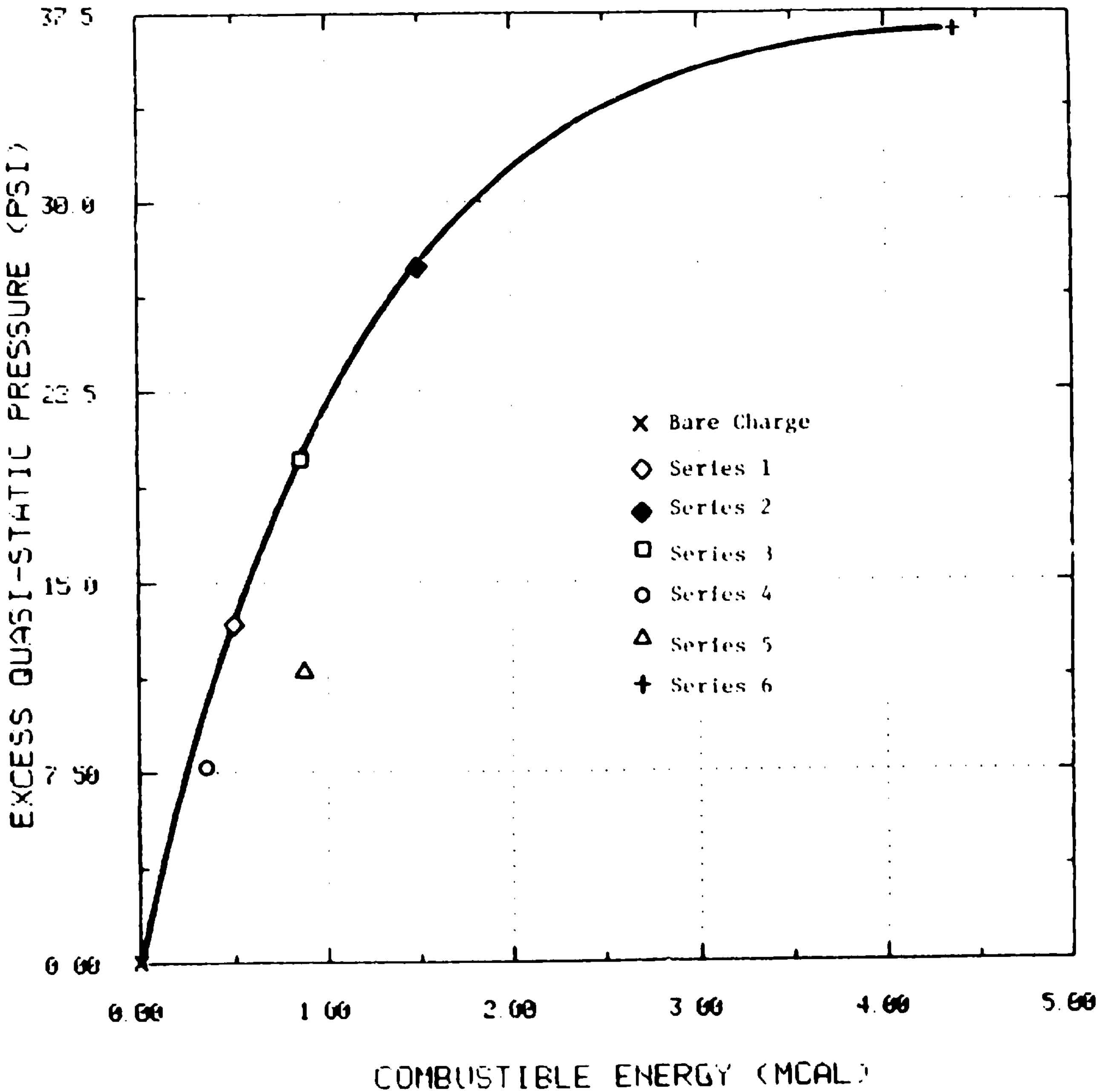


Figure 12. Excess Quasi-Static Pressure

Table 3. Heat of Combustion for the Various Combustible Test Materials

Material	Heat of Combustion (cal/gm)
PBX-9404	2369
Polycarbonate	7223
Acetone	7363
DMF	6259
Polyethylene	9400
Aluminum	7400

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2. W. E. Baker, et al., "Manual for the Prediction of Blast and Fragment Loadings on Structures," DOE/TIC-11268, U.S. Dept. of Energy, Pantex Plant, Amarillo, TX, Nov. 1980.

3. J. C. Hokanson, E. D. Esparza, N. R. Sandoval, and W. E. Baker, "Effects of Combustibles on Internal Blast Loads in the Damaged Weapons Facility, Final Report for Phase IV," Final Report on P.O. F091340 for Mason & Hanger - Silas Mason Co., Inc., Pantex Plant, Amarillo, TX, Oct. 1982.

4. J. C. Hokanson, E. D. Esparza, W. E. Baker and N. R. Sandoval, "Determination of Blast Loads in the Damaged Weapons Facility, Final Report for Phase I," Prepared for Mason & Hanger - Silas Mason Co., Inc., Pantex Plant, Amarillo, TX, January 1982.

5. J. C. Hokanson, E. D. Esparza, W. E. Baker, N. R. Sandoval and C. E. Anderson, "Determination of Blast Loads in the Damaged Weapons Facility, Final Report for Phase II, Prepared for Mason & Hanger - Silas Mason Co., Inc., Pantex Plant, Amarillo, TX, July 1982.

ABSTRACT

BLAST LOADING ON ABOVE GROUND BARRICADED MUNITION STORAGE MAGAZINES

Gerald Bulmash

Charles Kingery

A NATO munitions storage facility at Machrihanish, Scotland has armaments stored in aboveground magazines at $2W^{1/3}$ separation distance. The magazines are surrounded on 3 sides by earth berms. A mass explosion is simulated in a 1/23.5 scale model of this facility using a 1 kg bare hemispherical Pentolite charge to model the full scale mixed explosive load. The charge is detonated within a responding concrete donor structure, and measurements are obtained from pressure sensitive transducers mounted in a neighboring non-responding steel model. Visual evidence of the blast loading is obtained from a responding concrete acceptor structure. All models are surrounded on 3 sides by coarse sand berms or hardpacked soil berms. It was determined that sand berms attenuate the blast pressure more than hardpacked berms. The confining effects of the donor structure significantly reduced the blast pressure. Positive phase impulse was not significantly reduced by altering the berm material or confining the charge.

I. INTRODUCTION

A. Background

This study was sponsored and funded by the Department of Defense Explosives Safety Board (DDESB). Most of the munition stored by the three services are in standard arch-type earth-covered magazines. The safe separation distances for these storage magazines are well established and documented.[1,2] In some areas of Europe and the United Kingdom munition are stored in box-type structures with barricades between them but no earth cover over the structure. This is the scenario of the brick magazines located in Machrihanish, Scotland.[3] Specific magazines located at this site are the subject of this investigation.

B. Objective

The primary objective of this project is to determine through scale model experiments the blast loading on the walls and roof of an acceptor magazine in the event of an accidental explosion in a donor magazine. The assumption is that the net explosive weight (NEW) detonates in mass and contributes to the blast loading. That is, the effect of munitions casing on blast attenuation is not accounted for; but the effect of the magazine structure on blast attenuation is documented in this series of experiments.

A secondary objective added after the experimental program was in progress was to study the effect of barricade construction. Is a loose low density sand barricade better or worse than a highly compacted soil barricade? The results will be discussed in the Results section of this report.

II. TEST PROCEDURE

Discussed in the test procedures are five areas of interest. They are: the design of the scale models, the test charges, instrumentation, layout, and matrix.

A. Design of Structure Models

Two scaled models were designed for this test program. One was a steel non-responding acceptor model instrumented with piezo-electric pressure transducers. The second model design was a scaled concrete structure used both as a donor structure and a responding acceptor model.

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[1] *Frederick H. Weals, "ESKIMO 1 Magazine Separation Test," NWC TP 5430, April 1973.*

[2] *Charles Kingery, George Coulter, and George Watson, "Blast Parameters from Explosions in Model Earth Covered Magazines," BRL MR 2680, September 1976 (AD A031414).*

[3] *F.B. Porzel, J.M. Ward, "Explosive Safety Analysis of the Machrihanish Magazine," NSWC TR79-359, December 1979.*

1. Steel Non-Responding Model. The acceptor model (see Figure 1) is a 1/23.5 scale version of a munitions magazine located at the Machrihanish Facility in Scotland. Typically, one of these magazines may contain a variety of munitions. Assuming that a bare Pentolite charge equivalent to a full magazine load is 13,000 kilograms, the scaling to a 1 kilogram test charge would result in a 1/23.5 scale.

The scaled dimensions are 30.5 cm x 33.3 cm x 41.1 cm. The model was constructed from 2.54 cm thick steel plate. All surfaces were welded together except for the front wall which was bolted to the model to facilitate emplacing gauges, wires, and connectors. For stability the model extends 15 cm below the surface. Therefore the exposed dimensions are 15.5 cm x 33.3 cm x 41.1 cm.

There are 18 pressure transducer positions on the model: two each on the end walls, six on the front side-wall (closest to the charge), five on the roof, and three on the back side-wall (farthest from the charge).

2. Concrete Donor/Acceptor Model. The concrete donor (or acceptor) model is also a 1/23.5 scale version of a Machrihanish munitions magazine. This model is composed of five separate concrete slabs and a cardboard door. Refer to Figure 2, a photograph showing the floor, walls, and roof; the door closure is not present.

The slabs were poured in small wooden forms. Copper wire was criss-crossed in the soft concrete in the forms to provide reinforcement so that the slabs would not break while being handled. "Sakrete Sand Mix" was used; gravel mix would not work because the stones are larger in diameter than the slab thickness. The roof has a minimum thickness of 0.64 cm and the floor has a maximum thickness of 1.27 cm.

To create a complete donor model, the concrete slabs and cardboard door were placed together. The parts stood on their own; no binding was needed to hold the model together.

A responding concrete acceptor was placed on the test pad for Shots 4 and 5. The design is similar to the concrete donor. Neither pressure transducers nor other instrumentation devices was mounted on the responding acceptor. It was, however, photographed at 2000 frames per second with a high speed movie camera.

B. Test Charges

A convenient test charge weight for scale model work is one kilogram. The BRL Hot Melt Laboratory cast one kilogram bare hemispherical Pentolite charges (Pentolite has approximately 1.17 times the explosive power of TNT) which were used for the donor charges. The charges were detonated from the center of the flat side which was placed on the concrete floor.

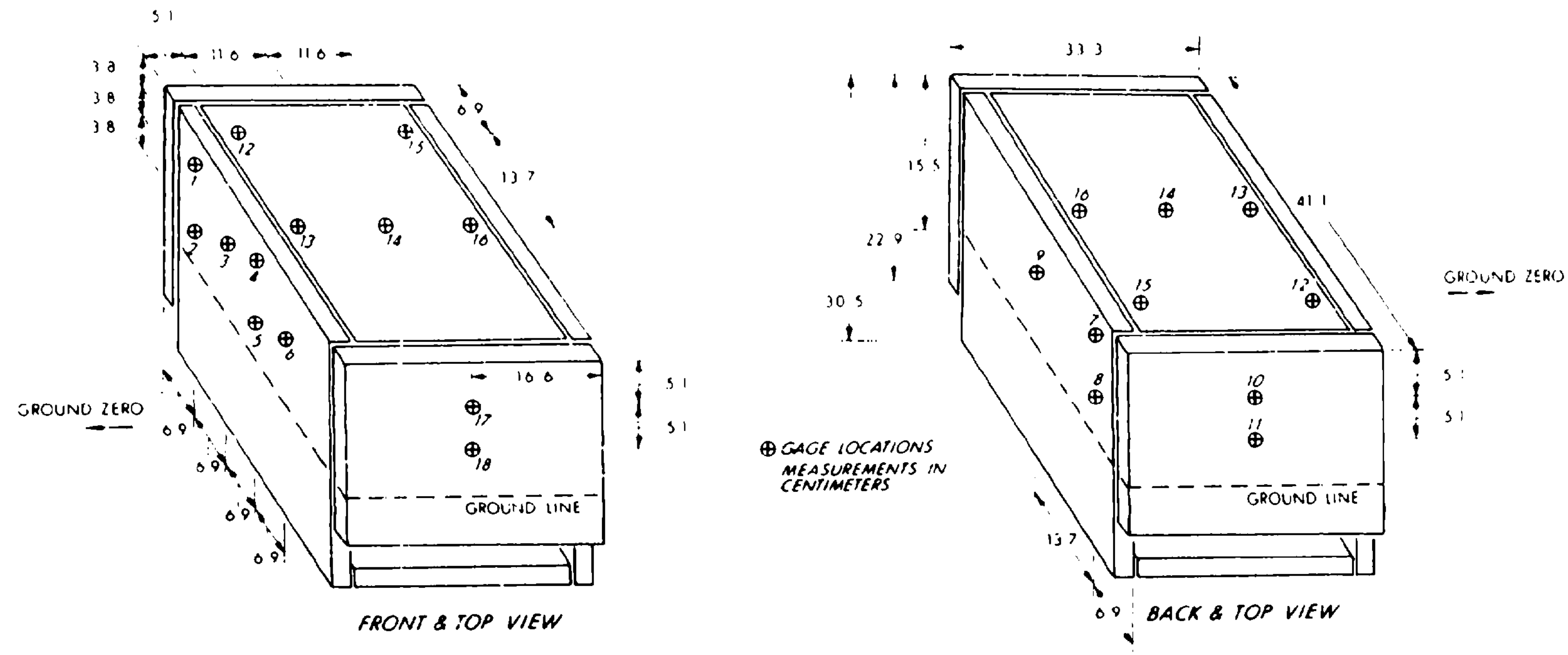


Figure 1. Non-Responding Acceptor Model

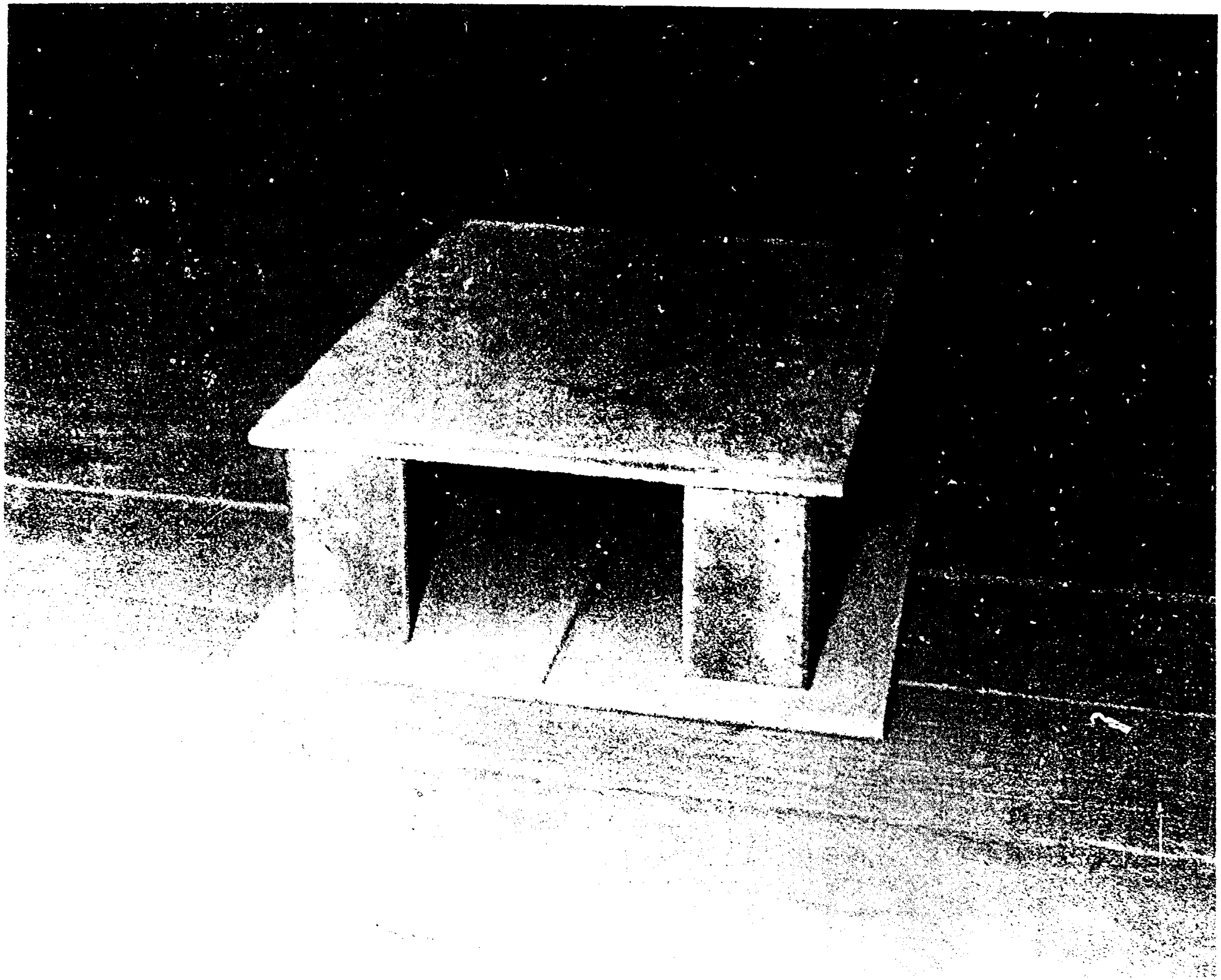


Figure 2. Photograph of Concrete Donor Model

C. Test Instrumentation

The instrumentation for this test series consisted of pressure transducers, magnetic tape recorder/playback, and a data reduction system. A block diagram is shown in Figure 3.

1. Pressure Transducers. Piezo-electric pressure transducers were used for this series of tests. The PCB Electronics Inc. models 113A22, 113A24, and 113A28, with quartz sensing elements and built-in source followers, were used extensively.

2. Tape Recorder System. The tape recorder consisted of three basic units, the power supply and voltage calibrator, the amplifiers, and the FM recorder (80 kHz response frequency). Once the signal was recorded on the magnetic tape it was played back and recorded on a Honeywell Visicorder. This oscillograph has 5 kHz frequency response and the overpressure versus time recorded at the individual stations can be read directly from the playback records for preliminary data analysis.

3. Data Reduction System. For the final data output, the tape signals were processed through an analog-to-digital converter, to a digital recorder-reproducer, and then to a computer. The computer (TEKTRONIX 4051) was programmed to apply the calibration values and present the data in the proper units for analysis. From the computer the data is put on a digital tape from which the final form can be plotted or tabulated. The digital tape can also be stored for future analysis.

D. Test Layout

1. Donor Charge in Structure. Figure 4 shows a diagram of the test layout, and Figure 5 is a photograph of the layout for Shot 4. The entire test site, i.e., the donor, acceptor(s), and berms, are 1/23.5 scale. Note that all models and berms were not used on every test and that the berm material was sometimes sand and sometimes soil. Refer to Tabel 1 in the Test Matrix Section for the exact test configuration of each shot.

The steel acceptor model, which remained in place during the project, was stabilized in several ways. The lower 15.2 cm of the walls were buried in the sand. Four steel straps were placed across and around the floor of the model, and these straps were secured with eight spikes, each 61.0 cm long, driven into the test pad. Furthermore, a sand bag was placed inside the model. These measures assured that the model remained non-responding.

Berms were constructed around the models as shown in Figure 4. The center of the floor of the concrete donor was placed at ground zero. The floor has a small center hole to allow for the detonator and charge placement. The walls, roof, and door were placed on the floor to complete the donor construction. On two shots a responding concrete acceptor model without instrumentation was also included in the test layout; refer to Table 1 in the Test Matrix Section.

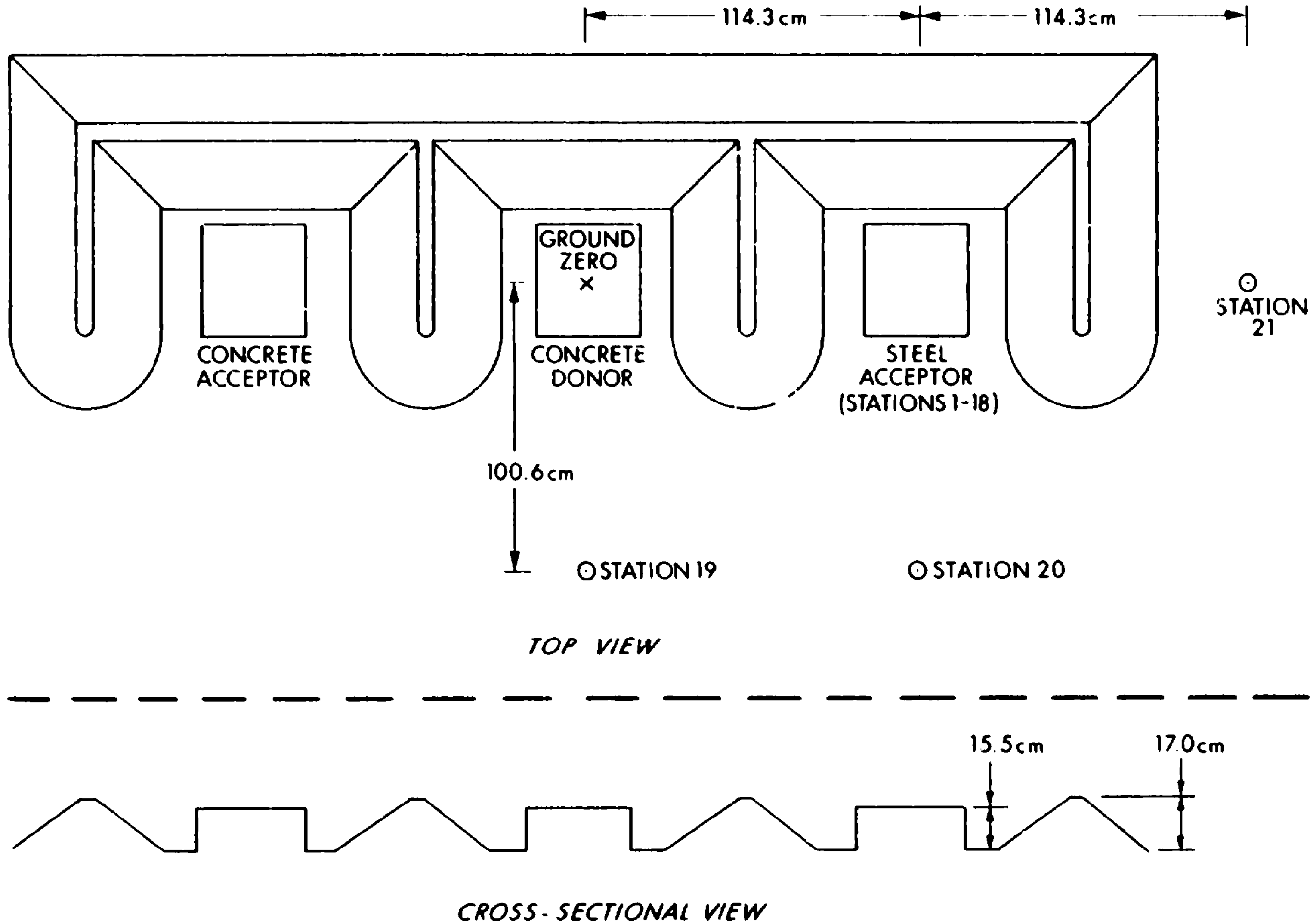


Figure 4. Test Layout

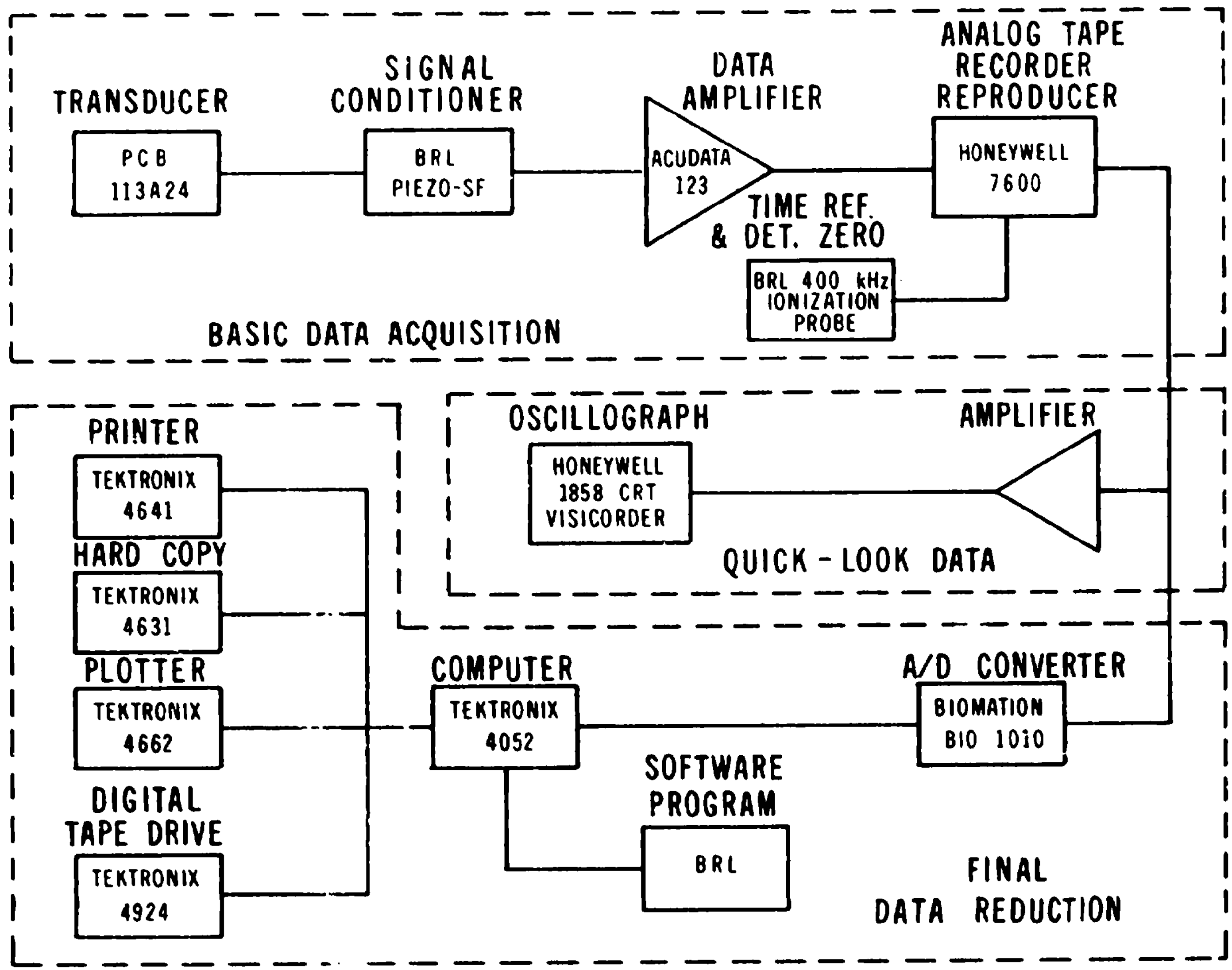


Figure 3. Data Acquisition/Reduction System

Figure 5. Photograph of Test Layout

With all three models in place, the test pad configuration is symmetric about an axis drawn through the donor model from front to rear and passing through ground zero. Refer to Figure 4. Because of this symmetry, the blast loading on the concrete responding acceptor and non-responding steel acceptor should be the same.

High speed cameras were used to photograph the blast event. One camera focused on the entire test layout; the other camera focused on one acceptor model.

Eighteen pressure transducers were mounted in the steel acceptor. Also, three pressure transducers were mounted in lead bricks to measure the pressure at three locations on the test pad. One (Station 19) was located 100.6 cm in front of ground zero; another (Station 20) was placed at the same distance in front of the steel acceptor, or 152.3 cm from ground zero. The third gage location (Station 21) was located 228.6 cm from ground zero. Refer to Figure 4.

2. <u>Donor Charge Unconfined.</u> On Shots 2 and 5 the concrete donor model was not used. The bare Pentolite charge was placed on the donor's concrete floor; but the walls, roof, and door were not used to confine the charge. The purpose of these tests was to determine the suppressive effect of the donor structure on the blast propagation. A pre- and post-shot view of the model and barricades are shown in Figure 6.

E. <u>Test Matrix</u>

Five test shots were fired during the period 5 August 1983 - 16 August 1983 at Range 8 on Spesutie Island. For a concise summary of the firing program, refer to Table 1.

On Shots 1, 2, and 3 the berms were composed of coarse sand. Shot 1 used a concrete donor and steel acceptor model. Shot 2 did not use a concrete donor; only the donor floor was in place. Shot 3 was a repeat of Shot 1.

For Shots 4 and 5 the berms were changed to soil which was packed down firmly. Additionally, for these last two shots, a concrete acceptor was placed on the test pad. Shot 4 used a concrete donor; Shot 5 was similar to Shot 4 except the donor was not used. Only the donor floor was present on Shot 5.

III. RESULTS

The results will be presented in the form of tables, pressure versus time records, and discussions of the blast loads impinging on the walls and roof of the acceptor structure for different donor charge confinements and barricades.

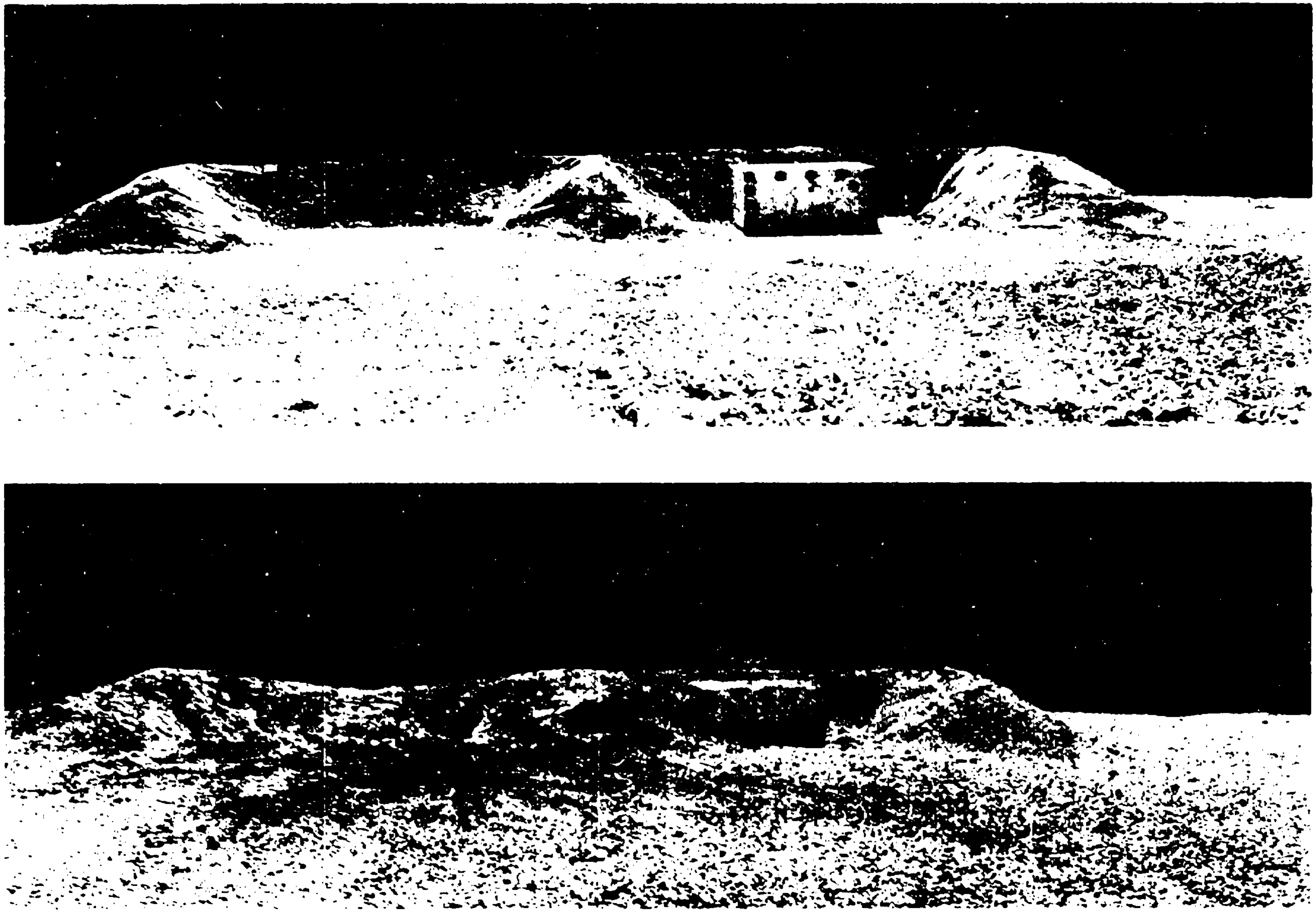


Figure 6. Pre- and Post-Shot View of Models and Barricades

TABLE 1. FIRING PROGRAM CHRONOLOGY

Shot No.	Date Fired	Concrete Donor	Steel Acceptor	Concrete Acceptor	Berm Material
1	5 Aug 83	Yes	Yes	No	Coarse Sand
2	10 Aug 83	Floor Only	Yes	No	Coarse Sand
3	11 Aug 83	Yes	Yes	No	Coarse Sand
4	15 Aug 83	Yes	Yes	Yes	Hardpacked Soil
5	16 Aug 83	Floor Only	Yes	Yes	Hardpacked Soil

A. Blast Loading on the Front Side-Wall of the Acceptor Structure

The blast loading on the front side of the acceptor structure (side facing the donor) will now be discussed. The result will be presented and compared for donor charge confined with loose sand barricades (Shot 3), donor charge confined with compacted soil barricades (Shot 4), and donor charge unconfined with compacted soil barricades (Shot 5). Blast parameter values are listed in Table 2. The authors' conception of the incident and reflected shock loading on two walls and the roof is presented in Figure 7.

The overpressures versus time recorded at Stations 1 and 4 for the three conditions (Shots 3, 4, and 5) are presented in Figure 8.* (The peak reflected pressures at Stations 1 and 4 show increases in order of Shot number.) The sand barricade gave pressures lower than the soil barricade (-15 percent), and the soil barricade with charge confined recorded pressures approximately 55 percent lower than the unconfined donor charge. The small reflection occurring on all records at 0.3 milliseconds is the reflection from the ground surface moving back up the wall.

The next two stations presented for comparison in Figure 9 are Stations 3 and 6. These stations are located the same distance down from the top, 0.076 m, and the same distance from the ends, 0.138 m. The overpressure versus time records are presented in Figure 9 for Stations 3 and 6 from Shots 3, 4 and 5. The general shape of overpressure versus time records is similar for the two locations. There is a difference in the pressures recorded from shot to shot. Shot 3 results are again lower (-15) percent) than Shot 4, and Shot 4 results are approximatly 50 percent lower than Shot 5. Note that the second reflection occurs sooner (0.25 msec) and is of greater magnitude than recorded at Stations 1 and 4.

The last two stations on the structure wall facing the donor are Stations 2 and 5. They are located 0.114 metres down from the top. Station 2 is 0.069 meters from the end, and Station 5 is along the center line. The overpressures versus time recorded at these two stations are presented in Figure 10 for Shots 3, 4, and 5. The stations are near the ground surface, and the reflected shock occurs sooner. The reflected shock is almost equal in magnitude to the incident shock with the exception of Station 5 on Shot 3 where the incident shock is smaller than the reflected shock. The authors have no explanation for this anomaly.

B. Blast Loading on the Roof of the Acceptor Structure

There were five stations on the roof of the acceptor structure. The numerical values of the blast parameters are listed in Table 3. The first two stations to be discussed are located near the front edge. The angle of the shock front striking the roof is quite different from the angle of the shock front striking the front side-wall. The front side is in a regular reflection region while the roof is in a Mach reflection region. This is deduced from the difference in the magnitude of the peak overpressure. Station 1 recorded 1112 kPa on Shot 3 while Station 12 recorded a value of

*Although all figures are titled pressure versus time they also include the overpressure impulse versus time.

TABLE 2. BLAST LOADING ON FRONT SIDE-WALL

Shot	Station	Peak Pressure kPa	Impulse kPa-ms	Arrival Time ms	Duration ms
3	1	1112	183	0.785	0.84
	2	1026	229	0.857	0.79
	3	821	195	0.850	0.70
	4	943	184	0.807	0.67
	5	1139	240	0.885	0.64
	6	891	188	0.840	0.63
4	1	1305	199	0.870	0.82
	2	1049	247	0.895	0.69
	3	1093	239	0.890	0.71
	4	1089	220	0.847	0.67
	5	1045	282	0.917	0.64
	6	993	237	0.872	0.62
5	1	2489	230	0.495	0.53
	2	2015	205	0.527	0.49
	3	2015	240	0.512	0.58
	4	2612	226	0.463	0.56
	5	1745	307	0.535	0.50
	6	2073	227	0.490	0.49

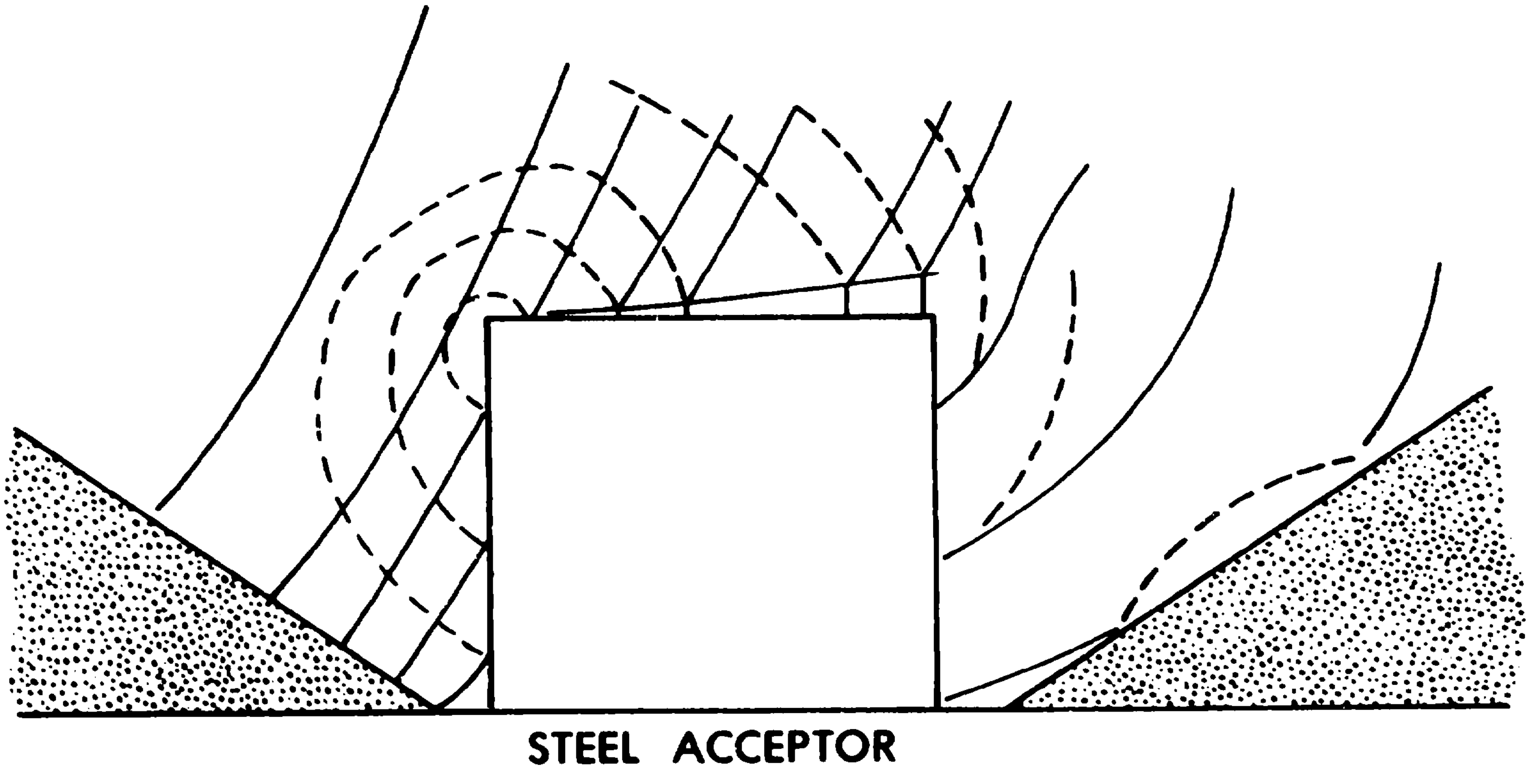


Figure [illegible]. Incident and Reflected Shock Loading on Acceptor

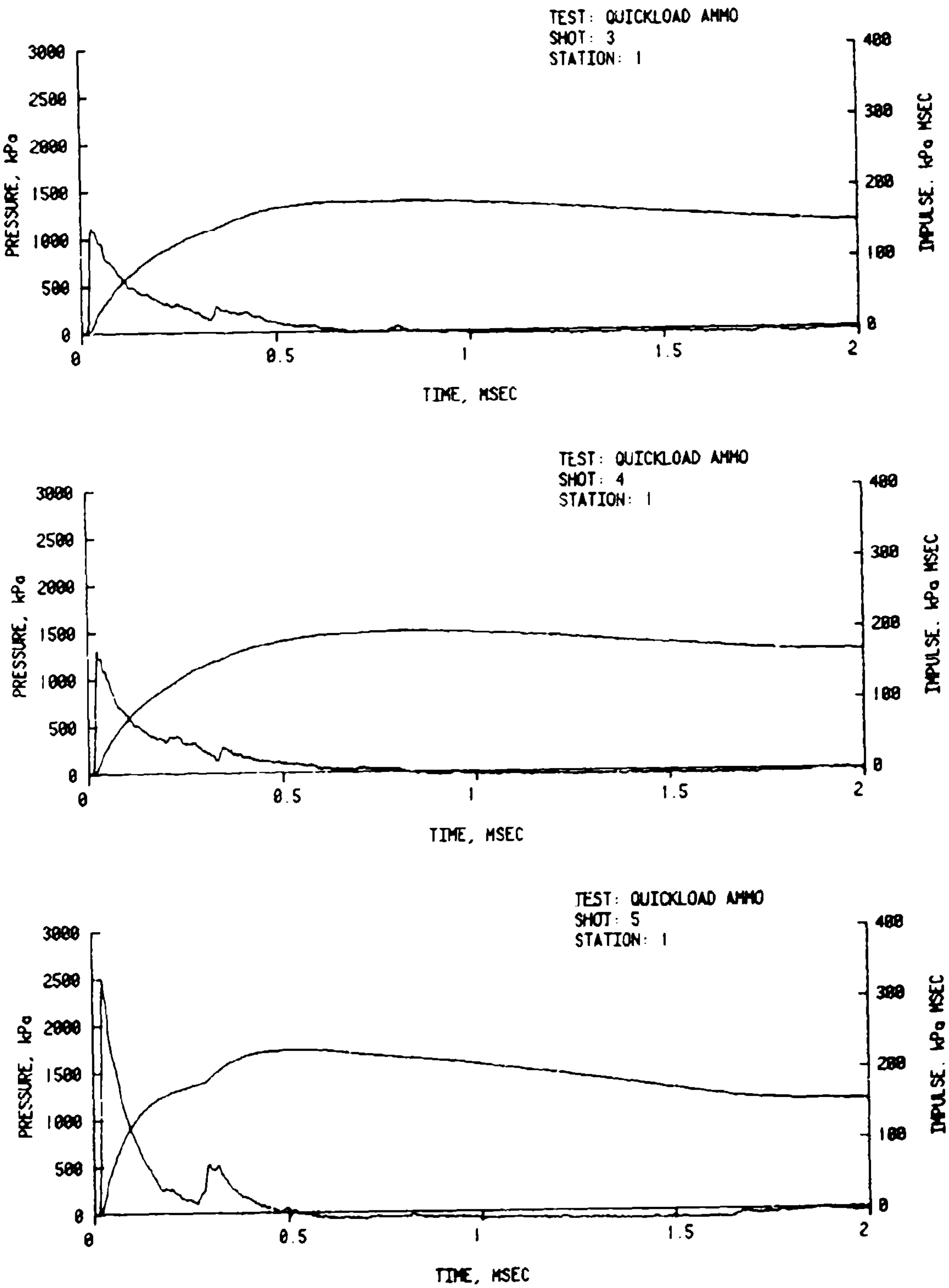


Figure 8. Pressure versus Time, Stations 1 and 4 for Shots 3, 4, and 5

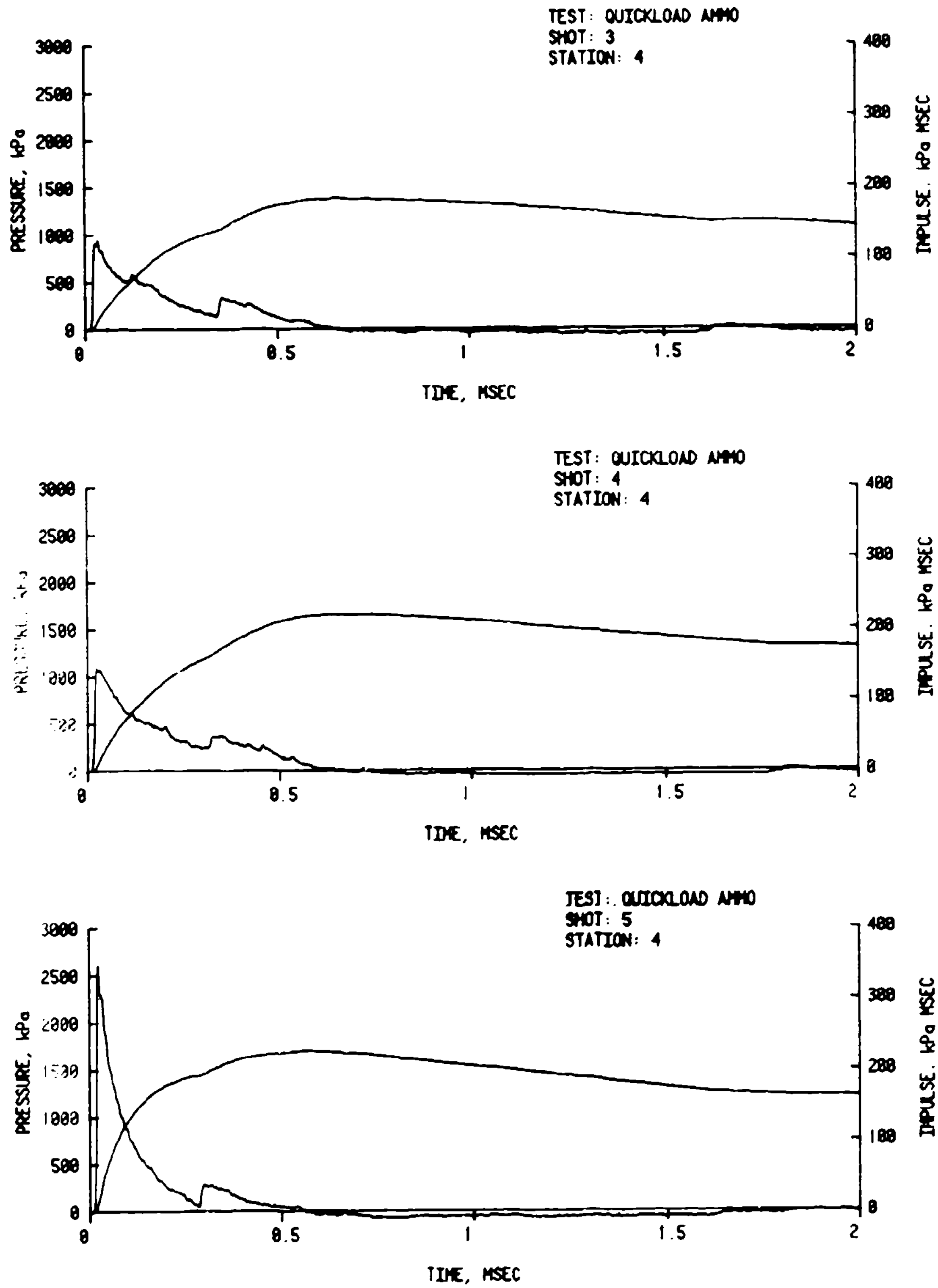


Figure 8. Pressure versus Time, Stations 1 and 4 for Shots 3, 4, and 5 (Continued)

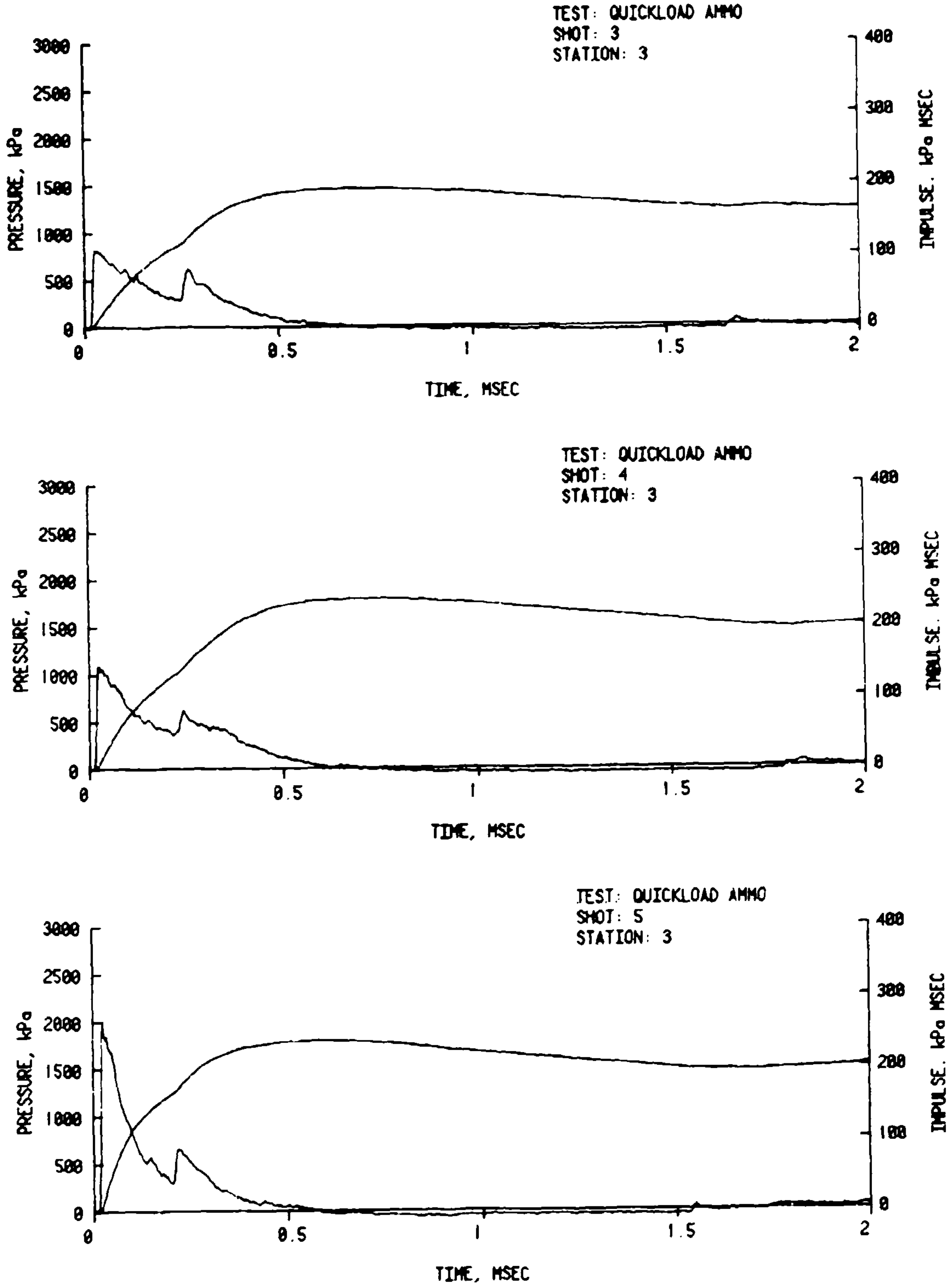


Figure 9. Pressure versus Time, Stations 3 and 6 for Shots 3, 4, and 5

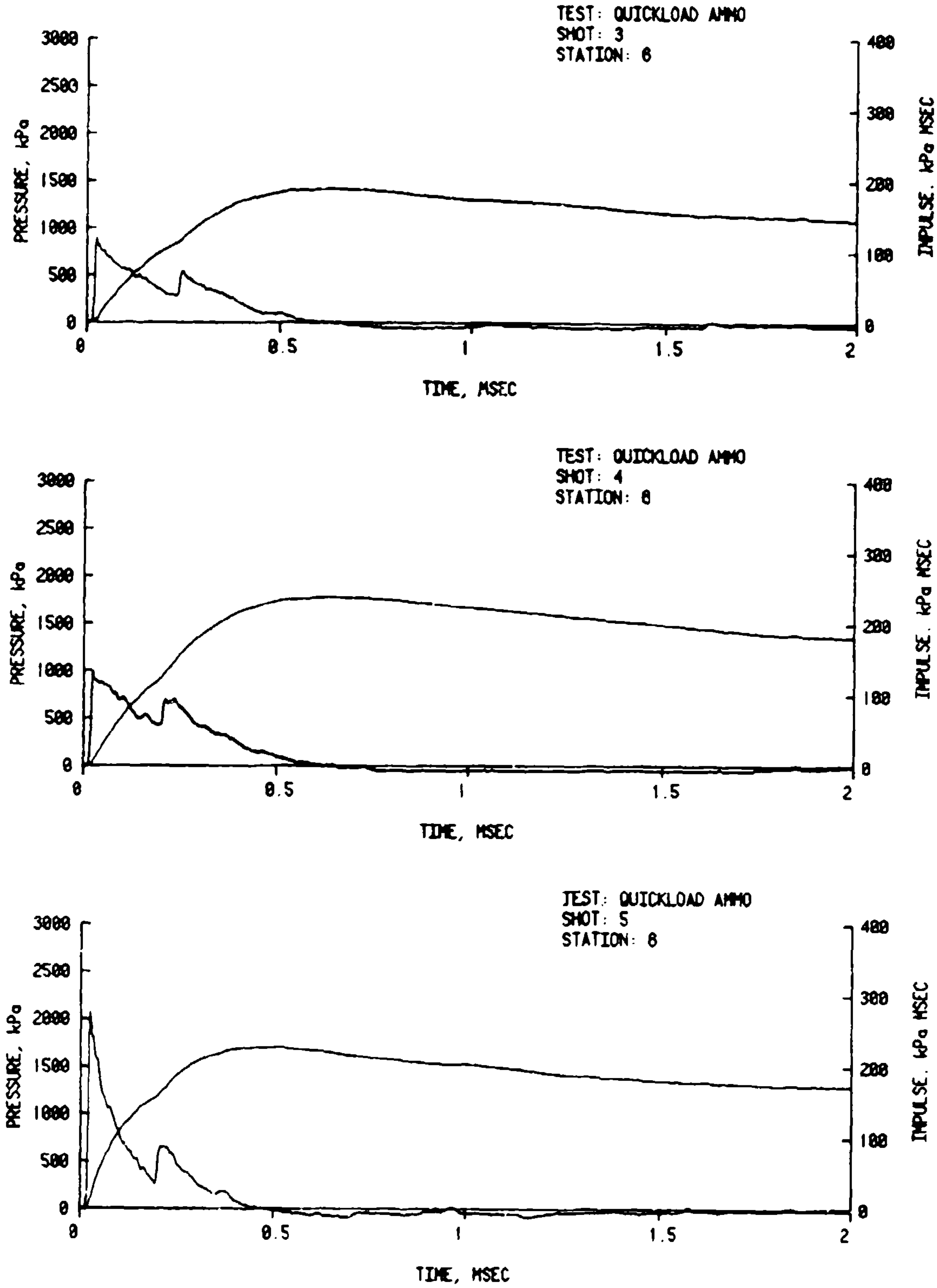


Figure 9. Pressure versus Time, Stations 3 and 6 for Shots 3, 4, and 5 (Continued)

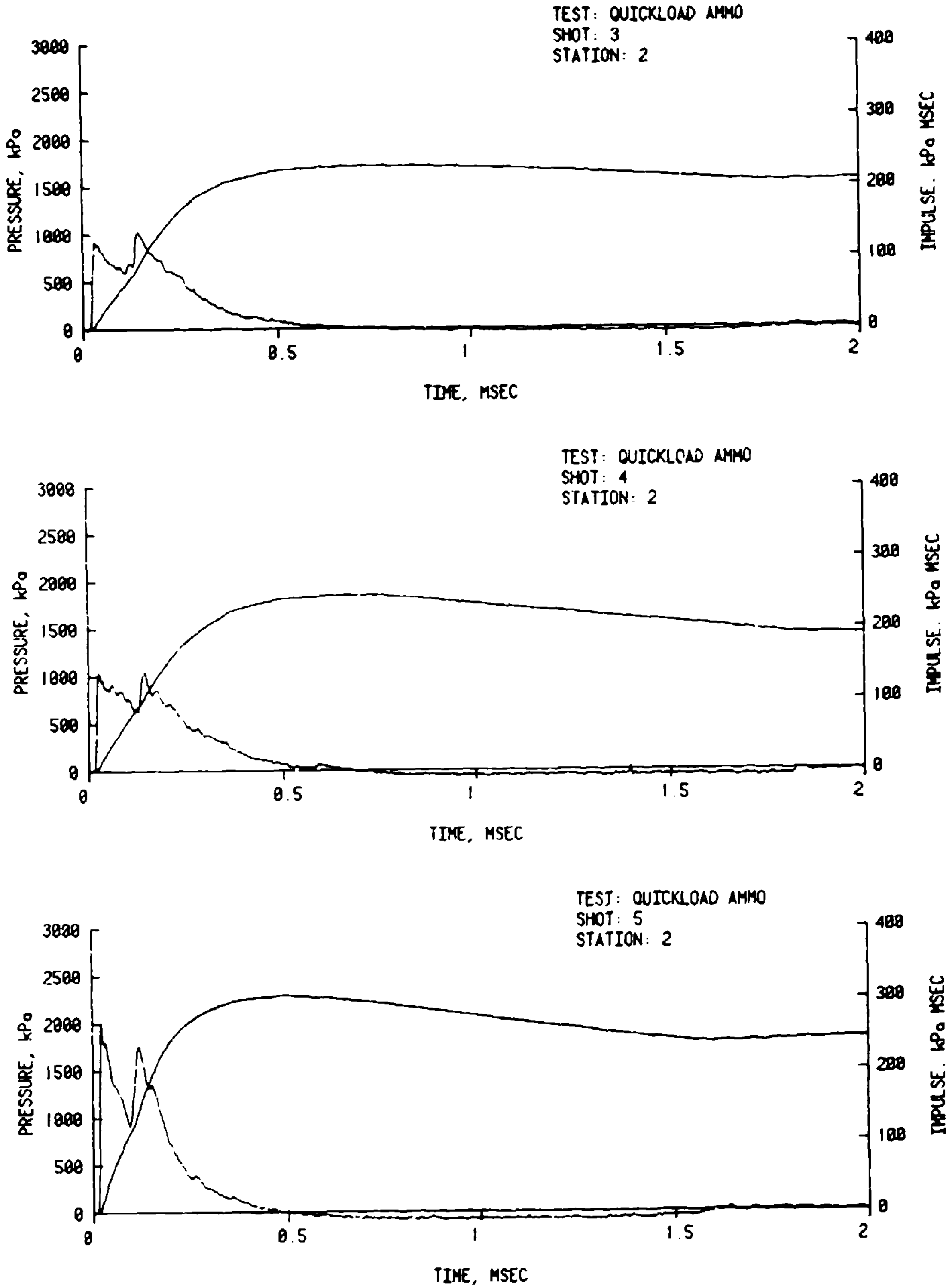
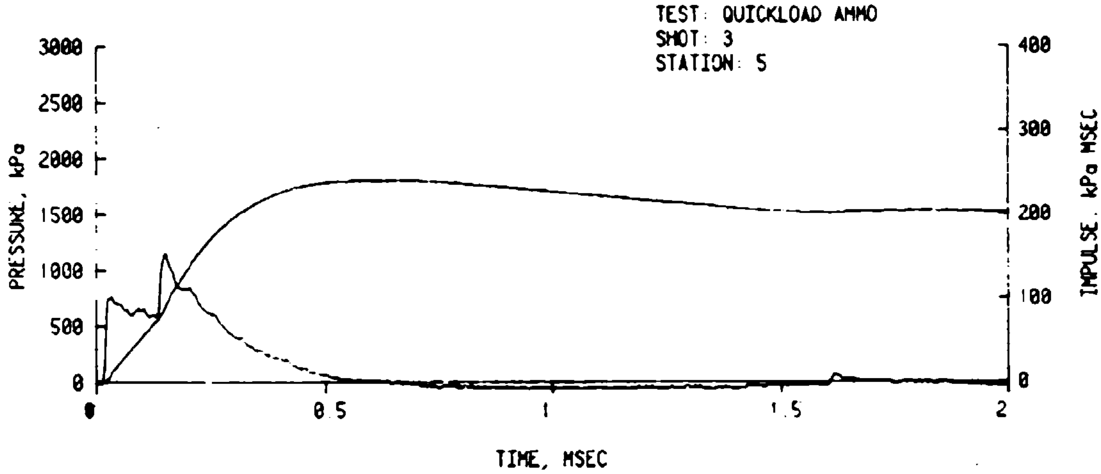
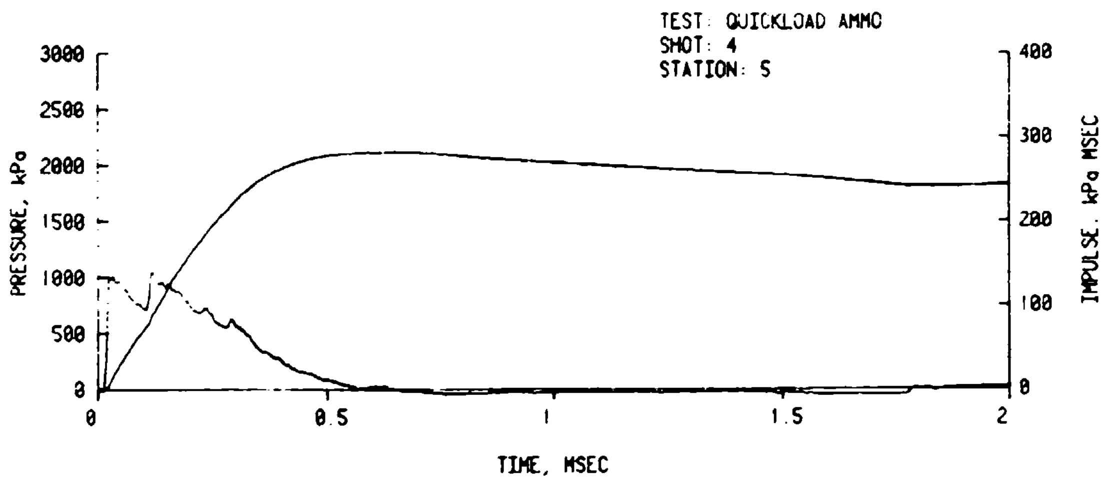


Figure 10. Pressure versus Time, Stations 2 and 5 for Shots 3, 4, and 5





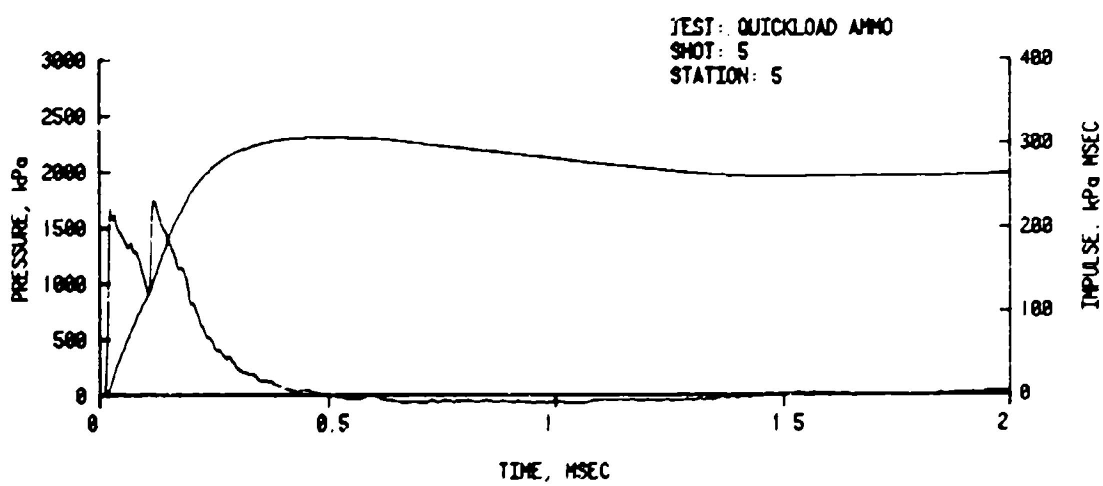


Figure 10. Pressure versus Time, Stations 2 and 5 for Shots 3, 4, and 5 (Continued)

TABLE 3. BLAST LOADING ON ROOF

Shot	Station	Peak Pressure kPa	Impulse kPa-ms	Arrival Time ms	Duration ms
3	12	419	109	0.845	1.12
	13	409	120	0.845	1.14
	14	348	121	1.007	1.50
	15	308	99	1.172	1.58
	16	288	111	1.182	1.60
4	12	423	106	0.830	0.97
	13	448	150*	0.867	1.70
	14	400	-	1.047	-
	15	277	91	1.225	0.91
	16	285	90	1.217	0.90
5	12	896	152	0.497	1.25
	13	977	124	0.482	0.85
	14	764	109	0.598	0.55
	15	609	110	0.740	0.70
	16	543	116	0.732	0.80

*Questionable value

419 kPa. Based on reflection factor curves for various angles of incidence,[4] it appears that the incident peak overpressure is 305 kpa; and the angle of incidence of the shock front striking the front wall is 27 degrees; and the angle of the shock front striking the roof is 63 degrees. At station 12 shown in Figure 11 there is no significant difference in Shots 3 and 4 in peak overpressure or overpressure impulse. Station 13 records a peak overpressure approximately 9 percent lower on Shot 3 than Shot 4. The peak overpressures recorded at Stations 12 and 13 on Shot 4 are 54 percent lower than recorded on Shot 5 (the unconfined donor charge).

Station 14 is in the center of the roof. The peak overpressure shown in Figure 12 is 13 percent lower on Shot 3 than Shot 4, and Shot 4 is 48 percent lower that Shot 5. The records from Station 14 also record a lower peak overpressure than Station 13 because of the pressure decay associated with distance from the donor.

Stations 15 and 16 are located on the rear edge of the roof - away from the donor. In Figure 13 the peak overpressures versus time recorded at Stations 15 and 16 on Shots 3 and 4 show no significant differences. The peak overpressure falls within ± 6 percent of a mean value and the impulses fall within +13 percent -9 percent. The peak overpressures recorded at Stations 15 and 16 are 51 percent lower on Shot 4 than on Shot 5. This follows the same trend established at the other stations on the roof and front face.

C. Blast Loading on the Back Side-Wall of the Acceptor Structure

Stations 7, 8, and 9 are located on the back side (away from the donor) of the structure model. A detailed analysis will not be made for each station and shot, but some general observations will be made. Station 7 is located at the top corner and as shown in Figure 14 receives the first shock expanding over the top with a decay associated with the vortex moving down the structure wall. The pressure increase starting at 0.75 msec is believed to be a reflection from the barricade back against the rear wall. Shot 5 produces peak overpressures somewhat larger than Shots 3 or 4 but not the magnitude noted on the top and front. Numerical values are listed in Table 4.

Station 8 is located in the center of the back wall. The overpressures versus time for Shots 3, 4, and 5 are presented in Figure 14. The first pressure is from over the top of the structure while the second pressure rise is from reflections off the ground surface and the barricade.

The second pressure rise is greater in Shot 4 than recorded on Shot 3. The record from Shot 5 is the same general shape as recorded on Shot 4, but the magnitude is much greater. The Shot 4 record is 40 percent lower in overpressure than Shot 5.

[4] *Charles N. Kingery and George A. Coulter "Reflected Overpressure Impulse on a Finite Structure," Tech Report ARBRL-TR-02537, December 1983 (AD A137259).*

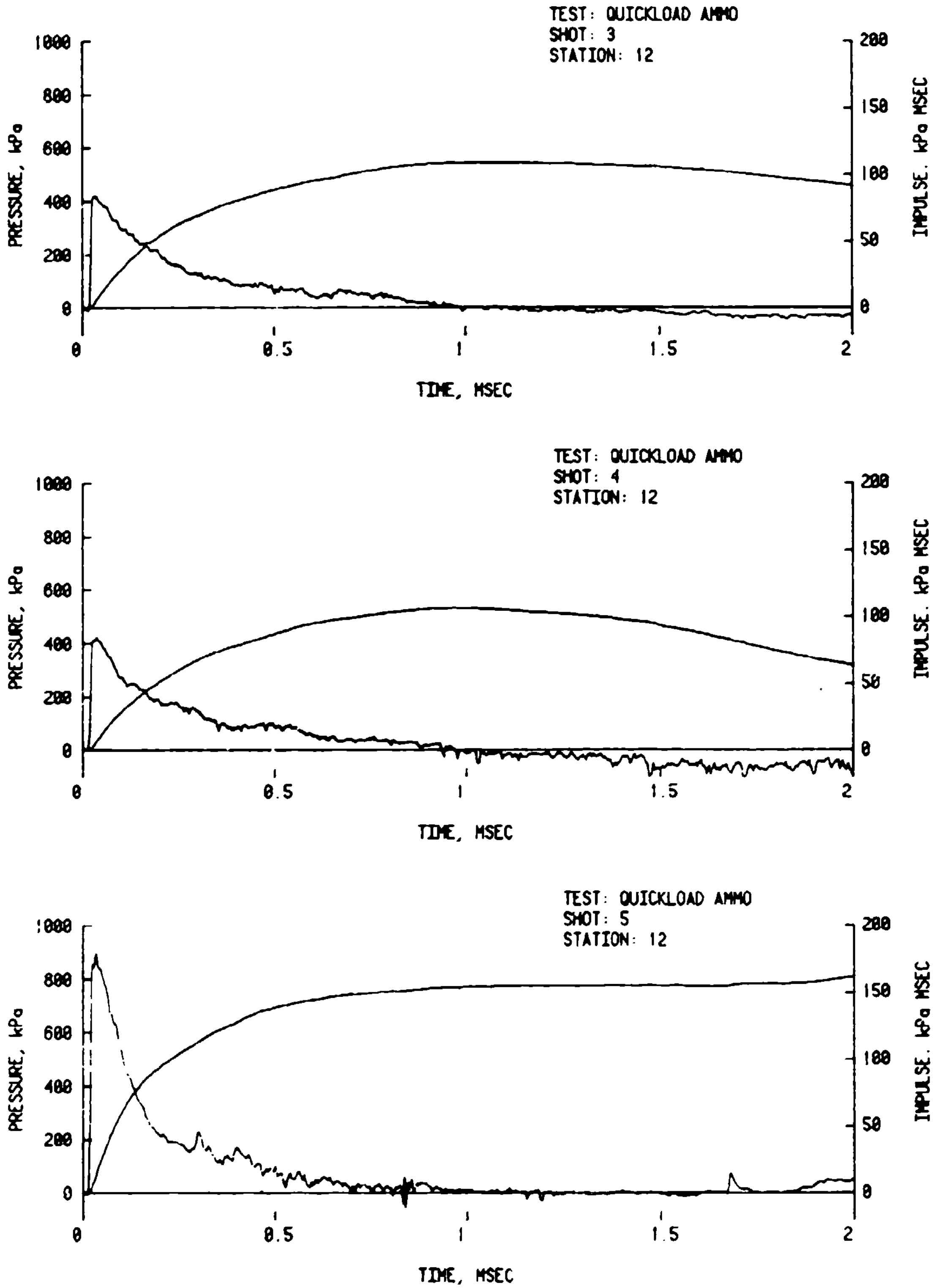


Figure 11. Pressure versus Time, Stations 12 and 13 for Shots 3, 4, and 5

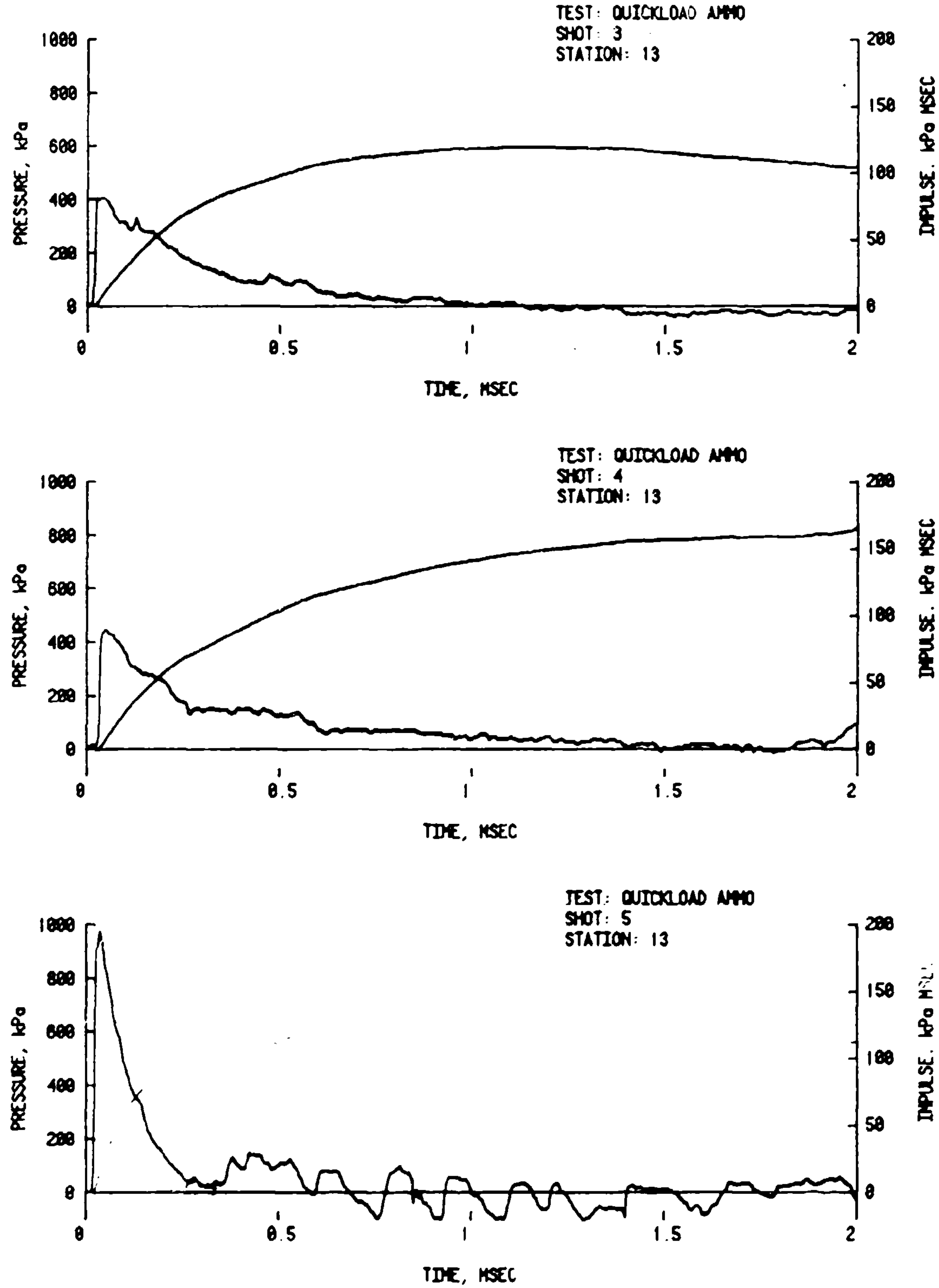


Figure 11. Pressure versus Time, Stations 12 and 13 for Shots 3, 4, and 5 (Continued)

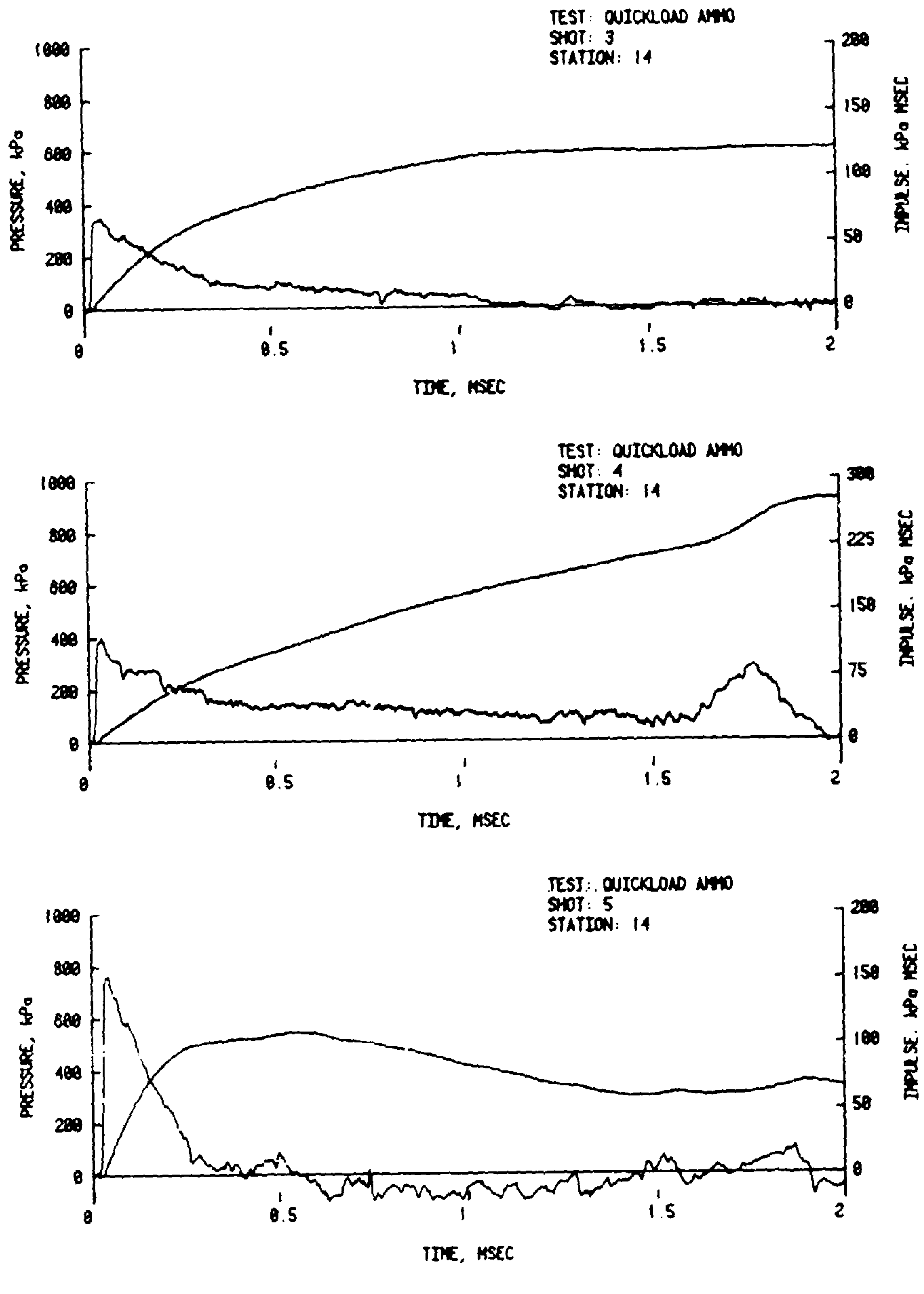


Figure 12. Pressure versus Time, Station 14 for Shots 3, 4, and 5

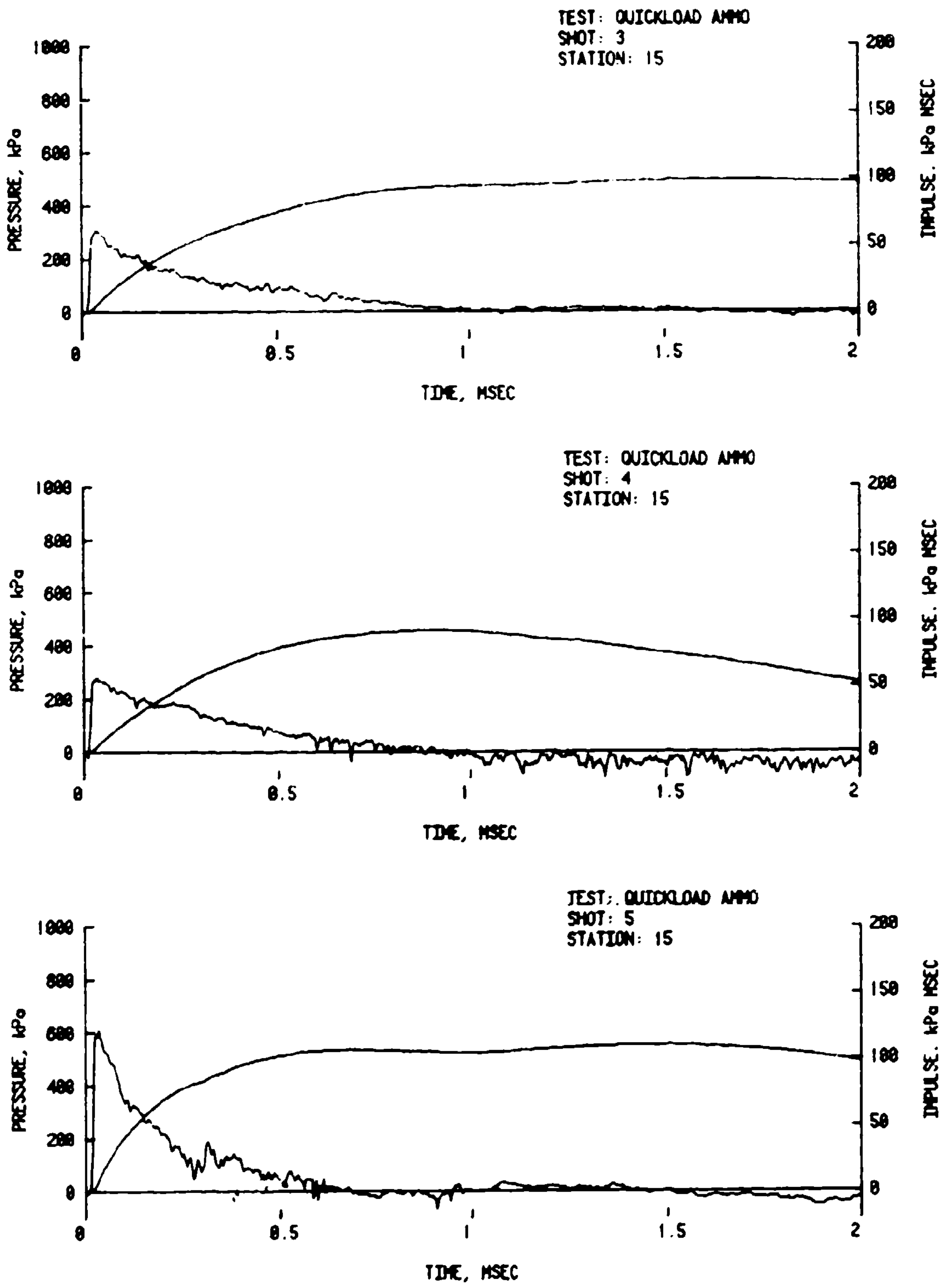
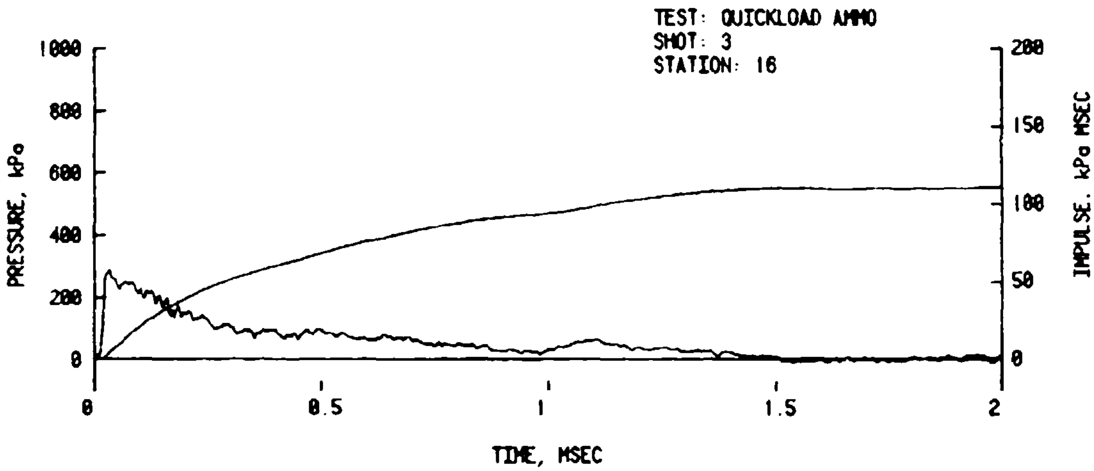
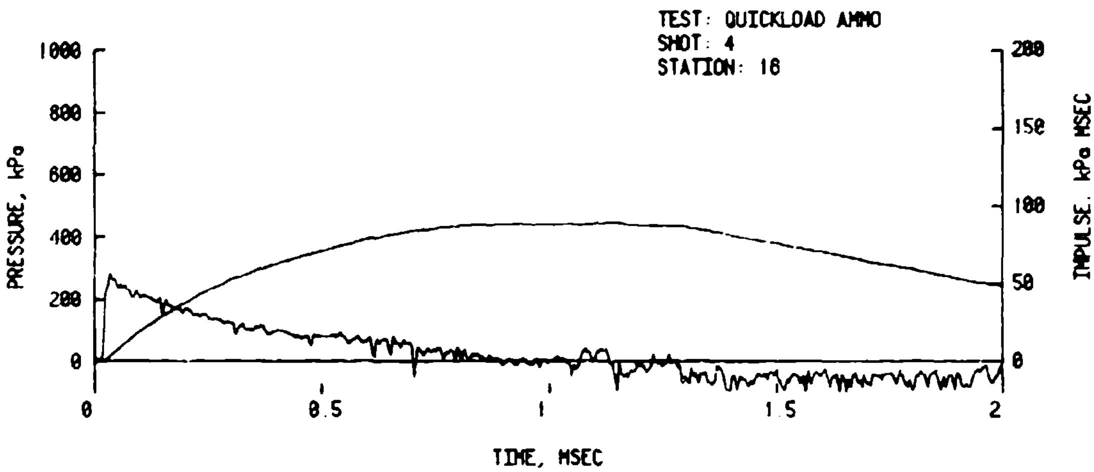


Figure 13. Pressure versus Time, Stations 15 and 16 for Shots 3, 4, and 5





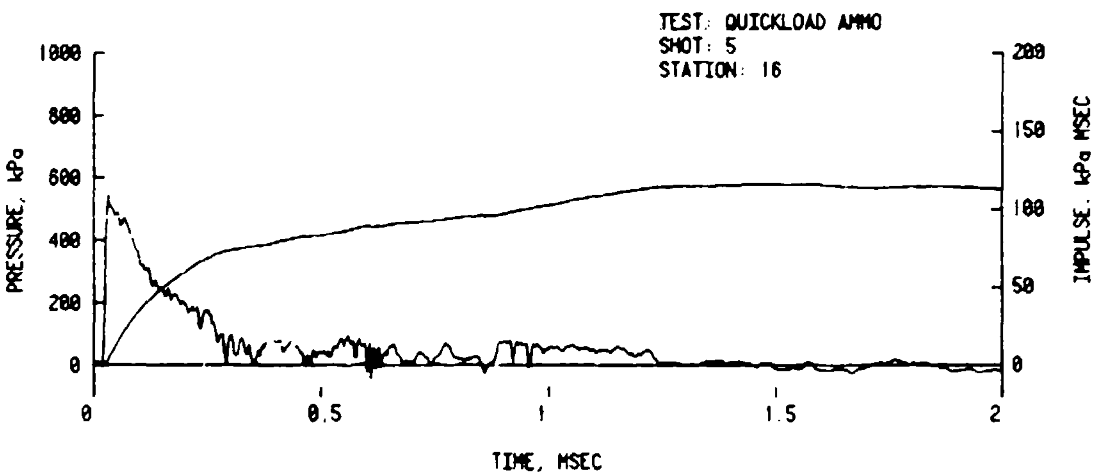


Figure 13. Pressure versus Time, Stations 15 and 16 for Shots 3, 4, and 5 (Continued)

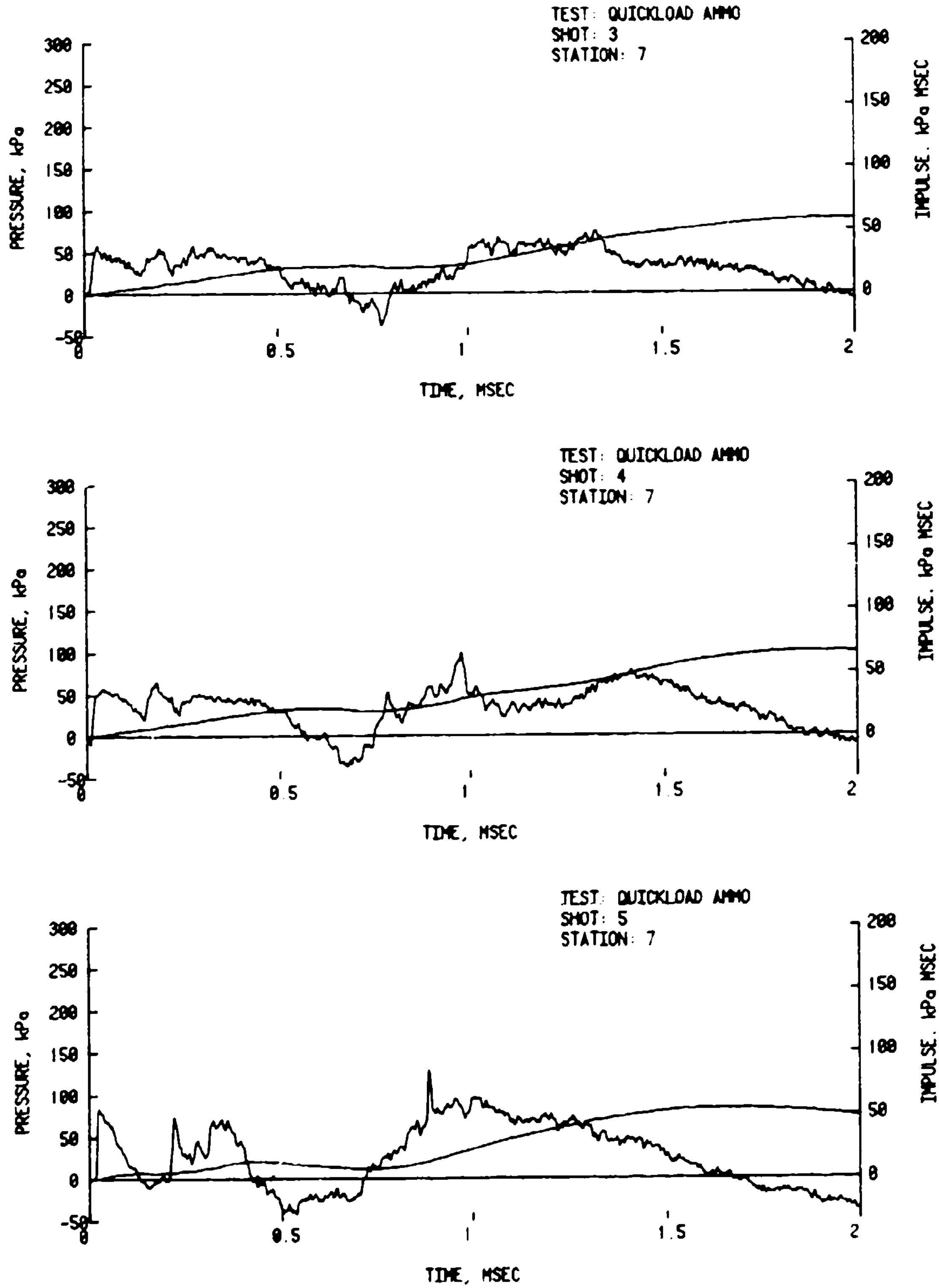


Figure 14. Pressure versus Time, Stations 7, 8, and 9 for Shots 3, 4, and 5

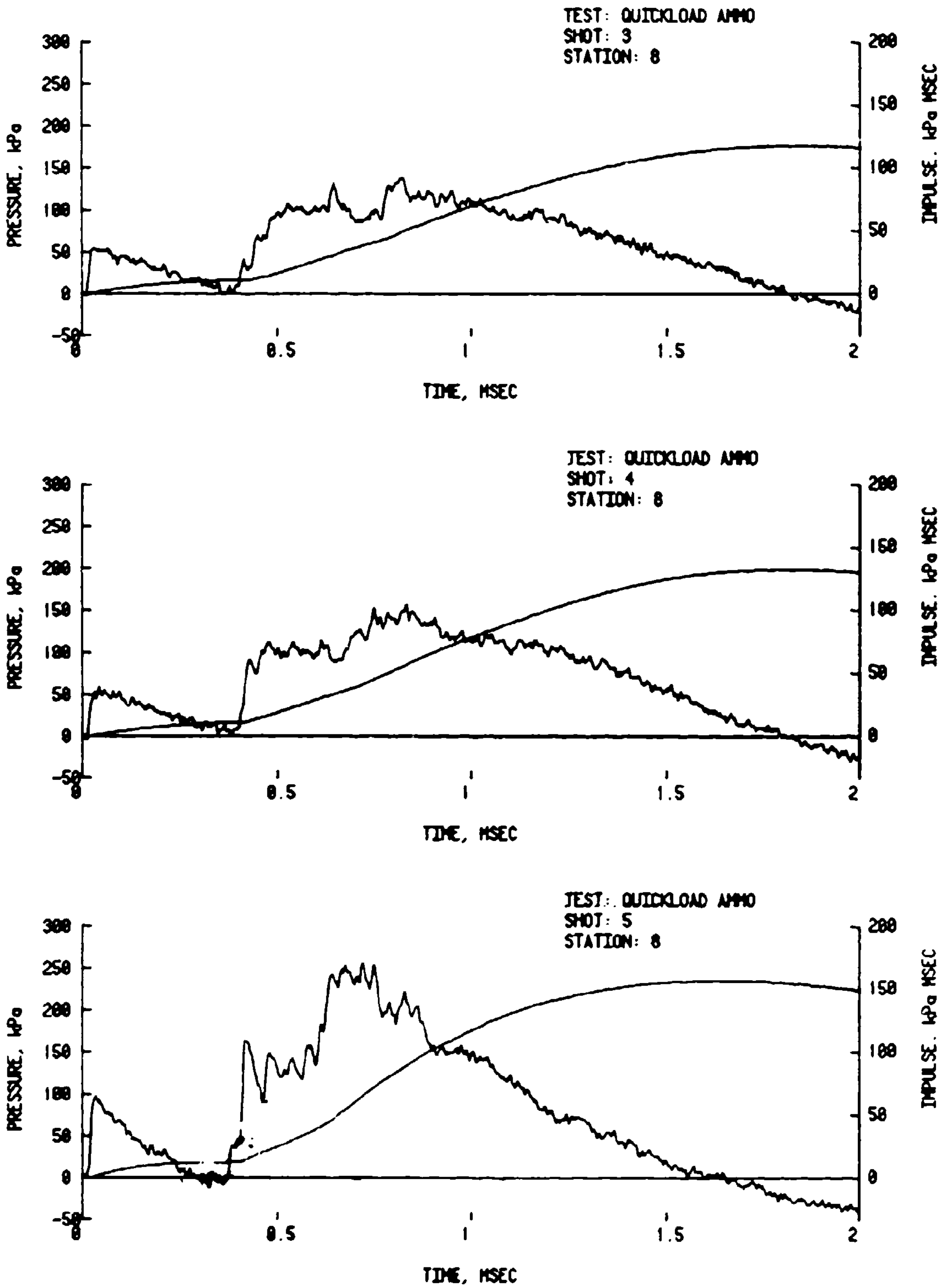


Figure '4. Pressure versus Time, Stations 7, 8, and 9 for Shots 3, 4, and 5 (Continued)

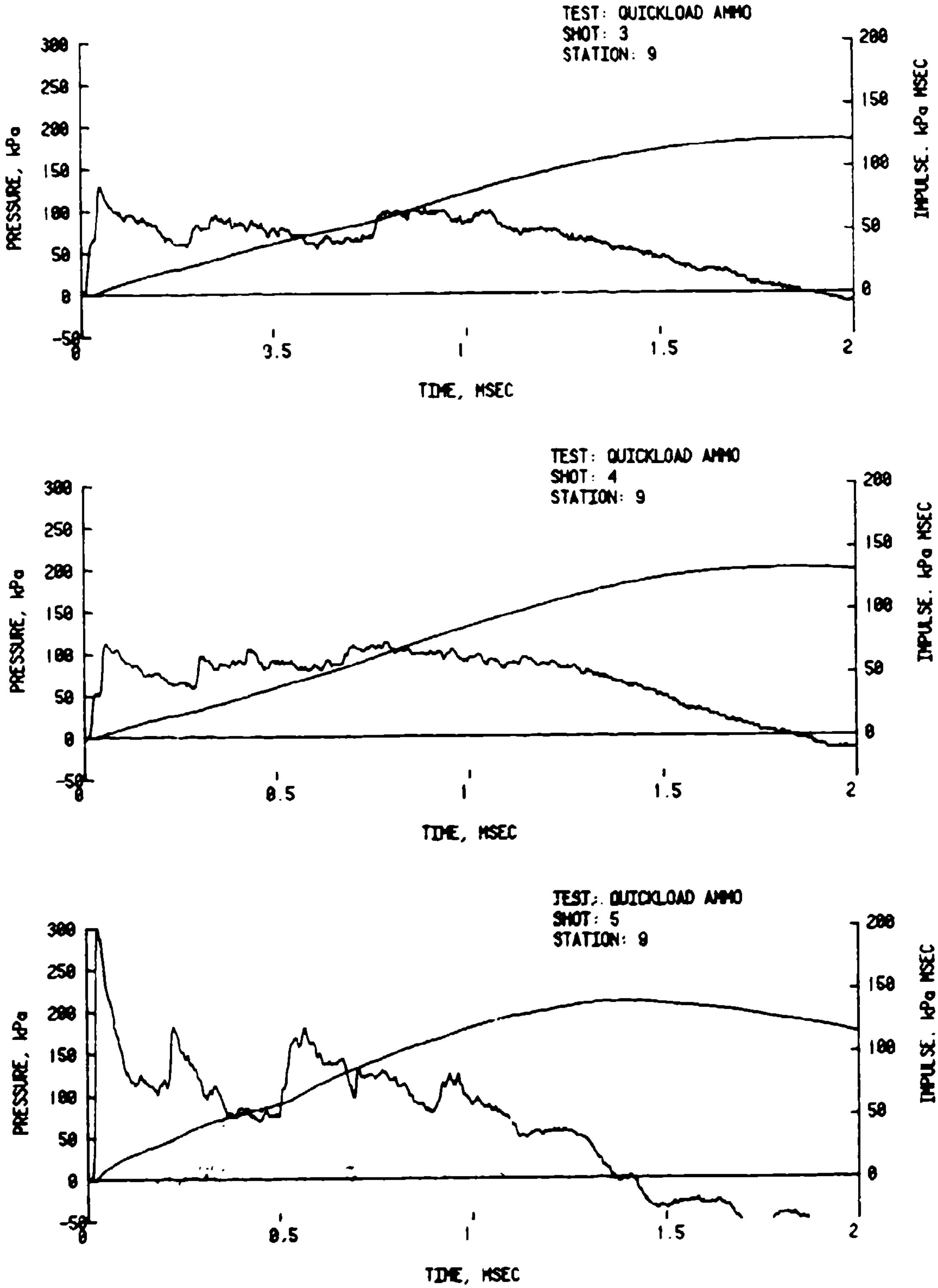


Figure 14. Pressure versus Time, Stations 7, 8, and 9 for Shots 3, 4, and 5 (Continued)

TABLE 4. BLAST LOADING ON BACK SIDE-WALL

Shot	Station	Peak Pressure kPa	Impulse kPa-ms	Arrival Time ms	Duration ms
3	7	60/73*	59	1.370	1.95
	8	52/139*	117	1.447	1.32
	9	130	122	1.525	1.90
4	7	60/98*	66	1.427	1.90
	8	55/156*	132	1.487	1.80
	9	112	133	1.577	1.84
5	7	80/129*	55	0.907	1.67
	8	96/256	157	0.962	1.66
	9	301	140	1.072	1.37

*Reflected Shock

Station 9 is located near the bottom of the wall and is subjected to reflected pressures immediately after the incident shock. Pressures versus time for Shots 3, 4, and 5 are presented in Figure 14. Shots 3 and 4 are similar while Shot 5 records the large reflected pressure produced from a re-entrant corner effect.

D. Blast Loading on the Ends of the Acceptor Structure

There were two station locations (10 and 11) on the back end of the structure and two (17 and 18) on the front (door) end. The predicted wave shape for Stations 10 and 17 would be an incident shock followed by a reflected wave from the ground surface passing back up the wall. At Stations 11 and 18 the reflected wave from the ground surface should arrive sooner and be of greater magnitude than recorded at stations 10 and 17. Because of the location of the barricade near the back end of the structure, the reflected wave from the ground surface would be predicted larger at Stations 10 and 11 than at Stations 17 and 18. Numerical values of the blast parameters are listed in Table 5.

Upon examining the pressures versus time recorded at Stations 10 and 11 for Shots 3, 4, and 5 (Figure 15), the same trend is seen here as noted earlier. That is, the soil barricade shot records pressure higher than the sand barricades and the unconfined charge produces higher pressures than the confined charge.

The same trend is noted at Stations 17 and 18 and shown in Figure 16. The sand barricades produce lower pressures, and the reflection from the surface occurs sooner and is greater at Station 18 than at Station 17.

E. Free-Field Pressure versus Time Recordings

Stations 19, 20, and 21 were mounted flush with the ground surface and located as shown in Figure 3. These gage locations were placed to monitor the blast wave propagating to the front and side of the donor and the overpressure versus time in front of the acceptor. The pressures versus time recorded at Station 19 on Shots 3, 4, and 5 are presented in Figure 17. On Shots 3 and 4 the donor charge was covered with a scaled concrete structure model with a frangible door. The blast was focused forward. Numerical values for the three stations are listed in Table 6. The difference in peak overpressure at Station 19 between Shots 3 and 4 is 31 percent, but the difference in impulse is only 10 percent. The difference in peak overpressure is quite large, but this cannot all be attributed to the sand versus clay barricades. The unconfined donor charge (Shot 5) produces 34 percent less peak overpressure and 25 percent less impulse than the covered donor on Shot 4.

The effect of the focusing to the front is quickly lost at Station 20 where the peak overpressure is 52 percent less and the impulse is 23 percent less on Shot 4, the covered donor charge, than on Shot 5, the uncovered donor charge. These records are shown in Figure 18.

TABLE 5. BLAST LOADING ON END WALLS

Shot	Station	Peak Pressure kPa	Impulse kPa-ms	Arrival Time ms	Duration ms
3	10	248/274	109	1.067	1.23
	11	327	112	1.102	1.22
	17	214/214	103	1.082	1.33
	18	200/272	109	1.120	1.23
4	10	200/358	99	1.120	1.08
	11	401	102	1.165	1.02
	17	250/300	107	1.082	1.26
	18	250/392	117	1.120	1.23
5	10	375/806	134	0.685	0.77
	11	375/1016	160	0.735	0.71
	17	390/350	122	0.670	1.00
	18	375/527	130	0.717	0.95

/Indicates two peaks

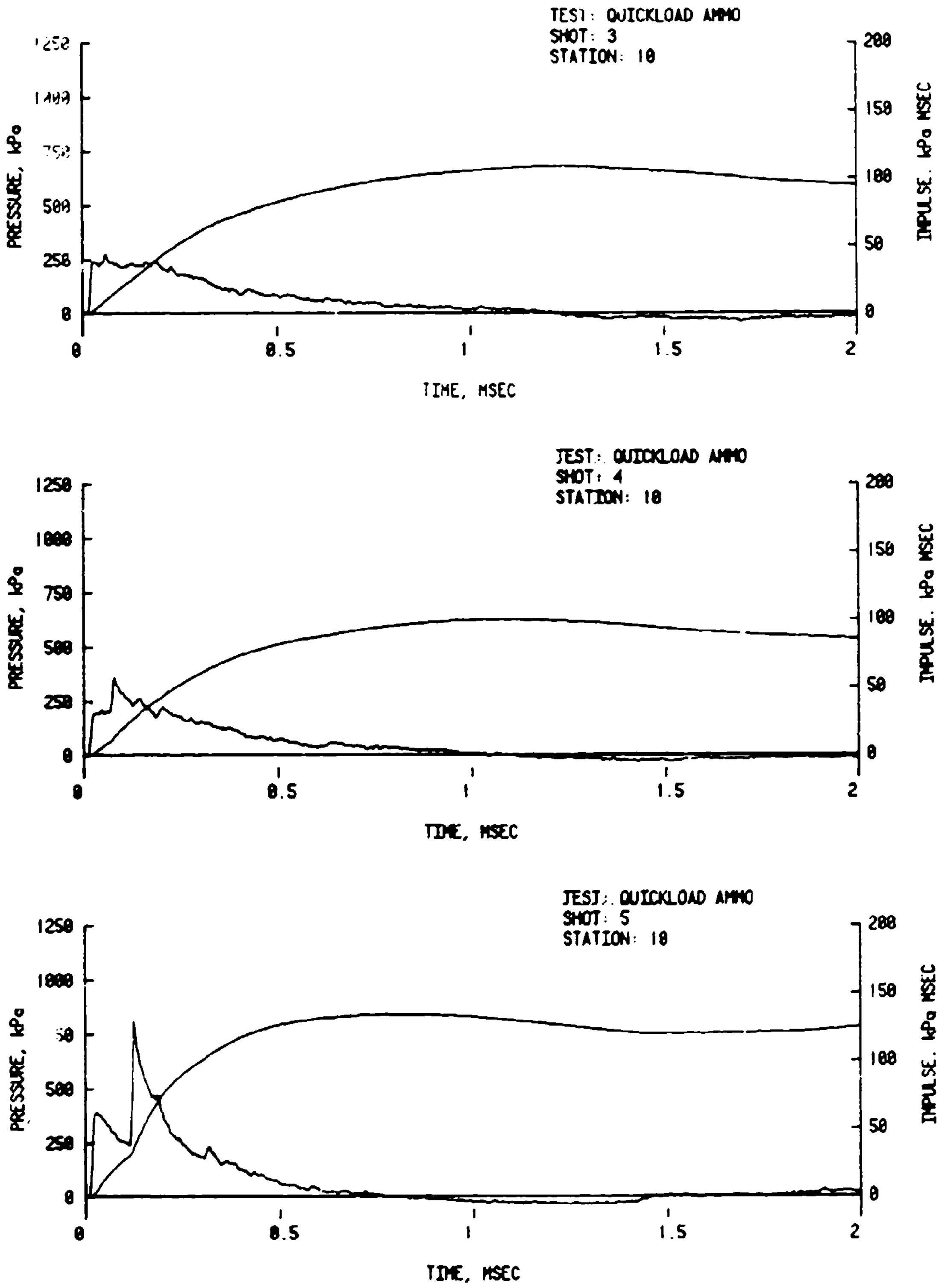


Figure 15. Pressure versus Time, Stations 10 and 11 for Shots 3, 4, and 5

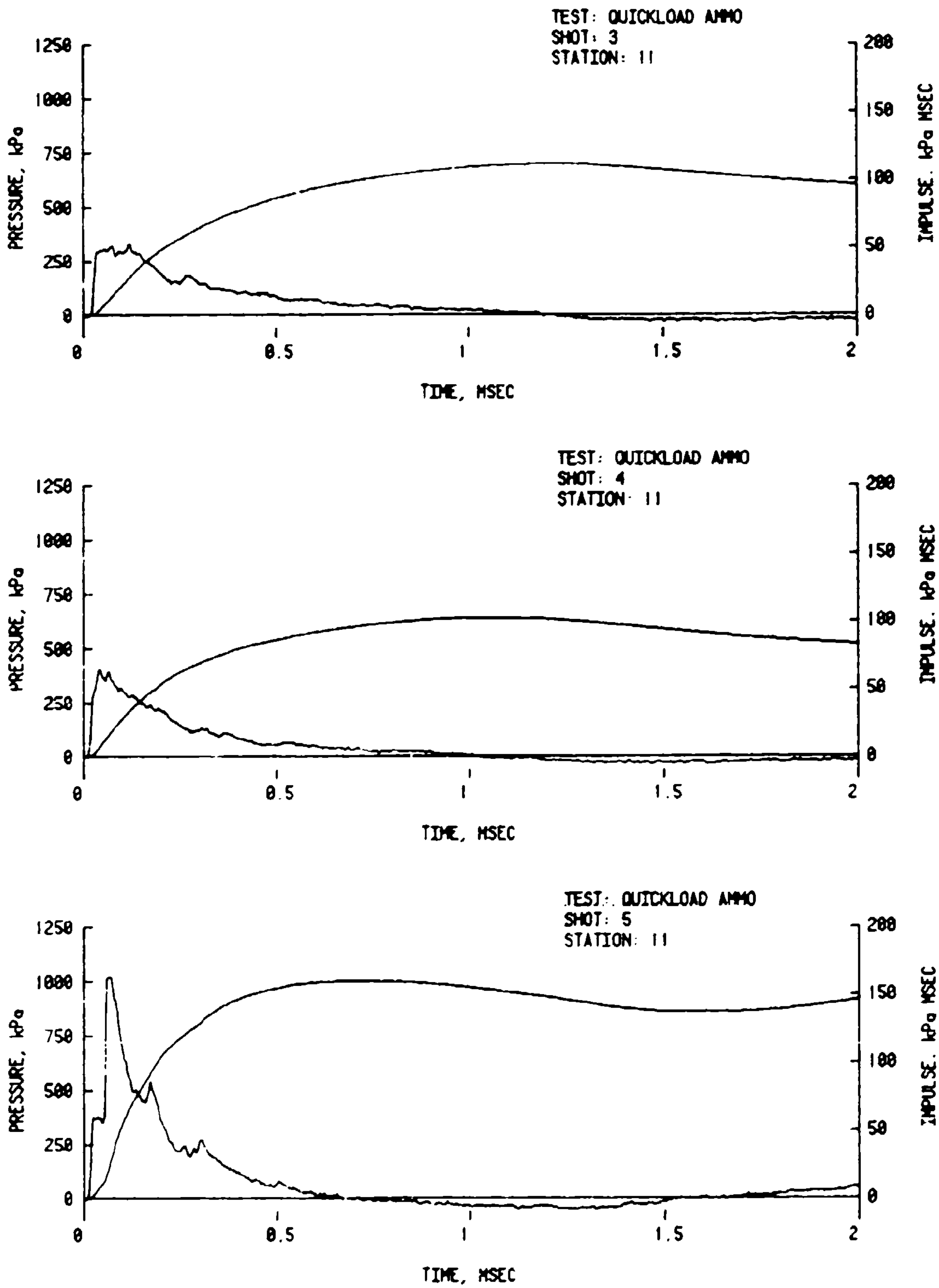


Figure 15. Pressure versus Time, Stations 10 and 11 for Shots 3, 4, and 5 (Continued)

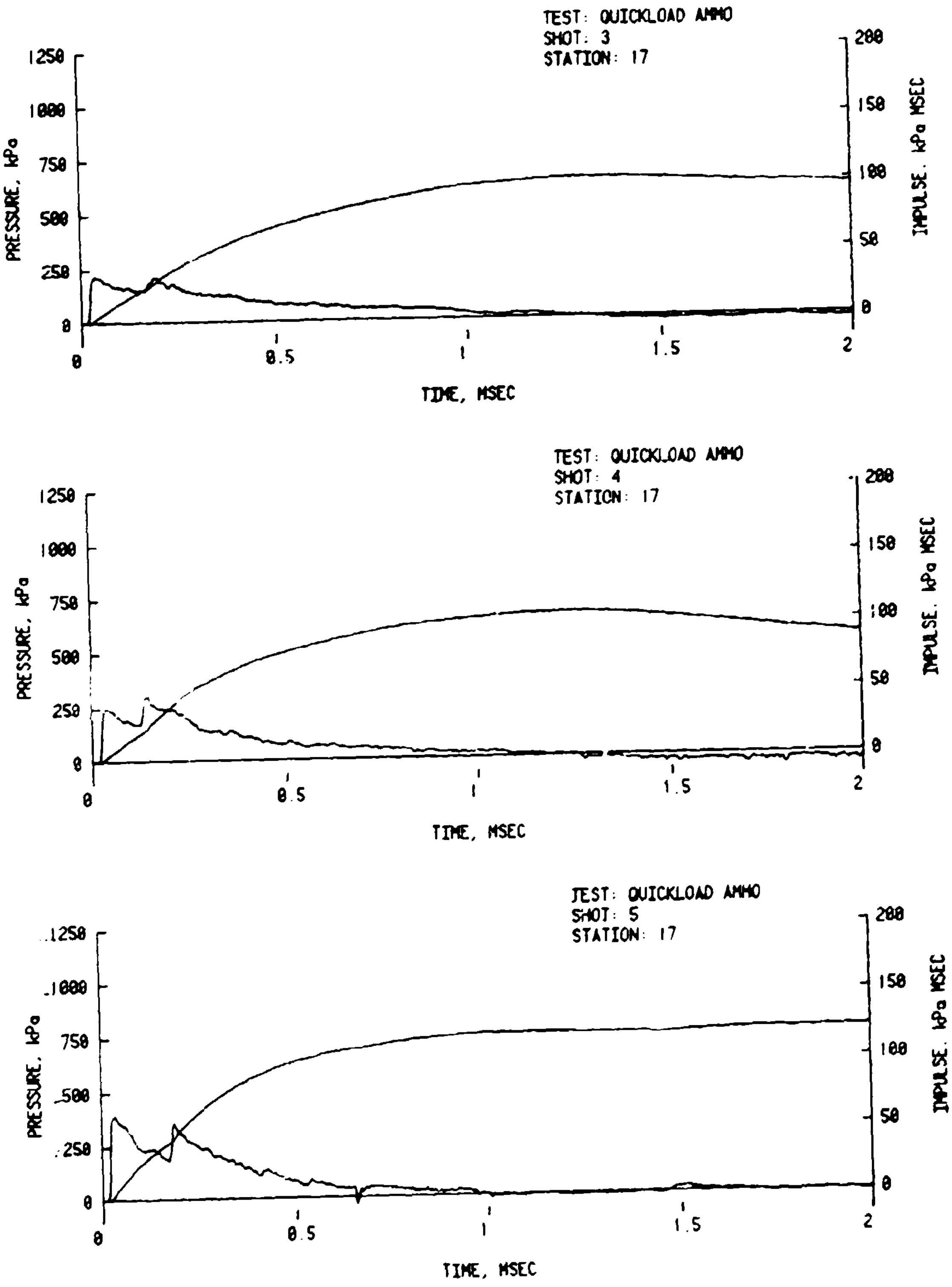


Figure 16. Pressure versus Time, Stations 17 and 18 for Shots 3, 4, and 5

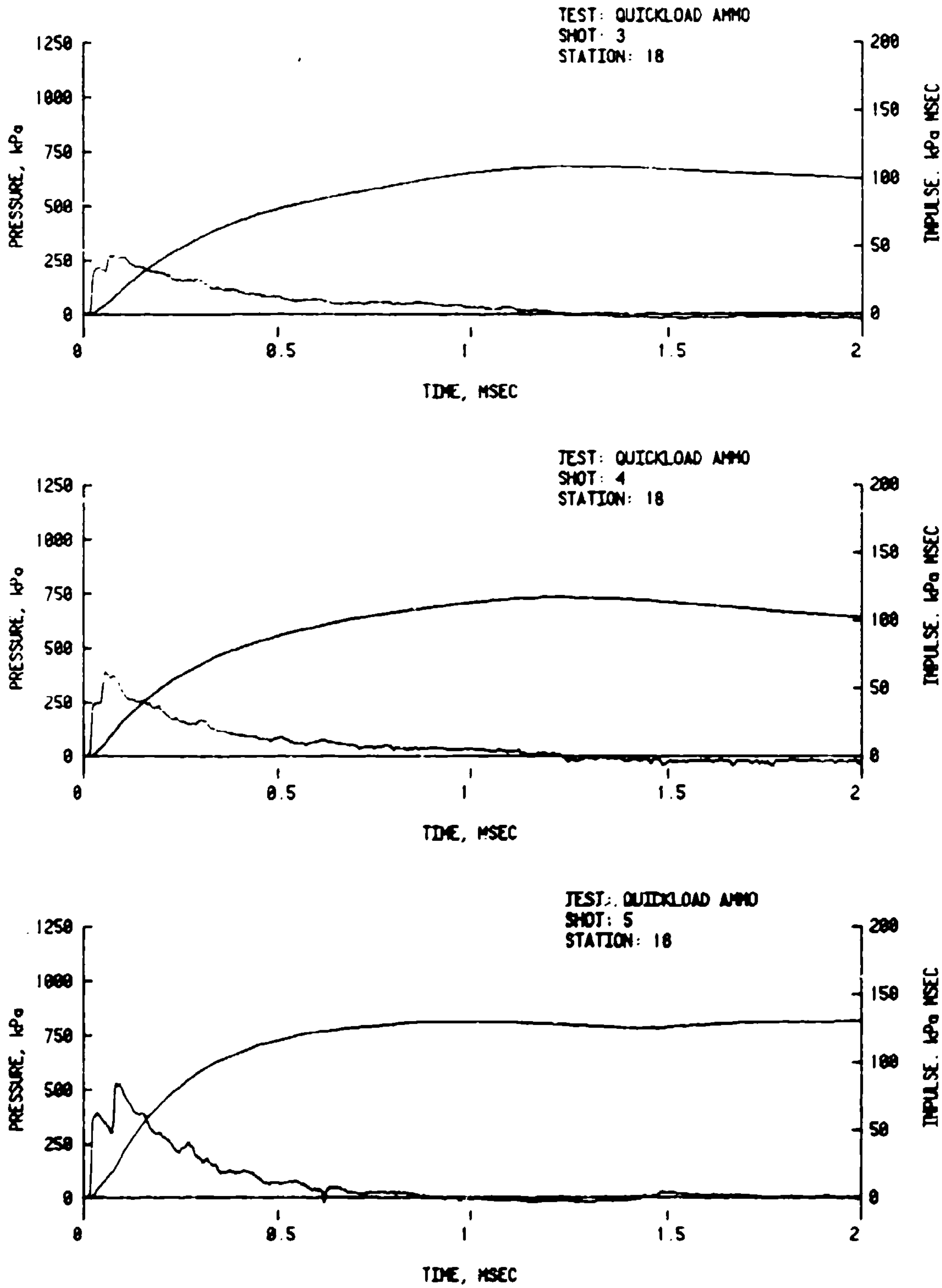


Figure 16. Pressure versus Time, Stations 17 and 18 for Shots 3, 4, and 5 (Continued)

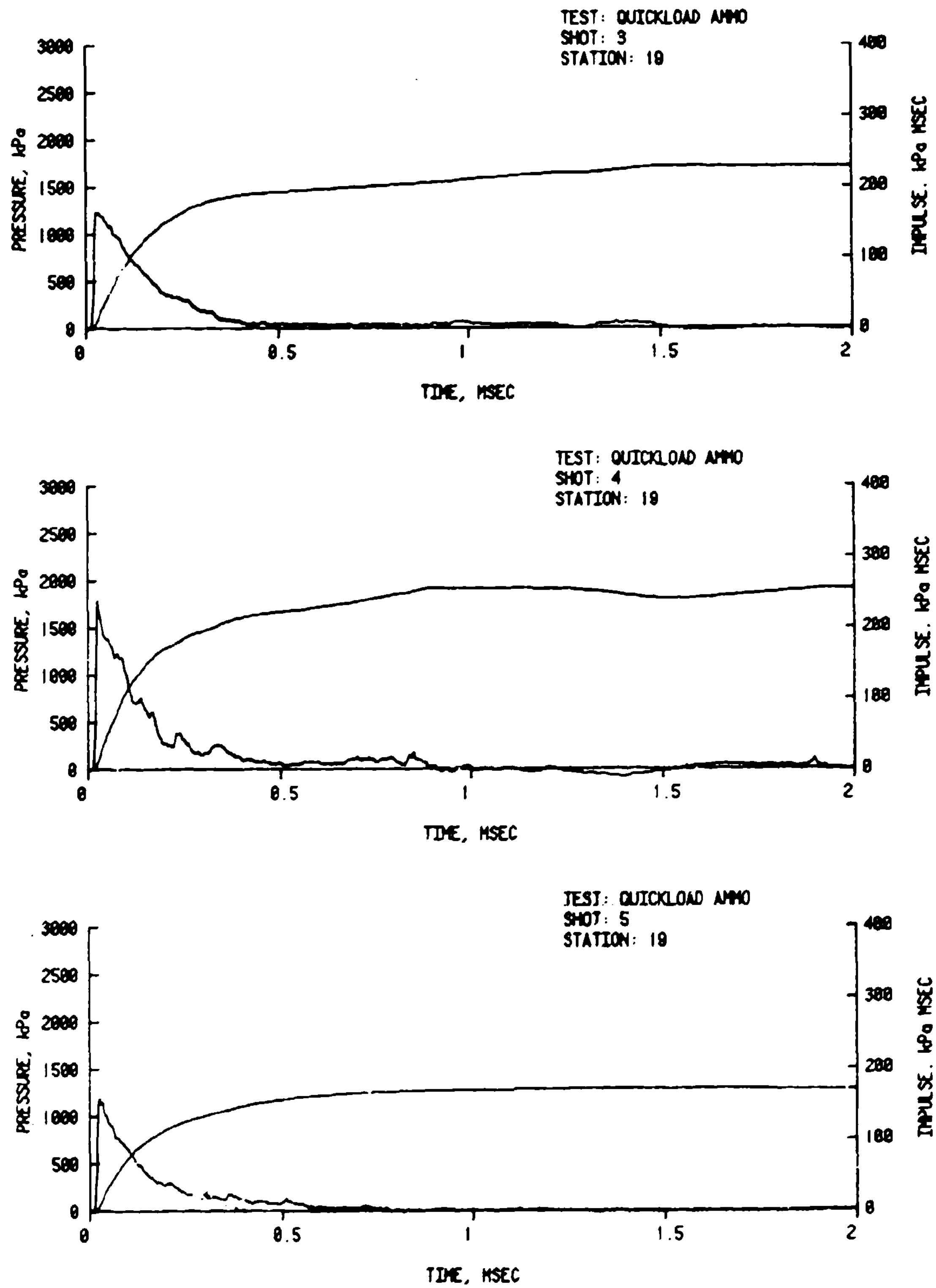


Figure 17. Pressure versus Time, Station 19 for Shots 3, 4, and 5

TABLE 6. FREE FIELD BLAST PARAMETERS

Shot	Station	Distance m	Peak Pressure kPa	Impulse kPa-ms	Arrival Time ms	Duration ms
3	19	1.006	1236	229	0.477	1.55
	20	1.523	245	-	1.347	-
	21	2.286	138	73	3.297	2.00
4	19	1.006	1796	256	0.380	1.11
	20	1.523	209	105	1.285	1.59
	21	2.286	150	-	3.330	-
5	19	1.006	1188	172	0.455	1.31
	20	1.523	434	136	1.035	2.00
	21	2.286	170	101	2.547	2.50

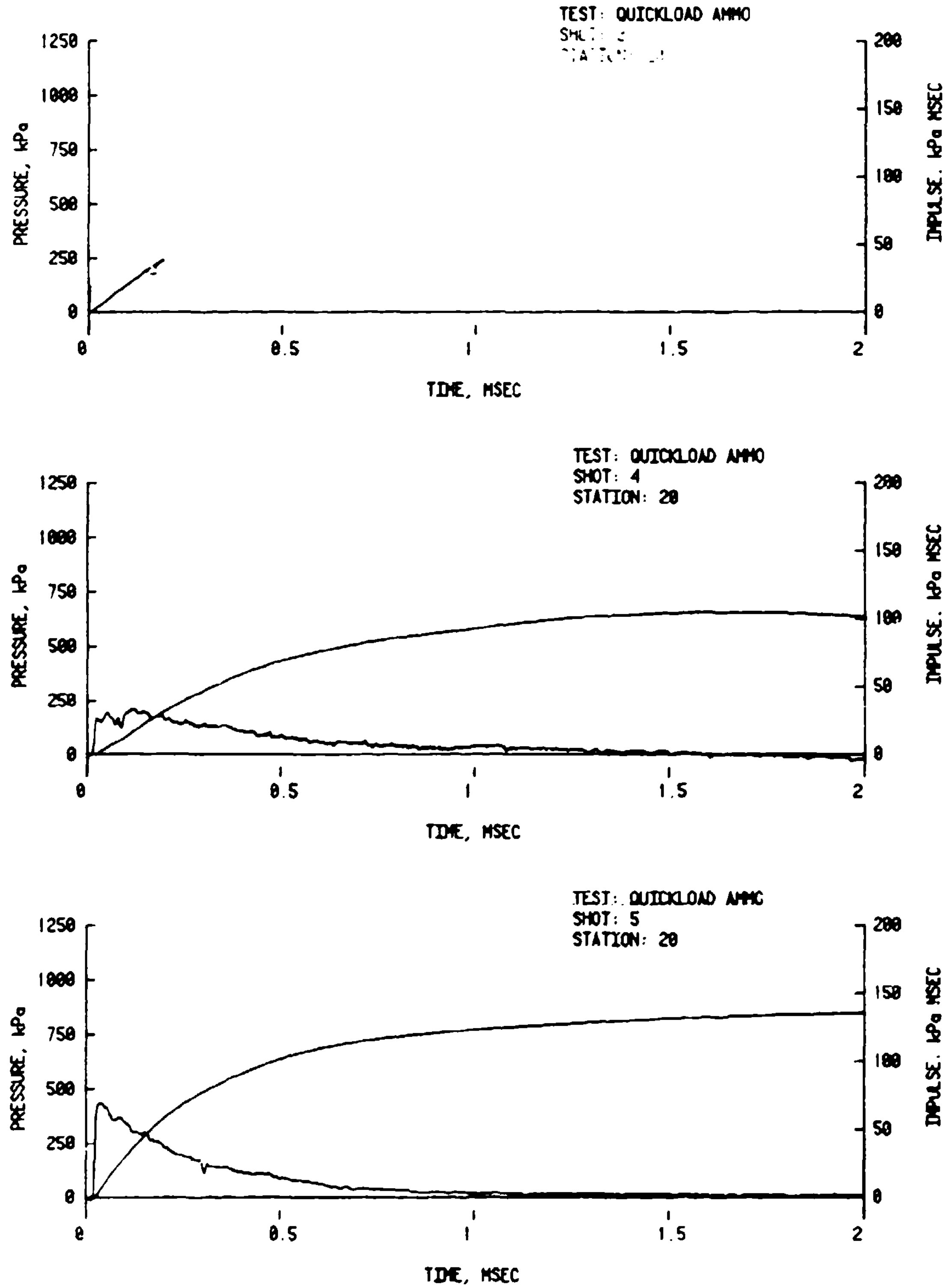


Figure 18. Pressure versus Time, Station 20 for Shots 3, 4, and 5

In Figure 19 the pressure versus time records from Station 21 are presented for Shots 3, 4, and 5. The peak overpressure recorded on Shot 3 is 8 percent lower than Shot 4, and Shot 4 is 11 percent lower than Shot 5. This implies that to the side of the donor the peak overpressure from an unconfined charge will be higher than a covered one, and the soil barricades will produce higher overpressures than the sand barricades. This conclusion would probably also be true for the blast propagating to the rear of the donor structure.

F. Exposure of Responding Acceptor Model

Direct visual evidence of the responding concrete model's dynamic behavior was not obtained although it was photographed at two thousand frames per second. The fireball enveloped the responding model in the first frame after detonation. Subsequently, a debris cloud obscured the model for the duration of the event.

Figure 20 shows the site after the event. Notice that the concrete slabs have moved and are partially buried. For both Shots 4 and 5, the responding acceptor slabs were cracked but not broken apart. Each slab remained substantially in one piece although small chunks were broken off. Figure 21 shows the condition of the slabs after the blast.

The authors had anticipated the disintegration of the concrete slabs. The slabs remained substantially intact. In scaling the test site by 1/23.5, the magazine mass was scaled correctly. The full scale roof, for example, has a volume of 17.26 cubic metres and a mass of 38,662 kilograms. Dividing the mass by 23.5^3 results in 2.98 kg scaled mass. The average mass of the model roof was 2.82 kg which is only 5.4% less than the actual scaled mass.

The authors did not specifically scale the material strength. Sand mix was a good common sense material to employ in creating a miniature model of a concrete and brick structure, but it must be remembered that the real munitions structure is more complex than a simple concrete slab structure. Copper wire was used to reinforce the model. This was not intended to scale the steel reinforcing bars in the actual structure. The wire was used to hold together very thin concrete sections. Therefore, it is possible that the responding acceptor was stronger than expected.

As previously stated the responding acceptor was not fixed in place or bound together. The positive phase blast loading duration on the closest surface of the non-responding acceptor was between 0.62 and 0.82 msec on Shot 4 and between 0.49 and 0.58 msec on Shot 5. The responding acceptor should have experienced the same loading. It was thought that because of this short duration most damage to the concrete slabs would occur before it began to move. Perhaps the response of this structure would have been different if the slabs were bound together and fixed in place on the pad.

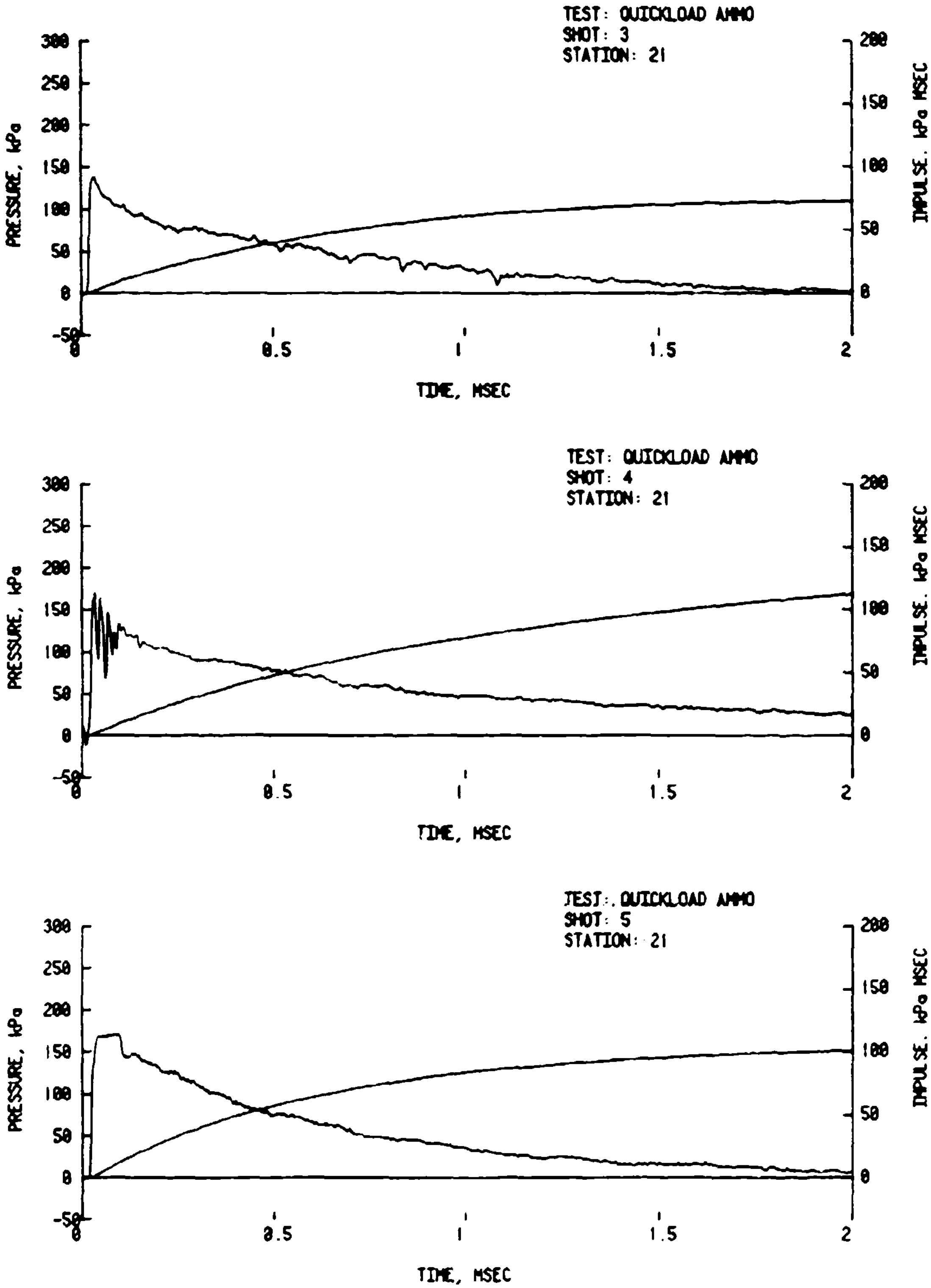


Figure 19. Pressure versus Time, Station 21 for Shots 3, 4, and 5

Figure 20. Post-Shot View of Test Site

Figure 21. Post-Shot View of Concrete Slabs

This report is concerned with the blast loading on a non-responding steel acceptor model. The responding concrete acceptor was included in this study as a prelude to a future experiment that will measure the velocity of fragments from a responding acceptor.

G. Effects of the Structure in Blast Suppression

The donor structure confined the bare pentolite charge, reducing the blast effects. To determine the confinement effects, Reference 3 was used to calculate the bare TNT equivalent weight of a confined bare Pentolite charge.

$$W_{TNT} = f_e \times f_c \times W_{NEW} \qquad (1)$$

where W_{TNT} = equivalent TNT weight

f_e = equivalent weight factor relative to TNT based on peak overpressure

f_c = case correction factor

W_{NEW} = net explosive weight

The pressure equivalent weight factor for Pentolite was obtained from Reference 5. For Pentolite $f_e = 1.17$. The case correction factor adjusts for the mass of the confining structure.

$$fc = 0.20 + \frac{0.80}{1 + \frac{W_{CT}}{W_{NEW}}} \qquad (2)$$

where W_{CT} = total case weight,

is the mass of the donor magazine walls, roof, and door. For Shots 3 and 4 an average value of f_c is 0.32. Therefore, from Equation 1, $W_{TNT} = 1.17 \times 0.32 \times 1.0 = 0.374$ kg.

The blast effects of the 1 kg Pentolite charge for Shots 3 and 4 should be equivalent to a 0.374 kg bare TNT charge. To check the calculation from Equation 1 the reflected pressures recorded on the center line of the roof of the structure on Shots 4 and 5 were plotted in Figure 22. Two curves of peak reflected pressure versus distance were established using the relationship

$$\frac{R_1}{(W_1)^{1/3}} = \frac{R_2}{(W_2)^{1/3}} \text{ for equal pressure} \qquad (3)$$

[5] *"Structure to Resist the Effects of Accidental Explosion," Dept. of the Army Technical Manual, TM 5-1300, June 1969.*

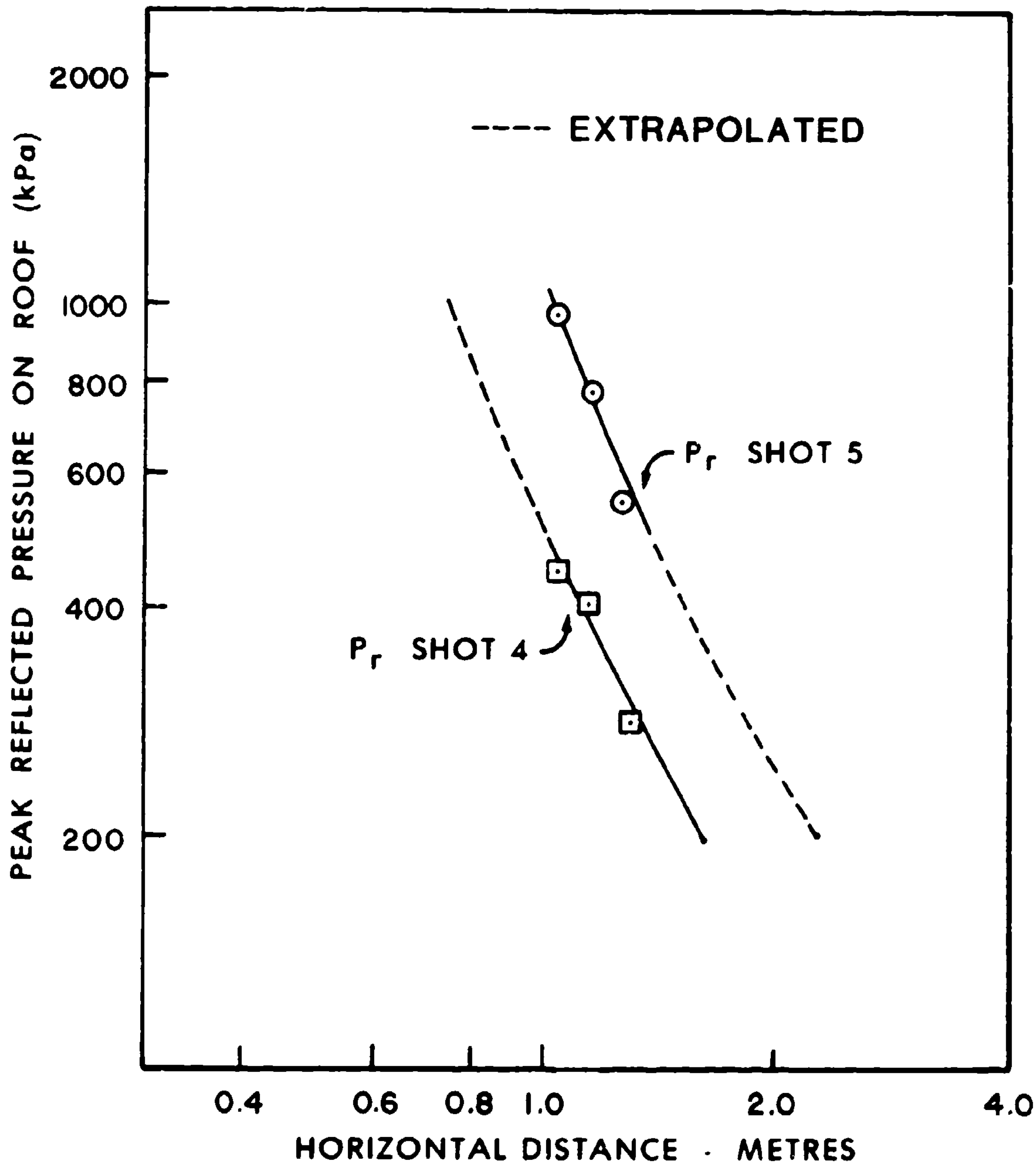


Figure 22. Reflected Pressure on Roof [illegible] Distance for Shots 4 and 5.

where R_2 = distance for selected peak pressure for W_2

W_2 = 1 kg explosive

R_1 = distance for same peak pressure

W_1 = explosive mass uncovered that will be equivalent to 1 kg covered

Calculations from Equation 3 establish W_1 equivalent to 0.384 kg of Pentolite. This means that a 0.384 kg Pentolite hemisphere uncovered should produce the same pressure on the structure as a 1 kg covered. The value of 0.384 kg determined from Equation 3 compares amazingly well with the value of 0.374 kg calculated from Equation 1 and 2. Referring to Table 3 it can be seen that this relationship does not hold for impulse measurements. While the peak overpressure is suppressed approximately 50 percent, the impulse is suppressed approximately 10 percent.

IV DISCUSSION

The intention of this report is to present through the use of scaled structural models certain trends that can be expected in the event of an accidental explosion in a full size storage magazine. The blast loading recorded on the acceptor model can be used to calculate the break-up of the full size structure, and estimates of the velocities imparted to the debris can be made. From the debris velocity a determination can be made on the probability of causing stored munitions to explode.

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2. Charles Kingery, George Coulter, and George Watson, "Blast Parameters from Explosions in Model Earth Covered Magazines," BRL MR 2680, September 1976 (AD A031414).

3. F.B. Porzel, J. M. Ward, "Explosive Safety Analysis of the Machrihanish Magazine," NSWC TR79-359, December 1979.

4. Charles N. Kingery and George A. Coulter "Reflected Overpressure Impulse on a Finite Structure," Tech Report ARBRL-TR-02537, December 1983 (AD A137259).

5. "Structure to Resist the Effects of Accidental Explosion," Dept. of the Army Technical Manual, TM 5-1300, June 1969.

SHIELD/BARRICADE TESTING AT AED

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ABSTRACT

This paper presents an overview of the APE Shield Testing Program at the Ammunition Equipment Directorate. Lessons learned, types of instrumentation used, and test results obtained will be discussed. A video cassette presentation will be given showing samples of high-speed photography and real-time CCTV taken during some of the APE shield tests.

INTRODUCTION

Our nation maintains enormous amounts of conventional munitions. Due to aging, manufacturing problems, obsolescence, etc., large quantities of these munitions become scheduled for disposal, or renovation. Disposal of munitions is commonly referred to as demilitarization (demil). Renovation is performed to salvage serviceable parts from unserviceable components and replacement components are added to refurbish the munition. Renovation, where applicable, is a cost effective method to reclaim and make serviceable our deteriorated stockpiles of conventional munitions.

Shields and barricades are often used to house demil or renovation equipment providing operator protection against possible detonation or initiation incidents during the demil or renovation process. There is an ongoing program at AED to determine the adequacy of these shields and barricades for protecting the operator from these incidents under MIL-STD 398.

The certification criteria which must be met to comply with MIL-STD 398 are as follows:

1. Overpressure not to exceed 2.3 psi peak positive incident pressure (P_{so}) measured at personnel locations.

2. Heat flux measured at personnel locations is not to exceed the value given by the equation:

$$\emptyset = 0.62t^{(-0.7423)}$$

where $\emptyset$ = heat flux in cal/cm^2-sec
t = time interval of exposure to measured heat flux in seconds

3. Fragments must be contained within the shield, or directed away from personnel locations.

4. Shield movement or deflection shall not be such that personnel injury could result.

TEST PROCEDURES

In general, a shield or barricade is set up and tested at the AEO Test Facility in building 1379 which is an accurate simulation of a standard ammunition maintenance bay.

Polaroid and 35mm photographs are taken before and after each test. High-speed movie cameras and Closed Circuit Television cameras are used to photograph and record the operator and surrounding locations.

Pressure transducers, thermocouples, heat flux sensors and other measurement devices are mounted on specially designed stands and positioned at strategic locations for recording air blast overpressures, temperatures, heat flux etc.

INSTRUMENTATIO

Instrumentation used on the shield/barricade tests is housed in a 40 foot semitrailer. This trailer has an environmentally controlled atmosphere which provides optimum operating conditions for the electronic equipment.

The electronic equipment consists of signal conditioners and amplifiers feeding signals from the transducers into a 14 channel, medium band FM magnetic tape recorder. The tape recorder has a maximum frequency response of 80 KHZ at 120 inches per second tape speed which will allow recording of air blast pressure peaks, for most of the shields tested, to within 95% of the true peak value[2].

Low impedance piezoelectric pressure transducers are used to measure air blast pressures. This type of transducer has the best frequency response, and is more tolerant to over-ranging than any strain gage or piezoresistive type gages.

Schmidt-Boelter thermopile type heat flux sensors are used to measure the heat transfer rate at operator locations.

Calibration of the pressure transducers is performed by applying accurately measured air pressure pulses to the diaphragms of the transducers and recording the output from the transducer amplifiers on the FM magnetic tape recorder. Five pressure pulse level steps from 0 to 100% full scale are recorded for each pressure transducer. The pressure transducers are mounted in a manifold for simultaneous calibration via a manually operated air valve on a large capacity air tank. A calibrated pressure gage measures the air tank pressure.

A voltage standard is used to calibrate the heat flux sensor data channel with the sensor removed from the channel. The sensor is than hooked back up to the data channel. The certificate of calibration from the manufacturer is used to determine the heat flux measured by the sensor data channel.

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2 Giglio-Tos, L.; Linnenbrink, T.E.; Air Blast Pressure Measurement Systems and Techniques, Minutes of the Fifteenth Explosives Safety Seminar, Vol. II, 18-19 September 1973, pp, 1359-1402.

High-speed 16mm movie cameras record the tests on 450 feet of color film. A 1,000 pulse-per-second timing signal is recorded on the film to provide a time base reference.

Control of the instrumentation system and high-speed cameras is by an automatic preset timing system in the instrumentation trailer.

SHIELD/BARRICADE TEST PROGRAM

Between 28-30 different types of shields/barricades have been tested since the beginning of this test program. The initial testing began in earnest in 1977 and has continued to the present time. Previous to 1977, a protective shield successfully passed a field test if it did not fall apart or collapse during the performed test.

Realizing that there is not sufficient time available to show all of the shields tested to date, a selected sample of five has been chosen. These will be taken in numerical order and discussed.

APE 1001M1--Machine, Vertical Pull Apart

The vertical pull apart machine is a semiautomatic multipurpose machine used for processing 37mm through 106mm fixed artillery ammunition and rocket motors. It performs the following operations:

a. Separate projectile from cartridge case.
b. Resize cartridge case mouth.
c. Assemble projectile to cartridge case.
d. Calibrate the pounds of pull required to separate the projectile from the cartridge case.
e. Crimp the cartridge case to the projectile.
f. Prime and deprime cartridge cases with press type primers.
g. Continuity test 2.75 inch and 3.5 inch rocket motors.

The machine is constructed with a base plate, operating table, three bolster rods, vise assembly, pull cylinder, and fulcrum arm assembly. The machine is powered by air. An operational shield is provided to protect the operator and allow attendant operations.

Due to the fact that this shield has a baffled top, it will vent flame and explosive gases upward which can then spill downward onto an operator. Therefore, for working with munitions larger than 40mm, this shield needs to have a rapid response deluge system for suppressing propellant fires. The deluge system has proven very effective when used on this shield.

APE 1196--Shield, Portable, Small Items

This portable shield is used to protect operating personnel during dissassembly of fuzes and similar small items. The shield is V shaped and has 3/4 inch thick steel walls. A wrench assembly is furnished with each shield.

Originally this shield had an open back. This concept is no longer acceptable by Safety personnel. Therefore, this shield has now been enclosed and has an access door for inserting the fuzes to be worked on. Sturdy support legs must be attached to this shield and these legs must be either secured to the floor or to a baseplate.

APE 1202--Defuzing Machine, Hand Grenade

The hand grenade defuzing machine is used to remove fuzes from hand grenades in a shielded operation. The machine consists of a six section turntable mounted in an operational shield. An air cylinder rotates the turntable 60 degrees at a time. Holding cups are mounted in each section of the turntable and are used to secure the grenade being disassembled.

Originally, this shield also had an open back. It has now been enclosed and all opening tolerances have been tightened to reduce flame venting. As with all shields discussed here, many design changes have needed to be incorporated to bring these shields into compliance with MIL-STD 398.

APE 2000--Machine, Vertical Pull Apart, Rotating

The Vertical Pull Apart Rotating Machine is used to pull or separate fixed type artillery ammunition ranging in size from 40mm to 106mm. The machine consists of a frame mounting a four station turntable. Each station is independent of each other and is mechanically operated. A projectile pickoff station removes the separated projectile from each pull apart station and exits the projectile from the working area. The machine is equipped with a protective barricade.

This shield is the most massive of any which have been tested to date. It has successfully passed MIL-STD 398 for 40mm munitions. Fragments from 105mm cartridge cases have not been successfully contained in this shield. A rapid response deluge system is scheduled to be installed on this machine. Tests with 90mm and 105mm cartridge cases containing propellant will then be performed in this machine. The APE 2000 shield could not sustain HE projectile detonations except for 40mm.

APE 2156--Machine, Hand Grenade Defuzing

The hand grenade defuzing machine is used to remove fuzes from M33 and M67 grenades at a high production rate. The actual defuzing operation is accomplished within the operational shield. The machine is pneumatically driven and controlled. It consists of a protective shield, defuzing mechanism, a grenade transfer system, and a control and drive system. The grenades to be defuzed are manually loaded onto the transport belt on one side of the machine. They are then mechanically transported into the barricade, thru the defuzing mechanism, and out on the opposite side of the barricade.

This shield has gone through more design changes than almost any other shield which has been tested. It started out much smaller than the final design. At one time it had a square vent stack with suppressive shielding on top. The stack was then changed to a round one which vents through the bay roof. The main access door for machine maintenance has been changed from a large massive single section unit to a split sectioned door for ease of access.

Having now briefly discussed the five different types of shields, a video cassette of tests performed on these will be shown.

CONCLUSIONS

The shield/barricade testing performed at the Ammunition Equipment Directorate, Tooele Army Depot, Tooele, Utah, has been invaluable in assessing the protective capability of shields/barricades. Weaknesses, trouble spots, venting problems, and personnel hazards of all kinds have been brought to light during the testing process.

Design changes, product and protection improvements have been incorporated in the shields/barricades so that the final tested products can meet MIL-STD 398 requirements.

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EXPLOSIVES SAFETY SEMINAR
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AMMUNITION DISASSEMBLY

AND

EXPLOSIVE SECTIONING

by

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ABSTRACT

Remote control methods were developed to disassemble 40 mm ammunition. The projectiles were pulled from the cartridge cases, fuzes were removed from the projectiles, and explosive components were sectioned. Operations were performed remotely and monitored via closed circuit TV. The methods were improved upon to increase the efficiency of the teardown.

1.0 INTRODUCTION

A requirement to tear down HEI-PD and HE-PFPX rounds was safely accomplished through use of remote-operated equipment. The rounds were separated into their component parts of cartridge case, projectile and fuze. Sectioning of the projectile was performed on selected rounds. Component parts were then examined to determine the effects, if any, of the various conditions the rounds were subjected to previously.

Prior to the teardown, each round was x-rayed to verify safe position of the fuze. The projectile was then pulled from the cartridge case using a hydraulic pull cylinder. An air-operated impact wrench was used to unscrew the fuzes from the projectiles. Projectiles were sectioned as required with a band saw.

Once the method to accomplish each task was determined, the procedure was improved to increase efficiency. Thus, the disassembly and sectioning of the ammunition was conducted both safely and in a cost-effective manner.

2.0 SAFETY CONSIDERATIONS

In conducting the teardown of the ammunition, safety was considered uppermost. Nearly all operations were controlled from a remote location, or at some distance from the operations building, out of line-of-sight.

The main control building was located approximately 500 ft. from the operations building. Several dirt and gravel barriers separated the two buildings. A third building was used for operating certain equipment. This third building was located 100 ft. from the operations building. A dirt barrier was in front of the operations building wall facing toward the other buildings and traffic. The site setup is shown in Figure 1.

Two-way radios (Realistic Voice-actuated FM Transceivers) were used to maintain contact between operators in the various buildings. Since the HE-PFPX rounds had fuzes with electronic components, some concern was expressed over the safety of using radios in their vicinity and possibly setting off the fuze. After discussion with the fuze manufacturer, it was decided that it would be safe to use radios during the teardown of the HE-PFPX rounds. Closed circuit TV was used to monitor the operations at all times. The TV monitor was located in the control building.

Constant communication was maintained throughout each operation between the control operator and any operators at the other two buildings. No operation was performed without the verbal assent of all operators. The control operator constantly monitored each operation via closed circuit TV (CCTV). This operator also controlled the equipment which had switches located in that building.

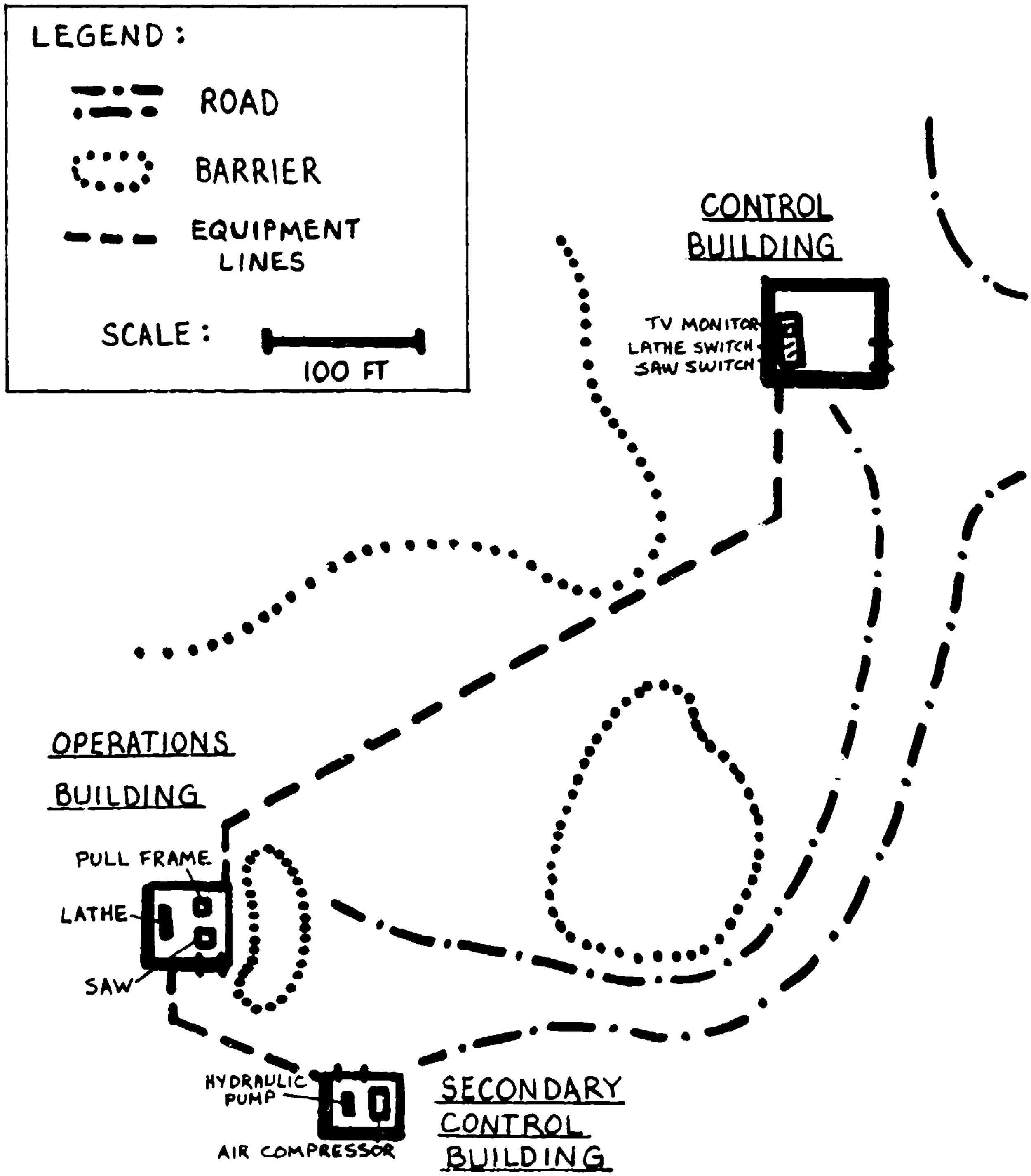

Figure 1. Site Layout.

A second (and, sometimes, third) field operator controlled some of the equipment and also switched rounds, recorded data and performed other tasks in the operations building.

3.0 X-RAYS

The first task in the teardown was to have the rounds x-rayed. The purpose for this was twofold. First, the x-rays were used to verify the safe position of the fuze prior to working with the round. Second, air voids in the explosive appearing in the x-ray could later be correlated to any voids found after sectioning of the projectile.

An outside vendor was chosen to do the x-ray field work. Preliminary x-rays of inert projectiles were taken to determine the best x-ray source and exposure time for the teardown requirements. Air voids could be seen most clearly from x-rays using gamma radiation with an iridium-192 source. Exposure time was approximately nine minutes with the source three feet from the film and rounds. X-ray radiation with shorter exposure times could have been used if safe fuze verification were the sole objective of the x-rays.

All of the HEI-PD fuzes and some of the HE-PFPX fuzes were previously marked as to the "0°-plane". X-rays taken along this plane showed the S&A device in a position which revealed whether it was safe or not. Rounds with unmarked fuzes had x-rays taken along two planes, 90° apart. In this way, one x-ray or the other showed the S&A device clearly enough to determine if it was in the safe position.

Selected rounds had x-rays taken along additional planes. These were rounds that showed the possibility of having air voids in the explosive. The additional x-rays would later be used to determine where the projectiles would be sectioned.

The HE-PFPX rounds have a tungsten-ball sleeve around part of the projectile. This sleeve had to be removed prior to additional x-rays being taken so that any air voids could be seen.

4.0 BULLET PULL

The next task in the teardown was to pull the projectile from the cartridge case. The propellant from the case was then weighed and the projectile de-fuzed.

An Enerpac Model RCP-55 5-ton hydraulic pull cylinder was used to pull the projectiles from the cases. The maximum force actually needed was 7100 pounds-force. Most rounds required only 4500-5500 pounds-force.

One end of the pull cylinder was attached to a heavy metal framework so that the cylinder hung vertically. A fixture, especially designed to fit the projectiles, was attached to the free end of the cylinder. This fixture clamped around the projectile and held on to the projectile by means of a small lip around the projectile. (See Figures 2 & 3).

The base (primer end) of the cartridge case slid into the bottom fixture. This fixture was welded in place on the framework at the necessary distance from the projectile fixture. The lineup of the assembly was checked for vertical straightness. If not straight, the projectile would be pulled with a sidewise jerk, possibly spilling propellant from the case.

The pull cylinder was operated from a remotely-located hydraulic pump. A closed circuit TV monitor, located in the control building, was used to monitor the operation. Two-way radios were used to provide communication between the two areas.

The first step in pulling the projectiles was to secure the round in the pull fixtures. Once in place, the building and area were cleared of all personnel. The field operator was positioned at the hydraulic pump and a control operator monitored the CCTV.

After confirming via radio that the pull was ready

Figure 2. HE-PFPX round in place for bullet pull.

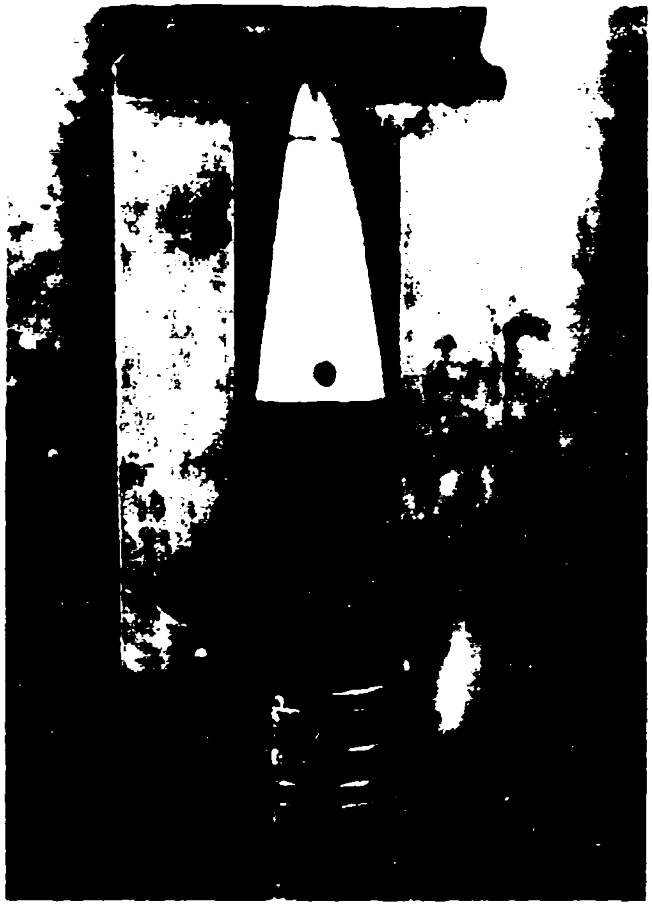

Figure 3. Close-up of HE-PFPX projectile in upper pull fixture.

to start, the field operator started the pump. The control operator then indicated when the projectile was free of the case. The field operator waited 30 sec. for an "all clear" from the control operator before entering the operations area. Any initiation of the propellant would become evident within 30 seconds after the pull. The field operator then entered the operations building to remove the separated components and load up another round. The propellant was weighed by either the field operator, or a third operator.

Once set up, the projectiles could be pulled at a rate of 20-25 per hour, with three operators working. Slowdowns occurred when the projectile fixture slipped during the pull. The fixture was then re-tightened and the pull tried again. Slippage usually occurred only with those rounds requiring higher pull forces, around 7000 pounds-force.

After being separated, the projectiles were placed in Velostat bags and stored in a small magazine until the fuze removal operation began. The propellant, after being weighed, was stored in a drum for later disposal. Cartridge cases were put back in the original shipping container and stored for later de-priming.

5.0 FUZE REMOVAL

After the bullet pull, the fuzes were removed from the projectile. The requirement was that the fuze be removed undamaged and shipped back to the vendor.

Several methods were considered for removing the fuze. It was initially thought that too much force would be required to unscrew the fuze from the projectile. Therefore, ways to cut the fuze off were examined first. Since these proved to be difficult, a means to unscrew the fuze was finally studied.

The HE-PFPX fuzes had two set screw holes which allowed a fixture to be attached to the fuze. The fixture allowed for easy removal of the fuze by turning it off. The HEI-PD fuze had no set screw holes for attaching a fixture. After some experimenting, a fixture with four pointed set screws was developed. The screws in the fixture could be tightened enough to grip the fuze and permit turning. The small indentations produced by the set screws were not considered damaging to the fuze.

Another fixture was designed to grip the projectile. Set screws in the fixture held the projectile by the brass rotating band. The projectile fixture could then be chucked into a lathe.

Initial attempts at using a lathe as a means of turning off the fuze, showed the lathe to lack the torque necessary to break the seal on the fuze threads. Either another, more powerful lathe, or another means of turning, would have to be tried.

An area of concern in unscrewing the fuzes was the possibility of setting off the fuze by rotating it too fast. The procedure at first called for turning the projectile while holding the fuze still. This procedure could be used with a lathe capable of providing the required torque. After some consideration, it was decided that rotating the fuze at low rpm's (1000, or so) while holding the projectile still would be safe.

The method finally used to remove most of the fuzes was to use an air-actuated impact wrench. The projectile was secured in the lathe and the fuze fixture was attached to the impact wrench. The wrench was clamped in place on the lathe frame. A remote-located air compressor was used to run the wrench through means of a valve.

The field operator secured the projectile and fuze into the fixture/lathe assembly. (See Figure 4). Upon clearing the area, and a go ahead from the control operator via radio, the field operator would open the air valve to turn on the wrench. The control operator monitored the operation via CCTV and radioed to the field operator when the fuze was removed and air to the wrench could be shut off.

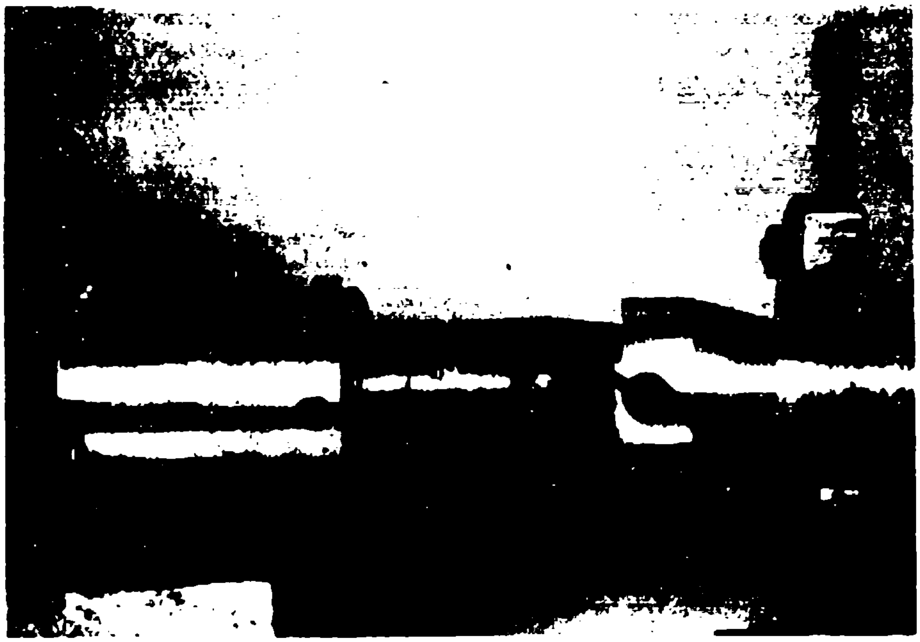

Figure 4. HE-PFPX projectile in fixtures for fuze removal.

After a wait of one minute to verify that the removal of the fuze didn't result in an initiation, the field operator then entered the operations building and removed the fuze and projectile from the assembly. The process was repeated for the next projectile.

Due to exudation of the explosive (as a result of high temperature conditioning), some HEI-PD fuzes wouldn't come free of the projectile even though they were unscrewed. Examination of the x-rays revealed exudation into the area around the booster which prevented easy removal of the fuze. An adaption of the bullet pull assembly was then used to remotely pull the fuze free of the projectile. In a few cases, the booster cup remained stuck in the projectile.

With certain of the HE-PFPX rounds, it was possible to safely remove the fuze by hand. These rounds were ones that had not undergone any temperature conditioning, and therefore, wouldn't have exudation in the fuze threads. A fixture was attached to the fuze which was then unscrewed manually.

6.0 SLEEVE REMOVAL

The HE-PFPX projectiles had a tungsten ball sleeve around two-thirds the length of the projectile body. This sleeve was removed from selected projectiles in order to allow a clear x-ray to be taken of the explosive and also to facilitate any sectioning.

A lathe was used to machine off the outer steel layer. Once this layer was removed, the tungsten ball sleeve was easily cut off. Initial attempts at cutting the outer sleeve off with a band saw were not successful. A mill could possibly have been used, but proved to be a too costly investment for this task.

A dummy fuze was screwed in the projectile which was then secured in the same projectile fixture in the lathe used to remove the fuzes. The lathe was then set to cut 0.005" to 0.015" off of the projectile. After setting up the lathe and starting the coolant, the field operator then cleared the area.

The controls for the lathe were located in the control building. The control operator, after receiving the go ahead from the field operator, started the lathe. The operation was monitored via CCTV and the operator switched off the lathe when the cutting tool reached the rotating band of the projectile.

The field operator, after waiting 30 seconds to make sure no problems developed, then entered the operations building. The lathe was readjusted to cut more of the sleeve off, and the operation continued until the entire metal part of the sleeve was removed. The field operator then used a knife to carefully cut the plastic between the tungsten balls and removed the entire sleeve. The projectile was then ready for further x-rays and/or sectioning.

7.0 SECTIONING

Certain projectiles were sectioned in order to expose the explosive inside and to reveal air voids detected in the x-rays. Some of the HEI-PD projectiles were sectioned at the booster cavity end in order to better see any exudation that may have occurred.

While it was easily decided to use a saw to cut the projectiles, the type of saw to be used required some consideration. First of all, the projectile cases were made of hardened steel (RC 40 to 45) which would be difficult to cut. Second, spark and excessive heat generation in the cutting process had to be non-existent due to the explosives in the projectile.

The first requirement suggested use of an abrasive saw. This choice was eliminated because of the sparking produced during cutting. Attempts to eliminate the sparking by cutting under water were unsuccessful. Also, the saws examined could not accommodate the projectile or were too expensive.

The next, and final choice, was a band saw. Both vertical and horizontal band saws were examined. Due to the possibility of having to make cuts in the projectile lengthwise, it was decided that a vertical saw would work best. The saw would have to be able to be remotely controlled and have some sort of automatic feed. A small, vertical band saw was chosen and a gravity feed system was built to use with it. A remote control switch was installed in the control building.

The gravity feed system was designed to be simple and easily adaptable. The feed tray itself could hold either HEI-PD or HE-PFPX projectiles in a number of positions. (See Figure 5). A hanging weight attached to one end of the tray provided the gravity feed. Different weights could then be used to vary the feed rate. A channel along one side of the saw table guided the feed tray in a straight line.

Bandsaw blades with an M42 edge were used to cut through the hardened steel projectile cases. A wide, but smooth, cut was produced with these blades. The cooling system used a synthetic, biodegradable coolant in water. The coolant was not recycled due to possible presence of explosive particles in the coolant.

From the x-rays, the plane of each cut was determined and then marked on the projectile. The projectile was placed in the feed tray in the desired position. In order to keep the projectile from rolling or moving in the tray, acrylic

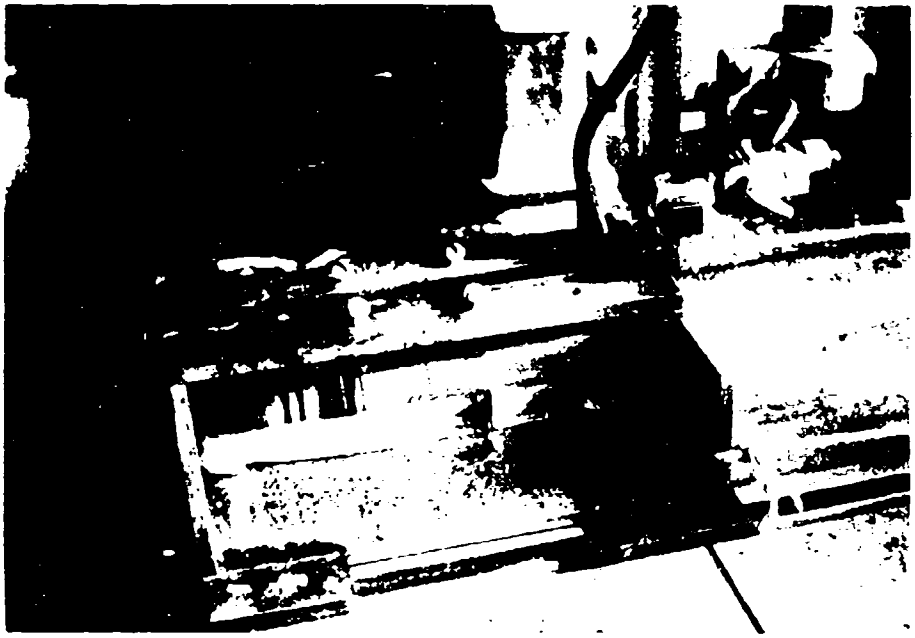

Figure 5. HEI-PD projectile positioned in feed tray for longitudinal cut.

pieces were formed to support the projectile. The set screws in the tray were tightened and alignment was checked.

Sectioning began with the field operator starting the cooling system. After clearing the area, the field operator informed the control operator that everything was ready to start. The control operator then started the saw and monitored the cutting. At any sign of a hang-up, or if the coolant stopped, the saw would be switched off. The field operator then waited one minute before entering the operations building.

A full longitudinal cut took approximately one hour and other cuts proportionally less. The saw speed was 55 ft./min. and the gravity feed weight varied with the projectile being cut. A 10 lb. weight was used most of the time while a lighter weight was needed to cut the thinner walls of de-sleeved HE-PFPX projectiles. Too large of a weight often caused the feed tray to jerk or the blade to jam. Too light of a weight would either take a long time to cut or wouldn't pull the tray at all.

Samples of the projectiles cut can be seen in Figures 6 through 9. Figure 6 shows a longitudinal cut of a HEI-PD projectile. Radial cuts of HEI-PD and HE-PFPX projectiles can be seen in Figures 7 and 8, respectively. The

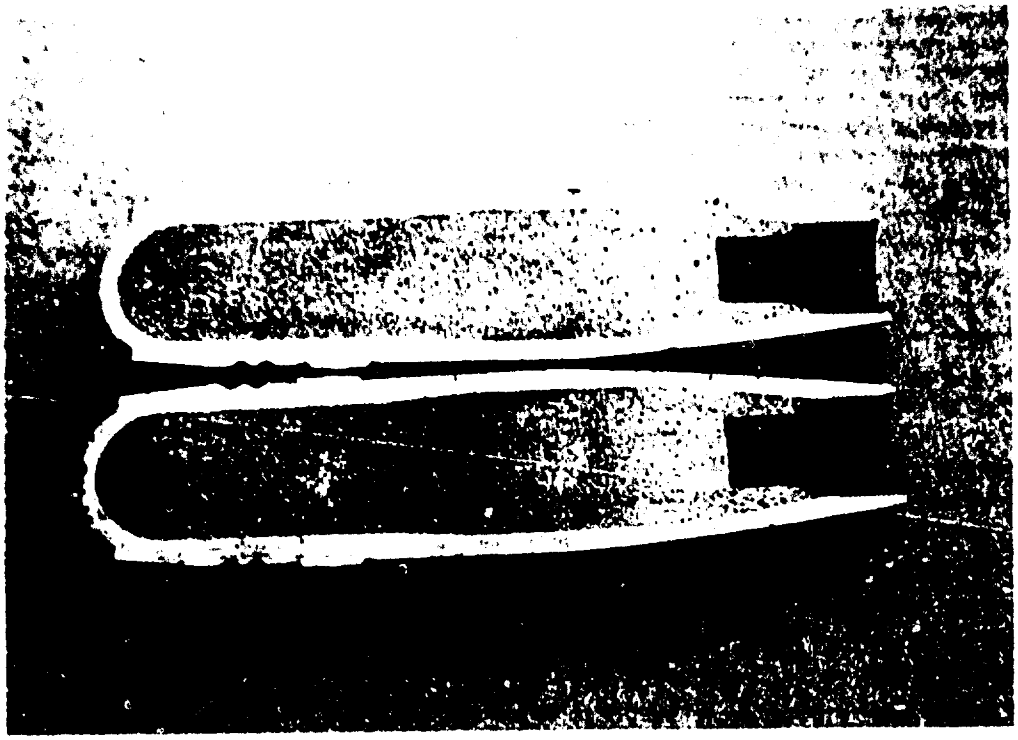

Figure 6. HEI-PD projectile
cut longitudinally.

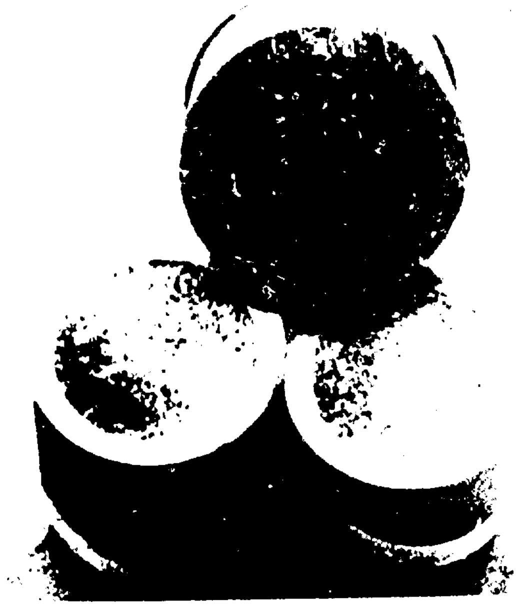

Figure 7. HEI-Pb projectile cut radially into three pieces. Air voids in the explosive can be seen in upper and lower left pieces.

Figure 8. HE-PFPX projectile cut radially into two pieces. Small air void in explosive is circled.

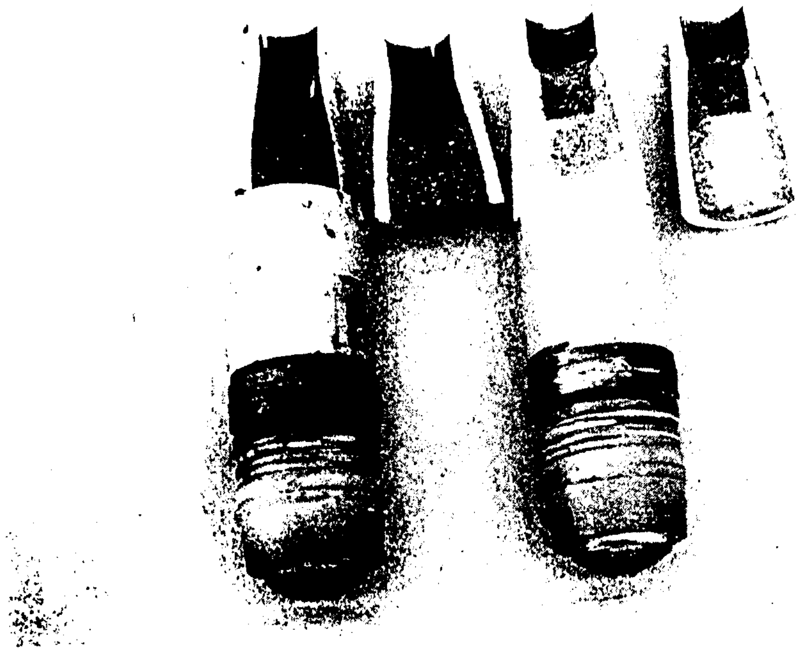

Figure 9. HET-PD projectiles cut to reveal booster cavity. Projectile on left was subjected to high temperature conditioning.

cuts were smooth enough to allow a clear view of some air voids in the explosive. The jagged cut seen in Figure 8 was the result of using too heavy a gravity feed weight during cutting. The blade jammed and the projectile had to be rotated to finish the cut. The cuts shown in Figure 9 were done to reveal the booster cavity more clearly. The HEI-PD projectile on the left had been conditioned at a high temperature and the cut shows the exudation around the booster cavity. The HEI-PD projectile on the right shows non-exudating explosive.

8.0 CONCLUSIONS

The procedures developed to disassemble and section the ammunition proved to be safe as well as efficient. The teardown of over 240 HEI-PD and HE-PFPX rounds was safely accomplished.

The objectives of the teardown were also successfully met. The methods used for each task allowed the results of conditioning the rounds to be easily examined. X-rays and sectioning revealed the air voids and exudation that were of concern.

The efficiency of each operation was improved as the work proceeded. Safety was continually emphasized throughout the teardown, with the result that the rounds were disassembled and sectioned in a safe and efficient manner.

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28-30 August 1984

ELECTROSTATIC SENSITIVITY

OF

MAGNESIUM-TEFLON COMPOSITIONS

by

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ELECTROSTATIC SENSITIVITY
OF
MAGNESIUM-TEFLON COMPOSITIONS

INTRODUCTION

Our infrared decoy flares are made with a magnesium-Teflon formulation. This composition has been variously characterized as to the safety hazards it presents. Under most circumstances, the composition is reported to have little or no tendency towards ignition from electrostatic discharge. Recent events at the Longhorn Army Ammunition Plant have changed this perception. Three fires have occurred at the press during removal of the RR-119 pellet from the consolidation die. We brought in Dr. Henry Shuey-Rhome & Haas, Mr. Al Camp - consultant, Mr. Gerald McKenzie - consultant, and Mr. Charles T. Davey of the Franklin Institute to help us evaluate the problem. As a result of their analysis, our investigations, and test data the most probable cause is due to ignition by electrostatic discharge.

MANUFACTURE OF RR-119 FLARE PELLETS

Flare composition is received in conductive rubber buckets of approximately 4.5 lbs. of composition each. The material for a pellet is weighed, passed over a magnetic separator and then dispensed into the die of a a shielded pre-consolidation press. The press consolidates the material into a "slug" which is approximately the same shape and size of the desired finished pellet. These slugs are placed in metal ammunition boxes inside a polycarbonate box until ten slugs are completed. The regular lid is then placed on the ammunition box and the box/pellets are moved to another bay.

The press bay consists of two consolidation presses located behind a steel plate shield. This shield extends from wall to wall and floor to near ceiling. The presses are side by side approximately three feet apart. There is a polycarbonate access door in front of each press.

There is a platform approximately 30 inches high and four feet from front to back extending from wall to wall in front of the shield/presses. There are three steps leading from the platform to the bay floor. On both sides of this platform there is a table with two polycarbonate boxes with lids. One box on each table houses an ammunition box of slugs and the other box houses an ammunition box of consolidated pellets. Each press is serviced by the corresponding table/boxes. The presses form the desired configuration of the pellets with a lower, side and top punch. The side and top punches move into place and the lower punch raises under hydraulic pressure, pressing the slug against the other two punches and the die.

When the ammunition box of slugs is received from the pre-consolidation operation, it is placed in one of the polycarbonate boxes with the ammunition box lid removed. The consolidation press is started in its cycle. The shield door opens to give access to the die. The punches all retract to make room for the slug. The polycarbonate shield box containing the slugs is opened and one slug is placed in the die and onto the lower punch. Palm switches are actuated to close the shield door and cause the side and upper punch to move into position. The lower punch then raises pressing the slug into the die and against the other punches to form the pellet to the desired configuration. After the predetermined dwell time, the lower punch relaxes and the other two punches retract to their load positions. The lower punch then raises to push the completed pellet completely above the die. After a one minute delay, the polycarbonate shield/door opens. The operator manually removes the pellet and places it in an ammunition box in the polycarbonate box on the table.

DESCRIPTION OF INCIDENTS

The first incident occurred at this location on July 26, 1983. During this incident, two people were burned and lost time from work. It was determined that this incident originated from a pellet removed from a press in the bay. The operator had removed the pellet and was turning to put it in a box when she saw that it was on fire. She threw the pellet and it landed on the floor near the legs of another operator. Although the operator was near the safety exit doors, the intensity of the fire caused severe burns to the legs and lower portion of the torso. The operator who removed the pellet received burns to the wrists and neck. The deluge system activated automatically and the alarm was automatically relayed to the fire station. Only minor damage was sustained by the equipment.

An investigation as to the probable cause was started. The material remaining from the mix that included the pellet that burned was tested for impact and friction sensitivity. Results did not show any unusual sensitivity. The mix was tested by a standard laboratory techniques for electrostatic sensitivity in both the loose powder and consolidated form. The procedure in this test was to charge a large oil-filled capacitor and discharge it through the sample. These tests were negative.

The operator was wearing proper cotton underclothing, Nomex coveralls, Nomex lab coat and appropriate safety equipment at the time of the incident. Her shoes had conductive soles and had been tested/checked at the start of the shift. The platform has a conductive rubber covering that was checked and showed positive grounding.

No definitive cause could be assigned to this ignition although electrostatic discharge was considered the most likely explanation with mix contamination as the second most likely cause.

A similar incident occurred on 3 December 1983. It occurred on the other press in the bay. The operator was removing a pellet from the press with her left hand. The pellet ignited when it was removed form the die. The operator again threw the pellet away from her body and the deluge system actuated. The intensity of the fire burned through the Nomex coat she was wearing, but did not have time to burn through the Nomex coveralls underneath. She suffered only minor reddening of the skin on her wrists.

We borrowed the electrostatic tester from the Franklin Institute for additional testing. We found that a large piece of flare composition could withstand several seconds of continuous discharge without ignition. Loose powder showed no tendency to ignite under any test conditions. It was theorized that the large piece of composition was capable of dissipating the energy from the discharge and the loose powder was blown out of the cup by the air heated by the discharge. Samples of flare composition were shaved from a pellet to give a sample thickness of approximately 0.050 cm. These samples were readily ignited from a discharge as evidenced by flashes and loud pops. The energy level of the discharge was calculated as 0.02 joules. The frequency of ignition indicated that the composition would probably ignite at even lower energy levels. The 0.02 joules represented the minimum that could be tested with the apparatus at hand.

Ignitions were more frequent when the sample was connected to the negative lead of the electrostatic tester than when connected to the positive lead. This is attributed to the build up of excess electrons in the shaving heading to more efficient energy concentration in the flare sample. This condition more closely approximates the conditions at the press since the electrons are present in the pellet and tend to flow through the flashing to jump to ground.

The ignitions did not propagate under the test conditions, but it was obvious that ignitions had occurred. Based on the frequency of press fires, it is likely that propagation is dependent on a rare combination of factors that only occasionally are encountered. From these tests and because of the operator's observations, it was decided that an electrostatic spark ignition the flashing on the pellet was the most probable cause for the incident.

An electrostatic voltmeter was used to measure the charge on the flare pellets. We measured charges as high as 3600 volts. A one minute delay was programmed into the press to allow static to bleed from the pellet prior to the press shield door opening. Other corrective actions included improved protective equipment, decreasing of bay personnel limits and improve lids on the polycarbonate shield boxes.

In both the 3 December and 26 July incidents, the operator was sure the pellets ignited on the bottom as they were removed from the lower punch. Based on statements by the operator and extensive checks of pellets immediately after consolidation with a static meter, the cause of both of these ignitions has been attributed to electrostatic discharge. This discharge/spark occurs as the pellet is lifted from the punch and ignites the flashing along the bottom edge of the pellet. This in turn ignites the pellet creating the situation where the pellet does not flare up until the operator gets the pellet to or out of the shield door.

On 20 January 1984, the operator removed a pellet from the lower punch with her left hand. As she removed the pellet from the lower punch, the pellet "popped" and ignited into a ball of fire. The operator threw the pellet onto the table and behind the polycarbonate boxes that served the press. No other pellets ignited. The personnel evacuated the building, and there were no injuries. There was only minor damage to the bay and equipment.

CORRECTIVE ACTIONS

Several ways to eliminate or reduce the static charge have been investigated. Attempts to use tongs for the removal of the pellets were not satisfactory. To remove mechanical removal from the die was considered. This is feasible, but would have taken too long to design, fabricate, and install.

It was found that the static charge did bleed down to relatively low levels on the ends and sides of the pellet during the one minute delay while the pellet sat on the lower punch. The bottom of the pellet bled down very little while still in contact with the punch. There was little difference in the static voltage indicated on the bottom of pellets removed immediately after ejection and those removed after a one minute wait. It was found that retracting the lower punch after ejection broke the pellet free from the die. This gave better bleed down from the bottom of the pellet.

A grounded copper bristle brush was used to pulled across the pellet as it rested on the die in the press. This was very successful in removing the charge from the top and sides of the pellet. The brush did not remove the charge from the bottom of the pellet except when the brush was pulled across the bottom. The readings of static voltage varied considerably from mix to mix and even within mixes. The relative humidity in the bay is controlled to 50 to 60% R.H. Wiping the slugs with water prior to placement in the die reduced the tendency to form a static voltage. It was further noted that wiping the slug with a mixture of isopropanol, butyl cellusolve, and water was even more effective in eliminating the static voltage. Neither of these methods was feasible at this time.

Tests have been run using an ionizing air system to blow ionized air across the surface of the pellets after ejection. This system is very effective in eliminating or reducing the static voltage. It is necessary to roll the pellet off the die so that the ionized air can reach the bottom of the pellet. This can be done on a practical basis in production in a short period of time, and is the one we chose. Until we could get the ionized air system installed on both presses and approved by Army Safety, we have to have an alternative and safe method to continue production. We adopted the procedure of lowering the bottom punch while the door is closed. This pulls the punch from the bottom of the pellet. The pellet sits loose on the top of the die for 60 seconds. The door then opens and the top and sides of the pellet are rubbed with a grounded brass bristle brush. This made a safe interim method. However, it make the process cycle too long for economical production.

The primary areas for pellet ignition by the discharge of static electricity are:

a. When the top punch is removed from the pellet.

b. When the pellet is removed from the lower punch.

c. When the side punch is removed from the pellet.

Tests showed the electrostatic voltage on the top of the pellet immediately after the top punch is withdrawn (the lower punch is in the up position with the pellet in place) ranges between 1200 and 3600 volts. This voltage decays to between 200 and 1400 volts within 30 seconds. The magnitude of the electrostatic voltage developed varies between mixes. Within a mix the variation is smaller. The electrostatic voltage on the bottom of the pellet immediately after it is removed from the bottom punch ranged between 1400 and 1800 volts. This was the same whether the pellet was removed immediately after ejection from the die cavity, or allowed to sit on the bottom punch for 60 seconds prior to removal. Sixty seconds after removing the pellet from the lower punch the voltage had decayed to between 200 and 650 volts. Generally, the voltage reduced by one-half in the first 15 seconds after removal from the punch. The use of a surface treatment on the slug prior to consolidation has shown potential to reduce static voltage on the pellet. Additional testing would be required to demonstrate that this surface treatment has no adverse effect on the pellet.

The question was raised as to why the electrostatic ignition had not occurred in the production of the M-206 flare since it is a similar composition. This can be answered by considering the energy levels generated by pressing the flares. The size and therefore the capacitance of the M-206 is approximately one-fifth that of the RR-119. Using the static voltmeter, the M-206 only showed about 600 to 800 volts after pressing. This is approximately one-fourth to one-fifth the voltage measured on the RR-119. Since energy is proportional to the capacitance times the voltage squared, the energy level available in the RR-119 is approximately 100 to 125 times that available in the M-206. This suggests that there is a mass effect in the system that results in a critical size of pellet required for hazardous conditions. It is likely that this critical size is in the range of 200 to 300 grams. This observation is in keeping with reported incidents of a similar nature from other sources.

The biggest problem we had with our decision to use ionized air is the present Army Safety Manual. DARCOM-R 385-100 prohibits the use of ionized air blowers in hazardous environments. To eliminate this problem we developed a system which effectively removes the ionizing air system from a hazardous environment. Our particular situation was best solved by placing several Simco Company ionizing air nozzles fore and aft of the pellet as it sits in the raised position. We have essentially encapsulated the system maintaining a positive air pressure at all times. This assures us of sufficient air velocity to prevent the ingress of gaseous or particular matter around the ionizing electrodes. (See design layout for complete details.)

Since we went to the interim procedure and now the ionizing air blowers, we have not had a pellet ignition at the press.

DOE HAZARD CLASSIFICATION FOR INSENSITIVE HIGH EXPLOSIVES (IHE)*

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It seems to me that the only valid rationale behind any system of hazard evaluation and classification is to assure that any operation is performed with the least possible risk to personnel. In other words, we seek to maximize the margin of safety for performing any operation. We recognize, however, that absolute safety is only obtained by not doing the experiment or operation. This is not, generally, an acceptable option. Thus any safety program, while conservative, must be positive, i.e., it must provide a means for operation with maximum safety rather than denying operation.

We must also keep firmly in mind that most, if not all, accidents occur because of the coincidence of two or more improbable conditions. I have heard it said that explosives accidents are statistical. That is, that one can perform an operation on the same material without incident for 1000 times, whereas on operation 1001 a tragic explosion my occur. This fatalistic idea is absolutely invalid. Any accident can be avoided by knowledgeable care.

Let me emphasize the words knowledgeable care. By knowledgeable, I mean intimate familiarity with the details of the operation so that the conditions providing the stimulus and confinement that could lead to a hazardous situation can be defined, and an understanding of the response of the material to these conditions. By care, I mean concern to detail in establishing operating procedures, care in monitoring the application of those procedures and care in continuously educating those involved in operations involving energetic materials.

Thus the human element is all important both in interpreting the results of evaluation tests and in applying that understanding to maximizing that margin of safety mentioned above. (Actually, if the understanding were complete the margin of safety could be absolute.) To thoughtlessly perform a checklist of evaluation tests and then to just as thoughtlessly follow a table of prescribed procedures is tantamount to accepting the statistical nature of accidents.

It is widely recognized that all energetic materials do not react the same to a given stimulus condition. The community generally speaks of primary and secondary explosives. (Some have also used the term "tertiary" explosives.) Primary explosives, of course, are those that

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respond violently to relatively low levels of stimulus; i.e., they are "sensitive." Secondary explosives are those that require a higher stimulus before they react violently; i.e., they are "less sensitive"?

Recognizing this difference in "sensitivity", different constraints are placed on the handling, storage, transportation, etc., of these materials. This is not to say that secondary explosives can be handled less safely but that primary explosives must be handled with greater restraint to obtain the same level of safety as the secondaries. Extending this approach, we now consider an additional class of energetic materials which we call "Insensitive High Explosives". These would require extremely high stimulus levels before reacting violently and consequently less constraint on handling to achieve the same level of safety as work with secondary explosives.

To date, we can only recognize one material, symmetrical triamino-trinitrobenzene or TATB as meeting this definition. Extensive experimentation has been performed on TATB; so much so that I feel comfortable in claiming that we understand the initiation and safety characteristics of TATB better than we do for HMX. TATB is truly insensitive to impact, friction, spark or thermal stimulus under any reasonable confinement condition. Only high amplitude shocks induce detonation and we have not found sustained lower level reactions.

In view of the existence of at least one material that can legitimately be called insensitive we accept the following definitions, similar to those accepted by the DDESB.

INSENSITIVE HIGH EXPLOSIVE (IHE): Explosive substances which, although mass detonating, are so insensitive that there is a negligible probability of accidental initiation or transition from burning to detonation. Those materials passing the DOE qualification tests are classified as IHE.

IHE SUBASSEMBLIES: IHE hemispheres or spheres with booster charges, with or without detonators, which pass the DOE qualification tests.

I must note at this point that we are speaking about materials that are by definition mass detonable explosives. They will detonate if the proper high amplitude shock pulse is provided. Therefore, if they are stored, handled, or transported in conjunction with more sensitive materials that could supply that pulse, they must be counted as hazard class 1.1 in any Q-D considerations. It is only when they are stored alone or with other IHE's that they can be considered as insensitive.

This approach must be viewed as a departure from traditional safety philosophy. It has previously been assumed that an initiating event had a reasonable probability of occurence and that the consequences of that event were predictable. Procedures and Q-D requirements were then imposed so as to mitigate those consequences. We are now proposing that there is no reasonable probability of the accidental delivery of sufficient energy to cause initiation. How does one go about establishing such a claim?

It is obviously not possible to simulate every hazard situation. Fortunately, however, the stimuli a material will experience as a result of an accident can be treated in five categories:

- Thermal
- Electrostatic
- Impact (including crushing impact).
- Shock
- Fragment impact.

Tests for each of these stimuli can be designed so as to be modelable both as to the level of stimulus and the nature of the response. This is not to say that we fully understand each of these initiation mechanisms. Far from it! However, we understand a lot more than we did just a very short time ago. We can use that understanding to better design our hazard tests and to better interpret the results of those tests.

The following are the tests selected by the DOE as a matrix for qualification of IHE and IHE subassemblies. You will recognize many of them as being rather standard in classification schemes; some you may be unfamiliar with. I will discuss those tests marked with an asterisk in somewhat more detail.

Thermal

Small Scale Burn Test	Same as TB-700-2. No explosions allowed.
One Dimensional Time to Explosion.*	No reaction greater than pressure rupture of container.
Bonfire	Similar to TB-700-2, no violent reaction. Test for subassemblies.
Slow Cook-off	No violent reaction. Test for subassemblies.

Electrostatic

Spark	No reaction at 0.25 joules.

Impact

Drop Hammer	Less sensitive than Explosive D.
Friction	No reaction at 5000 pounds normal force.
Spigot	No reaction, 120 ft. drop. For pressed billets and subassemblies.
Skid*	No reaction at 14^{0} impact angle from a height up to 20 ft. or just below the height at which the sample fails. For pressed billets and subassemblies.
Susan*	Less than or equal to 10% of TNT output at specified condition.

Shock

Cap	Similar to TB 700-2 #8 blasting cap.
Gap*	No reaction at 1.5 GPa impact.

Fragment Impact

Bullet Impact	No violent reaction with 5.56 mm and 0.50 cal. under specified conditions. Both materials and subassemblies.

NOTE: In subassembly testing, the booster/detonator must experience the hazard under realistic confinement.

The One Dimensional Time to Explosion or ODTX test is a fully contained, heavily confined thermal test with a one dimensional, isothermal boundary. It has been extensively characterized.

The idea behind a good thermal hazard test is to provoke the explosive to the highest level of reaction possible. This is accomplished as follows:

Confinement - moderately heavy, i.e., a few thousand psi. Light confinement will rupture before reactions can build. Much heavier confinement is unrealistic.

Containment - full containment, i.e., no free volume and no leak path. This condition prevents escaping gases carrying away latent heat and maintains any gas phase exothermic chemistry in contact with the decomposing explosive.

Thermal - the thermal boundary condition is chosen such that the Boundary entire explosive charge has reached the test temperature and such that a hot spot (self heating) is generated in the interior of the explosive charge. If the temperature is too low the slowly evolved gases will rupture the confining medium prior to self heating. If the temperature is too high, a thermal explosion will occur at the charge-boundary interface, rupture the container and quench. In neither of these instances will the maximum reaction be obtained.

Skid Test - In this test, a large, hemispherical billet of the explosive (> than 24 pounds) is dropped from a height and impacts a hard gritty surface at an angle of 14°. This is an impact test with a very large frictional component. The fracture of the billet on impact relieves the confinement required for reactions to build and is thus deemed no test: thus, the requirement to test below that height.

Susan Test - In this test, an aluminum projectile, loaded with the test material is fired from a 4" smooth bore gun and impacted against an armor plate target. The results are expressed as resultant energy as a function of impact velocity. (The standard is the full detonation of 280 grams of TNT.) I would like to make four points about the Susan test.

1. The test doesn't mock any reasonable hazard in the normal handling of an explosive.

2. This may or may not be a shock initiation test, depending on the impact velocity.

3. There is data scatter because of variation in projectile impact angle and gage sensitivity.

4. At higher velocities there is significant energy sensed simply from the kinetic energy of the projectile.

Gap Test - It is difficult if not impossible to suggest a scenario that would provide a shock impulse even approaching 0.1 GPa resulting from an accident. Unless, of course, there is a detonation in a neighboring material. Thus the gap test as it is generally employed is not an accident sensitivity test but a propagation test. (We accept that IHE's will propagate a detonation.) We have proposed a 1.5 GPa input as a significant overtest. The test must be designed to be both above the critical diameter and as nearly one dimensional as possible. Thus the booster must be sized correctly with respect to the acceptor.

Assuming that a material can qualify as an IHE according to the above criteria; how do we propose to handle such material?

1. Store as a Hazard Class 1.3 material - let me illustrate saving in real estate as follows.:

Weight of Material		Distance to	
Class 1.1	1500 lbs.	1500 lb. magazine	210 ft.
Class 1.3	100,000 lbs.	1500 lb. magazine	200 ft.
Class 1.1	1500 lbs.	Public highway	275 ft.
Class 1.3	70,000 lbs.	Public highway	270 ft.
Class 1.1	1500 lbs.	Inhabited Bldg.	460 ft.
Class 1.3	300,000 lbs.	Inhabited Bldg.	450 ft.

2. May be stored with mock HE without regard to quantity of mock.

3. Siting and design of storage and/or operating facilities based on hazard class 1.3 distances.

4. Concurrent machining (operator attended) operations if only IHE.

5. Operator attended hole drilling down to 5 mm.

6. Operator attended, dry machining under certain conditions.

7. Uncased HE-Pu activities in cased HE-Pu bays.

8. Storage and transportation of weapons based on Pu concerns.

In summary, the DOE has adopted a hazard classification of IHE and IHE Subassembly based on the premise of no probability of initiation and proposed a test protocol for that classification based on an in depth understanding of the hazards involved and the response of the energetic material to relevant stimuli.

HAZARD ASSESSMENT OF EXPLOSIVE SUBSTANCES.

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INTRODUCTION.

In France, the Explosive Materials Laboratory (EML) at CERCHAR deals mainly with the safety of explosive materials and related items.

At the request of the Ministry of Industry, approval tests are performed on civil explosive materials : explosives, detonators, detonating cords, propellants, pyrotechnics and other substances or articles.

The Laboratory also performs tests requested by the Government Agencies or under contrat with manufacturers : classification for transport, approval for use, ... on explosives materials or on more or less unstable substances (chemicals).

Because of this large field of activities and of frequent contacts with similar foreign laboratories, EML has developped a wide experience in explosives testing methods.

There are now 60 different test methods used for approval in France for different kinds of civil explosive materials and articles. They have been edited in a manual published by the Ministry of Industry. Supplementary tests on pyrotechnics are under development. It could be also noted that efforts are in progress to make tests on civil and military materials compatible.

Some of the civil tests have been chosen in 1981 to define a classification scheme which is required by the French regulation for safety

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of workers in the explosives industry. This scheme gives the acceptance procedure into class 1 and the hazard division assignment from 1.1 to 1.5.

Among all the tests, three seem us of particular importance for classification purposes. They are safety tests but are also of interest in characterizing the explosive properties. Our aim is here to present and comment on these three tests.

1./ A RELIABLE SHOCK SENSITIVITY TEST : THE FRENCH GAP TEST.

The shock sensitivity is a fundamental feature used to assess the hazards of substances from manufacturing process to their final use, especially the mass explosion hazard. A convenient method to determine the shock sensitivity is the gap test. An initiating explosive generates a calibrated shock in the test substance. The intensity of the shock is more or less reduced by interposition of an inert barrier (or "gap") of variable thickness between the initiating booster and the test substance.

The test is applicable to any substance.

Based on a similar US test, this test has been performed in France for twenty years (Ref. 1) ; there is thus many data available.

1.1.- Apparatus and materials.

The test apparatus and materials are shown in Figure 1. A steel tube (length 200 mm, internal diameter 40 mm, and 4 mm wall thickness) is placed vertically between two boosters. A gap, consisting in a given pile of cellulose acetate cards (thickness of one card : 0.19 mm), is placed between the initiating booster and the sample in the steel tube. The second (or reference) booster is in contact with the lower end of the tube and with a steel witness plate.

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For liquids, the lower end of the tube is directly in contact with a lead witness plate. Such a witness allows low-order detonations to be taken into account.

1.2.- Procedure.

The steel tube is filled with the substance to be tested. As shown in Figure 1, the different parts are assembled and the whole assembly is suspended above the ground. A detonator is inserted in the initiating booster.

1.3.- Method of assessing results and criteria.

The substance is deemed to have propagated detonation if the steel witness plate is punctured. In this case the result is said to be "positive". If not, the result is "negative".

The first trial is performed with a 200 cards pile.

Depending of the result, the gap is reduced or increased by choosing a new gap in the range defined by the following numbers of cards : 1, 2, 3, 4, 5 then 5 n (n from 2 to 80).

The value n1 which gives a "negative" result with a "positive" result for the next lower value in the range is then determined.

The test is carried out to obtain the minimal number N (minimal thickness of the gap) giving 3 "negative" in 3 trials, by beginning with n1 and increasing if necessary step by step in the above range. The test result is the limiting number N.

For classification purpose, the test procedure is simplified by fixing a given number of cards. Then, the test is carried out with 1 card or 240 cards to answer respectively the questions "Is it an explosive substance ?" or "Is the substance too insensitive for acceptance into class 1 ?".

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Under these conditions, the test is in good agreement with the USBM gap test (Ref. 2) performed without the gap (zero gap) or with the 2 inch gap.

Examples of our results are shown in Table 1.

SUBSTANCE	RESULT limiting number of cards
pentaerythrol tetranitrate	400
octogen	355
hexogen	335
trinitrotoluene, ships	300
m-dinitrobenzene	240
ammonium perchlorate, mean size 0.012 mm	235
ammonium perchlorate, mean size 0.1 mm	220
dinitrotoluene, crystallized	220
ammonium nitrate, very porous	215
trinitrotoluene, cast	175
slurry explosive, composition B sensitized	135
plasticized nitrocelluloses and various gun propellants	50 - 185
explosive reinforced, double base or composite propellants	50 - 100
composite propellants, non explosive reinforced	1
AN fertilizer, high density prills	1

Table 1 : Examples of results in the French gap test.

2./ AN ORIGINAL MECHANICAL STIMULUS SENSITIVITY TEST : THE 30 KG FALLHAMMER TEST.

Impact tests often used very small samples which are not necessarily representative of the test substance. In addition, it is not easy in

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those tests to gain an idea on how the reaction propagates following the impact. The large scale sensitivity tests , e.g. Suzan Test, are more convenient from this point of view, but they are often quite expensive and not applicable to all substances. The 30 kg fallhammer test presents the advantage of being inexpensive and applicable to any explosive including powdered substances. With only a few procedure modifications, this test has been performed in France for more than thirty years (Ref. 3).

2.1.- Apparatus and materials.

The test apparatus and materials are shown in detail in Figure 2.

A steel tray (wall thickness 0.4 mm), 8 mm deep, 50 mm wide and 150 mm long (volume 60 cm^3), uniformly filled with the test substance is placed on an anvil. The sample is impacted by the vertically falling hammer onto a point located at 25 mm from one end on the axis of the tray (Figure 2).

2.2.- Procedure.

The sample is said to have propagated explosion if the reaction length in the tray is greater than 100 mm from the impact point. Evidence of explosion is given by impression and deformation of the tray. If this condition is not fulfilled, the result is "no propagation". The drop height is in meter(s) :

$$h = 0.25\ k \quad \text{with } k = 1 \text{ to } 16.$$

The limiting height of propagation, is defined as the maximum height at which 3 failures in 3 trials are obtained. If one propagation is observed at the minimum height value (0.25 m), the result is reported as the limiting height lower than 0.25 m.

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2.3.- Method of assessing results and criteria.

To answer the question : "Is the substance too hazardous for transport (in the form in which it was tested) ?", the test may be reduced to a maximum of three trials at the fixed drop height 0.75 m. But in order to get more information on the sensitivity of the substance it could be of interest to carry out the extended test.

Some results in this test are given in Table 2.

SUBSTANCE	RESULT limiting height (m)
hydrazine nitrate, melted	0.25
nitroglycerine, pure	0.50
pentaerythrol tetranitrate, fine and dry	0.50
hexogen, dry	1
octogen, dry	1.75
trinitrotoluene, flakes	⩾ 4
trinitrotoluene, cast	⩾ 4
ammonium perchlorate	⩾ 4
nitroguanidine	⩾ 4
gun propellants	⩾ 4
solid composite and cast propellants	⩾ 4
composite explosives	⩾ 4

Table 2 : Examples of results in the 30 kg fallhammer test.

3./ HOW TO DETERMINE THE TENDENCY FOR A SUBSTANCE TO UNDERGO THE TRANSITION FROM DEFLAGRATION TO DETONATION : THE FRENCH TEST.

After the accident in Pont-de-Buis plant in 1975, stress has been placed in France on studying the possibility for small gun propellants to undergo the transition from deflagration to detonation. In addition, this hazard does exist, generally, for all propellants and a variety of other

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substances. It has been extensively studied by different laboratories in different countries.

For these reasons, taking into account the manufacturers experience, we designed a special test in 1977. In this test, the transition is made easier by the confinement brought by a steel pipe.

The test is applicable to all substances provided that they are able to detonate in the test tube.

3.1.- Apparatus and materials.

The experimental layout is shown in figure 3.

The sample is filled in a 42 mm inner diameter, 1 220 mm long, 3.2 mm wall thickness, seamless steel pipe.

This pipe is closed at one end by a cast iron screwed cap. The electric wire of the ignition device is fitted into a little hole drilled into the cap. At the other end the substance is held in the pipe at a given location by a cardboard disk.

The pipe is placed horizontally onto lead witness plates.

A probe monitoring the shock wave velocity may be placed in the sample.

3.2.- Procedure.

The charge length is one of the following : 100 - 150 - 200 - 300 - 400 - 500 - 600 - 800 - 1 000 - 1 200 mm.

Ignition at the cap end of the pipe is obtained by electric squib or by hot wire. If the transition occurs, it is determined normally after the

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impression on the lead. The predetonation length is noted.

The first trial is performed with a 1 200 mm charge length. If the transition occurs, the test is carried on with trials at stepwise charge length until the transition is obtained at one level and no transition in two trials is obtained at the immediately lower level.

3.3.- Method of assessing results and criteria.

This test can be used to select the very insensitive substances, candidates for hazard division 1.5, among the class 1 explosives with mass explosion hazard. For this purpose it could be decided that substances for which transition occurs with a charge length below 1 200 mm will be rejected.

Some results in the test are shown in Table 3.

SUBSTANCE	RESULT	
	transition	predetonation length (m)
ANFO	no	-
slurry explosive	no	-
aluminized gel	no	-
dynamite, gelatine	yes	0.82
dynamite, guhr	yes	0.30
small gun propellants	yes	0.15 to 1.2

Table 3 : Examples of results in the deflagration to detonation transition test.

CONCLUSION.

In connection with IPE (Inspection de l'Armement pour les Poudres et Explosifs) from the Ministry of Defense, EML is concerned with the discussions of the UN Group of Experts on Explosives (GEX). A classification scheme

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has been developed to identify the hazards presented by articles, packaged articles and substances. This scheme refers to series of tests and it was agreed that a few countries would propose test methods for inclusion into a test manual in preparation.

The three tests presented here have been proposed. They give important information on the explosives hazards. In order to be used in series of tests to answer a particular question about the flow chart, the method of assessing results in each test has been simplified : the test is so performed at one level and the result is "go" or "no go". Nevertheless, it is emphasized the interest to perform the extended test in each case is to get more information on the behaviour of the materials.

.../...

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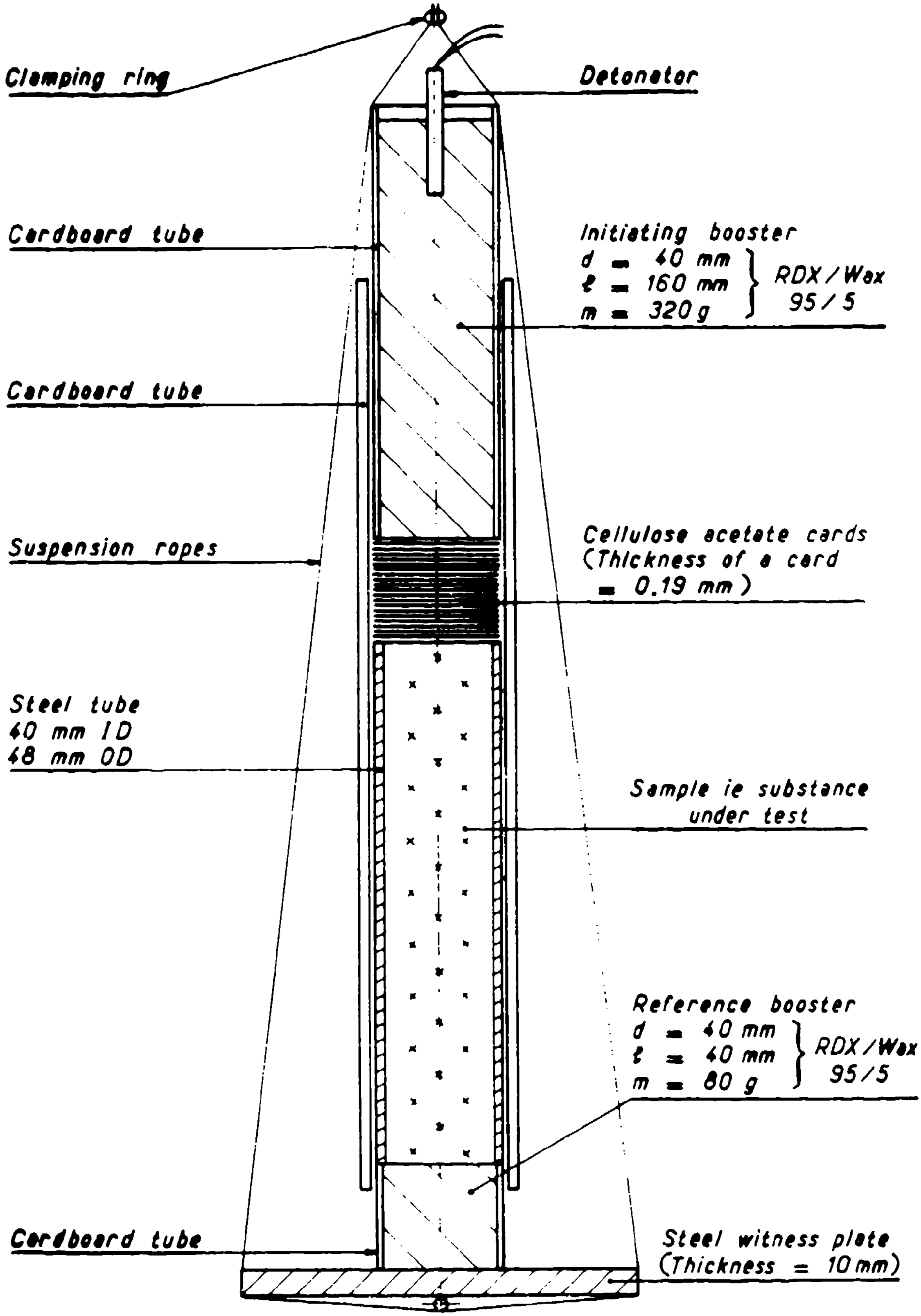

Fig. 1 _ FRENCH GAP TEST

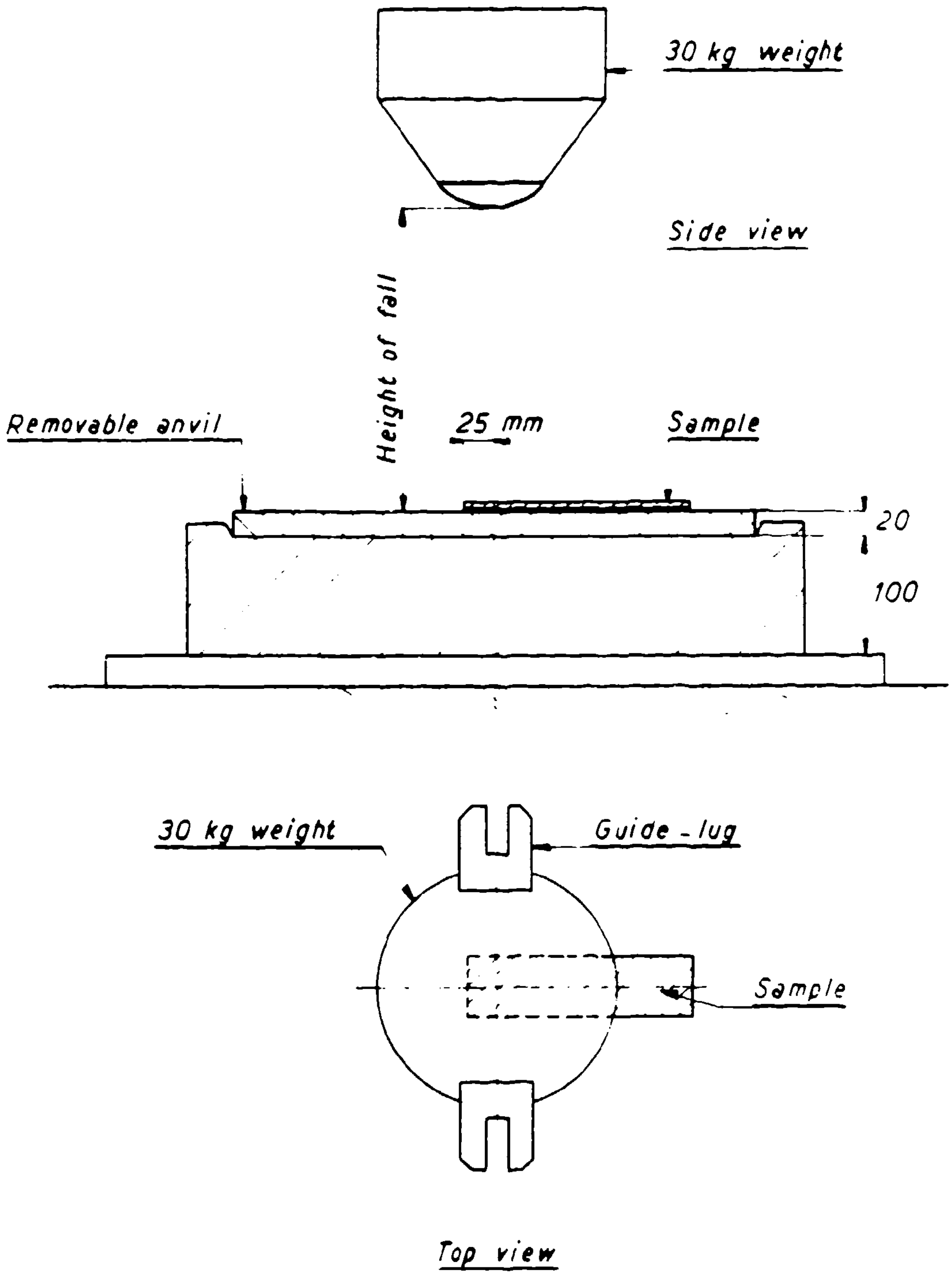

Fig. 2 _ TEST LAYOUT _ 30 kg FALLHAMMER TEST

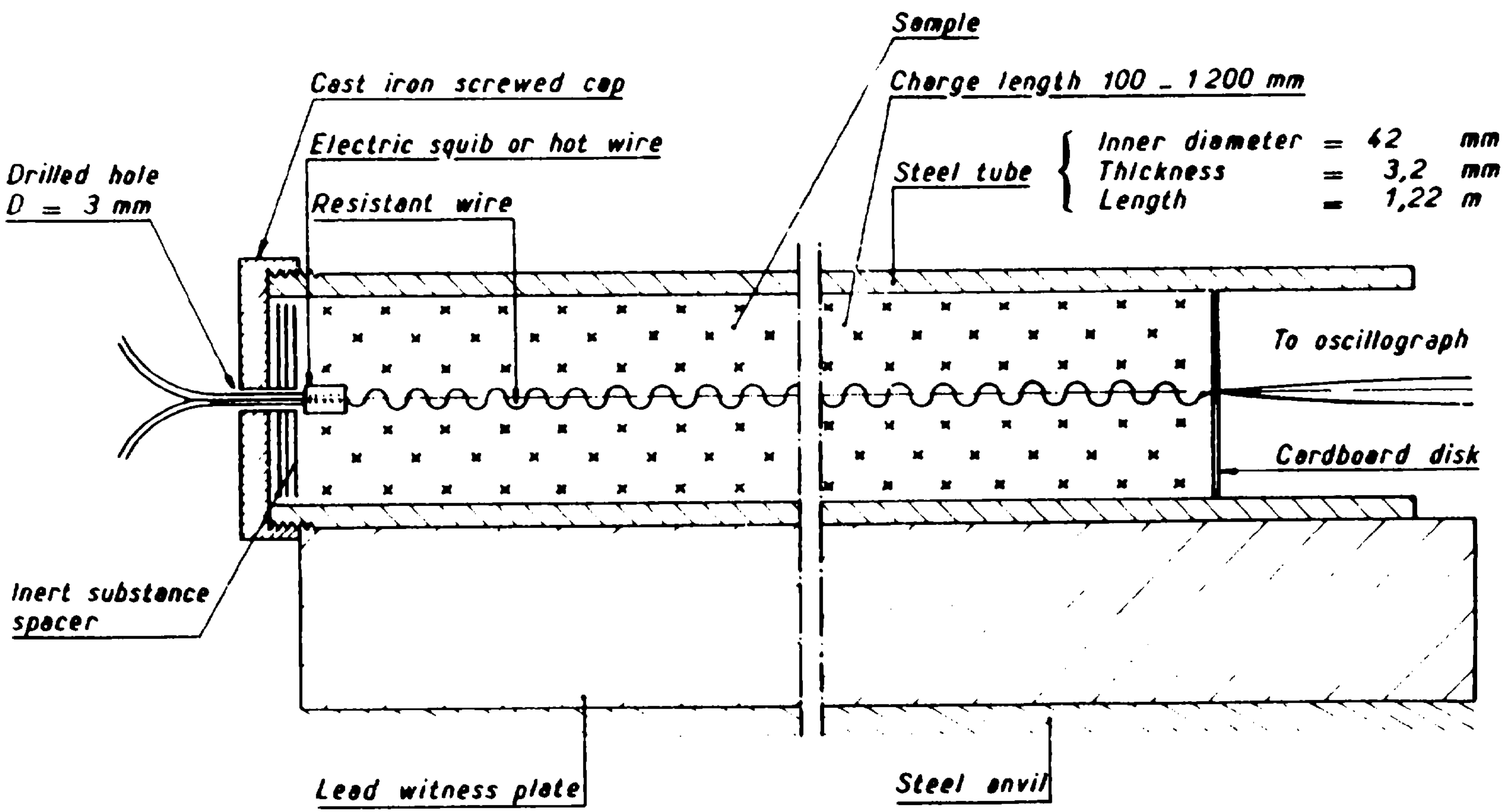

Fig. 3_DEFLAGRATION TO DETONATION TRANSITION TEST

EXPERIMENTAL LAYOUT

UNITED STATES DEPARTMENT OF DEFENSE

EXPLOSIVES SAFETY SEMINAR

27 - 30 AUGUST 1984

PROPELLANT CATEGORISATION TRIALS

Presented by:

NOEL ... TOZER
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Operational Safety Committee (Explosives)
Department of Defence Support
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ex1697

PRELIMINARY

The geographic size and isolation of Australia combined with its population density distribution, where major centres are few in number and remote from each other, make transportation and associated costs a sizable factor in commerce. It is therefore extremely important that the correct and most appropriate category be determined for hazardous materials. Furthermore, being an island continent sea transport of bulk materials is also significant and again appropriate categorisation is essential.

Of particular interest was the UN classification of small grain small arms propellants and the possible effect on that classification of packaging and containerisation. These had always been classified as the equivalent of UN HD 1.1 but if a classification of UN HD 1.3 could be shown to be appropriate, then significant cost savings in transport and storage would be realised compared to a classification of UN HD 1.1. The major concern was with AR2201 used in 7.62 mm Ball ammunition. However, there was insufficient spare propellant available so trials were conducted initially to see if a more readily available propellant would perform in a similar manner.

This report details the tests made, results obtained, the rationale behind the tests and discusses the features that diverge from the accepted classification test standards.

Australia normally follows UK practices in this situation and under ESTC 220 guidelines, fire trials are conducted at three levels. Briefly these are:

(a) Single Package Test - where an article near the centre of the package is ignited either using its own integral detonator or an igniter of similar power to the normal stimulant of the item.

(b) Stack Test - in which confinement is provided and the packages are arranged in a manner most likely to induce detonation and/or propagation. Ignition is effected in a manner similar to the single package test.

(c) External Fire Stack Test - in which a stack of packages located one metre above ground level are surrounded by kindling, to a depth of at least half a metre, which is set on fire.

This basic approach towards assessing the performance of propellant was followed, but it was felt that in a possible real life situation a "standard" fuel fire may be more realistic. The scenario considered appropriate was to finally test the transportation of palletised containers in an ISO 20 tonne freight container paralleling deck cargo on board a ship. Road and rail transportation fires, while possibly more likely to occur do not appear to present as great a hazard as a shipboard fire occurring in a port.

It was recognised that if initiation was caused by a detonator (either a commercial No 6 or No 8) then a 1.1 event would probably occur. But under normal civilian transport conditions, the accidental initiation of an event in the propellant through the use of a detonator is considered to be extremely improbable in fact almost impossible particularly locked in an ISO container. The tests were therefore structured around what was felt to be the real life situation proposed previously, namely the cooking off of the propellant due to an external fire.

INTRODUCTION

It was decided that the bulk testing would be done on Propellant AR5401 in lieu of AR2201. Both propellants are manufactured in Australia at the Mulwala Explosives Factory. AR5401 was based on a Foreign propellant manufactured under Licence but which has since been modified. However both are single base, perforated, non-porous, stabilised, moderated and glazed propellants and although physically different are similar in performance and sensitivity.

The following table shows the basic characteristics for the two propellants:

PARAMETER	AR2201	AR5401
Rotter Impact Test, F of I	19	25
Glancing Blow Test -		
Steel on Steel	11.0	>11.0
Brass on Steel	11.0	>11.0
Steel on Bakelised Cloth	1.7	1.1
Brass on Bakelised Cloth	1.7	1.1
Temperature of Ignition	165°C	175°C
Ignition by Electric Spark	Ignition at 4.5 joules	No ignition at 4.5 joules
Critical Height	13 inches	7 inches
Cut Length	0.050 inch	0.170 inch
Diameter	0.012 inch	0.114 inch
Web Thickness	0.0116 inch	0.014 inch
Structure	Single perforated tubule	19 hole perforated cylinder
Composition	Single Base (93% NC) DNT Glazed	Single Base (95% NC) Moderated Glazed
Usage	SAA	Med. Calibre Ammunition

While there are some differences, the variations are not great. AR2201 is slightly more sensitive to shock and electric spark, but AR5401 has a lesser critical height. The first objective of the tests was to see if the behaviour would be similar.

TEST DETAILS AND RESULTS

Four tests were conducted as follows:

Test 1

Four M2 cans of AR2201 were initiated individually by remotely activated matchhead igniters inserted into a bag of black powder. The first can was fired with the lid off to determine the effect but when there was no detonation the remaining three were trialed with the lids clamped on. All cans were standing with the lid end upwards when initiated. Air blast measurement was used to determine the effective explosive yield in the event that the propellant detonated. If this had occurred the trials would have been terminated as this would show that a category of HD 1.1 was appropriate. The four tests provided confidence in the reproducibility of the event.

The can without a lid fitted when ignited internally burned for forty five seconds. The cans with the lids clamped on had their lids blown off and the propellant was consumed within thirty seconds.

But no detonation occurred.

Test 2

The principal objective of this test was to compare the behaviour of AR2201 and AR5401 under identical conditions and to observe whether the performance would be different if the heating was entirely external.

In three separate trials, one M2 can of AR2201 and two M2 cans of AR5401 were suspended over the liquid fuel fire. Each can contained 55 kg of propellant. The fire was designed to achieve similar thermal flux behaviour to that laid down by the Ordnance Board (UK).

The fire hearth over which the cans were suspended was 1.5 metres square and 0.2 metre deep. The fuel consisted of kerosene with a 20 percent addition of petrol to ensure rapid ignition of the kerosene and the fire was initiated by remotely activated squirt igniters.

As in Test 1 air blast measurement was provided to determine the effective explosive yield in the event that the propellant detonated.

In this comparison test the behaviour of the two propellants was very similar. While no high order reaction occurred, as indicated by air blast pressure measurement, the cans were ruptured. This was an obvious difference in reaction when the propellant was ignited through the use of an extrnal fire and while there was no apparent difference between AR2201 and AR5401 the cans ruptured rather than merely blowing the lids off as occurred in Test 1. However, no detonation occurred.

Test 3

This test was used to determine the effect of containment and was again conducted in two parts; the first part using AR2201, the second with AR5401.

A two tiered pallet load, one with thirteen M2 cans of propellant on the lower level and thirteen M2 cans filled with sand/sawdust mixture on the upper layer, was burned over a liquid fuel fire. The net weight of propellant on the pallet was approximately 700 kg and the inert material was chosen so as to achieve a similar bulk density to that of the propellant.

The fire hearth was 2.5 metres square and 0.33 metre deep, with 1.0 metre of earth banking on three sides for wind protection. The fuel and fire initiation were intended to be similar to Test 2 but strong winds prevented reliable ignition. The squirt igniters were eventually supplemented by bags of mortar propellant.

In addition to air blast measurement instrumentation, temperature measurements were made using six fibreglass insulated chromel alumel thermocouples; five were positioned in cans and one just above the fuel surface.

Similar cook off times were recorded for both AR2201 and AR5401 and the severity of the reaction for both propellants was similar; when a can, or cans, ignited, rapid periodic burning or "roman candle" effect was observed. The fuel fire functioned properly and verified the accuracy of the previous test. The cans were ruptured and some were thrown from the pallet, but again there was no detonation. Cook off times for AR2201 varied from 13-19 seconds and for AR5401 from 13-29 seconds.

Test 4

This was the major trial and was designed to determine the severity of an event with small arms propellant contained in M2 steel cans and stacked into an ISO shipping container placed over a liquid fuel fire.

A twenty tonne steel ISO container was packed with twelve pallets of cans comprising nine tonnes of AR5401 propellant. The pallets were braced to prevent the load shifting during transportation as per IMCO requirements.

As in previous tests the liquid fuel consisted of a mixture of kerosene and petrol in a hearth. The hearth was 7.35 metres long by 3.5 metres wide and 0.36 metre deep, and ignition was by four squirt igniters which, as a result of previous trials, were modified to give a longer duration flame. The igniters were positioned midway along each side of the hearth and just above the fuel surface.

Extensive temperature measurements using eleven thermocouples and pressure measurement with transducers and a microphone were used to monitor the test in the event of a detonation occurring.

The tests, as can be seen, differ from the detail as laid down in ESTC 220; however, as stated previously, stepwise procedures were followed.

(a) The ESTC 220 single package test was directly copied in Test 1 and as the object of the tests as a whole was to find out what happened in a fire situation, Test 2 was conducted. Again, this was a single package test but with external stimulus to initiate the propellant.

Direct comparison of Tests 1 and 2 were possible to validate the continued use of external heat as being an acceptable alternative to internal ignition.

(b) In the ESTC 220 stack test the object is to produce propagation to detonation if possible by introducing confinement. In Test 3 the pallet load of inert cans was used to provide confinement over the propellant. Lateral confinement, as used under ESTC guidelines, was not possible due to the need to use fire as a stimulus.

Again it must be pointed out that Test 3 diverged from ESTC guidelines by the use of external heat rather than the use of an integral detonator or an igniter of similar power. However the use of external heat relates to the ESTC 220 external fire stack test.

(c) The burning of an ISO container over an open hearth of flaming kerosene is the nearest practical simulation to the ESTC 220 external fire stack test. While the container is not buried in a bonfire as required by ESTC 220, the flames from the fuel fire quickly engulf the container. Additional containment is effected by the ISO container and this may be considered a factor that enhanced the value of Test 4. It is believed that the test was a most realistic and severe test and one which could be practically produced.

After fuel fire ignition, as witnessed by a flash and smoke at the side of the container, there was no evidence of propellant burning until one minute five seconds after ignition when traces of white smoke were observed streaming from the container. Vigorous burning commenced about three minutes after ignition, reaching a peak at three minutes twenty five seconds when the container doors burst open displacing the container longitudinally about three metres. The fireball produced by this vigorous burning extended to a radius of about thirty metres. Cans were propelled from the open end of the container for a distance of about eighty metres and the propellant was totally consumed within four minutes, but again, there was no detonation.

DISCUSSION

A flame temperature of at least 550°C was achieved over the whole fire within 40.5 seconds and the propellant in the cans reached a temperature of 175°C in 31-33 seconds. The pressure wave generated by the burning propellant was too small to be accurately recorded by the pressure transducers.

As explained at the start of the paper, the objectivess of the trials were:

(a) to classify propellants AR2201 and AR5401 against a practical backdrop; and

(b) to determine if the propellants were sufficiently similar in response to warrant the classification of both by analogy.

It is considered the severity and similarity of reaction of single sealed M2 cans as cooked off over an open fuel fire did indeed indicate that the full scale trial using AR5401 could be used as a basis for the classification of AR2201.

With the full scale test using an ISO freight container, the reaction occurred in a progressive manner to a climax but did not proceed to detonation. The fireball was large, as may be expected, and projection of burning cans occurred with displacement of the ISO container. This is a typical description of a HD 1.3 category event which is described in part "as items which burn with great violence and intense heat .... firebrands and burning containers may be projected."

CONCLUSION

The tests conducted showed that medium calibre propellant AR5401, and by analogy small arms propellant AR2201, can be classified as HD 1.3 when transported in M2 cans palletised in an ISO freight container.

The tests do not cover the effects of an external detonation as may be experienced in times of hostilities but cover a typical severe practical disaster that may confront the civilian transportation of propellant.

Both AR2201 (critical height 13 inches) and AR5401 (critical height 7 inches) exhibited UN HD 1.3 behaviour in M2 cans with greater powder column heights. M2 cans have considerably higher venting pressures than the copper lined wooden boxes traditionally used for transport of small web powders.

The time which elapsed between fire outbreak and propellant ignition suggests strong possibility for fire control or "event minimisation" by the use of drenches, etc.

Both propellants have now been classified 1.3 for Commonwealth Transport in Australia. We have requested the UK authorities to conduct their Large Sealed Vessel Test for confirmation but to date no result has been given.

SLIDE NO	TEST NO	DESCRIPTION
1	-	Comparison of Propellant Grains
2	1	Ruptured M2 Can
3	2	Suspended Can
4	2	Suspended Can after Burning
5	3	Palletised Cans
6	3	Cans after Burning
7	4	Container
8	4	View of Test Site
9	4	Commencement of Propellant Burn
10	4	First Projection of Can
11	4	Mass Burning
12	4	Start of FIREBALL
13	4	Container after Fire
14	4	Container after Fire
15	4	General View of Area after Fire

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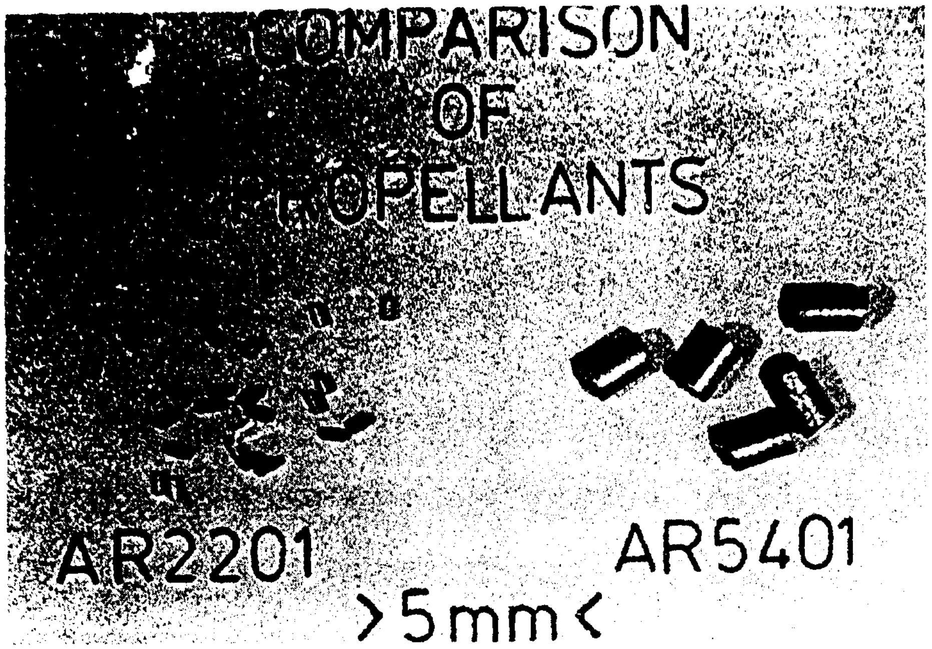
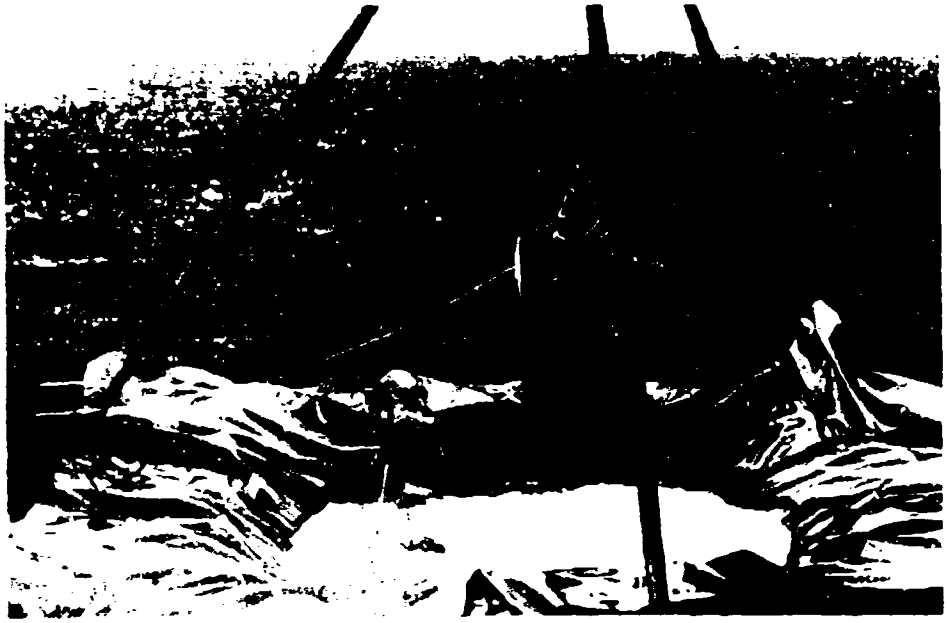


Comparison of Propellant Grains

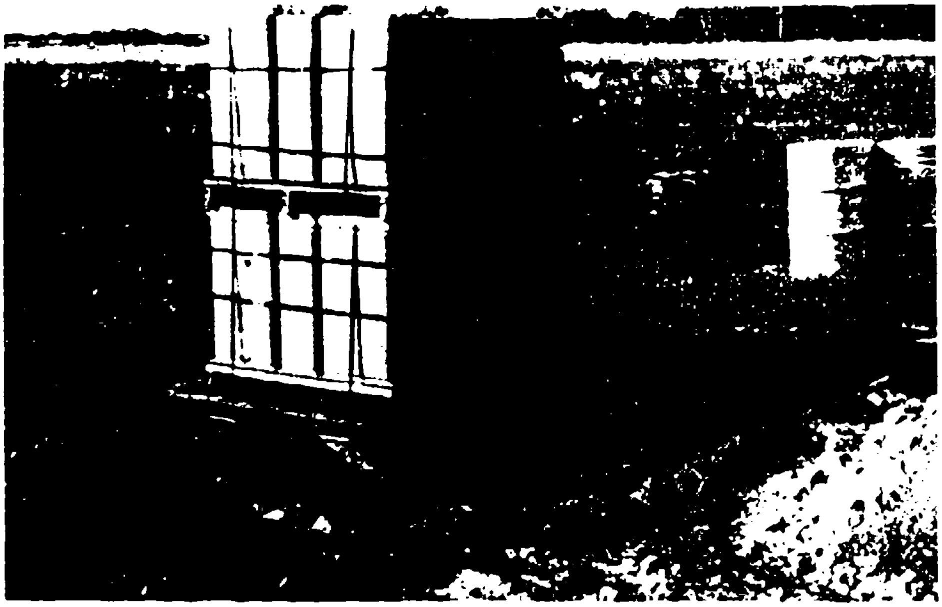
FIG. 1a - Photograph of the M2 can (with lid on) after burning (Trial 6A/77).

Ruptured M2 Can



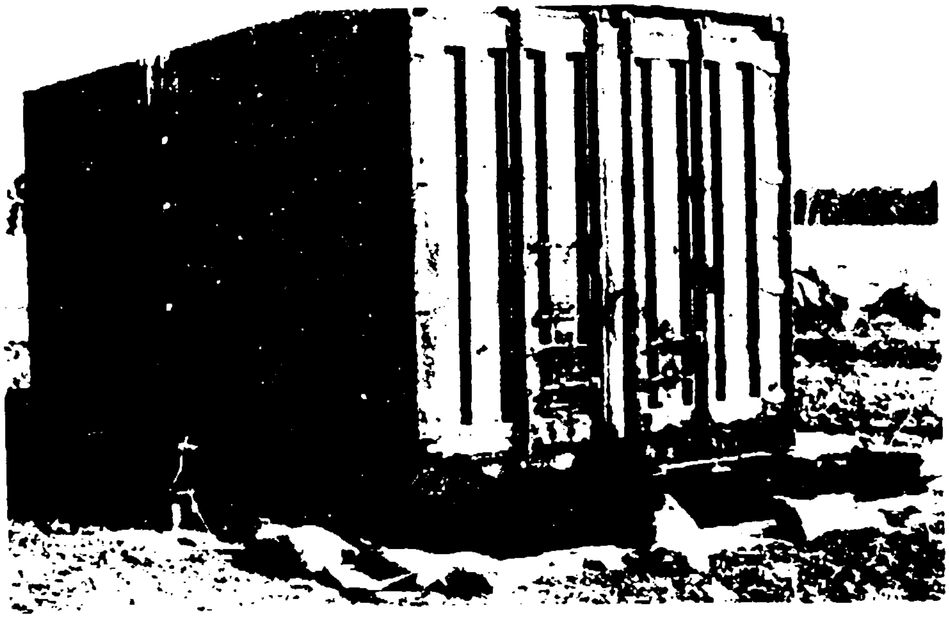
Suspended Can

Suspended Can after Burning



Palletised Cans

Cans after Burning



Container

[illegible] of Test Site

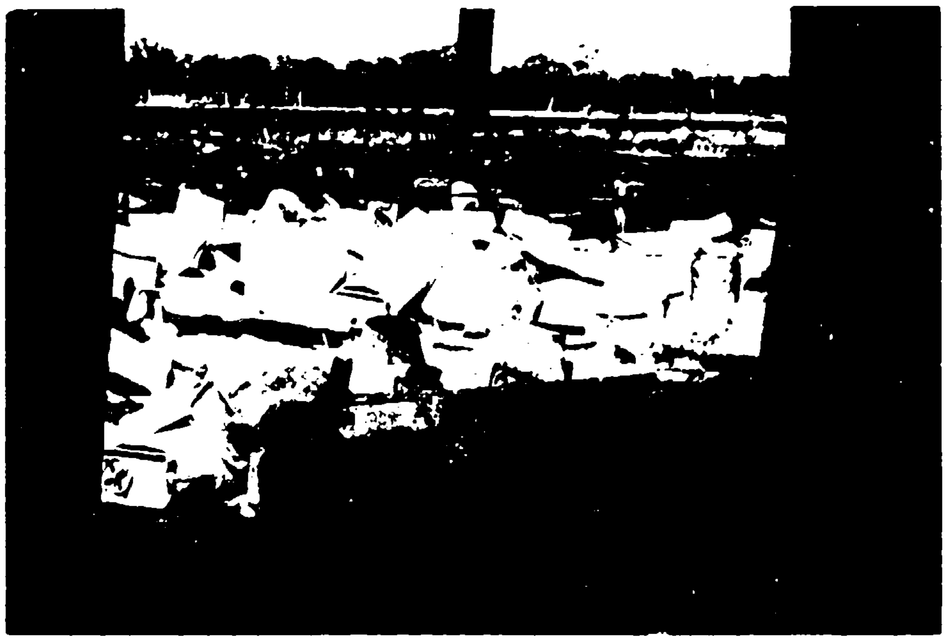
Commencement of Propellant Burn

First Projection of Can

Mass Burning

Start of FIREBALL

Container after Fire



Container after Fire

General View of Area after Fire

USA SMALL-SCALE COOKOFF BOMB (SCB) TEST

by

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ABSTRACT

This report describes the use of a Small-Scale Cookoff Bomb (SCB) for the UN Classification of explosives with regard to their thermal response. The SCB test simulates transport and storage situations involving external heating of substances. (A similar report has been written for inclusion in a compilation of test methods to be published as an addendum to the UN Orange Book, "Transport of Dangerous Goods.")

INTRODUCTION

At the August 1979 meeting of the UN Group of Experts on Explosives, a general set of test procedures was established to determine to which hazard class various substances and articles should be assigned. UN Test Series 1 is part of the acceptance procedures used to determine whether or not a substance is accepted into Class 1. UN Test Series 2 is used to determine whether or not an explosive substance is too insensitive for acceptance into Class 1. UN Test Series 5 is being established to determine whether or not an article can be assigned to 1.5 hazard classification. These test procedures were agreed upon and published in UN Paper ST/SG/AC.10/C.1/R.51. The paper herein presented discusses a thermal response test that can be used in these series of tests for hazard classification of explosives.

Among the tests proposed for the thermal response tests were the Koenen test, the United States (US) Internal Ignition test the US External Heat test, the United Kingdom Time/Pressure test, the United Kingdom Sealed Vessel test, and the US Deflagration-to-Detonation Transition (DDT) test. The External Heat test (Refs. 1 and 2) used by the US Department of Defense (DOD), has been proposed and accepted as an alternate to the present in-use Koenen test. A report on the SCB test will be published with other test methods as an addendum to the UN Orange Book. (The External Heat test is also known as the SCB test.)

The SCB test can be used to assess the severity of the cookoff reaction by examination of the SCB case and witness plate damage caused by the test substance when subjected to external heating. Criteria are provided herein for rating each test result as a burn, deflagration, explosion, or detonation based on the degree of damage sustained by the test fixture. This rating is described below and is suggested for use in relating the severity of the cookoff reaction to the UN criteria for thermal response.

EXPERIMENTAL PROCEDURE

Apparatus and Materials

The SCB experimental arrangement is shown in Figure 1. The sample to be tested is contained in a 400-milliliter steel vessel with walls 3 millimeters thick. Two 400-watt electric heater bands are fastened to the steel vessel, as shown in Figures 1 and 2.

The vessel has a threaded steel cover with two feedthrough fittings for thermocouple leads and for a pressure take-off. The complete fixture consists of the capped steel vessel clamped between two 13.5- by 13.5- by 1.27-centimeter thick steel witness plates held in place with four 1.27-centimeter diameter bolts. The SCB is instrumented with one or two plate-type thermocouples. When only one substance is being tested, a thermocouple is spot welded to the inside center of the vessel wall (see Figure 1). When two substances are tested, i.e., a liner material and an explosive material, a second thermocouple is used between the two substances. The plate-type thermocouples consist of a 0.3-millimeter thick nichrome ribbon approximately 1-centimeter square, with the thermocouple wires fanned out and individually spot welded to the nichrome. The welder used should be designed for thermocouple welding, or should be a welder that is current-limited for use with small wire or thin metal. Plate-type rather than bead-type thermocouples are used for this test since plate-type thermocouples respond faster and provide a more representative measurement of the temperature at the interfaces.

Procedure

The substance of interest is loaded into the SCB steel vessel to within 1 centimeter (approximately) of the top. The space remaining above the substance of interest allows for thermal expansion. The substance of interest can be a solid, liquid, slurry, powder or a gas under modified assembly and fill conditions. The test unit is assembled complete with the 400-watt heater bands and placed in a safe testing bay for remote firing. At the test bay, the thermocouple leads are connected to a strip-chart recorder which is used to record the temperatures and the time to cookoff. The two heater bands are wired in parallel and then connected to either a 110-VAC or 220-VAC safety-key controlled firing line. Which voltage selected depends upon which heating rate is desired. Once the test setup is completed and the site cleared of all personnel, the units are "fired" by turning the key to activate the heaters. The test is completed when a cookoff reaction occurs.

Data Reporting

Time and temperature of the cookoff reaction are taken from the strip-chart records, and an assessment of the severity of the reaction is made from the number and condition of the vessel fragments and the condition of the witness plate. Levels of reaction severity and the associated rating usually identified are given in Table 1.

TABLE 1. Thermal Response Rating of SCB Tests.

Vessel Condition	Witness Plate Dent	Cookoff Reaction	Rating
No change	No change	Burning	R-0
Intact, but bulged	No change	Burning	R-1
Open, one piece	<0.05-inch (0.13 cm)	Deflagration	R-2
Two pieces	<0.05-inch	Deflagration	R-3
Three/four pieces	<0.05-inch	Deflagration	R-4
Five+ large pieces	<0.05-inch	Explosion	R-5
Many pieces	<0.05-inch	Explosion	R-6
Many pieces	<0.20-inch	Explosion	R-7
Many small pieces	>0.20-inch (0.5 cm)	Explosion	R-8
Many small pieces	Almost punched	Partial Detonation	R-9
Many small pieces	Punched hole	Detonation	R-10

The time-temperature record is suggested for use in determining whether or not the substance of interest has met a minimum temperature requirement to be established for the UN Test Series 2(b). The minimum temperature requirement would be used to determine if a substance is too hazardous for thermal reasons (thermal stability criteria).

Figure 3 shows the experimental results used in evaluating the cookoff data and for assigning cookoff ratings of R-1 through R-10. The witness plate damage provides the strongest argument as to whether or not a substance has undergone a deflagration-to-detonation transition. *If the witness plate is flat with no apparent bending or concavity, then the reaction is considered not-a-detonation nor a reaction that would lead to a detonation. If, on the other hand, the witness plate has a measurable dent, then this is a strong indication that a detonation might develop if a larger sample were used.*

Criteria

A. *For UN Test Series 1(b)* (Suggested)
The test is considered positive if deflagration (R-2 or greater), as defined in Table 1, occurred.

B. *For UN Test Series 2(b)* (Suggested)
The test is considered positive if an explosion (R-5), as defined in Table 1, occurred prior to 100°C at the interface between the case and the substance.

C. *For UN Test Series 5(b)* (Suggested)
The test is considered positive if a partial detonation or detonation (R-9 or greater), as defined in Table 1, occurred. This test series is suggested for use for consideration of articles to be placed in Division 1.5.

DISCUSSION OF RESULTS

Test results for some typical explosives are given in Table 2. The SCB is a technique that has been used to empirically predict the time to cookoff and the severity of the cookoff reaction for a given explosive in hardware. The technique has been used to evaluate a large number of military high explosive compositions and their ingredients for predicting their reaction in a fuel fire under the confined condition of a munition. Since a liner material is usually used with a high explosive fill in a munition, the steel vessel can be lined with the selected liner material, explosively filled, and tested. In this manner, the effect of the liner material on the high explosive can be determined with regard to its influence on the cookoff time and the severity of the cookoff reaction. Studies have shown that certain liner materials can make the cookoff reaction of a given high explosive more *or* less severe.

Another factor which must be considered when using this technique is that the actual heating rate is nonlinear and averages out to be approximately 0.2°C/s when connected to 110 VAC. When the same heaters are connected to 220 VAC, the heating rate averages out to be approximately 3°C/s. When an item is heated in a fuel fire, the heating rate is nonlinear in the same manner as has been described for the SCB. The approximate heating rate will depend on the heat given off by the fire in relationship to the mass of the item and the thickness of the wall through which the temperature is measured. The 3°C/s rate is approximately that experienced by a high explosive (HE) fill in a heavy wall steel munition subjected to a fuel fire test. The 0.2°C/s heating rate is representative of that experienced by a HE fill in a thermally protected heavy wall steel munition subjected to a fuel fire. In general, cookoff reactions become more severe as the heating rate decreases.

It is proposed to use the SCB to determine if a substance has any significant explosive properties when subjected to a thermal stimulus (UN Series 1(b) Test). It is further proposed that substances that yield only a burning reaction (i.e., see those listed in Table 2) should be considered too insensitive for inclusion in Class 1. Although the cookoff reaction listed as a deflagration does show some explosive properties for a given substance, this reaction should also be considered too insensitive for the lower limit of thermal sensitivity in the UN Series 2(b) Test. It is thus proposed that the cookoff reaction listed as a deflagration should be considered too insensitive for Class 1, unless retained in Class 1 based on the results from another test (such as those listed in UN Series 1(b)).

A number of substances from Table 2 have cookoff reactions listed as deflagrations. One substance that appears to be out of line is the flake TNT. The test with flake TNT would indicate that in a fire the TNT could have a mild cookoff reaction. Once all or most of the TNT is molten, the cookoff reaction can become more severe, leading to a detonation. These data show that the physical state of the substance is important to the reporting of test results.

CONCLUSION

The SCB test fixture has been and will continue to be an excellent technique to determine the thermal behavior of explosives with regard to cookoff time, temperature and the severity of the cookoff reaction. The technique can be used with other laboratory techniques to more fully evaluate the thermal response of confined explosives.

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2. C. M. Anderson and J. M. Pakulak, Jr., "The Prediction of the Reaction of an Explosive System in a Fire Environment. Coated RDX Systems for Pressed Explosives." *J. of Hazardous Materials*, Vol. 2 (1977/1978), pp. 143-161.

TABLE 2. SCB Test Results on Selected Explosives.

Explosive type	Heater Voltage, VAC	Cookoff Temperature, °C	Cookoff Time, min	Cookoff Reaction
Pressed Composition A-5	110	225	14.0	Detonation
Pressed CH-6	110	222	12.9	Detonation
Pressed RDX/EVA (97/3)	110		12.8	Explosion
Pressed RDX/Estane (95/5)	110		14.6	Detonation
Pressed Composition A-3	110	248	6.8	Detonation
Pressed RDX/PE (91/9)	110		18.6	Detonation
Pressed RDX/EVA (91/9)	110		17.1	Explosion
Pressed Tetryl	110	215	14.5	Detonation
Flake TNT, loose fill	110		11.	Deflagration
Cast TNT	110	>400	6.1	Detonation
Cast Composition B	220	250	1.9	Detonation
Cast EA Eutectic mixture	110	260	14.9	Explosion
Cast EA Eutectic mixture	220	316	1.4	Explosion
Flake TATB, loose fill	220	388	2.8	Deflagration
HBD-powder NQ, loose fill	110	281	4.1	Explosion
Dupont GSX, AAN Sensitized	110	250	6.	Explosion
GSX, TNT Sensitized	110	360	4+	Deflagration
Hercules GSX, Al Sensitized	110	390	8+	Deflagration
5-6 μ powder AP, loose fill	110		33.	Deflagration
200 μ powder AP, loose fill	110		34.	Deflagration
Cast PBCT/Al/AP Rocket propellant	110		7.2	Deflagration
M6 Gun propellant, loose fill	110	201	4.2	Deflagration
M6 Gun propellant, loose fill	220		1.2	Deflagration
Single Base (NC) Gun propellant	220		1.3	Burning
MAN 85% solution	110		23.	Explosion
~ 10 μ powder AN, loose fill	220		3.0	Burning
~ 10 μ powder AN, loose fill	110	339	13.0	Burning
~ 10 μ powder, GN, loose fill	220	~340	3.8	Burning
~ 10 μ powder GN, loose fill	110	368	14.3	Deflagration
p,p'-oxy-bis(benzene sulphonhydrazide), loose fill	220	190	0.9	Burning

Definitions:

AAN = Aliphatic amine nitrate
Al = Aluminum
AN = Ammonium nitrate
AP = Ammonium perchlorate
EA = Ethylene diamine dinitrate/Ammonium nitrate (Potassium nitrate phase stabilizer) eutectic mixture
EVA = Ethylene-vinyl acetate copolymer; USI, UE-638-04
GSX = Gelled slurry explosive
HBD = High bulk density
MAN = Methylamine nitrate
NC = Nitrocellulose
NQ = Nitroguanidine
PBCT = Polybutadiene, carboxy terminated
PE = Polyethylene, emulsion, MIL-E-63218
GN = Guanidine nitrate
RDX = Hexogen = cyclo-1,3,5-Trimethylene-2,4,6-trinitramine
TATB = Triaminotrinitrobenzene
TNT = 2,4,6-Trinitrotoluene

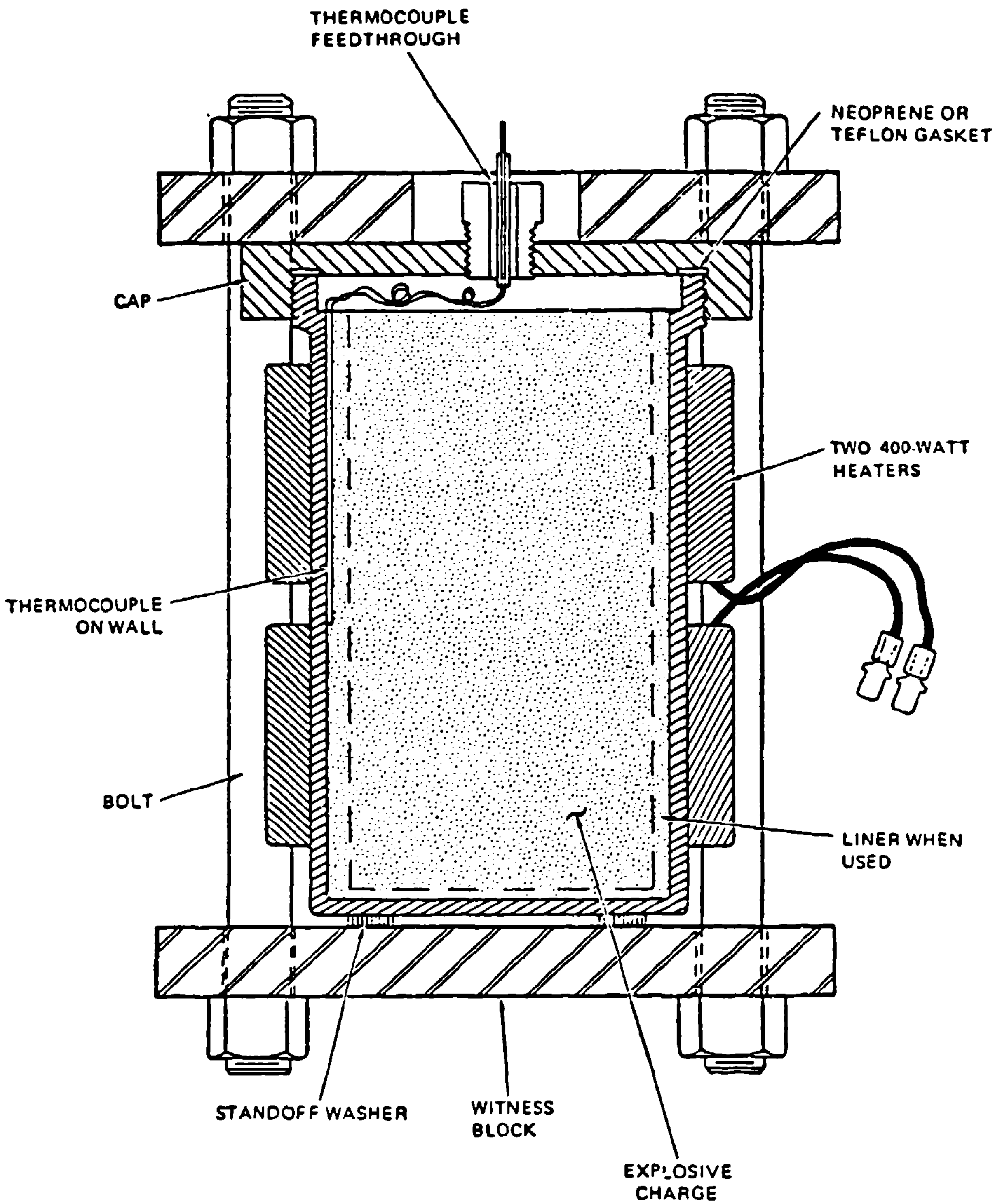


FIGURE 1. SCB Test Fixture.

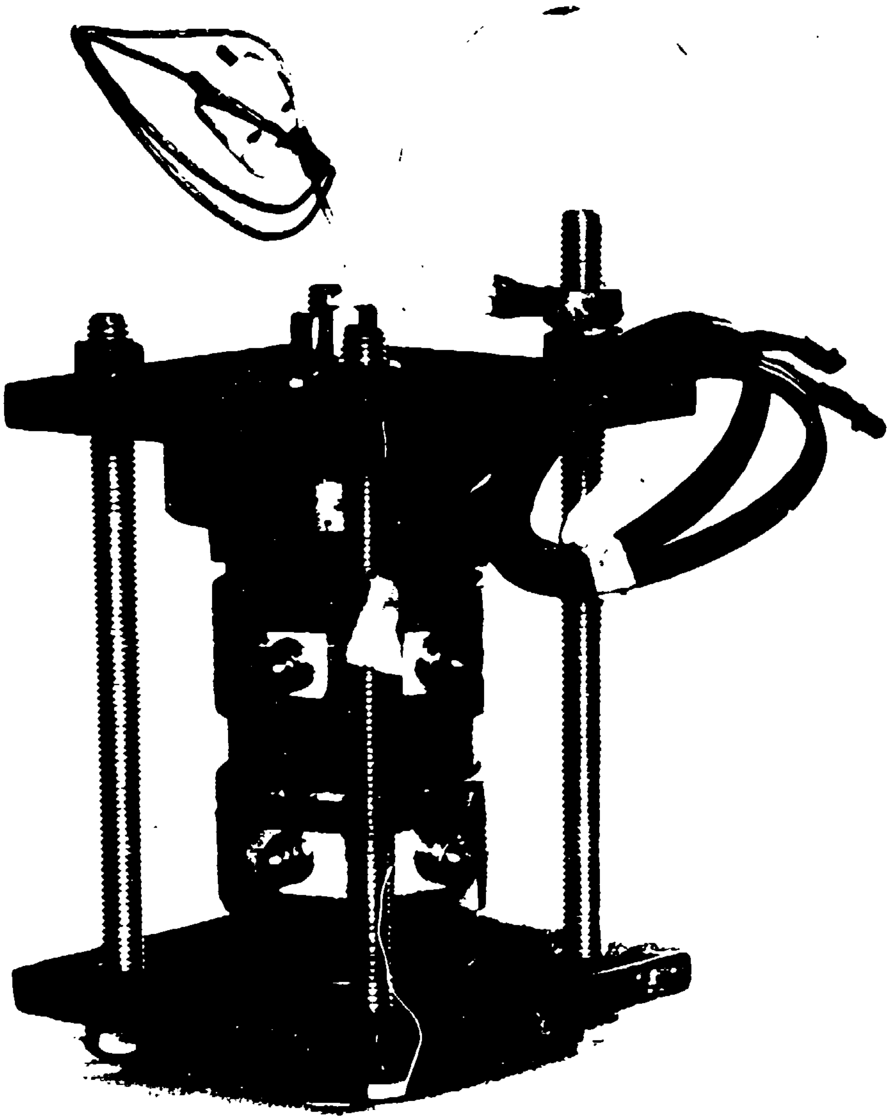
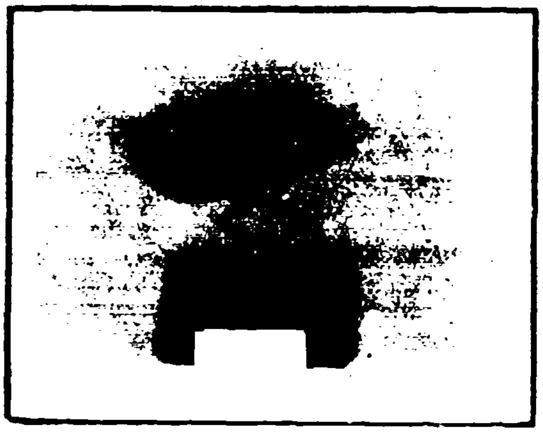
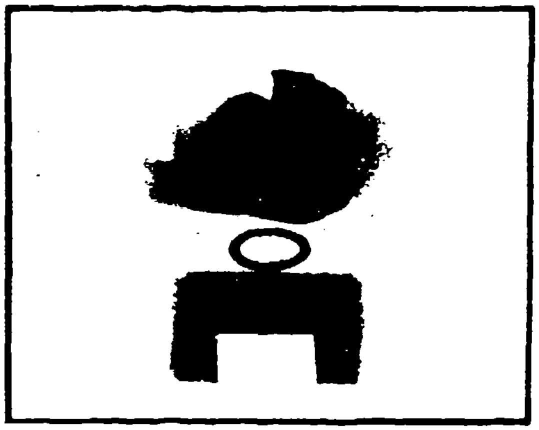


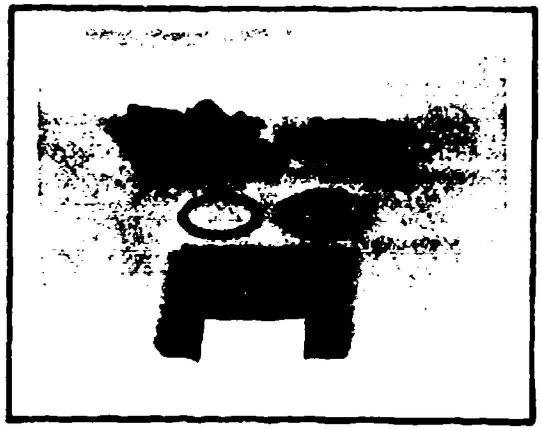
FIGURE 2. SCB Test Setup.



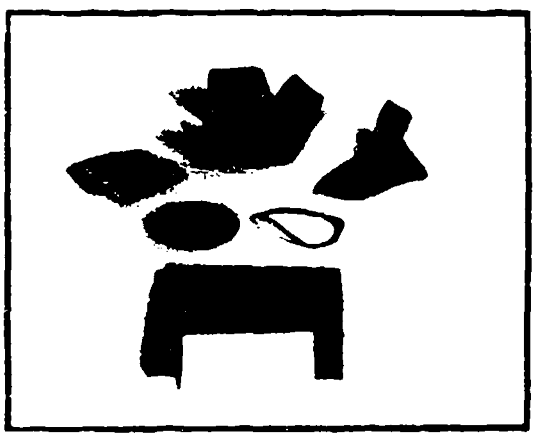
R-1 case intact but bulged, no plate dent, burning.



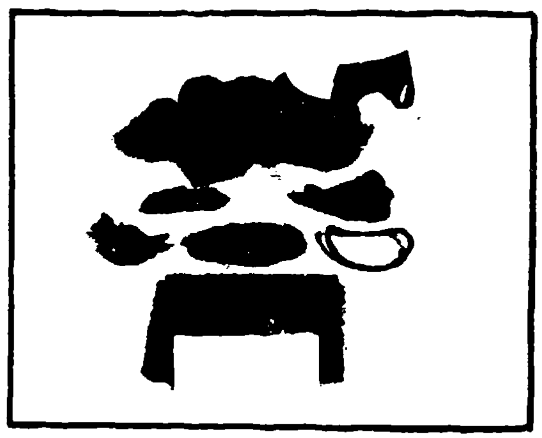
R-2 case open, 1 piece, plate dent 0.05 , deflagration.



R-3 case, 2 pieces, plate dent 0.05 , deflagration.

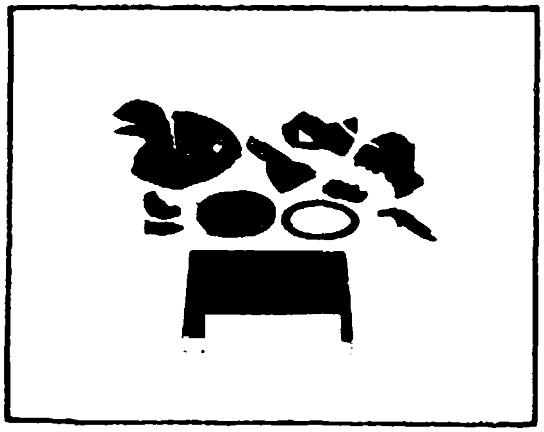


R-4 case, 3/4 pieces, plate dent 0.05 , deflagration.

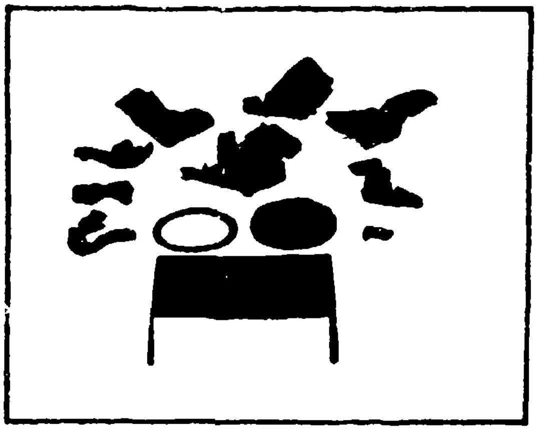


R-5 case, 5+ large pieces, plate dent 0.05 , explosion.

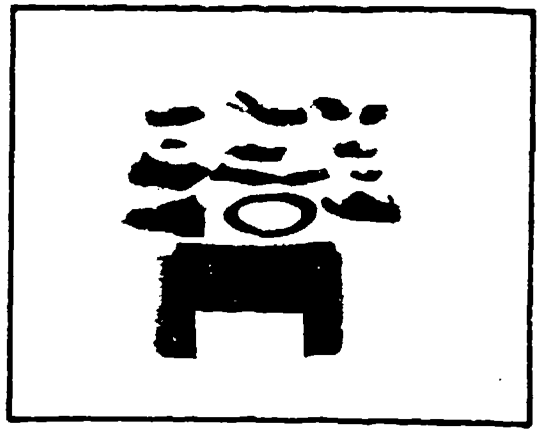
FIGURE 3. Analyzed Reactions.



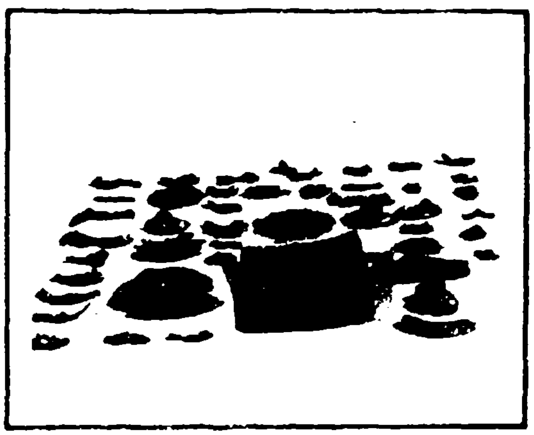
R-6 case, many large pieces, plate dent 0.05 , explosion.



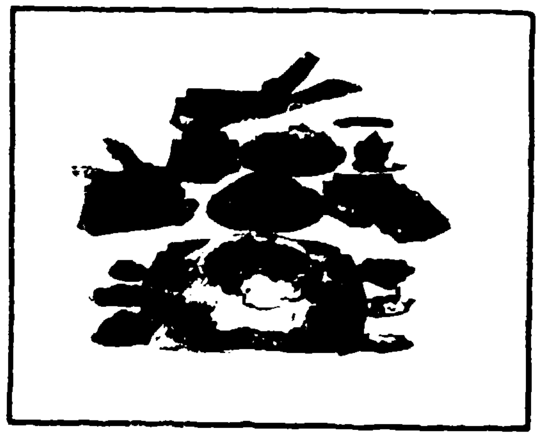
R-7 case, many large/small pieces, plate dent 0.2 , explosion.



R-8 case, many large/small pieces, plate dent 0.2 no punch, explosion.



R-9 case, many small pieces, plate almost punched, partial detonation.



R-10 case, many small pieces, plate punched, detonation.

FIGURE 3. Analyzed Reactions. (Contd)

BLAST PRESSURE MEASUREMENTS FOR
THE FULL-SCALE GRAVEL GERTIE TEST

by

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28-30 August 1984

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Mr. V. E. Kerr, Sandia National Laboratories - NTS
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Norma Sandoval for digitizing and plotting the data;
Jim Hokanson for developing the data processing software used on this test and consultation during the data reduction process.

I. INTRODUCTION

In the 1950's, the AEC designed a special type of protective structure, colloquially named "Gravel Gertie," for safe containment of blast effects and attenuation of radiation effects in the event of accidental detonation of an explosive-plutonium assembly within its operating bay. A full-scale prototype structure was built and tested at Nevada Test Site (Ref. 1) in the late 1950's. Test results indicated that the structure, when closed, would contain an internal explosion of 550 pounds of an (unknown) high explosive and that there would be no external plutonium contamination. There apparently was some attempt to measure blast pressures on the interior wall surfaces of the Gravel Gertie operating bay, but there were no reported time histories, and the reported peak overpressures are very doubtful. There was no mention of external blast caused by the explosion within the closed structure.

Following the tests of the prototype structure, a number of containment structures using this concept were designed and built at several Atomic Energy Commission facilities. The general size and configuration of the operating bay, with its cylindrical shape and cable-supported thick gravel roof was retained, but the attached corridor and operating bays were of much different configuration and had much larger volume than the corrugated steel culvert assembly in the prototype tested.

Recently, the Department of Energy has planned to design and build more structures for the same use as the existing Gravel Gertie structures. But, the limited data on aerosol escape and blast loading from the earlier tests raised questions regarding the ability of the structures to function as intended in the event of an accidental explosion in the operating bay. Therefore, the prototype structure at Nevada Test Site was unearthed and inspected in 1982 to determine whether it was still structurally sound enough for refurbishing for another test. It was, and the structure was repaired and rebuilt in a configuration somewhat similar to the original, with a buried steel culvert arrangement which duplicated the volume of corridor and staging bays of existing Gravel Gerties, but not the geometry.

Figure 1 shows the cylindrical, reinforced concrete bay of the original prototype structure with the new steel culverts. Figure 2 shows the support cables and wire mesh for the gravel roof. A plan view will be shown later in the discussion of the blast instrumentation.

The testing of the refurbuished prototype structure was planned and conducted in 1982 by the Sandia National Laboratories. Southwest Research Institute (SwRI) was contracted to make internal and external blast measurements through Mason & Hanger-Silas Mason, Inc., Pantex Plant, Amarillo, TX. Figure 3 shows the Gravel Gertie structure almost completed. It was at this stage of the construction that SwRI arrived at the Nevada Test Site to implement the blast pressure measurement systems. Figure 4 shows the Gravel Gertie structure just prior to time zero. In this paper we describe the transducer locations and installation, the instrumentation system, and the test results. The results are discussed and compared with pretest predictions used to range the instrumentation.

II. PRESSURE TRANSDUCER INSTALLATION

Two types of transient pressure sensing transducers were employed in the blast measurements. Most of the transducers were fast-response piezoelectric gages for measuring time histories of initial and later reflected blast waves from the explosive detonation. These gages were all manufactured by PCB Corp., and were of various models, as shown in Table 1. The rest of the transducers were of somewhat lower frequency response, but were of the piezoresistive type with static pressure response capability for recording the relatively long duration gas pressures. One of these gages was made by Kulite, and the rest by Endevco. Model numbers are given in Table 1. Figure 5 shows a plan view of the Gravel Gertie structure with all the internal transducer locations identified. A similar layout showing the nine external transducer locations appears in Figure 6. As noted in Table 1, blast gages B1 through B9 were external blast sensors mounted along two lines radiating from the center of the cylindrical operating bay, and along a third line on the axis of the blast door tunnel.

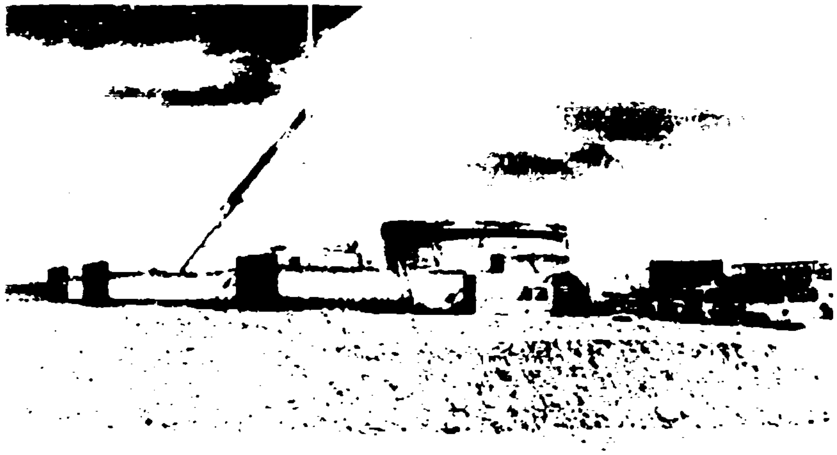


Figure 1. Refurbishing of the Gravel Gertie Structure

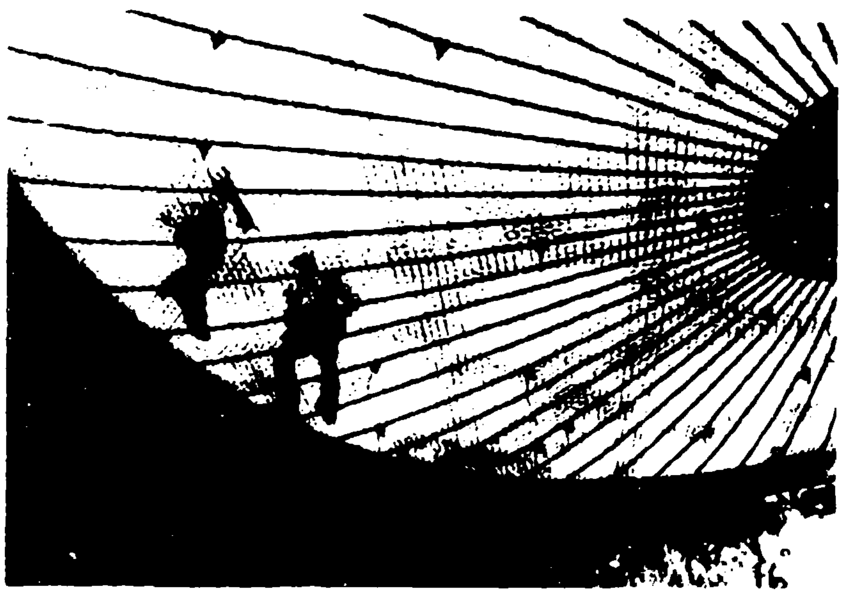


Figure 2. Support Structure for Gravel Roof

Figure 3. Earth Fill Around Gravel Gertie

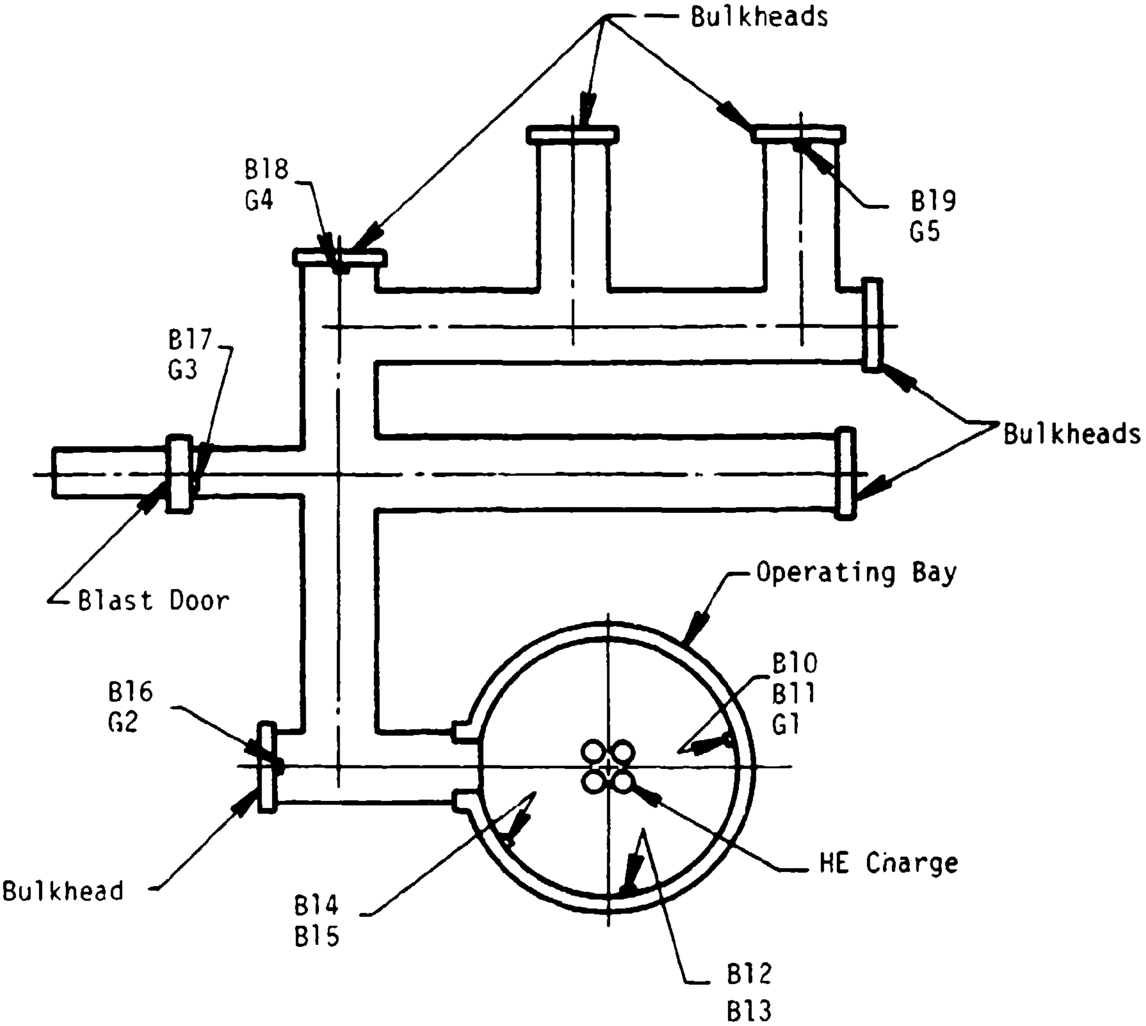
Figure 4. Gravel Gertie Structure Just Prior to Test

TABLE 1.

Gage Types and Locations

Gage No.	Manufacturer & Model No.	Purpose
B1	PCB 102M94	Side-on external blast along a radial line from center of operating bay.
B2	PCB 102M94	
B3	PCB 102A05	
B4	PCB 102A05	Side-on external blast along a second radial line, 90° from first line.
B5	PCB 102M94	
B6	PCB 102M94	
B7	PCB 102M94	Side-on external blast in line with blast door. Distances measured from blast door.
B8	PCB 102M94	
B9	PCB 102A05	
B10	PCB 102A03	Flush-mounted blast gages in operating bay. These are of different elevations and azimuths, with two near the entrance opening.
B11	PCB 102A	
B12	PCB 102A03	
B13	PCB 102A	
B14	PCB 102A03	
B15	PCB 102A	
B16	PCB 102A03	Bulkhead and blast door blast loads. Flush-mounted near center of door and bulkheads.
B17	PCB 102A	
B18	PCB 102A	
B19	PCB 102A	
G1	Kulite HKS-375	High-range gas gage in operating bay.
G2	Endevco 8511A	Medium range gas gages, mounted beside B16-B19.
G3	Endevco 8510A	
G4	Endevco 8510A	
G5	Endevco 8510A	

Note: "B" numbers were blast transducers, "G" numbers were gas transducers. See Figures 5 and 6 for locations.



Notes:
1. Transducers B10, B12, B14, and G1 were located 7 ft above floor.
2. Transducers B11, B13, and B15 were located 15 ft above floor.
3. Transducers B16, B18, B19, G2, G4, and G5 were located 5 ft above floor, centered on bulkhead.
4. Transducers B17, and G3 were located 4 ft above floor, adjacent to blast door.

Figure 5. Plan View of Gravel Gertie Structure with Internal Transducer Locations

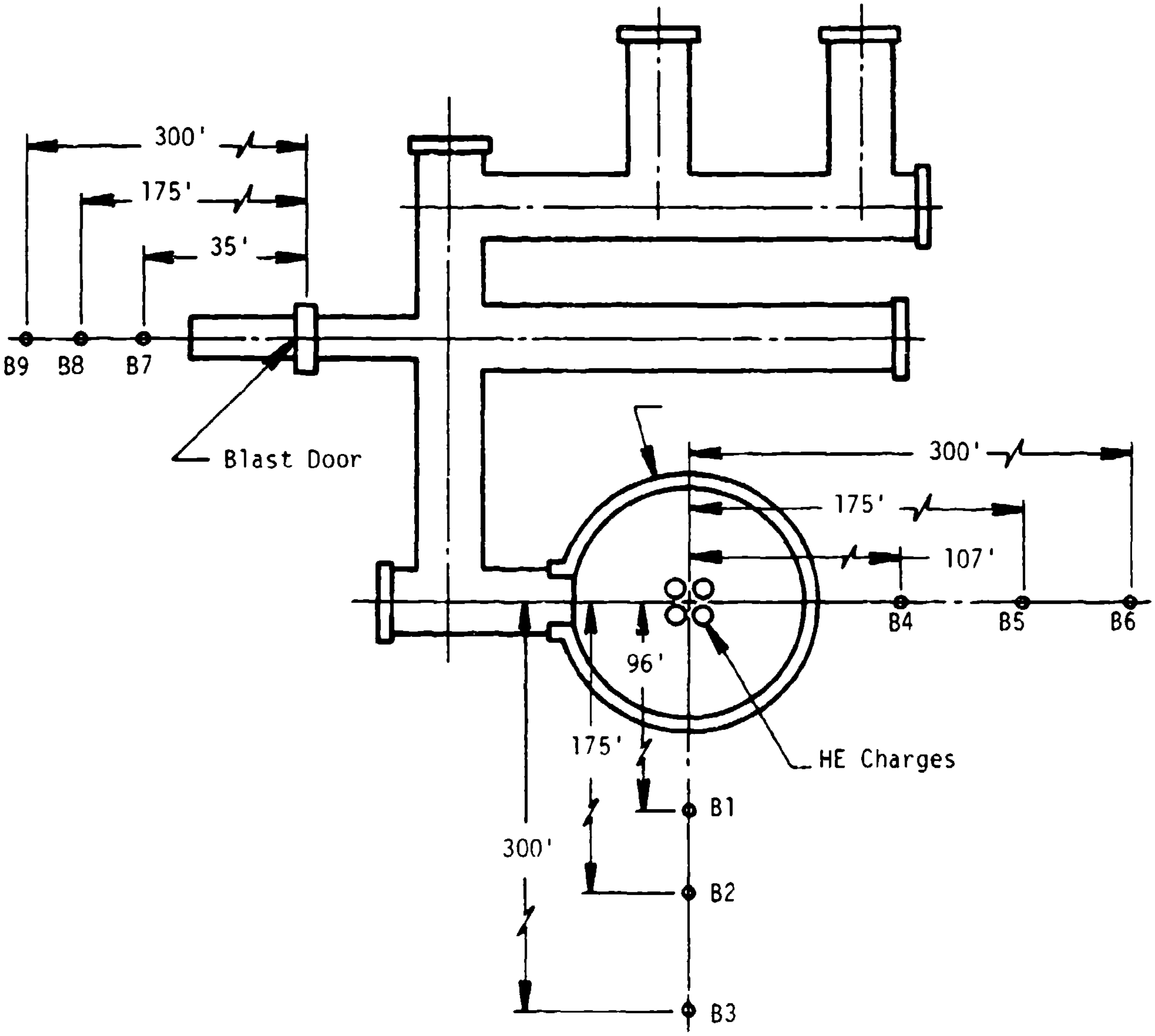


Figure 6. External Blast Pressure Transducer Locations

All internal pressure gages were flush-mounted in thick, circular steel adapter plates of 13-inch diameter which were in turn attached with machine screws to short 12 inch, schedule 80 pipe sections, 5 inches deep. Steel, 2-inch pipes attached to the larger pipe sections provided protection for the transducer cables. These assemblies were welded to steel bulkheads (Figure 7), and attached with anchor bolts to the concrete interior surface of the operating bay (Figure 8). The cable conduits were supported by grout in the operating bay to prevent premature motion and possible cable failure. At one location in the operating bay and all four locations on bulkheads, a blast gage and a gas gage were mounted side-by-side near the center of the circular adapter plate. At the remaining five locations in the operating bay, a single blast transducer was centered in the circular adapter plate. Transducer cable conduits were attached to horizontal conduits beneath a new concrete floor cast in the structure, and lead out to external junction boxes.

To avoid small perturbations in reflected shock pressures, a complete flush mount for all internal blast transducers would have been desirable. However, because the structure was almost completed when SwRI was involved in the program the mounts and adapters described were the best compromise we could effect in adapting to the existing structure. The mounting hardware used should have caused only minor perturbations in reflected shock time histories. Gas pressure records should be unaffected.

III. INSTRUMENTATION SYSTEM

The instrumentation system used for these transient pressure measurements was the same as that used for blast and gas pressure measurements in the eighth-scale model of the Pantex Damaged Weapons Facility. The system is well described in reports of testing of that model (see Ref. 2), but we repeat its salient features here. Our amplifying and recording equipment was housed in and operated from the Sandia arming and firing trailer, B11.

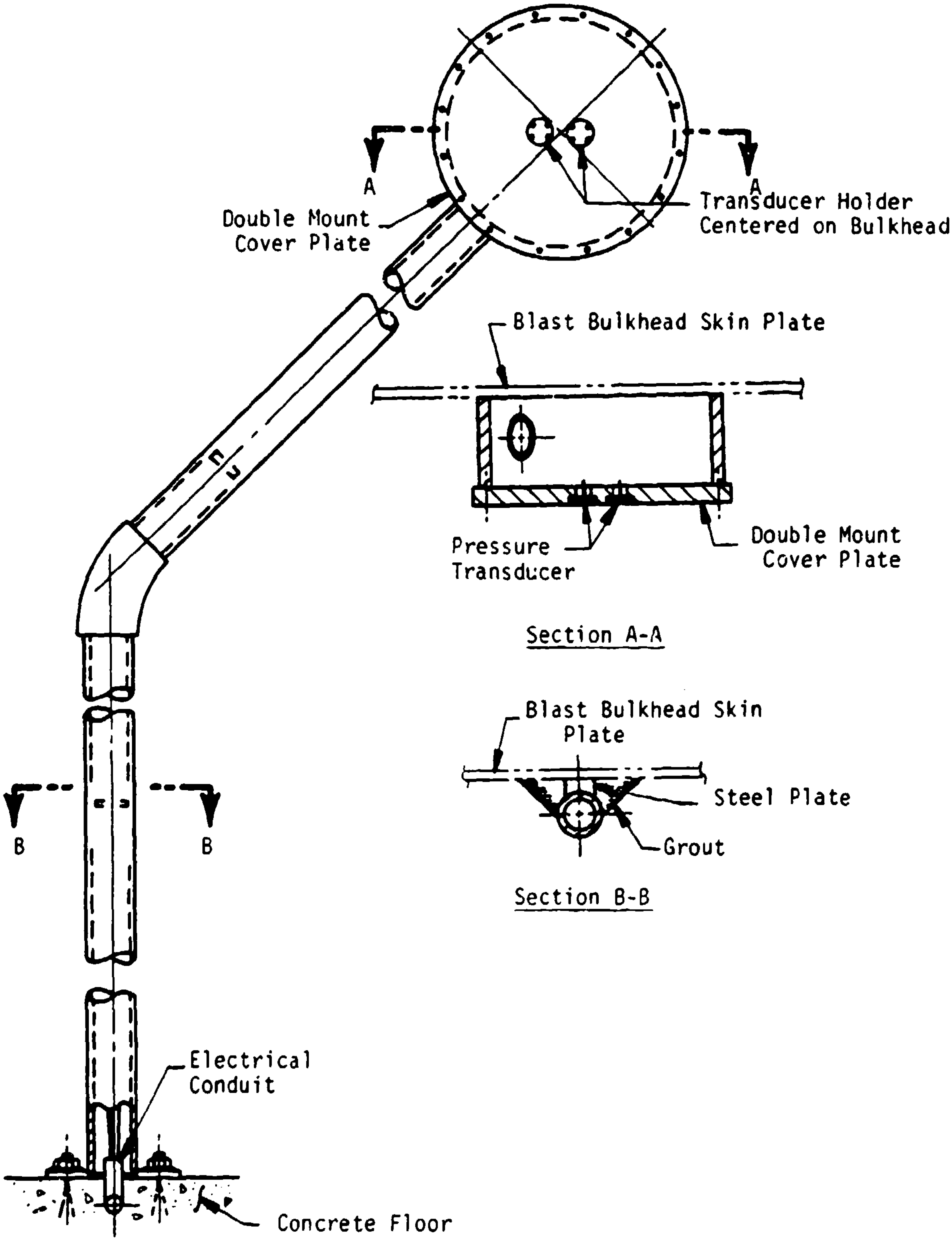


Figure 7. Typical Pressure Transducer Installation on Bulkhead

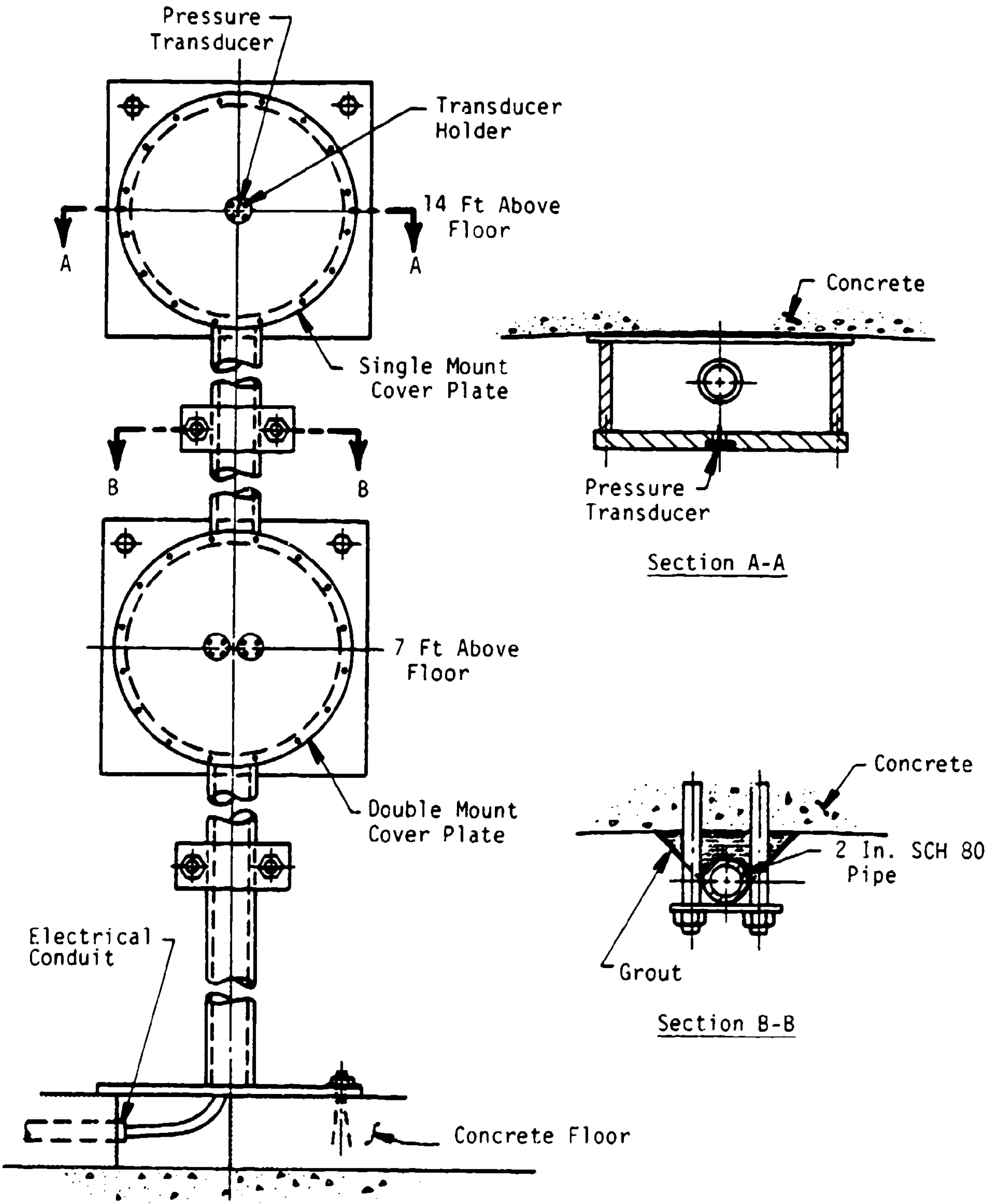


Figure 8. Typical Pressure Transducer Installation in Operating Bay

Internal and External Blast Pressures

Each PCB transducer utilizes an acceleration-compensated, quartz (piezoelectric) pressure sensing element coupled to a miniature source follower within the body of the transducer. This micro-electronic amplifier converts the high impedance output of the quartz element into a low impedance, high level output signal. Regardless of range or configuration, all of these transducers have a rise-time capability of one microsecond. Each transducer was connected to an FM magnetic tape recorder as shown in Figure 9. The system frequency response was 0.08 to 180,000 Hz (-3 db), sufficiently high to record the fast rise times of blast waves with good fidelity.

Internal Gas Pressure

Measurement of the gas pressure in the operating bay and the bulkheads were made using Kulite and Endevco transducers. These sensors use a four-arm Wheatstone bridge diffused into a silicon diaphragm. These piezoresistive transducers feature greater than 100 mV full-scale output voltage, high resonant frequency, good linearity, and static pressure response. These transducers are capable of recording blast pressures. However, because of their static pressure response capability, they were set up to sense the gas pressure rise, while at the same time providing a reasonable survival rate to the higher amplitude blast pressures.

Both types of gas pressure transducers were connected into the measurement system in a similar manner, as shown in Figure 9. The gas pressure data were also recorded on the FM magnetic tape recorder. However, the amplifiers for these transducers were set at a response frequency of 0-10,000 Hz ($\pm$1 db), more than sufficient for the gas pressure data.

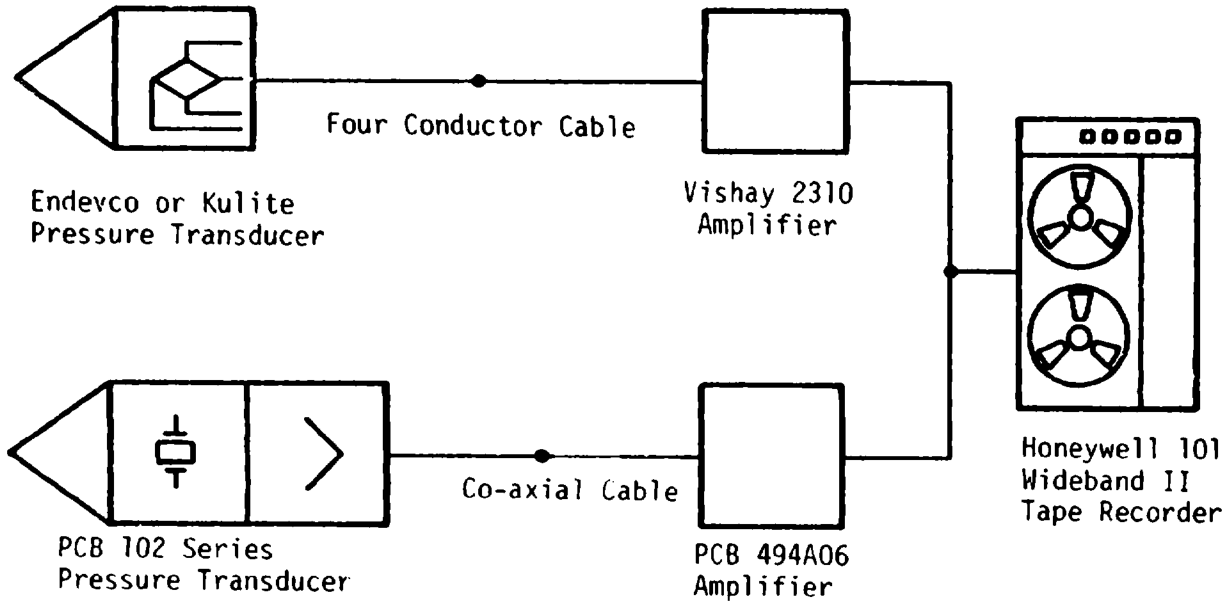


Figure 9. Blast and Gas Pressure Measurement System

Pressure Transducer Calibration

All blast and gas pressure transducers were calibrated by the manufacturer and checked by SwRI. The calibration check at SwRI was done using either a pneumatic pulse calibrator, or a hydraulic dynamic calibrator, or both, depending on the anticipated pressure range over which a particular transducer was to be used.

The pneumatic pressure calibrator generates a known step-function with a rise time of about 5 milliseconds over a pressure range of 0-150 psig. The reference transducer for this nitrogen-driven device is a precision, 12-in., bourdon tube dial gage with an accuracy of 0.1 percent of full-scale (0.15 psi). The accuracy of this Heise reference gage is checked with a deadweight tester, an NBS traceable secondary standard. The manifold of the calibrator accommodates two transducers mounted symmetrically such that two pressure transducers can be calibrated simultaneously. All of the blast pressure transducers located outside of the high bay and all the gas pressure gages were calibrated using the pneumatic pulse calibrator.

The blast pressure transducers which were to be used inside the Gravel Gertie were also checked using the hydraulic dynamic calibrator. This calibrator consists of a triangular chamber filled with oil. Two symmetric ports are provided for flush mounting a reference and a test transducer. The pressure pulse is generated by dropping a weight down a guide tube onto a piston which extends through the top of the chamber. This device produces a half-sine, positive pressure pulse with peak amplitudes from 100 psi to about 14,500 psi, and rise times of 1 to 2 milliseconds. Different weights and drop heights are used to vary the peak amplitudes. The reference transducer used was first calibrated at 10% and 100% of its range using a dead weight hydraulic tester which has an NBS traceable calibration. The reference transducer, with a 10,000 psi range, is used to determine the pressure input to the test transducer.

Playback Electronics

The test data were played back and digitized using the system shown in Figure 10. Up to four channels of data were played back at one time through the analog filters into a Biomation Model 1015 four-channel transient recorder. This recorder digitizes the incoming analog signals at sample intervals of 0.01 milliseconds or greater. Since this unit has four separate analog-to-digital (A/D) converters, the samples for each of the four data channels are time correlated. The maximum number of samples which can be taken is 1024 per channel. The A/D units are 10 bit units, which means that the analog signals are digitized with a resolution of one part in 1024 of the full-scale voltage setting. The minimum full-scale voltage setting is 0.1 volts.

Once the test data (or calibration waveforms) are properly formatted in digital form, a DEC 11/23 computer extracts the data from the transient recorder memory through the CAMAC data buss and stores them on an 8-in. flexible diskette. A graphics terminal is used to display each data trace for verification. The data stored on the diskettes were then read into a DEC 11/70 minicomputer; then, the appropriate data processing plots were prepared using a Printronix 300 printer/plotter.

IV. TEST RESULTS

The results of the Gravel Gertie test are presented in this section of the report. Three types of pressue measurements were made by SwRI: internal reflected blast pressure, internal quasi-static gas pressure, and external side-on overpressure.

Blast Pressure

Ten piezoelectric transducers (B10 through B19) were installed within the structure specifically to measure the reflected blast pressures. Therefore, the amplifier and tape recorder settings were set up to record the

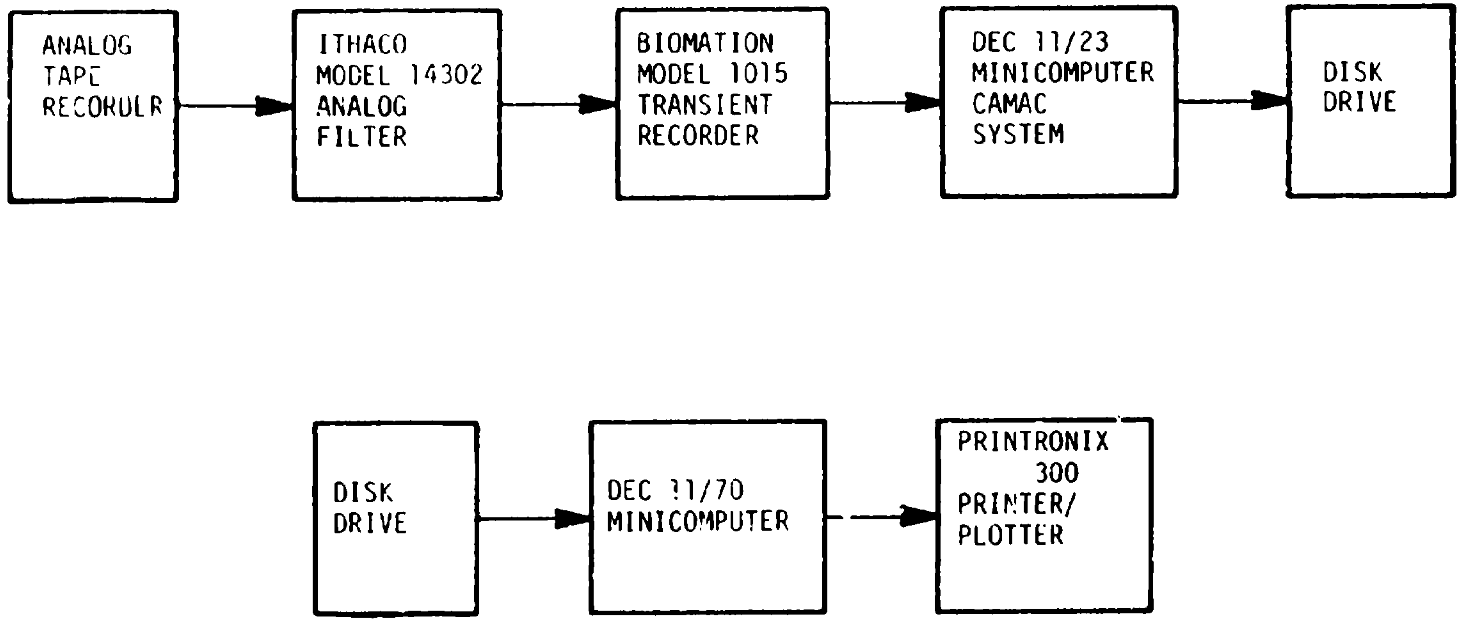


Figure 10. Test Data Playback System

estimated peak blast pressures, which in all cases (particularly, in the cylindrical operating bay) were expected to be of higher amplitude than the gas pressure that eventually developed.

As described previously, six of the blast pressure gages were installed in the operating bay, and the remaining four or three bulkheads and the blast door. To obtain the fidelity required to read an accurate peak blast pressure, the data records were digitized at the fastest sampling rate possible over the shortest time interval that included the peak pressure. However, for reporting purposes, another digitizing interval was also selected for the transducers outside the operating bay to be long enough to show zero-time as well as the peak pressure. Figure 11 is an example of two of the blast pressure-time histories recorded in the operating bay showing the initial pressure pulse only. In Figure 12, similar blast pressure traces from the transducers mounted on the blast door and on one of the bulkheads are shown. Note that these two figures show only the early part of the total pressure-time history recorded to illustrate the reflected blast waves measured.

In addition to the peak blast pressure, other blast wave data were obtained. The other blast parameters quantified were: time of arrival (t_A) of the initial shock wave at each transducer location, approximate duration (t_B) of the initial wave plus significant reflections not separated in time, and the impulse (I_B) from the initial wave and significant reflections. The blast data are summarized in Table 2. In this table, dashes indicate that that particular parameter could not be obtained from the data trace due to cable malfunctions at the beginning of the blast loading. Note that this table includes blast data obtained from a transducer (G2) set up to measure gas pressure at a station adjacent to blast transducer (B16). These blast data from a gas pressure transducer were included because channel B16 failed at blast wave arrival time. Because channel G2 had a frequency response only up to 10 kHz, the peak blast pressure is probably slightly higher than the value in the table. However, impulse data should be as accurate as any others listed.

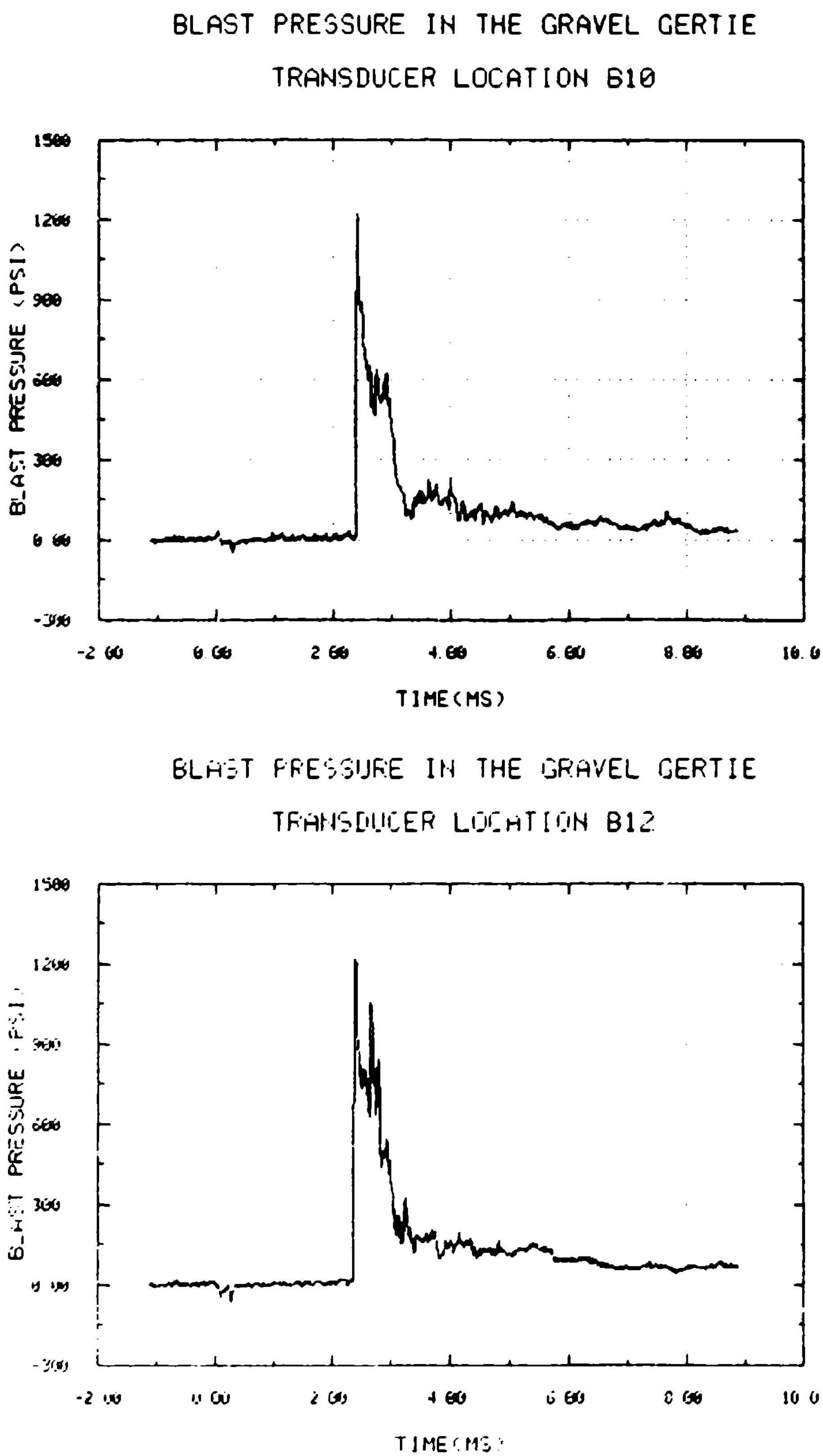
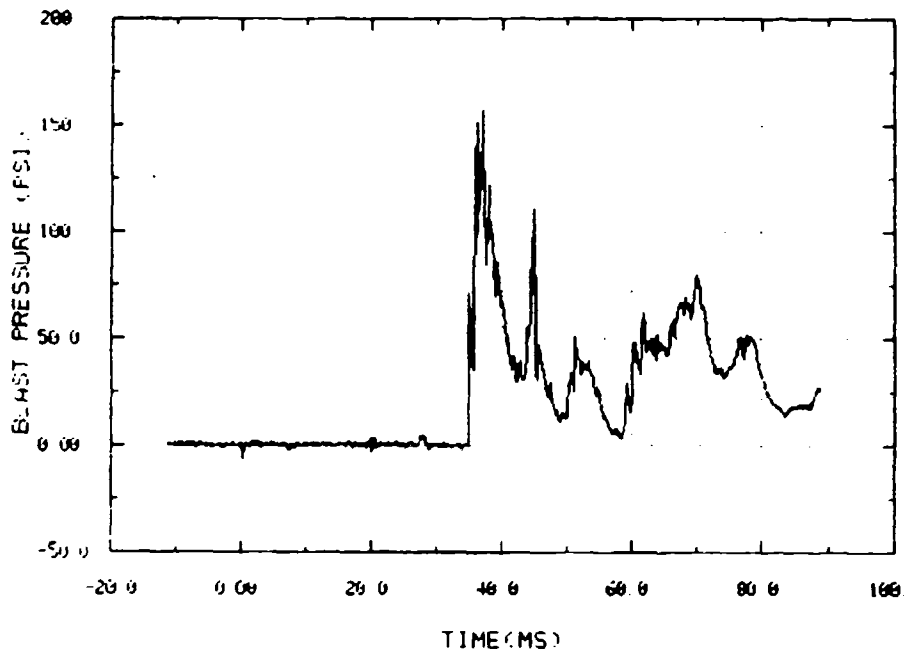


Figure 11. Examples of the Initial Reflected Pressure in Operating Bay

BLAST PRESSURE IN THE GRAVEL GERTIE

TRANSDUCER LOCATION B17



BLAST PRESSURE IN THE GRAVEL GERTIE

TRANSDUCER LOCATION B19

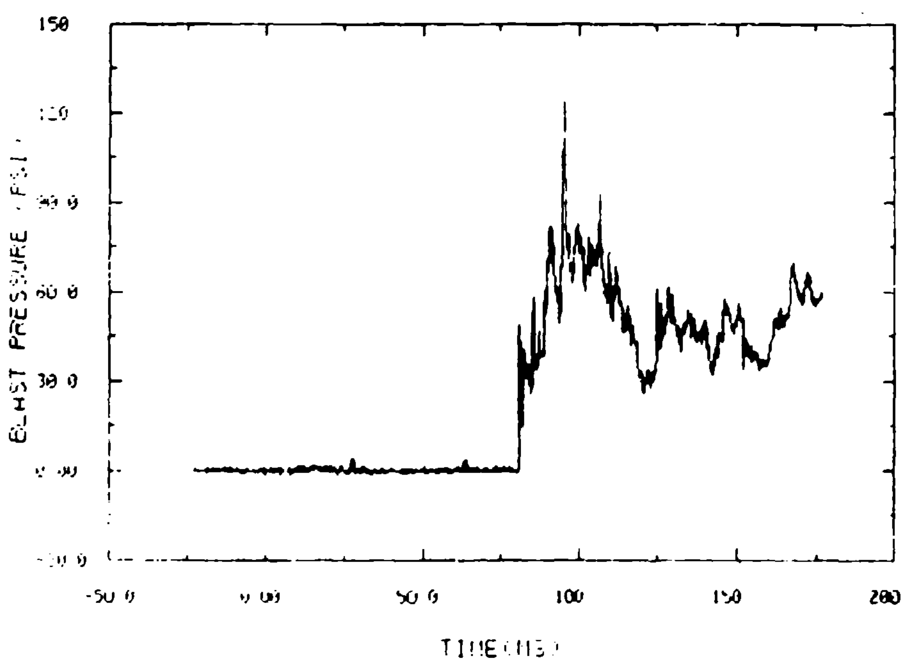


Figure 12. Reflected Pressures on Blast Door and Bulkhead

TABLE 2.

Summary of Blast Data for Gravel Gertie Test

Transducer Location	t_A (msec)	P_B (psig)	t_B (msec)	I_B (psi-sec)
B10	2.37	1,221	23.1	1.61
B11	2.55	964	23.4	2.27
B12	2.34	1,218	22.7	2.11
B13	2.64	1,202	24.2	2.00
B14	2.02	782	25.2	1.56
B15	2.15	982	25.0	2.25
B16	10.2	-	-	-
G2	10.2	>297	28.7	1.90
B17	34.7	159	74.0	1.98
B18	38.7	204	65.4	2.27
B19	80.6	124	79.1	2.64

Gas Pressure

Five piezoresistive transducers (G1-G5) were installed within the structure specifically to measure the quasi-static gas pressure rise that developed from the detonation of the four PBX 9501 explosive spheres weighing a total of 423 lb. These transducers, though capable of measuring blast pressures, were set up to record the quasi-static gas pressure, which in most cases was expected to be lower in amplitude than the peak blast pressure. Therefore, amplifier gain and frequency response settings were such that most blast pressure peaks would be clipped or slightly attenuated to obtain better resolution for the gas pressure amplitudes.

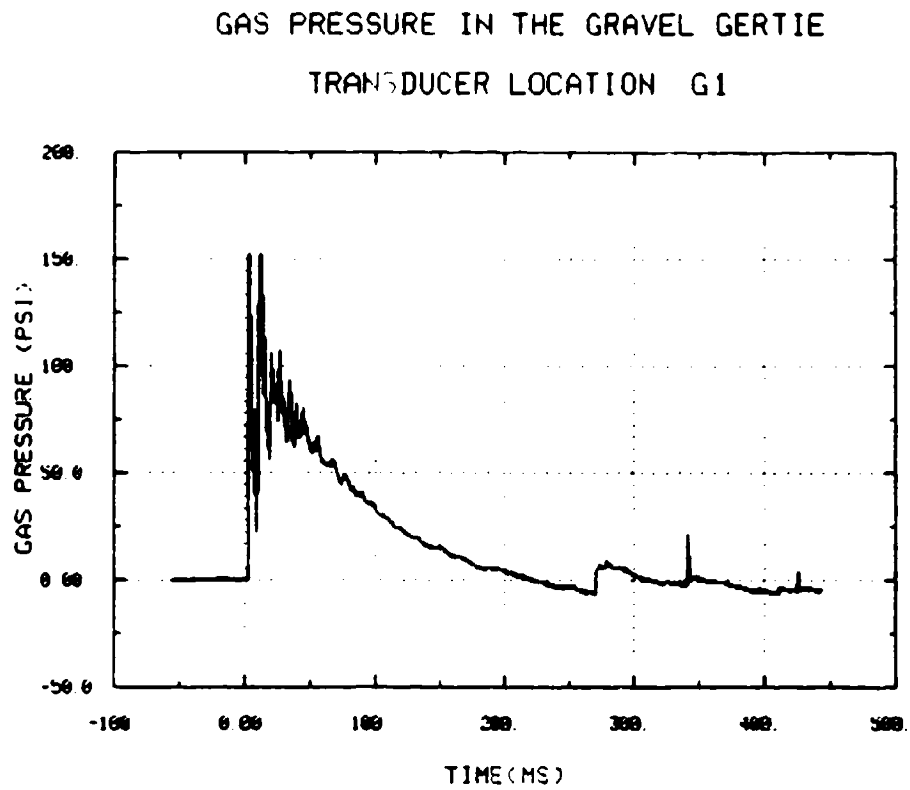
One gas pressure transducer was installed in the operating bay, one on the blast door, and one on each of three bulkheads. To be able to see the complete time history, gas pressure records were digitized at relatively long sampling rates which attenuated further any blast pressure peaks.

To obtain additional gas pressure data, the blast pressure records were also redigitized at much lower rates than were used to get the blast data. However, because gain settings were lower on the blast pressure transducers, data to noise ratios were worse on these records than on the gas transducer records. Although the piezoelectric blast gages do not have DC response, their time constant is in the order 100 seconds, long enough to obtain reasonable accurate gas pressure records. Figure 13 shows the data from the one gas pressure transducer in the cylindrical bay and from one of the blast gages digitized at a similar rate. Another example of quasi-static pressure records from both piezoresistive (gas) and piezoelectric (blast) transducers is provided in Figure 14 for the blast door transducers. In Figure 15, the data trace obtained with the gas transducer mounted on the blast door is also shown plotted using two different time scales.

Besides peak gas pressure, gas pressure duration and "impulse" were also obtained, whenever possible. The gas pressure data are summarized in Table 3. Dashes in this table indicate that the particular parameter could not be obtained from the data trace because of cable or transducer failure at the beginning or during the event, temperature drift during the decay of the gas pressure, or transducer system malfunction.

Side-On External Pressure

Nine low pressure transducers were fielded outside the Gravel Gertie to measure possible vented pressures along three radial lines. As shown in Figure 8, two of the arrays were positioned along radial lines from the center of the operating bay. The transducer locations ranged from 96 to 300 ft away from the center. The third transducer array was in line with the blast door and the transducers positioned 35 to 300 ft away from the door.



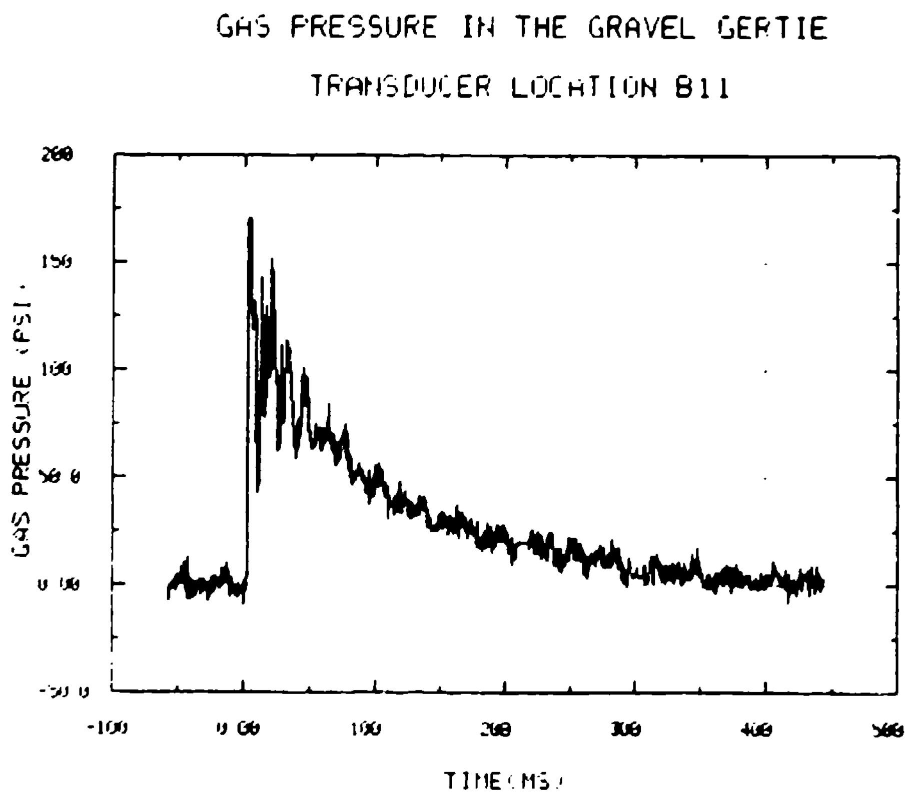
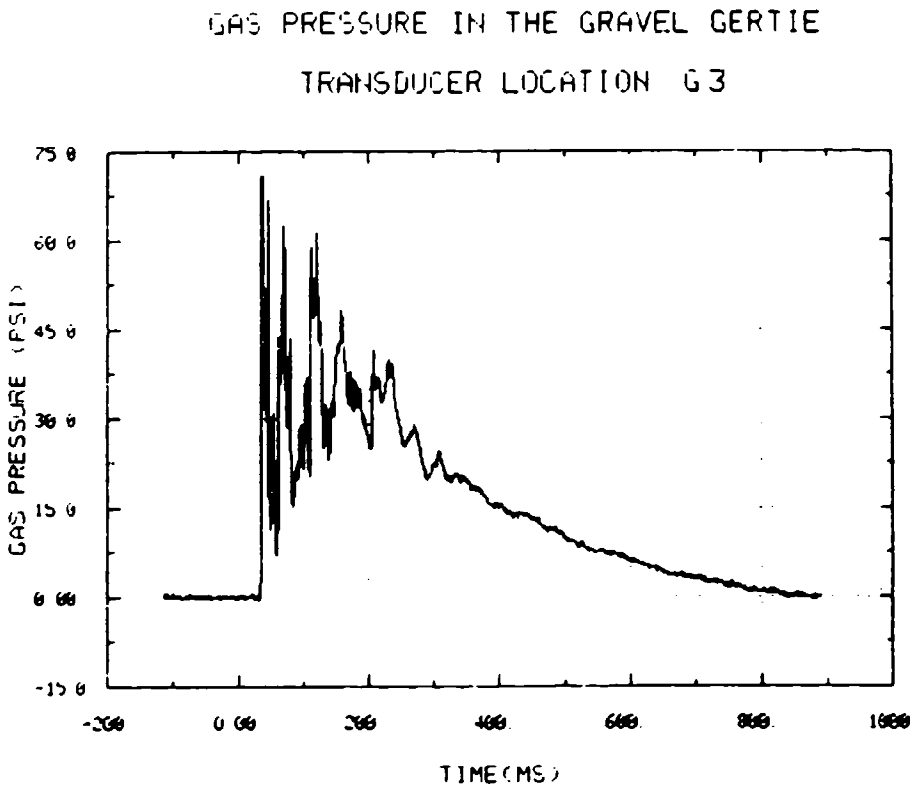


Figure 13. Gas Pressure Records from Operating Bay



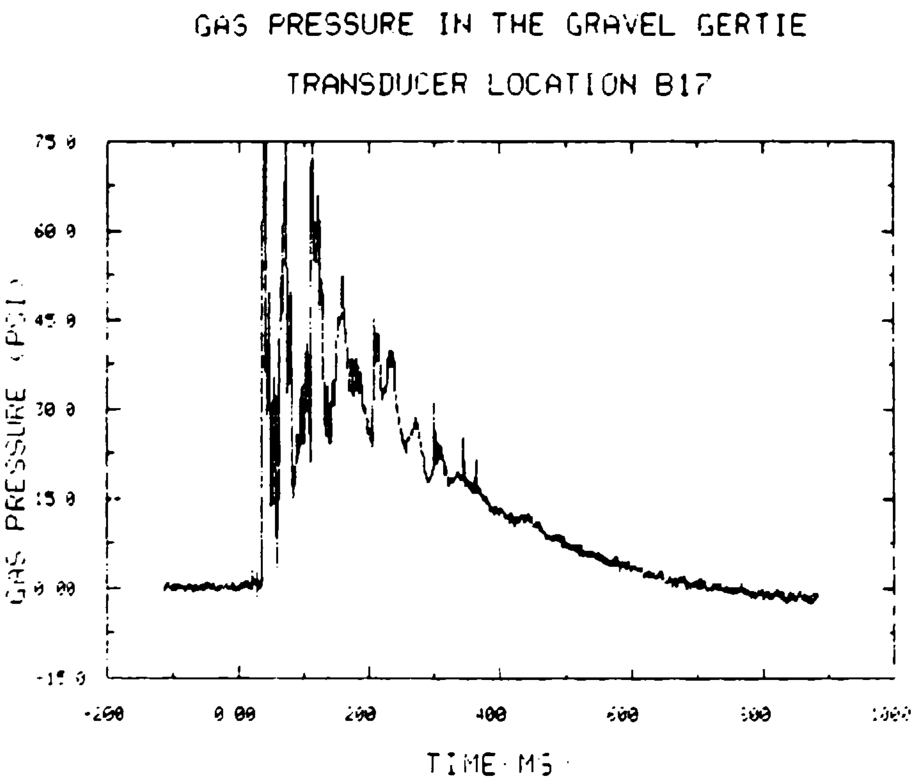
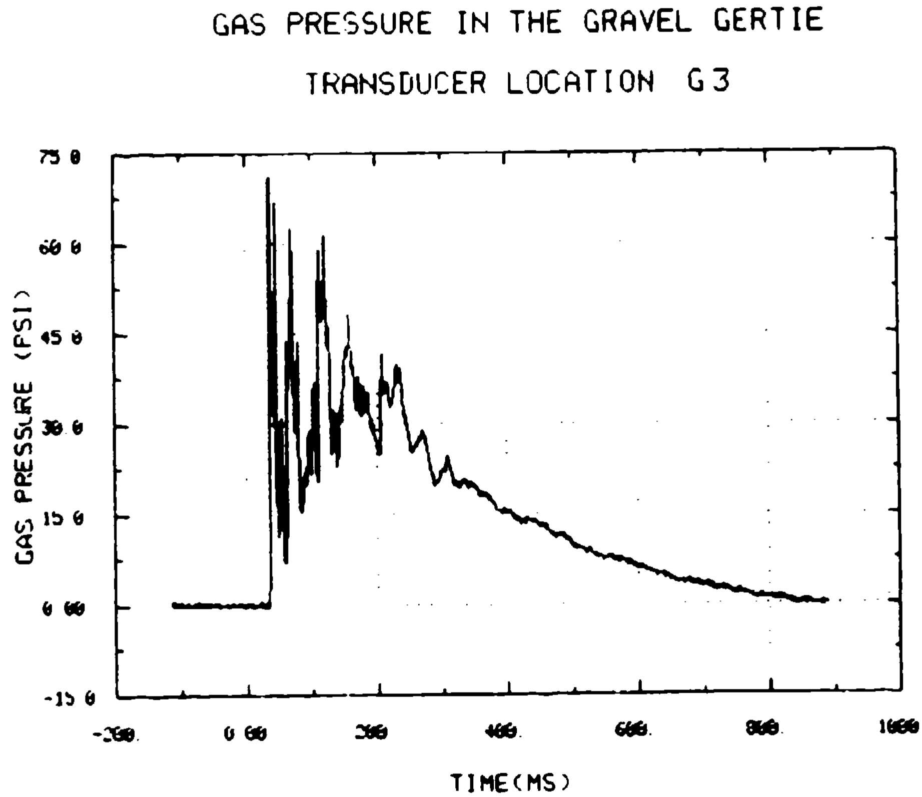


Figure 14. Gas Pressure Records from Gas and Blast Transducers on Blast Door



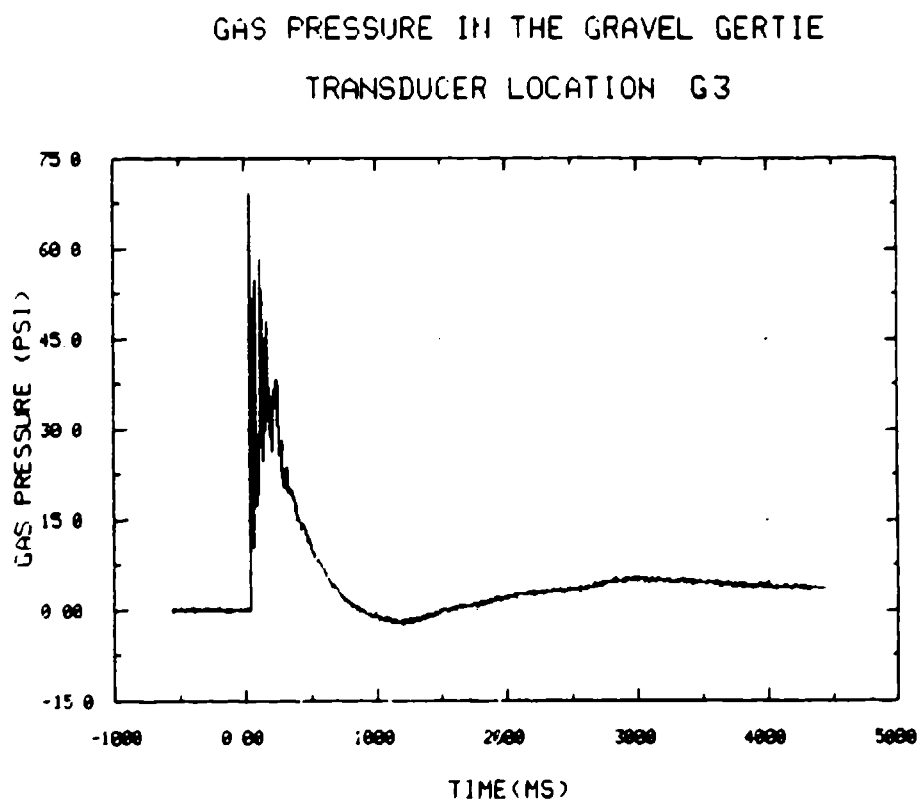


Figure 15. Blast Door Gas Pressure Measurement, Two Time Scales

TABLE 3.

Summary of Gas Pressure Data for Gravel Gertie Test

Transducer Location	P_G (psig)	t_G (sec)	I_G (psi-sec)
G1	91	-	-
B10	92	-	-
B11	94	-	-
B12	97	-	-
B13	87	-	-
B14	90	-	-
B15	-	-	-
G2	83	0.70	10.3
G3	37	0.82	13.0
B17	38	0.72	12.6
G4	40	-	-
B18	44	0.81	14.9
G5	-	-	-
B19	41	0.67	13.3

All nine data recordings indicate that, if any pressure was vented from the structure, its maximum magnitude was less than 0.02 psig at the closest gage station. Only three of the pressure records showed some slight deviation from 0 psig after the explosion. However, because the maximum amplitudes recorded represent less than 2% of the lowest useable range of the transducers used, it is extremely difficult to ascertain that any pressure data were actually recorded. Signals of the magnitude recorded (less than 2 millivolts peak) on these three channels could have been caused by the vertical ground motion induced by the explosion, crosstalk from the much higher internal blast channels, or random noise levels present in the measurement system. Since no external pressure was measured these data will not be discussed further.

V. DISCUSSION

In this section, a discussion of the test results is presented including any apparent anomolies. Wherever possible, comparisons with predicted quantities are made.

Blast Pressure

Of the ten blast pressure transducers in the Gravel Gertie, six were installed in the operating bay. Three of these six were installed at a height of 7 feet above the floor, and the other three were above the first three at a height of 14 feet. As shown in Figure 5, each pair of pressure sensors was located approximately equidistant covering half of the operating bay, starting at one side of the opening.

Because the four PBX9501 spherical charges were to be centrally located in the operating bay with their lower surfaces at a height of 2 ft above the floor, pretest blast pressure estimates for the operating bay transducers were made assuming an equivalent single charge of the same weight (423 lb) and centrally located. Assuming a TNT equivalency of 1.0, and a floor reflection factor of 2.0, the reflected pressure at locations B10, B12, and B14 was estimated using Reference 3 to be 1970 psig. The corresponding reflected impulse, multiplied by 1.75 to account for reflections, was estimated to be 1.4 psi-sec and the arrival time to be 2 milliseconds. At the slightly more distant locations B11, B13, and B15, the corresponding pretest estimates for the reflected pressure, effective impulse, and arrival time were 1180 psi, 1.1 psi-sec, and 2.7 milliseconds. These estimated peak pressures were used in setting gains and selecting ranges for the test instrumentation.

The data presented in Table 2 show that the peak pressures measured at locations B10, B12, B14 averaged 1,074 psi (with an estimate of the standard error of ±19%) and those at locations B11, B13, and B15 averaged 1,049 psi (±10%). The measurements at the lower (nearer) locations averaged slightly higher pressure than those at the higher locations, as was expected.

However, the difference is not as great as had been estimated using the single charge approximation. Furthermore, both measured averages were of lower amplitude than had been estimated.

The difference between the pretest estimates and the measured reflected pressures is due to a number of factors. Probably the greatest part of the difference is due to the geometry of the actual "charge." Its geometry is probably best approximated by a pancake rather than by a sphere. Such a pancake charge would have directional effects, with higher pressures being generated towards the floor and roof and less towards the wall of the operating bay. The fact that the four-charge array was initiated at the bottom rather than at the center also would probably reduce pressures at the wall.

In estimating the blast parameters, a reflection factor of 2.0 was assumed. If some cratering occurred on the floor, a lower reflection factor would be more realistic. For example, if we had assumed a reflection factor of 1.5, the peak reflected pressures estimated would have been 1500 psi and 980 psi, much closer to the measured values. Thus a combination of charge geometry effects and lower reflection factor would account for most of the differences between estimated and measured blast pressures. Note, however, that for the purpose of setting up the measurement systems, the peak pressure estimates were adequately accurate and provided some conservatism so that no data were lost due to lack of dynamic range.

The time of arrival data (t_A) for the six blast gages are generally self-consistent and close to the estimated values. The average arrival time for the three lower transducers was 2.24 msec (±7%) as compared to the estimated values of 2.0 msec. The average for the three higher transducers was 2.45 msec (±9%) as compared to the estimated value of 2.7 msec. The slight differences in the measured arrival times at one location in the bay versus a similar location at another station, as well as between measured and estimated times, are probably due to the same factors already discussed for the peak pressures. In addition, the accuracy with which the charge array was actually positioned in the operating bay will have a corresponding effect on the arrival times. Finally, whether a transducer was positioned directly opposite one of the four charges or in between charges would result in some time differences.

The duration (t_B) and impulse (I_B) data listed in Table 2 are more arbitrary than the peak pressure and arrival time data because they depend on the interpretation of the analyst. In this test, the duration was taken to include the initial wave and two subsequent major reflections or a reasonable equivalent time if reflections were not well defined. For the six transducers in the operating bay, the average duration of 23.9 msec (±4%) was essentially the value read for all cases. The resulting average impulse for all six pressure-time records was computed to be 1.97 psi-sec (±14%). This value is larger than the impulse of 1.4 psi-sec estimated using the 1.75 multiplying factor for the lower gages, and also larger than the 1.1 psi-sec for the higher gages. For this test it appears that multiplying the predicted reflected impulse by a factor more like 2.5 to account for reflections would better compare with the data as they were analyzed.

The other four blast transducers (B16-B19) were installed outside the operating bay on three bulkheads and the blast door (see Figure 5). For these transducer locations, estimating blast pressure was more difficult. To obtain some idea of what pressure magnitudes to expect, data were taken from References 4 and 5 to follow the progress of a blast wave out of the operating bay as it travelled through the various tunnels. Though these procedures do not provide accurate estimates, they did yield very conservative estimates to assist in setting up the instrumentation gains.

Except for arrival time, no other data were obtained for channel B16. The data trace indicates an intermittent cable opening for this channel. However, reasonably accurate blast data were obtainable from gas transducer G2 mounted adjacent to B16, and is included in Table 2. The time of arrival and peak pressure data for the transducers outside the operating bay are self-consistent, with relative amplitudes behaving as expected. Durations and impulse data are again subject to interpretation. The impulse for the four locations averaged 2.2 psi-sec (±13%). This value is similar to that computed for the transducers within the operating bay.

Gas Pressure

As mentioned in the previous section, gas pressure data were obtained not only from the five gas pressure transducers (G1-G5), but also from some of the blast pressure transducers.

The peak quasi-static gas pressure in the operating bay was measured by one gas gage and five of the blast transducers. The average pressure was 91.8 psig (±3%). This measured value falls between the pretest estimates of 125 psig and 75 psig. The higher estimate, used in designing the measurement systems in the operating bay, was obtained from a curve in Reference 3, using only the volume of the operating bay and assuming a TNT equivalency of 1.0 on the charge weight. The lower estimate was obtained by increasing the volume to that of the entire structure. No effort was made in either case to include the expanding volume created by the lifting roof. The lower estimate was used to select gain settings for the data channels located outside the operating bay.

Gas pressure durations and impulse data were not obtained from the transducers in the operating bay, including G5. Three of the blast channels (B12, B14, and B15) were damaged prior to the gas pressure returning to ambient. Broken cables were probably the cause since two of the mounting plates holding the transducer (B12 and B14) were found to have popped off during a post-test inspection. The other four channels did not fail. Instead, drifts due to temperature effects were apparent making it impossible to read an accurate duration and compute a realistic impulse. The gas pressure obtained from G2, located at the nearest bulkhead, was 83 psig, slightly lower than in the high-bay but higher than that measured on the blast door and the other instrumented bulkheads. A duration of 0.70 sec yielded a total impulse of 10.3 psi-sec.

All of the rest of the gas pressure measurements were similar to each other in amplitude, duration, and impulse. Therefore, they have been averaged together to obtain a pressure of 40 psig (±6%), a duration of

0.76 sec (±8%), and an impulse of 13.5 psi-sec(±7%). Only one of the gas transducers (G5) did not yield any data at all. The data trace indicated a malfunctioning sensor during the event.

The gas pressure data indicated that the quasi-static pressure generated in the operating bay peaks and then decays as the pressure vents into the tunnels and into the enlarging volume caused by the lifting roof. The flow into the tunnel system increases the pressure there, peaking at a considerably lower value except at the nearest bulkhead where it was only slightly lower. A low amplitude pressure rise was also present in the gas transducer records at about 3.0 seconds after time - zero probably due to the falling roof. An example of this late pressure pulse in the gas pressure data is shown in longer time plot in Figure 15.

In conclusion, the blast and gas pressure data obtained in the full-scale Gravel Gertie test conducted in 1982 have been used by architect-engineer firms, in conjunction with other data from model experiments such as those in Reference 6, to define the design loads for the new generation of Gravel Gertie and other blast containment facilities.

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THE FAILURE MODE OF LAYERED CONCRETE CONSTRUCTIONS DUE TO CONTACT CHARGES

by

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1. INTRODUCTION

One of the most severe loading modes of concrete slabs is the loading due to contact charges. To increase the resistance of the structure a layered concrete construction is applied. The behaviour of these layered concrete construction loaded by a contact charge has been investigated in a theoretical and experimental study.
In the experimental part of the study concrete slabs and concrete sandwich constructions with various intermediate layers such as reinforced concrete, lightweight concrete with polystyrene pellets, polystyrene pellets sec, sand and air were loaded by a contact charge. The results of tests with solid reinforced concrete slabs were used as a reference.
This study has proven that the failure mode of the loaded slab determines the behaviour of the whole construction. This paper describes the failure process and failure mode of the loaded slab, the way this failure mode governs the loading of the other parts of the construction and the failure mode of the whole construction.
The description accounts for the experimental test results and makes it possible to give some design rules for layered constructions.

2. THE FAILURE MODE OF A SOLID CONCRETE SLAB

By the detonation of the contact charge the temperature and the pressure increase to such a high level that in the direct vicinity of the charge the concrete melts and is completely crushed. Because of the high pressure the strength of the material is of little or no significance. When the pressure wave expands the pressure in the slab decreases with increasing distance to the charge and the strength of the material becomes more and more important. The shock wave generated by the detonation expands, the overpressure decreases and the shape of the wave changes continuously until the overpressure reaches the linear elastic stress level.

In the concrete slab the material is loaded by the expanding pressure wave. The failure of the concrete material is determined by the stress level and by the shape of the pressure wave and these two are dependent on the stress-strain behaviour of the concrete. Because of this it is necessary to give a description of the stress-strain behaviour of concrete.

2.1. The stress-strain relation for high stress levels

Concrete is a composed material of aggregate particles embedded in a cement matrix. With increasing pressure first the cement matrix is crushed and the internal cohesion of the material decreases and the deformation increases. When the matrix is fully crushed the aggregate particles are loaded directly and the stiffness increases. Figure 1 gives the stress-strain relation of concrete for hydrostatic pressure and volumetric strain. This relationship governs the wave velocity (c) and the profile of the pressure wave (Figure 1).

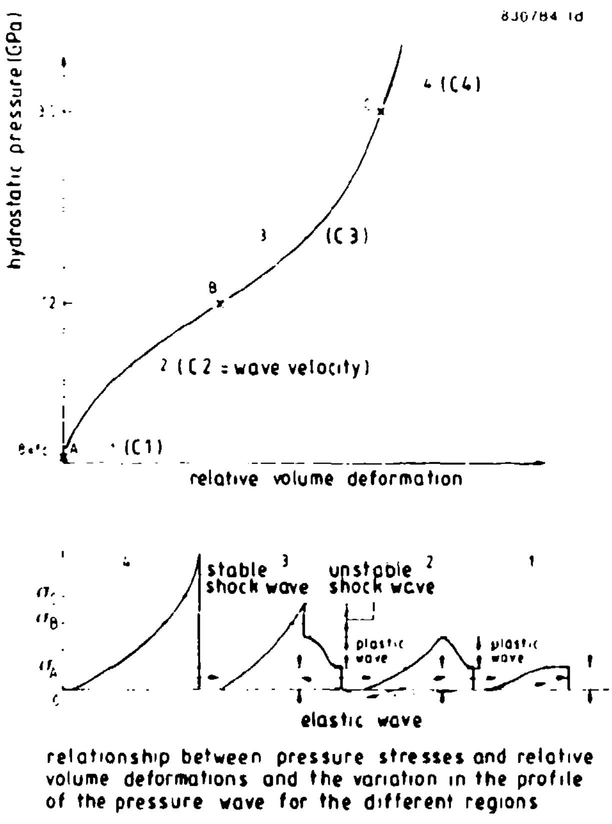


Figure 1.

Under the conditions of an instantaneously increasing pressure concrete starts loosing its internal strength at a stress level of about eight to ten times the static compression strength (f'_c).

First the cement matrix fails. This point is marked in Figure 1 with "A". In the region A-B the internal strength decreases more and more. At point B the cement matrix is completely crushed and the loose material is totally compacted. For stress levels beyond σ_b the material of the aggregates is loaded directly and finally this material is crushed too. At point C the stiffness exceeds the stiffness of the elastic region for stresses lower than σ_a.

2.2. The initiated stress wave due to the contact charge.

The stresses at the interface of explosive gases and concrete are about 15 to 20 GPa. Immediately after the explosion a stress wave with the profile of region 3 (cf Figure 1) is initiated.

The overpressure rapidly decreases and the shape of the stress wave changes to the profile of region 2.

This means that first of all the concrete is loaded by the precursor, the elastic wave, with a stress level of about 8 to 10 f_c'. After this wave front the concrete is crushed and the stress level increases. The velocity of the expansion of the region in which the concrete is totally crushed is c_{cr}. Velocity c_{cr} is lower than c_1 ($c_{cr} \approx \frac{1}{3} c_1$). This means that the cratering process in a concrete slab, which can only occur in the crushed zone, can be disturbed by the elastic wave reflected from the back of the slab. The consequences of this interference will be discussed later on.

2.3. Cratering in a concrete slab

The particle velocity due to a plane stress wave is given by

$$u = \frac{p}{\rho c}$$

where u = particle velocity

p = pressure

ρ = density

c = propagation velocity of longitudinal wave

When the material is crushed velocity u will increase due to the increasing stress and the decreasing velocity c ($c_{cr} < c_1$). So the movement of the particles in radial direction is resisted by less crushed material. When the resistance is sufficient the radial trajectories are deflected, the crushed material is ejected and a crater is formed.

2.4. Spalling in a concrete slab

On explosion a pressure wave propagates in three directions in the concrete slab. This pressure wave with the elastic precursor is reflected at the free surface of the back of the slab as a tensile wave.
Although the precursor has a constant stress level the material will not become stressless by the combination of the pressure and tensile wave as in the one-dimensional case. Figure 2 gives the trajectories of the tensile stresses due to the pressure and tensile wave.

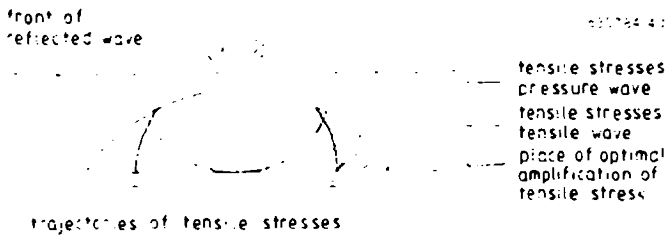


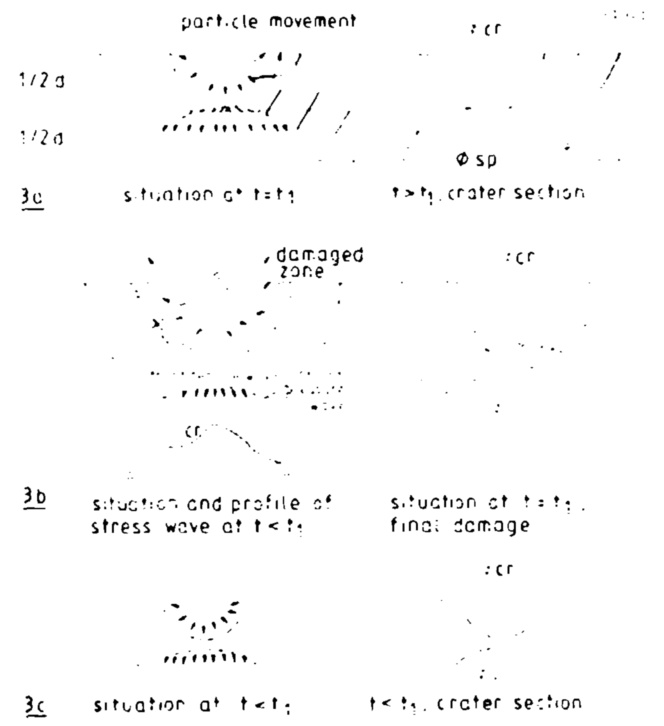
Figure 2.

Only on the axis of symmetry are the trajectories of the tensile stresses perpendicular and only on this axis can the material become stressless. Because of the small tensile strength of concrete and the fact that after reflection of the precursor of the pressure wave there are resulting tensile stresses spalling can occur over nearly the whole area. In this area there is a plane in which the tensile stresses of both waves have the same direction thus rendering chance of cracking optimal.

2.5. Interaction of cratering and spalling

The resistance of the material in front of the crushed zone to the movement of the particles in this zone decreases continuously by
(a) the expansion of the crushing zone (limited slab thickness)
(b) spalling and cracking
The reflected (tensile) wave reaches the crushing zone of a slab with thickness d at $t = t_1$, at a distance of ½ d from the loaded surface ($t_1 = \frac{3}{2} \frac{d}{c_1}$; $c_{cr} \approx \frac{1}{3} c_1$).
From the moment $t = t_1$ the trajectories of the particle movements in the crushing zone are deflected downwards. The resistance to this movement is decreased to zero, the particles are ejected downwards and cratering is stopped.

Figure 3a shows a picture of the damage of the slab. It will be clear that the time $t=t_1$, relative to the duration of the cratering process is a very important parameter of the failure process and failure mode of the slab.



crater sections and the degree of damage at different times for different slab thicknesses

Figure 3.

By varying the slab thickness the failure mode will change. The influence mentioned in points (a) and (b) imply that there are two extreme situations. In the first place the situation that cratering is over before the reflected wave reaches the crushing zone. It depends on the stress level of the reflected zone to what extent the material outside the crater, which is severly damaged by the pressure wave will be damaged by the reflected wave. This situation is depicted in Figure 3b. Alternatively there is the situation of a thin slab. In this case before $t=t_1$ the resistance of the material outside the crater gets insufficient to deflect the trajectories upwards. The particles in the crushed zone punch through the uncrushed material and through this punched hole the particles are ejected (Figure 3c).
To enable a description of the response of the structural parts under the directly loaded slab it is important to know which situation occurs.

In the last mentioned situation these parts will be loaded not only by expansion of the pressure wave and spalling particles but also by the particles which are ejected through the punched hole. Because of the high stresses in the region next to the charge the energy of the concentrated stream of particles may be high. To distinguish the different situations the relative and critical thickness are introduced. The relative thickness is defined as

$$d_r = \frac{d}{W^{1/3}}$$

where d = thickness of slab (m)
W = weight of charge (kg)
d_r = relative thickness ($mkg^{-1/3}$)

If the relative thickness is smaller than the critical thickness (d_c) the slab is punched through and the concentrated stream of particles appears.

2.6. Cracking by wave expansion

Due to the expansion of the pressure wave and the reflections cracking occurs. The crack pattern is determined by the geometry of the slab and of the wave expansion.

From the source the pressure wave expands in radial direction so in this direction cracking may occur. Without reflections a pattern of radial cracks is expected at loaded and unloaded slab surfaces. After reflection at the unloaded surface and at the edges interference of pressure and tensile wave occurs and there are spots of optimal conditions for cracking due to the parallel tensile stresses. The crack pattern of the loaded and unloaded surfaces are given in Figure 4 a+b. At the unloaded surface a tangential crack pattern may occur due to reflection. It depends on the stress level of the pressure wave whether the radial or tangential crack pattern develops. Figure 4 c shows the expected crack pattern in a section.

Finally the slab bends and yield-lines develop. If a square slab is loaded by a force in the middle of the slab, theoretically diagonal yield-lines and lines ending in the middle of the edges may develop. So these cracks may be the most pronounced cracks in the final crack pattern of the slab. (Figure 4a.)

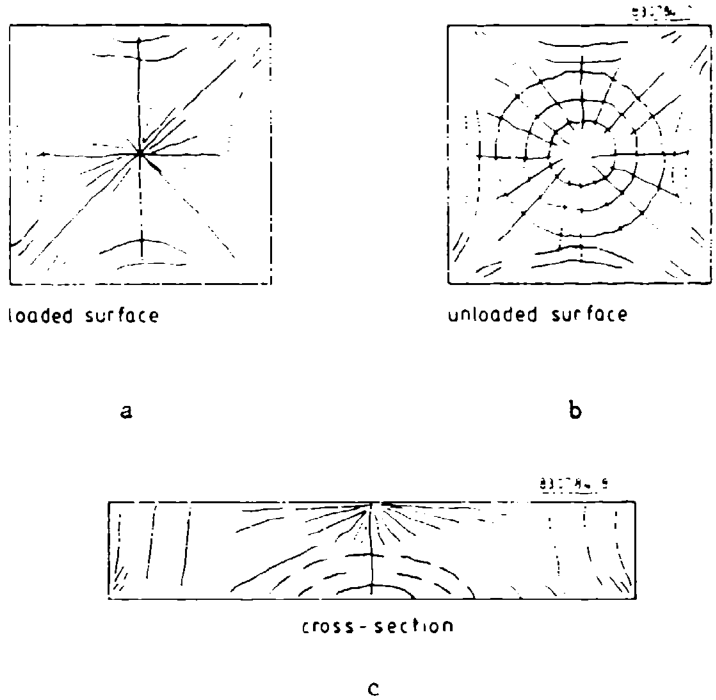


Figure 4. Crack patterns due to wave expansion

2.7. Comparison of the theoretical and experimental failure mode and final crack patterns

The failure mode of a solid slab due to a contact charge depends on the relative thickness of the slab as shown in Figure 3 and described above. In the test programme solid slabs with a thickness of d=18 cm were investigated. Figure 5 shows a picture of a middle section of a solid slab loaded by a charge of W=300 g (80 % penthrite). The damage and crack pattern is similar to the theoretical damage of Figure 4b.

Figure 5. Picture of the damage of a solid slab.

In the dark area in the picture, between the crater and the spalling zone, the structure of the concrete is severly damaged. The radius of this area is about the slab thickness (d) and is equal to the crater radius. Figure 6 shows a picture of the slab when the loose material is removed.

Figure 6. Picture of the damage of a solid slab with the loose material removed.

It can be seen that for the situation given in Figures 5 and 6 the cratering and the spalling process have nearly reached each other but the critical situation is not reached. The crack pattern in these Figures is the same as given in Figure 4 so it can be explained by wave expansion, reflections and interference of the pressure and tensile waves.

There is one crack though which was not expected. In concerns the crack along the reinforcement at a distance of $\frac{2}{3}$ d from the loaded slab side (Figure 5). This crack can be explained by the mechanism of the failure mode given in Figure 3c, of a slab with a thickness smaller than the critical thickness. The intermediate material is loaded by the difference of the particle velocity of crushed material in the crater zone and the material behind the front of the tensile wave. In the weakest section shear failure will occur and a hole is formed. By the reinforcement this more or less concentrated load is distributed and the bond between steel and concrete partly fails thus forming a crack along the reinforcement. This horizontal crack is formed before the vertical cracks due to the reflection of the pressure wave at the edges. This is proved by the fact that these vertical cracks do not intersect the horizontal crack.

The experiments with the solid slabs have shown that the damage and crack patterns can be explained by the theory described before. The critical situation is not reached during the test programme but the experimental results given in Figures 5 and 6 show that for a bigger charge the spalling and cratering (crushing) zones will reach each other in or somewhat above the middle of the slab.

This means that the velocity of crushing front (c_{cr}) is given by

$$c_{cr} \lesssim \frac{1}{3} c_1$$

In the experiment with a slightly bigger charge (W = 325 g) a hole was formed indeed. The shape of this hole proved that it was partly formed by punching. The damaged zone at the back of the slab had no circular shape as shown in Figure 5. The damage was more like the situation of a thin slab (Figure 4c).

In view of these results it is to be expected that the failure of the loaded slab in a layered structure can be described in the same way as for the solid slab.

3. THE LAYERED STRUCTURE

3.1. Influence of the impedance of the intermediate layer.

The failure mode of the directly loaded slab in the layered configuration can be described with the theory given for the solid slab when the influence of the properties of the intermediate layer on the failure process of this slab is known. The only way the intermediate layer can influence the stress situation in the first, loaded, slab is by changing the reflection of the pressure wave. The reflection is governed by the quotient of the acoustic impedance of the two layers.
This quotient determines
- the part of the impinging pressure wave which is reflected
- the part which proceeds as a refracted wave and
- whether spalling occurs in the first layer.

The stress levels of the reflected and refracted waves are given by:

$$p_r = p_1 \cdot \frac{\rho_2 c_2 - \rho_1 c_1}{\rho_2 c_2 + \rho_1 c_1} \quad ; \quad p_2 = p_1 \cdot \frac{2\rho_2 c_2}{\rho_2 c_2 + \rho_1 c_1}$$

$$u_r = \frac{-p_r}{\rho_1 c_1} \quad ; \quad u_2 = \frac{p_2}{\rho_2 c_2}$$

where p_1 = stress level of impinging wave (first layer)
p_r = stress level of reflected wave (first layer)
p_2 = stress level of refracted wave (second layer)
$\rho_1 c_1$ = acoustic impedance first layer
$\rho_2 c_2$ = acoustic impedance second layer

If the impedance of the second layer is higher than that of the first layer the reflected wave is a pressure wave and there will be a radial crack pattern at the back of the directly loaded slab and no spalling will occur. The reflected pressure wave will not weaken the material so the crater will develop completely. For the other parts of the structure the stress level of the refraction wave is amplified. In the test programme the acoustic impedance of the second layer was equal or lower than the impedance of the first layer.
The tested materials are listed in Table I.

TABLE I: Acoustic impedance of the investigated materials

Material	ρ [$\frac{kg}{m^3}$]	c_1 [$\frac{m}{s}$]	ρc [$\frac{kg}{m^2 s}$]
concrete	2500	3600	$9\ 10^6$
sand	1400	500	$7\ 10^5$
lightweight concrete	445	127	$5{,}7\ 10^4$
polysterene	16	112	$1{,}8\ 10^3$
air	1,2	330	$0{,}4\ 10^3$

Because of the lower acoustic impedance of the second layer and the small thickness of the directly loaded slab this slab will fail in the way as described before for the solid slab with a thickness smaller than the critical thickness (Figure 4c).
During the test no cylindrical hole as given in Figure 4c was formed. But in the tests with three concrete slabs an indentation is formed in the second slab with the same diameter as the hole in the first slab. So the second layer is loaded by a stream of particles with a diameter equal to the punched hole in the upper slab.
The failure mode for relatively thin slabs described in section 2.5 has been observed during the whole test programme.

3.2. The loading on the second layer

When the acoustic impedance of the second layer is lower than that of the directly loaded outer layer, as investigated during the test programme, the loading on the second layer can be divided into two parts. The first part is formed by the refracted pressure wave with the spalling material. The second part is the concentrated load due to the stream of particles.

The stresses are not measured during the tests so only an estimate can be given of the stress levels of the two parts of the loading.
The structure of the concrete is changed by stresses higher than 8 to 10 times the static strength f_c'. So the stress level of the first part of the loading is given by

$$p \cong 20 f_c' \left[\frac{\rho_2 c_2}{\rho_2 c_2 + \rho_1 c_1} \right]$$

The stress level in the concrete just after detonation is about 200 f_c'. When the slab is punched through the stress level decreases and is estimated to be 50 f_c' and the velocity of the particles which are propelled through the hole is

$$u = \frac{50 f_c'}{\rho_1 c_1}$$

The duration of the loading will be of the order of 10^{-4} seconds.

3.The ideal properties of the second layer.

The second part of the loading is the most severe and will damage the other parts of the construction most. The loading on the third layer will only be acceptable if the second layer has the properties

(a) to decrease the stress level

(b) to distribute the concentrated load

(c) to stop the stream of particles

(a) To decrease the stress level the acoustic impedance of the second layer must be lower than that of the first. But this causes spalling and the critical failure mode of the first layer. Another possibility of decreasing the stress level is to dissipate the energy of the stress wave by geometrical or internal damping by which the stress level decreases and the duration of the wave increases.

(b) The concentrated load can be distributed by the second layer when the strength and the stiffness of this layer is sufficient. Test with a steel plate in the intermediate layer of sand have proved that only when thick steel plates are used is the concentrated load distributed sufficiently to increase the resistance of the whole structure significantly.
Other tests with different thicknesses of the intermediate layer have proved that the stream of particles is not distributed geometrically.

(c) The stream of particles is stopped better when the density, the modulus of elasticity and the strength of the material are increased.

These points show that there is no ideal material for the intermediate layer. The choice of density and stiffness always has a drawback. A high density and modulus of elasticity will prevent spalling of the first layer, but the stress level of the refracted wave is higher. When a low density and modulus of elasticity is chosen the first layer fails in a critical way and the concentrated load is formed for which the resistance of the other parts of the structure is low.

3.4. The failure mode of the third layer, the lowest concrete slab

The lowest concrete slab is subject to a concentrated loading due to the critical failure mode of the upper slab and/or the pressure wave resulting from the detonation. When only the pressure wave is important the lowest slab will fail by spalling or finally by bending. By the concentrated loading spalling occurs and the slab fails by bending or punching.

The crack pattern in a concrete slab due to a concentrated load and the bending moments are given in Figure 7. The tangential cracks at the loaded side of the slab and the radial cracks at the other side cannot be caused by the expanding pressure wave (Figure 4).
So the crack pattern of the lowest slab shows which part of the loading was dominant.

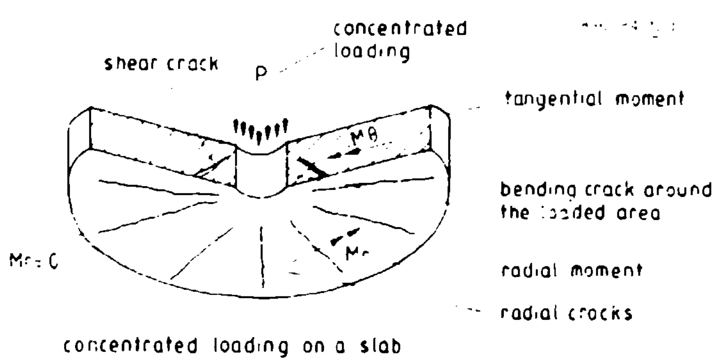


Figure 7.

3.5. The failure mode of the layered stucture

The tested layered structures can be divided into two groups. The first group has a relatively thin upper slab so this slab fails in a critical way and the concentrated loading is formed. In the second group the relative thickness of the upper slab is increased above the critical thickness (d_c).

Most of the experiments have been performed with an intermediate layer of sand. For the first group the two parts of the loading on the second layer, without geometrical and internal damping are given by

p = 91 MPa (first part)

p = .2500 MPa (second part)

On the third layer the loading is given by

p = 166 MPa (first part)

p = 4545 MPa (second part)

The properties and dimensions used are given in TABLE II.

TABLE II: Properties of the layers

	Thickness	c_1	ρ	ρc_1	f_c'
layer I/III	6 cm	3500 m/s	2500 kg/m^3	8,76 10^6 kg/m^{2}s	50 MPa
layer II	6 cm	625 m/s	1400 kg/m^3	8,75 10^5 kg/m^{2}s	

By geometrical damping the stress level of the first part can be decreased. In the experiments the diameter of the hole in the upper slab was about 200 mm. This means that the lowest slab is loaded by a concentrated load of $p \cong 1,5\ 10^5$ kN. Under static loading the slab fails when the load is about P_{st} = 500 kN. Because of the difference in magnitude it is not necessary to know the stress level exactly to determine the failure mode of the lower slab.

If the directly loaded upper slab fails in a critical way then the lowest slab fails by shear failure due to the concentrated loading. The same failure mode was observed in the tests with an intermediate layer of concrete. Figures 8 and 9 show pictures of a section of these tested structures.

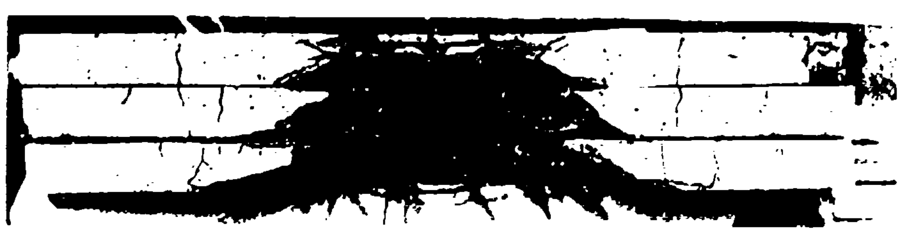


Figure 8. Section of a layered structure of three concrete slabs.

Figure 9. Detail of the damage with the loose material removed.

The shape of the hole in the lower slab is similar to the static case. At the back of this slab spalling occurred which has possibly decreased the shear resistance. The concrete surface shows that the cracks due to spalling are formed along the aggregate particles while the cracks due to shear failure are mostly formed through these particles.

Tentatively it can be concluded that the finally observed spalling surface is formed by the final bending of the structure and not by the concentrated load.

With the results of the experiments of the first group the critical thickness of the directly loaded slab can be defined by

$$d_c \cong 0{,}134\ W^{1/3}$$

where d_c = critical thickness [m]

W_c = weight of charge (80% PETN) [kg]

The test of the second group of the test programme have confirmed this result . No concentrated load was set-up in the structure and no shear failure occurred. The validity of this expression has been tested for thicknesses of about 100 mm. When the thickness of the slab approaches the critical thickness the deformation increases. Consequently the deformation capacity of the second layer must be sufficient otherwise the third layer will be loaded directly by the deforming upper slab.

4. CONCLUDING REMARKS

The results of the experimental and theoretical research programme can be summarized as follows.

- If a layered structure is used of two concrete slabs with an intermediate layer and the thickness of the directly loaded outer slab is smaller than the critical thickness

$$d_c \geqq 0.134\ W^{1/3}$$

  then this slab fails in a critical way. This means that a concentrated loading is created by the stream of particles which are ejected through the hole punched in the directly loaded slab. This concentrated load has a high energy content and dominates the failure process in the other parts of the structure.
- No geometrical damping occurs in the stream of particles.
- When the concentrated loading is formed this loading cannot be distributed economically by increasing the stiffness and strength of the second layer, and the lower slab fails as a result of shearing.
- If the thickness of the directly loaded slab exceeds the critical thickness the structure of the concrete will be changed in the area next to the crater. The residual strength of the concrete decreases significantly.
- When the thickness of the directly loaded slab approaches the critical thickness the deformation increases. The deformation capacity must be sufficient to prevent that the third layer is loaded directly by the deforming upper slab.
- The observed crack patterns and the damage in the layered construction due to loading by contact charges can be explained by the theory of wave expansion and the theoretical description of the failure process given in this paper.

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FAILURE ANALYSIS OF STRUCTURES SUBJECTED TO MULTIPLE BLAST LOADS

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INTRODUCTION

In the design of blast resistant structures, the design load environment is generally specified in terms of a load-time history produced by a specific weapon size detonated at a specific slant range from the structure. Procedures (Ref. 1, 2, 3, 4) for the design of such structures are fairly well established, and when a structure is designed in accordance with these procedures, there is generally little doubt but that it will survive the design load environment to a satisfactory degree. What such design procedures fail to address is the reliability of the given structure when subjected to load environments other than the design environment.

In the course of its life span, a blast resistant structure may be subjected to a single blast load that is more intense than the design load. It may also be subjected to multiple loads. These may have different peak load intensities, pulse shapes, durations and may arrive at the structure from different directions at different times or essentially the same time. The structure in question will experience damage to the extent that the imposed blast load environment is more intense than the design environment. The extent of additional damage from subsequent loadings will depend on the "available" strength of the structure, i.e., on the extent to which its strength has been degraded due to previous loadings.

Currently available manuals dealing with the design of structures to resist accidental explosions, Ref. 1 and 2, or blast loadings produced by nuclear weapons, Ref. 3, and 4, do not specifically consider the response of structures subjected to multiple blast loads. Specific design criteria relative to this effect do not appear to have been formulated.

This paper examines the problem of structural response in a multiple load blast environment. Due to the non-deterministic nature of the problem, the method described considers the failure probability of the structure after each

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blast. The structure is modeled as a single degree of freedom system with a resistance function which provides for an approximate degradation in strength. The method considers uncertainties in both structural and blast load parameters. Load and resistance are assumed to be lognormally distributed. A failure probability is computed after each blast.

The method of analysis is described. Assumptions and limits of applicability are noted. Its application is illustrated by means of an example problem. In the example problem the resistance of the structure is approximated by means of an effective linear resistance based on a bilinear resistance function. It is subjected to a series of identical blast loads. Failure probabilities are computed and combined. Results indicate that even as few as three repeated blast loads can significantly increase the probability of failure even for cases with a relatively high R/F ratio. The R/F (peak resistance to peak load intensity) ratio can be looked at as a measure of the relative strength of the structure or as an indication of its range from the point of detonation.

GENERAL ASSUMPTIONS

(i) The structure is modeled as a single-degree of freedom system

(ii) The applied load is assumed to consist of a series of step loads (see Fig. 1). of different peak intensities, F_i.

(iii) The resistance capacity of the structure is represented by means of an elasto-plastic resistance shown in Fig. 2. The yield and maximum displacements are represented respectively, by X_y and X_m. The stiffness of the elastic part is $k = R(X_y)^{-1}$ in which R is the resistance capacity.

(iv) The applied blast load will leave the structure undamaged if the ratio of load to resistance is less than 1/2, i.e. $F_i/R \leq 1/2$.

BASIC FORMULATION

The resistance function shown in Fig. 2 is further idealized by means of an "effective" linear resistance function shown in Fig. 3. The effective displacement X_e is found by equating the energy corresponding to elasto-plastic case and that of the corresponding linear case, Ref. 5. Such linearization yields

$$X_e^2 = X_y^2 \, (2 \, X_m/X_y - 1) \tag{1}$$

Introducing the ductility ratio $Z_i = X_m/X_y$, Eq. (1) may be written as

$$X_e^2 = X_y^2 (2 Z_i - 1) \tag{2}$$

or

$$Z_i = X_e^2/2 X_y^2 + 1/2 \tag{3}$$

Given the step load shown in Fig. 1, the maximum response of the linear system is, Ref. 5.

$$X_e = 2 F_i/k = 2 F_i X_y/R \tag{4}$$

In the light of Eq. (4), Eq. (3) becomes

$$Z_i = (2F_i X_y/R)^2/2X_y{}^2 + 1/2 = 2/(R/F_i)^2 + 1/2 = 2/\theta_i^2 + 1/2 \tag{5}$$

where $\theta = R/F_i$.

Damage is likely to occur if $F_i \geq R/2$. This corresponds to $Z_i \geq 1$. Thus the probability of damage P(D) is:

$$P(D) = P(Z_i > 1) \tag{6}$$

Using arbitrarily a lognormal probability distribution for θ_i, Ref. 6, the probability of damage is:

$$P(D) = \phi\left(\frac{\ell n \bar{Z}_i}{\Omega_{Z_i}}\right) \tag{7}$$

Where $\phi(.)$ = the standard normal probability function $\bar{Z}_i$ = the means of Z_i and Ω_{Z_i} = the coefficient of variation (C.O.V.) of Z_i representing the uncertainty in Z_i. If $\bar{\theta}_i$ and Ω_{θ_i} are respectively the mean and C.O.V. of θ_i, $\bar{Z}_i$ and Ω_{Z_i} are calculated as, Ref. 7:

$$\bar{Z}_i = 2/\bar{\theta}_i^2 + 1/2 \tag{8}$$

$$\Omega_{Z_i} = 8 \, \Omega_{\theta_i}/(4 + \bar{\theta}_i^2) \tag{9}$$

in which (Ref. 6)

$$\bar{\theta}_i = \bar{R}/\bar{F}_i \tag{10}$$

and

$$\Omega_{\theta_i} = (\Omega_R^2 + \Omega_{F_i}^2)^{1/2} \tag{11}$$

where $\bar{R}$ and $\bar{F}$ are, respectively the means of R and F_i and Ω_R and Ω_{F_i} are the respective C.O.V.

COLLAPSE OF THE SYSTEM

The collapse of the structure may be defined as a ductility level above which the system suffers extensive damage so that failure is certain. If M represents this ductility level, collapse is represented by $\mu_i > M$ where μ_i is the overall ductility of the system at time of the ith blast load, whereas Z_i is the ductility due to the ith blast only. The value of μ_i depends on the previous ductilities $\mu_1, \mu_2, \ldots \mu_{i-1}$. The probability of collapse, $P(C_i)$ at the ith blast load depends on whether or not $Z_j > 1$. From the total probability theorem (Ref. 6), the probability of collapse is:

$$P(C_i) = P(C_i \mid Z_i > 1)\, P(Z_i > 1) + P(C_i \mid Z_i \leq 1)\, P(Z_i \leq 1) \tag{12}$$

where $P(C_i \mid Z_i > 1) = P(\mu > M)$; whereas $P(C_i \mid Z_i < 1)$ depends on the ductility at (i-1)th blast. This can be postulated as $P(C_i \mid Z_i \leq 1) = P(\mu_{i-1} > M)$. Eq. (12), therefore, becomes:

$$P(C_i) = P(\mu_i > M)\, P(Z_i > 1) + P(\mu_{i-1} > M)\, P(Z_i \leq 1) \tag{13}$$

The probability $P(\mu_i > M)$ may be calculated as follows.

After application of load F_{i-1} as part of a series of loads F_1, F_2, ..., F_n if $Z_{i-1} > 1$, a permanent displacement $X_{p_{i-1}}$ will be produced. This displacement will be added to the displacement produced by load F_i (see Fig. 4). For the effective linear system, under the action of F_i the system starts from rest with a permanent displacement $X_{p_{i-1}}$, and the total displacement X_{e_i} (see Fig. 5) is

$$X_{e_i} = X_{p_{i-1}} + 2F_i/k \tag{14}$$

If $\mu_i = X_{m_i}/X_y$ a relationship between μ_i and μ_{i-1} may then be derived based on equating the energy of the elasto-plastic system and that of the linear one, (see Fig. 4 and Fig. 5) i.e.

$$\mu_i = \mu_{i-1} + 2/\theta_i^2 - 1/2 \tag{15}$$

For a special condition of i=1, there is no previous permanent displacement. This condition leads to $\bar{\mu}_o = 1$ so that Eq. (15) may still be used for i=1. Assuming lognormal distributions for μ_i and Z_i the collapse probability at ith blast may then be calcuated in terms of $\bar{\mu}_i$ and Ω_{μ_i} the C.O.V. of μ_i

$$P(C_i) = \{1-\Phi[(1/\Omega_{\mu_i})\, \ln(M/\bar{\mu}_i)]\}\, \Phi[(1/\Omega_{Z_i})\, \ln(Z_i)] + \{1-\Phi[(1/\Omega_{\mu_{i-1}})\, \ln(M/\bar{\mu}_{i-1})]\}\, \{[1-\Phi(\ln Z_i)/\Omega_{Z_i}]\} \tag{16}$$

SPECIAL CASES

For a large $\bar{\theta}_i$, μ_i may be smaller than $\bar{\mu}_{i-1}$. This, of course, is not possible. It is, therefore, more appropriate to set $\bar{\mu}_i \geq \bar{\mu}_{i-1}$ as a necessary condition in this formulation.

If for every blast, $\bar{\theta}_i > 2$. $\bar{\mu}_i$ remains constant and equal to 1. Although Ref. 8 specifies this conditon as a no failure case, the present formulation still yields a value for failure probability. This is because of the uncertainties associated with F_i and R.

NUMERICAL ILLUSTRATION

For a structure under repeated identical blast loads, the collapse probabilities for different $\bar{\theta}_i$ ranging from 1.0 to 2.0 were obtained using the above formulations. The uncertainties associated with F_i and R are taken as 20%. Furthermore a ductility level M = 2 is assumed for defining the borderline between failure and no failure. The results (see Fig. 6) show that even for relatively large $\bar{\theta}_i$ (i.e. $\bar{\theta}_i = 2.0$) the collapse probability may become significant after the 3rd or fourth blast load.

SUMMARY AND CONCLUSION

A method was formulated for studying the probability of failure of structures when subjected to repeated blast loads. It was applied to the analysis of a structure subjected to a series of identical blast loads. Results indicate that even as few as three repeated blast loads can significantly increase the probability of failure even for cases with a relatively high R/F. (The R/F ratio can be looked at as indicating the relative strength of the structure or as an indication of its range from the point of detonation.

The reason for using an "effective" resistance function (Fig. 3) instead of the actual bilinear resistance (Fig. 2) in performing the analysis, is that for an elasto-plastic resistance function and a step load (Fig. 1) the ductility μ_i is highly non-linear, i.e. (Ref. 9)

$$\mu_i = \frac{1}{2(1-1/\theta_i)} \tag{17}$$

This results in high uncertainties in μ_i when the ratio of $1/\theta_i$ approaches unity. The problem is only slightly improved when using decaying load functions. This subject area needs further analysis.

The method of analysis presented here can be extended to consider a variety of different loadings and resistance functions. For the design of blast resistant structures, this method is a potentially useful tool for evaluating the reliability of candidate designs.

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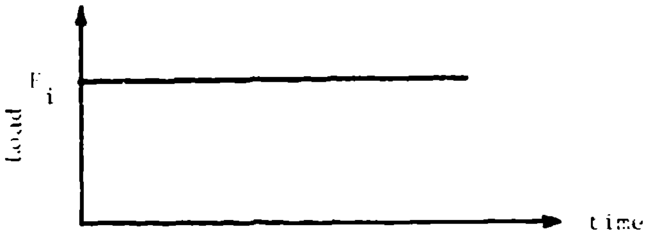

Fig. 1 Load Function

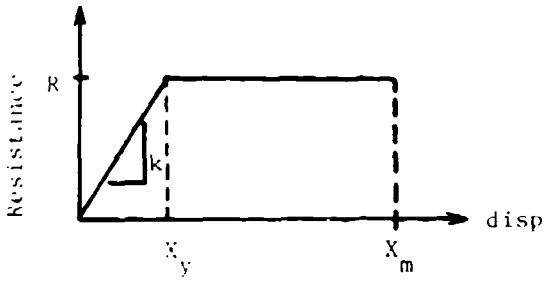

Fig. 2 Actual Resistance

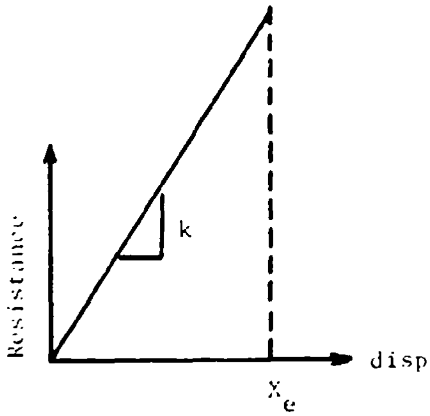

Fig. 3 Effective Resistance

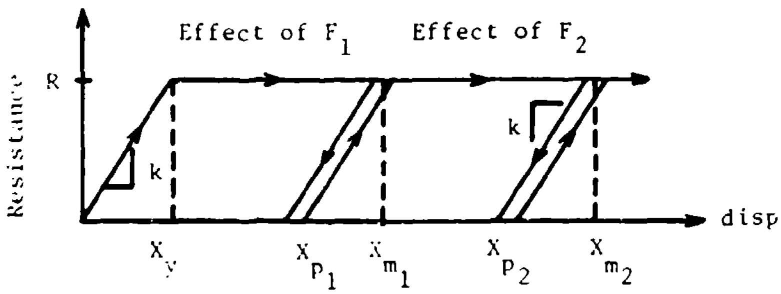

Fig. 4 Action of Repeated Loads

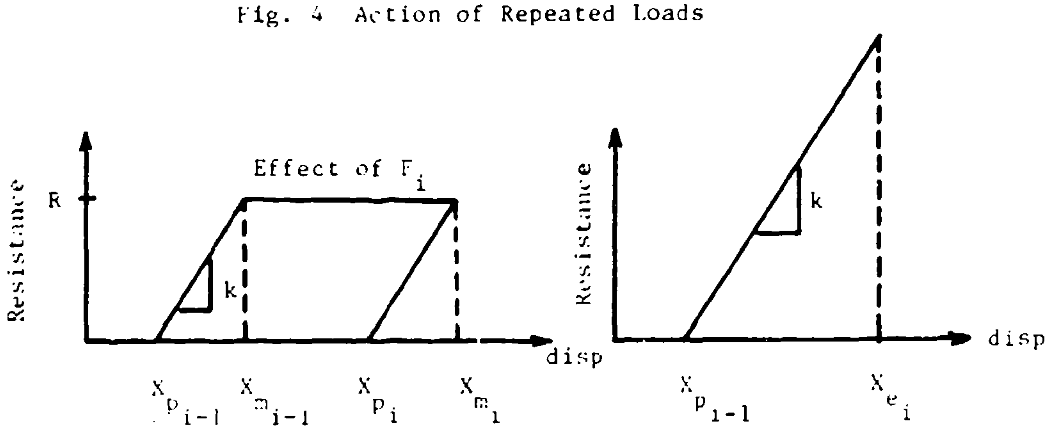

Fig. 5 Elasto-Plastic and Effective Linear Resistance

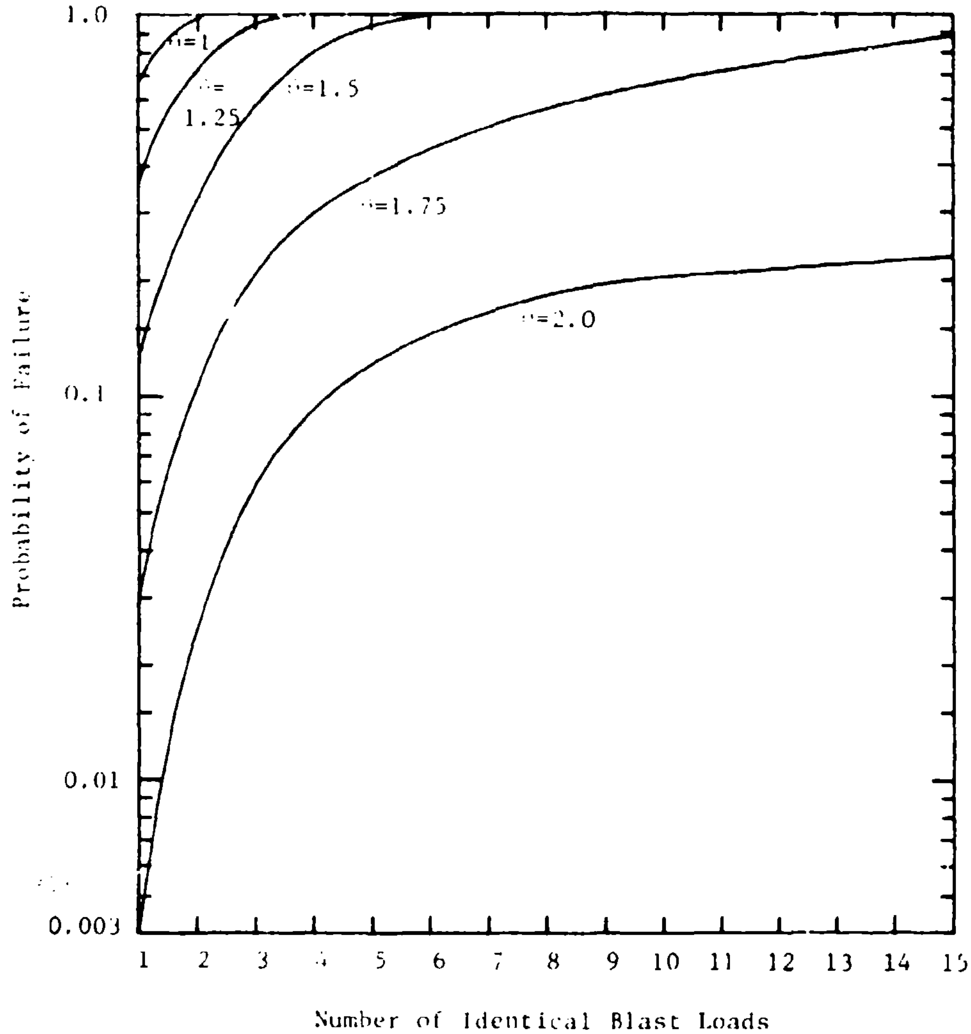

Fig. 6 Sample Illustration

RAPID RESPONSE DELUGE SYSTEM

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ABSTRACT

The development of a rapid response deluge system by the Ammunition Equipment Directorate (AED) for use in suppressing propellant fires during demil shows great promise. Prototype systems have been tested and data acquired on their efficiencies. Present system vs. previous generations and lessons learned will be discussed. A Video cassette of deluge system generation including sections of high speed filming, will be shown.

INTRODUCTION

The Ammunition Equipment Directorate (AED) has developed a rapid response deluge system for use with munition renovation/demilitarization operations. This system provides localized personnel protection from propellant fires on selected APE specifically the APE 1001 and the APE 2000 machines with shields.

The initial application was on two APE 1001 Vertical Pull Apart Shields at Letterkenny Army Depot, where protection from propellant fires occurring inside the shields is required. Tests by AED show that propellant fires inside a 1001 shield could produce significant personnel hazard due to flame venting, although there has never been an accidental propellant fire/deflagration in an APE 1001 Operational Shield.

RAPID RESPONSE DELUGE SYSTEM TEST RESULTS

Two generations of rapid response deluge systems evolved during development at AED. These were titled the prototype deluge and the production model deluge systems. Tests were run on actual propellant fires inside the APE 1001 shield with both of these systems.

Prototype Tests

The prototype deluge contained 5 gallons of water, precharged to 500 psig, which dumped through an explosively ruptured, non-fragmenting diaphragm and through a nozzle mounted on the large, side access door of the 1001 shield.

The nozzle directs two sprays into the shield: one 180 degree fan at 15 degrees above horizontal and above the case, and one 90 degree fan at 45 degrees below horizontal, onto the case. Figure 1 shows the test set up and Table 1 summarizes the test results.

The results of Table 1 indicate that about 75% of the M30 propellant can be prevented from burning providing that the water solution has access to the propellant. For the M10 propellant, 35% to 75% of the propellant can be prevented from burning; a function of how much propellant is blown outside of the case and how much water enters the case through the perforations. The perforated cases did not rupture.

Production Model Tests

The production model deluge contains 15 gallons of a water-calcium chloride solution with sodium chromate corrosion inhibitor, pressurized to 360 psig, which dumps through a non-fragmenting rupture diaphragm and through a nozzle centrally mounted at the top of the shield. Two smaller auxiliary nozzles are plumbed to locations alongside the cartridge case, to provide additional localized quenching for perforated cartridge cases (which may not rupture). The main nozzle has a 120 degree full spray angle which covers the full cross-section of the shield, blanketing any flames attempting to vent out through the top of the shield. The calcium chloride provides freeze protection down to -40 degrees Farenheit. One half percent sodium chromate is added to inhibit corrosion. Figure 2 shows the setup, and Table 2 summarizes the test results.

An electrically actuated initiator at the base of the container generates a shock wave which ruptures a non-fragmenting diaphragm, releasing the water. The initiator is functioned by a quick response firing circuit (less than 1 millisecond) designed and fabricated by AED which in turn is triggered by one of three methods. The fastest method is by a blast pressure switch mounted near the top (inside) of the shield (2 milliseconds); the next fastest method is by two ultraviolet (UV) flame detectors (10 milliseconds); and the slowest method is by a manually actuated switch mounted outside the shield in front of the operator. The blast pressure switch is suspended from the top baffle of the 1001 shield by four steel cables and vibration isolation mounts to prevent false triggering of the switch. The two UV detectors are wired in series; thus both detectors must see flame before they can trigger the firing circuit. This is done to reduce false triggering. Each UV detector has an integral self-check feature which assures that the detector lens is clean and that the detector tube and associated circuits are functional. In the first production models, this check had to be performed by the operator each time electrical power was applied to the circuit. In the latest production model deluge systems this function is performed automatically. Relay logic is used to isolate and ground the initiator during functional checks. This is done to prevent dumping the deluge system when it is not needed.

The deluge system is locked out so it cannot function until the load/unload door in the front of the 1001 shield is closed. This is done to prevent possible operator injury by the high energy water spray. A pressure gauge, mounted at the bottom of the container indicates container pressure, and must be checked occasionally by the operator.

The results of Table 2 indicate that about 88% of the M30 propellant can be prevented from burning providing the water solution has access to the propellant. For the M10 propellant, 60% to 70% of the propellant can be prevented from burning. The functionality expressed previously on the results of Table 1 are also applicable here.

Sunlight did not function the UV detectors on any of the performed tests or during the preparation for these tests.

LESSONS LEARNED

From the results of the testing performed on the prototype and production model deluge systems, the following lessons were learned:

1. The prototype system initially had a bladder inside the tank. This bladder would tend to seal off the tank opening shortly after initiation of the blast valve, thus restricting the amount of water which could be dumped into the shield.

2. The first two production model deluge systems had an emergency dump switch on them for manually initiating the deluge. This method of initiation caused more problems than it solved. Therefore, the switch was deleted from further production models. It seems that people have a tendency to push buttons which, in the case of the deluge system, would thus dump the pressurized water into the shields.

3. If initiation of propellants such as M10 or M30 is not suppressed with a deluge system, catastrophic results can occur.

Having now discussed the rapid response deluge systems, a video cassette of the tests performed on these will be shown.

CONCLUSIONS

1. A properly operating deluge system can significantly reduce the quantity of propellant that would ignite and burn in the event of an incident in a protective shield.

2. Suppression of propellant fires can definitely be accomplished thru the use of a properly designed deluge system.

TABLE 1
PROTOTYPE DELUGE TEST RESULTS ON APE 1001 SHIELD

TEST DATE (FILM NO.)	MUNITION	PROPELLANT TYPE	PROPELLANT NOM. WT. LBS.	WEIGHT OF PROPELLANT RECOVERED LBS.	WITH OR WITHOUT DELUGE (1)	OBSERVATION
9 Aug 79 (080979-1)	105mm M392	M30	6	3	With	Case did not rupture.
9 Aug 79 (080979-2)	105mm M392	M30	6		Without	Case ruptured at 30 to 50 millisec after initiation, filling shield with flame. Camera knocked over at 700 millisec, shield still filled with flame.
16 Aug 79 (081679)	105mm M323	M10	7.95	3	With	Munition functioned before camera up to speed. Flame out approx 1-1 1/4 sec after initiation.
13 Sept 79 (091379-1)	105mm M323	M10	3.98	3 1/4	With	Flame gone at 900-1,000 millisec after initiation.
13 Sept 79 (091379-2)	105mm M323	M10	3.98	1/2	Without	Flame gone at 1 1/4 sec and all illumination inside shield gone at 2 1/4 sec after initiation.
13 Sept 79 (091379-3)	105mm M392	M30	12.0	9 3/4	With	Case fragmented but shield intact, thus suggesting deluge prevented shield failure (Ref. Test 25 May 77, which blew 1001 side door open).

(1) 5 gallons water, precharged to 500 psig, see Fig 1 for setup.
(2) Based on high speed (2,000 frame/sec) color movies of shield interior and post test observations.
(3) Electric primer.
(4) Used half charge of propellant so APE 1001 Shield would not fail.
(5) Percussion primer initiated by electric blasting cap. Perforated case did not rupture.

TABLE 2
PRODUCTION MODEL DELUGE TEST RESULTS ON APE 1001 SHIELD (DELUGE USED ON ALL TESTS)

TEST DATE (FILM NO.)	MUNITION	PROPELLANT TYPE	PROPELLANT NOM. WT. LBS.	WEIGHT OF PROPELLANT RECOVERED LBS.	OBSERVATIONS
24 July 80 (072480 A&B)	None				Test determined system dump times. Tank emptied in about 4.9 sec. Water appeared at bottom side nozzle and at top side nozzle 59 millisec and 71 millisec after water at main nozzle, respectively. Used std. diaphragm backing ring.
18 Aug 80 (081880A&B)	105mm M323	M10	7.95	4.94	Both pressure switch and UV detectors operable on this test. System triggered off the pressure switch. 24.8 milliseconds after cap flash (initiation), the water solution was coming out the large nozzle. 100.6 milliseconds later the flame was quenched. A second partial flame flareup started 0.57 seconds after initiation but was gone 0.35 seconds later. Used standard diaphragm backing ring.
21 Aug 80 (082180 A&B)	105mm M323	M10	7.95	5.31	Blast switch made inoperable on this test. Only UV detectors used. High speed films were of little value on this test because smoke etc., obscured the inside view of the shield after initiation. From some instrumentation measurements the water solution was at the top large nozzle 23.64 milliseconds after initiation. Flame appeared to begin subsiding approx. 0.6 sec later. Used square opening backup plate behind diaphragm (to insure larger opening after diaphragm rupture). The 0.4 seconds later the flame appeared to be quenched.

TABLE 2 (Cont)
PRODUCTION MODEL DELUGE TEST RESULTS ON APE 1001 SHIELD (DELUGE USED ON ALL TESTS)

TEST DATE (FILM NO.)	MUNITION	PROPELLANT TYPE	NOM. WT. LBS.	WEIGHT OF PROPELLANT RECOVERED LBS.	OBSERVATIONS
25 Sept 80 (092580A&B)	105MM M392	M30	6.0	5.25	Blast switch made inoperable for this test also. Only UV detectors used. After initiation there was a period of about 0.56 seconds before a small amount of flame became visible. Water quench began about 1 second later with the fire being quenched in the next 0.27 seconds. A pressure transducer in the top large nozzle indicated lapsed time of 1.41 seconds before being affected by heat and an interval of 0.13 seconds when water quench began.

(1) 15 gallons water-calcium solution, precharged to 360 psig, see Fig 2 for setup.
(2) Based on high speed (1000 & 2000 frames/sec) color movies of shield interior, some trial instrumentation and post test observations.
(3) Electric Primer
(4) Used half charge of propellant so APE 1001 shield would not fail.
(5) Percussion primer initiated by electric blasting cap. Perforated case did not rupture.

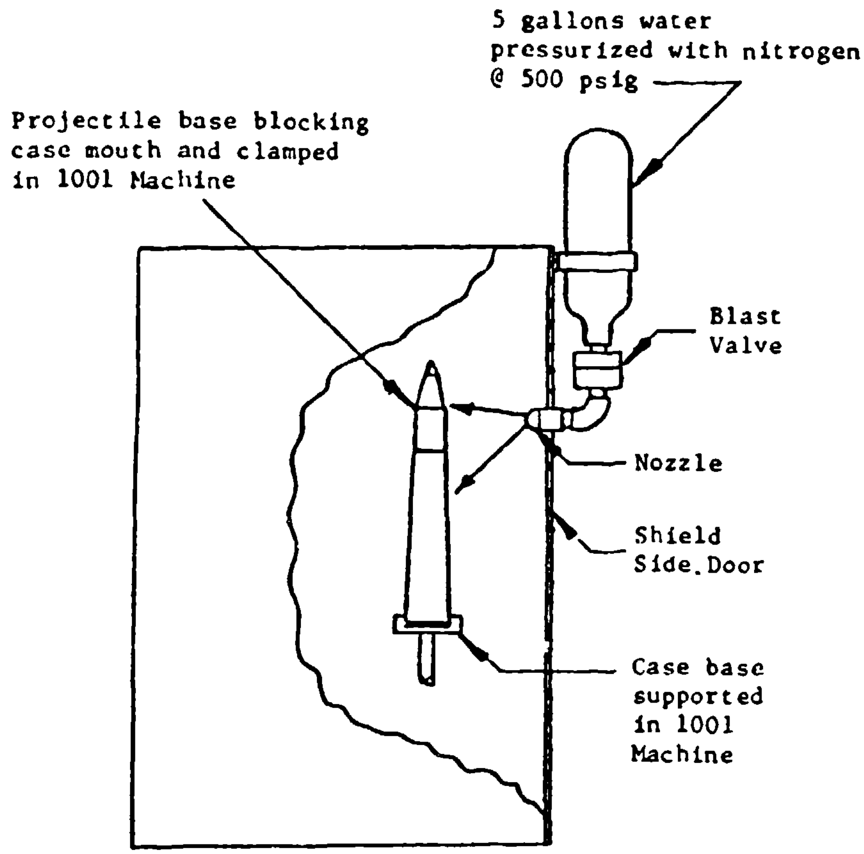

FIGURE 1: PROTOTYPE DELUGE ON APE 1001 SHIELD

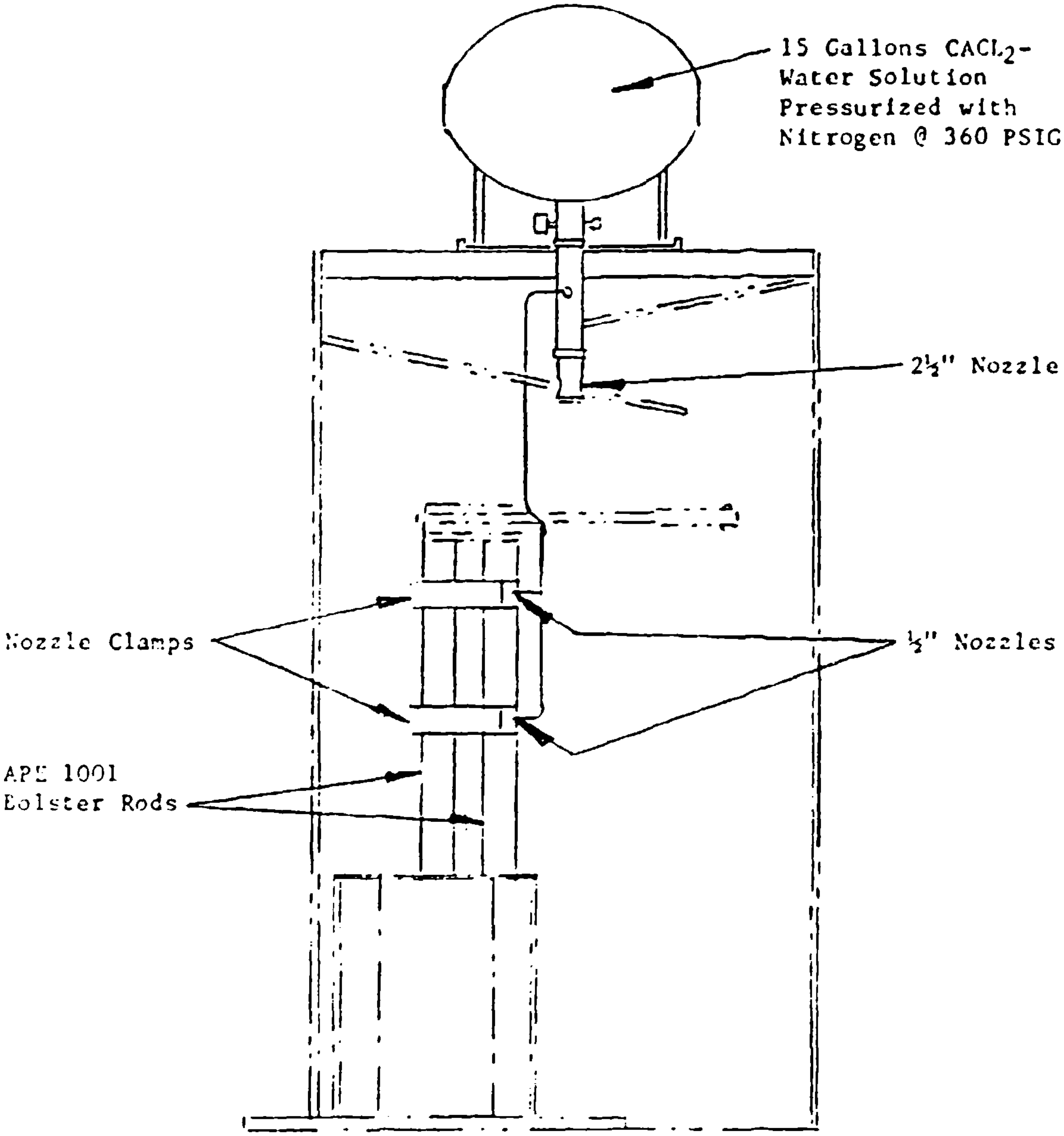

FIGURE 2 PRODUCTION MODEL DELUGE ON APE 1001 SHIELD

Fast-Acting Sprinkler System Design Considerations for Propellant Manufacture

by

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ABSTRACT

Fast-acting sprinkler systems for detection and suppression of fires in propellant operations, which require activation in the millisecond range in order to be effective, can be easily defeated unless particular attention is paid to design and maintenance details. Of primary consideration are detector selection and placement in processes to minimize the effect of environmental influences. Also important are nozzle placement, water flow density, water supply pressure, and pattern and sloping of piping. When all of these design criteria are properly implemented, water application can occur within 100 ms of fire detection.

INTRODUCTION

Fast-acting fire suppression systems are used extensively in conventional and automated propellant manufacturing lines at Radford Army Ammunition Plant (RAAP). The design, installation, and operation of these fast-acting sprinkler systems in new, automated propellant manufacturing equipment have resulted in increased understanding of their operation through evaluation, testing, and incidents. This experience has shown that special design considerations are required for automated propellant manufacturing equipment fire suppression systems. This experience can also be applied to conventional manufacturing operations. This paper presents several unique problems encountered with these suppression systems and their solutions which resulted in more functional and reliable fire suppression systems.

DISCUSSION

A typical RAAP fast-acting fire suppression system, as shown in figure 1, consists of:

1. A fire detection system, typically responding to infrared (IR) or ultraviolet (UV) radiation which provides an output for sprinkler activation,
2. An explosively-actuated valve which permits sprinkler water to begin flowing upon actuation,
3. A pressurized water supply upstream of the explosively-actuated valve,
4. Fully primed piping between the explosively-actuated valve and the application nozzles, and
5. Application nozzles with burst discs or caps which release upon application of pressurized water.

Reaction times, the time from fire detection until water flows from the nozzle, are in the 50 to 100 millisecond (ms) range for critical systems at RAAP.

Characteristics of Automated Lines Important to Sprinkler Design

Automated solvent propellant manufacture presents unique problems to sprinkler design not normally encountered in conventional manufacturing operations. First, since operating bays or equipment are often connected by continuous trains of propellant or ingredients, prevention of fire propagation via these combustible trains becomes a primary design consideration; e.g, often faster reaction times and an increased number of sprinkler systems are required. Second, since the majority of equipment is enclosed, special problems are presented such that detection and water application are more easily defeated. And finally, operations are usually remote and designed to operate for long periods of time, thereby inducing fire system maintenance problems. These characteristics of automated lines result in two major areas in which fire protection can be defeated in automated propellant lines: fire detection and water supply.

Fire Detection

Even if a sprinkler system can deliver water in less than 100 ms from fire detection, it is ineffective if fire detection is not prompt. Two major causes for defeat of fire detection systems in automated propellant operations have been identified: radiation-attenuating media between detector and fire, and insufficient fire radiation output in the detector sensitivity range.

As shown in figure 2, most of the automated propellant processing equipment is enclosed. Dusts and volatile vapors within will tend to collect or condense on detector viewing windows (figure 3). Research at RAAP has shown that these materials will attenuate radiation from a fire and defeat or delay fast-acting sprinklers.[1,2] For example, figures 4, 5, and 6 show the attenuation of UV radiation by solvent vapors, ingredient dust, and propellant dust, respectively. Selection of the detector viewing windows is also important. For example, transparent plastics such as acrylics will not transmit radiation in the typical 1850 to 2450-Angstrom sensitivity range of a UV detector (figure 7). The result is attenuation of radiation from any fire that may occur, and subsequent delay or defeat of fire detection. Solutions at RAAP include: air purging of viewing windows, supplementing radiation detection with pressure detection, and selecting detector windows that do not absorb radiation in the detector's sensitivity range. It is important to incorporate such considerations early in system design for easy implementation.

Inerting of automated propellant manufacturing equipment must also be considered in fast-acting sprinkler design. In one situation at RAAP, a fire detector was selected based on its ability to detect nitrocellulose (NC) burning in air. Later process changes were made to displace air in the equipment with nitrogen. The equipment was purged with nitrogen to eliminate a flammable hazard. This process safety improvement resulted in the potential for delay or defeat of the fire detection system for NC fires.[3] The existing UV radiation fire detection system was shown to be unreliable for detection of NC fires in a nitrogen atmosphere.[4] Typical test results are shown in figures 8 and 9. It is suspected that the output of radiation in the UV detector sensitivity range by an NC fire in a nitrogen atmosphere is greatly reduced when compared to the same fire in air.

Enclosed process equipment may also affect detector response by creating pressure fronts in front of a fire. High speed movies[5] have shown that the pressure fronts can generate dust clouds ahead of a fire. This dust will attenuate radiation (figure 5 and 6) and possibly delay or defeat a fire detection system.

The experience with NC fires in inerted atmospheres and dust generation ahead of a fire shows the need for careful selection of a fire detection device. Wherever possible, a fire detection system should be tested in conditions that closely simulate the process. Variables which may influence detector response and should be considered in test design include equipment size and geometry, physical condition of the material tested, atmosphere within equipment, and contamination of viewing windows. Measuring the spectral output and intensity of a fire will help determine the optimum detectors as detectors respond to different light spectra (figure 7).

Water Supply

A large number of problems may arise in obtaining or maintaining an adequate water supply to sprinkler systems in automated lines. The problems include loss of prime water, air in the primed piping, nozzle plugging, and simultaneous system activations, all of which may delay or defeat a sprinkler system.

If the prime water downstream of an explosively actuated valve is lost or depleted, system reaction time is greatly increased since air in the line must be compressed and eliminated before water flow can be established. In addition to normal leakage within a system, other conditions occur in automated propellant lines which increase the probability of losing prime water. Vibratory equipment increases the chance of piping and burst disc failures. High temperatures can cause plastic caps to fail. In one incident shown in figure 10, several nozzles of a large sprinkler system were placed in a high temperature, low pressure region. Not only did the plastic caps fail, resulting in loss of prime water, but process material was pulled from the higher pressure area and packed in the pipes. The sprinkler system was completely defeated.

Not only is prime water more likely to be lost in automated propellant lines, but detecting the loss is difficult. In conventional propellant operations, inspections for prime water loss and leaks can be made each shift. In automated lines, which are generally remote and long-running, shift inspections may not be feasible. Many nozzles are in enclosed equipment so that identification of leaks is difficult when inspections do occur.

At RAAP, these problems have been addressed by decreasing the chance for leaks and providing rapid identification of prime water loss if it does occur. Leaks have been reduced by using flexible connections to minimize vibration to discs and improving burst discs in vibratory equipment. Separate sprinkler systems are used for areas with different operating pressures. Work is ongoing for development of high temperature caps, but with little immediate success. In order to immediately detect loss of prime water, a prime leg with a level detector has been added. If water level falls, an alarm occurs. Some systems have remote water makeup capability. In many locations, quick-release connections have been added so that nozzles can be removed easily and inspected for leaks.

Experience has shown that air bubbles in prime water increase reaction time. As water sits in the piping, air comes out of solution and collects in any available traps in the piping. When the system is actuated, the compressible air increases reaction time. This problem has been minimized by careful installation of piping to prevent air entrapment. All piping slopes in an upward direction to a bleed location where the air can be released. In table 1, simple elimination of air pockets by sloping pipes is shown to decrease reaction time.[6]

Nozzles enclosed in equipment are subject to being plugged by process materials. For example, small propellant granules enter and become wedged in nozzles; even if not totally plugged, nozzle spray patterns are disrupted. This problem is addressed at RAAP by regular inspection programs and use of dust caps where required.

Finally, many automated propellant lines require simultaneous activation of several sprinkler systems. An error that has been made is that of measuring the reaction times of each individual sprinkler system. Realistically, individual reaction times are usually longer when several sprinkler systems are activated simultaneously due to the increase in demand on the water supply. Typical test results are shown in table 2. Reaction times should always be measured with sprinklers working as they would in a fire. Sprinkler system reaction time should be measured from detector response time to the time water flows in every sprinkler system which activates from that detector.

CONCLUSIONS

Automated propellant manufacturing operations present special design problems for fast-acting sprinkler systems. Enclosed equipment with dust, vapor, or inert atmosphere may produce conditions which defeat radiation-activated detection systems. Designing and maintaining clean detector viewing windows and testing detection in process configuration are very important. Detector viewing windows must be selected so that they do not absorb radiation in the detector sensitivity range. Sprinkler systems can also be defeated by faults in the water supply. Continuous level indication should be provided for prime water in continuous propellant line sprinkler systems. Reaction times of sprinkler systems should be measured with all adjacent systems activated as they would be in the case of a fire. Many of these findings can be selectively applied in conventional propellant or explosive manufacturing and handling operations.

REFERENCES

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2. W. A. Cabbage, "Effect of Environmental Influences on Telemac Infrared Detector Response," Hercules Report HA-77-R-9, Hercules Inc., Radford AAP, Radford, VA, December 1977.

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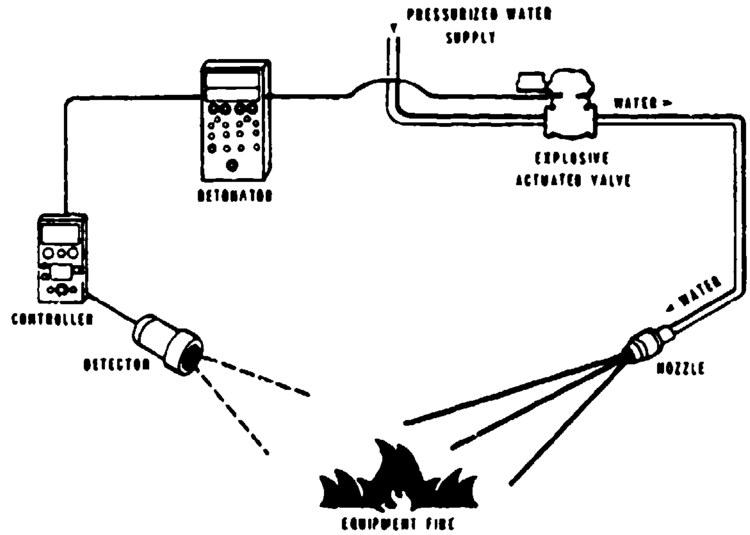
4. A. L. Matthews, "Hazards Analysis Review of CAMBL Fire Protection System, Report No. 1," Hercules Report HI-84-M-58, Hercules Inc., Radford AAP, Radford, VA, July 1984.

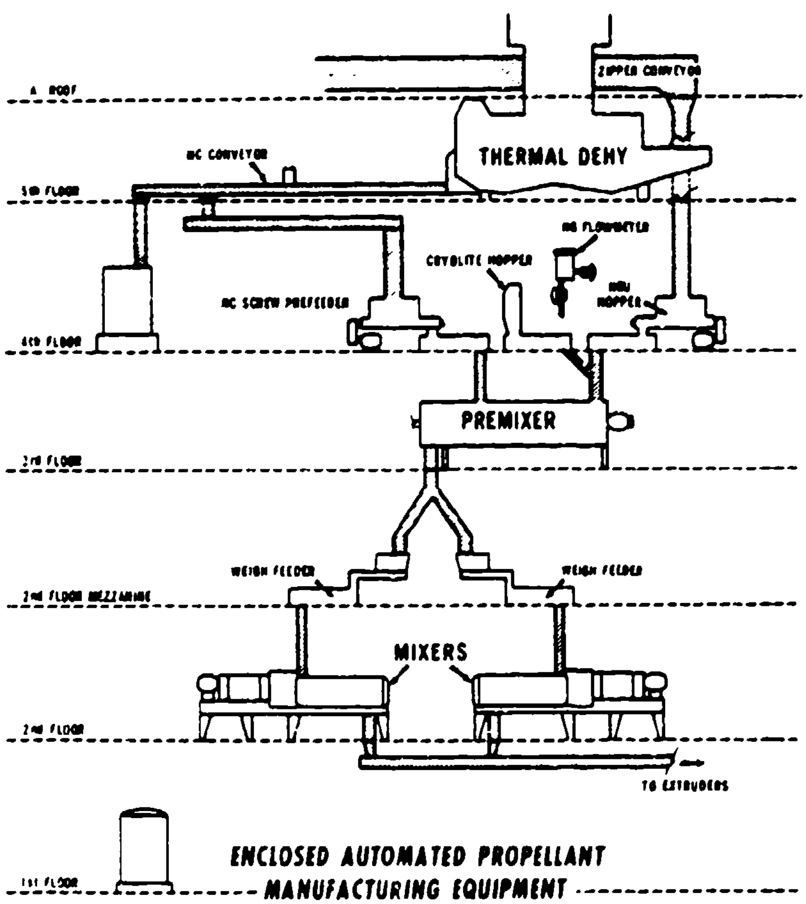
5. Hazards Analysis Small-Scale Sensitivity Test Files, Hercules Inc., Radford AAP, Radford, VA.

6. R. C. Kimball, "Sprinkler System Reaction Times," Hercules Inc., Radford AAP, Radford, VA, August 1984.



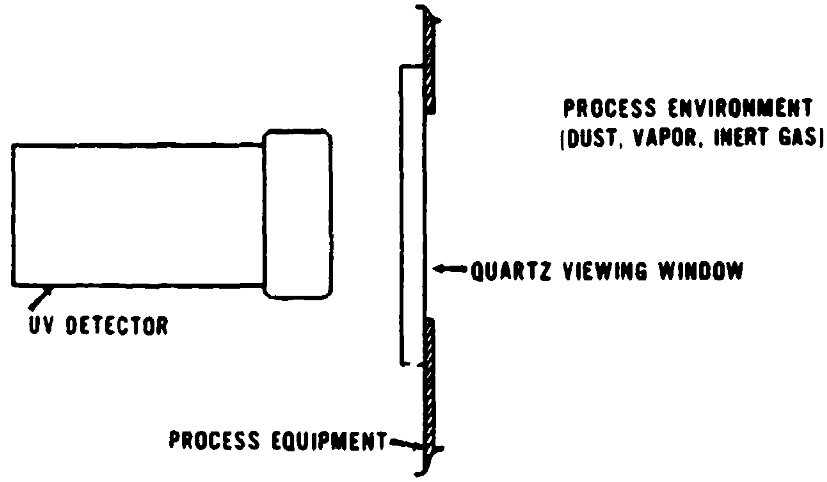
SIMPLIFIED WATER SUPPRESSION SYSTEM

FIGURE 1



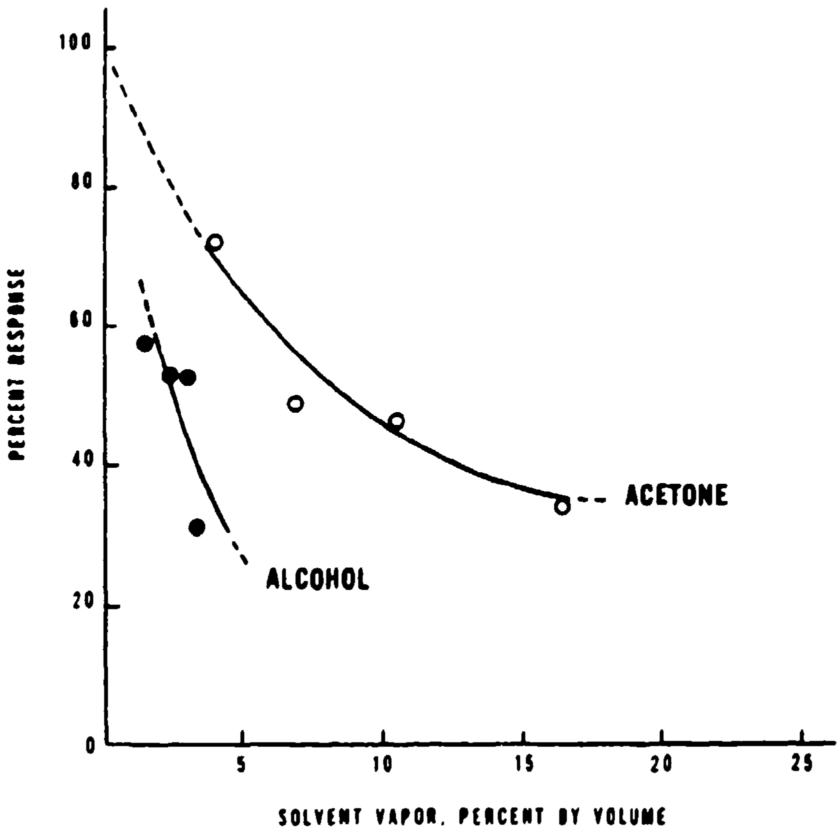
ENCLOSED AUTOMATED PROPELLANT MANUFACTURING EQUIPMENT

FIGURE 2



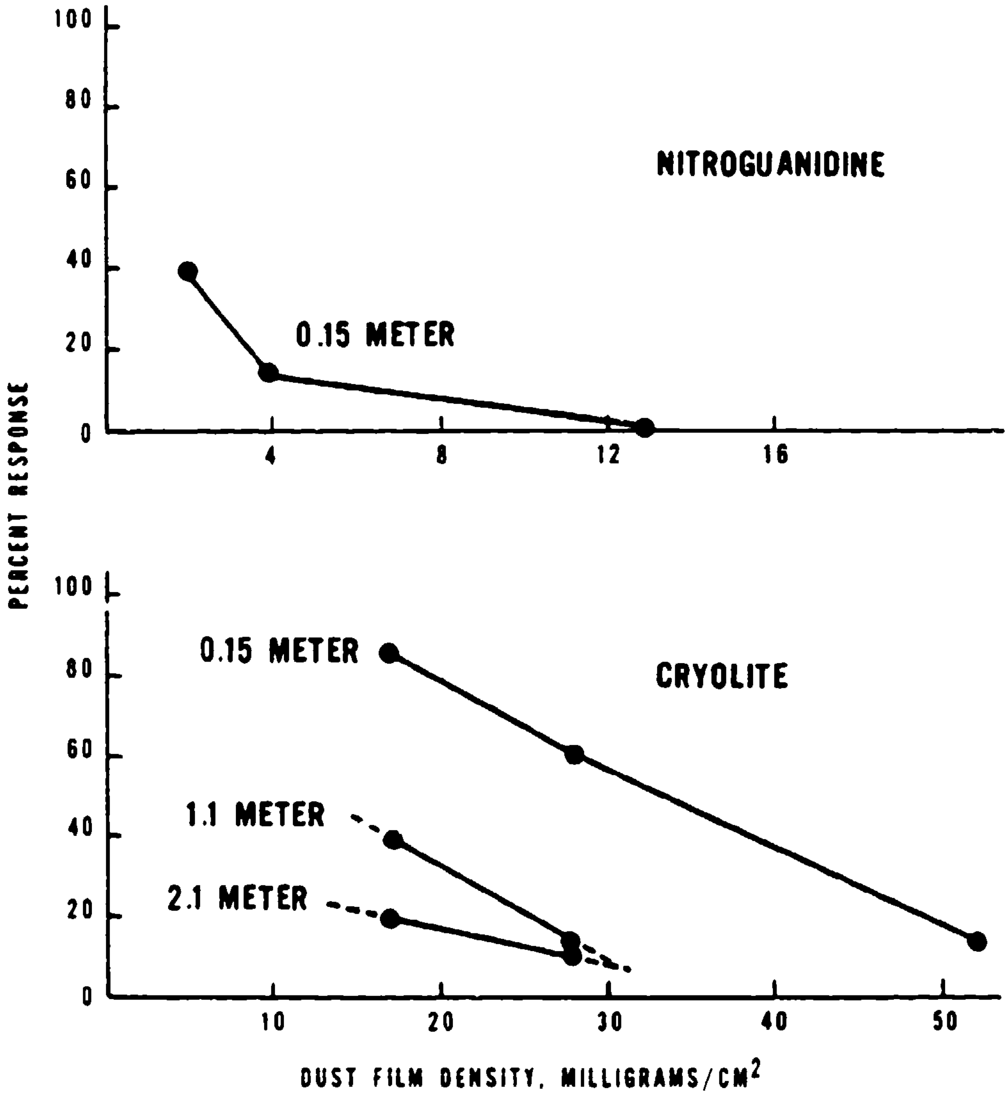
UV DETECTOR INSTALLATION IN ENCLOSED EQUIPMENT

FIGURE 3



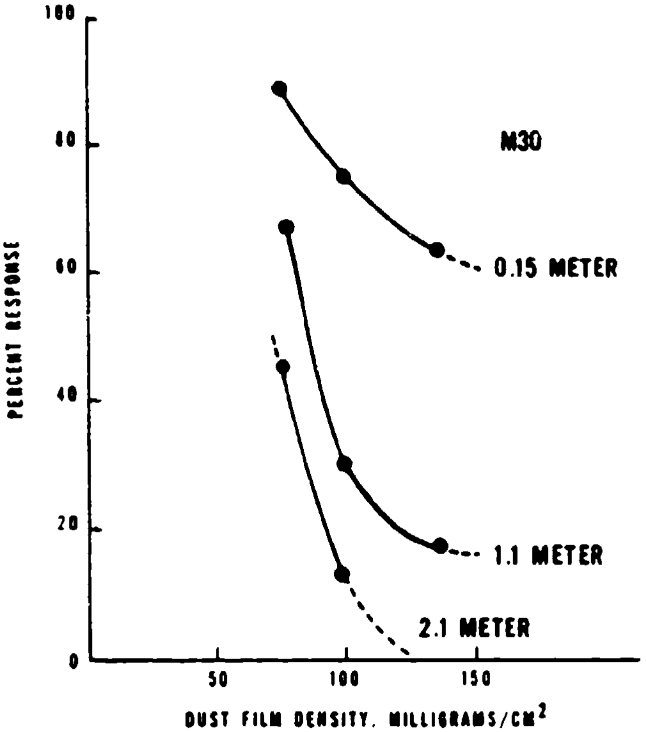
UV RESPONSE THROUGH SOLVENT VAPOR ATMOSPHERES

FIGURE 4



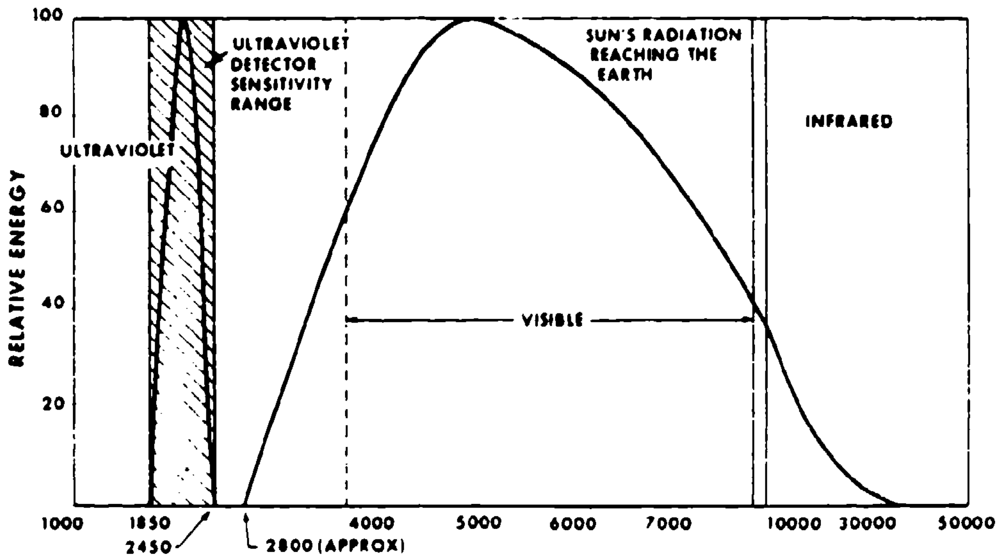
EFFECT OF INGREDIENT DUST FILMS ON UV DETECTOR RESPONSE

FIGURE 5



UV DETECTOR RESPONSE THROUGH PROPELLANT DUST FILMS

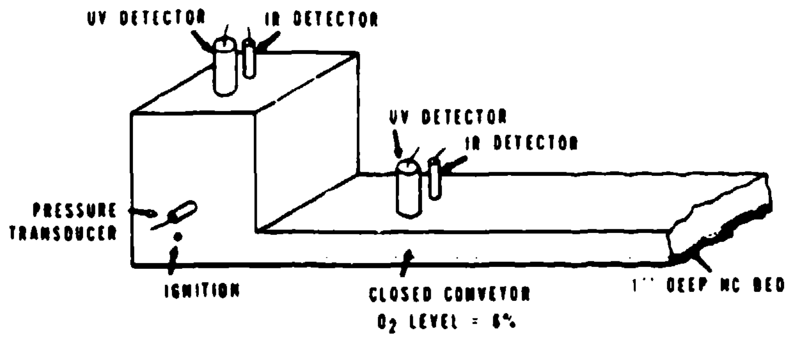
FIGURE 6



DETECTOR SENSIVITY RANGE

DETECTOR ELECTRONICS INC.

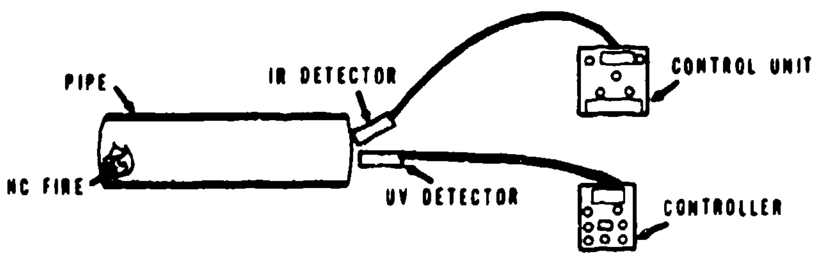
FIGURE 7



LOCATION	TEST	TEST ENVIRONMENT N_2	NC TV(%)	TIME (MS) FROM IGNITION TO DETECTION IR	UV	PRESSURE SENSOR
RADFORD AAP	1	YES	16	62	NO RESPONSE	60
	2	YES	10	51	NO RESPONSE	50
	3	YES	11	50	NO RESPONSE	50
	4	YES	16	53	NO RESPONSE	48
	5	YES	16	50	NO RESPONSE	50

DETECTOR RESPONSE PROFILE - HOPPER END OF CONVEYOR

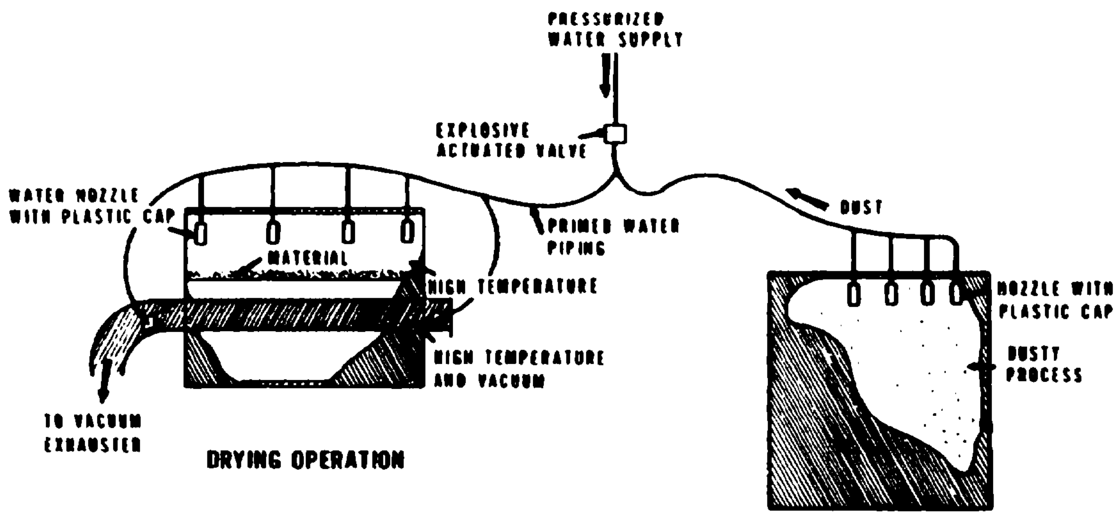
FIGURE 8



LOCATION	TEST ENVIRONMENT	COMBUSTIBLE	DETECTOR RESPONSE IR	UV
DET-TRONICS	AIR	DRY NC	YES	YES
	N_2	DRY NC	YES	NO

DETECTOR RESPONSE TO NC FIRE

FIGURE 9



PRESSURE DIFFERENTIAL IN HOPPER

FIGURE 10

IMPROVEMENT OF REACTION TIME

OPERATION	TIME (MS)[1] PIPING CHANGES BEFORE	AFTER
CONVEYING	516	130
COMPOUNDING	321	231
AIRVEYING PROPELLANT	234	137
PROPELLANT MACHINING	125	83
	158	82
	92	36

[1]MEASURED TIME FROM POWER TO SQUIB TO WATER FLOWING AT LAST NOZZLE.

TABLE 1

COMPARISON OF SPRINKLER REACTION TIMES

SPRINKLER SYSTEMS[2]	TIME (MS)[1] EACH SYSTEM ACTIVATED INDIVIDUALLY	SYSTEMS A, B, C, D ACTIVATED SIMULTANEOUSLY
A	70	200
B	70	140
C	140	240
D	180	180

[1]MEASURED TIME FROM POWER TO SQUIB TO WATER FLOWING AT LAST NOZZLE.

[2]SYSTEMS A, B, C ON SAME WATER SUPPLY RISER. SYSTEM D ON SECOND RISER. A SYSTEM CONSISTS OF COMPONENTS SHOWN IN FIGURE 1.

TABLE 2

RECENT ADVANCES IN HIGH SPEED DETECTION SYSTEMS FOR AMMUNITION PLANTS

Paper delivered at 21st Annual Department of Defense Explosives Safety Board Seminar -

Houston, Texas, August 28, 1984

by K. M. Klapmeier

Detector Electronics Corporation

Minneapolis, Minnesota.

In several previous DOD seminars, we have presented papers describing various applications of ultraviolet detection systems as applied to fire suppression in various types of propellant and pyrotechnic manufacturing and processing applications.

Today I would like to discuss application of UV detection systems in radioactive environments and application considerations of infrared, combination infrared, and combinations of ultraviolet and infrared. We will also review recent developments in high speed single frequency infrared detection systems and their applications to munitions processes.

To understand the techniques used in applying ultraviolet flame detection in hazards involving nuclear radiation, I would like to very briefly review the basic operating principles of UV flame detection. (Figure I)

This slide illustrates the general relationship between solar radiation at the earth's surface and the spectral response region of typical gas-filled ultraviolet sensors.

Ultraviolet fire detectors use a gas filled cold cathode sensor tube which is specifically designed to respond to an extremely narrow band of radiation of 1850 to 2450 angstroms. As you will note from the slide, the solar radiation spectrum is between 2850 to 30,000 angstroms. Therefore, the tube does not respond to solar radiation or normal ambient light. The visible region is from 4000 to 7000 angstroms and the infrared, beginning with the commonly defined near infrared spectrum begins at 7500 angstroms or 0.75 microns to as high as 1000 microns at the extreme infrared portion of the electromagnetic spectrum. We will return to the infrared portion of the spectrum later.

The UV detection tube produces an output of distinct current pulses. (Figure 2) Each pulse is produced when the photons of ultraviolet energy strike the photosensitive cathode ejecting an electron. This negatively charged electron is attracted to the anode which is at a plus 290 volt potential. Since the tube envelope is gas-filled, these electrons collide with gas molecules on their way to the anode, releasing more electrons which are also attracted to the anode. The result of this ionization process is a sharp increase in current flow within a few microseconds.

In a typical circuit, a detector tube will conduct current when there is a potential of 250 volts across the electrodes and a photon with the proper energy strikes the cathode. (Figure 3) Once the tube begins to conduct, it will continue to conduct unless the voltage is brought below the ionization voltage of approximately 175 volts. The basic tube electronics insures that there is enough voltage to initiate the ionization, and that the voltage decreases enough to extinguish the ionization. The result is an output of distinct pulses whose frequency is proportional to the intensity of the radiation. Therefore, it is necessary to measure a number of discharges per unit time (which sets the sensitivity) before any action is taken. It is important to remember that a single count or ionization can be initiated by normal background cosmic radiation.

The basic circuitry used for counting pulses in the past has been to take the pulse of the detector tube, amplify and square the pulse into a known time period and use that pulse to charge a capacitor. (Figure 4) After the capacitor is charged to a pre-calibrated threshold voltage, an output signal will energize the alarm relays and deluge systems.

With the advent of microprocessors in the mid-seventies it became possible to count and process the digital pulses from the UV detectors. (Figure 5) Now pulses no longer need to be stored in capacitors but can be individually counted, entered into the microprocessor, stored in memory and manipulated like any type of data processing information. Pulses can be added, subtracted, multiplied and divided in almost any way. This allows the design of flexible ultraviolet fire detectors using programmable memories and switches to provide an infinite number of combinations. Thus we now have a marriage of gas filled vacuum tube UV detection devices which have existed for several years with state-of-the-art microprocessors. One might ask since this is the age of solid state electronics, why have detector designers and manufacturers failed to utilize solid state ultraviolet sensors in their place? Major advances have been made in narrow band pass filters over the last decade, and it seems reasonable to apply them in the UV portion of the spectrum. The answer lies not in the sensors available nor in the filters available, rather in the radiation source itself. Remembering the fundamental purpose being detection of fire, and the typical industrial fire hazard being such things as munitions and hydrocarbons, the answer can be found in the emission spectrum of the fuel. (Figure 6)

This slide indicates the emission spectrum of a typical hydrocarbon ignition. The specific spectrum will of course vary with the material, but the profile is typical. Note the radiation has its greatest intensity in the IR region between 1 and 7 microns. Note also that the radiant energy axis is logarithmic and is 100,000 times less intense than that at 3 microns, for example.

Since it is true that all filters absorb energy, and since the signal strength from typical hydrocarbon fires is intrinsically low, it can be seen that any loss of signal due to filtering is intolerable. Thus the gas filled cold cathode tube possessing very high internal signal amplification is, and probably will continue to be an important element in fire detection systems.

Ultraviolet radiation detectors are good general application devices. (Figure 7) The fire signature they seek is the ultraviolet emitted by flames. Because they can be made solar blind and are not affected by heat radiation, they can be applied in a wide variety of applications.

Although UV fire detectors have many advantages, they also have their limitations. (Figure 8) Good application engineering techniques, coupled with new detector designs which actually sample their ambient conditions now permit use of ultraviolet detection in certain areas where smoke or UV absorbing vapors could occur. Lightning and welding problems have been eliminated using a combination of UV and IR detection. These systems require simultaneous sensing of both UV and IR radiation at selected frequencies. Such systems are finding wide use in applications such as aircraft hangars. However, the signal processing time required does not in general, provide the millisecond response needed in most munitions applications. We have pointed out that electromagnetic wavelengths below 1800 angstroms will not penetrate the tube envelope; however, the ultraviolet band is adjacent to that of xrays. This, in turn, is adjacent to that of gamma radiation. Both emit high energy particles that travel at less than the speed of light, and these easily penetrate the tube envelope. Once inside, they eject electrons from the cathode of the sensor in a similar manner as occurs with ultraviolet radiation. By pairing the UV sensor tube with a modern microprocessor, this application limitation has been eliminated through a technique known as nuclear surveillance. (Figure 9)

In a nuclear surveillance system there are two detectors; one is optically blinded, while the other is viewing the hazardous area. The blinded detector and the fire detector will respond similarly when exposed to nuclear radiation. If there is a fire in the area, the blinded detector will not respond but the fire detector will respond. If there is an amount of nuclear radiation in the area, but not enough to saturate the detectors, then the blinded detector will subtract that amount of radiation from the fire detector. The fire detector will still be able to respond to UV radiation from the fire. The nuclear radiation detectors can subtract about 75 milirads per hour of gamma radiation before locking out the system. The system will be automatically rearmed as soon as the radiation level goes below 75 milirads per hour. In a nuclear surveillance system setup of the detectors during initial installation is very important. If, for example, every time a nuclear hazard comes into the area the detectors become saturated and can't see a fire, then the system needs to be evaluated more closely and ultraviolet fire detection may not be suitable for this application. It is very important that both the fire detectors and the surveillance detectors are programmable so that they can take into account differing situations and not be unnecessarily desensitized. (Figure 10)

This slide illustrates the equipment used in a typical nuclear surveillance system. The detector consists of a standard UV detector mounted next to a similar detector module with its quartz window capped, making it blind to UV. The microprocessor based controller can accommodate up to 4 sets of detectors. Up to 4 controllers can be interconnected by a common data bus to provide up to 16 zones of detection.

Today's fire protection system designer has a wide variety of detection methods available. While the use of narrow band pass filters is limited in ultraviolet detection by the low signal strength by fires in that region, the opposite is true in the infrared spectrum. Advances in the development of commercially viable solid state sensors combined with excellent narrow band pass filters has led fire detector designers once again to the infrared end of the spectrum. However, as with ultraviolet there are advantages and certainly, limitations. (Figure 11)

Several advantages of IR units make them valuable in certain installations:

1. They do not respond to strong ultraviolet radiation from electric arc welding, and the infrared emitted by the heating of the metal is of low signal strength.

2. Xray and gamma radiation do not extend to the infrared and neither the single frequency or multi-frequency IR units are affected by them.

3. Smoke does not absorb strongly in the IR spectrum, making devices of this type particularly useful where heavy smoke concentrations may accompany a fire. Care must be taken that IR absorbing dusts are not part of the hazard.

Because of these characteristics, many combinations of UV and IR are now available to the fire protection designer, and properly applied will perform well in many commercial applications. However, it is extremely important to remember that the signal processing techniques necessary for reliable and stable detector operation slow down the response time of many such devices to several seconds. In contrast, the requirements of the munitions industry have become more critical, requiring faster overall detection to extinguishment response times. The IR spectrum is broad and there are many sources of IR which radiate over the entire IR band. Typical are hot manifolds, boilers, processing vessels, engines and the sun itself. The background radiation from a heat source can actually mask the presence of fire and result in failure to respond. Attempts to use the well known flicker principle cannot be totally relied on to discriminate flame from background because of such things as vibrating panels and manifolds. Easily imaginable occurrences such as sun reflecting from moving water will provide flicker frequencies that can confuse a sensing device. Many munitions applications require flame detection in enclosed spaces such as mixers, melters, conveyors and drying hoods, which deposit materials on the viewing windows of an optical detector. (Figure 12) The wavelength of infrared detectors operating in the near IR regions makes them more tolerant to lens contamination, and in general, can see through certain vapors more successfully than ultraviolet. However, to achieve the fast detection times needed, we cannot afford the luxury of the signal processing required to offset the effects of black body radiation and sensitivity to ambient light. Therefore, high speed infrared sensors must be carefully isolated from possible false alarm sources. Such sources include the sun and other black body radiation sources, high intensity lights, flashbulbs, fluorescent and, normal incandescent lighting. Ideal applications for these systems are characterized by strictly controlled, darker environments where a flash fire could originate. While simple high speed infrared systems have been available for many years, modern sensor and filter developments, coupled with state of the art electronics, have resulted in systems tailored for the munitions industry which are more selective within the electromagnetic spectrum, fast in response, and extremely flexible in application to suppression systems. (Figure 13)

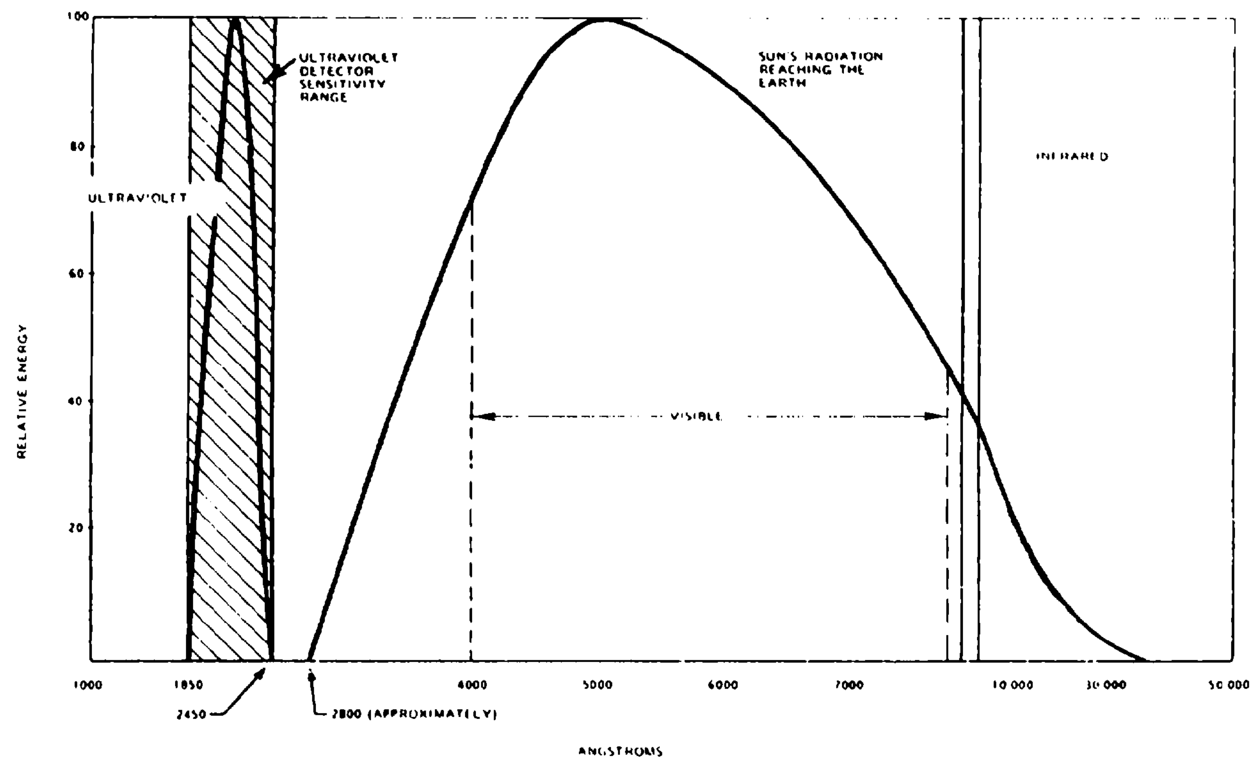
This slide illustrates a typical high speed, single frequency IR detection system which has been designed specifically for applications such as munitions manufacturing and processing. The detector consists of a solid state IR sensor operating in the 0.7 to 0.8 micron range. Since this is in the near IR spectrum, an optical filter is added to minimize extraneous and ambient light sources. The controller can accommodate up to four detectors and will respond when any one of the four senses IR radiation above the alarm threshold. Typically such controllers also electrically supervise interconnecting wiring and explosive squibs or solenoid valves by trickling a small current through the external circuits.

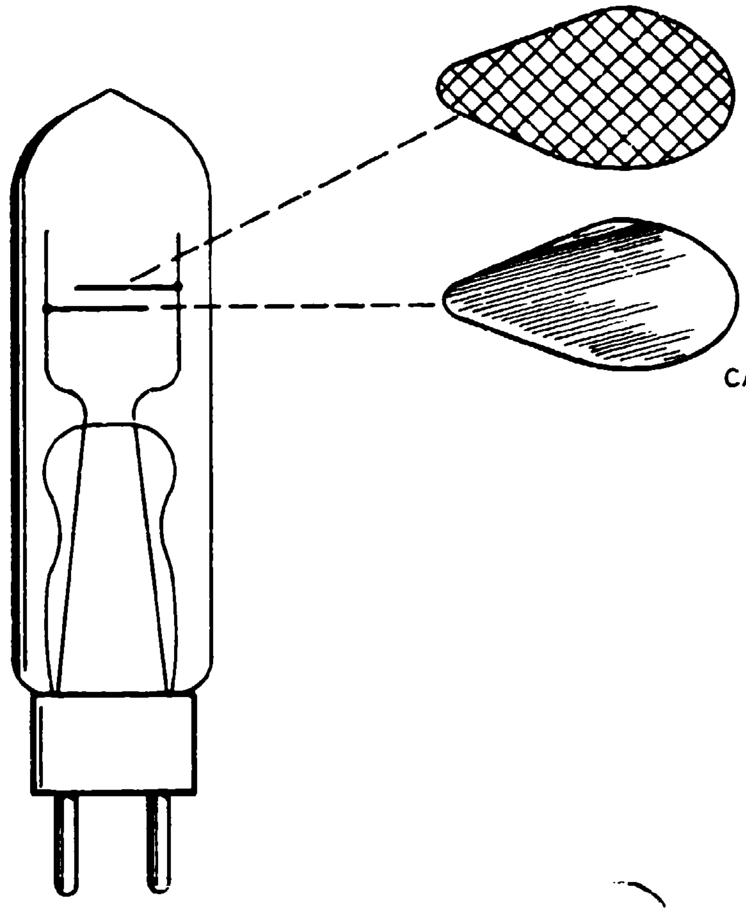
Response time of such systems is a function of ignition size, type of material, ambient air, fumes or vapor composition, distance and orientation of the fire source. Average response times to a high energy IR source can range from a few microseconds to several milliseconds at distances up to 3 feet.

Typically, these systems are recommended to be used in combination with the appropriate high speed ultraviolet systems, combining the advantages of ultraviolet for space protection, with infrared for enclosed areas.

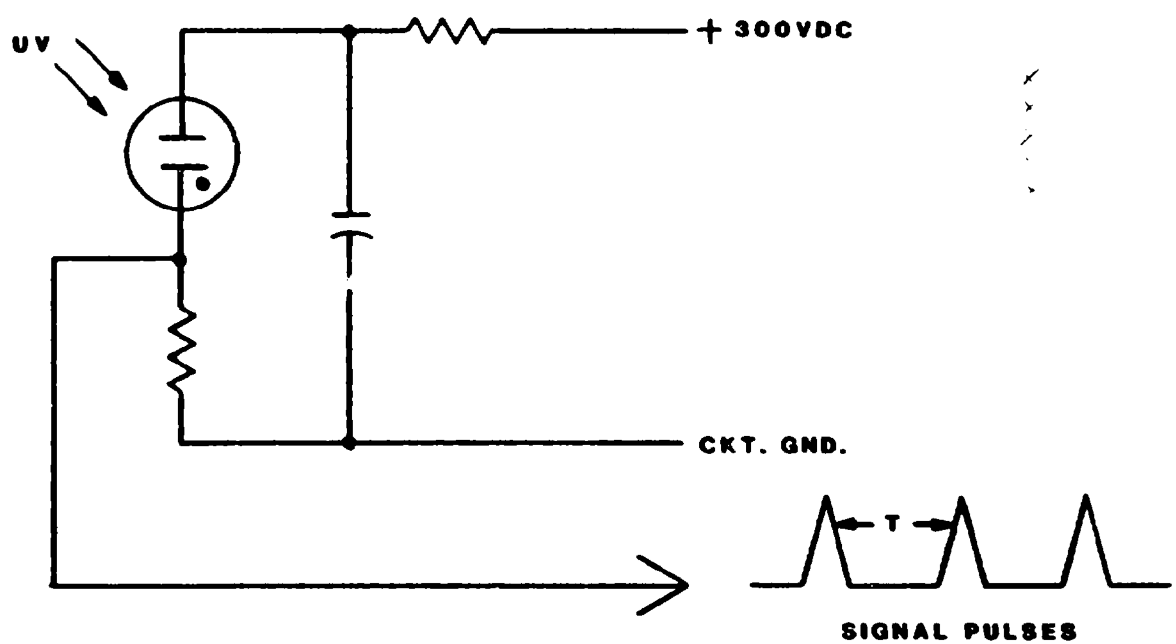
In summary, we have observed that ultraviolet and infrared fire detectors both have definite advantages, but also limitations. Combination detectors may be too slow for some munitions applications. By utilizing microprocessor technology, optical integrity and remote surveillance, previous limitations have largely been overcome. As fire detector manufacturers we feel a responsibility for clearly defining both the advantages and limitations of equipment we supply, which enables the fire protection engineer, and the end user as well, to skillfully and properly determine the correct detection equipment for a given application. A more detailed discussion of detector application is available in Det-Tronics' Detector Selection Guide, Form No. 92-1002.

We wish to express our appreciation to the organizers of this 21st Explosives Safety Board Seminar for the opportunity to present this material and to describe the advances in detection technology that have occurred since our last presentation.

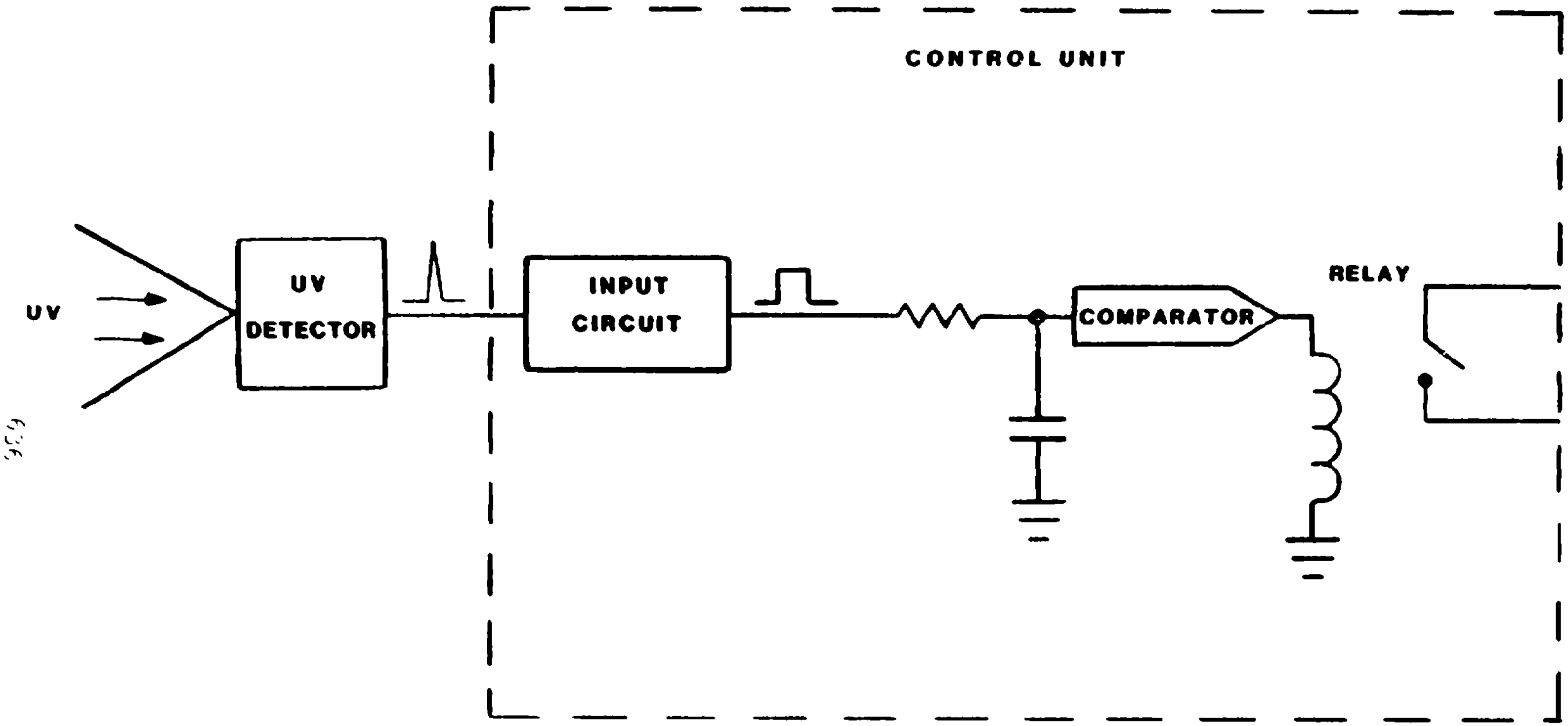

RELATIVE ENERGY
100
80
60
40
20
ULTRAVIOLET
ULTRAVIOLET DETECTOR SENSITIVITY RANGE
SUN'S RADIATION REACHING THE EARTH
INFRARED
VISIBLE
1000
1850
4000
5000
6000
7000
10 000
30 000
50 000
2450
2800 (APPROXIMATELY)
ANGSTROMS



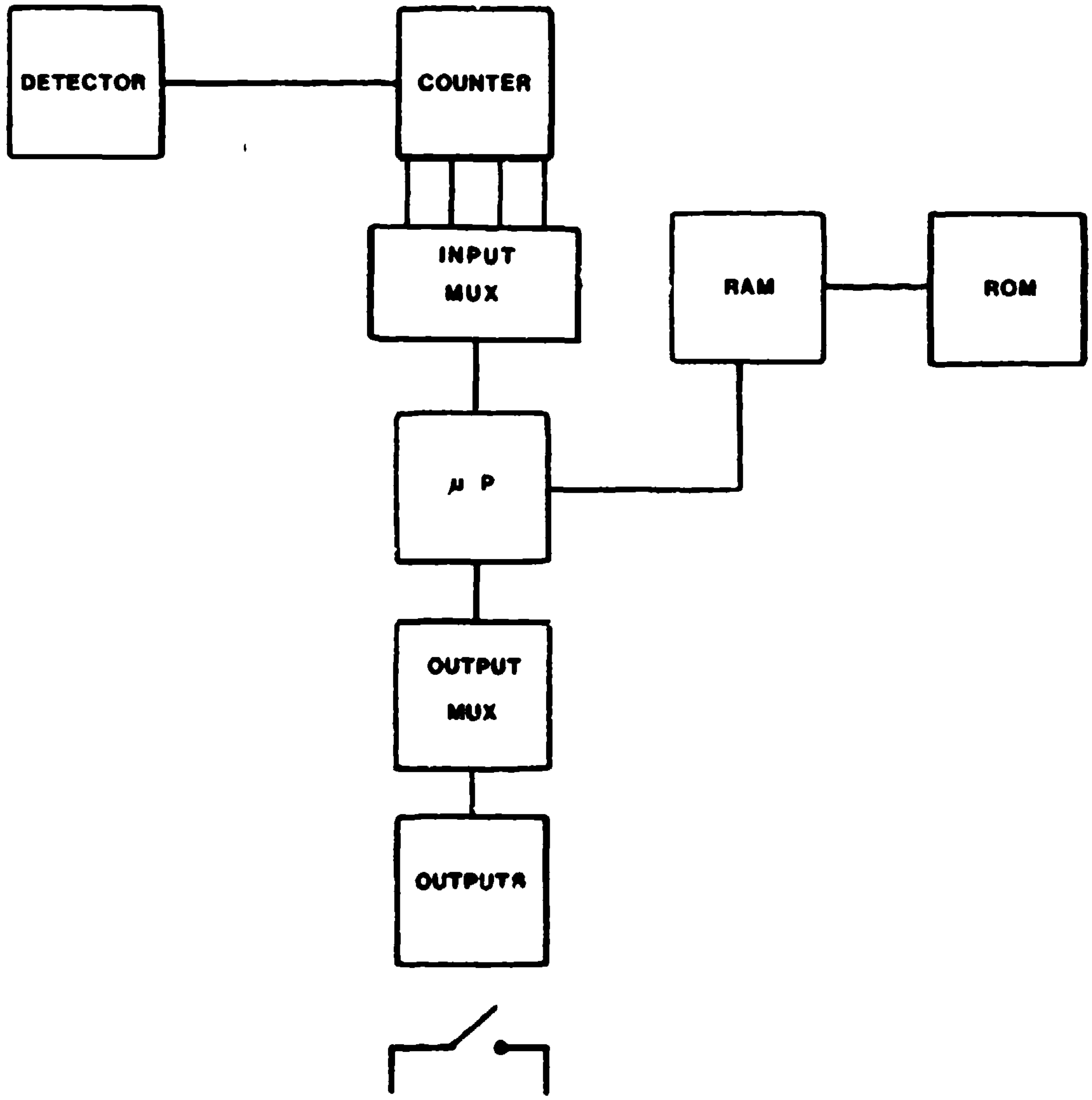
DET-TRONICS ULTRAVIOLET DETECTOR



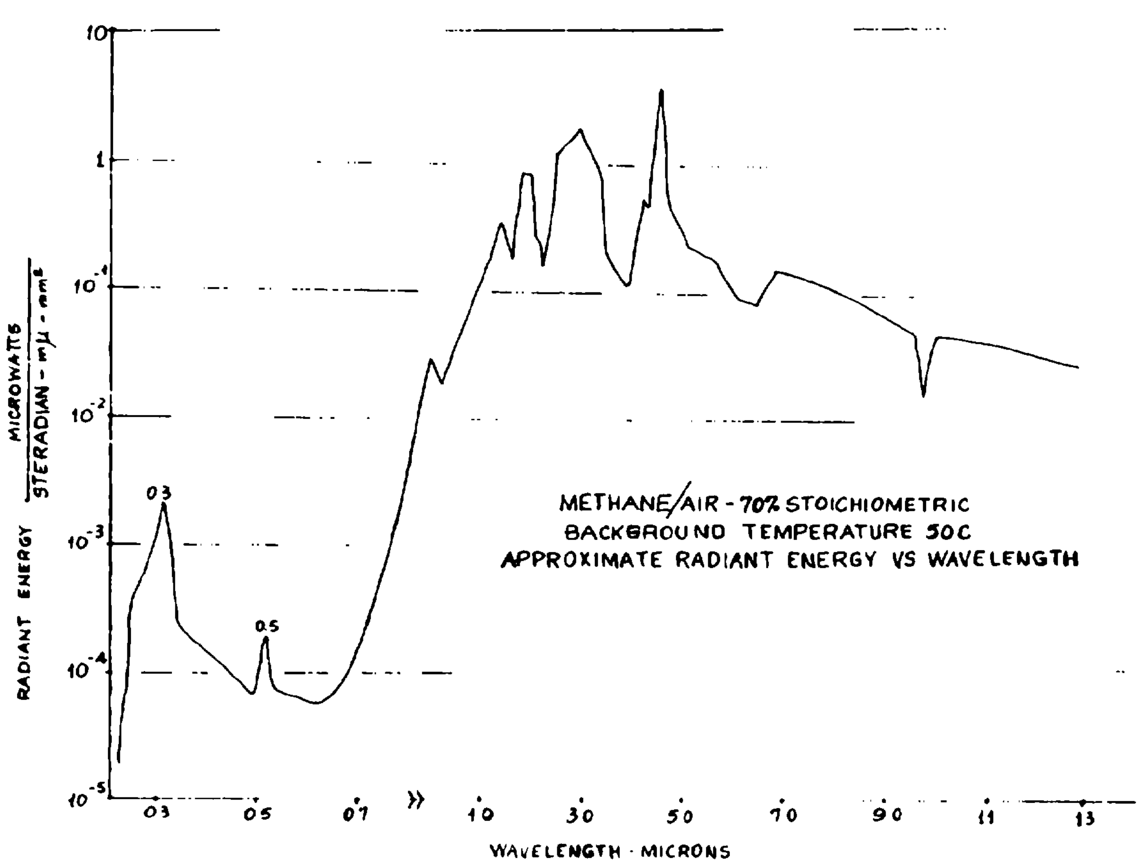
TYPICAL UV DETECTOR CIRCUIT



BASIC UV FIRE DETECTOR



MICROPROCESSOR (μP) BLOCK DIAGRAM


METHANE/AIR - 70% STOICHIOMETRIC
BACKGROUND TEMPERATURE 50C
APPROXIMATE RADIANT ENERGY VS WAVELENGTH
RADIANT ENERGY
MICROWATTS / STERADIAN - mμ - mm²
WAVELENGTH · MICRONS
0.3
0.5
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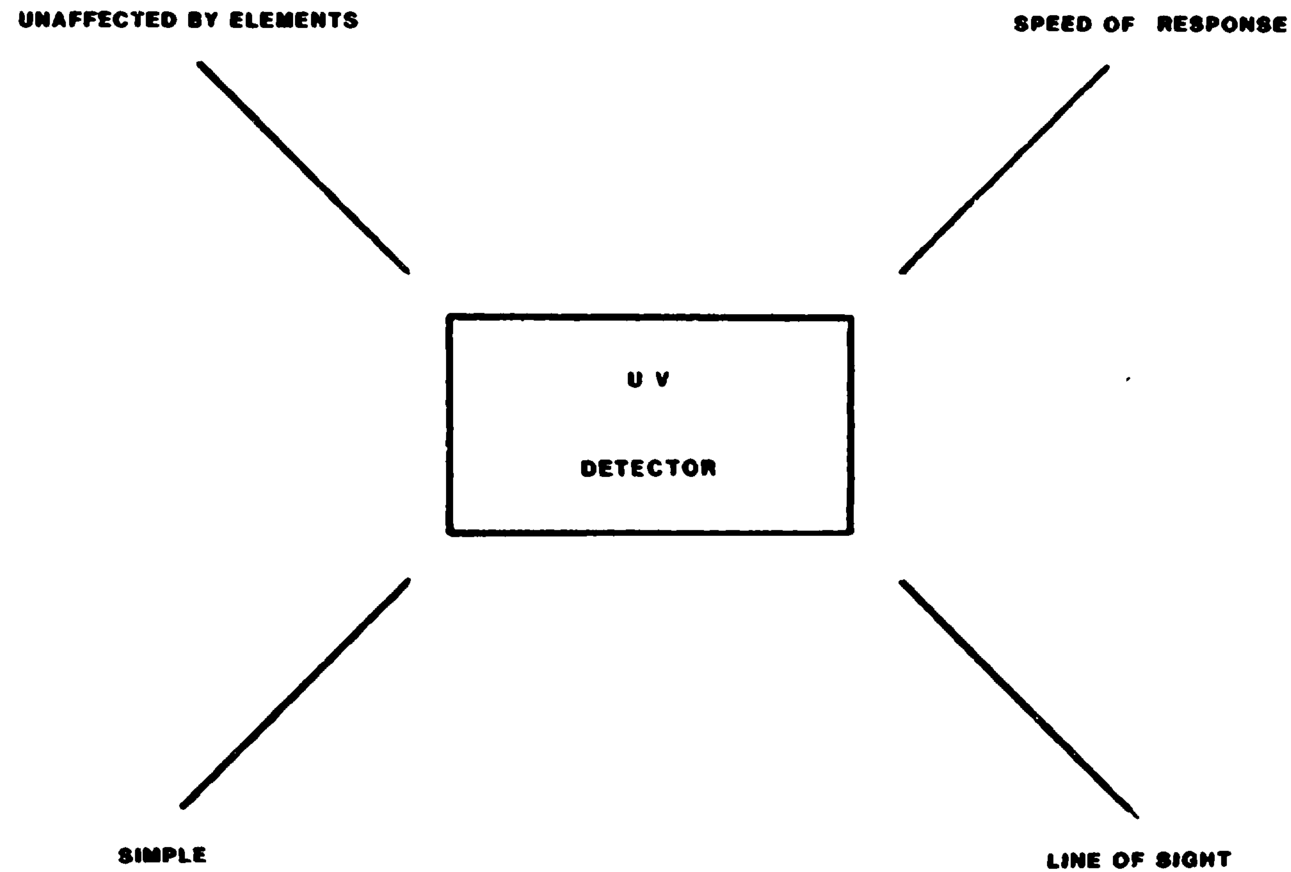
UNAFFECTED BY ELEMENTS
SPEED OF RESPONSE
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DETECTOR
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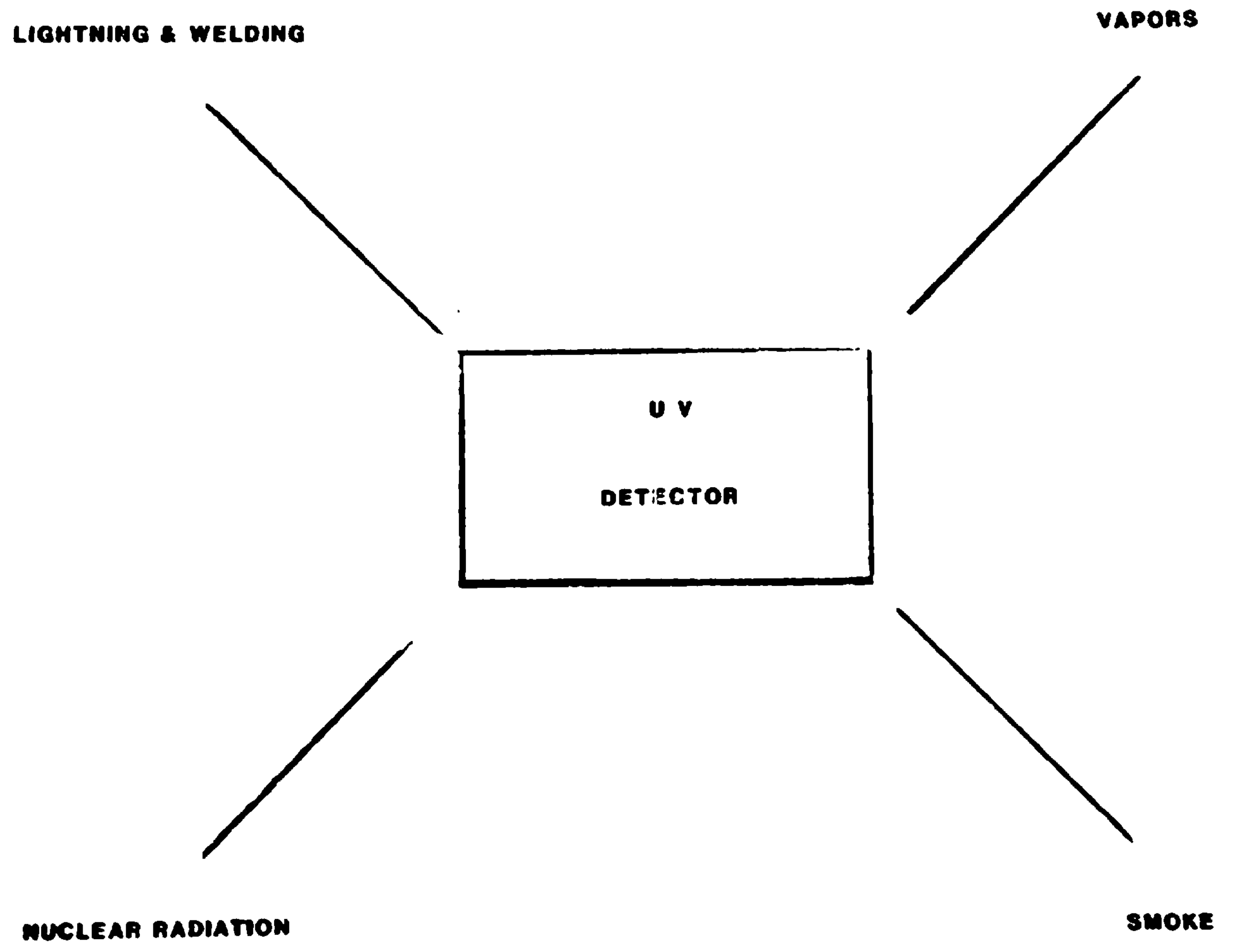
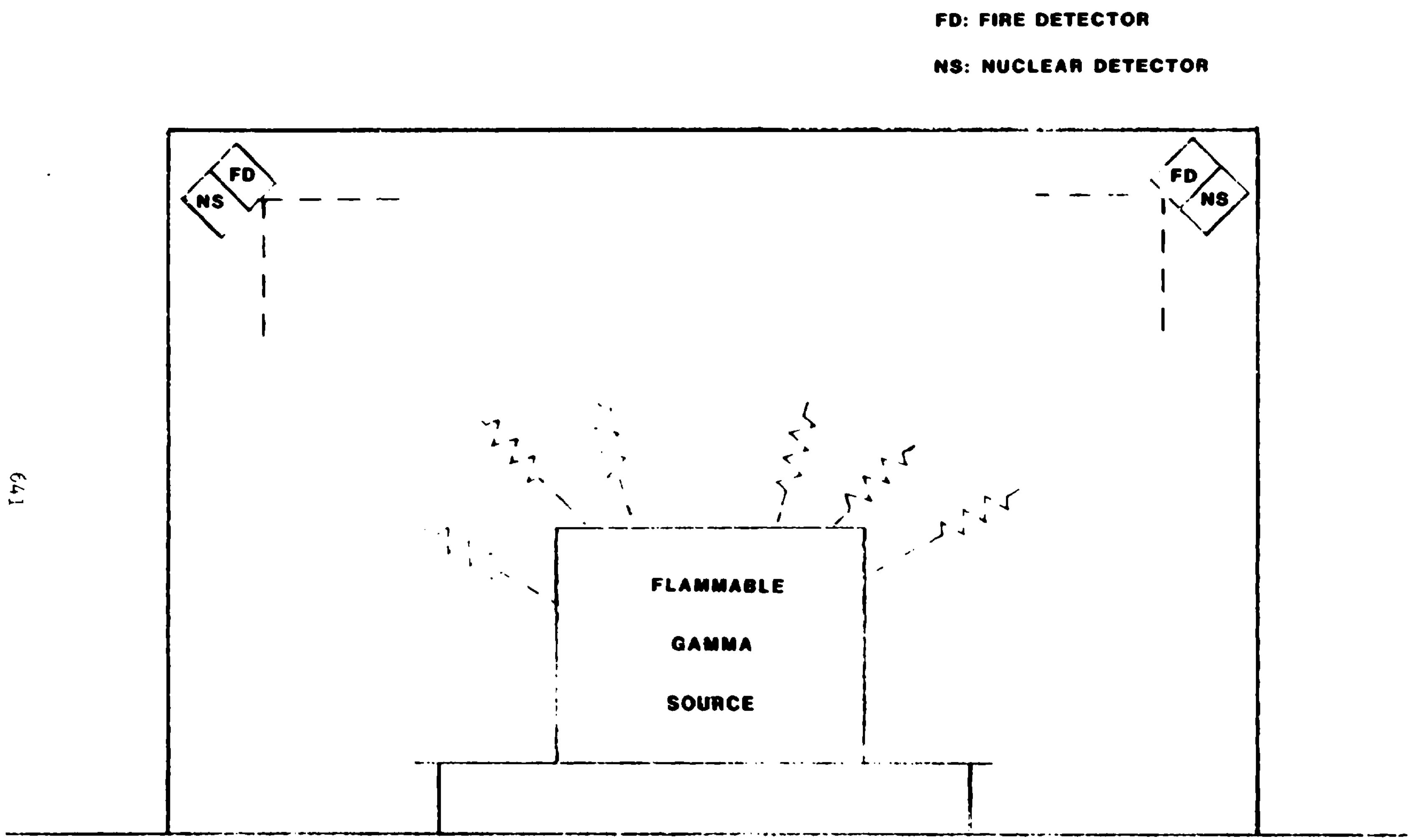
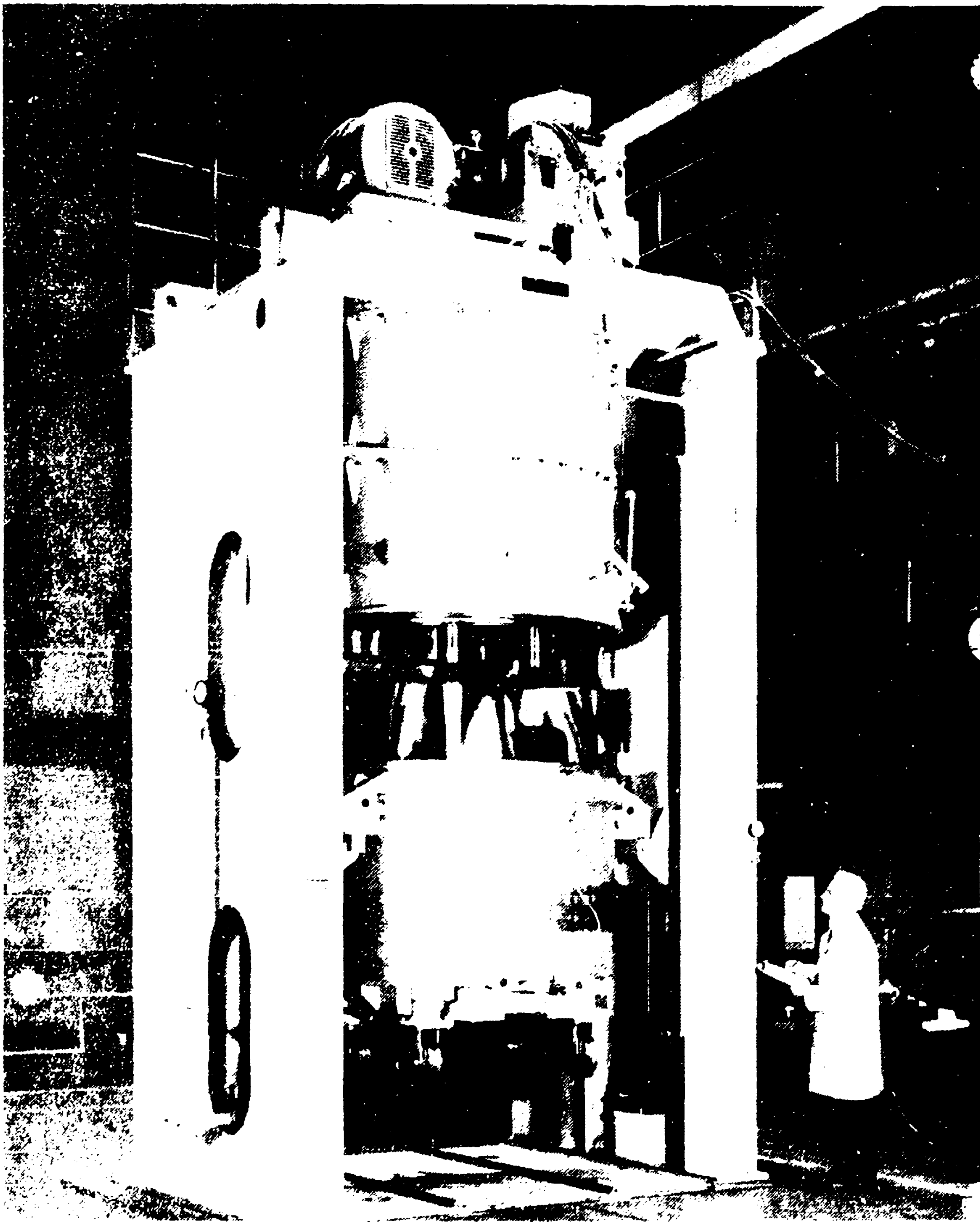
ADVANTAGES

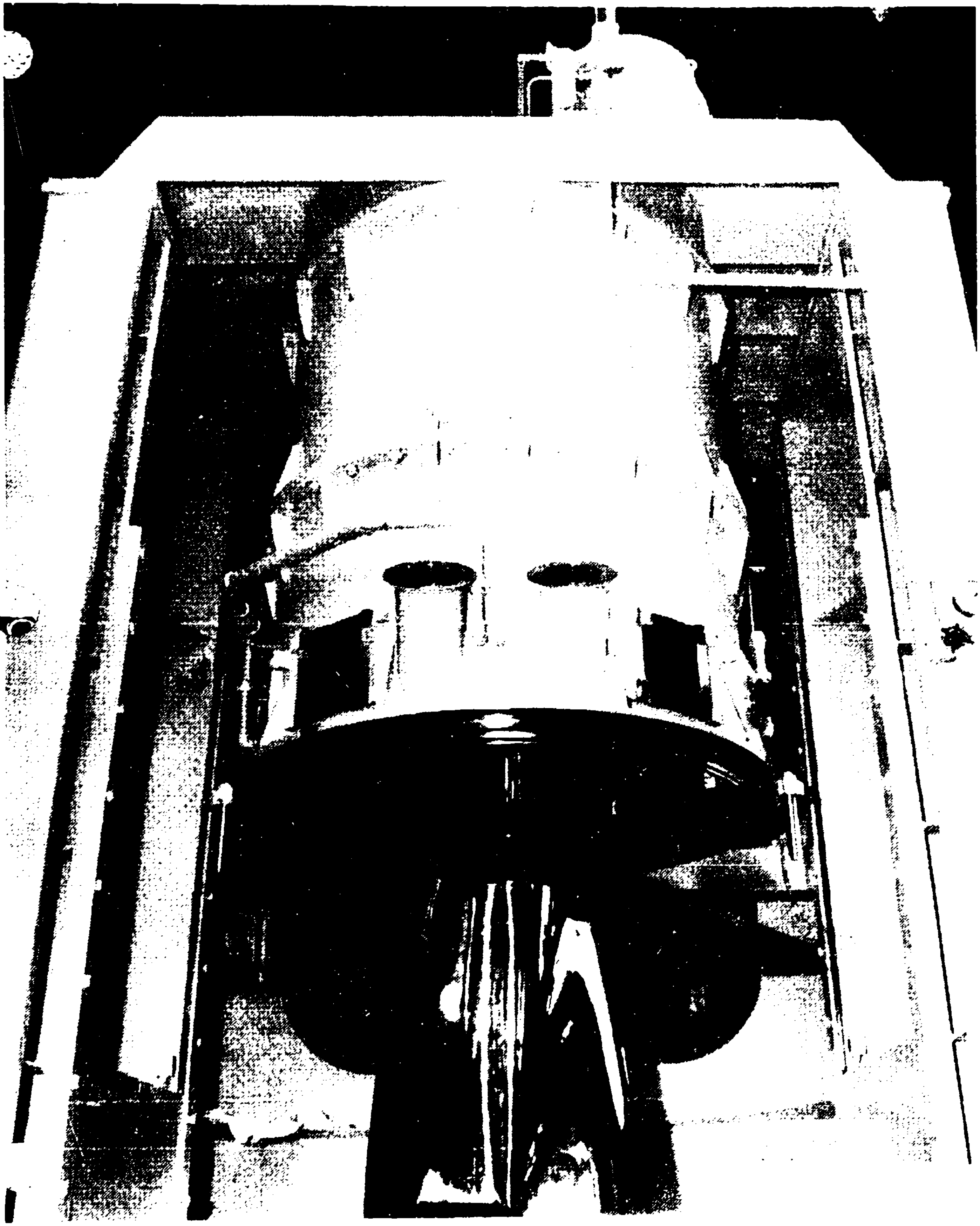


LIMITATIONS



NUCLEAR SURVEILLANCE





INTRINSICALLY SAFE ELECTRICAL CIRCUITS

THEIR APPLICATION IN EXPLOSIVE ENVIRONMENTS

Prepared

for

DEPARTMENT OF DEFENSE

TWENTY-FIRST EXPLOSIVES SAFETY SEMINAR

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by

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ABSTRACT

The successful application of intrinsically safe electrical circuits depends upon a complete understanding of the concept of intrinsically safe; the concept's utilization during design and evaluation. A discussion is presented reviewing the history of intrinsically safe and what it is. Further, its application in an explosive environment is explored and employment of the concept during design and evaluation is given. Also, the needs for further employment of its use are stated.

ACKNOWLEDGEMENTS

The author wishes to thank the National Fire Protection Association and Factory Mutual Research for permission to reproduce portions of their material.

Table of Contents

1. INTRODUCTION

Today in designing for the manufacture, maintenance, or demilitarization of ammunition, there is a choice of four different approaches which may be used to protect against an electrical spark in a hazardous area.

The first approach is to not use electrical energy in the hazardous area, to use it only in the non-hazardous area to drive pneumatic or hydraulic equipment which will provide the energy in the hazardous area. However, this provides for slow response time, especially if the devices are sensing or metering equipment.

The second approach is to encase the electrical energy in steel pipes with tight fittings, to design the motors and switches with wide flanges. This kind of design is called explosion proof. Not because it does not permit an explosion, but because in designing it, it permits an explosion. However, the explosion is of low magnitude; contained within the heavy construction; and does not spread to the outside.

The third approach is the use of purged enclosure. In this application, the use of positive pressure within the enclosed electrical circuit eliminates or reduces the amount of hazardous atmosphere which is available to react with a spark. Clean air or an inert gas is pumped into the enclosure from outside of the hazardous area to maintain this positive pressure.

The final approach is rather a new use of an old concept, the use of intrinsically safe electrical circuits.

2. HISTORY OF INTRINSICALLY SAFE ELECTRICAL CIRCUITS

At the turn of the century in Germany, research was begun on the effect of an electrical spark on methane-air mixtures. This work would play an important role several years later in Britain.

In Britain in 1912 and 1913 a rash of mine explosions lead to a formal court inquiry. It was found that at this time, the practice of signaling was accomplished by the rubbing together of two bare wires connected to a battery to form a circuit. As a result of the court findings, testing became required for signaling equipment in British mines.

This task was assigned to what is now called the Safety in Mines Research Establishment. It was at that organization where the concept of intrinsically safe electrical circuits was first defined by Wheeler after continuing the research into the ignition of methane-air mixtures.

In 1936, the first certificate was issued in Great Britain for an electrical device which was not to be used in a mining operation.

In 1938 in the United States, work was begun on rules for telephone and signaling equipment by the Bureau of Mines.

Up until the 1950's the use of intrinsically safe electrical circuits had little application in other than just battery operated signaling devices. Beginning at this time, it became technologically feasible to manufacture electrical circuits with solid state electronics.

The United States was the first to recognize this and in 1956 the National Electrical Code (NEC) introduced the use of intrinsically safe electrical circuits.

> "Equipment and associated wiring approved as intrinsically safe may be installed in any hazardous location for which it is approved, and the provisions of Article[1] 500 and 510 will not apply to such installation.

However, no guide was given for the construction or testing of the circuit.

In 1967, the National Fire Protection Association (NFPA) issued NFPA 493-1967 which defined specific tests and construction techniques to be used. Today, the current standard is NFPA 493-1978.

Intrinsically safe electrical circuits are now recognized around the world.

Great Britain	1959
Netherlands	1957
France	1965
West Germany	1965

However, the standard used in the U.S. does not coincide with the standards of Europe, due to the use in Europe of a different system of denoting the type of environments and a basic difference in the energy allowed to be used. Within the United States, NFPA calls for a safety factor of 1.5 on the amount of energy released, or for the components to operate at 2/3 their rated energy level. The International Electrotechnical Commission (IEC) and European Committee for Electrotechnical Standardization (CENELEC) require that a Safety factor of 1.5 on both the voltage and the current, which relates to a 2.25 factor of safety on the energy.

3. WHAT INTRINSICALLY SAFE ELECTRICAL CIRCUITS ARE

Webster's defines intrinsic as

> "naturally, essentially, or inherently"

and defines safe as

> "free from damage, danger or injury; unable to cause trouble or damage."[2]

From this the definition can be derived to mean:

> inherently and naturally unable to cause trouble, damage, or injury.

Many people use the above definition to mean if a circuit is of low voltage it is therefore intrinsically safe since it can not cause ignition. However this is not the case, because the definition as stated in NFPA qualifies the above definition.

> "1-4.1 Intrinsically Safe Circuit. A circuit which any spark or thermal effect, produced either normally or in specified fault conditions, is incapable, under the test conditions prescribed in this standard, of causing ignition of a mixture of flammable or combustible material in air in most easily ignited concentration".[3]

The qualification being not only in its normal mode of operation but, also, under specified modes of failure. Therefore, it is not enough to state that the circuit is of low voltage and because of this is intrinsically safe.

Throughout this paper the term used has been intrinsically safe electrical circuit. The reason for this, is because that is what has to be considered. Not just the electrical apparatus used in the hazardous environment, but the wiring and the apparatus located in the non-hazardous area. Further the effects of the apparatus in the non-hazardous area and the wiring must be considered as to how they effect the apparatus in the hazardous area, not only under normal operation but if a fault should occur anywhere in the circuit. To go even one step further, NFPA 493-1978 states

> "The most unfavorable combination of two faults and any subsequently related faults, with no additional factor [no safety factor of 1.5]"[4]

must be considered.

3.1 Faults - Normal and Abnormal

Further, NFPA 493-1978 defines two classes of faults - normal faults and abnormal faults.

3.1.1 Normal Faults

Normal faults are considered part of the normal operation and therefore are in addition to the faults which must be introduced in order to be considered intrinsically safe. They are:

1. shorting of the field wiring;
2. grounding of the field wiring;
3. opening of the field wiring;
4. adjustments at the most unfavorable settings;
5. tolerances of all components combined to form the worst case.[5]

3.1.2 Abnormal Faults

Abnormal faults are determined by analyzing the intrinsically safe circuit for all possible combinations of conditions which can cause the energy level to be increased. During this analysis, if a component is considered a protective component, a component which can not increase the energy level, it may be left out of the analysis to simplify the procedure. This analysis is not only of the electrical properties which might increase their energy levels but, also, of their physical layout in the circuit.[6] The conditions to be considered are accidental damage to wiring, failure of electrical equipment, applications of voltages too high, maintenance operations, and other similar conditions. The purpose is to locate possible spark ignition sources which can be caused by minimum resistances and impedance, maximum inductive and capacitive areas of the circuit which can result in the energy level being raised.

4. WHY BOTHER WITH INTRINSICALLY SAFE ELECTRICAL CIRCUITS

In spite of the above, intrinsically safe electrical circuits offer many advantages that the other three methods of electrical design do not.

First, once designed and evaluated, the safety of the system can not be degraded, because the safety is in the design, not protection added afterward. In fact the system will cease to fulfill the function for which it was designed before the safety can be compromised due to the requirement considering faults.

The only way for the circuit to become hazardous is if a component is replaced with the wrong type.

Secondly, the circuits do not require extra money to be spent on added protection as in the case of explosion proof or purged systems. These systems can lose their protective nature by just a fitting not being tightened correctly.

Finally, intrinsically safe electrical circuits offer speed in response time which is not available through the use of pneumatic or hydraulic systems.

Today with the increasing use of remote control, robotics, and sophisticated measuring devices, the use of intrinsically safe electrical circuits would appear to be the answer.

5. CONSTRUCTION AND EVALUATION

5.1 Construction and Evaluation Principles

Primarily there are just three (3) principles to keep in mind when designing or evaluating an intrinsically safe electrical circuit. They are:

1. Limit Energy
2. Separating Circuits
3. Separating Raceways

5.2 Limiting Energy

All intrinsically safe electrical circuits depend upon limiting the energy available to be released. This is accomplished by limiting the voltage and limiting the current. NFPA 493-1978 contains in chapter 5 a set of graphs, which can be used as a guide during the design process. These graphs are for resistance circuits, resistance-inductance circuits, and resistance-capacitance circuits. The graphs show the minimum ignition curve for groups A, B, C, D, and Methane based upon the electrical properties of the particular circuit involved.

5.2.1 Limiting the current.

The current is easily limited by the use of resistors. For intrincically safe circuits. There are two classes of resistors which may be used - a standard resistor and a protective resistor.

If a standard resistor is used in the current, then redundancy needs to be added. Generally the use of three is sufficient unless other precautions are taken.

A protective resistor is defined as

> "current-limiting resistors shall be considered not subject to short-circuit, if they are of the metal or metal-oxide film type, of the wire-wound type with protection to prevent unwinding of the wire in the event of breakage or of similar construction[7] whose normal failure mode increase resistance and withstand continuously [i.e. until temperatures become stable or until is obvious that no further deterioration will occur] 1.5 times the maximum fault voltage across the resistor or shall fail by increasing resistance, or by decreasing resistance by not more than 10 per cent. Resistors shall not flame during the test."[8]

further stating

> "Properly derated film and wirewound resistors have been found suitable as protective components for use within intrinsically safe apparatus and associated apparatus. Resistors included on the Department of Defense Qualified Products list and meeting the specifications of MIL-R-10509F, MIL-R-11804E or MIL-R-22684B and operated at no more than two-thirds of their rated power under normal or fault conditions do not normally require test."[9]

5.2.2 Limiting Voltage

The limiting of the voltage can be accomplished in several ways. However, it is usually done at the interface between the intrinsically safe portion of the circuit and the non-intrinsically safe portion in the non-hazardous area. The exception being for circuits which use a battery, are totally self-contained and reside in the hazardous area totally.

The use of a transformer is acceptable if it meets the requirements of NFPA 493-1978 3-5.1 and is classified as a protective component.

Gas tubes may also be used; however their use in today's world is not seen very often.[10]

The most widely and acceptable method of limiting voltage[11] is the use of a zener safety barrier. A zener safety barrier consists of zener diodes connected back to back with the connection of two, grounded, therefore any voltage apppearing between the diodes and ground will be limited in value. The working rating of the zener diodes is therefore chosen to be above the peak value of the normal working voltage of the intrinsically safe circuit. Several companies manufacture modular forms[12] which offer flexibility of design and at the same time are tested and approved for use in intrinsically safe circuits.

5.2.3 Other Energy Considerations

Relays can also be used in intrinsically safe electrical circuits to limit voltage. They must conform to the requirements of NFPA 493-1978 3-6.3.

The use of series connected semi-conductors, in general, is not an acceptable means of limiting the current because they can easily short-circuit.

Blocking capacitors may be used. They must be in series of two and be able to withstand twice the voltage of the circuit plus 1000 volts across them. They must, also, be ceramic or hermetically sealed; electrolytic and tantalum capacitors are not acceptable.

5.3 Separating Circuits

After the design of the intrinsically safe electrical circuits has met the requirement for limiting the available energy which could cause ignition, it then becomes necessary to physically separate the intrinsically safe electrical circuits from the non-intrinsically safe electrical circuits. This can be accomplished by distance, enclosure, partitions and insulation. The objective of the physical separation is to meet the requirements of Table 3-1, NFPA 493-1978, for creepage and clearance. If the values do not meet the requirements of the table or qualifications of the table as listed in Chapter 3, then the deficiencies must be considered a normal fault condition.

5.3.1 Distance Separation

The minimum distance for separation of terminals between an intrinsically safe electrical circuits and a non-intrinsically safe electrical circuits is two (2) inches.

The minimum distance for separation of insulated wires of intrinsically safe electrical circuits and non-intrinsically safe electrical circuits is 0.116 inches and is determined by Table 3-1 based on the sum of the two circuits involved.

5.3.2 Enclosure

The intrinsically safe electrical circuits and non-intrinsically safe electrical circuits may be separated by enclosing each in a separate enclosure. If the enclosure is within a common enclosure, then consideration must be given to prevent excess wire of either circuit from being able to contact the other.

5.3.3 Partitions

The use of rigidly constructed, grounded metal or insulated partitions may be used to separate the intrinsically safe electrical circuits from the non-intrinsically safe electrical circuits. Again, the consideration must be given to excess wire of either circuit.

5.3.4 Insulation

In addition to physical separation above, the insulated wire for the circuits must meet these requirements.

For the intrinsically safe electrical circuits, the insulation must be capable of withstanding an ac test of twice the normal working voltage or 500 volts rms, whichever is greater.

For the non-intrinsically safe electrical circuits, the insulation must be capable of withstanding an ac test of twice the working voltage plus 1000 volts or 1500 volts rms, whichever is greater.

Further, if the wiring of the non-intrinsically safe electrical circuits is not rated as NEC Class 2 or 3 power-limited circuit, then the wiring of one of the two circuits must be enclosed in a grounded shield.

5.4 Separating Raceways

The final step in the design or evaluation is to consider the raceways of both the intrinsically safe electrical circuits and non-intrinsically safe electrical circuits.

5.4.1 Separate Raceways

The wires of the intrinsically safe electrical circuits should be installed so that they do not come into contact with the non-intrinsically safe electrical circuit's wires; contact any live parts; or electronic devices, due to induction and capacitive pick-up, which would add to the available energy for release. This is most easily accomplished by providing separate raceways for the intrinsically safe electrical circuits and non-intrinsically safe electrical circuits. The raceway being an enclosure which provides rigid separation and provisions for grounding.

In addition, if the wires of different intrinsically safe electrical circuits come in contact with each other and are not protected from being cut or damaged, then they either have to be separated by the distance of Table 3-1 or must be considered to be one circuit during analysis of normal faults[13].

5.4.2 Grounding and Bonding

Within an enclosure, containing both intrinsically safe electrical circuits and non-intrinsically safe electrical circuits, a separate grounding cable should be used. This cable should be insulated and separated from the grounding cable of the non-intrinsically safe electrical circuits. This will preserve the integrity of the intrinsically safe electrical circuit. The maximum resistance allowable is one ohm, measured from the furtherest point on the grounding bus to the ground reference point.

Bonding shall be used for all metal enclosures of intrinsically safe electrical circuits which will insure connection with the grounding point for the intrinsically safe electrical circuits as described above. This is usually accomplished by bonding to the structure of the building, to a ground system, or to the grounding point of the intrinsically safe electrical circuits in the enclosure.[14]

5.4.3 One Last Raceway Consideration

The raceway for the intrinsically safe electrical circuits must be sealed where it enters the hazardous area. This is done to prevent gas, vapors, or dust from migrating from the hazardous area into the non-hazardous area.

5.5 Marking and Interchangeable Parts

5.5.1 Marking

Intrinsically safe electrical circuits and intrinsically safe apparatus and circuits should be marked as per the requirements of NFPA 493-1978 4-2. This section, in addition to the use of lettering, calls for the intrinsically safe electrical circuits, intrinsically safe apparatus, and intrinsically safe electrical circuits wiring to be indicated by using bright blue as the indicating color.

5.5.2 Interchangeable Parts

The intrinsically safe electrical circuits must be designed in order to prevent replacing of an intrinsically safe component with a non-intrinsically safe component. This can be accomplished by the use of different types of plugs and receptacles.

6. PUTTING IT ALL TOGETHER

After having designed and evaluated an electrical circuit to conform to NFPA 493-1978, can it now be considered intrinsically safe? In a word, no!

OSHA Safety and Health Standards (29 CFR 1910)[15] recognizes certain independent agencies to conduct tests to determine if certain electrical apparatus is safe. Intrinsically safe electrical circuits are one of the type required to be tested by either Factory Mutual Research or Underwriters Laboratories. This testing can either be done by analogy or through actual testing as contained in NFPA 493-1978, Chapter 7 and 8.

However, there is a way to use intrinsically safe circuits and avoid the expense and time of having the circuits tested for approval. Both Underwriters[16] and Factory Mutual[17] publish directories or guides of equipment which has been approved to be used as intrinsically safe or to be used with intrinsically safe apparatus.

Further, NFPA 493-1978 states

> "One of the serious problems which has faced both manufacturers and users in applying the intrinsic safety concept has been the inability to interconnect apparatus of different manufacturers and be assured that the combination is still intrinsically safe. The marking scheme below .... [explains the marking system and requirement] .... The above [marking system] information and cable characteristics are all that are necessary to determine that independently certified intrinsically safe and associated apparatus may be interconnected, without loss of intrinsic safety. It should be recognized that this procedure results in systems which are evaluated with as many as four independent faults.

The rest of the section goes on to explain how to determine the necessary characteristics of the cables.[18]

Therefore, it is easier to go to either source and select the components necessary for the intended application. Time is saved by not having to reinvent the wheel.

7. CONCERNS ABOUT THE USE OF I.S.

The use of intrinsically safe electrical circuits brings about certain concerns. These concerns are for defining the hazardous environment in which it must operate; identifying the circuits as intrinsically safe; awareness of what is required of maintenanced personnel; and procurements involvement.

7.1 Defining the Hazardous Environment

The first concern in using intrinsically safe apparatus and intrinsically safe electrical circuits is that the type of hazardous environment must be clearly defined. Much of the apparatus listed in the guides are for Groups A, B, C, D, E, F, G; Div. I and II. But, not all of them are.

Therefore, when using intrinsically safe, it is of the utmost importance to clearly understand and define the type of environment the equipment the equipment will be operating in. In this way, intrinsically safe electrical circuits can be designed using the appropriate type of equipment. It is not necessary to use equipment for all groups, if the required apparatus is available for that certain environment only. This, again, will reduce costs.

7.2 Identifying the Intrisically Safe Circuit

Another concern is identifying the intrinsically safe electrical circuits and intrinsically safe apparatus. Early in the paper, it was mentioned that bright blue is to be used for intrinsically safe. It is important that this be used; and maintenance personnel in the field are aware of what intrinsically safe is and what it requires to remain intrinsically safe. Only through the interchanging of a non-intrinsically safe part for an intrinsically part can all the safety of the system be lost.

7.3 Procurement

The final area of concern, and probably the greatest, is procurement. This is especially true for the government sector. It is important that procurement be made aware of the necessity when purchasing intrinsically safe components to insure compatability between the components of the same circuit. This can only be accomplished by the engineer doing the design or the maintenance person ordering a replacement part, to take the time to completely describe the requirements of the component. The requirements should, also, state that the item must be approved by either Underwriters Laboratories or Factory Mutual as intrinsically safe.

In many situations, this may not be sufficient, and procurement may not purchase the required component. It may be necessary for the government sector to come up with special procedures for the handling of procurement of intrinsically safe apparatus.

Finally, as a last resort during the design process, in order to insure the apparatus is intrinsically safe, it may require that the paper work be done to select a company's components as sole source.

6. CONCLUSION

Many of the items, listed in either of the sources mentioned earlier, are for instrumentation. This provides the controls needed for fast response time when dealing with pneumatic or hnydraulic systems. It lessens the amount of piping required, because electrical wires can be used in place of long runs of piping for controls. Electrical wires are also easier to install and maintain than piping. It offers an electrical system which will fail its purpose long before it becomes unsafe. It reduces costs because the safety is in the design, not added afterward.

Finally, to quote Ernest C. Magison,

> "Hazard reduction is, therefore, not an exercise in absolutes. It is an exercise in low probabilities."[19]

This is exactly what intrinsically safe affords, the opportunity to lower the probabilities of an incident involving electricity in a hazardous area to zero.

i. END NOTES

1. National Electrical Code, Article 500, 1956

2. Webster's Twentieth Century Dictionary, 2nd Ed., Unabridged, William Collins + World Publishing Co., Inc.

3. NFPA 493-1978

4. NFPA 493-1978 Par: 2-1.2.1 (b)

5. NFPA 493-1978, Par: 2-1.1

6. A Safety Analysis Computer Program for Evaluation of Complicated Electrical Circuits, Bureau of Mines Open File Report 43-76, offers a Fortran IV program for evaluation.

7. NFPA 493-1978 3-5.3

8. NFPA 493-1978 7-2

9. NFPA 493-1978 Appendix A-7.2

10. Ernest C. Magison, Electrical Instruments in Hazardous Locations, Instrument Society of America, Research Triangle Park, N.C., 1978, includes an example on page 265.

11. Garside, Robin, Intrinsically Safe Instrumentation, A Guide, Instrument Society of America, 1983, Research Triangle Park, S.C., has a good discussion of zener barriers.

12. Garside, Robin. "Modular Zener Barrier Design Simplifies IS Installations" page 45, Control and Instrumentation, Vol. 11, No. 1, Jan 1979

13. NFPA 493-1978 Table 3-1

14. NFPA 493-1978 does not contain a good definition of grounding requirements. However, ISA-RP12.6[20] does and was used as a guide.

15. OSHA 1910.308(d)(2)

16. Hazardous Location Equipment Directory, Underwriters Laboratories Inc,., Publications Stock, 333 Pfingstem Rd., Northbrook, Ill. 60062

17. Factory Mutual Approval Guide, Factory Mutual Engineering & Research, Training Resource Center, 1151 Boston-Providence Research, Training Resource Center, 1151 Boston-Providence Turnpike, Norwood, MA 02062

18. NFPA 493-1978 A-4-2

19 Magison, Ernest C. Electrical Instruments in Hazardous Locations, page 118

20. "Installation of Intrinsically Safe Instrument Systems in Class I Hazardous Locations, Instrument Society of America, Research Triangle Park, N.C., 1976

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Intrinsically Safe Apparatus and Associated Apparatus for Use In Class I, II, and III Division 1, Hazardous Locations, UL 913, Underwriters Laboratories, Inc., Nov 1982

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NOTE: The only standard in English for installing intrinsically safe apparatus.

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Capp, B. and Widginton, D.W., "The Intrinsic Safety of Resistive Circuits", 2nd International Conference on Electrical Safety in Hazardous Environments, 9-11 Dec 1975, pages 43-47

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DOD LIGHTNING PROTECTION REQUIREMENTS FOR STRUCTURES HOUSING EXPLOSIVES

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RISK ASSESSMENT BRANCH (E52)

FOREWORD

This report presents the results of the Department of Defense Lightning Protection Working Group when tasked to produce a new chapter to DOD 6055.9-STD (1) on Lightning Protection for DOD Facilities. The Working Group consisted of the following:

NAME	REPRESENTING
Ignacio Cruz, Chairman	Department of Defense Explosives Safety Board (DDESB)
Raymond Vaselich	Naval Sea Systems Command (NAVSEA)
Eric Livingston	Department of Army Readiness Command (DARCOM)
Mike Aimone	Air Force Headquarters (AF/LEEEU)
John Eddy	Defense Nuclear Agency (DNA)
Scott Dow	Defense Logistics Agency (DLA)
Anthony Brown	Naval Facilities Command (NAVFAC)
Howard Stickley	Naval Facilities Command (NAVFAC)
John Gilson	Army Corp of Engineers (ACE)
Mitchell Guthrie	Naval Surface Weapons Center (NSWC)

The author of this paper is Chairman of the National Fire Protection Association Subcommittee on Lightning Protection for Structures Housing Explosives. He will discuss this parallel commercial effort during the presentation; however the text of this paper will be limited to that of DOD 6055.9-STD, Chapter 7.

References 2 through 7 provide some background information utilized in drafting of the Standard. References 2, 6, and 7 are suggested reading for those requiring a greater amount of detail on the subject.

The requirements of this Standard will often be supplemented by additional requirements from each of the services. References 8 through 11 are samples of these additional requirements.

LIGHTNING PROTECTION

A. GENERAL

The National Fire Protection Association Lightning Protection Code (NFPA 78) and the National Electrical Code (NFPA 70), as supplemented by the requirements of this Chapter, provide the minimum criteria for the design of lightning protection systems for facilities involved with development, manufacturing, testing, handling, storage, maintenance, and demilitarization or disposal of ammunition and explosives. Military Handbook 419 provides additional guidelines on surge suppression, bonding, and shielding for incoming power, communication, and instrumentation lines.

B. REQUIRED LIGHTNING PROTECTION

Lightning protection systems identified in section C., below, shall be used to protect all facilities used for development, manufacturing, testing, handling, storage, maintenance, and demilitarization or disposal of explosives in areas with more than 5 thunderstorm days per year. If thunderstorms are severe, DOD Components may determine it necessary to provide lightning protection for such facilities even if the number of thunderstorm days per year is 5 or less. Otherwise, required lightning protection may be omitted for the following:

1. Facilities equipped with an adequate lightning warning system (see section G., below), when operations can be terminated before the incidence of an electrical storm, all personnel can be evacuated, and the expected damage due to a lightning strike will not impact seriously the mission of the installation.

2. Facilities where personnel are not expected to sustain injury and at the same time the resulting economic loss to the structure, its contents, or surrounding facilities is minimal.

3. Earth-covered magazines used for the storage of ammunition and explosives in closed containers or in their approved shipping configuration. The bonding and surge suppression requirements of this Chapter apply for such magazines.

4. Facilities containing ammunition and explosives or items or systems incorporating explosive components that cannot be initiated by lightning as determined by the DOD Component concerned. These facilities and contents must not be subject to fire in the event of a lightning strike. The bonding and surge suppression requirements of this Chapter apply for such facilites.

C. PROTECTION SYSTEM DESIGN

Lightning protection systems designend for explosives facilities shall be based on a 100-foot striking distance arc as shown if Figures 1 and 2. However, for a Faraday cage this striking distance is not a consideration.

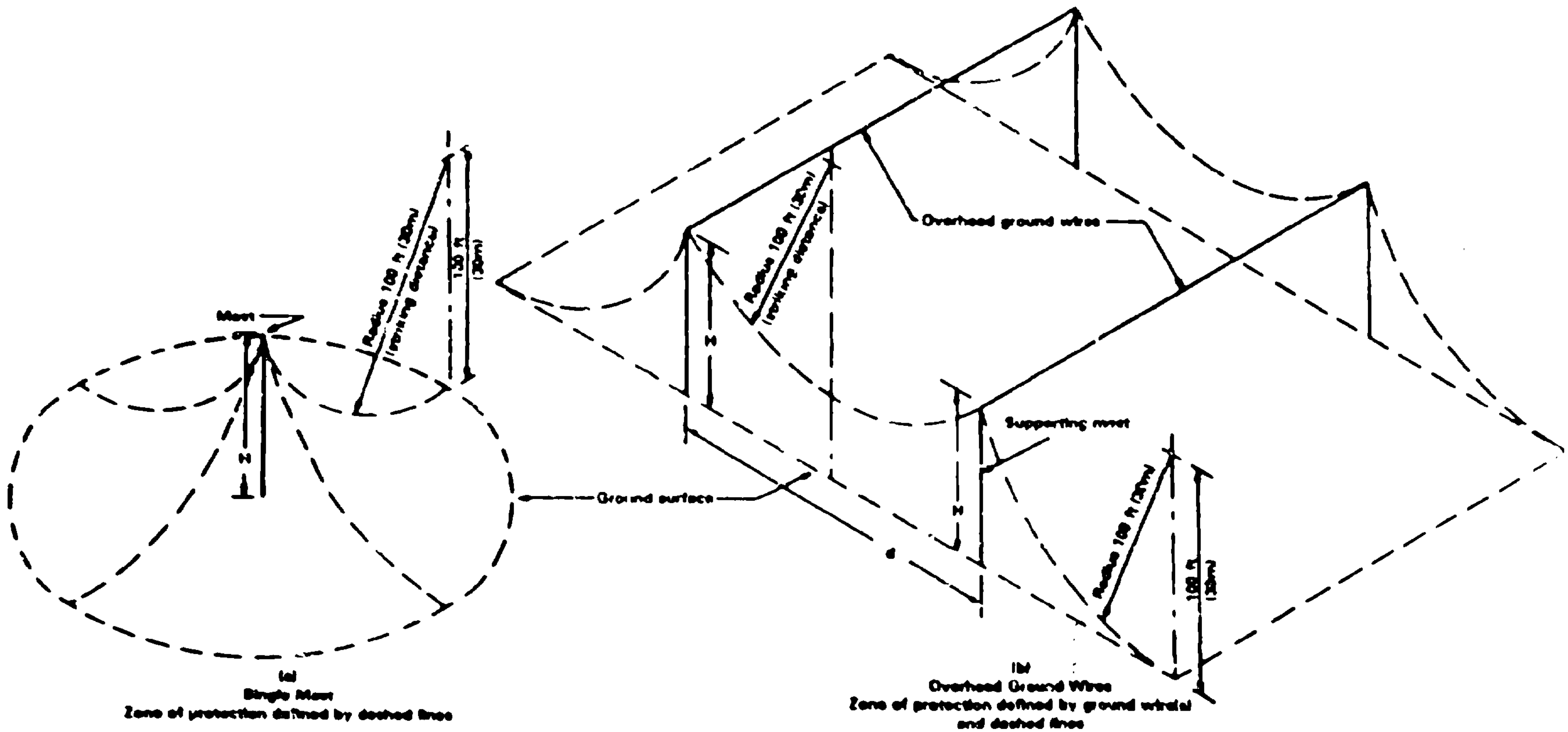

Figure 1 — Zone of Protection for Mast Height "H" Exceeding 50 Feet (15m)

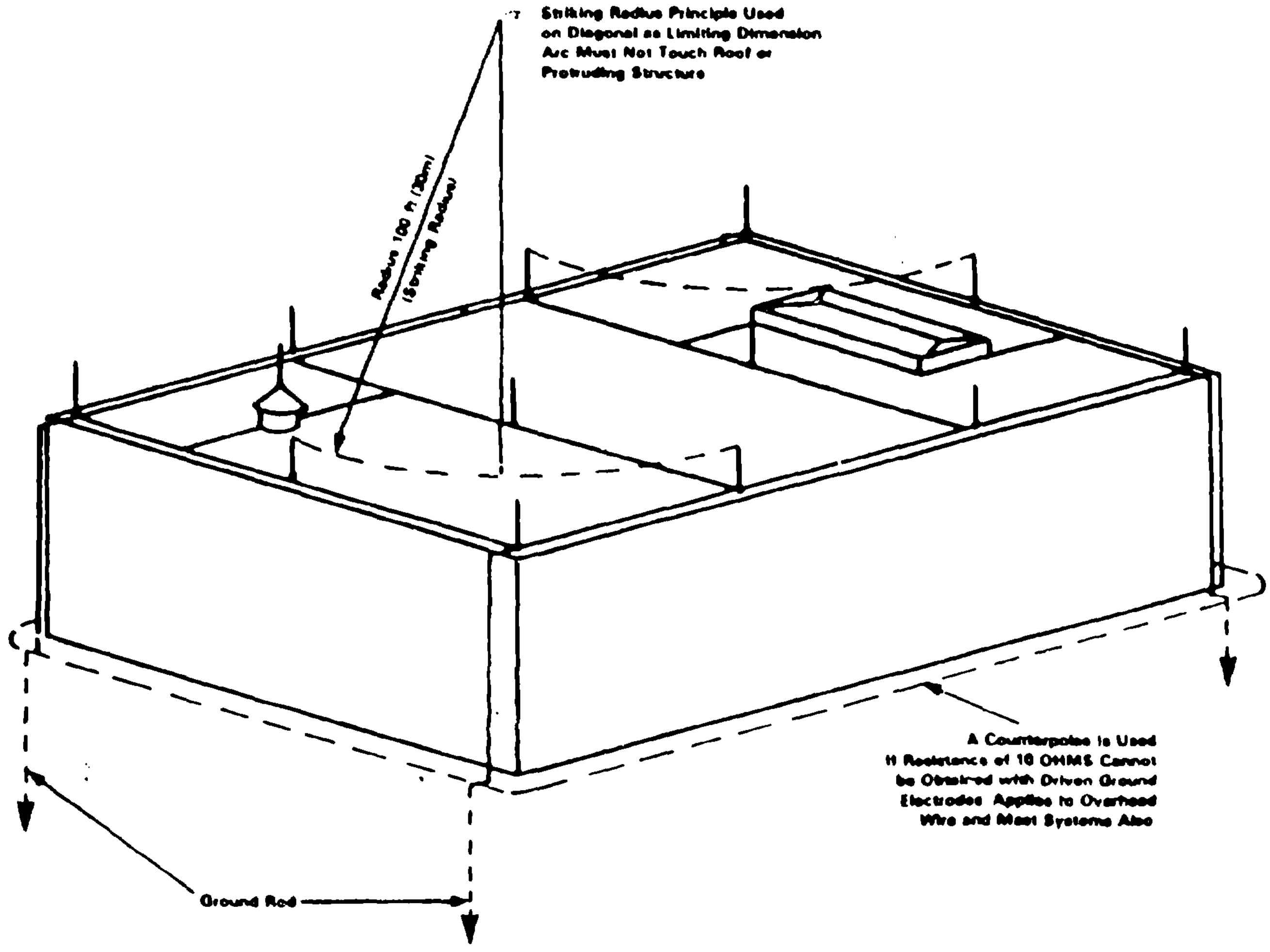

Figure 2 — Zone of Protection for Integral Systems
(100 foot striking distance)

D. TYPES OF SYSTEMS

There are four types of lightning protection systems acceptable for the protection of structures housing ammunition and explosives. They are overhead wires, masts, integral, and Faraday cage lightning protection systems.

1. Overhead Wire System

a. An overhead wire lightning protection system consists of grounded, elevated horizontal metallic wires stretched between masts surrounding a structure. Each wire shall be a continuous run of not less than No. 1/0 AWG copper or copper-coated steel cable suspended above the protected structure and connected to ground rods at each end or to a buried ground ring. The ground ring is required only if 10 ohms maximum resistance to ground is not readily attainable with ground rods. The overhead cable shall be supported by masts to ensure a minimum separation distance of 6 feet from the protected structure (including any projections), increased by 1 foot for every 10 feet of horizontal cable run parallel to the structure greater than 50 feet. The supporting mast shall be separated at least 6 feet from the structure, increased by 1 foot for every 10 feet of structure height above 50 feet.

b. An overhead wire lightning protection system will minimize hazardous side flashes and reduce otherwise necessary bonding when compared to integral and Faraday type systems. A system of this type is often recommended especially for structure with perimeters greater than 300 feet.

2. Mast Systems. A mast-type lightning protection system uses masts that are remote from the structure to provide the primary attachment point of a lightning discharge. The height of the mast shall ensure that the entire structure is enclosed in a zone of protection. Each mast shall be separated at least 6 feet from the structure, increased by 1 foot for every 10 feet of structure height above 50 feet.

3. Integral System. An integral system consists of sharp or blunt grounded air terminals of 2-feet minimum height configured on the structure. Down conductors shall be as nearly vertical as possible without unnecessary bends. Any bend shall be as gradual as possible, have a minimum radius of 8 inches, and not exceed 90 degrees. Air terminal spacings shall be designed on the 100-foot striking distance as stated in section C. above, as opposed to the 150-foot design used in Chapter 3, NFPA 78 (see Figure 2). Adequate bonding is critical to ensure that side flashes are eliminated. An integral system that is removed (for example, to permit roofing repair) shall be retested after reinstallaton.

4. Faraday Cage and Faraday Shield. The optimum scheme for protecting extremely sensitive operations from all forms of electromagnetic radiation is to enclose the operations or facility inside a Faraday cage. However, the Faraday cage is difficult to construct and economically justified only for "one-of-a-kind" facilities that are DOD-essential or when extremely sensitive operations warrant the level of protection it provides. The Faraday cage affords excellent protection from lightning. Effective lightning protection is provided in a similar manner by metallic enclosures such as formed by the steel arch and reinforcing bars of concrete end walls and floors of steel arch magazines and the reinforcing steel of earth-covered magazines constructed of reinforced concrete.

E. GROUNDING, BONDING, AND SURGE PROTECTION

1. Grounding. Resistance of 10 ohms or less to ground for a lightning protection system is the desirred optimum. If 10 ohms resistance cannot be achieved with ground rods alone, a buried ground ring system is acceptable even if its resistance exceeds 10 ohms.

2. Bonding. The bonding of metallic bodies is required to ensure that voltage potentials due to lightning are equal everywhere in the facility. The resistance of any metal object bonded to the lightning protection system may not exceed 1 ohm to the grounding system. The material used shall be compatible with the metallic mass and down conductor to minimize corrosion. NFPA 78 shall be used as minimum acceptable bonding requirements for DOD facilities. Wires and connectors on lightning protection systems shall not be painted. Earth-covered magazines shall have their metal ventilators (if used), steel doors, metal door frames, and steel reinforcing bars bonded to the structure's grounding system. Fences shall have bonds across gates and other discontinuities and shall be bonded to the lightning protection system if they come within 6 feet of the system. Railroad tracks run within 6 feet of a structure shall be bonded to the structure's lightning protection system or its grounding system. The lightning protection system shall be bonded to all grounding systems of the protected facility.

3. Surge Protection. A lightning protectiton system for structures housing sensitive materials shall be designed for surge protection as well as lightning stroke interception. Nearby flashes will produce electromagnetic pulses that can b coupled into internal and external power, communication, and instrumentation lines. Consequently, one or more of the following shall be provided on all incoming metallic power, communication, and instrumentation lines to reduce transient voltages to a harmless level: lightning arrestors, surge arrestors, surge protectors, surge suppressors, transient power suppressors, fiber optic data lines, and isolation transformers. These power and communication lines shall enter the facility in shielded cables or in metallic conduits run underground for at least 50 feet from the structure. In addition, intrusion detection systems, utility lines (such as water, steam, and air conditioning) and other metallic lines shall run underground for at least 50 feet from the structure. The use of low-pass filters shall be considered for added protection on specific critical electronic loads as determined by the user.

F. TESTING

1. Seven-Month Test. The lightning protection system shall be inspected visually every 7 months for evidence of corrosion or broken wires or connections. All necessary repairs shall be made immediately. Transient suppression networks also shall be inspected visually at 7-month intervals.

2. Fourteen-Month Test. The lightning protection system shall be tested electrically every 14 months to afford testing of the system during all seasons. The test shall be conducted in accordance with the appropriate instrument manufacturer's instructions, by personnel thoroughly familiar with lightning protection systems.

3. Test equipment. Only those instruments designed specifically for earth-ground system testing are acceptable. The instrument must be able to

measure 10 ohms, plus or minus 10 percent, for ground resistance testing and 1 ohm, plus or minus 10 percent, for bonding testing.

4. Records. The most recent test results will be kept on file.

G. LIGHTNING WARNING SYSTEMS

1. Lightning warning systems provide a positive, reliable means of continuously monitorirng and recording atmospheric voltage gradients and can detect atmospheric conditions that may produce lightning in the vicinity. Lightning warning systems that are installed and maintained properly can detect thunderstorms up to 200 miles away and indicate the direction of approach. This may mean several hours of warning of an approaching thunderstorm.

2. Installations with lightning warning systems shall establish a specific criteria for terminating ammunition and explosives operations at the approach of a thunderstorm. This criteria shall be based on the sensitivity of the operation involved and the amount of time required to safely terminate the operations.

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EMISSION FACTORS FROM DEACTIVATION OF MUNITIONS, PART I

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1. ABSTRACT

Calculations and measurements are at last becoming available for the identification and concentrations of pollutants which result from the deactivation of most types of munitions. Open burning and detonation have been confirmed as environmentally sound for certain munitions. For recovery of metals from some munitions, the preferred deactivation methods involve incineration or chemical treatments.[43] A catalog is being compiled for munition emissions. Energy recovery during deactivation has been demonstrated with a few highly energetic materials.[42,43] And significant progress has been made in materials recycle and recovery.[44] Details from the reports on energy and materials recovery are not repeated here.

2. EMISSION FACTORS FROM MUNITION DEACTIVATION METHODS

The term "emission factor" has a unique and useful meaning, namely the amount of emission per unit of starting material. Emission factors are expressed as pounds of emission per ton of starting material (or as kg per metric ton). Air emissions are a prime concern for incinerator flue gas, deflagration or open burning and open detonation (obod). Waste water emissions result from wet scrubbers in furnace systems, wash-out plants, chemical treatments, and cleanup. Emission factors from soil contamination are of concern with obod and deflagration.

Pollution which results from military operations concerns both the concentration of emissions and the absolute amount of emissions. Damage to environment and danger to health is mostly a function of the concentration of pollutants and particle size of particulates. But regulatory agencies also attempt to reduce the total amount even when the concentration is safe. Judgments of pollution control should be based on a case-by-case balance of the importance of the operation with cost and availability of state-of-the-art pollution control equipment, as well as with danger to health and environment. Open burning and detonation are the only methods available for disposal of certain munitions, and some of these cannot be stored indefinitely while awaiting development of other methods.

2.1. Incineration and Low-Temperature Open Burning

Aromatic nitro explosives such as TNT and ammonium picrate, which are burned in an incinerator at a rate of 300 lb/hr, or subjected to low-temperature open burning give up to 100 pounds of NO_x per ton, because of incomplete degradation. With proper combustion air feed rate, firing chamber design and temperature control, the NO_x emission factor from incineration can be reduced to 0.001 lb/ton or less.

Particulate emission factors in the final plume from the carbon, hydrocarbon fragments and organics alone can run as high as 100 lb/ton without pollution control. This can be reduced to less than 0.01 lb/ton by incinerators with cyclone and filter baghouse or scrubber, or by incineration with an afterburner. But if metals, inorganic salts or other compounds are part of the formulation in a munition to be deactivated, there may be a solid ash particulate remaining even with total degradation, depending on what the inorganic component is.[43]

With sufficient residence time in proper firing chamber conditions there will be no CO, Cl_2, HCN, C, organic fragments, carcinogens, or undegraded explosive. In practice, sufficient residence time is not always attained without afterburners. Particulates, including inorganic ingredients that go into the flue train as metal oxides, are usually separated by cyclones and filters.

In some processes such as incineration, RCRA will require the removal of 99.99% of POHCs present among the munition components. See Appendix VIII of 40 CFR 261, a section of RCRA, the Resource Conservation and Recovery Act. POHCs are the Principle Organic Hazardous Constituents. However, 99.99% removal may not always be good enough to satisfy other safety factors. For example, if bulk primer or a munition containing primer is deactivated in an incinerator at the rate of 300 lb/hr, then the remaining 0.01% of undegraded explosive will go into the pollution control equipment at the rate of 14 grams (1/2 ounce) per hour. The solid in the filter will also contain up to 18% combustible carbon black with such munitions. If a long-lived carbonaceous or tracer spark survives the few seconds to transit the entire length of the flue train it could easily start a fire in such a mixture of carbon and explosive in the filter residue. Baghouse fires have occurred during incineration of such material. If the 99.99% removal is attained by baghouse separation rather than by 99.99% degradation, the mixture of carbon black and other solid residue from the baghouse will contain still more explosive. Typical samples assay about 3% explosive. An afterburner eliminates both the C black and the organic residues including explosive and other POHCs from even being present in baghouse and cyclone residue.

Possible hazardous wastes from the incineration process for deactivation of small arms and projectile parts might be made up of the following, depending on the particular formulations and other specifications:

Gases: CO, NO_x, SO_2, HCl, PO_x, HCN, organic fragments, and vapors of Hg, Cd & Pb which subsequently condense to liquid or solid.

Particulates: Metal oxides (potassium, magnesium, aluminum, etc.), carbon and carbonaceous soot containing carcinogens, partly degraded and undegraded explosives or other components.

2.2. Deflagration

Some confusion has arisen from indiscriminate classification of open deflagration as open burning. Although it is a high temperature vigorous open burning, deflagration is an explosion, with the longest available residence time at high temperature degradative conditions of any common treatment. As such, open deflagration provides complete deactivation and total degradation. Open deflagration of oxygen deficient nitrocellulosic propellant has given 3.2 lb NO_x/ton. (See section on nitrocellulosic propellants.)

2.3. Detonation

The CO emission factor at the time of detonation may be as high as 1480 lb/ton for oxygen deficient explosives like the nitroaromatics, but with subsequent prompt oxidation of the CO to CO_2 within a few seconds. The CO emission factor for nitroglycerin, however, is zero, because it is an oxygen rich explosive, which means it contains more than enough internal oxygen to convert all C to CO_2 and H to H_2O without use of air oxygen.

2.4. Obod Emissions Study

Measurement attempts are now in the first stages to determine emission factors from open burning and detonation of many types of munitions and bulk explosives, by use of an instrumented helicopter. A few results are available for this presentation. A summary is also included for some past laboratory and detonation chamber measurements, and theoretical calculations, which have been proven dependable for the explosion state, but not representative of subsequent reactions in field conditions. Obod of some items such as nitrocellulosic propellants is non-polluting altogether.

3. BACKGROUND

3.1. Regulation, General Categories Versus Unaddressed Military Needs

Most open burning is to be eliminated by the Resource Conservation and Recovery Act (RCRA), but open burning and open detonation of explosives are allowed by RCRA,[39c] to provide a means of disposal for explosives, which cannot be disposed of by other methods. RCRA and other Environmental Protection Agency (EPA) regulations have yet to address some of the unique characteristics of the private and military explosives industries. However, EPA is now considering a solution to this need.

A proposed wording of a RCRA subsection to apply to propellants and explosives was submitted to EPA by the Department of Defense (DOD) in 1983. The EPA considered that specific wording was unnecessary for lack of enough explosives industry to warrant specific attention. Instead, EPA expects to publish a proposed section of 40 CFR 260 to cover all unique special cases, explosives included. This should appear toward the end of 1984.[40] It will be worded to give general guidelines, so that the pertinent environmental agencies can work on a case-by-case basis in mutual cooperation with the installation involved. This is intended to allow the greatest possible flexibility to the installation in addressing the unique situation of explosives, while satisfying the needs of disposal and simultaneous protection of health and environment. This can be successful only if the intended flexibility and mutual cooperation are not spoiled by wrong attitudes or lack of understanding on the part of either the industry or the regulatory authorities. The following paragraph is taken from the federal notice.[40]

"The planned standards would establish several environmental performance criteria, similar to 40 CFR 267 standards, that would be applied on a case-by-case basis in issuing permits. We believe that this approach will provide a flexible standard against which permits can be written. Under these rules, the owner or operator of each facility will do a site-specific environmental analysis against a set of environmental and human health criteria. This will enable the Agency to consider site-specific and waste-specific characteristics of each facility on their merits while providing full protection to human health and the environment."

3.2. Unique Properties, and Terminology of Explosives, Including: Burning, Combustion, Oxidation, Explosion, Deflagration, Detonation

Open burning, in terms of combustion and burning, is defined in RCRA[39c] mainly for application to environmental aspects of other industries, and does not handle the needs of the explosives industry. The terms 'burning' and 'combustion' have several connotations, and are sometimes used as exact synonyms. But to promote understanding in discussions of propellants, explosives and pyrotechnics (PEP), the terms should not be equivalent. For best PEP use 'burning' is a flaming process, and 'combustion' is a flaming oxidation reaction with air or oxygen. Whereas typical examples of burning are indeed flaming reactions with air oxygen, 'burning' is nevertheless not always chemical reaction with oxygen; indeed, burning is not necessarily 'combustion' at all. A jet of oxygen or air will burn smoothly in a room full of natural gas (methane), just as a jet of natural gas (such as a pilot light for a water heater) will burn smoothly in a room of air. These two examples are both combustion. But a jet of chlorine gas will burn smoothly in a room full of hydrogen gas, and so also will a jet of hydrogen gas burn smoothly in a room of chlorine gas. These two examples of burning are not combustion.

In the general sense, 'burning' is a flaming chemical reaction. Highly energetic chemicals, such as explosives, will usually burn smoothly without detonation. The flaming reaction may propagate by virtue of continous internal decomposition of the explosive chemical, without air combustion. In this case, burning of explosive in an incinerator or in the open is not necessarily combustion. If air is present, there will be some combustion just because the fuel is hot and in contact with oxygen, but this is an incidental side reaction, not needed for the flaming propagation. In some cases there is not even any incidental oxidation, which brings us to another unique aspect of explosives disposal, totally overlooked by RCRA. Flaming of explosives can be totally non-polluting, and simultaneously void of combustion. (Note that some schools have invented other narrow chemical uses of the terms oxidation and reduction, which have advantages for understanding certain chemical processes. For example, oxidation or reduction can mean: gain of an entity with low or high negative charge density; loss of an entity with high or low negative charge density; loss or gain of electrons; increasing or lowering level of oxidation state; gain or loss of a proton; gaining of an acidic or basic entity. This discussion is not concerned with such specific uses, but rather takes the more general definition: oxidation = combination with oxygen.)

Open burning of explosives is not always the stereotyped smoky bonfire in an open field. In PEP work some open burning is deflagration, which is a type of explosion. It is a high temperature vigorous flaming process. Although deflagration is an explosion it is not a detonation. (Detonation is an explosion in which the chemical reaction proceeds through the medium faster than the speed of sound.) Thus, open burning of a nitrocellulosic solid propellant on the ground is actually an explosion of the deflagration type, attaining a temperature of 5000 to 6000 degress F and lasting only one-half second per hundred pounds. This has been adequately demonstrated by the Ammunition Equipment Directorate (AED) at Tooele Army Depot, Utah (TEAD) in disposals of 50,000 to 100,000 pounds of outdated propellant daily for over a month, totalling over 2 million pounds. AED showed that the resulting white clouds were free of pollution to a greater degree than required by the Occupational Safety and Health Administration (OSHA) for worker breathing air supply. This type of disposal by open burning should preferrably be referred to as deflagration, to emphasize that it is not the stereotyped low temperature, drawn out burn with its typically polluting smoke. It is an explosion of low order, but does not qualify as detonation, because there is no shock wave. Open deflagration and open detonation in this sense are classed together as opposed to open burning. When proper understanding of the various types of open burning become common knowledge, non-polluting deflagrative open burning will not be hindered by false notions that all open burning is polluting.

Complete degradation of an explosive containing only carbon, hydrogen, nitrogen and oxygen, is the conversion of all the carbon to carbon dioxide, hydrogen to water, and nitrogen to diatomic nitrogen gas. The internal rearrangement of the atoms to utilize the self-contained oxygen within the structure to form water and carbon oxides can be properly called 'autocombustion'.

Two quotes on this subject now follow, taken from the Encyclopedia of Explosives and Related Items, volume 3, p D38, and volume 2, p B343 (3b, 2a respectively):

"The burning of deflagrating explosives usually proceeds rather violently and is accompanied by a flame (or sparks) and a hissing (or crackling) sound but not with a sharp loud report as in the case of detonating explosives... 'Deflagration' is a mode of explosion distinguished from detonation and consitituting the very rapid autocombustion of particles of explosive as a surface phenomenon."

"Burning in common usage is defined ... as a combustion in which material is consumed by fire resulting from interaction of the material with atmospheric oxygen at high temperature and accompanied by flame and sometimes sound... The term combustion implies the process of burning and in the popular mind is generally associated with the production of flame. So far as terrestial conditions are concerned, combustion is due to the combination of a combustible substance witn oxygen and the consequent evolution of heat. The appearance of flame is due to the oxidation of gases or vapors at a very rapid rate so that high temperatures are obtained, the molecules involved thereby becoming very radiant. Scientifically, the term combustion has a broader meaning and is extended to other forms of oxidation...

"Combustion must be distinguished from deflagration, explosion and detonation."

To distinguish these differences in a manner most beneficial to the explosives industries, the common usage must be avoided, which equates burning and combustion, as explained in the first two paragraphs of 3.2.

4. CHEMICAL ASPECTS OF OPEN BURNING, OPEN DEFLAGRATION AND DETONATION (OBOD)

4.1. Thermodynamic and Kinetic Factors

Consider the following known thermodynamic equilibria of carbon monoxide:

$$\text{Heat} + C + CO_2 = 2CO$$

$$\text{Heat} + C + H_2O = CO + H_2$$

$$\text{Heat} + CO_2 = CO + 0.5\ O_2$$

In each case, increased temperature shifts the equilibrium mixture to the right, i.e., more carbon monoxide, less free carbon and carbon dioxide. In each equation, one volume of gas on the left goes to a greater volume of gas on the right; so increased pressure shifts the equilibrium mixtures to the left, i.e., increasing carbon dioxide and solid carbon while decreasing carbon monoxide.

Thermodynamic equilibrium and kinetics (the speed of reaction) are related in the following manner. For specified beginning concentrations of each entity, which are then allowed to react at a certain temperature and pressure, there will be a constant final concentration of each entity after equilibrium is eventually attained. This equilibrium may be a dynamic situation, in which the various entities are continuously changing into other entities present. But the concentration of any one form remains constant. The rate of decrease of any form equals the rate of its formation, at equilibrium.

Kinetics, on the other hand, has to do with how rapidly the final equilibrium concentrations are attained after the various concentrations, the temperature and pressure are first altered, or specified. Reactants may pass through an activated or complex intermediate state on the way to another final form. The activation energy barrier may be a strong barrier in one direction and a weak one in the reverse direction. The energy of detonation shock is supplied in such a short time that very strong barriers to reaction are overcome. The atoms within a molecule are actually dismembered from each other momentarily. Burning, with its gradual release of energy may not even approach this degree of activation. Mixtures of reactants in either case may be quenched before equilibrium is attained.

4.1.1. Open detonation case. Explosions which are conducted under conditions with any physical confinement such as in detonation chambers, demolition of buildings, etc., reflect the pressure inward and tend to delay its dissipation. But the heat from the high explosion temperature (5000-6000 degrees F or about 3000 degrees C), is rapidly absorbed by the confining materials and debris. Both the temperature and pressure effects tend to minimize the carbon monoxide ratio, and increase the free carbon in the equilibrium equations.

Unconfined, or so-called free explosions expose the reacting material to the much less dense medium of air in contrast to confining solids, and so retain the high temperature longer. The high pressure is dissipated sooner than in the confined case. Thus both the temperature and pressure effects maximize the carbon monoxide ratio and minimize the black carbon, in open-air detonations. Initial TNT products in detonation chambers typically show a $CO:CO_2$ ratio of 30:1 or more in explosions with less confinement and only about 2:1 in confined explosions. $CO:H_2$ ratio is about 3:1 with less confinement and 7:1 with confinement, trends which are in agreement with the given equilibrium equations and the principles discussed above. However, measurements following the initial blast in open air detonations indicate that the carbon monoxide is then oxidized to carbon dioxide.[33,34,35] If the foundation beneath the base of the material is not controlled, there may be more earthen dust thrown into the air from detonation than the amount of soot emitted from low temperature open burning. The shockwave may cause damage or initiate complaints if the location is not remote or provided with a sound muffling barrier. With proper choice of location, underlayment and barrier, detonation is often acceptable, whereas low temperature burning usually puts out serious pollution.

Even the longest of the relative durations of high temperature and pressure in the examples discussed above will not ensure complete chemical reaction of the explosive components with the surrounding air molecules, before the heat and pressure are dissipated. A chemical explosion is a fast reaction, one which generates energy much faster than it can be dissipated smoothly. The resulting pressure, heat, light, sound, chemical process, fragmentation, or radiation can be overwhelming. However, the fast evolution of energy propagates internal chemical changes that would not occur with gradual dispersion of the heat and pressure. Detonation is a high-order explosion, but has also been given a specific definition as a reaction which proceeds through the material faster than the speed of sound (0.33 kilometers, 0.21 miles, or 1100 feet per second at sea level).[32,39c]

Highly brisant explosives such as TNT, ammonium picrate and nitroglycerin cause the disruption of the bonds connecting the atoms within the molecules, to give momentary isolation of probably all the atoms in molecules so affected. This extreme condition is not because of the enormous energy release alone, but rather its application in a short time span to do work upon material in a narrow region of space. Hess[37] first defined brisance as the amount of work done by a unit weight of explosive per unit time. The high temperature of detonation -- 5000 to 6000 degress F -- lasts only a few seconds, and the sharp crest of the shock wave at about 3 million pounds per square inch passes in a fraction of a second. The atomized material rearranges, i.e., recombines with itself long before it can interact much with the surrounding air molecules. Furthermore, the mixture may or may not have time to equilibrate totally to the most thermodynamically favored forms for such high temperature and pressure, but a mixture representing a shift toward the favored equilibrium is quenched by the sudden loss of temperature and pressure extremes. Adiabatic expansion and convection then soon level the temperature and pressure to ambient values. Measurements made by AED following ignition of 4000-pound lots of propellant showed that ambient temperature was regained within 30 seconds. It is expected that detonation of equally large amounts of high explosive is also followed by recovery to ambient pressure and temperature rapidly. During the leveling period and thereafter, normal, slower chemical reactions of the detonation products with the atmosphere take place, such as oxidation of metals, hydration of oxides, and conversion of trace reactive organic species. Further reaction of nitrogen oxides proceeds slowly even if the mixture is quenched in nonequilibrium ratios of components.

Nitric oxide, NO, is indirectly hazardous, by conversion to nitrogen dioxide. This occurs in the atmosphere slowly by a mechanism totally different from the interconversion of NO and NO_2 in the extreme conditions of PEP disposal. As shown in the equilibrium equation, nitrogen dioxide, which is more stable than nitric oxide at 100 to 1000 degrees F, requires a net addition of energy to be converted to nitric oxide. Increased temperature therefore shifts the equilibrium in the following equation to the right, in favor of nitric oxide.

$$\text{Heat} + NO_2 = NO + 0.5\ O_2$$

At 1100 degrees F a mixture of NO and NO_2 at complete equilibrium is nearly void of NO_2, but at 275 degrees it is nearly void of NO. The most stable form of nitrogen is N_2, but if a detonation mixture is quenched it will contain some NO and NO_2. About 0.001 pound of total NO_x results from deflagration of one pound of high explosive or propellant. NO_x following detonation is mostly from the nitrogen within the explosive itself. But with open burning, there is slightly more NO_x from incomplete decomposition, and from reaction with air due to the longer reaction time.

4.1.2. Deflagrative open burning. Extremely high temperatures (5000-6000 degrees F) and long burn times (5 to 10 seconds per ton) compared with incineration, give open deflagration a marked advantage, because polluting emissions are slight or nil, such as in the deflagrative open burning of bulk propellants. See section on propellants.

4.1.3. Low temperature (non-deflagrative) open burning. Despite the high temperature and pressure of open detonation, a small amount of explosive may escape decomposition, and a small amount may be only partially degraded. But non-deflagrative open burning usually gives far more undegraded and partially degraded explosive than open detonation does. The heavy black soot produced by such open burning contains not only free carbon, but also many carcinogens and other hazardous constituents. The reason for this is clear from the kinetics and thermodynamics of the process. Open burning does not have the high pressure (2 to 3 million pounds per square inch incident with detonation. Explosives ordinarily burn slowly, but localized confinement of a portion may occasionally lead to detonation, because the gases released in confinement build up pressure, and the heat released cannot be dispersed quickly enough to avoid extremely high pressure and temperature. The normal low temperature burning takes place 2000 to 4000 degrees F cooler than open detonation. Furthermore, the propagating energy which gives the burn its continuation is supplied sufficiently well by the decomposition of the highly energetic chemical structure of the explosive, although some combustion with the air oxygen can occur because of its immediate availability and the long reaction time. These factors of non-deflagrative open burning: no high pressure, the lower temperature, and the propagating energy source are next compared in detail to the conditions of open detonation.

There is the absence of catalytic shock to dismember the atoms toward further reaction. The absence of the pressure wave tends to increase CO and decrease C. But the lower reaction temperature has an even greater effect in the opposite direction. With the propagation energy being independent of air combustion, the result is partial degradation with incomplete oxidation of the hydrocarbon fragments. Thirdly, those explosives with an oxygen deficiency tend to burn as though in a reductive flame, like the cool yellow flame of an acetylene torch without sufficient oxygen. This also gives a very sooty smoke containing carcinogenic fuzed ring aromatics and numerous exotic, hazardous constituents, such as imino-, nitroso- and other pi-bonded structures.

Aromatic ring with substituents

Benzpyrene and other carcinogenic fuzed-ring structures

Once formed, the carbonaceous soot is very slow to oxidize, even though thermodynamics show it will give more stable products. The reaction rate in getting there is very slow for a heterogeneous reaction. Heterogeneous here means that the reactants are not all in the same phase, or state of matter: solid, liquid or vapor. The carbonaceous soot is no longer in a highly energetic condition, as was the original explosive, and does not sustain a flame to overcome the activation energy barrier. It does not easily supply vaporous fragments to give a homogeneous reaction with oxygen.

Carbon and carbonaceous soot are very good insulators of heat, thus slowing transfer of the lesser heat still remaining, and preventing it from initiating the desired chemical reactions toward complete degradation.

Low temperature open burning, therefore, has at least five major factors which oppose attainment of the desired complete reactions. Open detonation gives near total degradation, carbon monoxide being the only substantial pollutant, and only in detonation of oxygen deficient explosives. Low temperature open burning gives substantial carbon monoxide with such explosives, along with numerous other hazardous products. Detonation of oxygen deficient explosives, as mixtures with oxygen rich explosives or added oxidants, overcomes the formation of carbon monoxide. Nitroglycerin and related explosives have excess oxygen. Peroxides and perchlorates are good additives, which, however, may produce salt or oxide particulates in the emission clouds.

4.2. Measurement and Theoretical Calculation of Emissions from PEP

Theoretical calculations have been made for the expected emissions from detonation and burning of explosives. Such information has been calculated by several authors on the basis of thermodynamics, kinetics, equations of state and known chemical behavior (e.g., 8, 21, 38). Actual analyses of the product have been made from deflgrations conducted on a small scale under laboratory conditions, in autoclaves and in detonation chambers designed to simulate field conditions (see references cited in 4.2. to 4.5.). There is good agreement of the main products and their amounts, as well as the principles involved. Many minor products have been identified which are present in only a few parts per million or parts per billion. The measured and predicted abundances of trace products differ according to the methods used. And until the last few years the technology has not been available to make accurate measurements of the explosion products in the atmosphere following actual field operations with large amounts of explosives. Explosives authorities have acknowledged the need for better sampling methods and more sensitive instruments. The complexity of the chemical processes inolved in explosions vary with many subtle factors. The following statements are taken from an authoritative 1958 publication of the American Chemical Society.[21]

"Unfortunately, the experimental measurement of the actual composition of the detonation products in field application is not possible by present methods... The products of detonation one measures in (laboratory) instruments depend critically on the loading density, the mode of initiation, confinement, whether the gases expand adiabatically and reversibly, freely, or against light burdens, and even on the chemistry of the surrounding medium."

The U.S. Bureau of Mines has categorized explosives permissible for use in coal mining according to the amount of poisonous fumes emitted per 1.5 lbs of explosive as measured in a certain autoclave method allowing the gases to expand freely without doing work, and then cooling slowly by heat transfer. Class A represents the generation of less than 2 moles of poisonous gas per 1.5 lbs of explosive, class B up to 4 moles, and class C (now discontinued) up to 6 moles. Few commercial explosives in use generate as much as 2 moles in actual field conditions. AED measurements and calculations indicate that less than 1 mole of total NO, NO_2, CH_4, NH_3, and HCN is expected from 1.5 pounds of most common explosives under field conditions. The amount of CO generated can be 10 moles or more per 1.5 lbs if the explosive is highly oxygen deficient (like TNT -- 70% deficient) and has a low packing density. (The classes of permissibles referred to here do not coincide with DOT designations of class A, B, and C explosives.) Besides these gases there is sometimes a measurable amount of undegraded explosive present among the products of detonation and burning, but not usually of deflagration. Some explosives are toxic, especially when inhaled as dust suspended in air. The small amount that sometimes exists from open detonation is well dispersed to insignificant concentrations, within a few seconds of fire ball and cloud expansion.

During the last few years mass spectrometry, microchromatography and other methods of analysis have become available or inexpensive enough for small industries to use in determining chemical emissions at parts per billion sensitivity, and in some cases at parts per trillion or better. Careful theoretical calculations are being confirmed by these methods and are more reliable than fume-gauge methods of measurement.

4.3. Propellants

4.3.1. Nitrocellulose (NC). Nitrocellulose also gives more polluting emissions with slow decomposition than with detonation or deflagration. Thermal decomposition without deflagration gives nitrogenous acids from the NO_x and moisture products, which then cause autocatalysis of accelerated decomposition with eventual transition to explosion (16b p308-309). With thermal decomposition up to 315 degrees F, as much as 50% or more of the nitrogen in the products can be in the form of NO_x.[27,28,29] Hydrogen cyanide, formaldehyde, and related substances are also produced initially (16b p317). Publications of Kast,[30] Rideal[31] and others summarized by Urbanski[16b] indicate the unique situation of nitrocellulose. It burns vigorously in the open with evolution of much heat, a mode of explosion properly called deflagration.[36] Such a deflagrative burn does not fit the usual characteristics of so-called 'open burning' (low temperature burning), as discussed in the section on thermodynamics. Low temperature burns can result from mixing the NC with sawdust or other dispersing flame suppressants, with the resulting noxious thermal decomposition products mentioned above, and the smoky flame typical of ordinary open burning. Detonation results from deflagration under confinement, which causes an exponential increase in reaction rate, from the undispersed heat and pressure buildup.[4b] Detonation of nitrocellulose gives little pollution, and open deflagration gives practically none besides carbon monoxide. Based on AED calculations, the amount of NO_x to be expected from open deflagration of one ton of nitrocellulose is 0.01 to 1 mg/m3 after 3 minutes with normal air conditions, and after 8 minutes with worst air conditions. The corresponding CO concentration is 1 to 25 mg/m3. In comparison, the OSHA breathing air standards for the workplace are 440 mg/m3 for CO, and 10 mg/m3 for NO_x (Short Term Exposure Limits = STEL).[41] The CO first formed in the deflagration quickly oxidizes to carbon dioxide as the medium cools to ambient and very little monoxide remains. Real time measurements in these plumes show CO to be some unknown value less than 0.5 ppm within a minute.

4.3.2. Ammonium perchlorate. Ammonium perchlorate is very insensitive and difficult to initiate as an explosive or propellant. It has 27% excess oxygen over that needed to give complete degradation, and it gives only gaseous products. For these reasons it is commonly used as an additive with other explosives. In the immediate oxidative environment present following explosion of ammonium perchlorate, the chlorine from the perchlorate is essentially all in the form of diatomic chlorine Cl_2. However, diatomic chlorine gas is not the final stable form of chlorine, which easily reduces to chloride ion in the form of hydrogen chloride, HCl, or chloride salts such as NaCl or KCl. Ammonium perchlorate and ammonium chlorate, as other perchlorates and chlorates, benefit from the presence of alkali metal salts in the formulation, which then provide a route for the chlorine to be converted to chloride without the formation of acidic hydrogen chloride gas. Either hydrogen chloride gas or solid suspension of chloride salts must be expected. The ambient concentration of chlorine gas in the atmosphere is zero, because it is converted so easily to hydrogen chloride. The nitrogen from ammonium perchlorate explosion is converted to nitrogen gas, N_2, and the hydrogen to hydrogen chloride and water. Organics from multibase PEP containing ammonium perchlorate are converted to water, nitrogen gas, and to carbon dioxide so long as the excess oxygen is still available. Inorganics present may add metallic salts or oxides, some of which are converted to hydroxides from the moisture present. Because they corrode gun barrels when used in small arms ammunition, perchlorates are used instead for pyrotechnics, blasting explosives, and propellant (20, p 91-2, p 230-2). High temperature deflagrating burns produce some nitrogen oxide, from conversion of the internal nitrogen and air nitrogen. Decomposition of ammonium perchlorate is catalyzed by the presence of transition metal salts and oxides (8, p P150-1). The concentration of the emissions is quickly dispersed to insignificant levels in detonation and deflagration, but not usually in low temperature degradation or burning.

4.4. Aliphatic (Non-aromatic Organic) Explosives.

4.4.1. PETN. The explosive, pentaerythritol tetranitrate, PETN, ignites with greater difficulty than nitroglycerine upon contact with a flame,[26] and then continues burning at a very slow rate. Thermal decomposition at 410 degrees F gives a mixture which contains 70% nitrogen oxides.[24] Decomposition initiated by mechanical shock gives 30%. But initiation by detonation gives only 5%, along with he lowest total of NO_x + CO of the three cases.

Again much less pollution is expected from open detonation in contrast to other mechanical initiation, and to either burning or thermal decompositions at low temperatures (<1000 degrees F).

4.4.2. RDX. Thermal decomposition of RDX at temperatures up to 570 degrees F gives much NO_x and CO.[16c] Above 440 degrees F it ignites and decomposes within seconds. However, detonation gives mainly CO, CO_2, N_2 (nitrogen gas), water and a trace of hydrogen. Open burning of RDX is thus more polluting than open detonation, which has essentially only carbon monoxide to consider. AED calculations indicate that the CO will be oxidized to CO_2 quickly, leaving only insignificant CO concentrations within seconds following open detonation.

4.4.3. Nitroglycerin (NG). Thermal degradation of nitroglycerin without detonation forms a small amount of nitric acid (16b, p 47), but detonation gives total conversion to water, nitrogen and carbon dioxide. The extremely clean detonation is due to the internal 5.88% excess of oxygen over the amount sufficient to convert all components to the totally oxidized forms. In work reported by Bowden and Yoffe,[24] nitrogen and carbon dioxide accounted for only 19.3% of the product composition if the NG was heated to 180 degrees C to initiate explosion, with the rest accounted for by nitric oxide NO, nitrous oxide N_2O, carbon monoxide CO and hydrogen H_2. These polluting side products were not present after initiation by detonation, but were present at 59.5% if the explosion was initiated by mechanical shock, in comparison with 80.7% after thermal initiation. (Side products may also be caused by other variations of the parameters and by unusual conditions of the testing mechanism, such as in bomb calorimeters, etc.). Side products may be formed in disposal of crude waste fractions from manufacture of nitroglycerin or munitions containing it. Here again, open burning gives noxious side products, which can be minimized or avoided by open detonation with a nitroglycerin supplement. Thus even nitroglycerin, which does not ordinarily produce carbon black in disposal, gives noxious products, such as formaldehyde[16b, 26] and others listed above with low temperature burning or thermal treatments or with insufficient initiation energy in explosions, etc, but it gives complete conversion to N_2, CO_2 and O_2 with no side products in proper disposal by open detonation.

The behavior of nitroglycerin to give polluting emissions from burning, but no pollution from strong detonation, is explained by evidence of two successive reaction stages.[25] The first of these is only slightly exothermic, with partial degradation. The second is highly exothermic, with total degradation to non-polluting products. It is not easily ignited, but once ignited it burns readily.[22] No detonation results if the material is not confined. With confinement, the gases build up pressure, which rapidly surpass the critical pressure to initiate detonation.

4.4.4. Nitroglycerin/nitrocellulose mixtures. In practice, oxygen-rich nitroglycerin (NG) is advantageously mixed with nitrocellulose (NC), giving explosives and propellants which explode to vapor with little or no polluting gases at all. Blasting gelatine is such a mixture with the oxygen excess of NG just balanced by the oxygen deficiency of NC. The mixture with 8% NC and 92% NG gives only carbon dioxide, nitrogen and water.[22] AED measurements of plume concentrations following deflagration of 4000-pound lots of 1:1.2:2 NG/NC/nitroguanidine propellant showed NO_x at 0.5 mg/m3 three minutes after the explosion, and CO at <0.5 mg/m3 after only 30 seconds. The amount of carbon monoxide (1700 mg/m3) initially formed by this 32.5% oxygen deficient mixture would disperse to 27 mg/m3 in 3 minutes. But the measurements show it is rapidly depleted to neglible concentration by air oxidation following the initial reaction.

4.5. Aromatic Explosives (See References 1 to 10)

Measurements of initial TNT products in detonation chambers (17 v3, ch 29; 18 ch 45; 16a 318; 38) typically indicate a $CO:CO_2$ ratio of 30:1 or more for free explosions and only about 2:1 in confined explosions. $CO:H_2$ ratio is about 3:1 in the open and 7:1 in confinement. However, carbon monoxide concentration is depleted or reduced drastically following the initial reaction in open air detonations.

Loading density of the explosive makes a difference in the ratio of detonation products, as shown by autoclave measurements and calculations based on well founded principles. For example, Schmidt[23] calculated that an increase of loading density of TNT from 1.0 to 1.59 g/cm3 lowered the CO/CO_2 ratio from 6.0 to 1.7, while giving a 46% increase in elemental carbon, and a 45% decrease of ammonia and hydrogen cyanide. Similar trends were observed for nitrophenols such as picric acid. Extensive calculations on various explosives were made more recently by Cook,[21] which confirm and broaden these observations.

A very significant behavior of the carbon monoxide from TNT has been observed.[33,34,36] Whereas the production of carbon monoxide is initially high from oxygen deficient explosives like TNT, as predicted by calculations and confirmed in bomb calorimeter and detonation chamber tests, measurements following free explosions indicate the subsequent conversion of the CO to CO_2. In such tests, no carbon monoxide is left at all, due to conversion with air oxygen as the heat and pressure disperse.

Other aromatic explosives behave similarly. Picric acid, picrates, etc., also burn with a sooty flame, but detonate in the open to much cleaner clouds.

5. TYPICAL INDUSTRIAL PRACTICE AND PREFERENCE

AED has communication with explosives industries throughout USA. The following summary represents their preferences and typical practices in disposal of rejected batches and other wastes that are not recycled. Incineration is sometimes used for PEP manufacturing waste, but is seldom preferred over detonation or deflagrative open burning.

5.1. Aromatic Explosives.

Detonation is much preferred. Burning and incineration give much black smoke. require as much or more attention, take too long, and cost too much. Incinerators with afterburners are effective but costly. Detonation gives little smoke or other pollutants.

5.2. Nonaromatic Explosives.

Detonation and deflagration are much preferred. Non-deflagrative burning does not give as much smoke as burning of aromatics, but is smokier, costlier and more inconvenient than detonation. Some types, such as inorganic blasting agents require a strong initiator to burn or detonate, but then give convenient and complete degradation. But residue mixed with sawdust or fuel gives a polluting burn.

5.3. Propellants.

Detonation or deflagration is much more preferred than low temperature burning (<1000 degrees F). Most propellants deflagrate well, taking about 6 seconds per ton, generating temperatures of 4000 to 6000 degrees F, and emitting very little if any pollution. Wastes in solvent or aqueous solution are best mixed with explosive or propellant for deflagration or detonation. Mixing with sawdust or fuel for burning is highly polluting, but is the only available method in some locations.

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EXPLOSIVES WASTE DISPOSAL SITES: A DOD-Wide Problem

CASE STUDY: Milan Army Ammunition Plant O-Line Settling Ponds

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Abstract: Past disposal practices associated with explosives manufacturing and loading, assembling, and packing operations at US Army facilities has resulted in environmental contamination at a number of these sites. A case study at Milan Army Ammunition Plant is examined delineating the effects of disposal practices on the environment and the actions taken to prevent additional contamination in an environmentally acceptable and safety conscious manner. Groundwater contamination is extensively examined and an in-place closure action of the O-line settling ponds (used for disposal of pink water from washout operations) is presented addressing both safety and environmental considerations.

INTRODUCTION

Promulgation of the Comprehensive Environmental Response and Liability Act (CERCLA) has identified the need to remedy past waste disposal practices at formerly utilized hazardous waste sites. The disposal of hazardous wastes during this century has impacted upon the quality of the environment including surface water and groundwater resources. The disposal of explosives-laden waste water from munitions manufacturing prior to implementation of currently acceptable environmental controls (e.g., filtration, activated carbon absorption) commonly entailed the use of earthen surface impoundments (ponds) in conjunction with drainage ditches. This procedure resulted in contamination of surface and groundwater, and associated soils and sediments. In order to prevent additional environmental damage remedial actions must be undertaken. These actions must be based upon site investigations and proper planning/design of the appropriate remedial actions.

This paper describes the site investigation and remedial action (under construction) at the O-line settling ponds located at Milan Army Ammunition Plant (MAAP), Milan, Tennessee. This project has been implemented as part of the US Army Installation Restoration Program through the US Army Toxic and Hazardous Materials Agency located at Aberdeen Proving Ground (Edgewood Area), Maryland. The assistance of MAAP, the US Army Engineer Division, Huntsville, and the US Army Engineer District, Mobile, has been instrumental in the progress of this action and is greatly appreciated.

SITE DESCRIPTION AND HISTORY

The 12-acre O-line settling ponds site is located within MAAP, approximately 5 miles east of the City of Milan, Tennessee (Figure 1). The ponds are part of the O-Line facility that is used for conventional munition demilitarization. Defective and outdated munitions loaded, assembled, and packed (LAP) at the plant were disposed at this line.

The major function of O-line was to remove explosives (2,4,6-trinitrotoluene (TNT) and cyclotrimethylenetrinitramine (RDX)) from bombs and projectiles by injecting a high pressure stream of hot water and steam into the open cavity of the munitions. Waste explosive was separated from the resulting water phase and collected for reuse or for disposal at the MAAP explosive burning grounds. Effluent wash water was then passed through baffled concrete sumps outside the wash-out building where it was cooled, and entrained explosive particles were removed by screens. Cooling was aided by a cold water spray at the surface of the sump chambers. The screens and sumps were periodically cleaned to remove collected explosive particles.

Until 1941 the water effluent from the sumps was discharged to an open drainage which ran through the O-line area. However, in 1950 holding ponds were constructed at the site to provide an additional settling capacity for the waste water. The ponds consist of 11 individual basins connected by spillways and open ditches with baffles and distribution boxes to allow several configurations of ponds to be employed in series (Figure 2).

The ponds have a total capacity of approximately 5.5 million gallons and cover an area of about 280,000 square feet (excluding the dikes).

In operation, the ponds received water from the plant sump through an open concrete flume. Most of the solid explosive particles settled to the bottom of the first receiving basin. Effluent from the last basin in the series overflowed through a bank of carbon-filled tanks before being discharged to the area drainage ditch. The carbon from the tanks was periodically removed and burned. The drainage ditch ultimately discharged across the north boundary of the installation to the Rutherford Fork of the Obion River.

In 1971, sediments were dredged from the ponds using a drag line, and the dredged spoils were placed at the northwest corner of the pond area. An attempt was made to burn the sediments at the explosives burning ground; however, the material would not burn, so the remaining dredged spoils were left in the area.

In 1981, MAAP drained the ponds, treated the effluent, moved the spoils pile back into the dredged ponds, and lined the empty ponds with synthetic liners as a temporary remedial measure to prevent additional groundwater contamination.

SITE INVESTIGATION

Field investigations were conducted at MAAP and the O-line area in order to define the magnitude of contamination resulting from the O-line operation. In order to evaluate the impact of the O-line settling ponds site on the environment production records were reviewed to assess the amounts and types of waste disposed at the site. In addition, geohydrologic information, along with topographical and meteorological data pertinent to the area was reviewed in order to determine probable pathways of contaminant migration (e.g., 246-TNT and RDX) from the site.

Results of this review determined that explosives contamination migration was probable via two mechanisms; surface water migration of explosives by means of the drainage ditch located in and adjacent to the O-line area, and groundwater migration of explosives by means of the settling ponds and to a degree the drainage ditch. Both the settling ponds and drainage ditch allowed for infiltration of explosives into the groundwater flow system beneath MAAP when waste water was present. The extent of contamination from the site could not be assessed from the review and actual installation of monitor wells and collection of environmental samples from the area for chemical anlayses was required.

Monitor well installations were based on the geohydrologic setting present at O-line. Available information indicated the Claiborne and Wilcox formations as the shallow water bearing units (aquifer) underlying MAAP. These formations consist chiefly of sands with lenses and interbeds of clay at various stratigraphic horizons with an average total depth of 300 feet beneath MAAP (Figure 3). Groundwater flow at the site was thought to be in a northwest (NW) direction. This was close to the actual situation at the O-line site, however, the direction of groundwater flow at MAAP is greatly influenced by topography and surface streams that alter flow patterns throughout the plant (Figure 4). Depths of the wells varied in order to monitor the upper, middle, and lower portions of the aquifer for explosives contamination. The correct placement of monitor wells was essential in evaluating the magnitude of contamination originating from the site. In this case monitor wells were placed downgradient of groundwater flow from the settling ponds within distances that contamination was anticipated to be present based upon groundwater hydraulics of the area.

Environmental samples were collected from the drainage ditch, settling ponds and groundwater monitor wells. Explosive compounds and asociated degradation products (Table 1) were analyzed in the samples. In addition geohydrologic information was collected from the monitor wells (Figure 5) in order to define groundwater flow, soil types, and groundwater hydraulic properties specific to the site.

Results of the sampling indicated the O-line settling ponds and associated groundwater as major areas of contamination. Sediments from the ponds indicated up to approximately 5% explosives content in the top 12 inches of materials (Figure 6). These levels decrease with increasing depth of sediment indicating leaching of contaminants into the subsurface zones. Groundwater was found to be contaminated with explosives 1 1/4 miles downgradient of the settling ponds (Figures 7, 8, and 9) and flowing in the north-northwest (NNW) direction. The contaminated groundwater zone (plume) was limited to the middle section of the Claiborne Formation indicating vertical stratification of the contaminants. Levels of contaminations were in some cases above US Army Interim Drinking Water Criteria (RDX - 34 ppb and TNT - 44 ppb). The presence of explosives at high levels (Figure 10) adjacent to the settling ponds and the existence of a sizeable plume migrating toward the installation boundary adjacent to the Rutherford Fork, of the Obion River, indicated a remedial action was required to prevent further environmental damage. Samples collected in the drainage ditch indicated explosives were present, however, the low levels found (under 50.0 mg/kg) did not justify additional study or remedial actions.

REMEDIAL ACTION

Various remedial action (closure) alternatives were considered for use at the O-line settling ponds site, these include:

a. In-place containment using migration barriers such as containment walls and low-permeability caps.

b. Onsite treatment of sediments using rotary kiln incineration.

c. Onsite waste disposal in a newly developed facility.

d. Removal and offsite disposal/treatment.

The selection of a remedial action was largely restricted to the in-place containment option due to restrictions on disposal of reactive wastes (i.e., explosives) into landfills, and the lack of proven technologies (e.g., incineration) for treatment. Treatment technologies are currently being developed and should be available within the near future for treatment of explosives waste. These technologies are needed for sites where an in-place containment action is not suitable as a means of closure.

The O-line site was very favorable to an in-place containment closure. The geohydrologic conditions at the site provides for adequate isolation of the waste materials after installation of the low permeable cover system (grass/topsoil/clay-gravel-clay) and containment wall. The depth of groundwater below the ponds, surface drainage, and soil types are adequate to prevent surface water and groundwater from contacting the contaminated sediments and forming leachate that could flow into the groundwater system beneath the ponds. In addition, borrow material (e.g., clay, inert fill used for construction) are available at MAAP.

The closure at O-line (Figure 11) acts primarily as a diversion for surface water from contacting the contaminated material in the ponds. A cross section of the cover system (Figure 12) illustrates the method water is diverted. The system utilizes a proper grade that allows a large portion of precipitation to runoff the site or be removed through evapotranspiration of the grass cover. Any remaining portions of water percolate through the upper soil into a gravel drain layer that allows for additional runoff. The gravel layer contains a perimeter piping system that routes collected water to the outside of the cover system. The clay layer is the final protective layer in the system. This layer is designed to prevent percolation of water for an extended period. By compaction of low permeability clays percolation of water is prevented until saturation of the layer occurs by residual water in the drain layer. However, the rate of percolation through the layer after saturation is minimal, restricting the flow of leachate into the groundwater flow system. Any possibility of lateral movement of infiltrating precipitation into the ponds is prevented by the perimeter containment wall obstructing flow toward the ponds.

Adequate depth to groundwater below the ponds is required in using an in-place containment system. The bottom of the ponds should be a distance far enough from the groundwater surface and capillary fringe area so that contaminated sediments are not in contact with groundwater. Otherwise contaminants will leach and migrate into the groundwater flow system. Groundwater depth at the O-line site is approximately 40 feet below the bottom of the ponds. This depth is more than adequate for the containment system.

Construction of the containment system required an assessment of the explosive potential of the sediments prior to any actual earthmoving operations. The low content of explosives in the sediments indicated the potential for any ignition of explosives was minimal, however, testing was conducted to determine if ignition could occur due to localized stresses on the sediments due to heavy earthmoving equipment.

A friction test using the US Bureau of Mines Pendulum Friction Apparatus was conducted on sediment taken from the site. The sediment was mixed with explosives at various levels ranging from 0-25%. Results indicated that sediments with up to 20% explosives were insensitive to the testing procedure with no moisture present in the sample The presence of moisture and a maximum concentration of approximately 5% explosives in the O-line site sediments indicated earthmoving operations could be performed.

Construction is currently in progress at the O-line site in MAAP. Following completion this fall (1984) a monitoring program will be initiated to monitor groundwater for explosive compounds. The effectivenss of the closure will be evaluated based upon the results of this monitoring.

TABLE 1.

Explosive Compounds and Associated Degradation Products

2,4,6-Trinitrotoluene (246-TNT)
1,3,5-Trinitrobenzene (135-TNB)
2,4-Dinitrotoluene (24-DNT)
2,6-Dinitrotoluene (26-DNT)
1,3-Dinitrobenzene (13-DNB)
Cyclotrimethylenetrinitramine (RDX)
Cyclotetramethylene Tetranitramine (HMX)

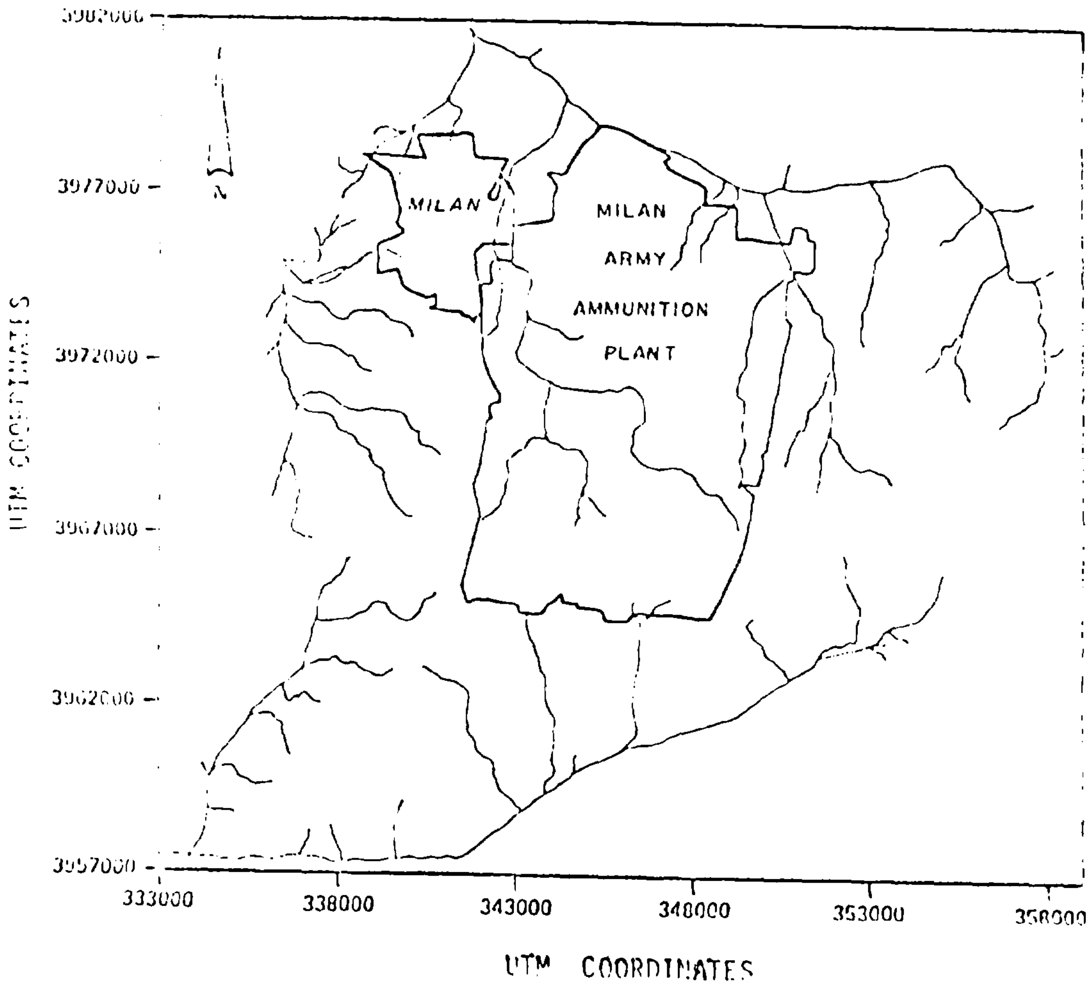

Figure 1. Location of City of Milan, Milan Army Ammunition Plant, and the O Line Settling Ponds.

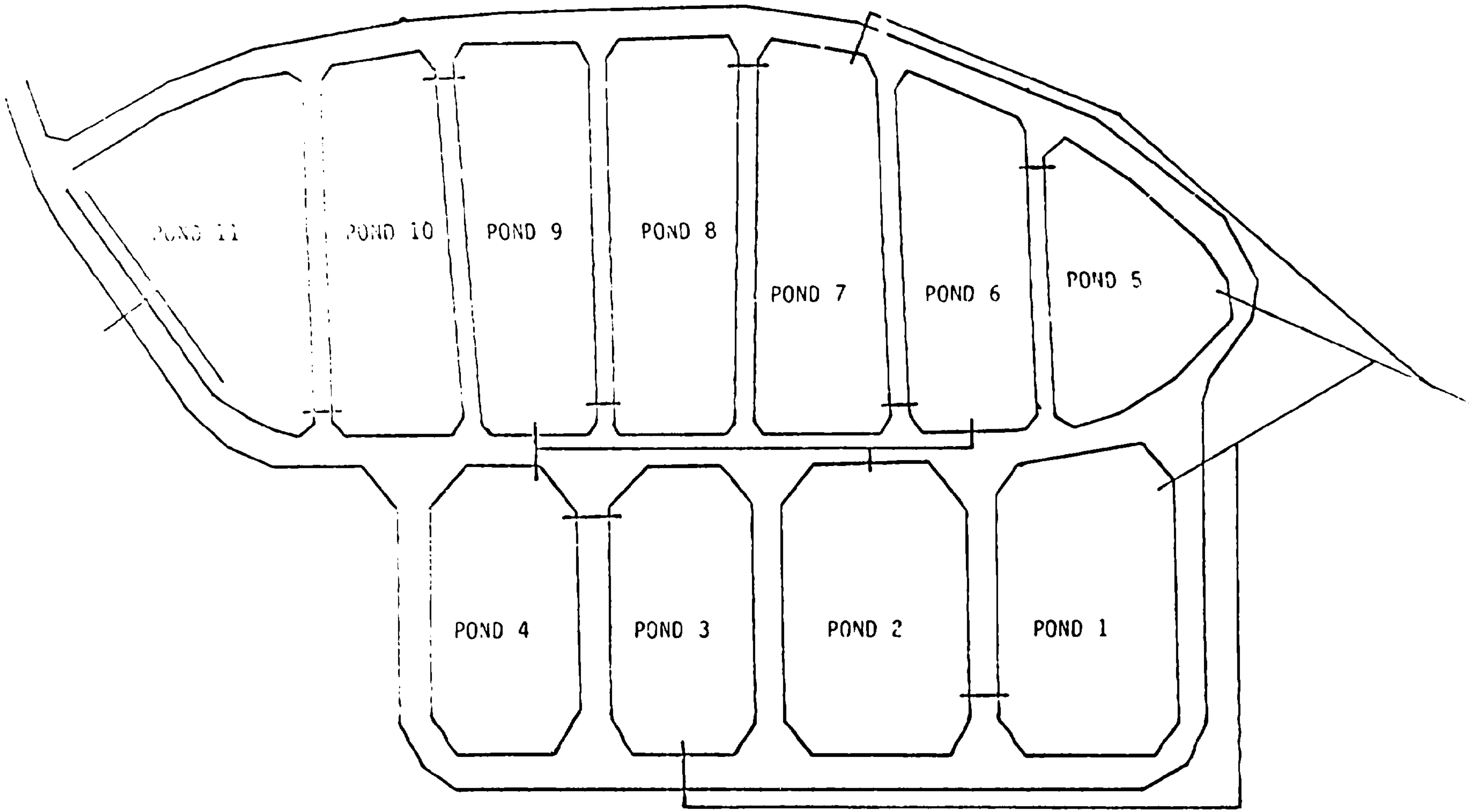

Figure 2. O Line Settling Ponds with Spillways and Baffles.

MILAN ARMY AMMUNITION PLANT

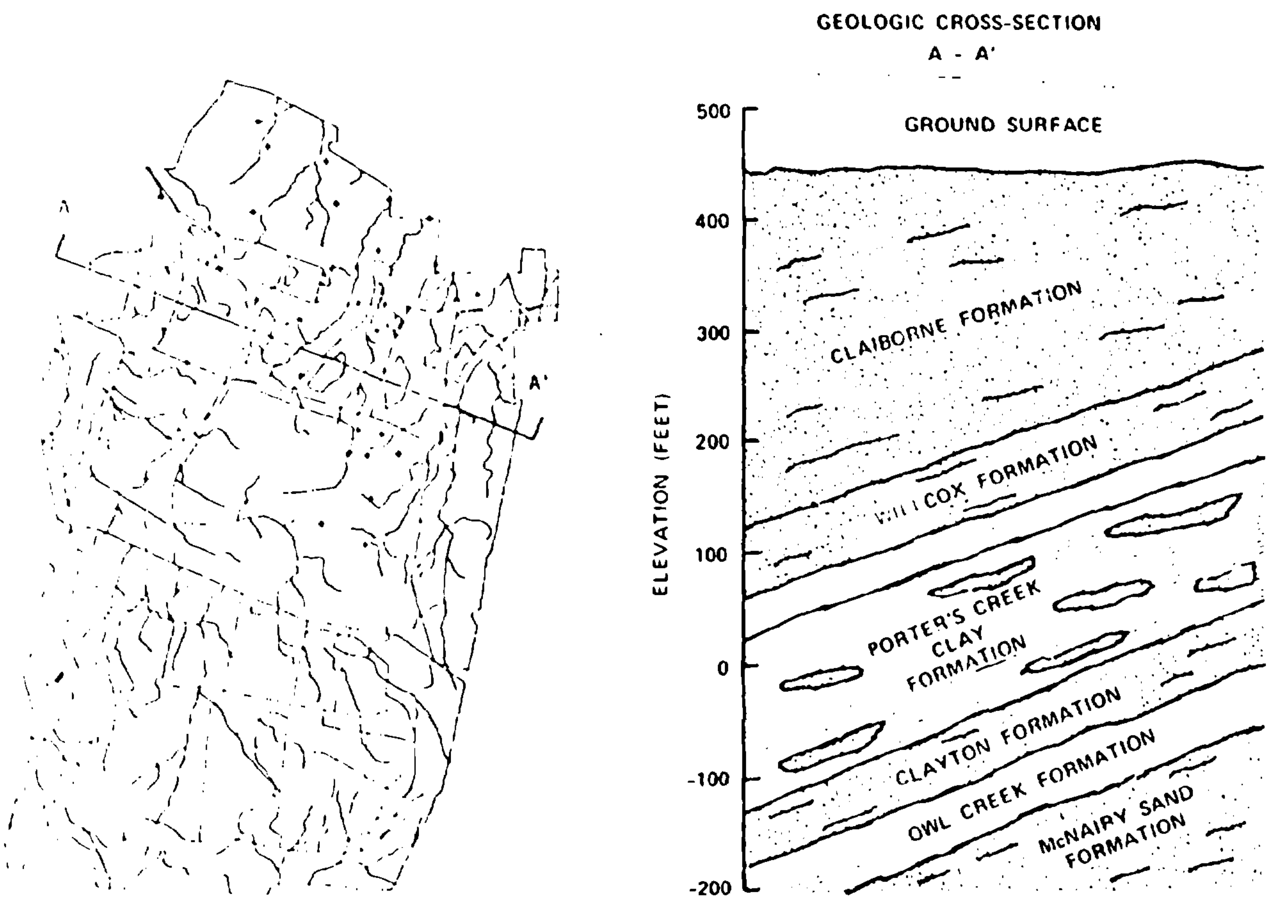

Figure 3. Geologic Cross Section for Milan Army Ammunition Plant.

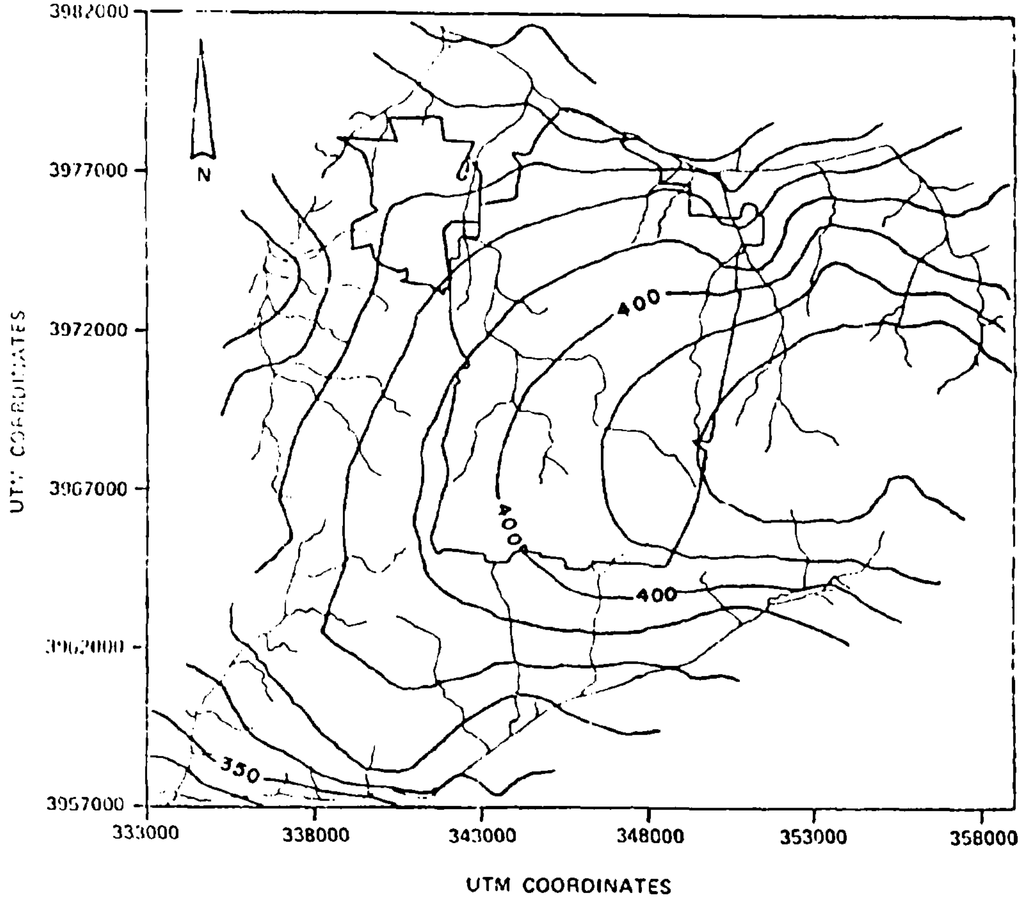

Figure 4. Piezometric Surface of Groundwater in the Claiborne Formation.

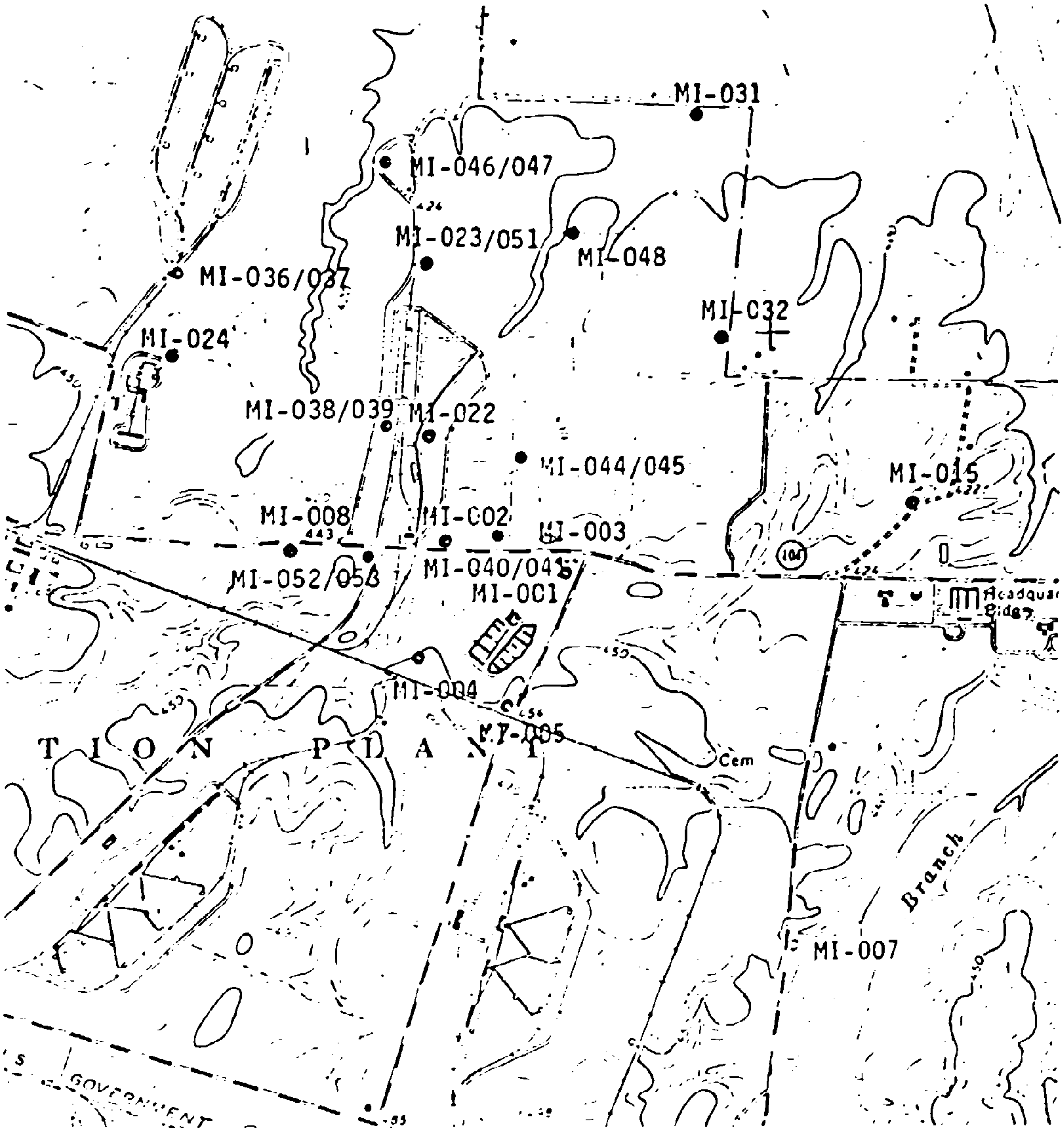

Figure 5. Monitor wells located in the vicinity of the "O" Line Settling Ponds. (Reprint with permission from USGS quadrangle, [illegible], [illegible]).

EXPLOSIVES CONCENTRATION VS. DEPTH

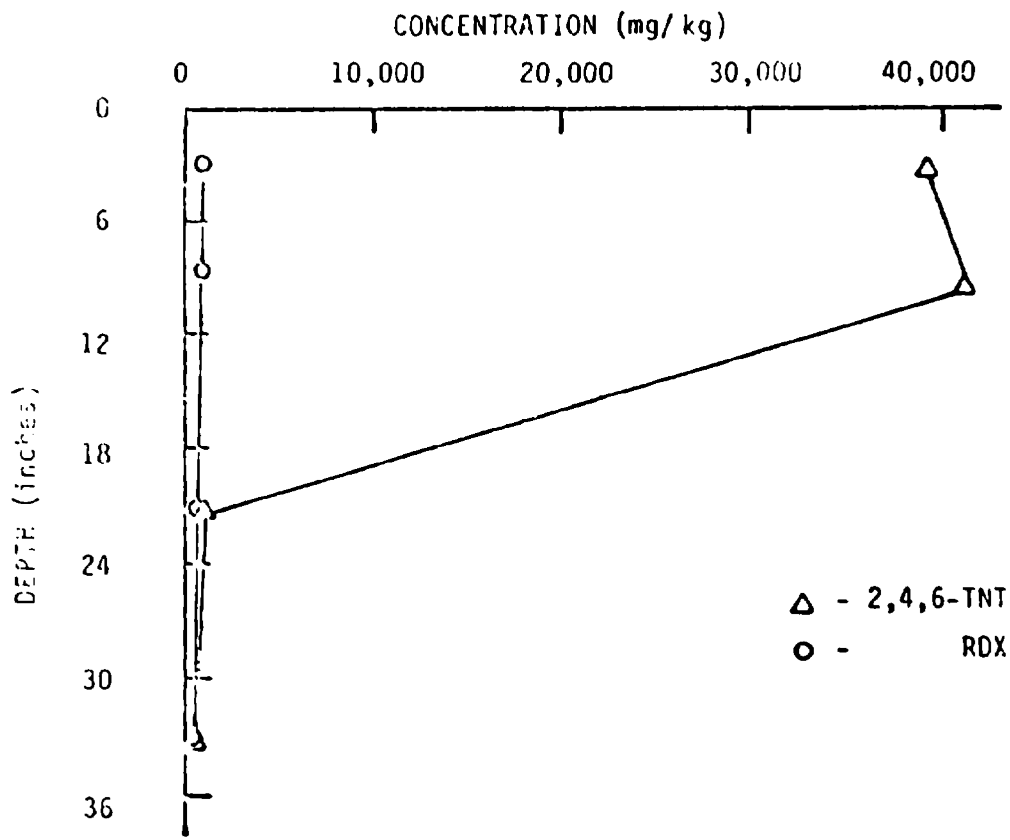

Figure 6. "O" Line Settling Pond 3 - Inlet; Contamination Profile.

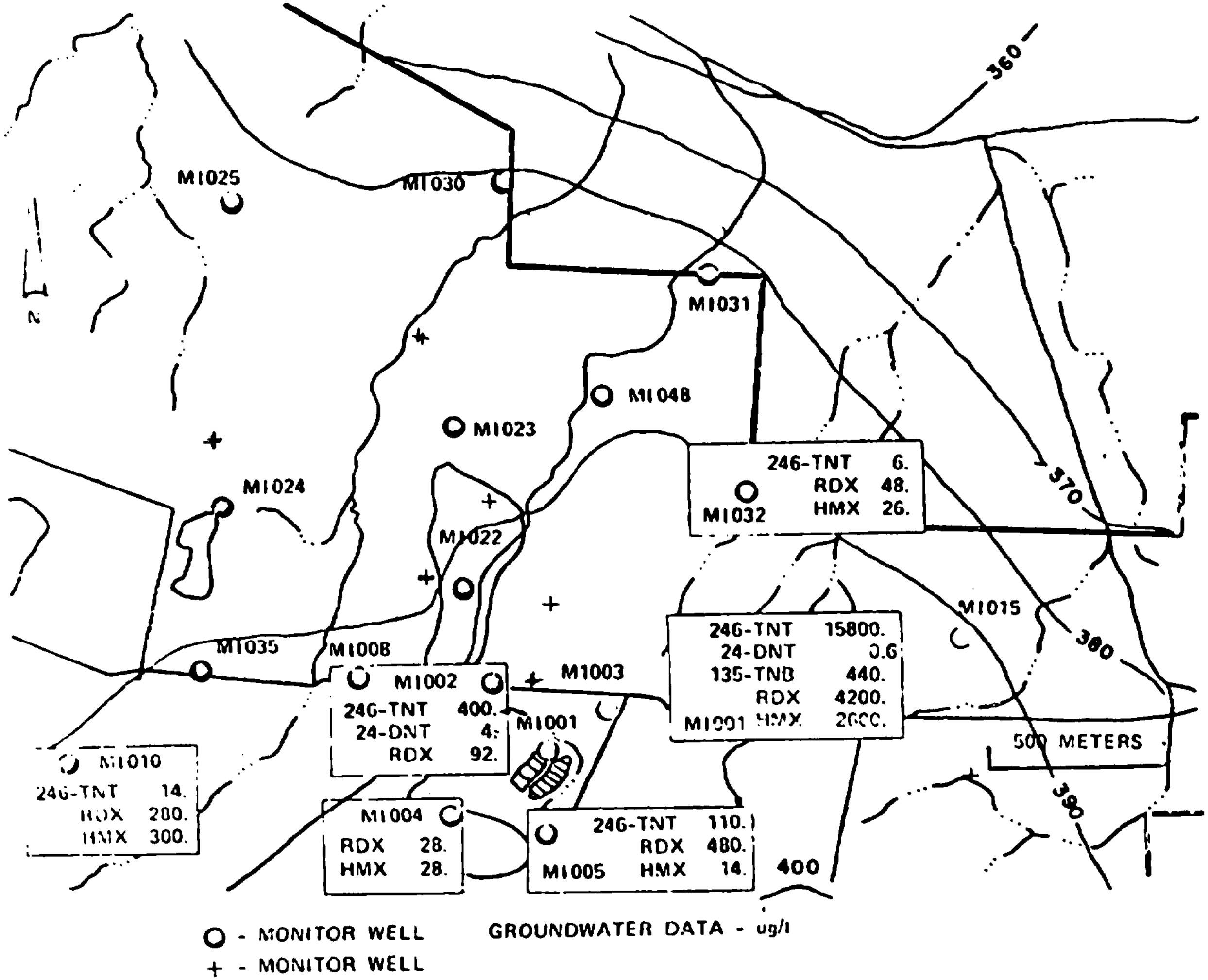

Figure 7. Groundwater Contamination in the Upper Section of the Claiborne Formation.

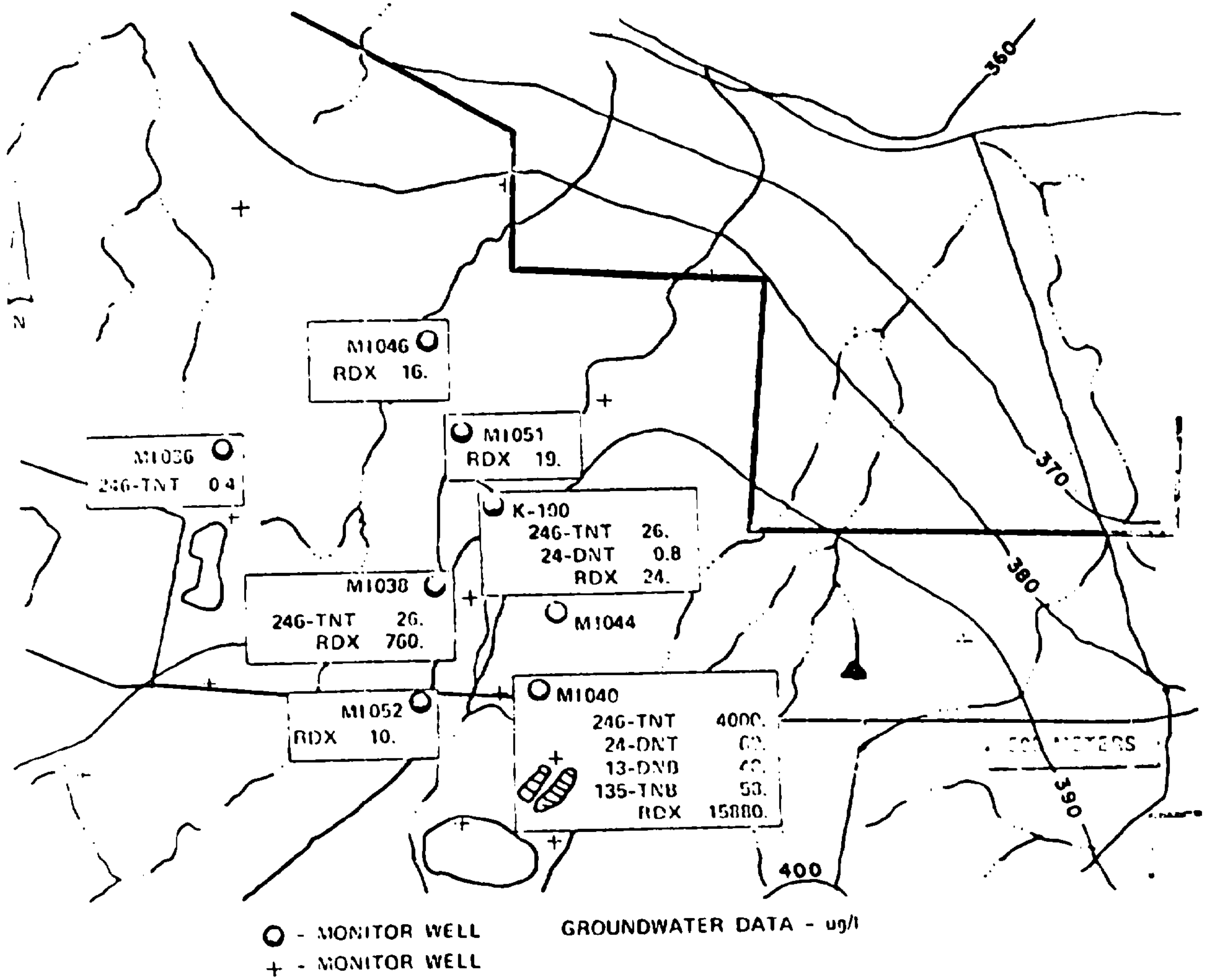

Figure 8. Groundwater Contamination in the Middle Section of the Claiborne Formation.

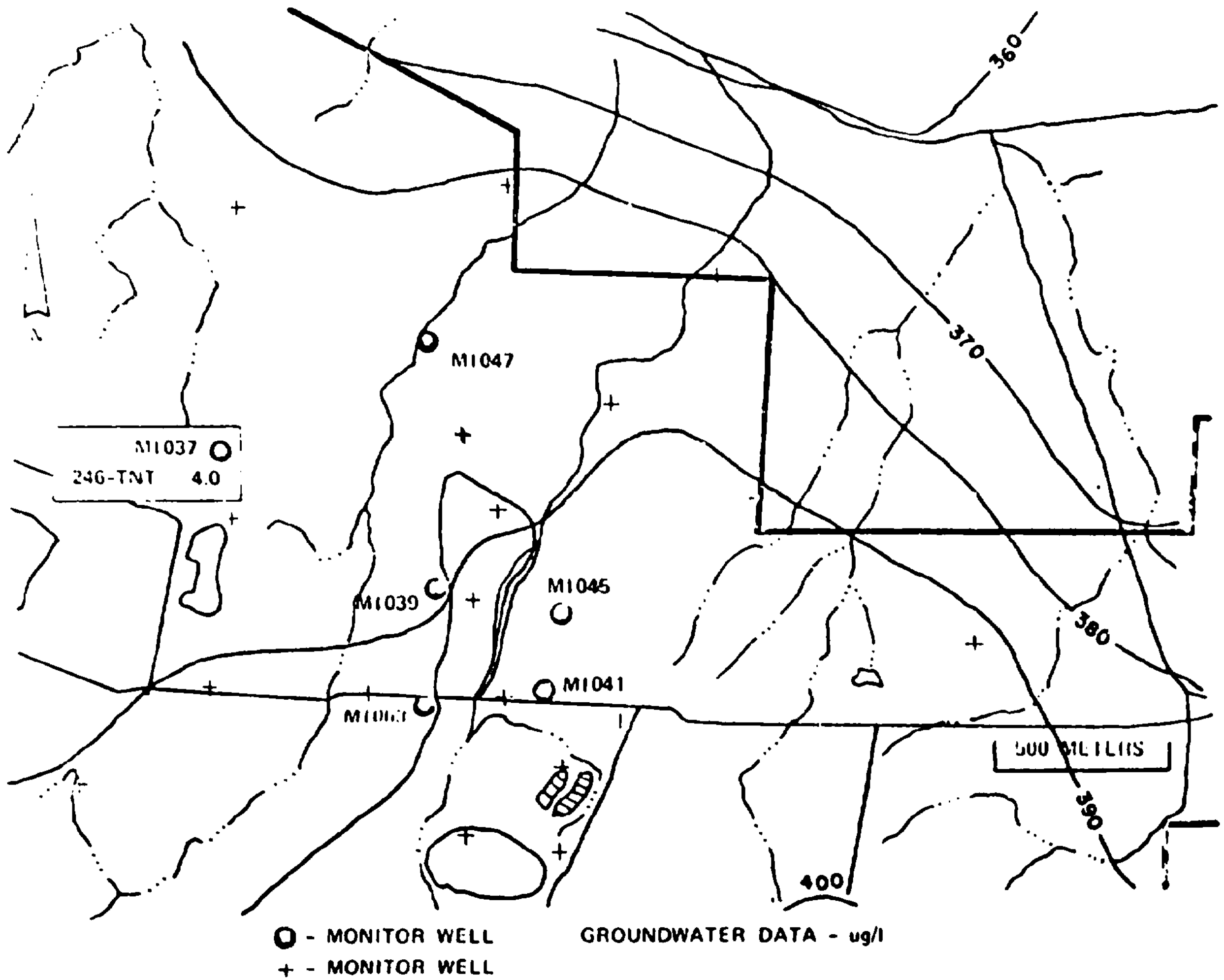

Figure 9. Groundwater Contamination in the Lower Section of the Claiborne Formation.

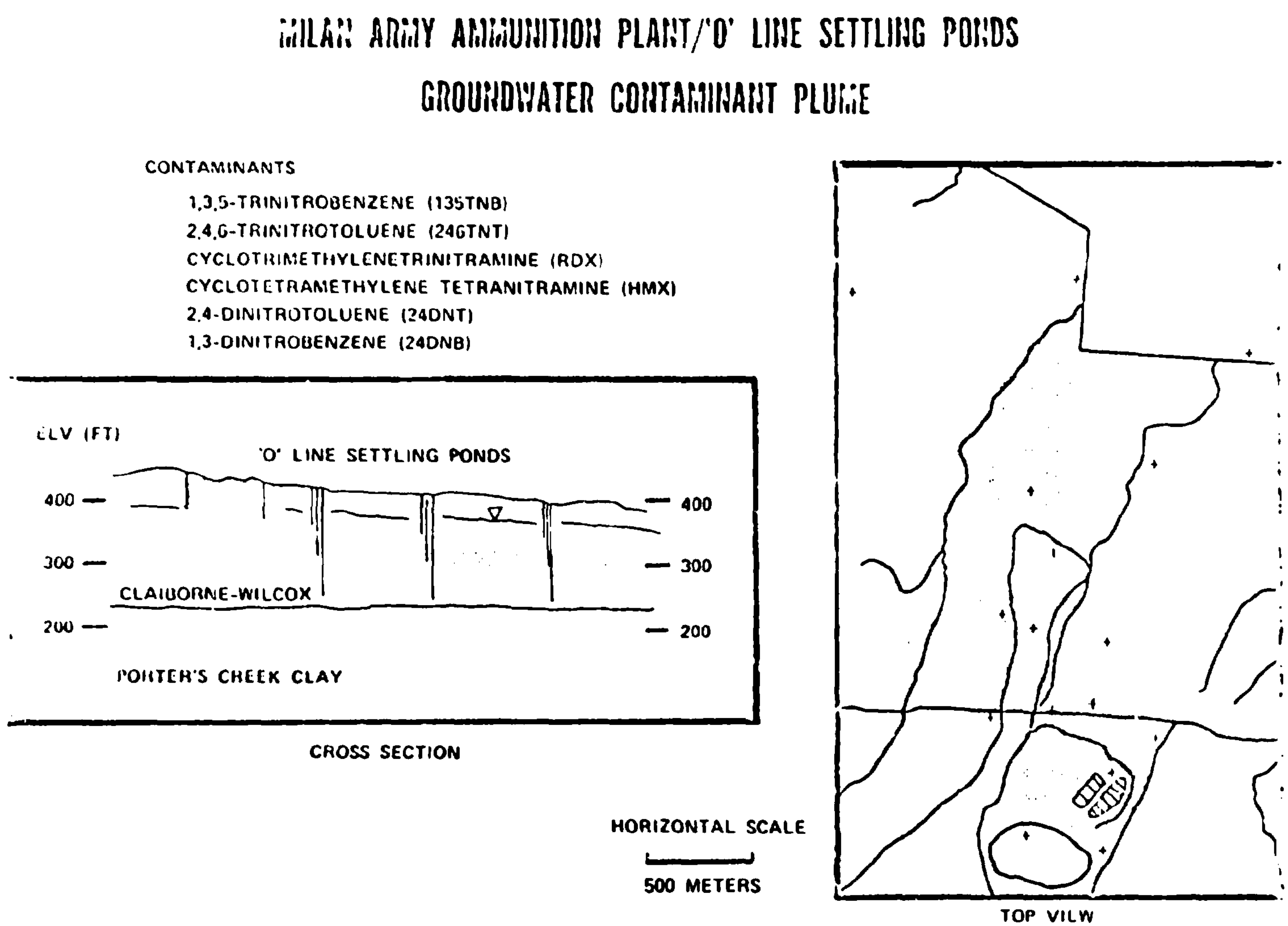

Figure 10. O Line Settling Ponds Groundwater Contamination Plume.

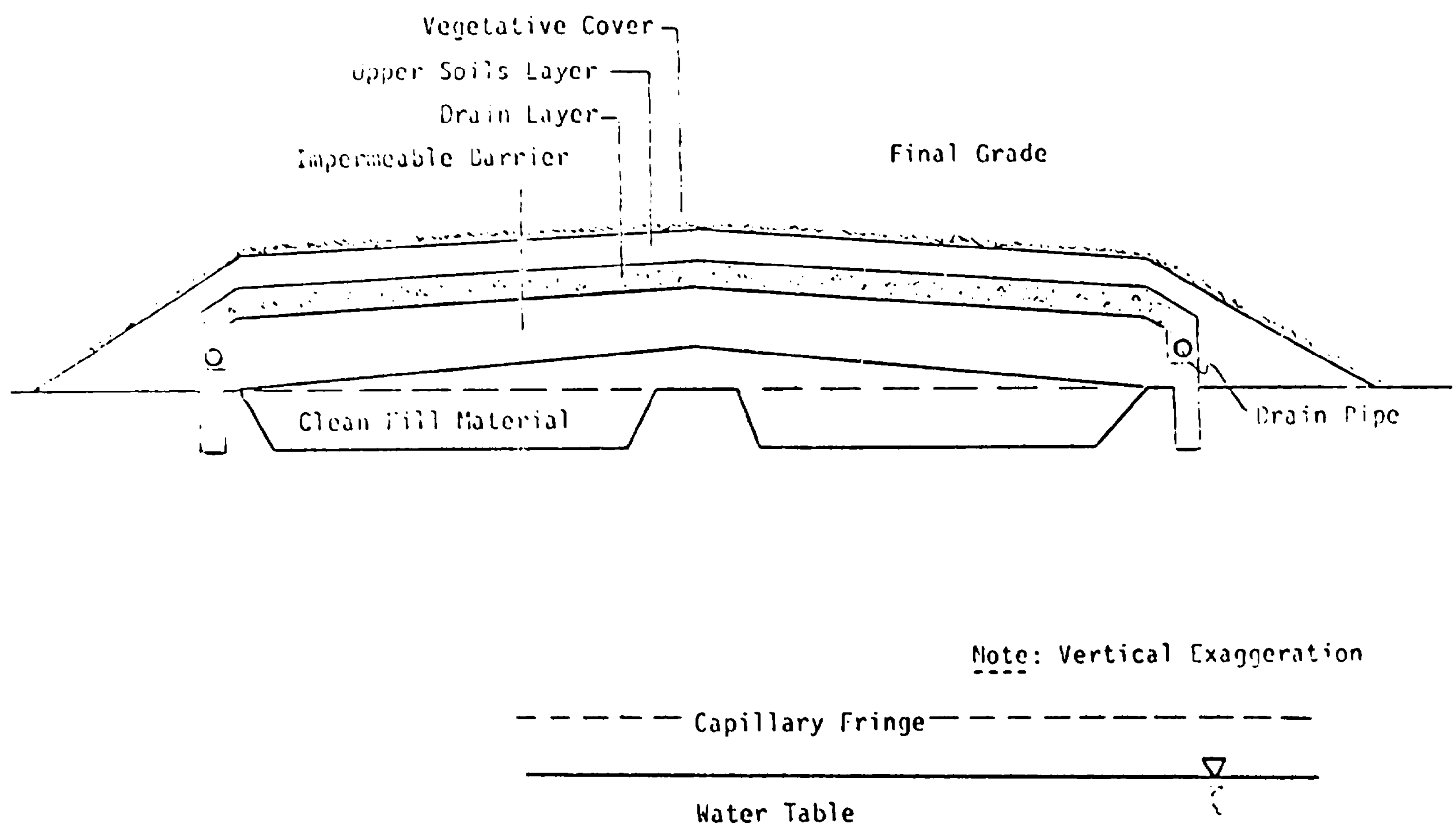

Figure 11. Profile of recommended cover configuration.

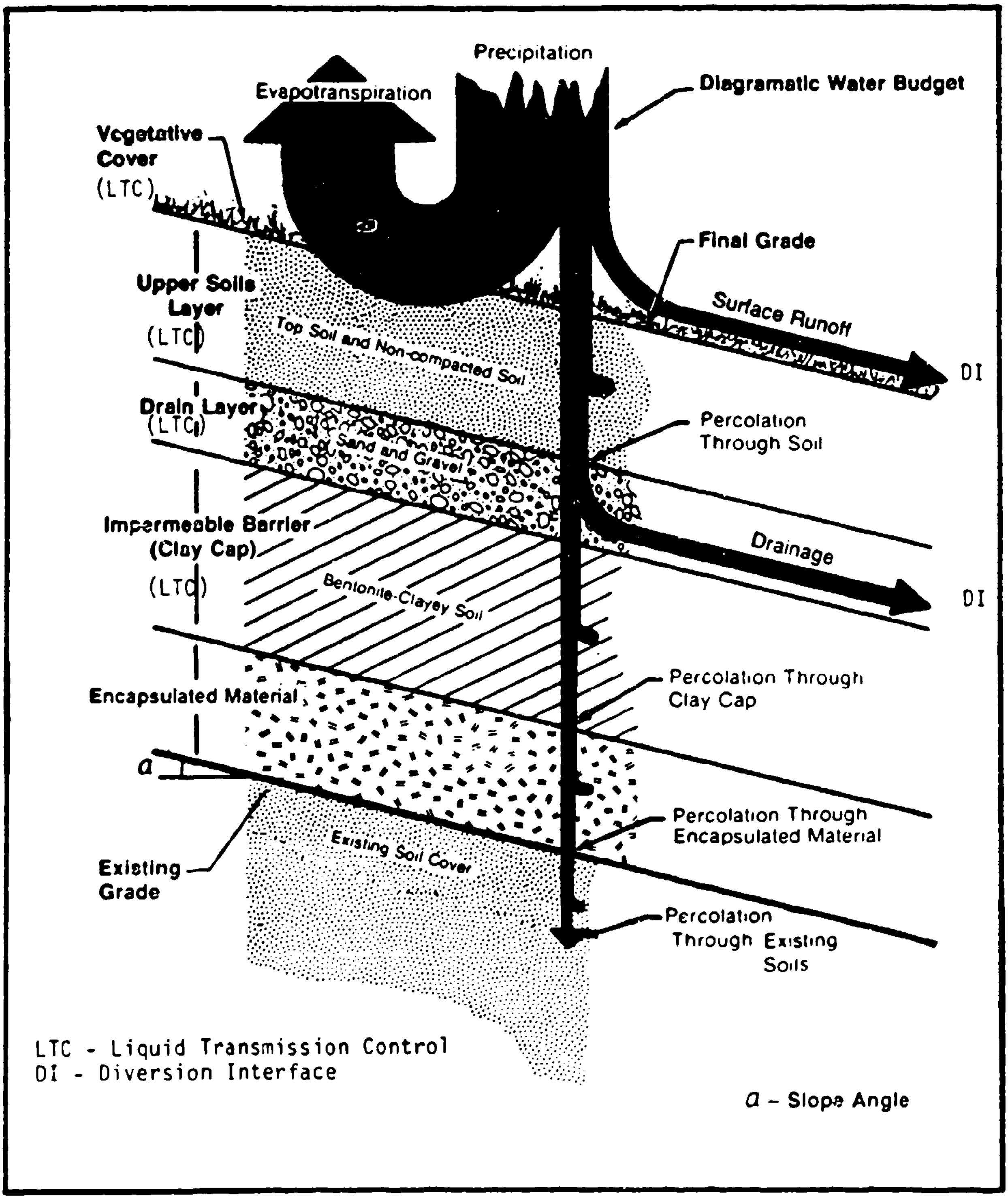

FIGURE 12 LIQUID ROUTING DIAGRAM OF COVER CONFIGURATION

CALCULATION OF TNT AND RDX CONCENTRATION LIMITS FOR FEEDLOT WATER SUPPLIES

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INTRODUCTION

The occurrence of a contaminant in groundwater frequently reflects on the quality of a drinking water supply taken from that source for use by human beings; such a water supply may have to be replaced with another source, often at considerable expense. Should the groundwater be used for cattle in a feedlot, the demand is likely to be considerably higher than for a human population living in a similar area. Thus, it is prudent to ask whether the water, though unfit for direct human consumption, might not be satisfactory for cattle. Such a situation was brought to light in 1983-1984 at the Cornhusker Army Ammunition Plant near Grand Island, Nebraska, where the Army's investigations identified a groundwater plume containing significant levels of TNT and RDX. The problem was approached from two viewpoints: (1) Would the health of the cattle be seriously impaired? (2) Would their meat, after slaughter, contain excessive levels of the two munitions compounds?

CONTAMINANT LEVELS IN WATER BELOW WHICH TOXIC EFFECTS TO CATTLE ARE UNLIKELY

If a contaminant is not expected to be a carcinogen, toxicologists conduct chronic (lifespan) or sub-chronic (generally 90-day) exposure studies to define a no-observable-adverse-effects level (NOAEL) in a suitably sensitive species. They then apply a safety (or "uncertainty") factor to estimate an acceptable level for human exposure. Results of 90-day studies[1] in rats and in monkeys, to which a safety factor of 1,000 was applied, were used to provide the acceptable daily doses to humans, D_Ts, for TNT and RDX, respectively (Table 1). The safety factor adopted for humans is unduly high for application to cattle; concern for the latter is almost exclusively economic. Moreover, allowable chronic levels for humans are conceived in terms of a lifetime of exposure; feedlot cattle are typically slaughtered at 16-18 months,[2] as compared to their natural life span of approximately 20 years.[3-5] Only part of those short lives is spent in feedlots. For these reasons, application of a safety factor of 10, rather than 1,000, to the NOAEL should be appropriate, i.e., an acceptable exposure level for cattle would be 100 D_T. At such a degree of exposure, minimal toxic effects, such as diminished growth rate, might occur in an occasional steer--leading to virtually undetectable economic loss. Based on the values in Table 2, the value for C_w' (allowable contaminant concentration in drinking water for feedlot cattle) can be calculated:

$$C_w' = \frac{100 \times D_T \times BW_S}{W_w'} = 1100\ D_T$$

Values of C_w' are therefore 1.54 mg/L for TNT and 1.10 mg/L for RDX, almost 16 times higher than values of C_w, which are based on considerations of human health.

CONTAMINANT LEVELS IN DRINKING WATER FOR CATTLE BELOW WHICH EXCESSIVE ACCUMULATION IN THE MEAT IS UNLIKELY

Estimates Based on Published Bioconcentration Factor Equation - Bioconcentration factors, BF, for compounds that are not readily metabolized and that concentrate almost entirely in fatty tissue, have been expressed[9] in terms of the ratio of contaminant concentration in the fat of beef to the contaminant concentration in their feed (dry weight basis) at equilibrium, i.e., $BF = C_{fat}/C_{feed}$. The following equation, with input values listed in Table 2, involves internal conversion to a basis of the ratio of concentration in meat to that in the drinking water and introduction of a factor for meat consumption by humans:

$$C_w' = \frac{C_w \times R_w \times W_{feed}}{BF \times R_m \times W_w' \times f_f} = \frac{C_w \times 2.0 \times 16.5}{BF \times 0.29 \times 45.4 \times 0.3} = \frac{C_w \times 8.355}{BF}$$

Hence, C_w' = 141 mg/L for TNT and 308 mg/L for RDX. Both of these values are higher than the solubility limits shown in Table 1, so that there should be no concern for contamination of the meat of cattle whose only source of TNT is their drinking water supply.

Estimates Based on Approximate Experimental Biological Half-Lives of Contaminants - One-time dosage of animals with radiolabeled TNT[14] and of RDX[15] can provide estimates of the biological half-lives of these compounds.

It is obvious from the tissue analyses for the TNT radiolabel (summary in Table 3) that significant storage of the compound or its metabolites (not distinguished, one from the other, by the methods used) occurs in various organs, not only in fat.[14] Based on the fraction F of the label remaining in the internal organs, the value for k_1, 3.46 day^{-1}, leads to a half-life of about 0.200 day (4.8 hours); in these calculations, unrecovered material was ignored. A far more conservative calculation involves the assumption that any labeled material not in the excretum remained in the animal; the assumption, was for male dogs, and leads to a k_1 of 1.25 day^{-1}. With such a value, the allowable drinking water concentration for cattle, C_w', that would derive from it would be considered a worst-case approximation.

Residual carcass radioactivity of orally delivered RDX in rats after four days[15] was 9.5%, which translates into a value of $k_1 = \ln(1/0.095) \div 4 = 0.588\ day^{-1}$, or $t_{1/2} = 1.18$ days. The carcass residual concentration for the parent compound only (not a radiolabel) was only 0.6%, whence $k_1 = 1.279\ day^{-1}$ and $t_{1/2} = 0.54$ day.

The present input-output argument involves equating the rate of ingestion of contaminant by cattle with the rate of loss when body concentration of the contaminant has reached equilibrium. (Note that no differentiation has been made between concentration in the whole animal and concentration in edible portions; that degree of fine-tuning is probably not justified in these calculations.)

$$C_w' \times W_w' = k_1 \times C_{meat} \times BW_s$$

Substituting $C_w \times R_w/R_m$ for C_{meat}, one obtains

$$C_w' = (k_1 \times C_w \times R_w \times BW_s) \div (W_w' \times R_m) = 76 \times k_1 \times C_w$$

For TNT, the more probable value of C_w' would be $C_w' = 76 \times 3.46 \times 0.049 = 12.8$ mg/L, while the worst case value would be $C_w' = 76 \times 1.25 \times 0.049 = 4.7$ mg/L.

For RDX, the more probable value of C_w' would be based on exclusion of metabolites, which were identified as "one-carbon intermediates," rather than potentially toxic RDX congeners, $C_w' = 76 \times 1.279 \times 0.035 = 3.4$ mg/L. The value derived on the basis of the radioactive label's fate is about half that.

Estimate for RDX Based on Subchronic Exposure in Rats[16] - Rats provided daily with drinking water saturated with RDX (50-70 mg/L) accumulated the compound more or less evenly in the various organs. At the end of 90 days, the concentration in the organs (brain, heart, liver, kidney, stomach, colon, and fat) ranged from 0.20 to 0.65 mg/kg. Thus, one may assume a value of C_w'/C_{meat} of 100. Since $C_{meat} = C_w \times R_w/R_m = 6.9C_w$, $C_w' = 690\ C_w = 24$ mg/L.

CONCLUSIONS

1. From the point of view of cattle safety, pollutant limits of 1.54 mg/L for TNT and 1.10 mg/L for RDX in drinking water are suggested. This statement does not imply dire consequences from exceeding these values to some degree; it only suggests the need for increased observation of the state of animal health.

2. On the basis of published bioconcentration equations, even drinking water saturated with TNT or RDX is predicted not to pose a problem of undue flesh contamination. These compounds do not concentrate heavily in body fat, but evidently do accumulate in experimental animals to a greater degree than the equations predict. Of the drinking water concentration levels estimated to be acceptable, with regard to flesh contamination, according to various assumptions, the most reasonable appear to be 13 mg/L for TNT and 24 mg/L for RDX. These permissible values are considerably higher than levels that have been found in off-post wells near Cornhusker Army Ammunition Plant.[17]

TABLE 1. PHYSICOCHEMICAL PROPERTIES AND ACCEPTABLE DAILY DOSE

Property	TNT	Reference	RDX	Reference
Log K_{ow}	1.84[a]	6,7	0.87	8
BF (calc'd)[b]	2.90×10^{-3}	9	9.51×10^{-4}	9
Solubility in Water (mg/L)	124 (20°C)	10	60 (23.5°C)	8
Acceptable Daily Dose, D_T (mg/kg)	1.40×10^{-3}	1	1.00×10^{-3}	1
Drinking Water Criterion,[c] C_w (mg/L)	0.049	1	0.035	1

a. Calculated from the value for trinitrobenzene,[6] with suitable adjustment for the methyl group.[7]
b. Through equation, log BF = -3.457 + 0.500 log K_{ow}.
c. $D_T \times 35$, expressed in mg/L.

TABLE 2. EQUATION INPUT DATA NOT SPECIFIC TO THE CONTAMINANTS

Definition of Symbol	Symbol	Value	Reference
Body weight of a steer	BW_s	500 kg	11
Fraction of fat in beef	f_f	0.3	12
Mass of fat in adult beef cattle	M_f	75 kg	13
Rate, per day, of human meat consumption	R_m	0.29 kg	12
Rate, per day, of human water consumption	R_w	2.0 L	13
Wt. of feed ingested daily by adult cattle	W_{feed}	16.5 kg	12
Daily wt. of water consumed by adult cattle	W_w'	45.4 kg	13

TABLE 3. LOSS OF TNT RADIOACTIVITY IN FOUR SPECIES 14 HOURS AFTER ORAL DOSING[14]

Distribution	Rat		Mouse		Rabbit		Dog	
	M	F	M	F	M	F	M	F
Internal[a] (% of dose)	1.09	1.89	2.68	1.18	2.08	3.54	6.02	6.91
Excretion[b] (% of dose)	90.53	100.54	77.38	59.25	75.57	85.40	71.33	81.34
Recovered (% of dose)	91.62	102.43	80.06	60.44	77.65	88.94	77.35	88.26
Internal ÷ Recovered = F	0.0119	0.0185	0.0335	0.0193	0.0268	0.0398	0.0778	0.0783
(100-Excretion) ÷ 100 = F_{max}	0.0947	-	0.2262	0.4075	0.2443	0.1460	0.2867	0.1866
$k_1(day^{-1})^c = \ln(1/F)$	4.43	3.99	3.40	3.94	3.62	3.22	2.55	2.55
$t_{1/2}{}^d = 0.693/k_1$	0.156	0.174	0.204	0.176	0.191	0.215	0.272	0.272

a. Blood, liver, kidneys, lungs, spleen, brain, muscle.
b. GI tract plus contents, feces, and urine.
c. The disappearance rate constant, k_1, is assumed to be first-order, i.e., the disappearance rate is proportional to the amount present at any given time.
d. $t_{1/2}$ is the half-life, assuming first-order disappearance kinetics.

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Interim Total Containment Test Fire Facility Pantex Plant Amarillo, Texas

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August 1984

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I. INTRODUCTION

General

This report documents the results of a test program conducted by members of the Development, Plant Engineering, Quality, and Safety and Fire Protection Divisions of Mason & Hanger-Silas Mason Co., Inc., (Operating Contractor of the USDOE Pantex Plant) for the U.S. Department of Energy at Pantex Plant, Amarillo, Texas.

The test series consisted of a series of explosive tests within a confinement chamber called the Interim Total Containment Test Fire Facility. Internal pressures, using both gas pressure transducers and blast pressure transducers, were measured. Also, an internal thermocouple was installed to measure the maximum temperature observed within the chamber. The maximum strains, both axial and hoop, using externally mounted strain gages were also measured. The entire series of tests were performed using LX-10 explosive with the exception of the first shot which consisted of a detonator. The name interim applied to the chamber means that the chamber has a possible limited life and data have been gathered and will continue to be gathered during test fire shots to prove out the feasibility of the chamber and provide data for future designs.

The chamber was designed for maximum explosive charge of 29 lb of TNT. The chamber design is based on a test fire shot involving a maximum of 15 lb of Class 1.1 high explosive as defined in DARCOM-R 385-100[1].* The 29 lb TNT equivalent design charge was arrived at by multiplying the 15 lb HE charge by a 1.3 TNT equivalency factor by the 1.2 safety factor recommended by TM5-1300[2] and then by the 1.25 proof test factor recommended by DARCOM-R 385-100[1]. The maximum amount of HE to be repeatedly fired within the chamber was later reduced to 11.2 lb of LX-10. The chamber is a vertical steel cylinder with hemispherical head and mounted on a concrete foundation. The chamber has a small bunker to the north for instrumentation and an exhaust system to the east connected with piping, valves and filters for exhausting the toxic products of combustion after an explosive test.

Purpose and Objectives

The purpose and objective of the testing were to determine the effectiveness of the chamber to contain the blast loads and hazardous fragments generated by the largest HE charge expected to be fired within the chamber. The initial premise was that the chamber

* The numbers in brackets refer to listed references.

structure would not exceed its yield strength, including appropriate safety factors, so that repeated firings would not damage the chamber. Early in the formulation of the test plan, it was decided that the best approach would be to slowly work up to the maximum limit by a series of ever increasing larger shots, the objective being to reach the maximum of the 125% overtest required by DOE application of DARCOM-R 385-100[1]. The 125% overtest is required to be performed on all explosive containment chambers used within the U.S. Department of Energy complex.

The test series consisted of the following high explosive test fires:

1. A 1.5 lb charge of LX-10 in the center of the chamber approximately 33 inches off the floor.

2. A 5.6 lb charge of LX-10 in the center of the chamber approximately 33 inches off the floor. This was a so called 50% (of the maximum to be fired) test shot.

3. A second 5.6 lb charge of LX-10 in the center of the chamber approximately 33 inches off the floor.

4. A 13.7 lb charge of LX-10 in the center of the chamber approximately 33 inches off the floor. This was a so called 125% (of the maximum to be fired) test shot.

5. A 11.2 lb charge of LX-10 in the center of the chamber approximately 33 inches off the floor. This was a so called 100% (of the maximum to be fired) test shot.

6. A second 11.2 lb charge of LX-10 in the center of the chamber approximately 33 inches off the floor.

At the present time the total containment chamber is the only structure of its kind at the Pantex Plant. The chamber was designed to totally contain and filter toxic effluents generated from high explosive test fire shots. Consequently, the response of the chamber under internal explosion is of considerable concern. For this reason a test program using the above stated HE charges was performed with the following stated objectives in mind:

1. Establish pressure load history profile for the chamber walls.

2. Monitor dynamic response of the chamber (i.e. stresses and strains).

3. Monitor the blast and quasi-static gas pressures within the chamber, including time history.

4. Monitor the temperatures generated within the chamber, including time history.

5. Verify that the chamber can safely be reused for several planned test shots.

6. Gather information for future designs of similar structures.

It should be noted, as stated earlier, that for the chamber to be safely reused for several planned test shots, all portions of the chamber are to respond within the elastic range of deformation. Otherwise, the structural capability to absorb energy will be reduced with each detonation and rupture may eventually occur.

Report Content

In the following sections we describe the design and construction of the facility, the specific location of the various transducers and gages, and the tabulated results of the six test fires performed to date.

II. DESCRIPTION OF THE FACILITY

General

This high explosive test fire facility is to control the toxic effluents generated by high explosive test fire shots. This facility as shown in Figure 1 and Photographs 1 and 2 consists of a test-fire chamber, a control bunker and an effluent filtering system. The facility is located inside the Firing Site area of the USDOE Pantex Plant, Amarillo, Texas. The siting of the facility satisfies the requirements of DARCOM-R 385-100[1], DOE Order 5430.1[4] and TM5-1300[2]. In addition, this facility is located a minimum of inhabited building distance from all other existing and planned facilities and quantity-distance separation for protection of underground service installations or a minimum of 50 feet from the existing 14-inch water main.

Control Bunker

The control bunker houses the electronic test fire control equipment and surveillance cameras. The bunker is an earth covered steel arch structure on a concrete pad foundation with approximately 250 square feet of working area. The bunker is separated essentially into two halves, a camera room and a control room.

Containment Chamber

The containment chamber is of steel construction. The outer chamber shell as shown in Photograph 3 consists of a 15 foot high cylinder, 20 foot diameter with a hemispherical head and a steel plate floor, the total height being 25 feet overall.

The lower 7 foot-6 inches cylindrical section is 1½ inches thick with the upper 7 foot-6 inches cylinder and hemispherical head having a thickness of 1 inch. A 42 inch diameter manhole with an associated hinged closure as shown in Photograph 3 provides personnel access into the chamber. Ring stiffeners as shown in Photograph 6 spaced 3 feet-8 inches apart vertically were installed to accommodate anticipated rebound loads.

In order to ensure the integrity of the chamber shell, the interior surfaces must be protected from missiles (hazardous fragments) generated from the detonation. Hence, the chamber surfaces are protected by utilizing a combination of gravel-filled boxes, gravel-filled bags and fragment shields. The fragment shields are mounted to the ring stiffeners and protect over half the cylinder surfaces as shown in Figure 2 and Photograph 7. The gravel-filled boxes and gravel-filled bags are arranged about the test-charge in such a manner as to protect the remaining exposed shell surfaces as shown in Figure 2. The test shot inside the gravel-filled bags and gravel-filled box arrangement also is surrounded by steel plate and on the floor to further protect those areas of the chamber not covered by the fragment shields. The steel plates are sacrificed as part of the test fire and are replaced as necessary after each test fire. Wood blocks as shown in Photograph 6 and 7 are situated between the fragment shields and the chamber wall to transfer blast loads from the fragment shields to the outer shell. The containment chamber is bolted to a 28 feet square by 4 feet-6 inch thick steel reinforced concrete pad which acts as a foundation for the chamber. A 1½-inch thick steel plate is attached to the concrete pad to serve as the floor for the chamber.

Filtering System

The chamber will contain the residual gases until the gases can be bled off through the filtering system. The gases generated by the test fire detonations contain small quantities of soot, ash and toxic effluents, which are passed through a filtering system so as not to contaminate the surrounding area. The air filtering system consists of nozzles, pipe, blast resistant valves, a pressure reducing valve (PRV), high efficiency particulate air (HEPA) filters and an exhaust fan as shown in Figure 3 and Photographs 4 and 5. The chamber nozzles, blast valves, and connecting pipe are designed to withstand the effects of the test fire detonation and protect the rest of the filtering system from damage. The blast valves are operated manually from a central control panel inside the control bunker. The chamber pressure and temperature are monitored by remote gages. Safety interlocks protect the HEPA filters from excessive temperature and/or pressure and prevent releasing of contaminated air to the outside.

After the test fire shot, when the residual gas temperature and pressures inside the chamber and pipes have dropped below 150°F and 60 psi, the blast valve at the pressure reducing valve (PRV) is opened. The PRV reduces the residual pressure to 10 inches of water column (0.36 psi) to prevent overpressuring the HEPA filters. Before passing through the PRV, the residual gases are first screened through 0.125 inch and 0.065 inch strainers to retrieve any large particles in the system. The residual gas pressure is then reduced and discharged through a pre-filter and two HEPA filter assemblies (the second HEPA filter is redundant) and exhaust fan (not operating). When the residual pressure inside the tank reaches ½ psi, the bypass valve will open to allow the remaining gases to pass more quickly. Once the inside pressure is atmospheric (0 psi), the exhaust fan will start creating a slightly less than atmospheric pressure (-0.25 inches of water column), which in turn will open three blast valves located on the tank itself. The high pressure exhaust fan will ventilate the chamber until the air inside is clean enough for decontamination personnel to enter. The exhaust fan will continue to run to produce a slightly less than atmospheric pressure inside the tank whenever the chamber closure is opened.

The HEPA filters have a minimum efficiency of 99.97 percent on 0.3 microns. The filter housings have "bag out" features to prevent the operator from coming in contact with any material that may be held by the filter. [5]

III. DESIGN OF THE CONTAINMENT CHAMBER

General

Since the containment chamber is the most critical structure of the facility, its design considerations are mentioned here so that the reader may better understand the results of the test fire detonations contained in Section V of this report.

Design Load Criteria

1. Floor Live Loads, Roof Live Loads, and Snow Loads - In accordance with ANSI A58.1[6].

2. Wind Loads - In accordance with the Pantex Plant Design Criteria Manual (PDCM)[7] for a 100-year recurrence level (92 mph). (Tornadoes are a possible hazard in the Panhandle area of Texas, but this facility does not fall within the USDOE criteria that requires tornado resistant construction.)

3. Seismic Loads - In accordance with the UBC [8] for Zone 1.

4. Dead and Construction Loads - As determined by the design engineer.

5. High Explosive Blast Loads - The internal blast loads were predicted based on methods presented in TM5-1300[2]. An equivalent cubicle 17.7 feet square and 21.7 feet high was used to approximate the area and volume of the actual chamber. The equivalent cubicle was utilized in producing the vessel load history profile because methods outlined in TM5-1300 apply only to cubicles. Figure 4 shows the predicted blast profile used in the design of the chamber, based on the equivalent cubicle calculations[9].

Design Basis

The containment chamber was designed by Mason & Hanger-Silas Mason Co., Inc. The design of the chamber was based on the ASME Boiler and Pressure Vessel Codes[10], where applicable. However, not all provisions were followed in order to make use of the dynamic properties of the vessel and components.

An allowable tensile stress of 75 percent of the yield stress was used for ring tension in the cylinder walls. Plate steel meeting ASTM A537 Class I requirements was chosen due to its ability to remain relatively ductile for low temperature service. A "no break" temperature of -40°F was specified based on the drop weight test ASTM E208 for all plate steel used in the vessel. In addition, it is required that no test explosion is conducted in ambient temperature below +50°F. This insures ductile behavior of the steel chamber under the dynamic shock pressures from the test fire detonations.[9]

The reinforced concrete foundation for the chamber was designed based on the loads determined above in the design of the chamber. The reinforcing steel is ASTM A-615 Grade 60 and the concrete was specified to have a 28-day compressive strength of 4000 psi minimum.

The fragment shields as shown in Figure 2 and Photographs 7 and 8 were fabricated of ASTM A36 steel 1½ inches thick and are bolted to the ring stiffeners using ASTM A307 bolts through slotted holes. The shock absorbing wood blocks are bolted to angles welded to the chamber wall. The fragment shield plates are approximately 3 feet 7 inches high by 3 feet long and rolled to a curvature to fit the curvature of the chamber; six bolts hold the plates in place. Extra plates were fabricated for replacement when examination shows that the plates are damaged beyond their usable life.

IV. INSTRUMENTATION

General

The chamber was instrumented with blast, gas pressure and strain gages. The location of the blast and pressure gages with their numerical identifiers for later data reduction and comparison are shown on Figure 2. The strain gage locations with their numerical identifiers are shown in Figure 5.

Types of Gages

Gage Type	Number	Manufacturer/Model Number
Blast	2	PCB Piezotronics Model 102A
Blast	3	PCB Piezotronics Model 102A04
Gas	3	Kulite Model HKS 375-500SG
Strain	22	BLH Model FAE 25-35-56ET

A copper constantan thermocouple was available for Test #4. An iron constantan thermocouple was available for Tests #5 and #6.

Recording and Data Reduction

The output of the gages were recorded on two Sangamo 80 14 channel (total available channels 28) magnetic tape recorders. The coupling between the gages and the recorders is in accordance with manufacturer's recommendations.

The magnetic tapes were played through a CEC Model HR2012 for a quick review and through a Biomation Model 8100 Digital Waveform Recorder to digitize the analog signals. The digitized data were recorded on magnetic disc with an appropriately interfaced HP 9835 computer. The discs provide the input for an HP 9845 computer.

The digitized voltages and times are converted to appropriate engineering quantities (i.e. pressure for the blast and gas gages, microstrain for strain gages and temperature for the thermocouple) using calibration voltages and developed software. Plots of these quantities as a function of time were provided for further analysis. Most of the data werefiltered by a Fast Fourier Transform.

Blast and Gas Pressure Gage Locations

Blast and pressures seen by the outer chamber shell due to an HE detonation are not uniformly distributed. In order to obtain a blast history profile, blast and gas pressure gages were mounted to the ring stiffeners opposite, and at 90 degrees to, the entrance manhole as shown on Figure 2. These gages are mounted on the stiffeners to avoid drilling holes through the outer shell in order to flush mount the gages.

Strain Gage Locations

Areas of high stress concentration are located at points where the shell geometry changes and/or the construction medium changes. At these locations, shear and moment forces are required to guarantee radial displacement continuity. Consider first the welded seam where the cylindrical shell attaches to the hemispherical head near location 5 in Figure 5 and 6. Under internal pressure, the cylinder and hemisphere tend to expand by different amounts as shown in Figure 6a. In the actual chamber, this discontinuity of displacement is prevented by shear, Q, and moment, M, forces. These discontinuity effects create bending stresses in the vicinity of the joint. However, there is an additional force Ps due to the ring stiffener which restrains the cylinder displacement. Nevertheless, at some distance from the joint, membrane shell theory will yield results of sufficient accuracy. By mounting strain gages at locations 5 and 12, membrane stresses were calculated as well as forces Q, M, and Ps.

The same argument applies at the joint between cylinder halves where the shell thicknesses change. Under internal pressure, the cylinder halves tend to expand by different amounts due to change of shell thickness from 1 inch to 1½ inches for upper and lower cylinder halves, respectively as shown in Figure 6b. A ring stiffener located near the joint produces a force, Ps, which prohibits the radial displacement at the lower half. Because of the location of this ring stiffener, forces Q and M become greater than if the ring stiffener was not present. By mounting strain gages at locations 6 and 7, stress strains, and forces, Q, M, and Ps can be found. The same argument applies for placing gages at locations 4 and 8 as shown in Figure 7a with the exception that the foundation is considered rigid.

Several openings penetrate the outer shell to allow for venting, cameras, wiring and personnel entrances. Theoretically, whenever a round hole penetrates an "infinite" plate, the stress concentration at the edge of the hole is three times that of the normal stress some distance away. By reinforcing the openings, as in Figure 7b, the concentrated stresses at the edges are reduced. Since the personnel entrance is the largest opening, it is believed to be the most critical. By mounting gages at locations 9 and 10, stresses at these critical points are determined. Strain gage location 11, Figure 5, is for determining the response of the entrance door.

A total of 22 strain gages were mounted on the outside of the chamber at 12 locations. Single strain gages were installed at locations 1, 3, 5, 9, 10, 11, and 12 and three each at locations 2, 4, 6, 7, and 8 as shown in Figure 5. The three gages as shown in Photograph 10 at each location identified, were mounted in a triangular pattern to attempt to obtain both direction and maximum strain. The right triangle clusters consisted of three gages, one mounted vertically (identified as direction A). one mounted horizontally (identified as direction B), and one mounted at 45° (identified as direction C). Not all strain gages were connected to the recorder during all the tests, since we only had 28 channels of recording capability, two of which had to be used for monitoring the system leaving 26 channels for data. Since we had 8 gas and blast gages, this left only 18 channels available for strain gages and one thermocouple added at Test #4 and thereafter. As the test progressed we adjusted the numbers of gages recorded both due to knowledge gained and due to loss of blast gages and gas gages inside the tank from various destructive mechanisms. It was discovered toward the latter part of the test that the strain gages were providing the best information and we concentrated more heavily on the strain gages and eliminated the blast and gas pressure gages. This is further explained with reasons for elimination of a particular gage in Section V.

V. TEST RESULTS

General

The results of the six test fire shots are summarized in this section of the report. All experiments were conducted using LX-10 explosive and they were essentially located in the center of the chamber a nominal 33 inches off the floor. The various amounts used for each test are listed below.

For clarity purposes, it is mentioned here that the actual first shot was a detonator fired in the center of the chamber to exercise the system and check out instrumentation. No recording of the results was attempted since the weight to volume ratio (weight of HE to volume of chamber) was very small. The volume of the chamber is approximately 6800 cubic feet, and a detonator contains a few grams of explosive. However, it did serve the purpose for which it was intended and all systems indicated that the firing system was functional and the data gathering system had continuity back through the amplifiers, signal conditioners, etc., to the recorders.

It was decided early in the formulation of the test that the best approach to check out the chamber would be to fire an ever increasing amount of HE until the stated limit of a 125% overtest was reached, then to continue monitoring test shots at or below the rated limit of the chamber. Although the tested limit might be exceeded as will be seen from the test results and it is discussed further in Section VI.

Test Fire No. 1

The first HE shot was fired on June 8, 1983, and had a nominal weight of 1.2 lb. The results of this first shot were inconclusive and therefore the results are not tabulated. Basically this shot gave us a more positive check-out of our entire fire control, instrumentation and recording system. The entire sequence was recorded and the data reduced, but again the weight to volume ratio was too small to provide useful data. In summary, this shot barely exercised the instrumentation and, as far as structural integrity is concerned, it proved that it was possible to obtain data from our blast, gas and strain gages.

For record purposes, data (such as it was) were obtained from Gas Gages No. 1 and 2, Blast Gages No. 1, 2, 3, and 4 and Strain Gages No. 2, 4, 5, 6, 7B, 7C, 8A, 9, 10, 11, and 12. Most of the data obtained was outside (below) the calibration range of the gages and those strain gages and one blast gage which are not listed read nothing or their readings were below the threshold noise level.

Test Fire No. 2

The second HE shot was fired on June 15, 1983, and had a nominal weight of 5.6 lb. This was the first so called 50% (of the maximum to be fired) test shot. The first half weight shot produced some good data, but it also exposed some problems with our instrumentation and data reduction.

This test was our first indication that the blast and pressure gages might not be giving us credible data and verified our earlier belief that we should look toward the strain gages for providing the data to determine the structural integrity of the chamber.

As a result of this test, necessary adjustments were made in the instrumentation to eliminate inconsistencies.

The results are tabulated in Table 1.

Test Fire No. 3

The third HE shot was fired on August 1, 1983, and had a nominal weight of 5.6 lb. Essentially this was a repeat of Test Fire No. 2 with numerous corrections made to the instrumentation. This shot gave us some consistent results and proved to our satisfaction that we had corrected our instrumentation problems.

The blast and gas pressure gages seemed to have settled down with the loss of only one blast gage. All the strain gages reported excellent results. The maximum stress (8377 psi) was encountered at strain gage No. 2. This reading was encouraging in face of the 37,500 psi design stress limit set for the chamber.

The results are tabulated in Table 2.

Test Fire No. 4

The fourth HE shot was fired on August 17, 1983, and had a nominal weight of 13.7 lb. This was the 125% overtest mentioned earlier. The results of the proof test were excellent and well within the bounds set by the design. The blast gage information was inconclusive as had been the experience with past shots; however, they were not pertinent to the certification of the chamber. The gas gages gave values well within the predicted and acceptable range; the average predicted quasi-static gas pressure was 32 psi and this test gave a 39 psi average.

The strain gages gave the actual proof that the chamber was well within the recommended design limits. As a design consideration, the maximum allowable stress in the steel was set at 75% of its yield strength. The steel used in constructing the chamber has a yield strength of 50,000 psi. Applying the 75% factor, a maximum allowable of 37,500 psi stress is obtained. The maximum stress obtained from the strain gage readings was 17,397 psi at strain gage No. 2 with most strain gages indicating a stress around a nominal 10,000 psi.

As mentioned earlier, a thermocouple was installed for the first time during this shot. However, the temperature over-ranged the limit of 750°F of the thermocouple and it was decided that the copper constantan thermocouple should be replaced with an iron constantan thermocouple for the next shot with a maximum range of 1200°F.

Further, it was decided to examine the usefulness of the blast and pressure gages based on the first four shots providing inconsistent data. A discussion of our findings follows under Test Fire No. 5.

The results are tabulated in Table 3.

Test Fire No. 5

The fifth HE shot was fired on October 27, 1983, and had a nominal weight of 11.2 lb. This was the first actual shot, for which the chamber was designed, fired in the chamber. This was the so called 100% test shot mentioned earlier.

The results of the gas and blast pressure readings were less than satisfactory. We had already eliminated all but one of the blast gages and used these channels for additional strain gage data. The gas pressure gages gave readings that are totally inconsistent and at least one order of magnitude above predicted values.

Tests were made on the gages to check their sensitivity to heat. The tests were made with gages in their mounting plates. A heat gun that produces 12[illegible]°F temperature was used as the heat source. The amount of time the gage and mounting plate were exposed to the 1200°F temperature, the gage output reading in millivolts and the equivalent pressure are shown below:

Time (seconds)	Millivolts	Equivalent Pressure (psi)
10	0.98	54.8
20	3.47	193.9
60	5.37	300

The heat was removed from the gage and the mounting plate. The gage and mounting plate were allowed to cool in a 70°F room. The readings are listed below:

Time (Minutes)	Millivolts	Equivalent Pressure (psi)
1	3.32	185.5
5	2.86	159.8
10	1.74	97.2
20	0.87	48.6

It is our opinion the gas gages are too heat sensitive to ever obtain useful data. Some new gages were checked the same way and were found to follow the same pattern. A peak temperature of 1150°F was recorded on the thermocouple used in this shot. Thirty to forty seconds after the shot the temperature in the chamber was still a nominal 600°F.[11]

It was decided at this time to essentially eliminate all but two of the gas pressure gages for the next shot and use these additional channels for additional strain gage readings.

The strain gages responded very well as in the previous shots. The maximum stress recorded was 16,409 psi (well below the 37,500 psi allowable) with most strain gages indicating a nominal 10,000 psi stress. The peak strain was read on strain gage 8.

The results are tabulated in Table 4.

Test Fire No. 6

The sixth HE shot was fired on May 18, 1984, and it had a nominal weight of 11.2 lb. This test was essentially a repeat of Test Fire No. 5. However, for reasons stated earlier all but two of the gas gages were eliminated for this shot. They were left in to see if we could get repeatability of the very high readings that we got in the previous shot. Unfortunately one gage was destroyed and the second gage gave a reading totally inconsistent with the previous shot. The consensus at this point is that for future shots the value of the gas gages needs to be further evaluated. Possibility exists that less heat sensitive gages may be found or some form of insulation can be found to prevent the gages from responding to the thermal effects, but still respond to the pressures.

The strain gages again responded very well and gave us consistent results when compared to previous shots. The maximum stress recorded 15,590 psi (well below the 37,500 psi allowable) with most strain gages indicating a nominal 10,000 psi stress. The peak strain was read at strain gage 4.

The thermocouple was however over-ranged this time with a maximum reading of 1380°F.

The results are tabulated in Table 5.

VI. DISCUSSION AND CONCLUSIONS

General

The blast and gas pressure gages have not given us useful data about the loading of the chamber due to a HE detonation. The inconsistencies observed, and in particular, the sensitivity to high temperature as discussed in Section V of this report indicates that further work in this area is necessary. It is anticipated that we will attempt to obtain other type gages and try to find an insulating material that will reduce thermal sensitivity and read the correct pressure. The response of the tank is well within acceptable limits; however, we would like to obtain additional blast and gas pressure data.

The strain gages indicated stresses within about 15% of the predicted values. The variation in values is, of course, attributed to the location of the gages upon the chamber. As can be seen from the results of the 125% overtest, Test Fire No. 4, Table 3, the yield strength of the steel is not even approached. The maximum stress was 17,397 psi versus an allowable of 37,500 psi. The two 100% tests, Test Fires 5 and 6, Tables 4 and 5, indicated a maximum stress of 16,407 psi and 15,590 psi which again is well within the 37,500 psi allowable. The results show that essentially the maximum stress is at one half of the allowable and at one third of the maximum. This gives a wide margin of safety and allows a large number of shots to be fired in the chamber without fatiguing the steel. The major concern is to stay out of the plastic yield range of the steel (which is of course over 50,000 psi) to allow repeated use of the chamber.

Structurally, the chamber is acceptable for repeated shots of a maximum of 11.2 lb of high explosive. The chamber, of course, will have to be examined after every shot to assure that it has not suffered any undue damage from the actual shots. Welds in particular are always suspect and should be closely monitored. Any damage to the chamber due to fragments should be closely examined since they are points of high stress concentration (as much as three times normal as shown on Figure 7). We will continue to monitor the chamber during future shots.

Recertification Between Test Fires

The chamber is inspected and recertified between test shots. A visual inspection, both internal and external, is made between test shots to determine the extent of damage, if any to the chamber. All the welds in the chamber were radiographed during the manufacturing process and these records are maintained by Mason & Hanger-Silas Mason Co., Inc., to establish data base for comparison with later radiographic examinations. Longitudinal weld seams and the base ring to cylinder wall junction are visually spot checked after each shot to insure integrity of critical components. Likewise, any other suspected locations found during visual inspection will be radiographed to determine the extent of damage.

Between every test shot the chamber is pneumatically pressurized to a nominal 10 psi and the entire system (chamber, piping, valves, filters, etc.) is checked for leaks. A volumetric analysis is performed by monitoring the pressure drop, temperature and atmospheric pressure over a 24-hour period. The maximum permissible leak is determined by 0.2% of the chamber volume. All bolted, flanged, valved, etc., connections are further checked with a soap-water solution to detect any minor leaks in these areas. Any leakage beyond the nominal is repaired before the next test shot is fired.

Environmental Health and Cleanup Between Test Shots

The responsibility for monitoring concentrations of contaminates generated from the use of the chamber and associated test shots is the responsibility of the Environmental Health Department of Mason & Hanger-Silas Mason Co., Inc., at Pantex Plant. Disposal of the contaminated debris is the responsibility of the Waste Management Department of Mason & Hanger-Silas Mason Co., Inc., at Pantex Plant.

During all the monitoring and cleanup phase after a shot, the toxic products leakage was several orders of magnitude below the maximum permitted by the Environmental Protection Agency and the Texas Air Quality Control Standards.

Future Tests

As stated earlier, we will continue to monitor the chamber very closely and try to obtain additional data for future designs. Keep in mind that this is an interim facility and the results of the test will be used to construct future test fire chambers.

A word of caution is in order here. It is tempting to assume that larger HE quantities than the maximum of 11.2 lb allowed by the certification tests be fired in the chamber since we are essentially at one half of the design allowable yield strength of the steel shell. We would not recommend that this limit be exceeded without repeating the 125% certification procedure for whatever the amount over the 11.2 lb one wished to fire in the chamber. There are too many unknowns to assume that, for example, one can double the HE charge just because we are at a nominal one-half of the maximum yield strength. We would not do this and it is pure folly to consider such in any explosive test chamber. A methodical evaluation is the only acceptable method in certifying a test fire chamber for a given amount of high explosive. We learned a lot about response of large containment vessels to high explosive shock and have a whole lot more to discover in future shots and evaluations of other test fire chambers.

Conclusions

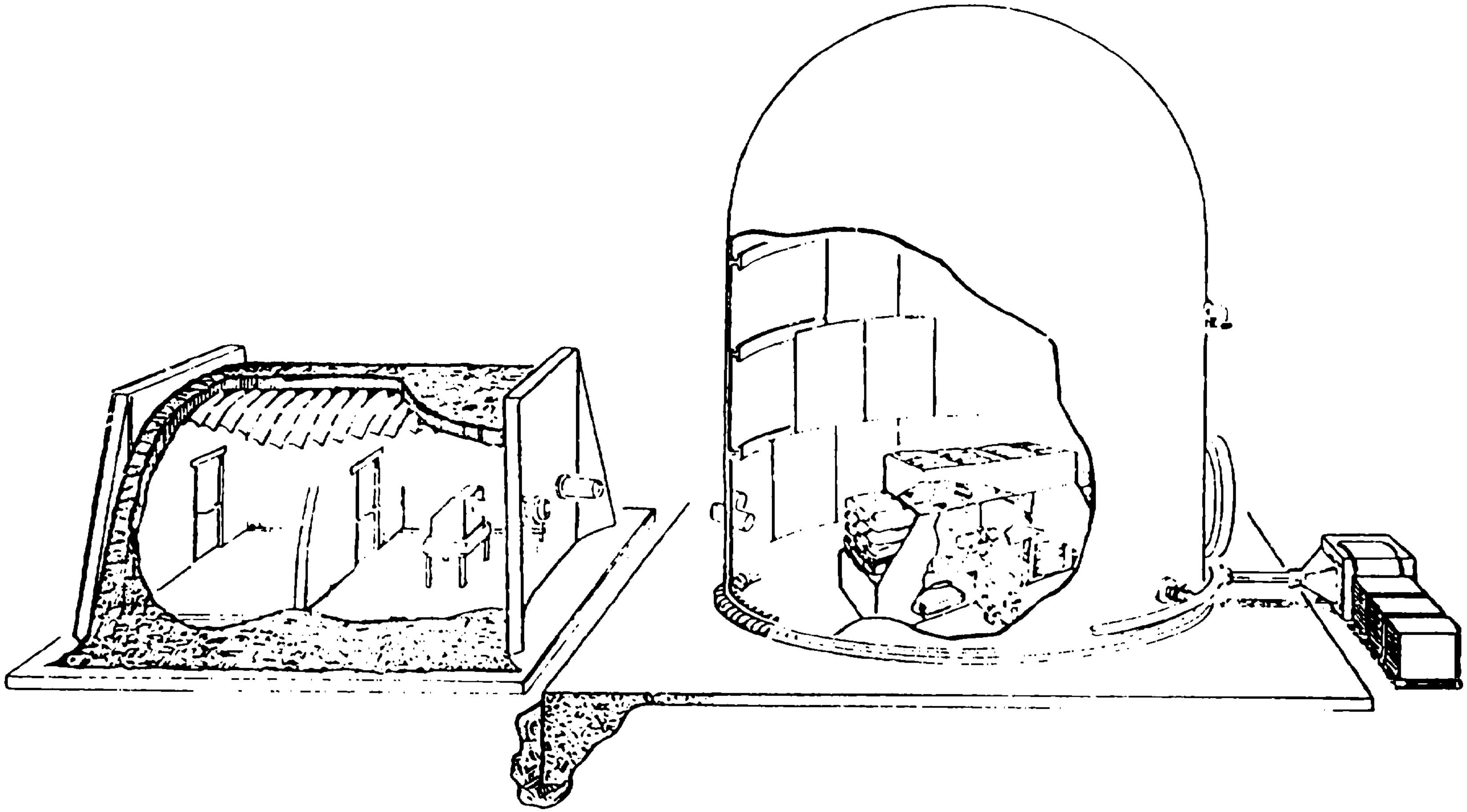
1. Strain gage data show that the strains are typical of stresses that are well within the design allowable stresses (about one-half).

2. Gas and blast gages failed to produce credible data, probably due to thermal sensitivity.

3. The thermocouple data show that maximum temperature is about 1200°F and returns to ambient in about eight minutes.

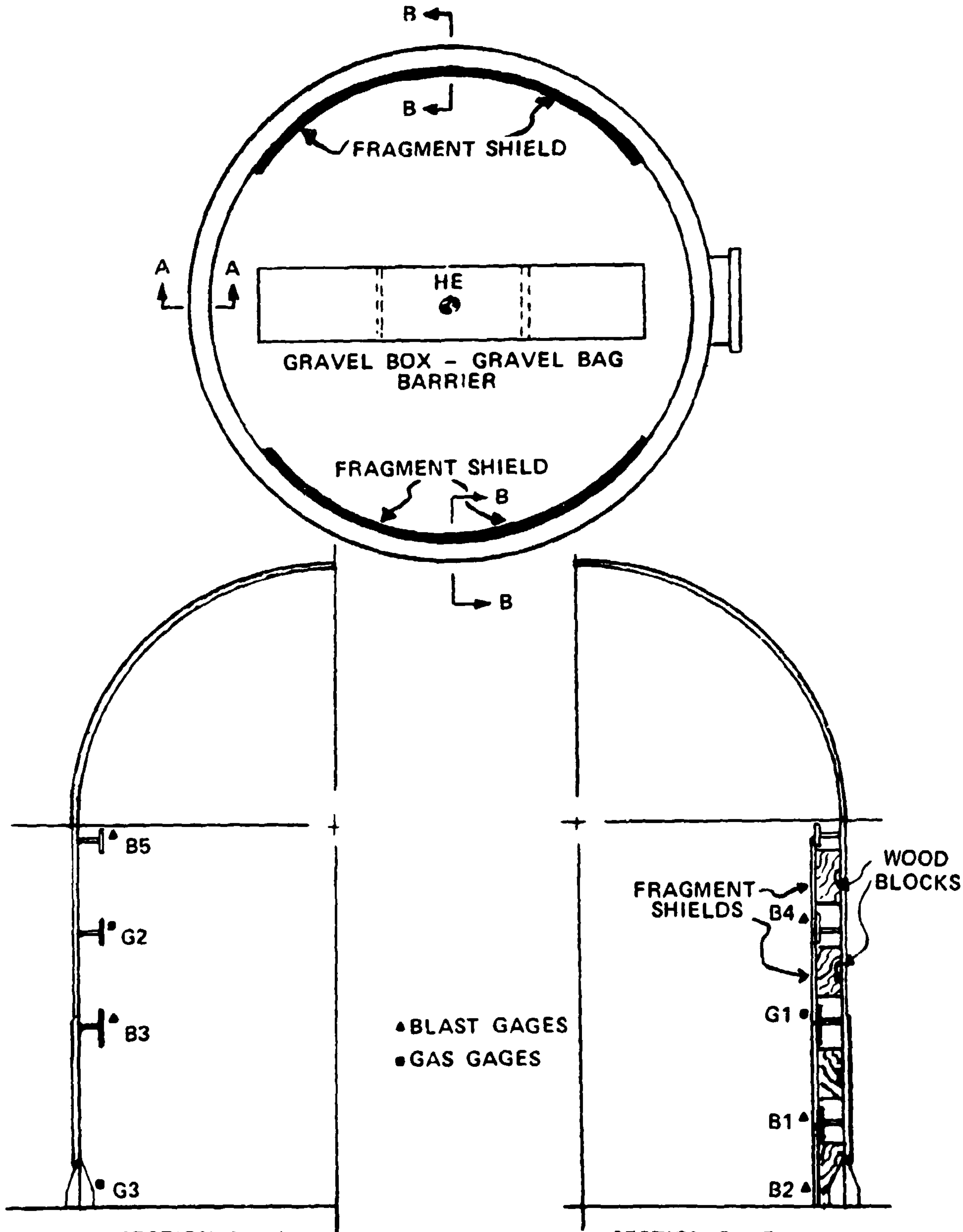
4. Toxic products leakage is well below the maximum permitted by the Environmental Protection Agency and the Texas Air Quality Control Board.

5. The chamber is safe for repeated shots of 11.2 lb or less of HE.



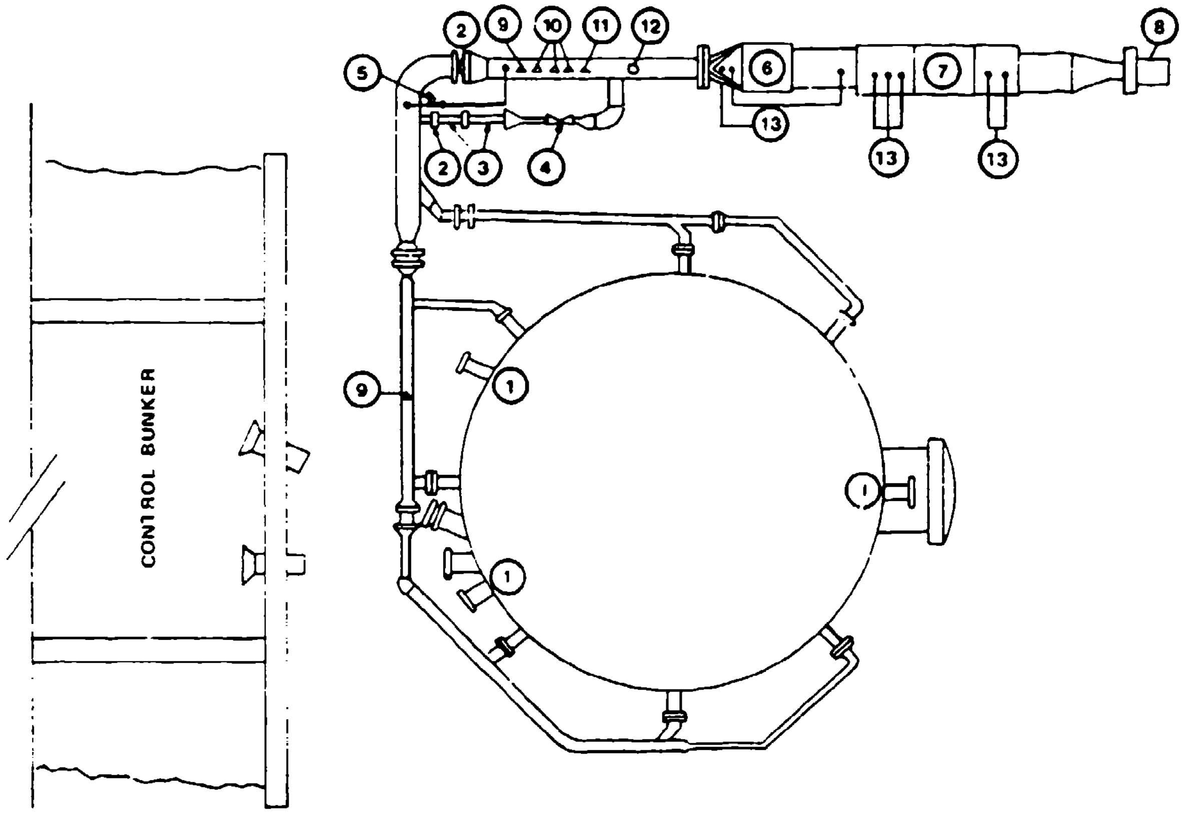
ISOMETRIC VIEW OF THE FACILITY

FIGURE 1



CONTAINMENT CHAMBER

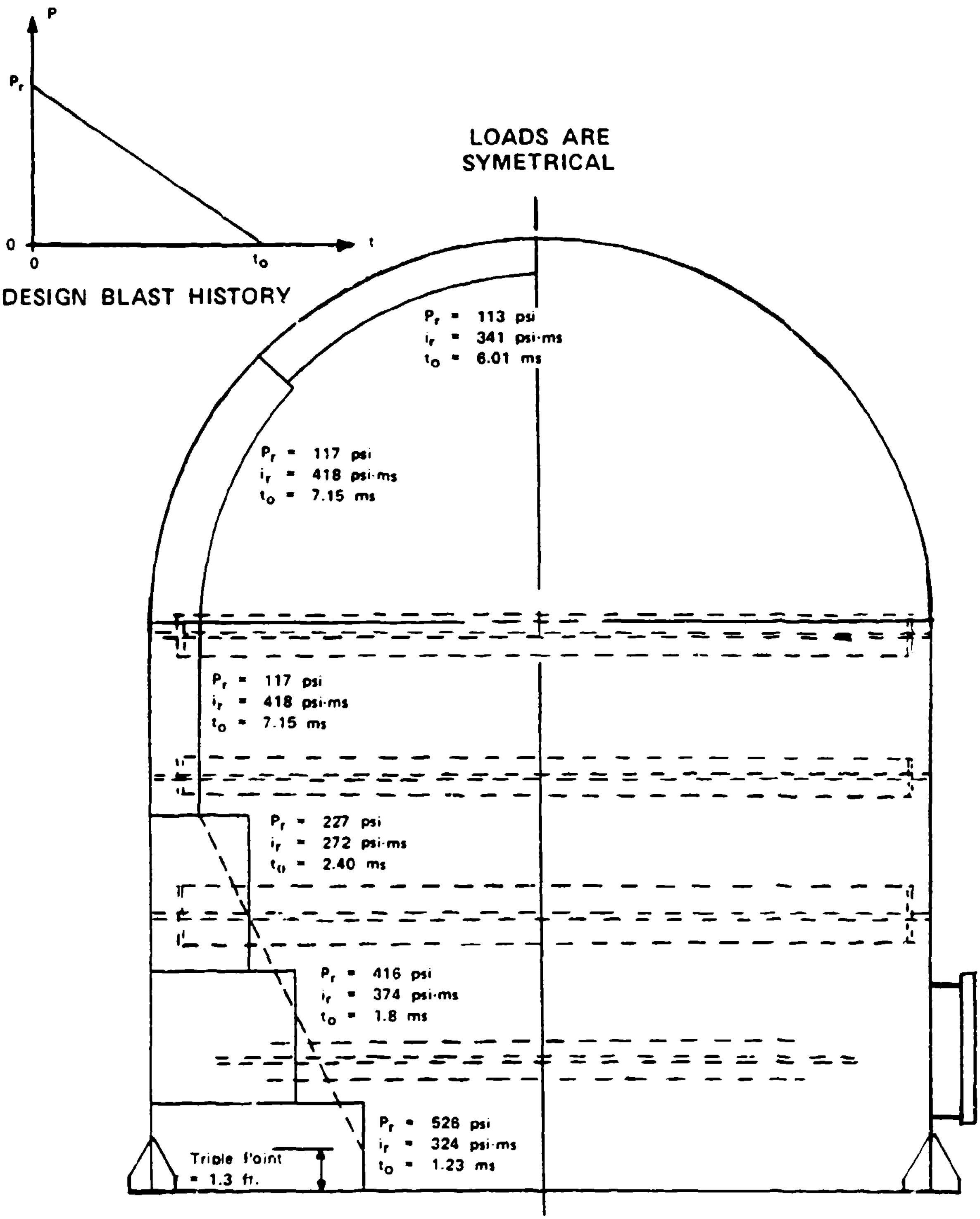
FIGURE 2



① BLAST VALVES (LUGGED TYPE)
② BLAST VALVES (WAFFER TYPE)
③ STRAINER SCREENS
④ PRESSURE REDUCING VALVE
⑤ BYPASS VALVE
⑥ ROUGHING FILTER HOUSING
⑦ HEPA FILTER ASSEMBLY
⑧ EXHAUST FAN
⑨ PRESSURE SWITCHES (Operate at 1/2 psi)
⑩ PRESSURE SWITCHES (Operate at 0.25 inches of water column psi)
⑪ PRESSURE SWITCHES (Operate at 0 psi)
⑫ TEMPERATURE SWITCH (Operate at 150° F)
⑬ PRESSURE INDICATORS

FILTERING SYSTEM

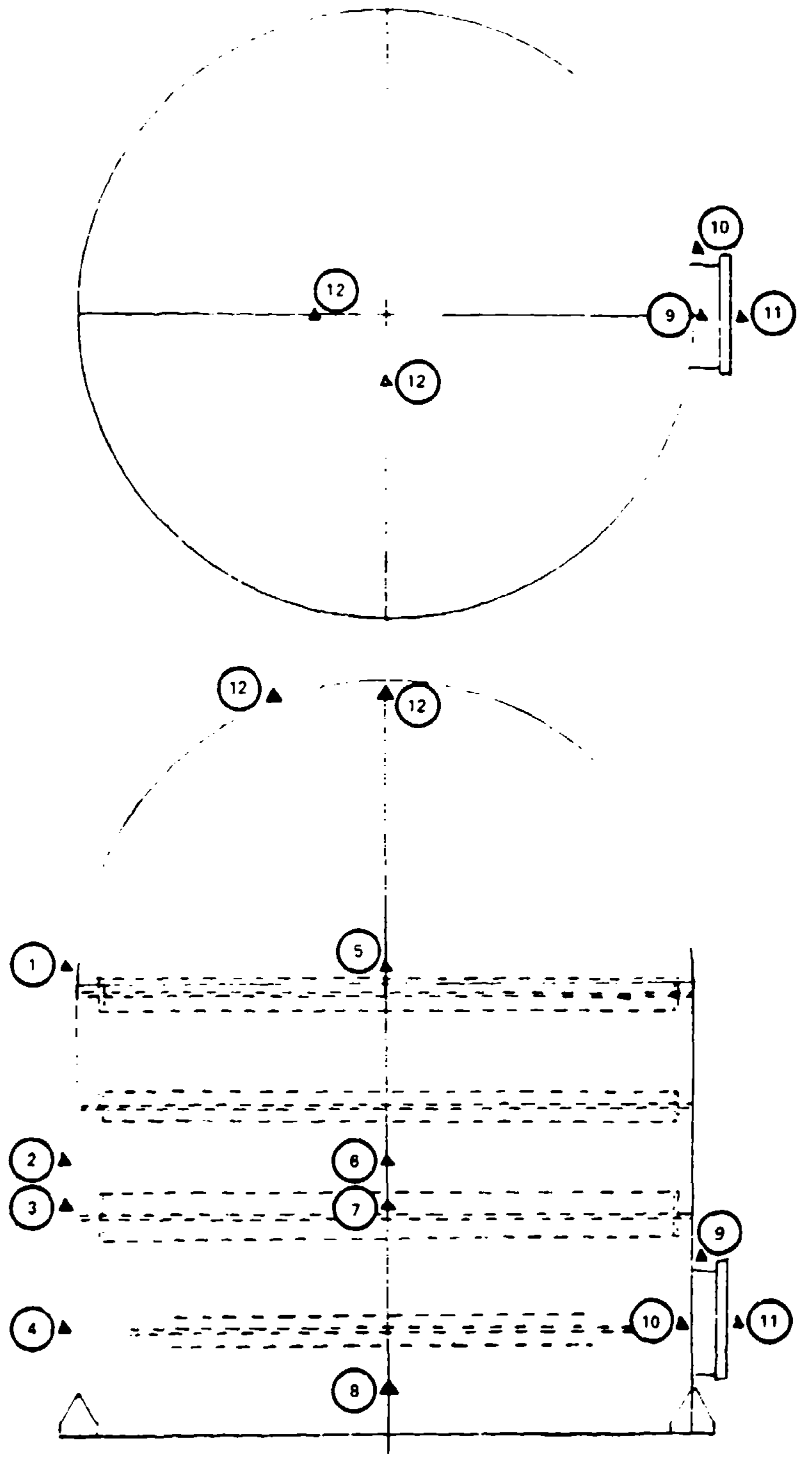
FIGURE 3



DESIGN CHARGE = 29.3 LBS. TNT
DESIGN GAS PRESSURE = 48 psi

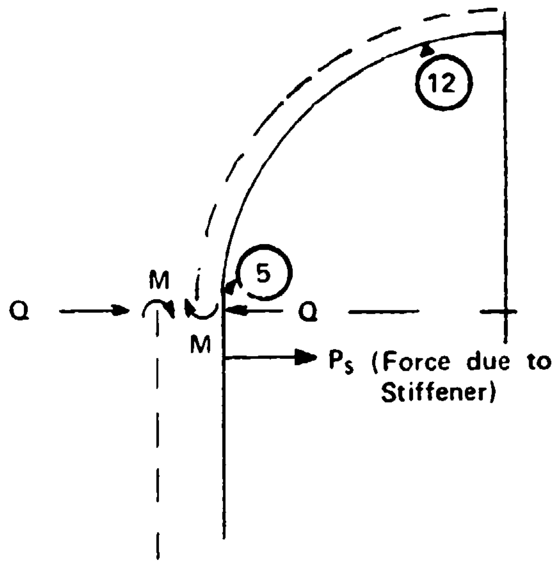
DESIGN BLAST LOAD PROFILE

FIGURE 4



STRAIN GAGE LOCATIONS

FIGURE 5



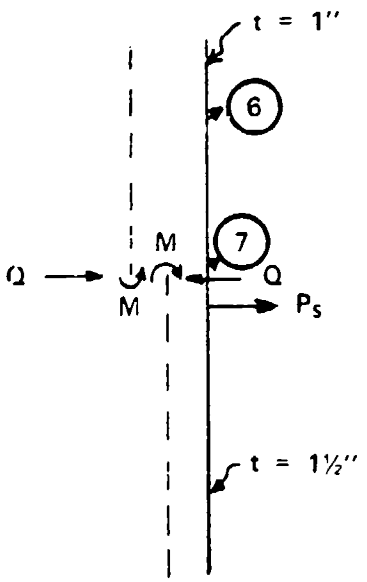
GAGE 12

1. Provides "unrestrained" membrane stresses of hemisphere
2. Desire same load history as Gage 5

GAGE 5

1. Along with information obtained from Gage 12, Can, find Q, M, and P_s required for displacement continuity

(a)



GAGE 6

1. Provides "unrestrained" membrane stresses of cylinder, (t = 1")
2. Assuming similar load history as Gage 7

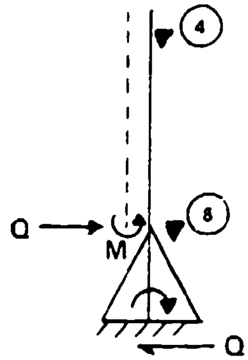
GAGE 7

1. From information obtained from Gage 6, Can, find Q, M, and P_s

(b)

STRAIN TO STRESS CONVERSION METHODOLOGY FOR STRAIN GAGES 5, 6, 7, AND 12

FIGURE 6



(a)

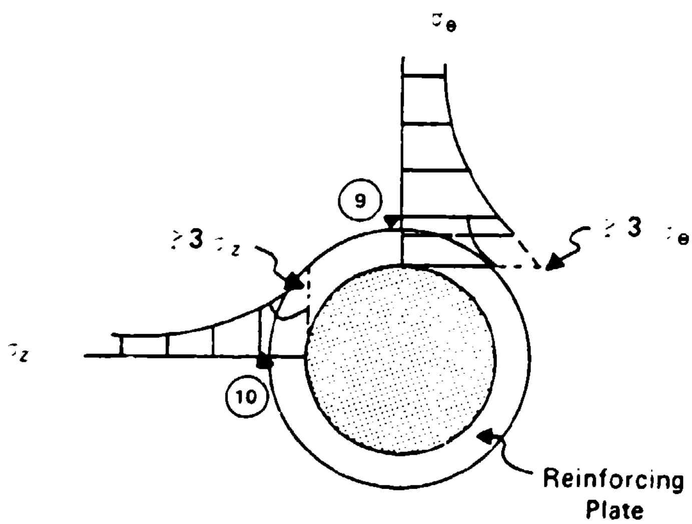
GAGE 4

1. Provides "unrestrained" membrane stress of cylinder (T = 1½")

2. Assume approximately same load history as Gages 8, 9, 10

GAGE 8

1. From information from Gage 4, compute Q & M



(b)

GAGE 9

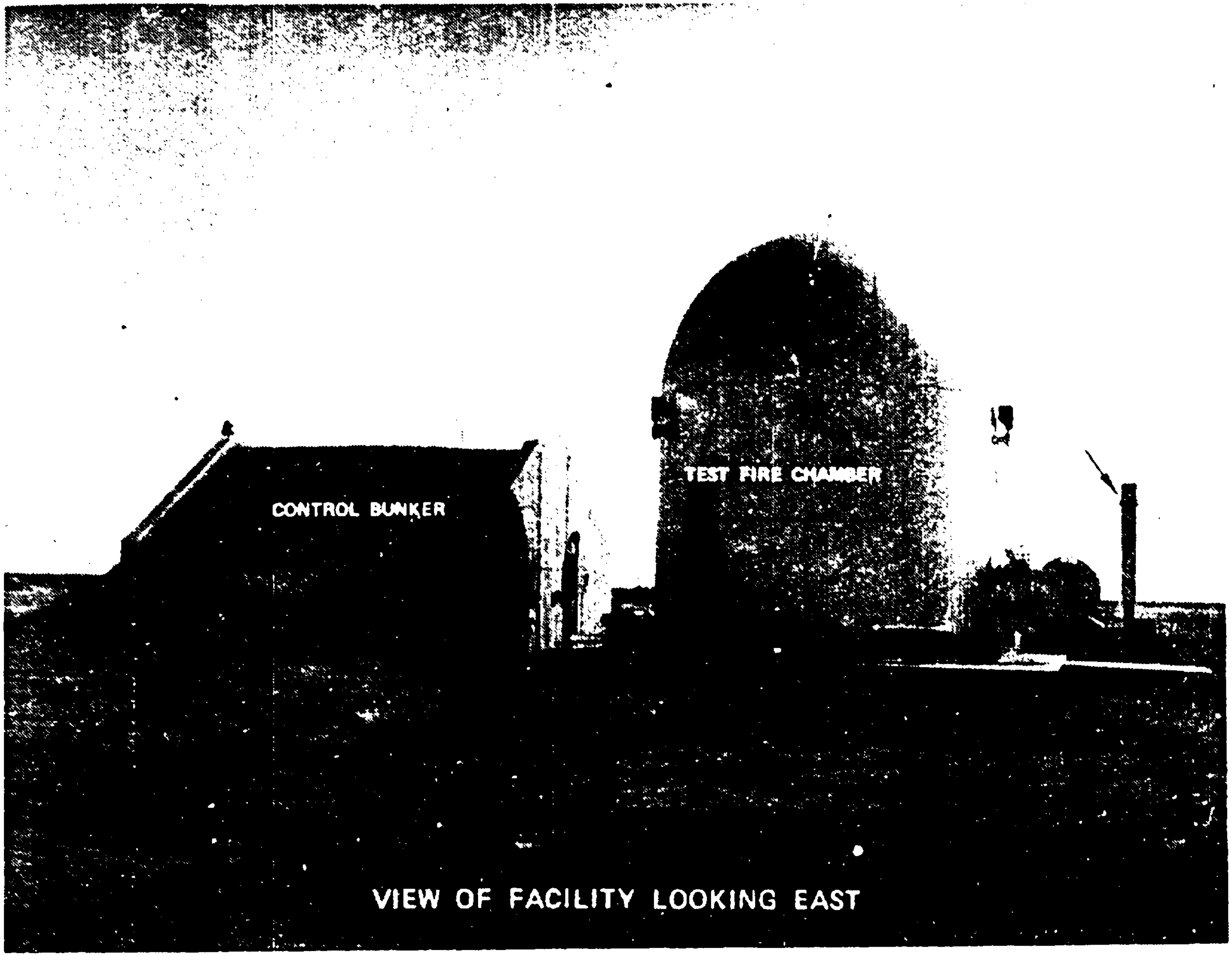
1. Find hoop stress concentration values

GAGE 10

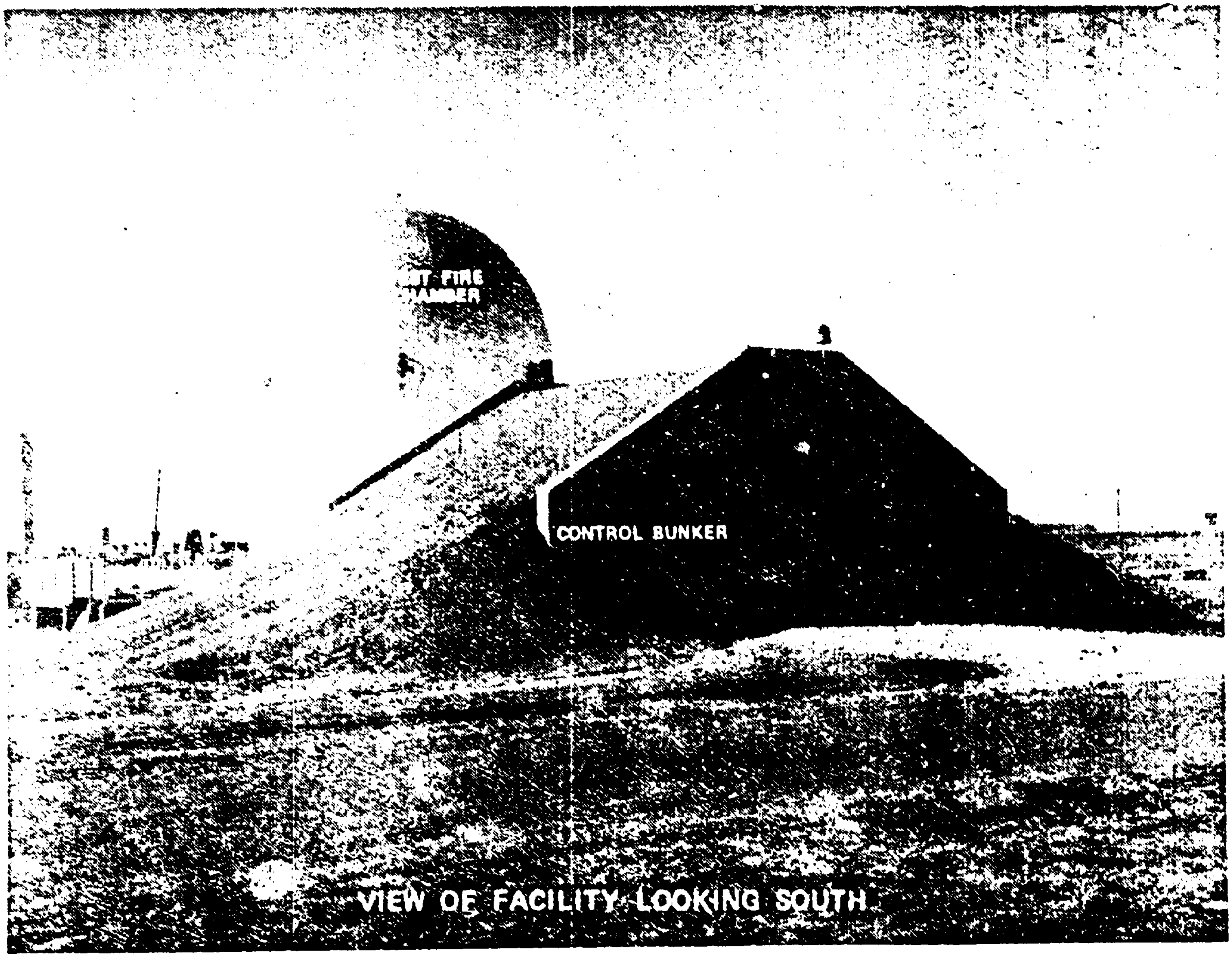
1. Same as Gage 9 but for axial stresses

STRAIN TO STRESS CONVERSION METHODOLOGY FOR STRAIN GAGES 4, 8, 9, AND 10

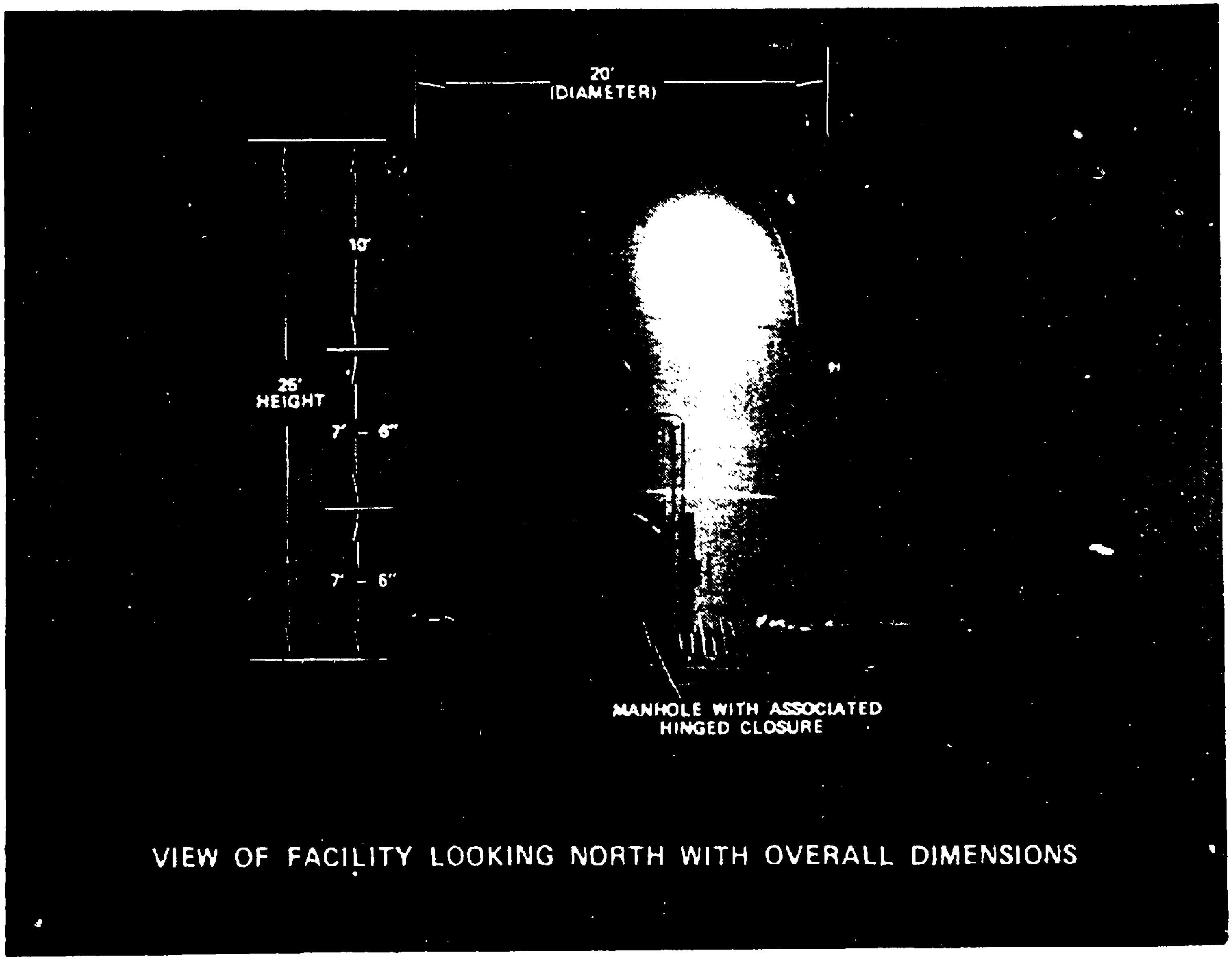
FIGURE 7



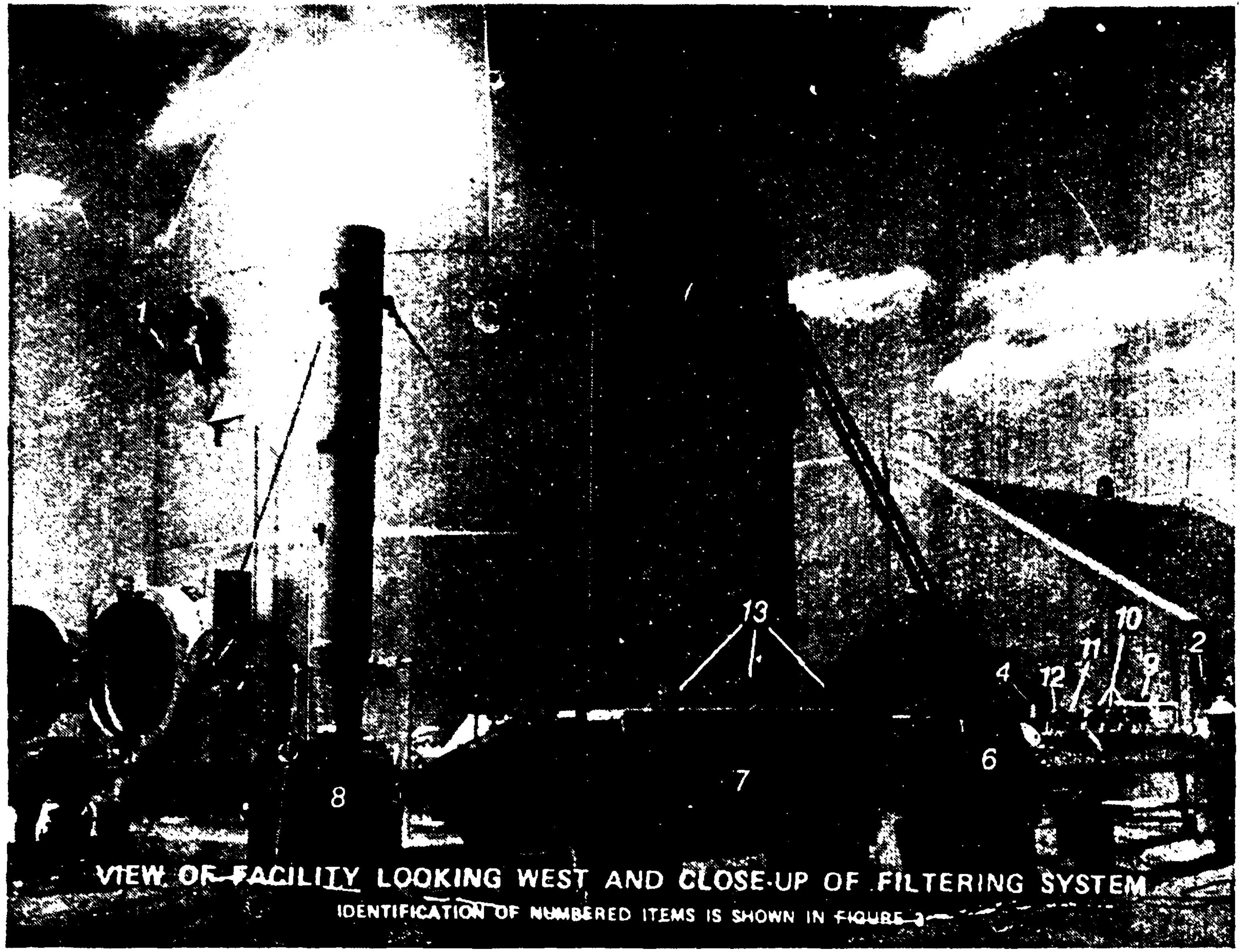
Photograph 1



Photograph 2



Photograph 3



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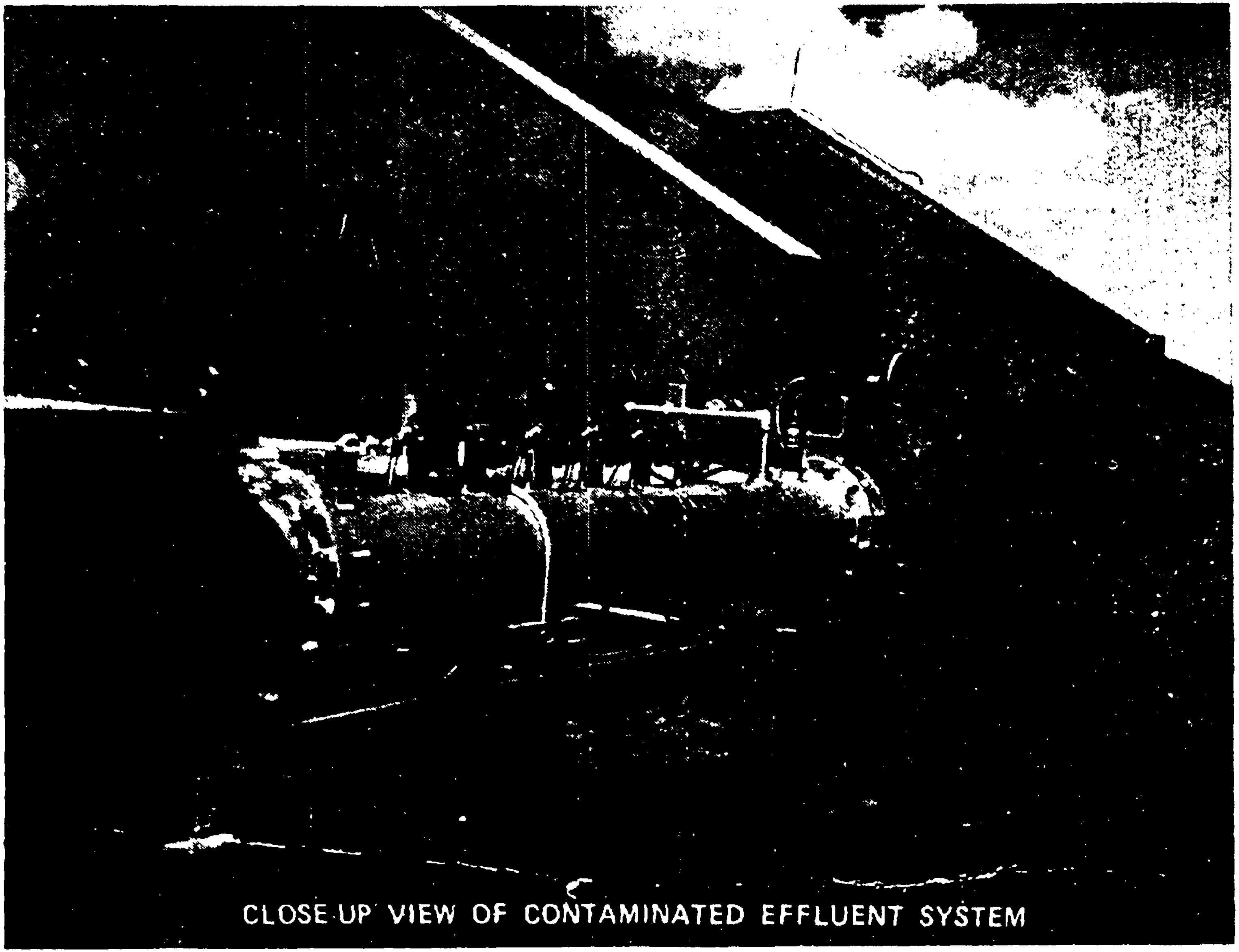
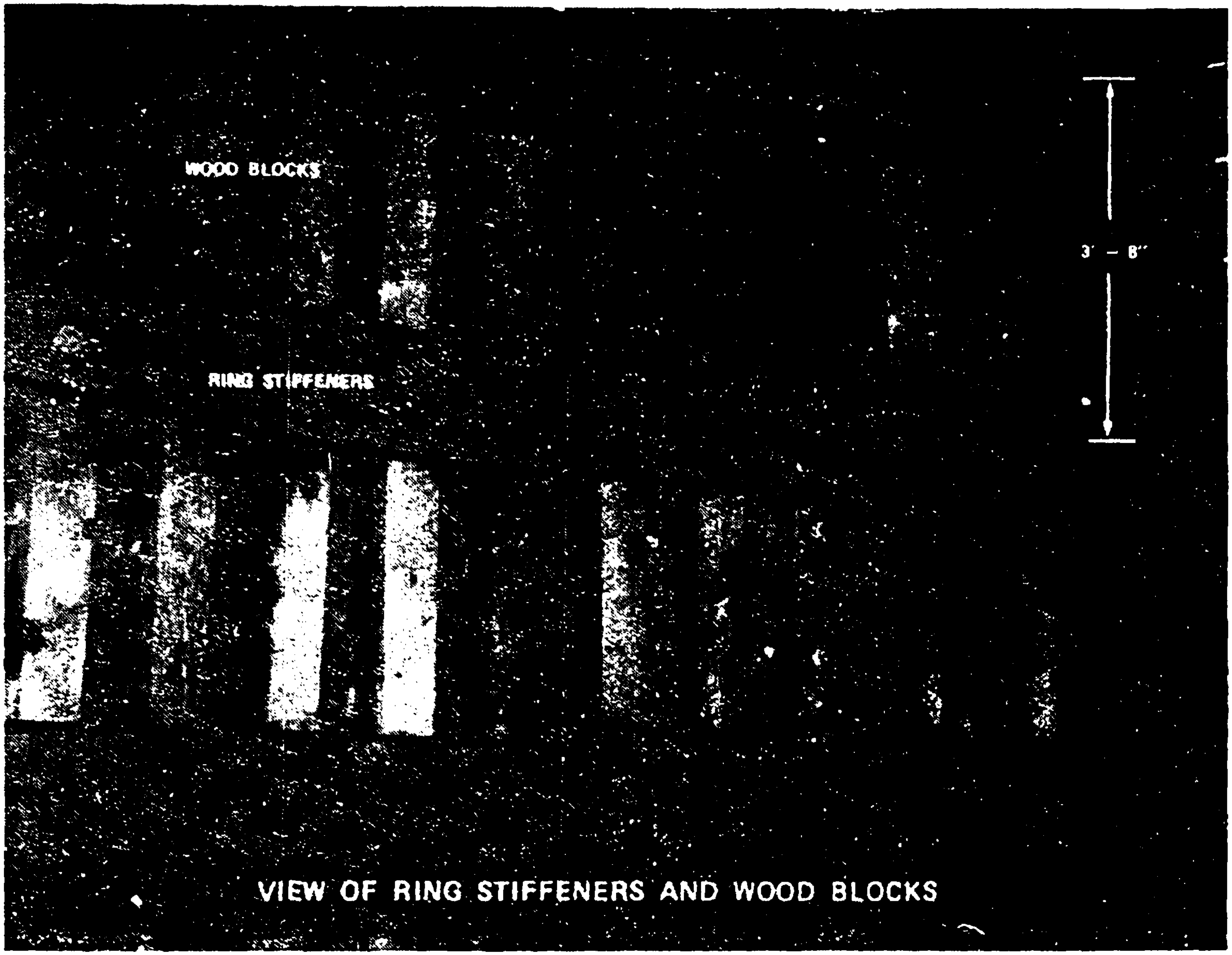


Photograph 5



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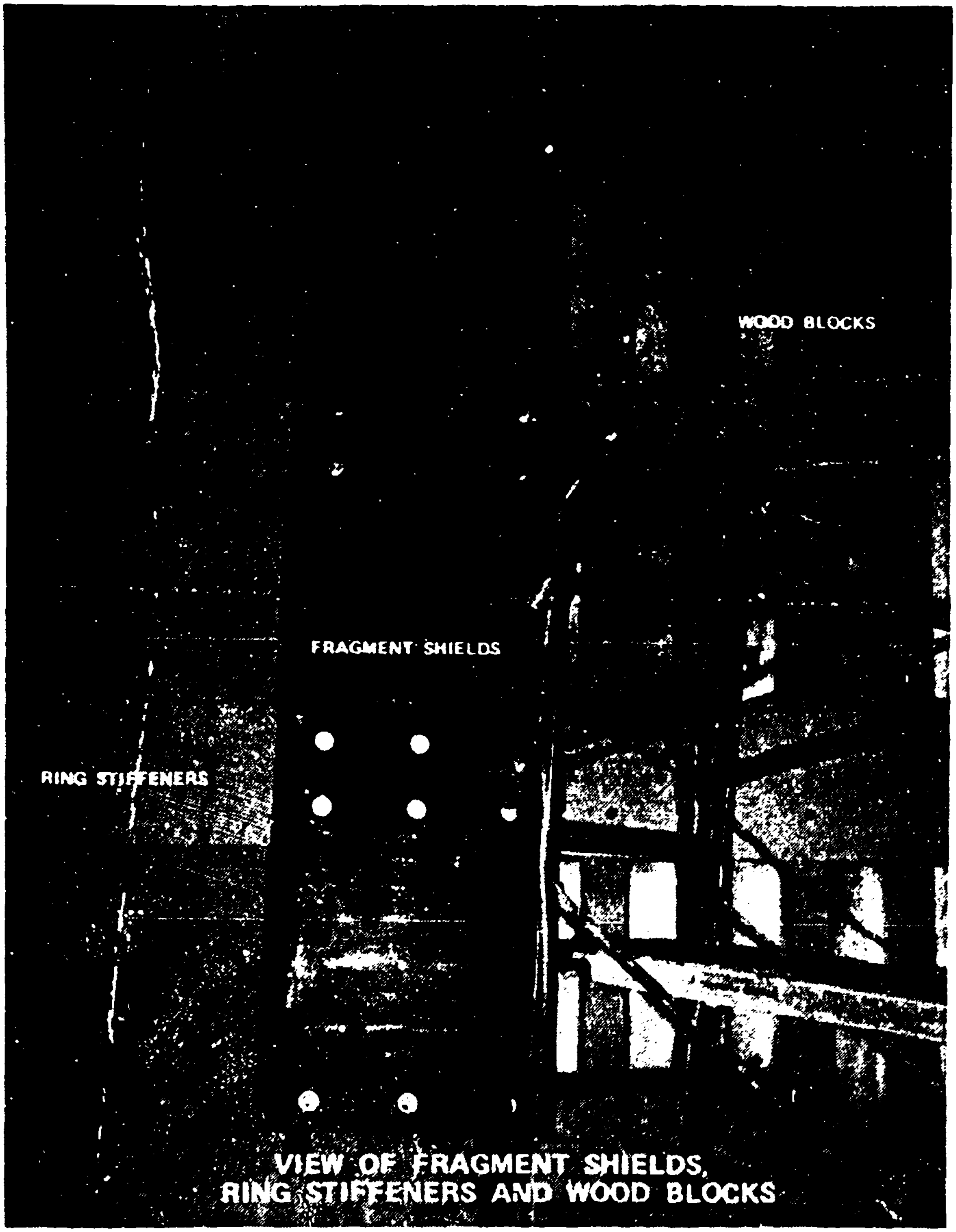

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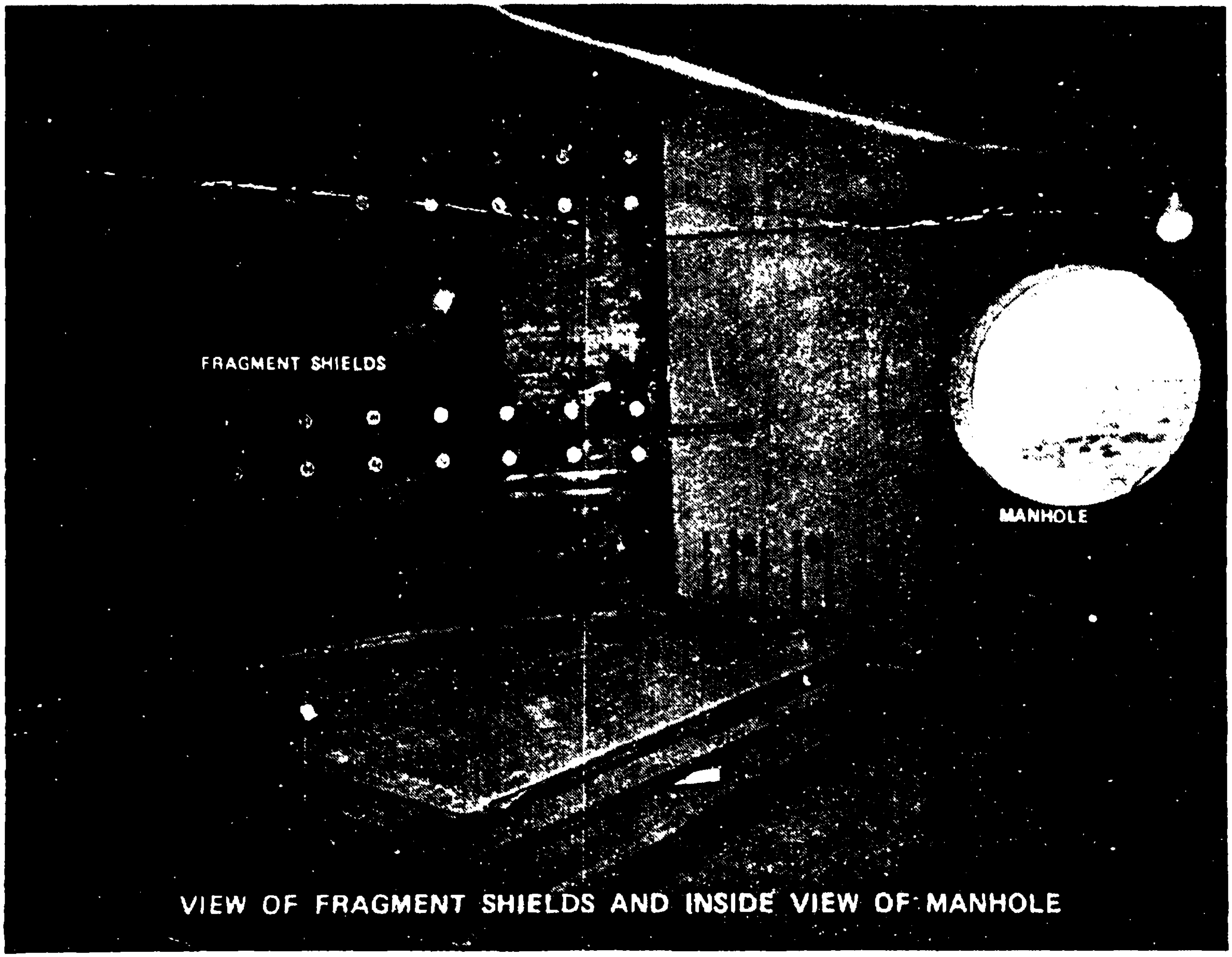

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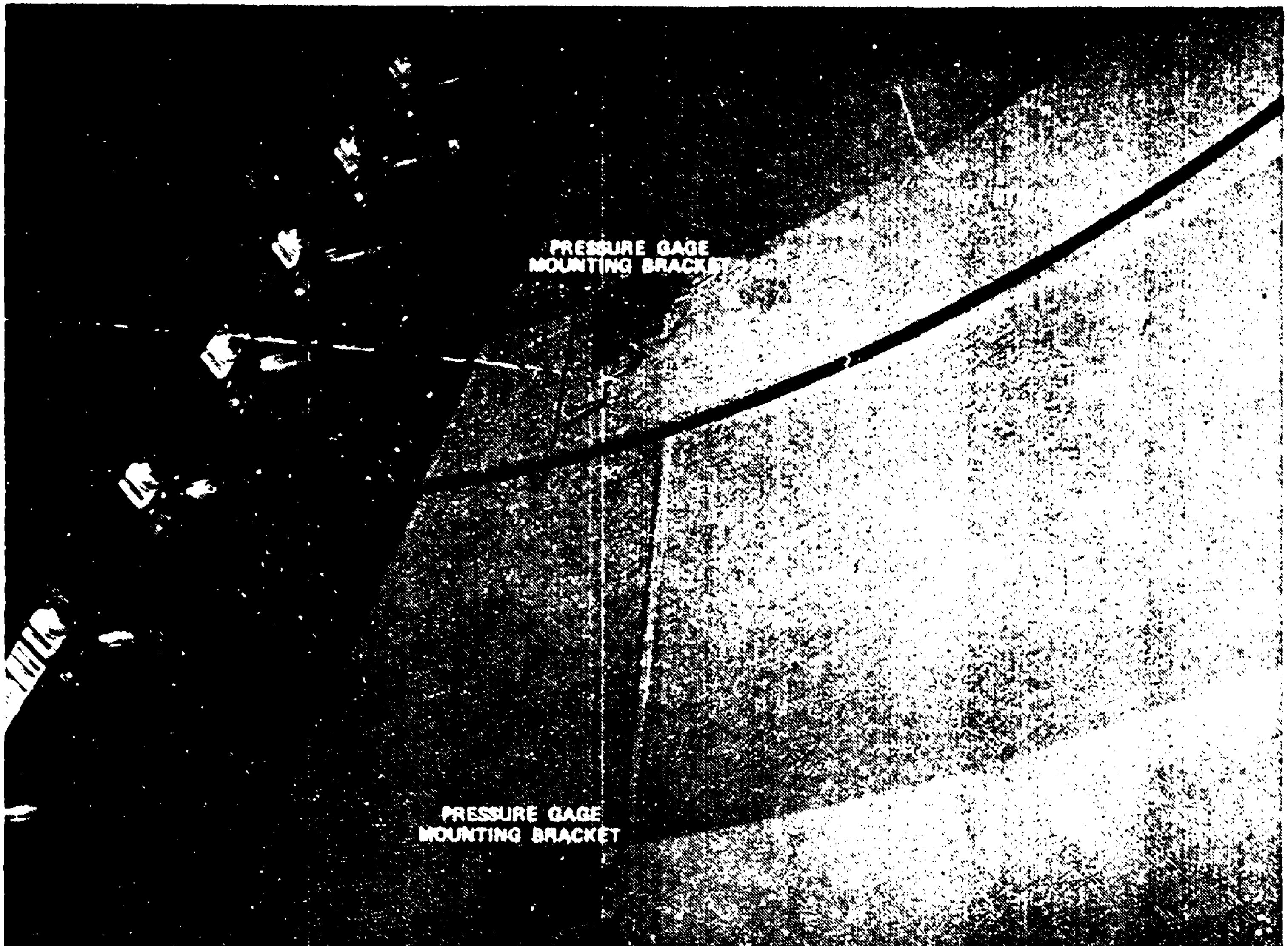
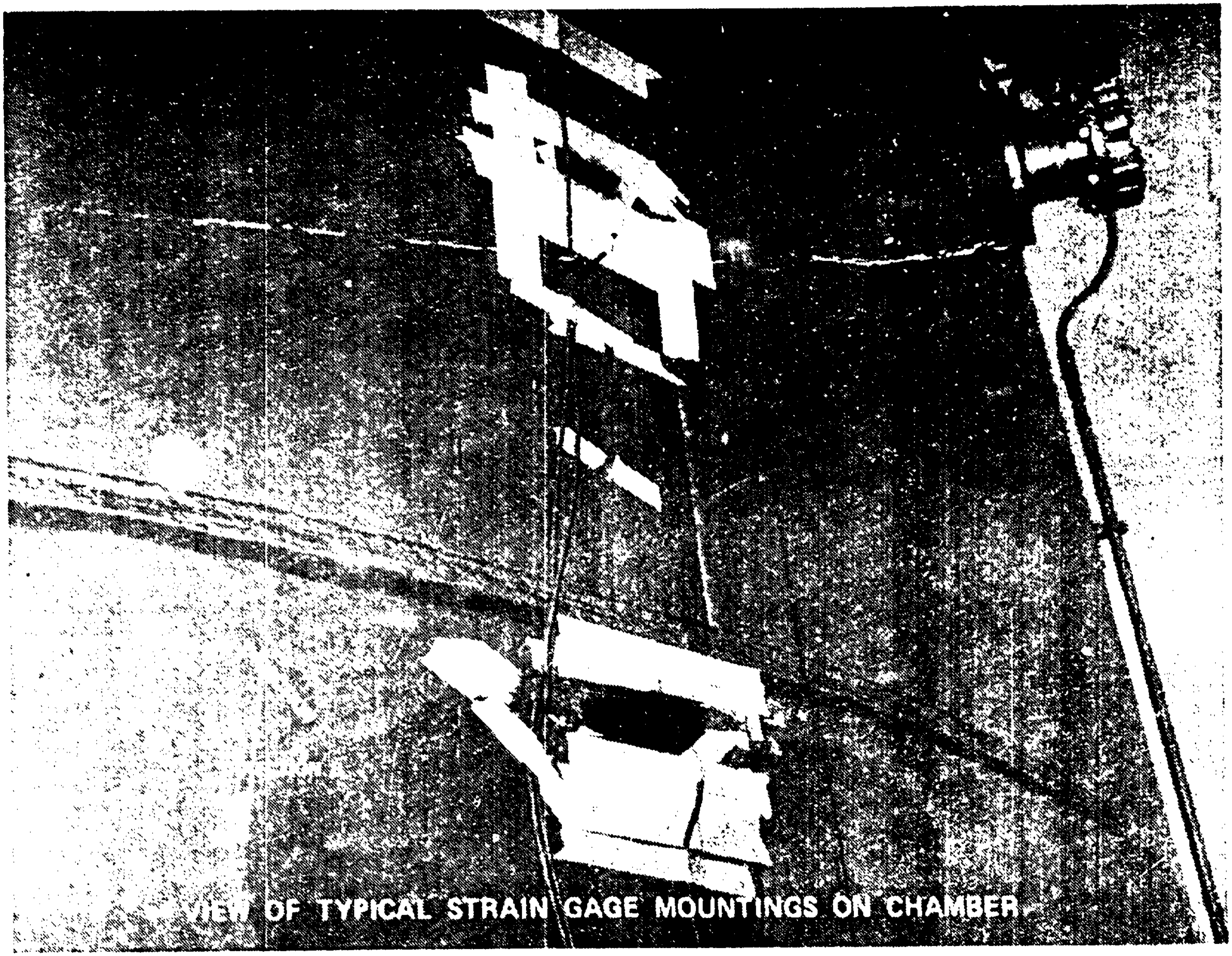


VIEW OF MOUNTING BRACKETS FOR PRESSURE GAGES

Photograph 9



Photograph 10

Table 1.

Test Fire No. 2, 5.6 lbs LX-10

Gas Pressures

Gage No.	Max press psi	Recorded cutoff time-sec	Press at recorder cutoff-psi	Elapsed time from max pressure to cutoff-sec
1	*			
2	12.5	32	9.2	19
3	8.7	25	6.3	10

Blast Pressures

Gage No.	Max press psi
1	
2	350
3	
4	
5	

Strain & Stress

No.	Strain gage reading μ in/in	Actual Hoop μ in/in	Actual Hoop psi	Actual Axial μ in/in	Actual Axial psi	Principal Hoop μ in/in	Principal Hoop psi	Principal Axial μ in/in	Principal Axial psi
1	100	100	2900						
2A	250	250	8538			250	8538		
2B	85			85	4770			85	4770
2C	168								
3	150	150	4350						
4A	120								
4B	69	120	4336			120	4336		
4C	95			69	3172			69	3172
5	100	100	2900						
6A	60	60	3025			60	3025		
6B	136			136	4761			136	4761
6C	98								
7A	50	50	3675			50	3675		
7B	250			250	8242			250	8242
7C	1[illegible]								
8A	190	190	5510						
8B									
8C									
9	130	130	3770						
10	95	95	2755						
11	5	5	145						
12	120	120	4767	120	4767	120	4767	120	4767

* Blanks indicate no data was recorded on purpose, data was lost or the data is meaningless.

Table 2.

Test Fire No. 2, 5.6 lbs LX-10

Gas Pressures

Gage No.	Max press psi	Recorded cutoff time-sec	Press at recorder cutoff-psi	Elapsed time from max pressure to cutoff-sec
1	8.4	200	4.9	178
2	13.0	200	1.8	182
3	17.5	200	3.5	180

Blast Pressures

1	260
2	270
3	78
4	70
5	*

Strain & Stress

		Actual				Principal			
	Strain gage reading	Hoop		Axial		Hoop		Axial	
No.	μ in/in	μ in/in	psi	μ in/in	psi	μ in/in	psi	μ in/in	psi
1	120	120	3480						
2A	230	230	8377			230	8377		
2B	140			140	6322			140	6322
2C	185								
3	165	165	4785						
4A	195	195	6801			195	6801		
4B	83			83	4243			83	4243
4C	139								
5	100	100	2900						
6A	140	140	5773			140	5773		
6B	165			165	6344			165	6344
6C	153								
7A	100	100	3761			163		12	
7B	75			75	3190		4368		2584
7C	125								
8A	115	115	5371			115	5371		
8B	210			210	7540			210	7540
8C	163								
9	200	200	5800						
10	150	150	4350						
11	35	35	1015						
12	160	160	635[illegible]	160	6356	160	6356	160	6356

* Blanks indicate no data was recorded on purpose, data was lost or the data is meaningless.

Table 3.

Test Fire No. 4, 13.7 lbs LX-10

Gas Pressures

Gage No.	Max press psi	Recorded cutoff time-sec	Press at recorder cutoff-psi	Elapsed time from max pressure to cutoff-sec
1	27	180	20	160
2	48	180	21	165
3	44	180	7	170

Blast Pressures

1	630
2	1480
3	750
4	160
5	200

Strain & Stress

		Actual				Principal			
	Strain gage reading	Hoop		Axial		Hoop		Axial	
No.	μ in/in	μ in/in	psi	μ in/in	psi	μ in/in	psi	μ in/in	psi
1	280	280	8120						
2A	500	500	17397			500	17397		
2B	208			208	10729			208	10729
2C	354								
3	230	230	6670						
4A	420	420	14109			420	14109		
4B	115			115	7144			115	7144
4C	267								
5	250	250	7250						
6A	325	325	12320			325	12320		
6B	255			255	10721			255	10721
6C	290								
7A	300	300	11072			362		138	
7B	200			200	8790		11464		8400
7C	200								
8A	260	260	9822			344	10529		
8B	200			200	8451			116	7745
8C	175								
9	400	400	11600						
10	170	170	4930						
11	80	80	2320						
12	270	260	10726	260	10726	260	10726	260	10726

*' Blanks indicate no data was recorded on purpose, data was lost or the data is meaningless.

Table 4.

Test Fire No. 5, 11.2 lbs LX-10

Gas Pressures

Gage No.	Max press psi	Recorded cutoff time-sec	Press at recorder cutoff-psi	Elapsed time from max pressure to cutoff-sec
1	480	180	230	170
2	380	180	170	170
3	240	180	50	165

Blast Pressures

Gage No.	
1	*
2	
3	
4	
5	

Strain & Stress

No.	Strain gage reading μ in/in	Actual Hoop μ in/in	Actual Hoop psi	Actual Axial μ in/in	Actual Axial psi	Principal Hoop μ in/in	Principal Hoop psi	Principal Axial μ in/in	Principal Axial psi
1	150	150	4350						
2A	350	350	13060			371	13128		
2B	250			250	10776			229	10706
2C	325								
3	150	150	4350						
4A	375	375	13842			380	13[illegible]5		
4B	250			250	10987			245	10983
4C	300								
5	150	150	4350						
6A	250	250	9509			250	9509		
6B	200			200	8367			200	8367
6C	225								
7A	375	375	13630			375	13630		
7B	225			225	10205			225	10205
7C	300								
8A	425	425	15194			594	16409		
8B	22[illegible]			225	10627			56	9412
8C	[illegible]								
9									
10	125	125	[illegible]625						
11									
12	300	300	11917	300	11917	300	11917	300	11917

* Blanks indicate no data was recorded on purpose, data was lost or the data is meaningless.

Table 5.

Test Fire No. 6, 11.2 lbs LX-10

Gas Pressures

Gage No.	Max press psi	Recorded cutoff time-sec	Press at recorder cutoff-psi	Elapsed time from max pressure to cutoff-sec
1	96	200	41	192
2	*			
3				

Blast Pressures

1
2
3
4
5

Strain & Stress

	Strain gage reading	Actual				Principal			
		Hoop		Axial		Hoop		Axial	
No.	μ in/in	μ in/in	psi	μ in/in	psi	μ in/in	psi	μ in/in	psi
1	180	180	5220						
2A	340	340	12747			490	14067		
2B	250			250	10692			100	9371
2C	200								
3	170	170	4930						
4A	250	250	11114			o9	9834		
4B	390			390	14311			551	15590
4C	430								
5	200	200	5800						
6A	210	210	8680			202	8653		
6B	250			250	9594			258	9621
6C	220								
7A	380	380	13914			383	13915		
7B	240			240	10717			237	10715
7C	320								
8A	370	370	13685			538	15099		
8B	250			250	10945			82	9531
8C	200								
9	150	150	4350						
10	110	110	3190						
11									
12	100	100	3973	100	3973	100	3973	100	3973

* Blanks indicate no data was recorded on purpose, data was lost or the data is meaningless.

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THE DESIGN OF
BLAST CONTAINMENT ROOMS FOR
DEMILITARIZATION OF CHEMICAL MUNITIONS

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INTRODUCTION

This paper presents a short discussion of the design of blast hardened containment rooms within a new facility being developed to perform demilitarization of obsolete chemical munitions. This facility will perform the demilitarization operations required on a production basis and will conform to all required safety and environmental regulations. The hazard potential associated with chemical munitions dictates that process operations related to removing explosive components must provide complete containment of blast pressures and fragmentation and near total containment of quasi-static gas pressure. Widely used hardened structures design procedures were the foundation of this effort. However, the unique nature of chemical munitions dictated development of additional test data and prediction methods to properly define the blast and fragment loadings.

Additional design considerations, which develop as a result of full containment, are also discussed. The concept of "full containment" itself has a different context when discussing blast and fragments as opposed to confinement of toxic gas products.

The facility being discussed is the Johnston Atoll Chemical Agent Disposal System (JACADS). This facility is under design and will be sited on Johnston Atoll where an existing stockpile of chemical munitions earmarked for disposal is located. This is the first of several new disposal plants planned for construction over the next several years. Management responsibility for the chemical demilitarization program rests with the U.S. Army Toxic and

Hazardous Materials Agency (USATHAMA) located at Aberdeen Proving Ground, MD. The Huntsville Division (HND) of the U.S. Army Corps of Engineers is acting as the contracting authority for the design of the JACADS process and main process facility. The process design is being performed by the Ralph M. Parsons Company under contract to HND. The facilty design is being performed concurrently with the process by Stearns-Catalytic. Technical review of these design efforts is being performed by USATHAMA and HND engineering staff. Specialized consultants are also used where necessary. Among these, Southwest Research Institute has provided major support in the area of blast and fragment analysis.

FUNCTIONAL DESCRIPTION

The JACADS Facility houses a production process which will accept several types of chemical munitions and perform the necessary operations to safely separate explosive components and liquid agent from the munitions and then incinerate the explosives and agent and thermally decontaminate the metal parts. All process operations are conducted in a single building. Figure 1 shows the JACADS facility site, including the layout of the various equipment and other facilities required to support the main process building, the Munitions Demilitarization Building (MDB). Within the MDB the ventilation system is designed to provide increasing levels of negative pressure from non-hazardous areas towards hazardous areas. This prevents leakage of toxic vapors from hazardous areas to other areas. Those munitions with explosive components are placed in two functionally identical explosive containment rooms (ECRs) on the second floor of the building. The explosive components are removed by automatic equipment and then gravity fed to an incinerator on the first floor. Figure 2 shows the MDB second floor ECRs, and Figure 3 shows the first floor with the Deactivation Furnace System (DFS) below.

The hazardous nature of the explosive removal operations required Category 1 blast and fragment protection for the remainder of the building. This required the two ECRs to provide total containment. It was also necessary that the two rooms provide a high degree of vapor containment after an explosive incident. The high production rates required of the facility generated several operational requirements which influenced containment room design. These are listed in Figure 4. The influence of each of these requirements on the design of the blast containment rooms is discussed.

TOTAL CONTAINMENT OF BLAST AND FRAGMENT EFFECTS

The required operational configuration of the ECRs and the remote construction site dictated reinforced concrete as the most cost effective construction material. Well proven methods are available for designing blast resistant, reinforced concrete structures (Ref. 1), given the expected blast and fragment environment. Because chemical munitions are designed to function differently than the more typically encountered fragmenting rounds, it became necessary to develop additional blast and fragment data to predict loads. Figure 5 summarizes this effort. The results of these sources (Ref. 2 and 3) were the basis of the blast pressures and fragments used in the design. It is significant to note that fragmentation of the chemical munitions considered resulted in more severe fragment shapes and depths of penetration than would have been calculated using Reference 1.

CONTAINMENT OF GAS PRESSURE

The highly toxic nature of the chemical agents in the munitions dictated that the ECRs provide a high degree of containment of the post-accident gas products. This near total containment of high temperature contaminated gas must be maintained until the heat is conducted away by the structure. As the gas cools, the temperature and pressure will drop and eventually reach a level where it can be safely processed through the building ventilation system. Figure 6 shows a temperature/pressure decay curve for the ECRs after a typical accident scenario. No concrete structure can be expected to be completely gas tight unless a liner plate is provided. The cost of a liner plate is significant, and the risk of agent contamination behind the liner was undesirable. An alternate course of action was to use an unlined concrete structure that was contained within an outer negative pressure ventilation area which was capable of handling any small leakage through the ECR structure. This concept is shown in Figure 7 and was chosen as the basis of design. Results of explosive model testing (Ref. 4) for a similar concrete containment structure was used to predict outgassing through the concrete after an incident. Leakage through the structure is a direct function of the internal pressure after an event. As the confined gas cools, pressure decays fairly rapidly; and the leakage rate decreases proportionately. Figure 8 shows graphically the comparison of pressure drop due to leakage relative to pressure drop from cooling. Analysis has shown that total leakage is only a small percentage of the allowable leak rate in the surrounding areas.

VENTILATION SYSTEM BLAST PROTECTION

Process operations in the ECR can result in the introduction of agent vapor into the room. To minimize this hazard a high ventilation rate is maintained continuously during process operations. In the event of an explosive incident, the supply and exhaust ducts must be quickly isolated from the ECR to prevent serious damage and personnel risk to the remainder of the building. To accomplish this each duct has a fast-acting blast valve in series with a gas-tight valve which is tied into the process control system. Figure 9 shows the blast protection for the ECRs. The blast valves protect the ventilation system from shock pressures and the controllable gas-tight valves provide positive isolation capability for other situations. It is interesting to note that, even though fast-acting blast valves are used, an attenuated shock will pass the valve and enter the ventilation system. The peak value of the shock is a function of losses through the valve and the duration depends on the valve closure time. For the ECR design, peak shocks at the valve inlet were derived from scale model test data. Shock intensity after the valves are obtained from the valve manufacturer's test data. Figure 10 shows the typical ECR shock pulse upstream and downstream of the valves. This "leakage" shock was then traced through the ventilation system to assure no risks to the system or personnel occurred.

BLAST RESISTANT PENETRATIONS

All doors, conveyor gates and drop chutes in the ECRs must provide blast and fragment resistance, be operationally reliable and be as air tight as feasible. The worst case fragments in the ECR design required a steel thickness of 2.5 inches. Obviously, plates of this thickness resulted in complex hinge assemblies and powered operating mechanisms. All operating closures are tied to the process control system and interlocked to assure closing during hazardous operations. Door assemblies are installed in the ECR prior to placing concrete to assure a reliable installation. All conveyor gates and doors will have compression seals to limit leakage after a blast to specified maximum valves.

SURFACE COATING MATERIALS

Day-to-day exposure of the ECR to agent vapor required that all interior surfaces be coated with an agent resistant epoxy paint. This finish prevents agent from impermeating the concrete and provides a smooth resistant finish for regular washdown with decontamination solutions. The coating also significantly improves the gas tightness of the structure.

The use of this coating raised the question of potential combustibility causing an increase in the quasi-static gas pressure. Figure 11 presents the classical pressure-time history within a containment structure. It consists of a high peak, short duration shock pressure, followed by a relatively long-term quasi-static pressure which decays as the gas cools. Figure 12 shows a reproduction of a pressure trace of a model containment structure (Ref. 4) in which a wall coating material used to seal the structure apparently burned. The increase in gas pressure is dramatic.

Available data on the proposed wall coatings was not sufficient to assure its combustion characteristics when exposed to a fireball, as would occur during an accidental incident. A test program (Ref. 5) was therefore conducted to evaluate the three coatings which were acceptable from the standpoint of agent resistance. Results proved that these particular materials did not pose a risk with regard to combustion pressures. It is interesting to note that this issue is normally not even considered in a vented structure.

STRUCTURE REUSABILITY

In the event that an explosive incident occurred during normal operations, it is desirable to limit damage to minor refurbishment efforts so that the ECR can be brought into service quickly. To achieve this, structural damage criteria was defined as shown in Figure 13. These criteria are much more restrictive than values normally used in hardened structure design. This assures a higher degree of containment. Inelastic deformation is very useful and desirable when a transient load is to be resisted. In the case of a containment structure, this condition exists during the shock phase of the loading and up to the time of maximum response of the structural element. However once this transient load has passed, the remaining quasi-static load is basically steady-state. During this phase, the maximum design deformation must be within the elastic limit of the element. Similar logic applies to the use of Dynamic Increase Factors (DIF) which increase material allowables based on rate of strain during loading. Use of a DIF during the quasi-static phase is not appropriate.

SUMMARY

Design of concrete structures for full containment applications is generally similar to design of other hardened structures, such as vented cubicles. Several additional factors can be present which must be considered to assure a complete evaluation of the loading and the structure response. Several recent model tests (Ref. 4, 5 & 6) have supported the design philosophies applied to these containment rooms.

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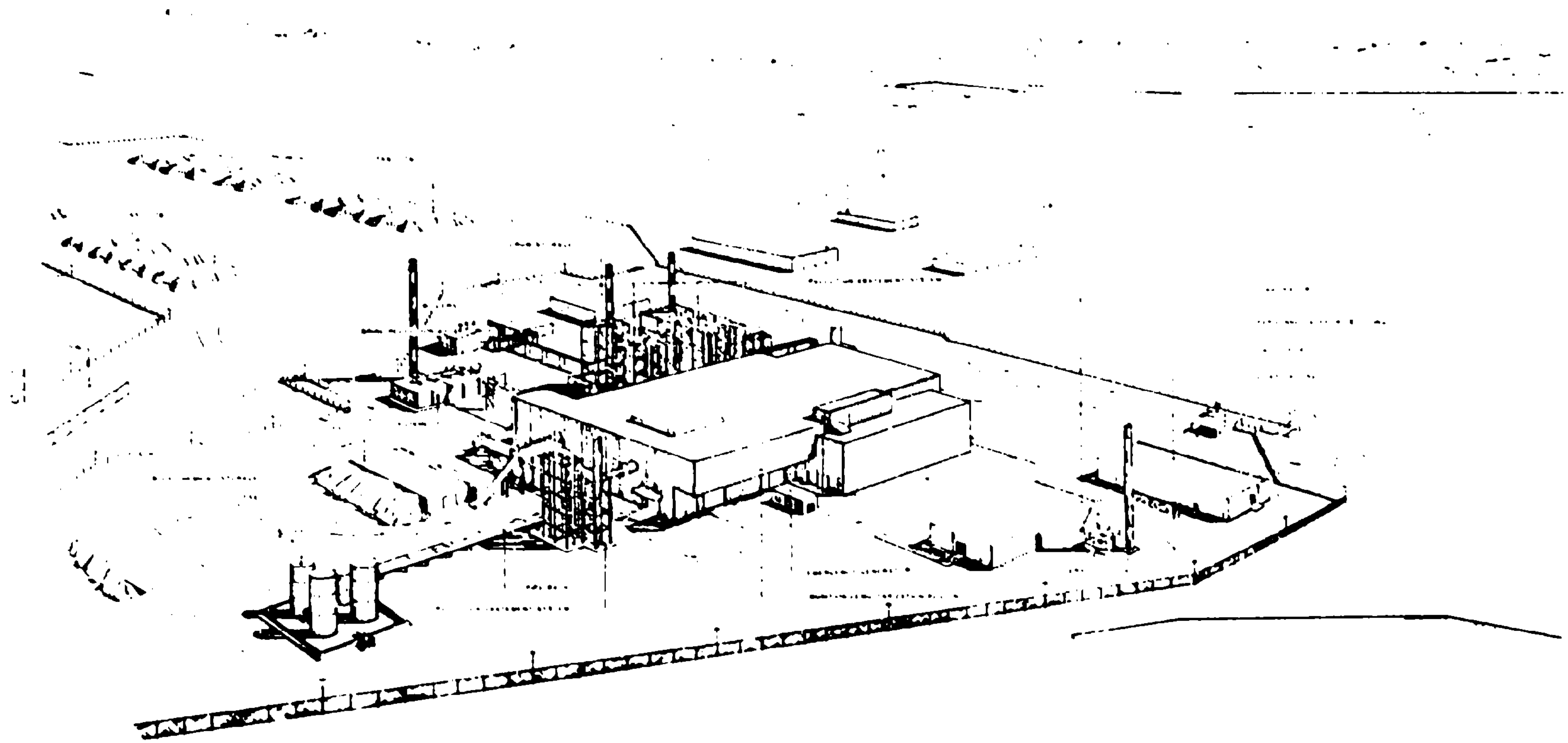
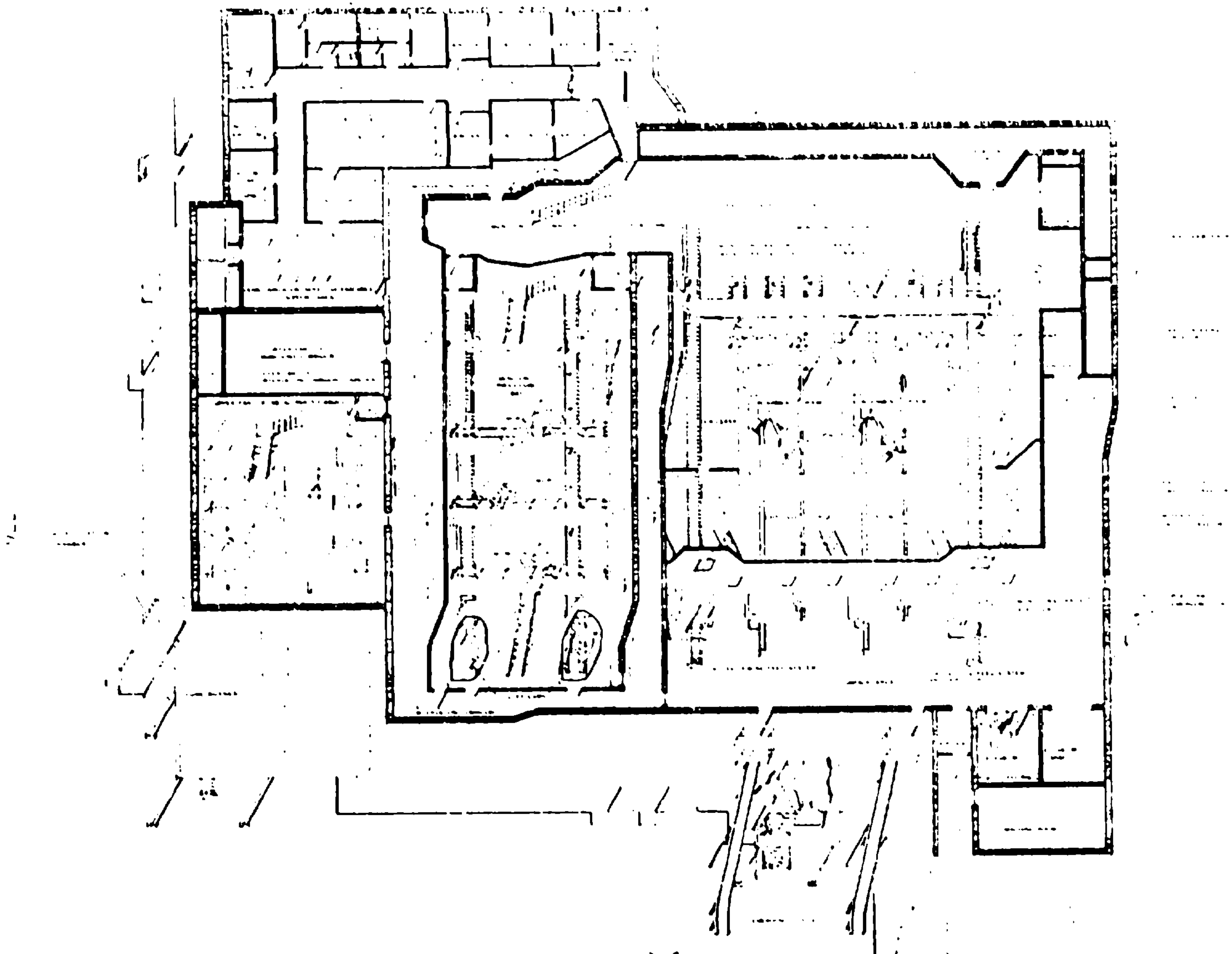


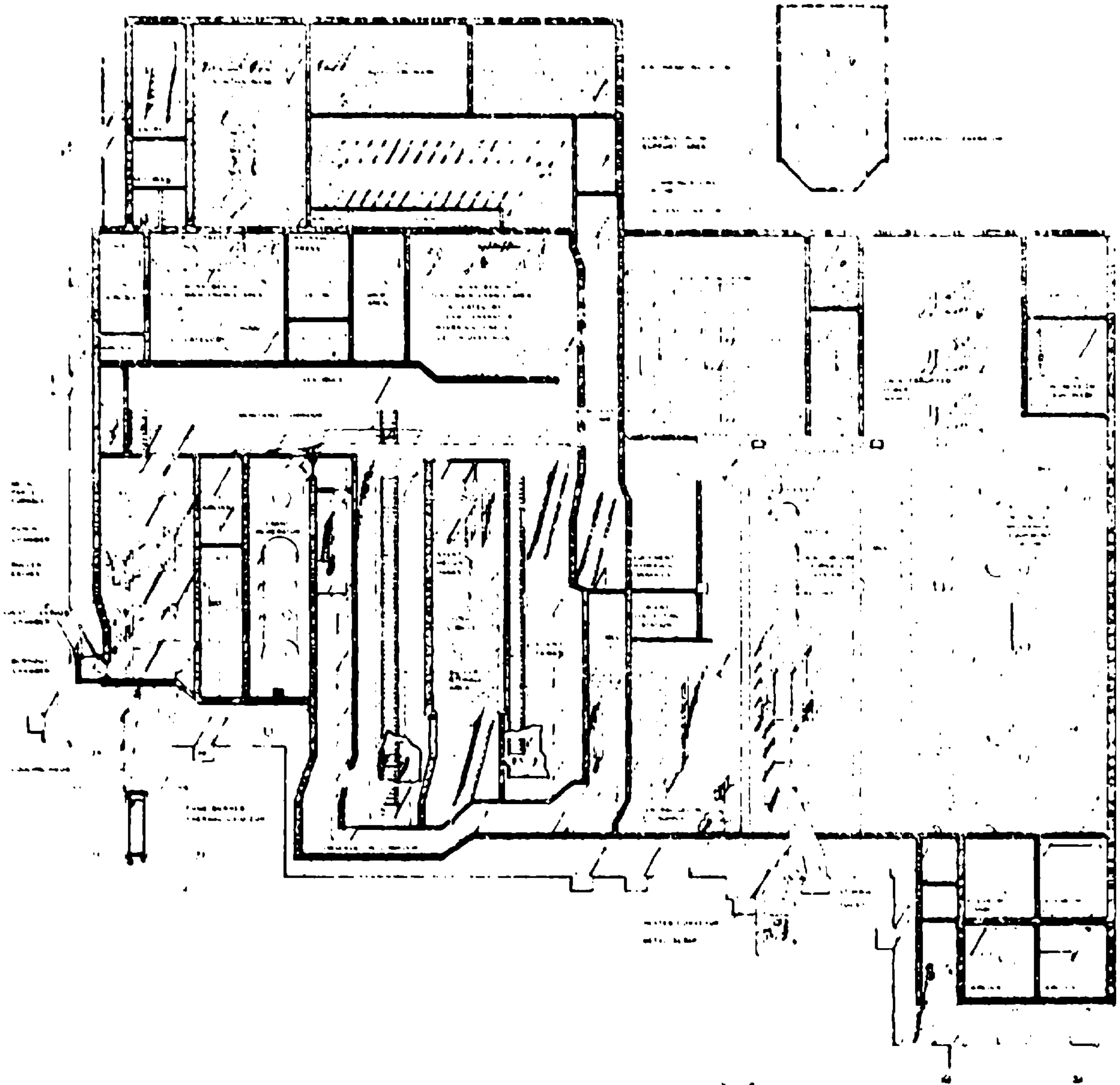
JOHNSTON ATOLL CHEMICAL AGENT DISPOSAL SYSTEM JACOBS

Figure 1



JOHNSTON ATOLL CHEMICAL AGENT DISPOSAL SYSTEM

Figure 2



AXONOMETRIC VIEW OF FIRST FLOOR
JOHNSTON ATOLL CHEMICAL AGENT DISPOSAL SYSTEM

Figure 3

JACADS FUNCTIONAL REQUIREMENTS FOR EXPLOSIVE CONTAINMENT ROOMS

- TOTAL CONTAINMENT OF BLAST AND FRAGMENTATION — CATEGORY 1
- NEAR TOTAL CONTAINMENT OF POST-INCIDENT HOT GAS PRODUCTS UNTIL SAFE FOR PROCESSING
- PROVIDE CONTINUOUS VENTILATION SYSTEM PROTECTED BY BLAST VALVES
- PROVIDE BLAST RESISTANT LEAK-TIGHT DOORS, CONVEYOR GATES AND OTHER PENETRATIONS.
- INTERIOR SURFACE FINISH NON-COMBUSTIBLE, AGENT AND CAUSTIC RESISTANT
- REUSABLE AFTER EXPLOSIVE INCIDENT

FIGURE 4

BLAST AND FRAGMENTATION PREDICTION FOR CHEMICAL MUNITIONS

REQUIRED ACTION

- DETERMINE INFLUENCE OF LIQUID SURROUNDING BURSTERS ON THE BLAST AND FRAGMENT CHARACTERISTICS OF CHEMICAL MUNITIONS

RESULTS

- EXTENSIVE TEST PROGRAM AT THE NAVAL SURFACE WEAPONS CENTER TO CHARACTERIZE CHEMICAL MUNITIONS
- DEVELOPMENT OF SOUTHWEST RESEARCH INSTITUTE OF A MANUAL WHICH PROVIDES BLAST AND FRAGMENT PREDICTION METHODS APPROPRIATE FOR CHEMICAL MUNITIONS.

FIGURE 5

PRESSURE-TEMPERATURE DECAY

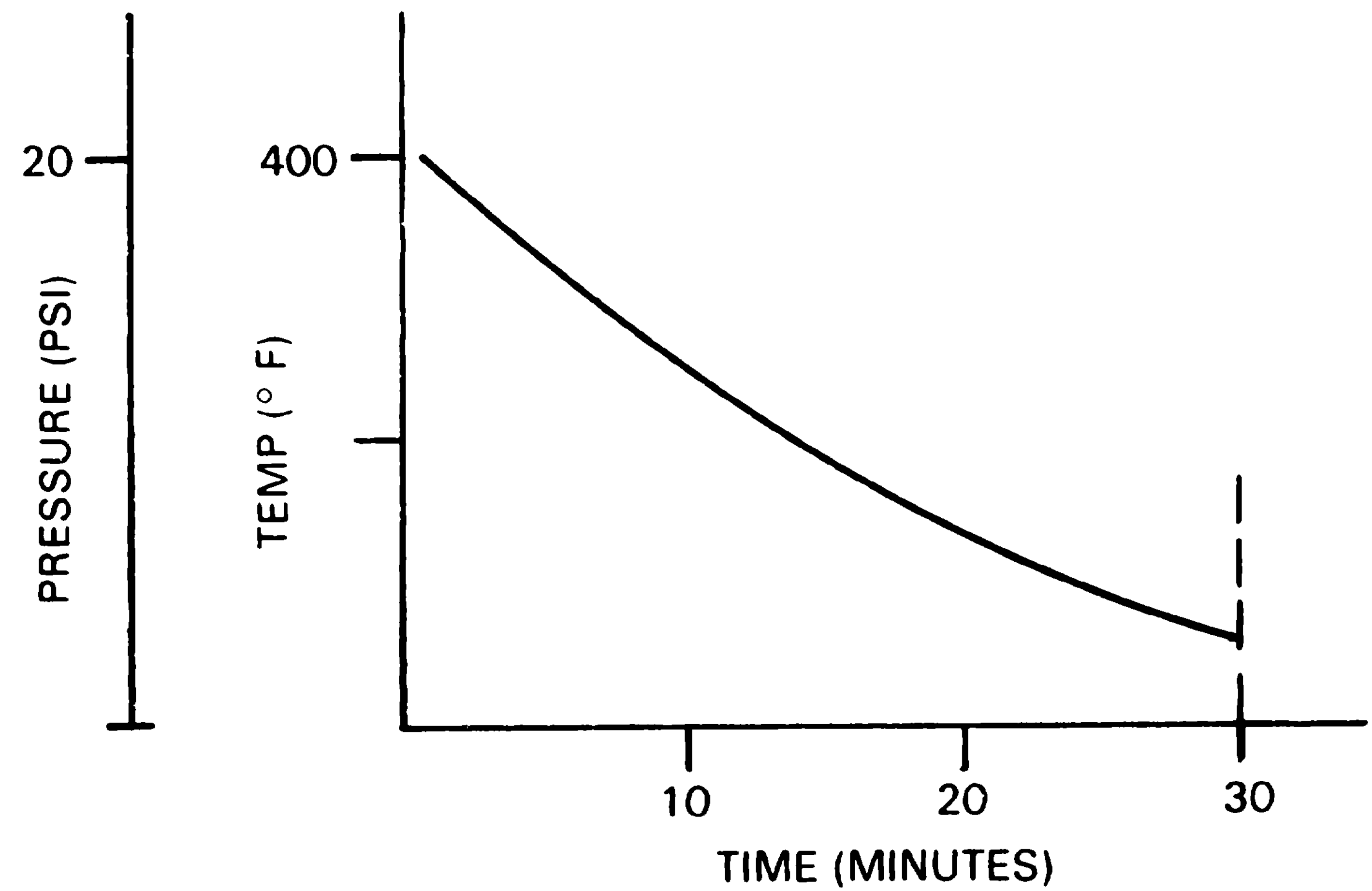


FIGURE 6

SECTION THROUGH ECR/DFS

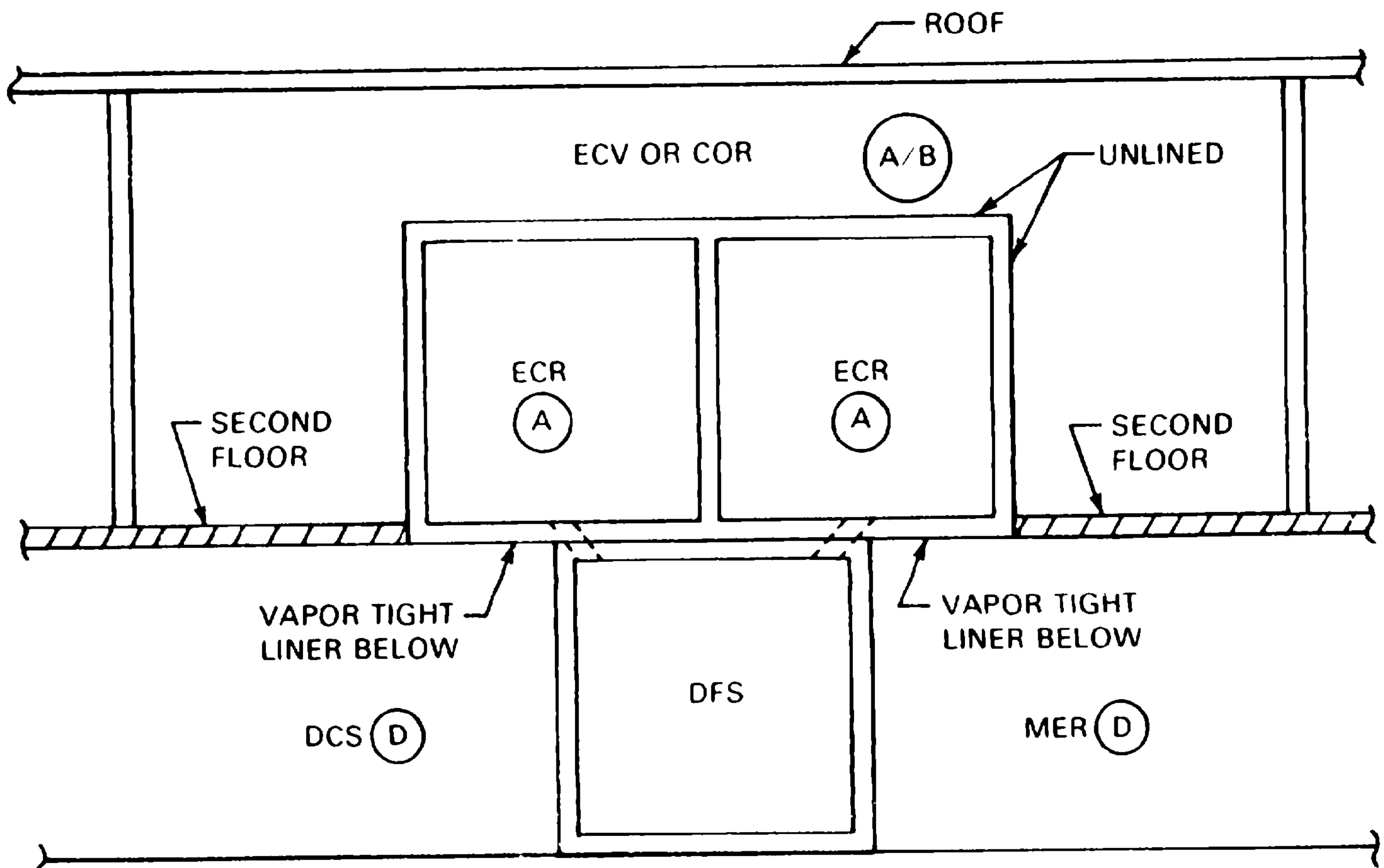


FIGURE 7

ESTIMATED LEAKAGE

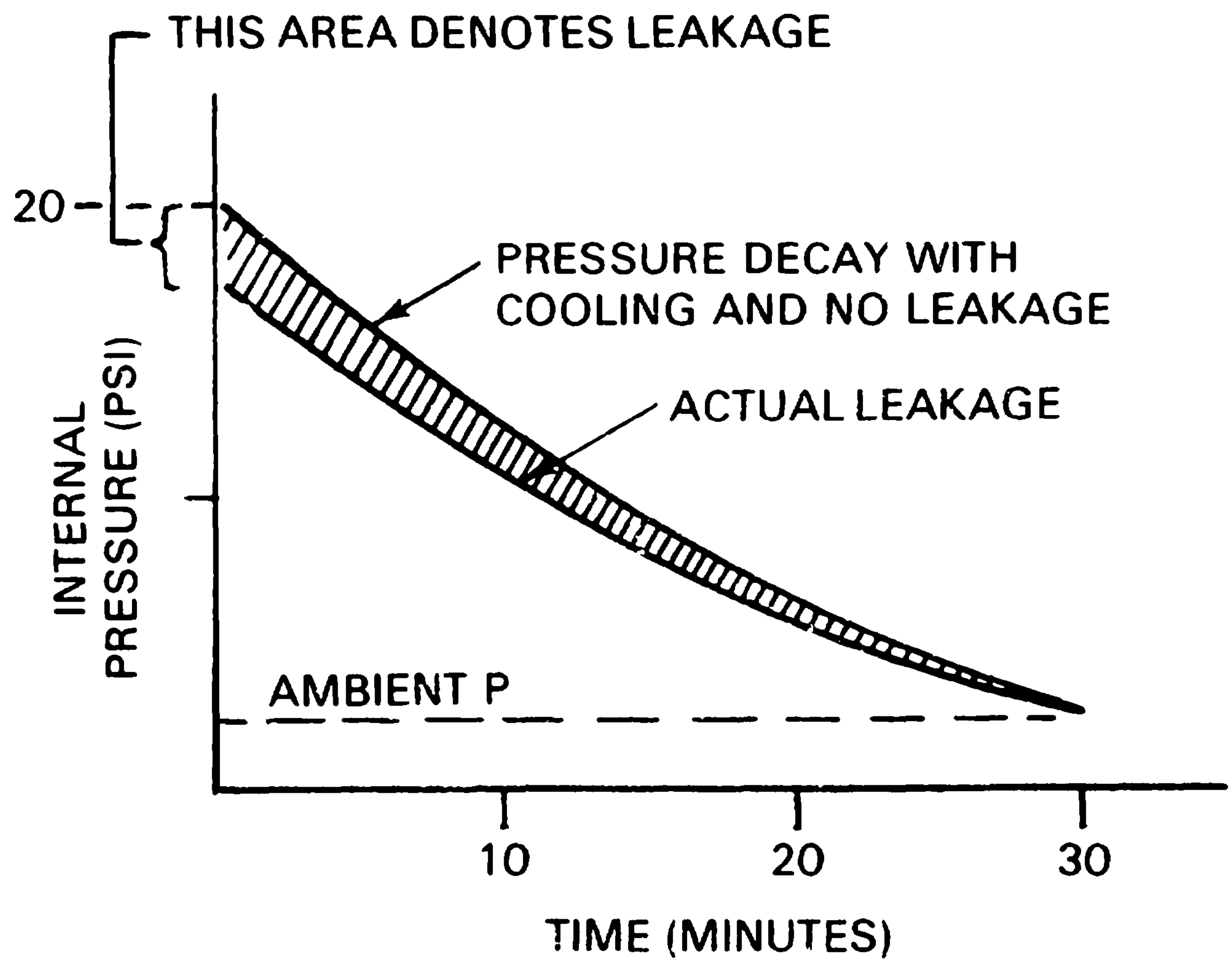


FIGURE 8

ECR VENTILATION SYSTEM BLAST PROTECTION

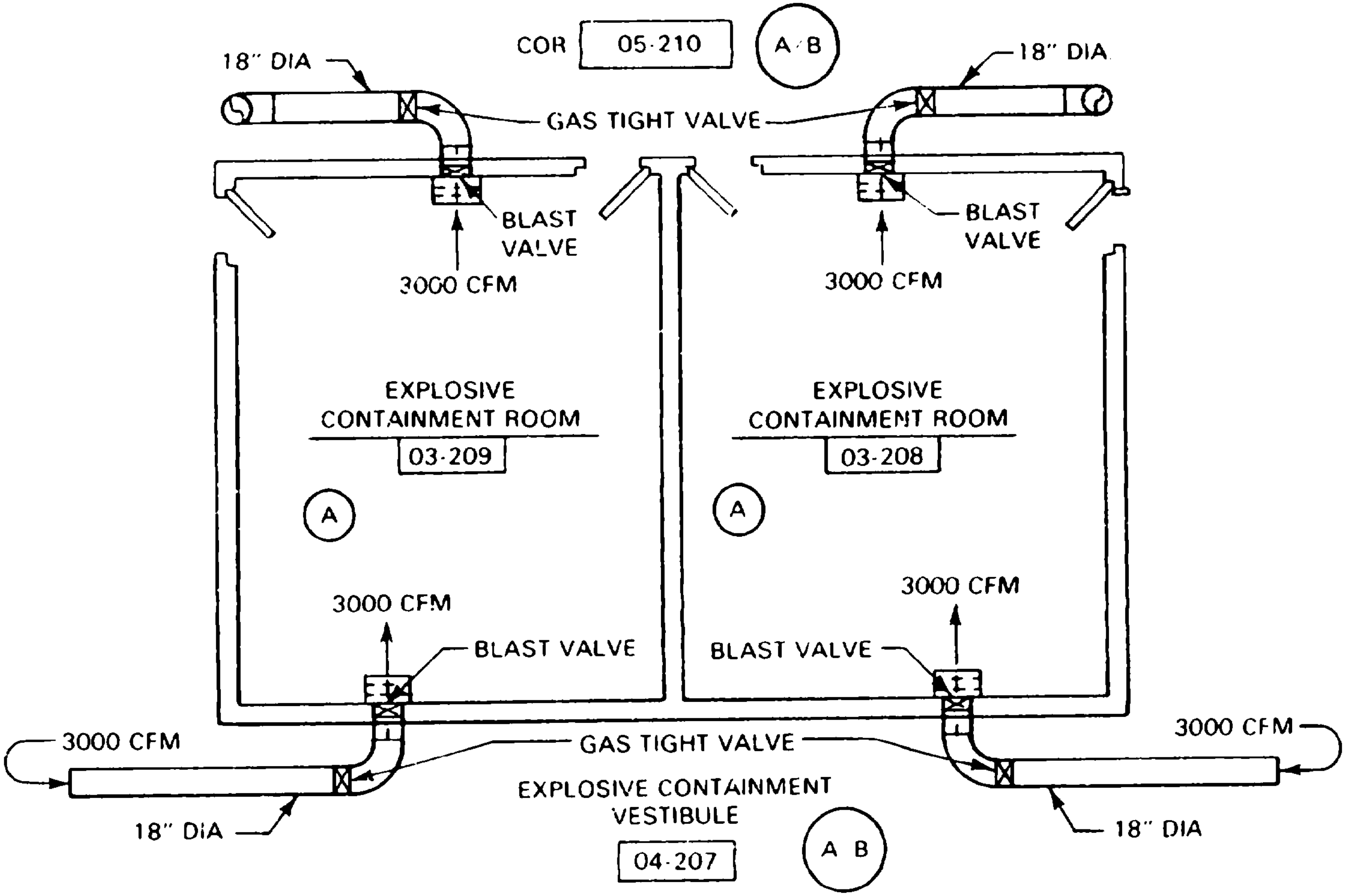


FIGURE 9

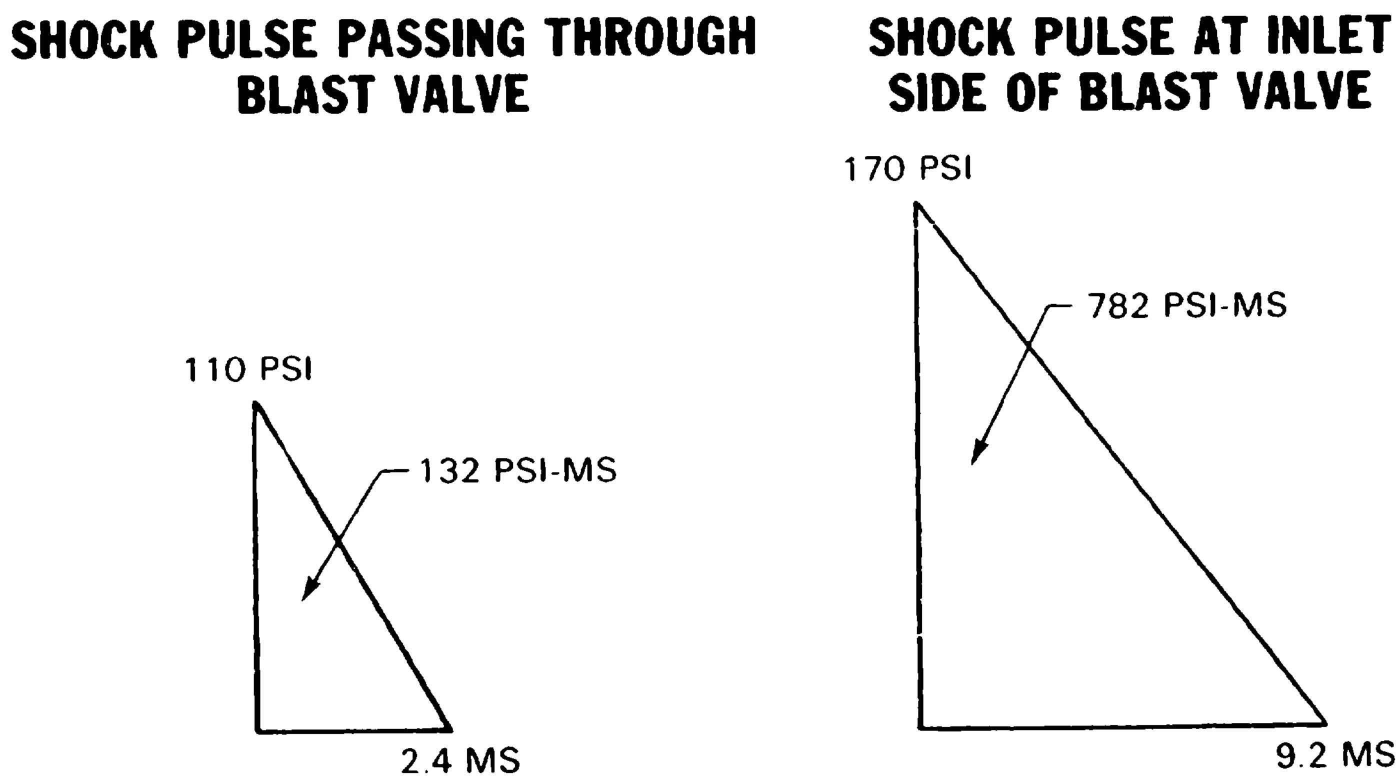

SHOCK PULSE PASSING THROUGH
BLAST VALVE
110 PSI
132 PSI-MS
2.4 MS
SHOCK PULSE AT INLET
SIDE OF BLAST VALVE
170 PSI
782 PSI-MS
9.2 MS

FIGURE 10

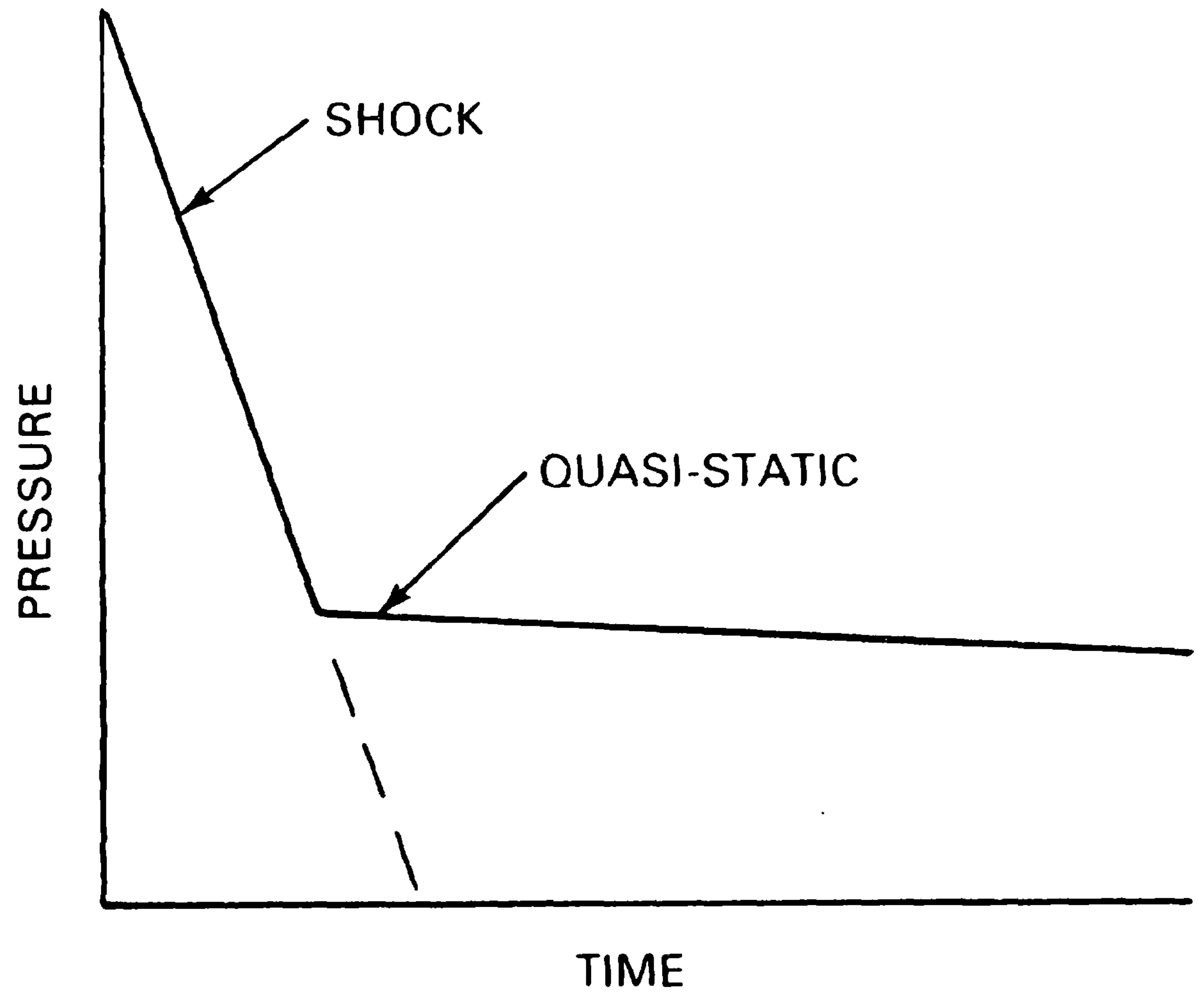


FIGURE 11

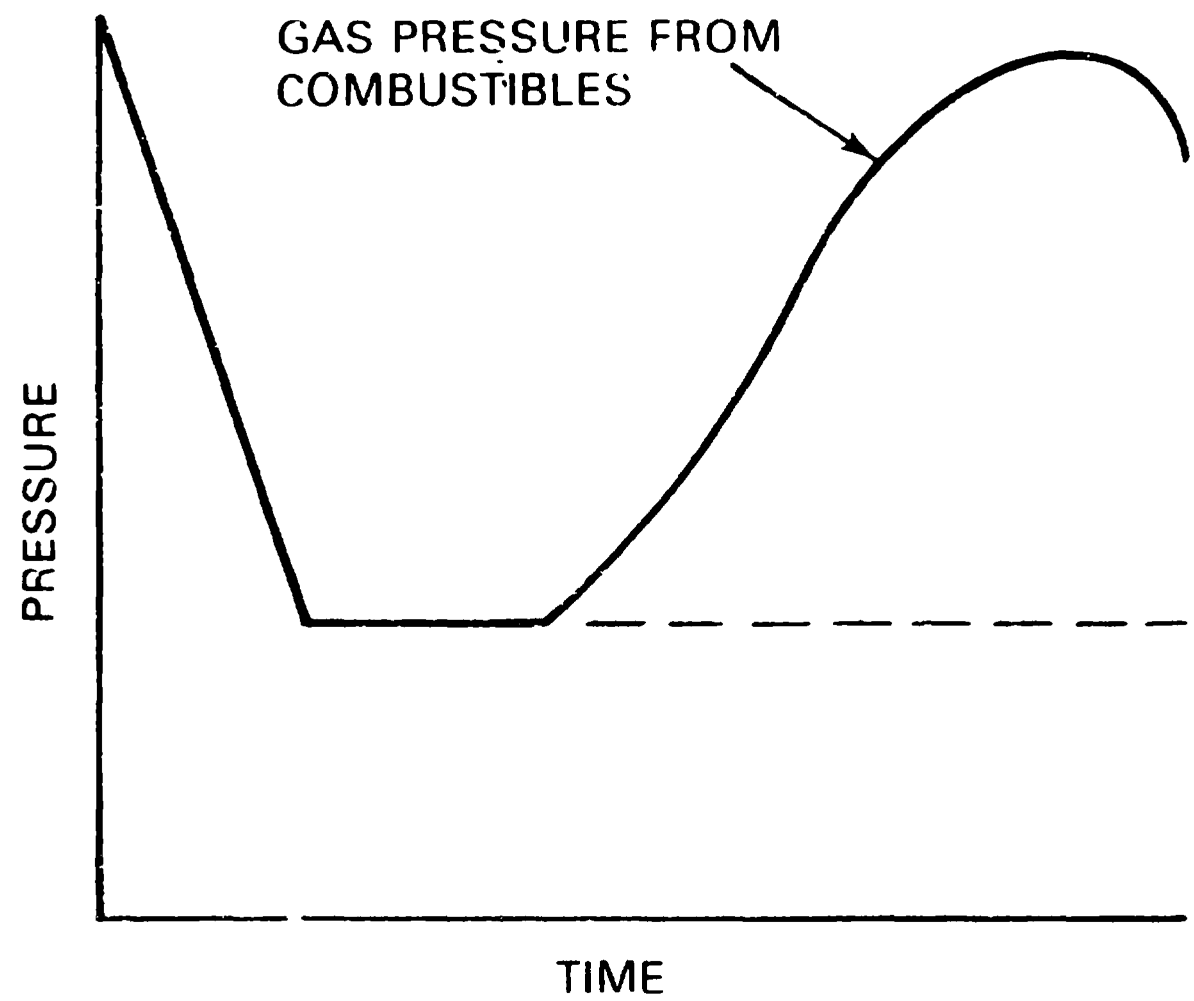


FIGURE 12

STRUCTURAL DAMAGE CRITERIA

- DURING SHOCK LOAD PHASE $T \leq T_m$ ELEMENT JOINT NOTATIONS $\leq 1°$ OR $\mu \leq 3$ DYNAMIC INCREASE FACTORS USABLE

- DURING QUASI-STATIC PRESSURE $T > T_m$ ELEMENTS MUST REMAIN WITHIN THE ELASTIC LIMIT DYNAMIC INCREASE FACTORS NOT VALID.

FIGURE 13

REACTION PROPAGATION ALONG AN ENCLOSED CONVEYOR

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ABSTRACT

Tests were conducted to study the likelihood of explosive reaction propagation along an enclosed explosive handling conveyor. An initiation scheme was selected and tests conducted which insured a high order detonation over the entire length of an explosive increment. A full scale mockup of a 125-foot enclosed section of conveyor was constructed. A 50-foot increment of explosive was detonated. A 25-foot air gap and a 50-foot acceptor increment were also present. The acceptor did not detonate, nor even react violently. A small amount of self-extinguishing burning was also observed.

INTRODUCTION

BACKGROUND

In the early 1970's, the Department of the Navy began efforts to modernize and upgrade an existing bomb loading facility at the Naval Ammunition Depot (NAD), McAlester, Oklahoma. One of the innovative features of the modernized plant is the use of a belt conveyor to move the explosive ingredients from the unloading building to the mix-melt kettles. Many safety questions about such a system were raised.

A series of tests were conducted by the Naval Weapons Center (NWC), China Lake, California, to determine certain properties of the conveyor-based explosive handling system. These tests investigated, in part, the following:

1. the minimum bed depth for reaction propagation,

2. reaction propagation across an air gap,

3. reaction propagation between adjacent conveyors.

The China Lake experiments reached the following conclusions (among others):[1]

1. It is relatively easy to initiate a detonating reaction in flake TNT. Only an electric blasting cap is required. However, this type of energy input will be unlikely to occur in the powder handling areas of the proposed bomb line.

2. A 5-cm thickness of flake TNT will readily sustain a detonating reaction.

3. If the thickness of a patch of loosely-piled TNT is approximately 2 to 3 cm or less, the detonation will probably not be sustained.

4. Flake Comp B does not detonate as readily as flake TNT.

5. Detonation of 50 mm deep Tritonal (80/20 TNT/Al) will not propagate from one charge across a gap of 14.3 meters (47 feet) or 7.16 meters (23.5 feet) to another charge of Tritonal constituents in a conveyor configuration.

6. A dual belt installation probably does not represent a greatly different problem to the design of the plant than a single belt does.

The China Lake work also introduced the following caveat: "These are free-air values--a conveyor enclosing could change them."

Based on the NWC tests and safety committee recommendations, the conveyor design shown in figure 1(a) was chosen. The belt has an overall width of 18 inches with an inside service width of 13 1/4-inches. The bottom surface of the belt carrying the explosive is located approximately 10 1/2-inches from the top of the container.[2] The conveyor is totally enclosed in a rectangular stainless steel structure 1/4-inch thick. The maximum explosive depth is maintained at 1.5 inches (or less). The explosive is dispersed in 50-foot increments with a 25 to 50 foot air gap between increments.

CONCERNS

Recent safety analyses[2] have raised several concerns about the previous tests and analyses performed for the "A" line modernization. These questions included the following:

1. reliability of the initiation system used in the original tests,

2. the effect of conveyor width on reaction propagation,

3. the effect of the protective enclosure on the severity and propagation of reactions along the conveyor.

In the NWC tests, detonation was started with an E-99 electric blasting cap. The adequacy of this detonation source was determined by detonating a 1/2-pint cardboard container filled with flaked TNT. A plywood witness plate was used to assess the results. The flaked TNT appeared to detonate. As a result, the remainder of the NWC tests used simply one or more blasting caps as the detonation source. The question has been raised as to whether or not a true high order detonation was achieved.

The NWC tests used an explosive width of 18 inches; the as-constructed system has an explosive width of 13 1/4-inches. As pointed out in Reference 3, Army data indicate that there may be a conveyor width effect for high order propagation along conveyors. The McAlester "A" line conveyor width has not been tested.

The total effect of the steel enclosure around the conveyor could not be determined. In general, the effect of an enclosure on explosive reactions is to increase the rate of reaction, the severity of the reaction, or both. It was felt that the enclosure could change a dying or non-propagating reaction into a sustained high-order detonation and moreover, allow the detonation to jump the gap between explosive increments.

During the conveyor experiments conducted at NWC, only lightly-confined conveyors were considered. The heavy, steel-enclosed conveyors were not envisioned and, thus, were not tested.

CURRENT PHILOSOPHY

With this background and concerns in mind, a new test program was devised by the Naval Surface Weapons Center (NSWC). The program would take as a "given," the unlikely event of a full detonation of one increment along a conveyor. The consequences of this event would then be investigated:

1. Would reaction propagate across the shortest gap actually proposed for McAlester (25 feet)?

2. What were the effects of the steel enclosure on the reaction?

To eliminate any questions about the effect of the conveyor width or material, actual conveyor material from the "A" line at McAlester was used for all the current tests.

PRELIMINARY TESTS

INITIATION TESTS

A "given" in the program was the full, reliable detonation of one explosive increment along a conveyor. The detonability of flaked TNT was demonstrated by duplicating the NWC 1/2-pint container test. A 1/2-pint cardboard container was filled with flaked TNT and placed on a steel witness plate. A number 8 detonator was used as the detonation source. Based on the dent in the witness plate, it was surmised that the flaked TNT did detonate high order.

The next step was the achieving of a high order detonation of a distributed charge of flaked TNT. A trough, as shown in Figure 2 was used for two tests. In each case, the trough was filled with flaked TNT and detonated from both ends simultaneously. The aluminum plate in the center acted as a witness plate for judging the intersecting shockwaves from the two detonation sources. Two detonation schemes were tried, one using several layers of DETASHEET explosive and one using layers of Composition C-4. The DETASHEET proved the more satisfactory. As a result of these tests, the initiation system depicted in Figure 3 was chosen. Four layers of DETASHEET, the height of the flaked TNT (1 1/2-inches) and the total width of the conveyor (18 inches) were used. The total DETASHEET weight was approximately 120 grams.

INSTRUMENTATION CHECK TEST

Because the full scale conveyor test was to include the steel enclosure, it was decided that a preliminary test would be held in the open. This would allow for instrumentation check-out as well as demonstrating that a high-order detonation was achievable over an explosive length of at least 25 feet.

The field setup for this shot is shown in Figure 4. Piezoelectric airblast transducers were used to monitor the airblast produced. Shock front location along the length of the charge was monitored with Dupont targets inserted into the explosive. These targets require pressures of over 30 kilobars before they respond.

A 25 foot section of conveyor material, supported by a wooden platform was used on the test. Approximately 175 pounds of flaked TNT were placed on the conveyor. Figure 5 shows photographs of the pre-test setup. The entire 25 foot length detonated high order. This was verified by all aspects of the instrumentation. The shock-front position-time (as recorded by the detonation velocity probes) indicated a sustained detonation at a rate of 10,300 feet per second. The high speed photographs showed a fireball typical of TNT detonations--a bright white flash, followed later by a sustained burning. Since the test site was at an altitude of approximately 5,200 feet, the airblast results were scaled to sea level conditions. These sea level results are also shown in Figure 6.

FULL SCALE TEST

CONSTRUCTION

Nearly all of the significant features of the "A" plant line were duplicated in the full scale test. Two 50-foot increments of TNT (each 1 1/2-inches deep) were used; each increment was separated by a 25-foot air gap. Actual conveyor belting from McAlester was used on the test. The internal details of the conveyor enclosure were somewhat simplified for this test. Figure 1(a) shows a cross-section of the McAlester enclosure. The rollers, bearings, and return conveyor were eliminated for this test. Moreover the enclosure was fabricated from mild steel, rather than the stainless steel used in the actual enclosure. Figure 1(b) shows a cross-section of the conveyor, as constructed for this test.

At McAlester, the top of each section of the enclosure is held on by hundreds of bolts. For this test, the top of each 10-foot section was constrained with bolts every 6-inches along the donor; the spacing was increased to 18 to 24 inches in the air gap and the acceptor.

Because the McAlester conveyor is inclined, the test conveyor was inclined at a 3^{o} angle. Figure 7 presents a schematic of the completed conveyor. The same detonation scheme and instrumentation techniques that were demonstrated in the preliminary test were used on the full scale test. Figure 8 shows the test setup field layout for this test, while Figure 9 shows photographs of the pre-test setup. A total of 700 pounds of flaked TNT was used--350 pounds in the donor and 350 pounds in the acceptor.

RESULTS

The donor detonated high order over its entire 50-foot length; the acceptor did not detonate, nor appreciably burn.

High order detonation in the donor was confirmed by two methods, one optical and one electronic.

The electronic data utilized Dupont targets inserted into the TNT bed at fixed locations. Upon crushing of the target, a signal was recorded on a digital oscilloscope. The photographic data was recorded with a HYCAM camera operating at 10,000 pictures per second. This camera traced the fireball location along the length of the conveyor as the fireball broke through the enclosure. Both of these sets of position-time information are presented in Figure 10. The electronic data indicate a detonation velocity of 13,840 feet per second; the photographic data indicate 14,200 feet per second. The Livermore Explosives Handbook[4] indicates that for this density of flaked TNT (approximately 0.8 gm/cm^3), a detonation velocity of 14,100 feet per second is expected. The airblast results, scaled to sea level conditions, are plotted in Figure 11.

The external airblast is somewhat different than what would be expected from a spherical charge in free-air. The pressures occurring in the 30 to 50 foot range (measured off the side from the center of the donor) are similar to free-air. However, at larger distances, the pressure decays faster than from a sperhical charge. This is to be expected, since the measurements are made off the side off an extended "line charge." Close-in, the pressures will be less than predicted in free-air due to the "mass-effect" of the enclosure.[5] This is shown as the dotted extrapolation in Figure 11.

Pressures were also measured at two locations inside the enclosure--at the center of the gap and at the start of the acceptor. Because of the extreme thermal environment, these records are difficult to interpret. The pressure at the acceptor is about 1000 psi--more than an order of magnitude less than that required for shock initiation.

None of the detonation probes in the acceptor were triggered. All were recovered intact after the shot. The high speed photographs indicated a fireball proceeding along the conveyor. The fireball did not propagate over the entire acceptor length--it stopped about 20 feet from the end. The film also showed unreacted TNT and apparently undamaged conveyor material being thrown from the enclosure. After the shot, there was also considerable evidence that the acceptor did not detonate: (1) there was over 70 feet of conveyor material remaining intact; (2) there was a crater running the length of the donor, none under the acceptor; (3) unreacted TNT was recovered; and (4) a large portion of the structure remained intact.

Figures 12 and 13 are series of photographs of the post-test conditions. There was some burning of the acceptor TNT; however, it quickly extinguished itself. This is evidenced by the discolored area on the ground around the acceptor.

SUMMARY

It should be remembered that the purpose of this test was not to prove that flaked TNT in the McAlester conveyor configuration would not detonate; rather, the test was designed to show the consequence of such a detonation on adjacent TNT increments. The NWC tests had already demonstrated that flaked TNT could be initiated. The current test arrangement was designed to provide an initiation of sufficient energy input to cause complete detonation of the donor charges. This test demonstrated that even with the full detonation of the donor charge, the acceptor did not detonate.

To achieve full detonation of the donor increment a very high energy input was required. A shock from 117 grams of DETA SHEET explosives (approximately a 300 kilojoule pulse) was utilized. This energy level is significantly higher than those attainable in normal handling accidents--crushing, pinching, etc.

The effects on adjacent conveyors were not addressed in this study. Based on the results of this and the NWC study, such effects should now be easily calculable.

This work has been reported in more detail in Reference 6.

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2. Hunt, R. G. and Groce, T. A., "Evaluation of Fire or Explosion Propagation on the "A" Plant Explosive Delivery Conveyors," Hercules Aerospace Division, Report No. A08338-520-03-041, Hercules No. 82-3, Jan 1982.

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4. Dobratz, B. M., "LLNL Explosives Handbook - Properties of Chemical Explosives and Explosive Simulants," UCRL 52997, 16 Mar 1981.

5. Porzel, F. B., "An Introduction to the Unified Theory of Explosions," NOL TR 72-209.

6. Swisdak, Jr., M. M. and Peckham, P. J., "Reaction Propagation Along an Enclosed Conveyor," NSWC TR 83-8, 5 Dec 1982.

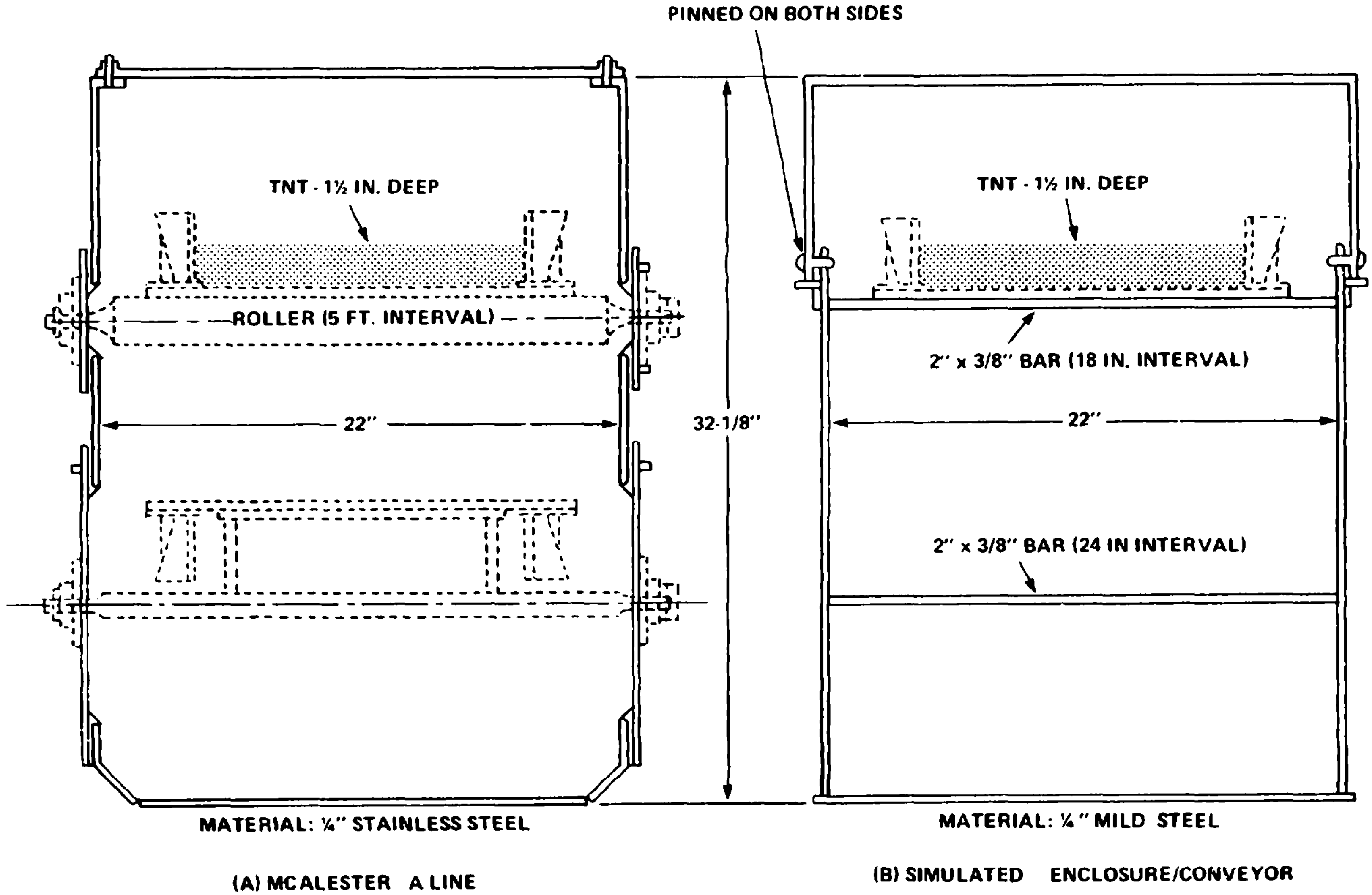


FIGURE 1. COMPARISON OF CONVEYOR CROSS SECTIONS

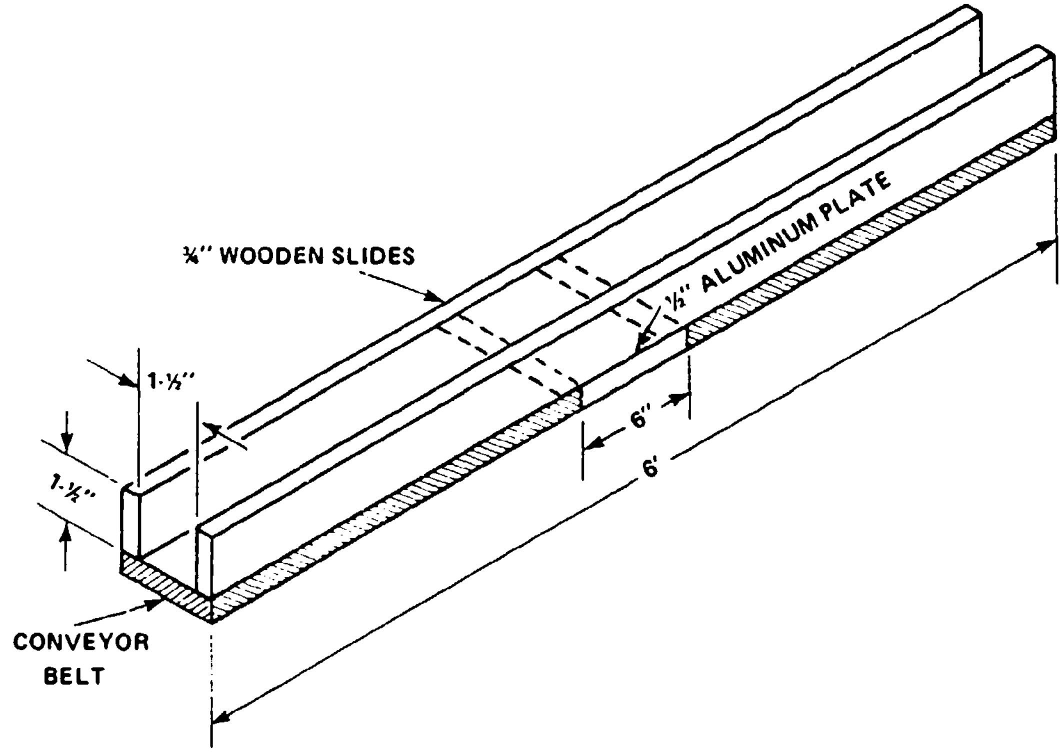


FIGURE 2. TROUGH USED FOR SMALL SCALE DETONATION TESTS

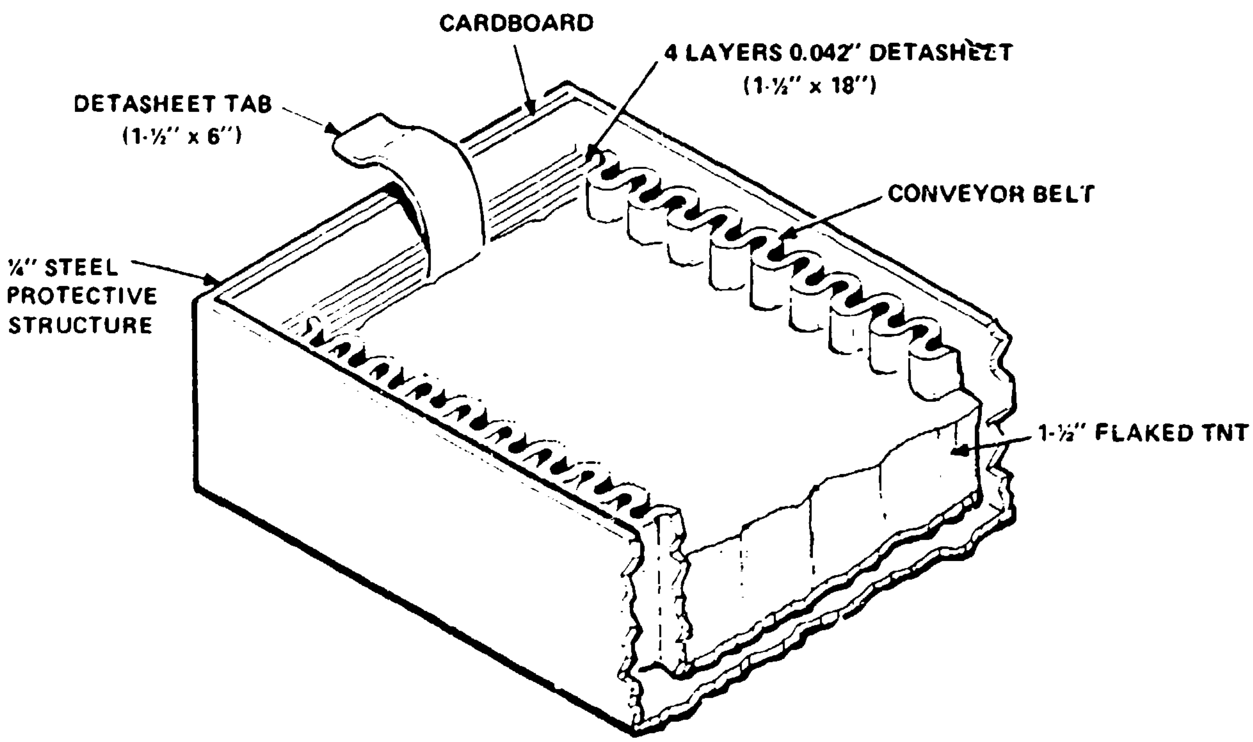


FIGURE 3. INITIATION SYSTEM USED IN CONVEYOR TEST

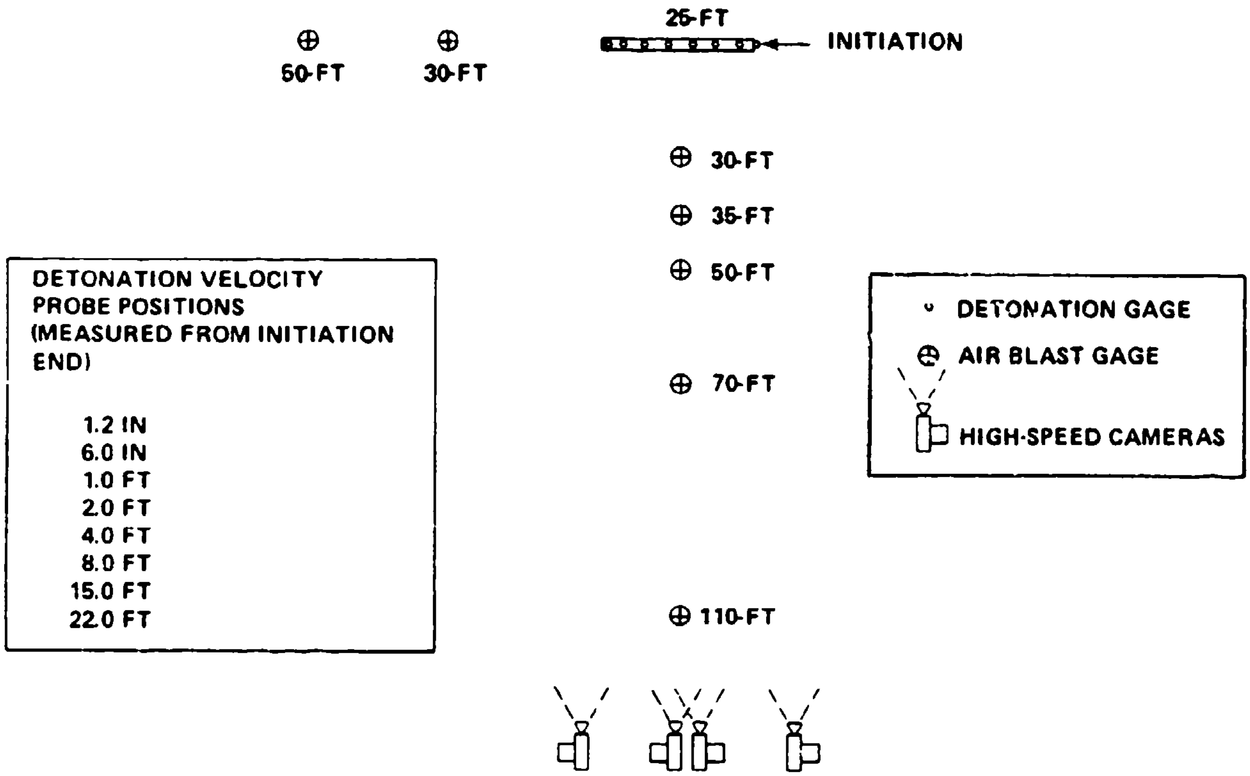
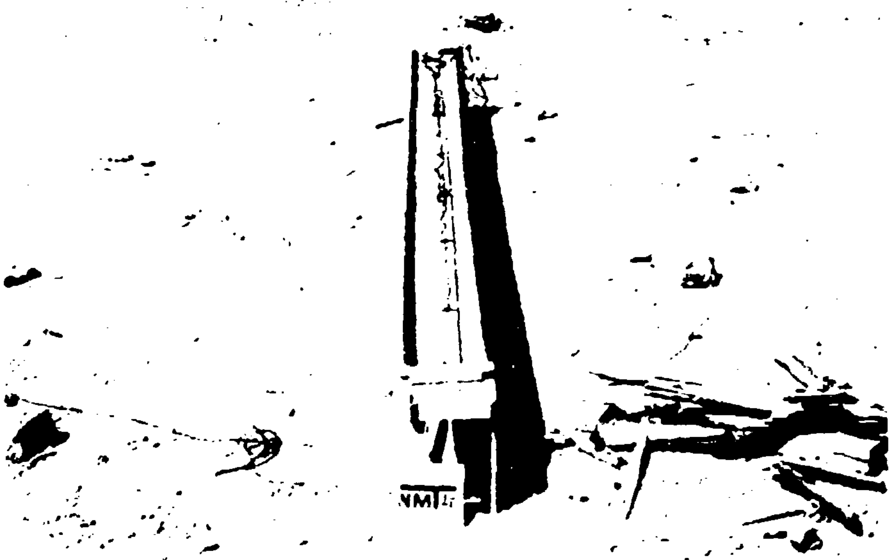


FIGURE 4. TEST SETUP FOR CALIBRATION TEST

(820722MS13)



(820722MS9)

FIGURE 5. PRE-TEST OF CALIBRATION SHOT

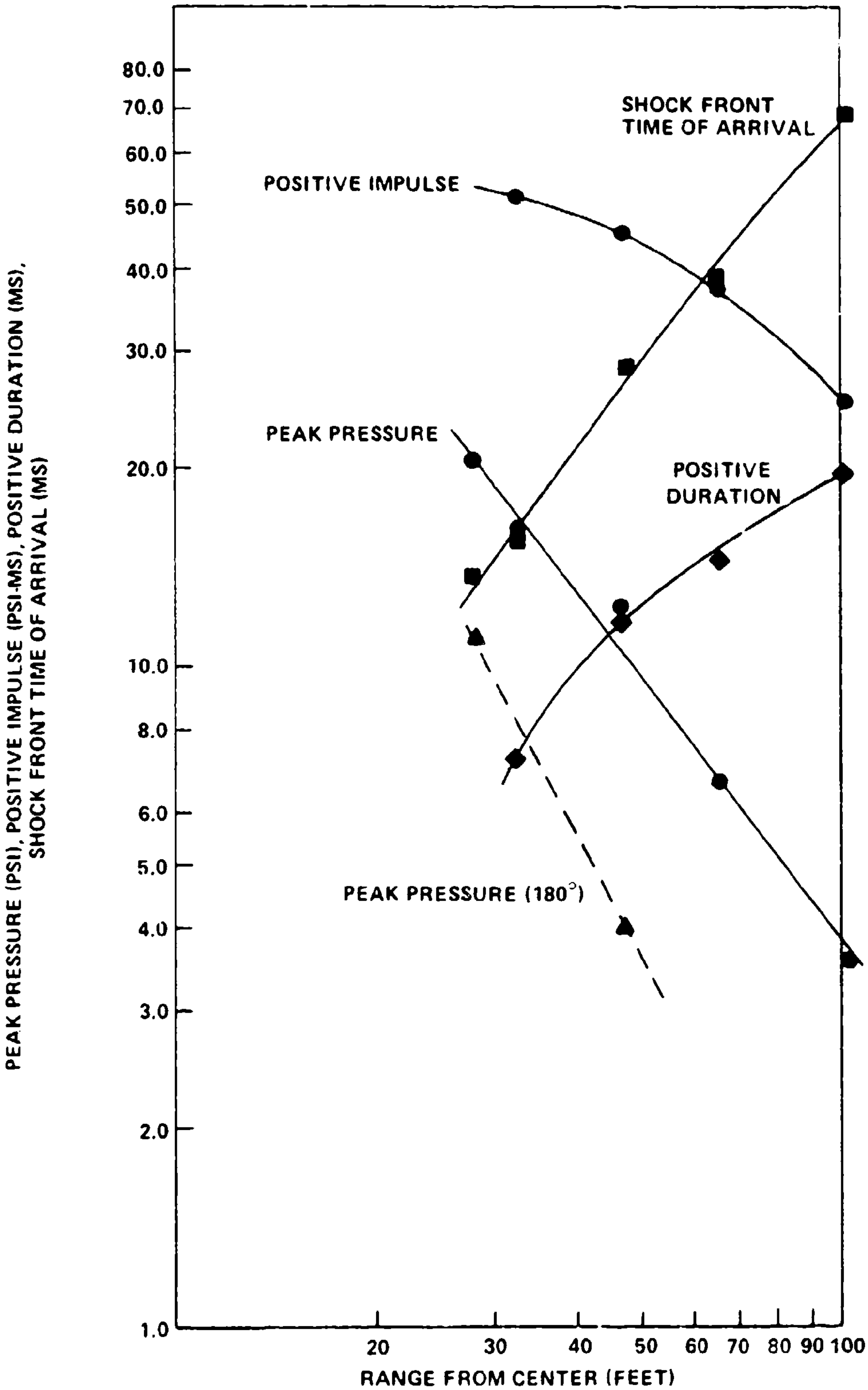


FIGURE 6. AIRBLAST PARAMETERS MEASURED ON CALIBRATION SHOT (SCALED TO SEA LEVEL)

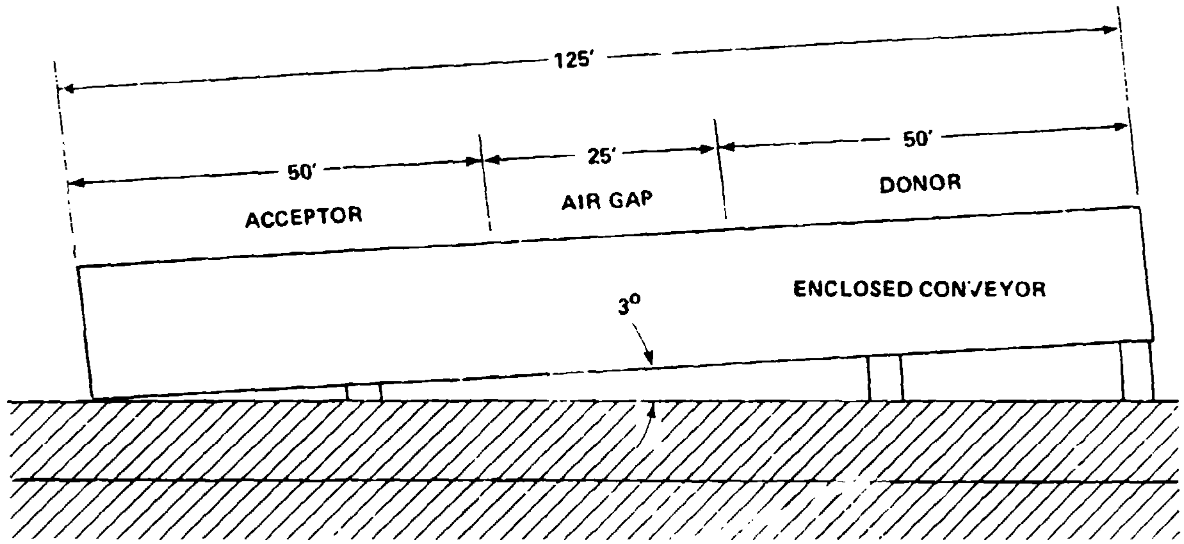
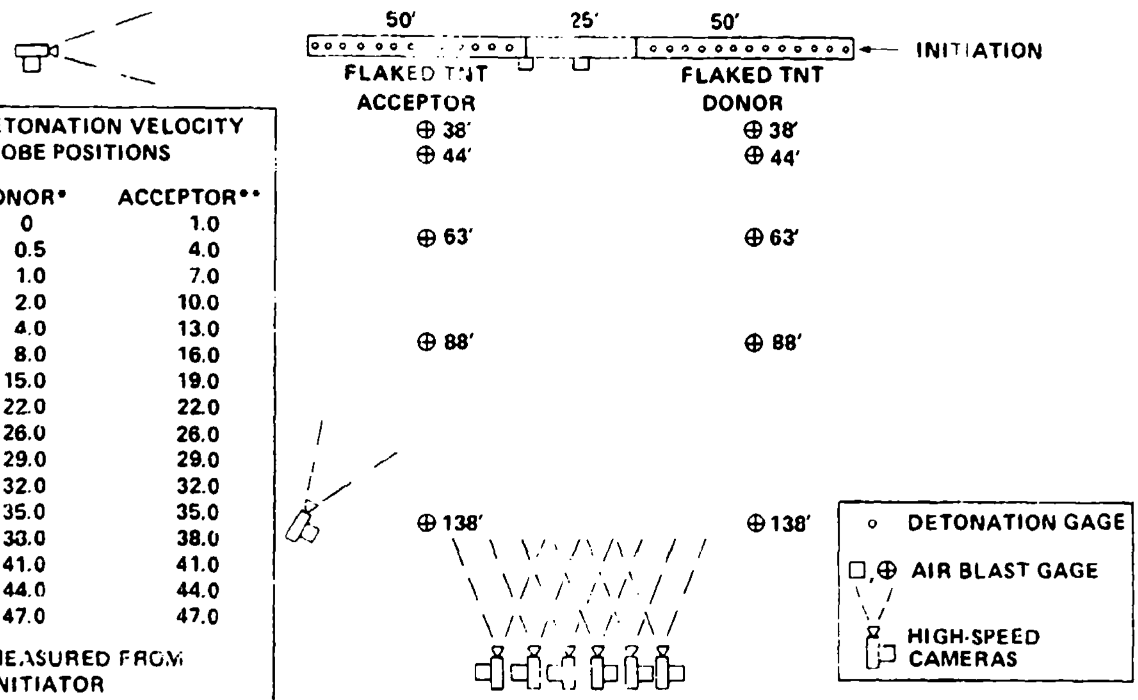


FIGURE 7. CONVEYOR SETUP



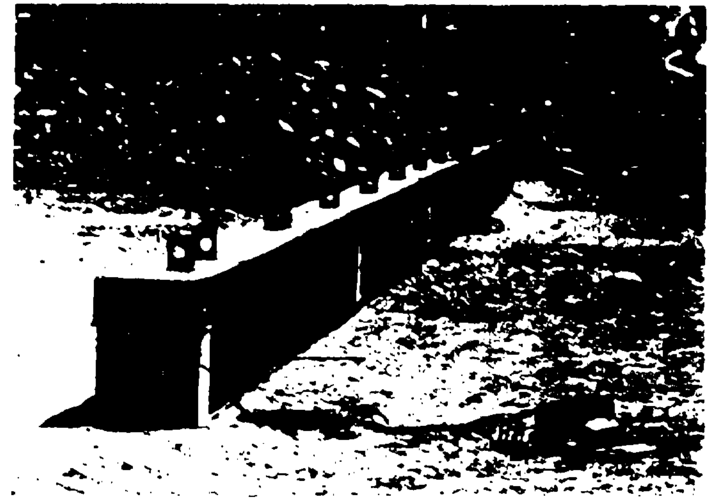
DETONATION VELOCITY PROBE POSITIONS

DONOR*	ACCEPTOR**
0	1.0
0.5	4.0
1.0	7.0
2.0	10.0
4.0	13.0
8.0	16.0
15.0	19.0
22.0	22.0
26.0	26.0
29.0	29.0
32.0	32.0
35.0	35.0
38.0	38.0
41.0	41.0
44.0	44.0
47.0	47.0

*MEASURED FROM INITIATOR
**MEASURED FROM START OF ACCEPTOR

FIGURE 8. TEST SETUP FOR CONVEYOR TEST

(820723MS7)



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(820723MS5)

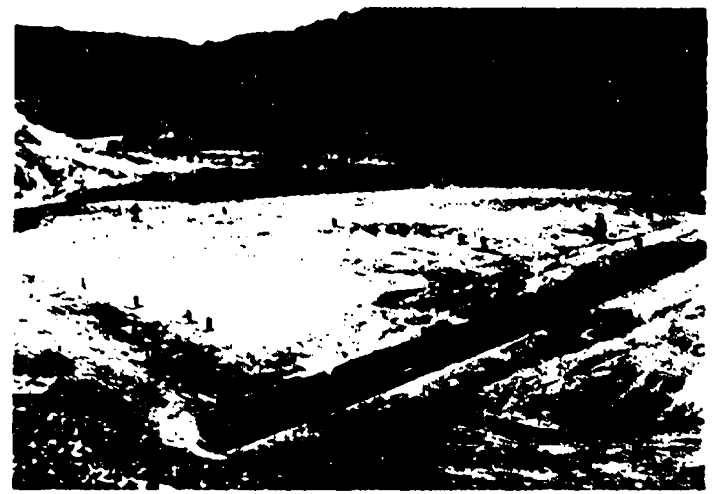

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FIGURE 9. PRE-TEST FIELD ARRANGEMENT

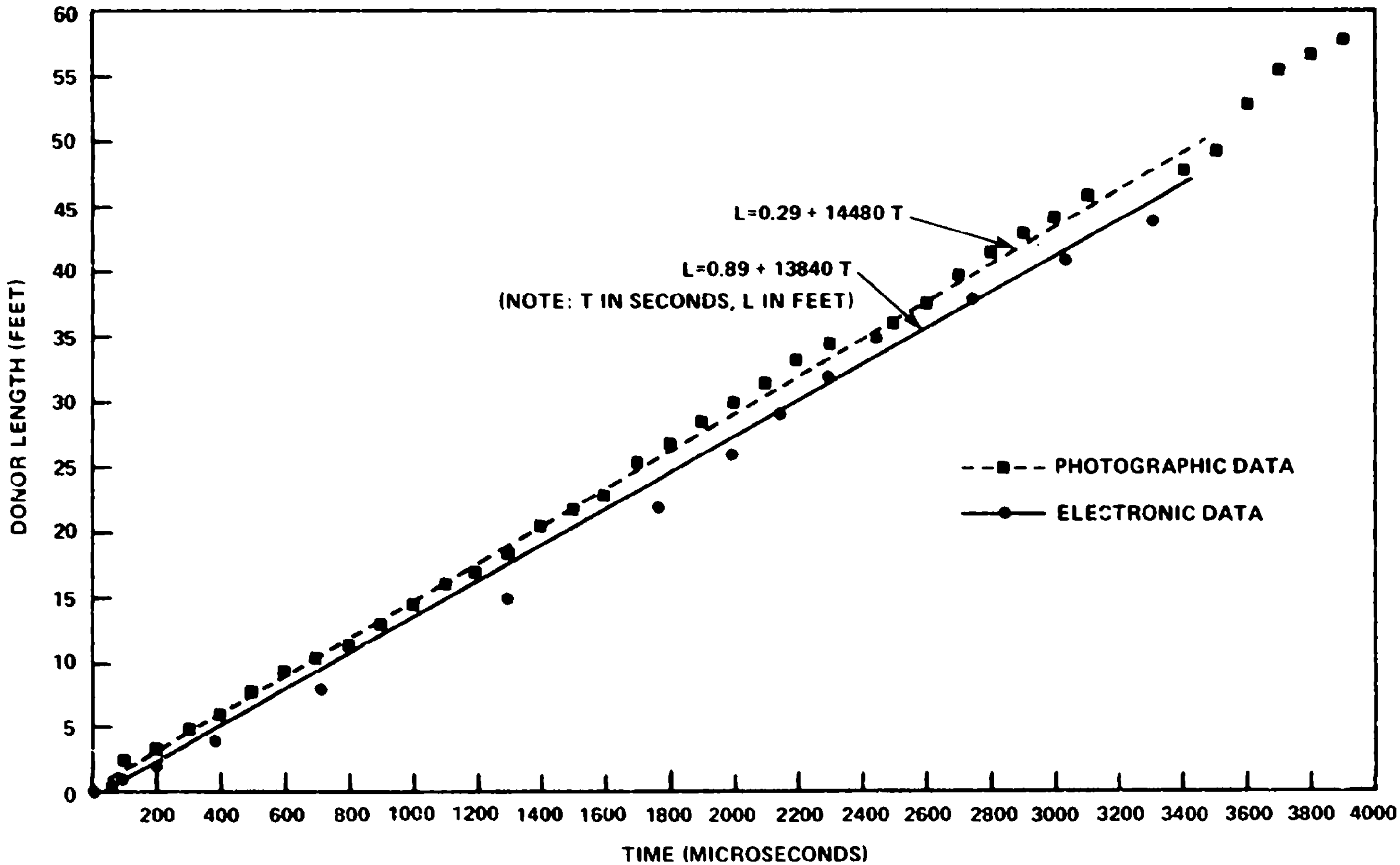


FIGURE 10. SHOCK FRONT POSITION-TIME (ENCLOSED CONVEYOR)

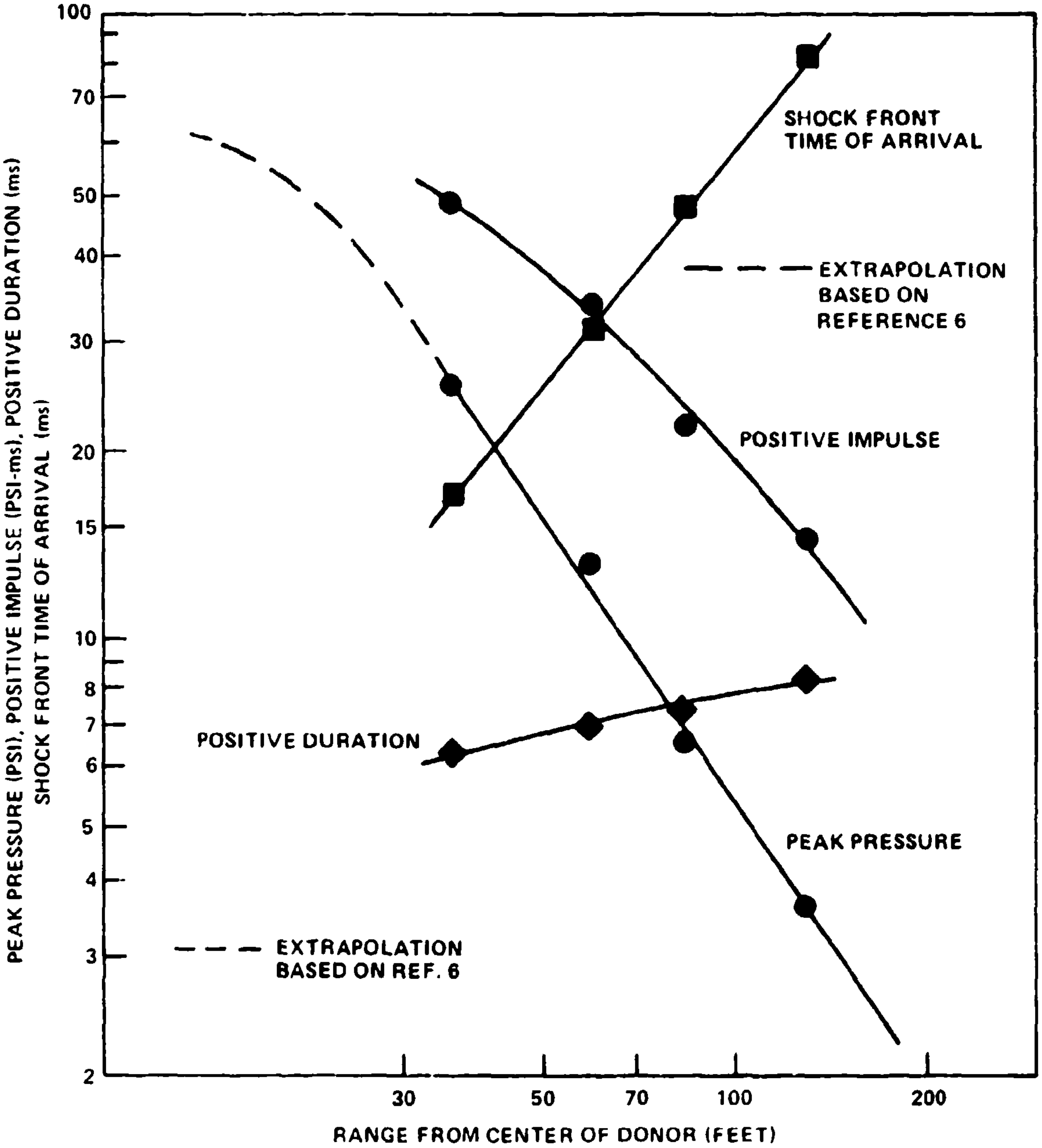
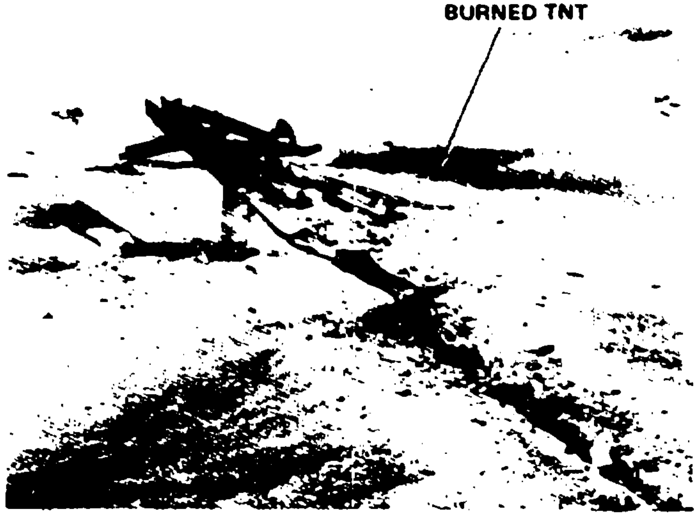


FIGURE 11. [illegible]BLAST PARAMETERS MEASURED FROM ENCLOSED CONVEYOR

(820723MS11)

(820723MS23)



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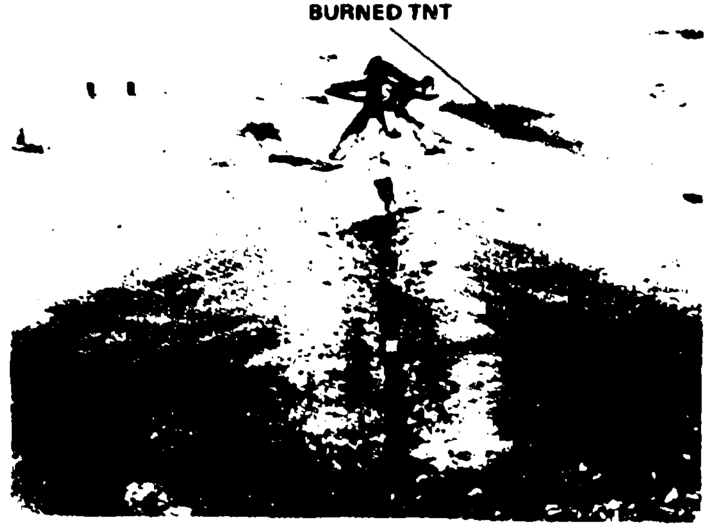

(820723MS10)

FIGURE 12. POST TEST RESULTS


(820723MS20)


(820723MS17)

(820723MS19)

FIGURE 13. POST TEST RESULTS

SOME EXPERIMENTS WITH 155 MM SHELLS AND DRAGON-MISSILES TO PREVENT A MASSDETONATION IN PALLETIZED STORAGE

by

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ABSTRACT

This paper describes the effects of appropriate shielding material with the aim to get a non-massdetonating reaction between 155 mm Artillery Shells on pallets and also between DRAGON-missiles packed in steel-containers on pallets.

As shielding material millboard-tubes around the shells and foamed polyurethan around the DRAGON-warheads was chosen and gave efficient solutions.

The results are described and documented with two typical photos from the 25 slide series presented at the Seminar.

Paper presented to the 21st DoD Explosives Safety Seminar, held at the Hyatt-Regency Hotel, Houston TX, 28 - 30 August 1984

A significant point of interest in the problems of ammunition storage is wether or not the storagetype will be of the UN-class 1.1

In the present manner of storage of the 155 mm shells and the DRAGON missiles they are both of the UN-class 1.1. Since storage room is expensive and not available in the scale as desired, we have to look for methods to obtain a non-massdetonating storage.

A US patent from Philip M. Howe[1]) gave us the idea how this problem could be solved.

The theory shows that when the diameter of a detonating shell has increased by ca. 20 %, the shell mantle is not entirely fragmented and an impact is approximately equivalent to a plate impact. A protective shield at this position has its best withstand and effect. Ph. Howe used as shieldmaterial Polyurethane and Polyethylen.

Without repeating all thoughts around this material, we started in Switzerland with cardboard or rather with millboard-tubes with an inner diameter of 183 mm and a wallthickness of 20 mm which were placed over the shells. Three acceptors were placed around a donor in three different distances (0; 25; 55 mm). The narrow ones detonated in a low order. The remotest was mechanically broken up.

---

1) US Patent 4 222 484, Sep 16, 1980
Antipropagation explosive packaging.....
by Philip M. Howe

A second set up used 5 shells with a millboard-tube with an inner diameter of 160 mm and 20 mm wallthickness.

The result was encouraging and we set up a "stack" of 9 shells. We did not find a prove of our conclusion. The effect of the confinement of the stack is more important then we thought.

The next set up was the same (9 shells) but with the millboard-tube with the inner diameter of 183 mm and 20 mm wallthickness. At the same time we tested the reaction to a second level of pallet. The result was very much satisfying. One shell of the bottom layer staid complete, the others detonated in a low order. The shells of the upper layer were thrown away.

In a second test series we tried to reach smaller tube diameters and wallthicknesses. We use again the set up of 3 x 3 shells. The inner diameter were now 173 mm and the wallthickness 12 mm. The result showed not for sure a non-massdetonating-behavior.

So we increased the wallthickness to 15 mm. 4 shells remaind complete and the rest detonated in a low order. To verify this result two other shots in the same configuration were made with the same result.

So we are able to say, that a palletized storage of 155 mm shells with a millboard-tube with an inner diameter of 173 mm and a wall-thickness of 15 mm, as non-massdetonating is possible.

Fig. 1 Typical set-up for propagation-test with millboard-tubes

Fig. 2 Final result with millboard-tube as a propagation shield (same view as Fig. 1)

The antitank missile DRAGON was another ammunition sort which is classified as mass-detonating.

The same interest was set to this ammunition to find a possibility to obtain the non-massdetonating storage.

The shipping container for the DRAGON is different to the US-one. It consists of a cylindric sealed metal container. The launcher is centered with 2 polyurethan-rings.

We were led by the 155 mm shell-tests and applied also the mill-board-tube as a barrier. The result was not as good as with the 155 mm shells.

Since Philip Howe speaks in his patent of foamed material, we tested the given material of the center-rings. We placed 5 such rings at the location of the warhead.

The result was very surprising. It seamed that no propagation took place. So far we used mainly two rounds, 1 donor and 1 acceptor, for the test.

To verify we built up a part of a 6 missiles-stack. There were 3 containers on the floor and at one end 1 container was placed above the other. This one (in the upper layer) was the donor.

The result was really impressive. The remotest missile was only mechanically damaged by blast and fragments. The two others detonated in a low order and burned out.

SUPPRESSION OF SYMPATHETIC DETONATION

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Michael E. Gunger

Bobby G. Craig

Gary H. Parsons

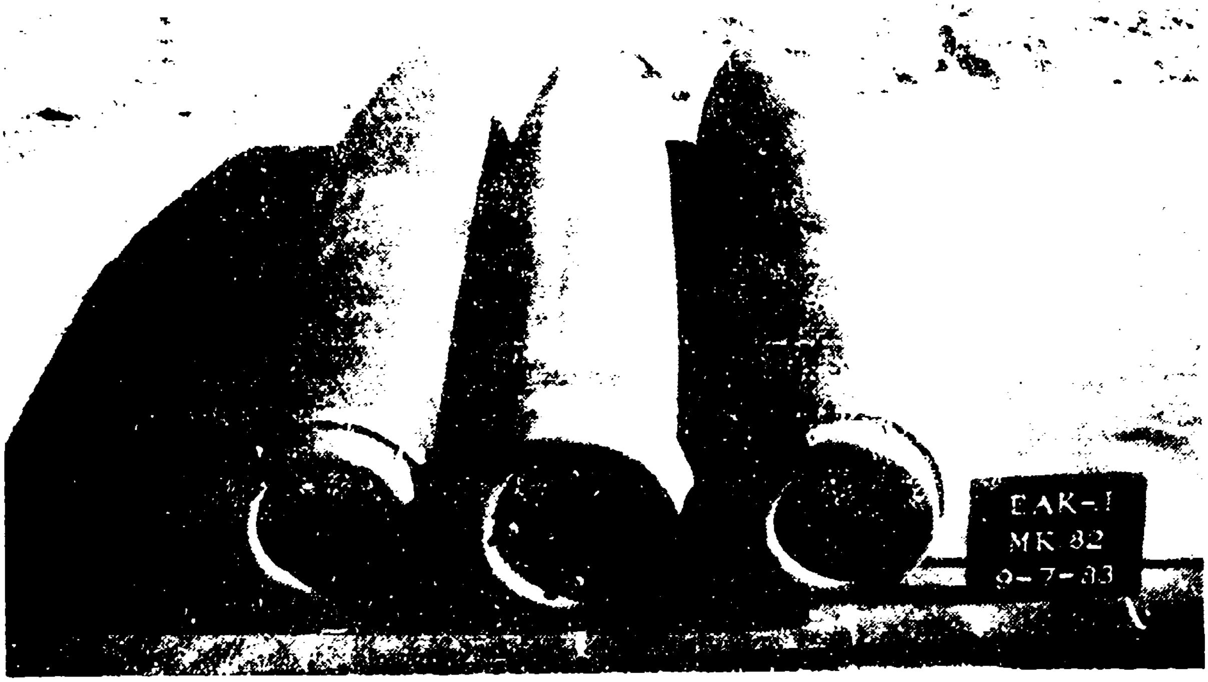
SECTION I

INTRODUCTION

In 1982, the Air Force Armament Laboratory undertook the development of an insensitive high explosive (IHE) for general purpose bombs. IHE is defined through a series of tests which reveal the explosive response to thermal, mechanical, and shock stimuli. A critical test for IHE-filled bombs requires that sympathetic detonation will not occur under normal storage configurations when a single bomb is intentionally detonated. The present pallet configuration virtually assures that sympathetic detonation between MK-80 series bombs loaded with tritonal will occur due to the close proximity of the rounds. Thus, a task was undertaken to decide how sympathetic detonation could be suppressed through either the use of barrier materials between bombs and/or the use of an alternate fill which is less sensitive than tritonal to the stimuli associated with sympathetic detonation.

During September 1983, a series of tests was conducted to observe how MK-82 bombs filled with an Air Force candidate IHE would respond to the detonation of a tritonal-filled donor (Figure 1). These experiments were conducted as a baseline and have come to be known as the "first point". The candidate IHE is called EAK, it consists of 46% ethylenediamine dinitrate, 46% ammonium nitrate, and 8% potassium nitrate. Simple expedient techniques, such as the insertion of flat plate separators, were tried to suppress sympathetic detonation (Figure 2). They were not successful. Figure 3 shows the damage done to an armor witness plate by the EAK-filled acceptor. Plate damage is characteristic of a detonation.

Following the September 1983 experiments, a series of calculations were undertaken to understand the processes involved in the sympathetic detonation phenomena. The calculational approach to the problem prohibited the


EAK-1
MK 82
9-7-83

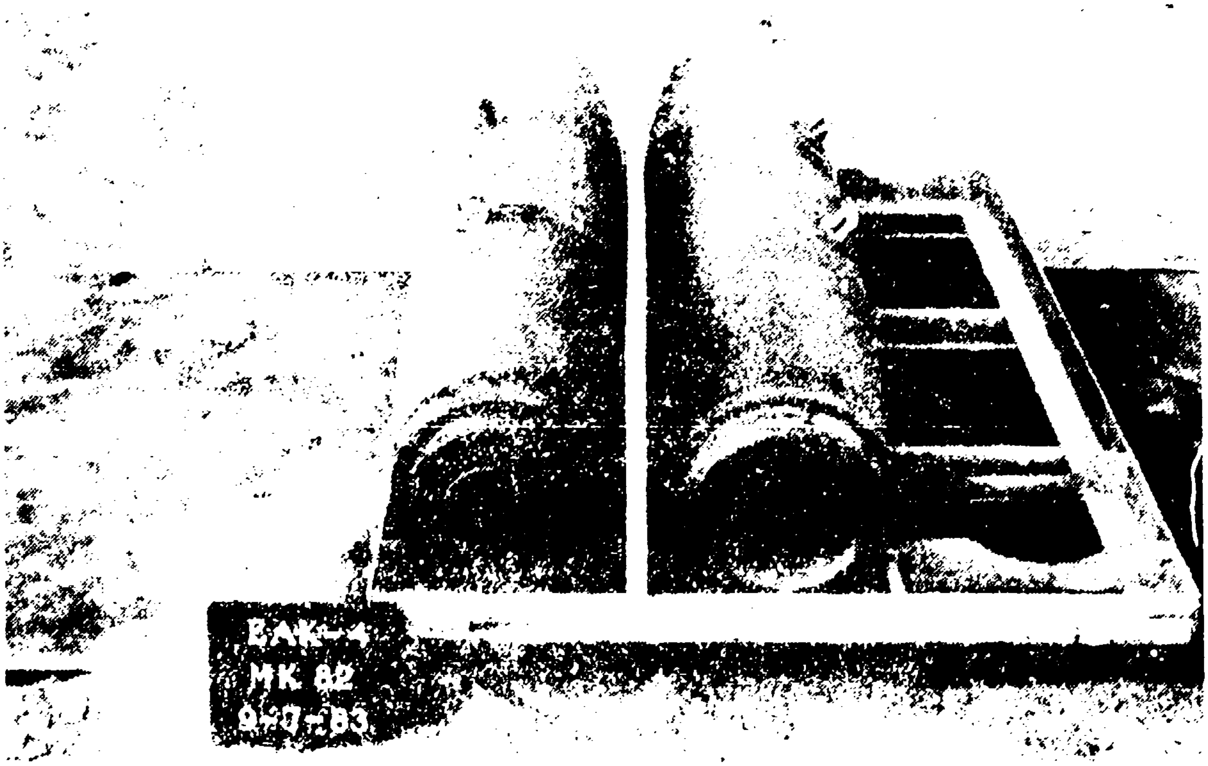

EAK-4
MK 82
9-7-83

Figure 3. Witness Plate Under EAK Acceptor

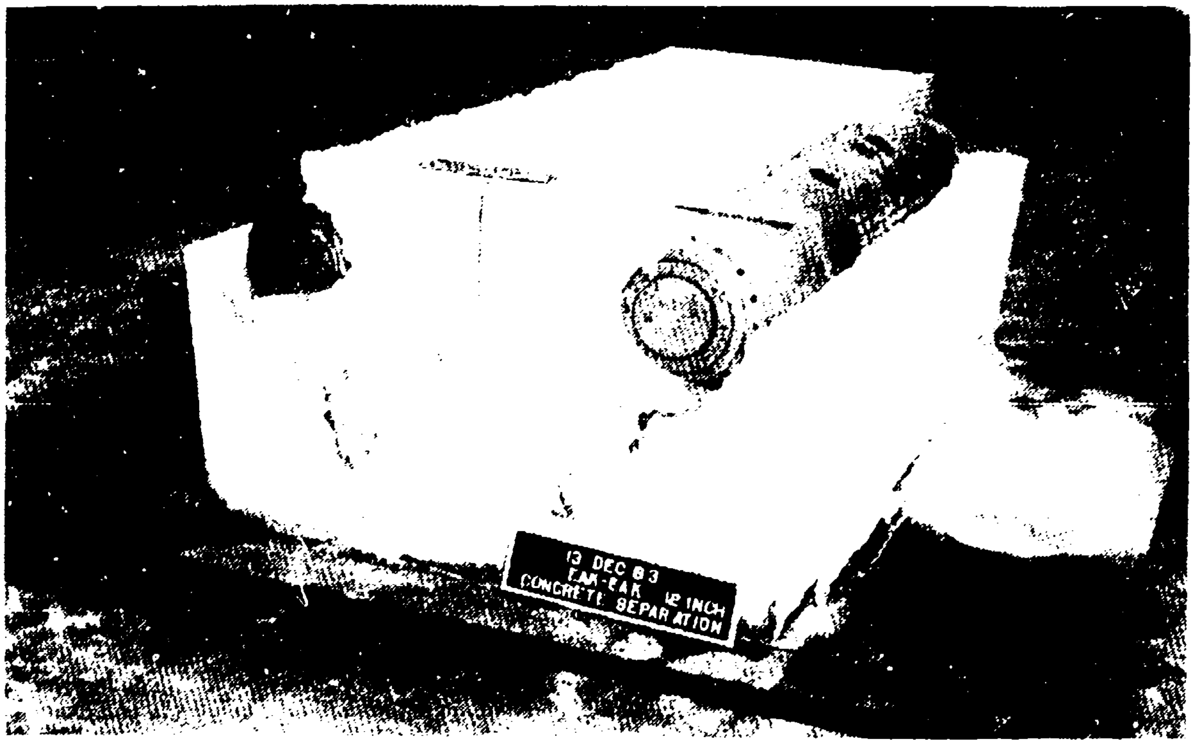


Figure 4. Experimental Set-Up for Controlled Propagation Tests

prediction of the degree of reaction in the experiment because the codes used do not calculate initiation and run up characteristics of explosives. Extensive research is required to execute this type of calculation with confidence. Rather, the approach used in the analysis of the calculations was the identification of the mechanical processes which transport energy from the donor bomb to the acceptor bomb. These processes are characterized as (a) flyer plate mode, (b) pure shock transmission, (c) mechanical distortion, and (d) fragment penetration. The primary difference between (a) and (d) is the distance between the items. As an indication of the relative efficiency of some of the processes, Table 1 lists the transmitted shock pulse through various 0.75-inch buffer materials. While air is not an efficient medium for shock propagation, it does allow large energy transfers by means of the flyer plate mode. Thus, the flyer plate mode would be characterized as very efficient when compared to shock transmission. Table 1 illustrates that peak shock pressure transmission for rounds in contact is about 60 Kbar, while rounds separated by an air space transmit almost three times the peak pressure due to impact of the donor case wall against the acceptor.

Next, a series of experiments were designed in an attempt to identify the relative importance and the critical levels associated with these processes. First, experiments were designed to determine the "second point"; that is the separation distance at which sympathetic detonation will not occur. Concrete was used to provide a conformal barrier between the donor and acceptor to insure that flyer plate or fragment impact mechanics would not be confused with shock transmission. Figure 4 illustrates the experimental set-up. Tritonal- and EAK-filled MK-82 bombs were evaluated as both donors and acceptors. Instrumentation included blast gauges, witness plates, and high speed photography (Figure 5). Tritonal-filled acceptors detonated at a spacing of

TABLE 1. RESULTS OF CALCULATED MATERIALS

Material	ρ	Co	$Z = \rho c$	Y	P	B
Air	1.225×10^{-3}	3.38×10^{4}	41	0	200×10^{9}	1.54×10^{10}
RHA	7.86	4.61×10^{5}	3.62×10^{6}	15×10^{9}	62.2×10^{9}	5.85×10^{9}
Pb	11.34	2.09×10^{5}	2.37×10^{6}	0.3×10^{9}	60.3×10^{9}	6.14×10^{9}
DU	19.05	2.48×10^{5}	4.72×10^{6}	15×10^{9}	54.0×10^{9}	3.23×10^{9}
Al	2.71	5.38×10^{5}	1.46×10^{6}	2.9×10^{9}	64.0×10^{9}	5.37×10^{9}
Ceramic	3.90	6.90×10^{5}	2.69×10^{6}	80×10^{9}	64.0×10^{9}	5.84×10^{9}
Nylon	1.14	2.29×10^{5}	2.61×10^{5}	0.5×10^{9}	70.0×10^{9}	3.44×10^{9}
Sand Contact	1.6	6.1×10^{4}	9.76×10^{9}	1.0	91.98×10^{9}	7.75×10^{9}
Sand Buried	1.5	6.1×10^{4}	9.76×10^{4}	1.0	126.32×10^{9}	9.99×10^{9}
RHA/Ceramic/ RHA	N/A	N/A	N/A	N/A	59.83×10^{9}	[illegible]

Figure 5. Instrumentation for Propagation Tests
(a) Photographic View

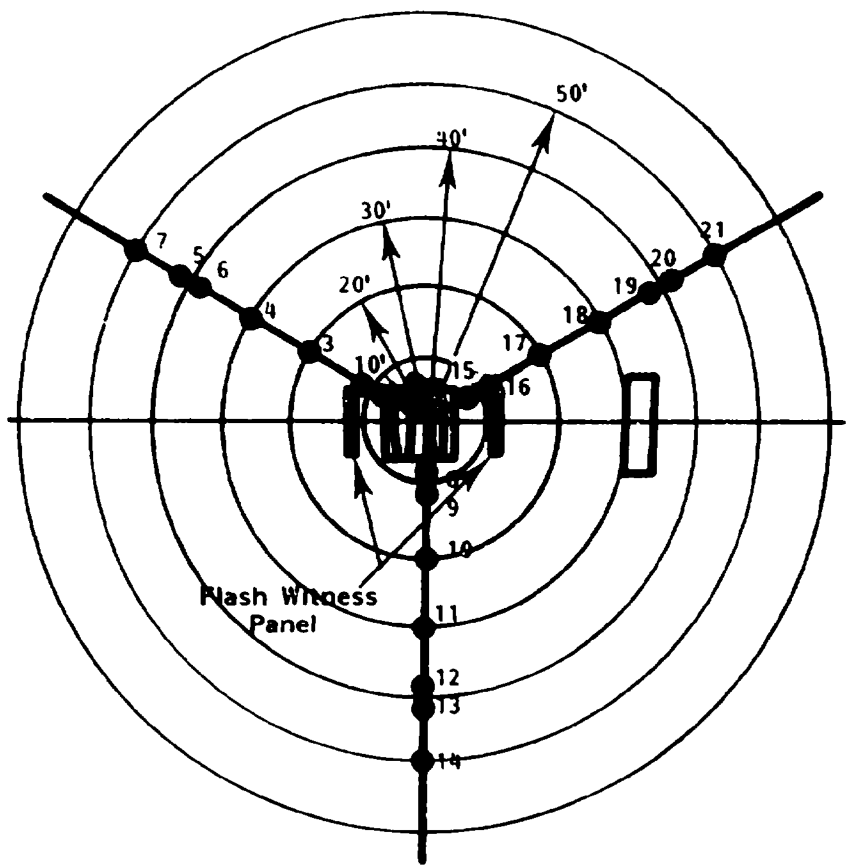


Figure 5. Instrumentation for Propagation Tests
(b) Arena Diagram

8 inches and showed essentially no explosive reaction at 12 inches. The bomb casing from the 12-inch experiment was recovered as a single piece with low pressure rupture. Acceptors filled with EAK explosive did not show a clear go/no go response. The violence of response of EAK-filled acceptors was a function of the pressure transmitted into the acceptor. Surprisingly, unreacted explosive was recovered even under conditions where the donor and acceptor were separated by only 3 inches. When a second EAK-filled acceptor in a donor/acceptor/acceptor configuration was added to the experiment, it also reacted violently leading us to conclude that these "partial detonations" produced high pressure. The principal conclusions from this series were: (1) Clarification of the unusual initiation behavior of EAK was essential; (2) MK-82 bombs are poor candidates for controlled experimental evaluation; and (3) EAK and tritonal behave markedly different when subjected to similar strength shocks.

SECTION II

SHOCK SENSITIVITY

Scaled experiments were designed to quantify the shock initiation process in EAK and tritonal and to evaluate materials which could be used as a barrier between the acceptor and donor. Figure 6 illustrates the hardware designed to measure shock sensitivity. It is basically a large scale gap test in which both donor and acceptor are encased in an 8-inch outside diameter by 0.5-inch wall steel pipe. Composition B donors, 8 inches long, were used to produce the transmitted shock. Acceptors were instrumented with time of arrival pins on 2-inch centers to measure shock velocity as a function of position in the acceptor. The completed test assembly was mounted on a 1-inch rolled homogeneous armor plate which served as a fragment witness. Plexiglas®, of varying thicknesses, and steel endplates were used to control

Figure [illegible]. Shock Sensitivity Set-Up Composition B Donor [illegible] Plexiglas Gap, and Acceptor Explosive the shock strength transmitted into the acceptor. Baseline experiments were conducted using concrete separator plate to establish comparability with the MK-82 experiments. Calculations were performed to describe input pressure as a function of gap thickness (Figure 8) and the pressure position profile of the transmitted shock (Figure 9) as a function of distance from the donor/Plexiglas® interface. The calculation to determine the pressure position profile was performed to enable clarification of the function of endplates in the role as shock attenuators. As can be seen, without endplates the pressure pulse decays rapidly until approximately 4 inches of Plexiglas® have been traversed, at which time an inflection point is reached and the decay is moderated. However, with endplates, the pressure decays much slower and, if an inflection point is reached, it occurs between zero and one inch. Also, the positive pulse duration of the transmitted pulse is longer with endplates than without endplates. To verify the predictive ability of the model, the standard Naval Ordnance Laboratory (NOL) gap test was also calculated. Figure 9 shows that our computer codes reproduce the pressure/distance profile for NOL gap test. Figure 6 shows the assembled experiment where donor and acceptor are separated by two 1/2-inch-thick endplates and 6 inches of Plexiglas®. The unusually large size of this gap test was selected to insure that experiments were well above the failure diameter of EAK and to better simulate the long duration shocks characteristic of sympathetic detonation in MK-82 bombs.

Table 2 lists the go/no go conditions for EAK and tritonal. EAK is slightly less sensitive to shock than tritonal since the go/no go spacing corresponds to about 14 Kbar. The go/no go pressure for tritonal is greater than 12 Kbar and less than 14 Kbar. These initiation pressures are far below the published values for tritonal (approximately 30 to 40 Kbar). Clearly

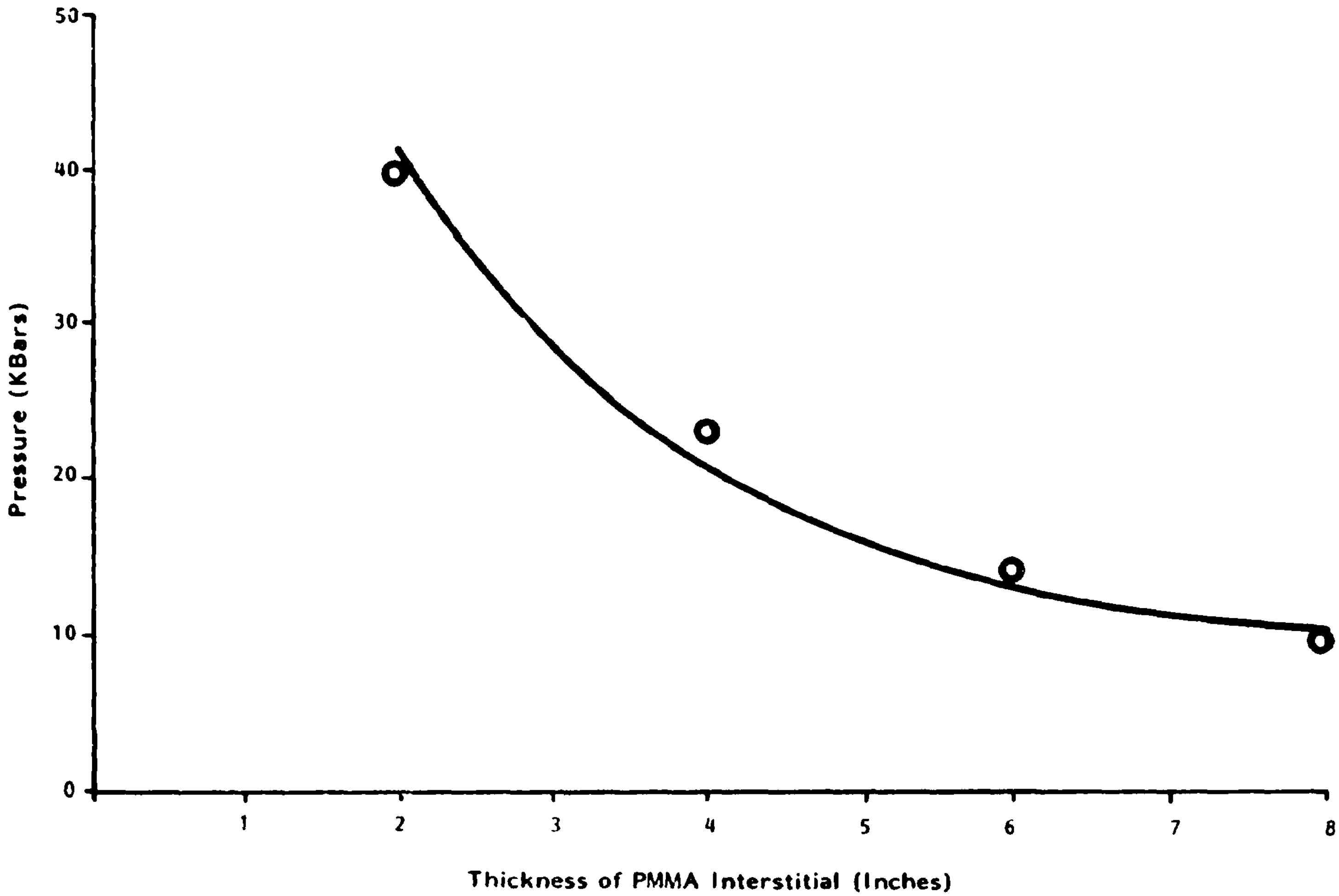


Figure 7. Centerline Pressure Pulse of EAK Acceptor ($\frac{1}{2}$" Into EAK) (Curve Calculated From $P={}^{K}/_{R}$)

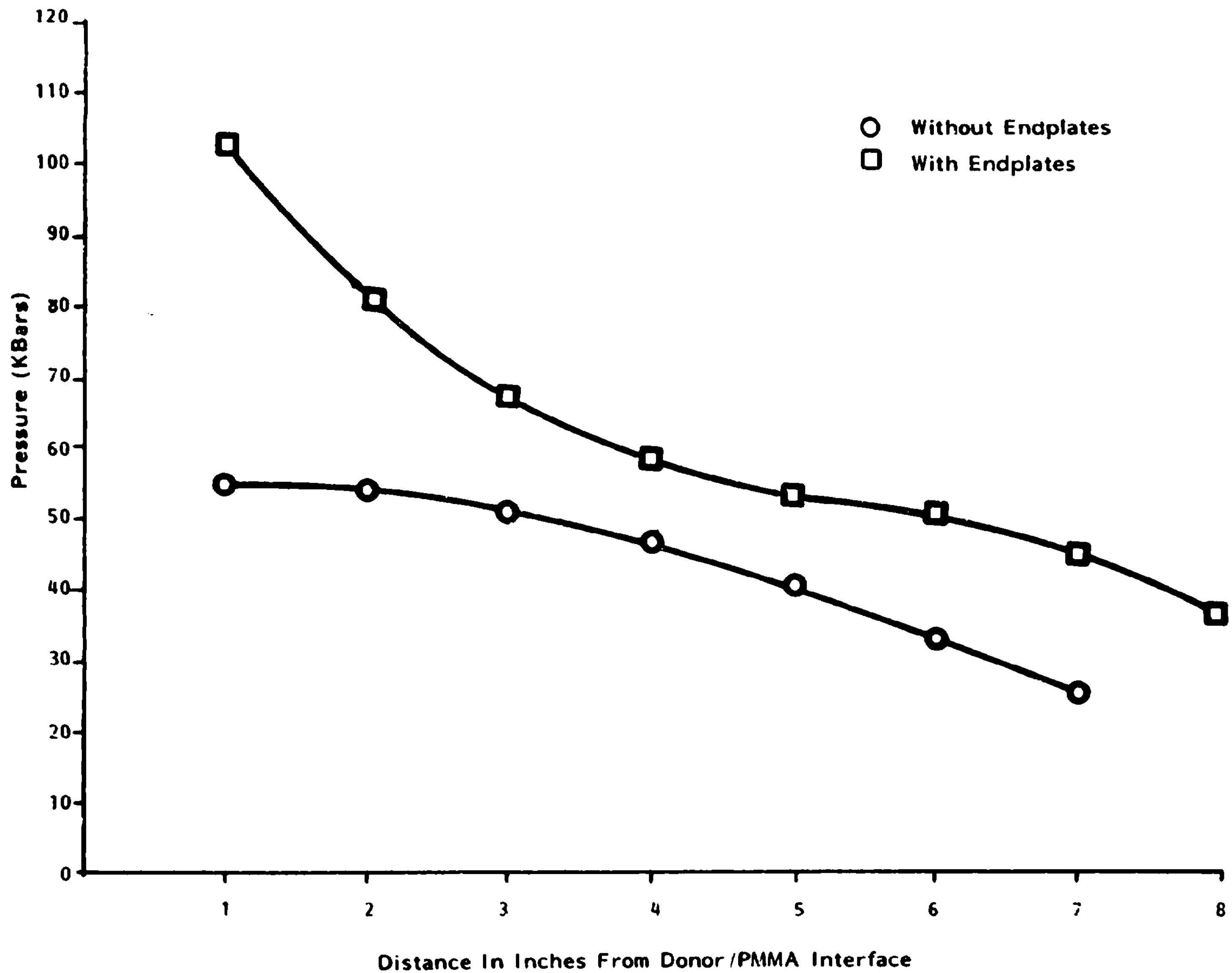


Figure 8. Influence of Endplates

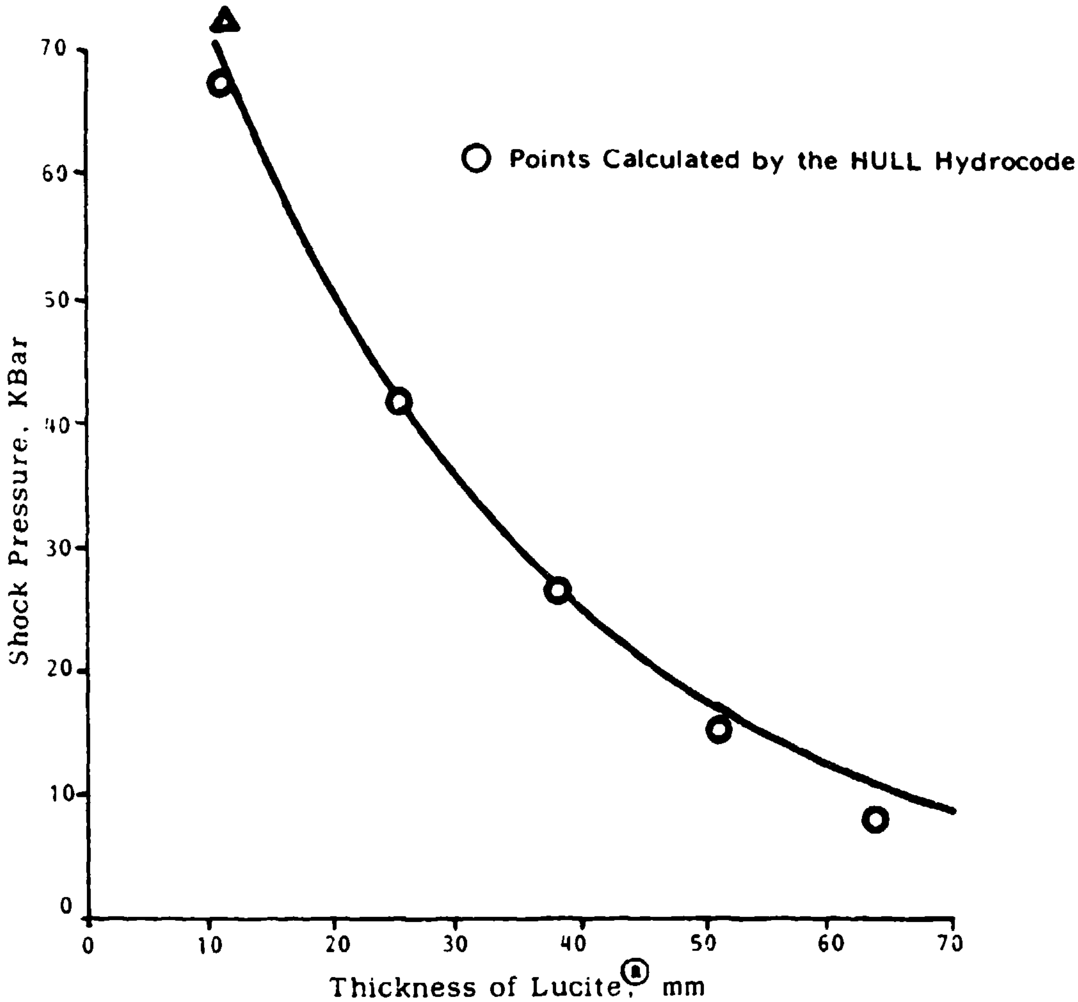


Figure 9. Shock Wave Pressure at the End of the Lucite® Gap in the NOL Gap Test

TABLE 2. GO/NO GO RESPONSE FOR VARIOUS EXPLOSIVES AT FIVE DIFFERENT THICKNESSES OF PLEXIGLAS® IN 8-INCH-DIAMETER GAP TEST

THICKNESS OF PLEXIGLAS®

2-inch	4-inch	6-inch	7-inch	8-inch
EAK 42-X	EAK 46-X	EAK 42-?	EAK 42-O	EAK 46-O
EAK 46-X	EAK/NQ-X	EAK 46-X	EAK 46-O	
EAK/NQ-X	TRI-X	EAK 50-X	EAK/NQ-O	
		EAK/NQ-O	TRI-O	
		TRI-X		

X - GO

O - NO GO

both amplitude and duration are important factors in initiation to detonation. Figure 10 shows shock velocity as a function of position in the EAK- and tritonal-filled acceptors. The very slow increase in velocity down the length of the cylinder for EAK was characteristic of this formula even when strong shocks were used as the initiator. On the other hand, tritonal quickly transitions to 6.9 km/sec.

It is believed that this difference in transition behavior accounts for variable reaction violence we observed in full-scale MK-82 bomb tests. The bomb diameter is small relative to the distance required to establish a high velocity detonation in EAK. Thus, increasing the input shock serves to increase the reaction velocity across the bomb and subsequent violence of the reaction. This conclusion is, in fact, supported by the fragment witness observed in the large scale gap tests. It suggests that EAK-filled rounds would not support sympathetic detonation as long as the very high pressures associated with case wall impact are not allowed to occur.

SECTION III
BARRIER DESIGN

Given that the shock sensitivity of the explosive has been defined, the second aspect of suppressing sympathetic detonation is that of attenuating or reducing transmitted shock and deflecting case wall fragments. Barriers between bombs are the most reasonable approach. Again the computer was used to evaluate a variety of materials. Figure 11 illustrates the computational layout, and Figure 12 gives the results. The calculation predicts peak pressure transmitted from a Composition B donor to the explosive fill in the acceptor. Figure 12 is a plot of peak pressures versus gap thickness recorded at Station 1 (see Figure 11). The length of the PMMA diverter remained constant (4 inches). The 0.5- and 1.0-inch airgaps were modeled between the

TABLE 3. ACCEPTOR RESPONSE TO VARIOUS BARRIER DESIGNS

TEST CONFIGURATION SUMMARY

TEST	DIVERTER t x W	DIVERTER Material	α (deg)	α′ (deg)	RESULTS
EAK 14	2" x 8"	Plexiglas®	14.48	14.0	NO GO
EAK 15	2" x 6"	Plexiglas®	16.60	14.0	NO GO
EAK 16	2" x 5"	Plexiglas®	17.92	14.0	NO GO
EAK 17	2" x 4"	Plexiglas®	19.47	14.0	NO GO
EAK 18	4" x 2"	Plexiglas®	23.58	26.57	GO
EAK 19	2 1/4" x 4"	Yellow Pine	19.47	15.71	NO GO
EAK 20	2" x 4"	Phenolic	19.47	14.0	NO GO
EAK 21	(1.) 3" x 1"	1020 Steel "H"	21.32	20.56	NO GO
	(2.) 1" x 1"	(1.) + (2.) + (3.)			
	(3.) 3" x 1"				

α = Included half-angle

α′ = Protection half-angle

Reference Figure 13.

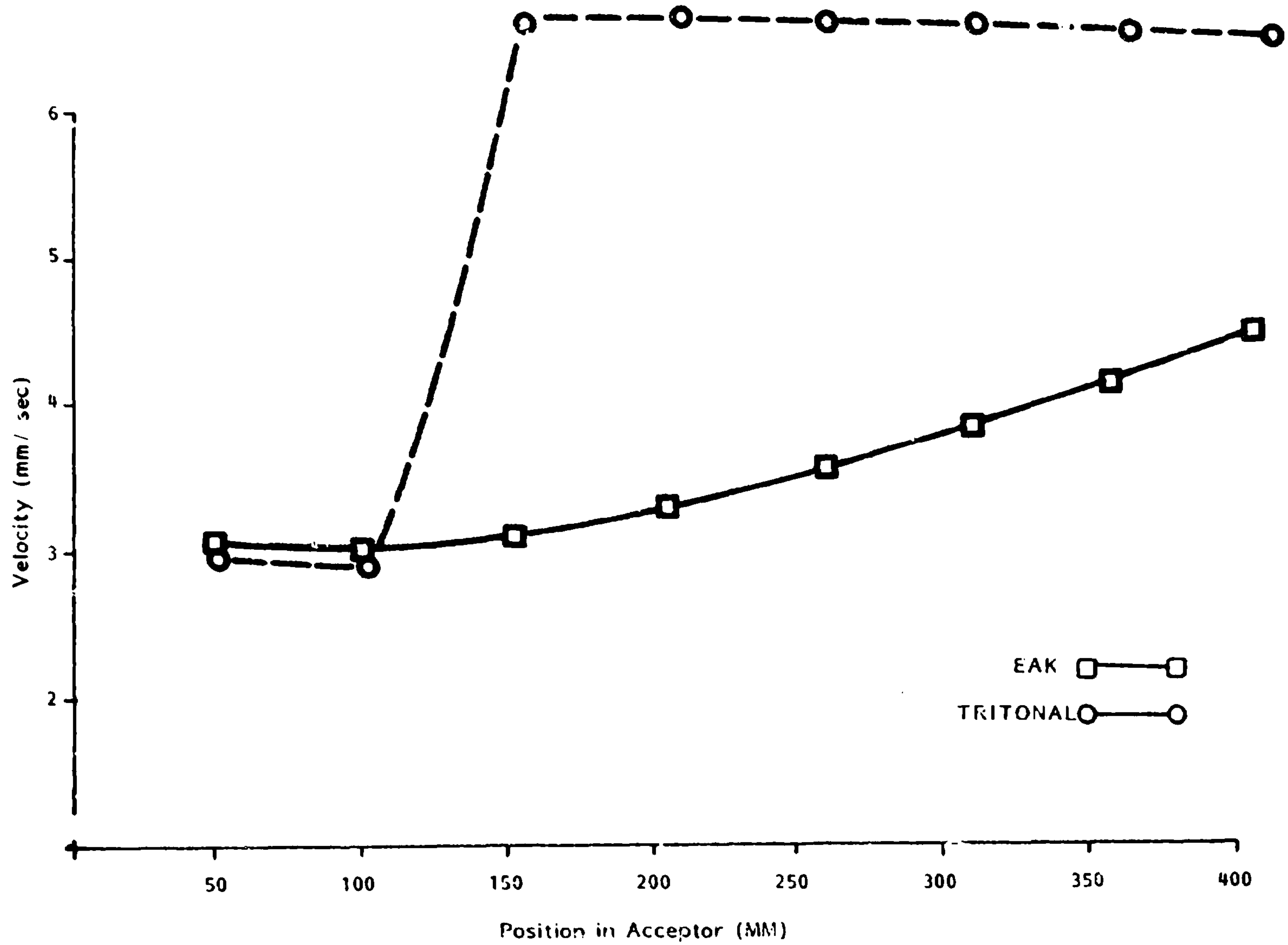


Figure 10. Shock Velocity for EAK and Tritonal With 14-KBar Input Pressure

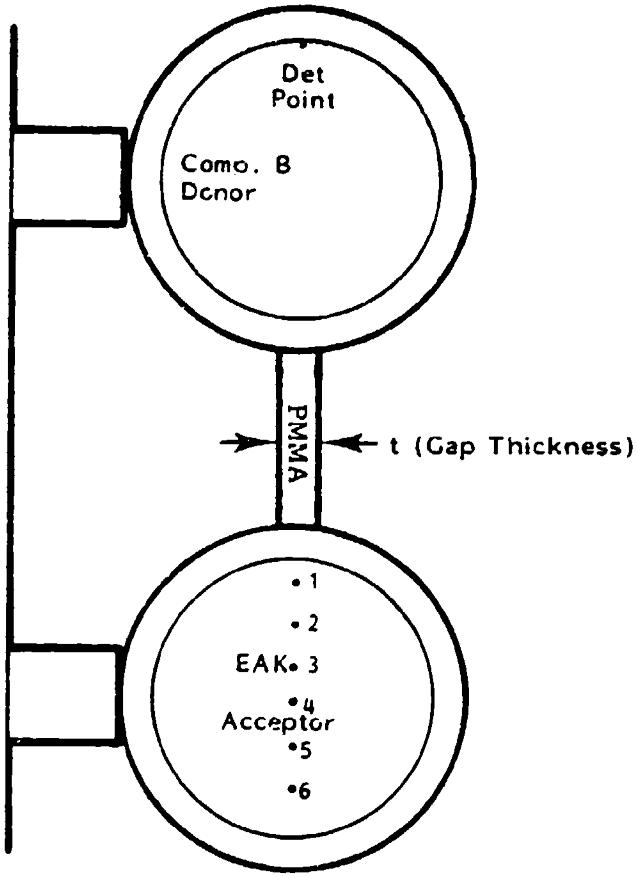


Figure 11. Computational Set-Up for Barrier Tests

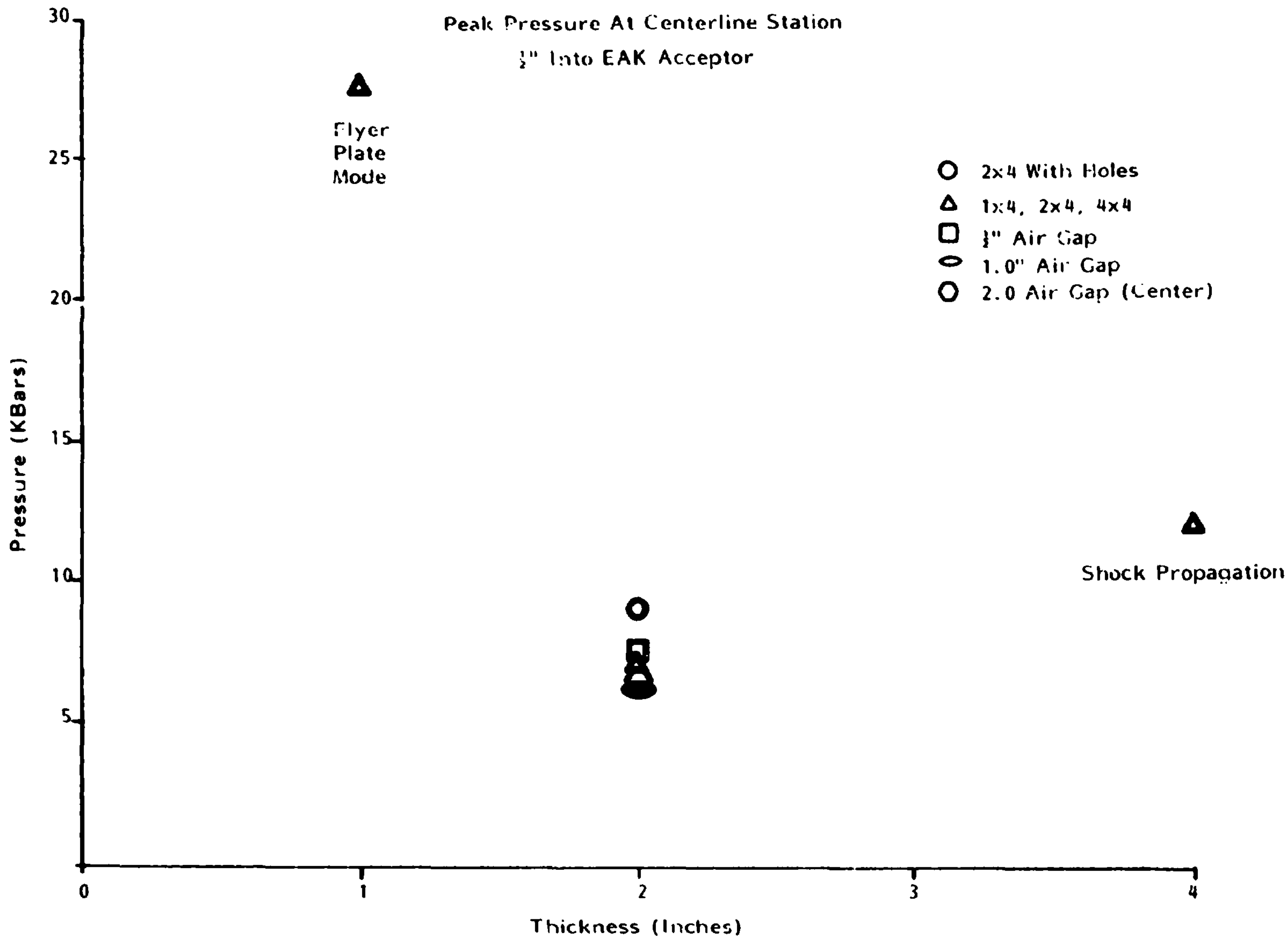


Figure 12. Peak Pressure Recorded at Station 1 in Figure 11 for Various Barrier Designs

diverter and acceptor/donor interface. The 2.0 airgap was modeled at the center of the PMMA diverter. The plot indicates that the 2 x 4 diverter allows the least combined flyer plate/shock transmission mode energy transfer to the acceptor. A number of materials were simulated using selection criteria such as density, sound speed, and strength. Differences between materials were not dramatic. Thus, for the experimental portion of this study plastic, wood, and steel were selected for the barriers. These were selected on the basis of cost, availability, and range density. Figure 13 shows the experimental design. The explosives were contained in the same type of cylinder used for the shock sensitivity tests except that the donor charge was now the same length as the acceptor charges. Again, Composition B was used in the donor. Figure 14 is a typical experimental set-up used in this test series. The width of the barrier determines the transmitted shock from donor to acceptor while the thickness provides protection from donor case fragments; minimizing the thickness consistent with sufficient fragment protection introduces the additional mechanics of shock attenuation down a thin membrane. Table 3 lists the response of acceptors to various barriers evaluated in this series. Figures 15 through 17 illustrate pre- and post-shot conditions of the acceptors.

Our results indicate that the membrane/diverter approach provides sufficient attenuation such that we can suppress sympathetic detonation using barriers approximately 1/3 to 1/2 the diameter of the round for explosives having the sensitivity of EAK and tritonal. These compare to 1 to 1.2 diameter of concrete demonstrated in the MK-82 experiments. Four-inch barriers of phenolic and Plexiglas® were effective as was the 3-inch steel "I" beam. We believe that considerable weight reduction could be achieved with the steel barrier. Fragment deflection can be achieved by insuring that the angle subtended by two lines emanating from the center of the donor to the

Typical Test Set-Up

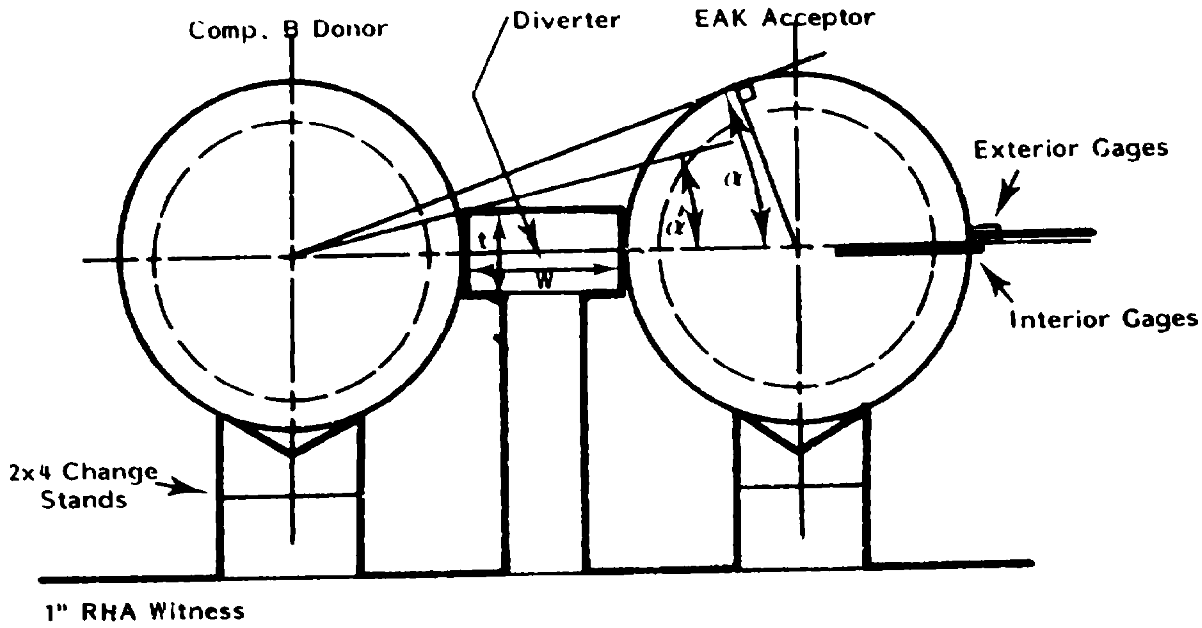
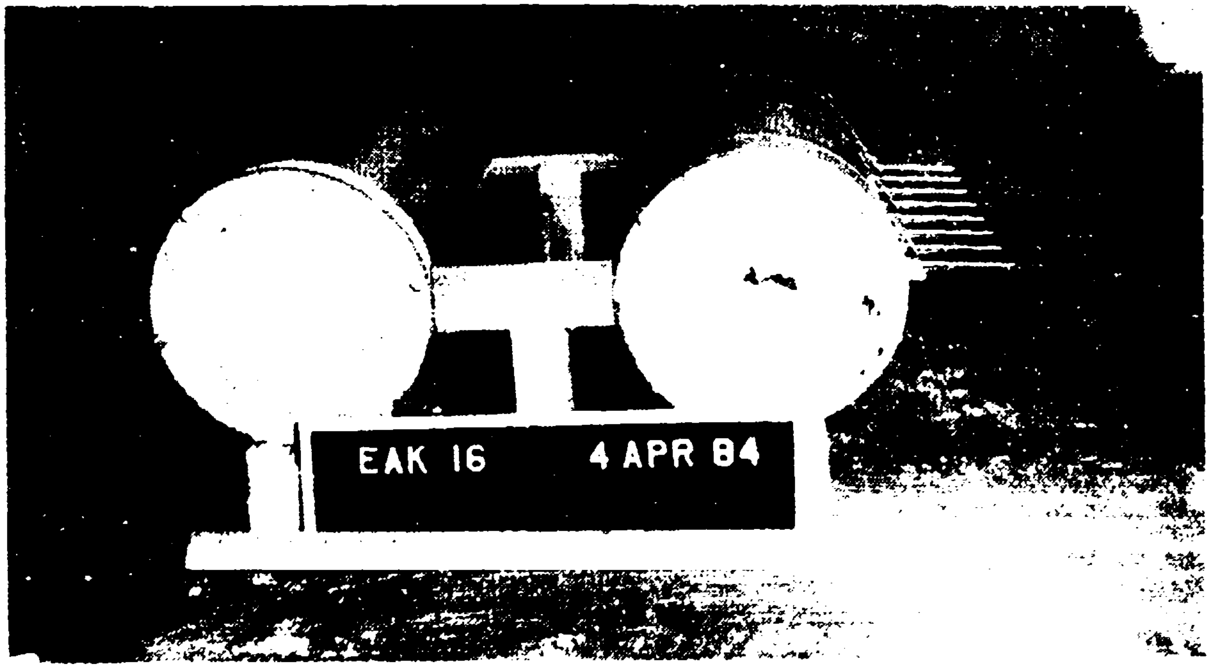


Figure 13. Experimental Design for Engineering Scale Sympathetic Detonation Tests


EAK 16 4 APR 84


EAK 16 4 APR 84

Figure 16. Recovered Explosive

Figure 17. Deformation of Acceptor Case

upper and lower edges of the barrier is greater than the angle, subtended by two lines also emanating from the center of the donor and being tangent to the acceptor (Figure 13).

SECTION IV

CONCLUSIONS

There are two basic approaches to suppression of sympathetic detonation. Minimizing the shock sensitivity of the explosive to long duration pressure will obviously reduce interround separation distances. However, given that the explosive sensitivity is fixed, then much can be gained through the use of simple barriers placed between the rounds. We have devised calculational methods for predicting shock transmission; experimental methods have been developed to characterize explosive shock sensitivity and observe the response of acceptors to barriers. We have shown that both EAK and tritonal can be initiated to detonation with relatively low pressure shocks of long durations. And we have shown that to be an effective barrier between the donor and acceptor, the material must attenuate shock and deflect fragments. Future actions will concentrate on refining the design of barriers to minimize weight, volume, and cost.

A SYSTEM FOR EXTINGUISHING POL AND ORDNANCE TYPE FIRES

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ABSTRACT

"Fire," a word that brings one of two thoughts to an ordnance man. First and certainly most preferable - the projectile is leaving the area. Secondly, and the least preferable - he is leaving the area.

The historical response to a fire involving ordnance and pyrotechnics is to vacate the area and let the fire burn out. Loss of facilities, equipment and ordnance due to fire has been accepted as a necessary facet of the business.

This symposium is the forum for you to find out that catastrophe is no longer the necessary price of incidents where fire engulfs ordnance or pyrotechnic devices. New fire elimination systems using the latest technology in pumps, monitors, nozzles, controls and surfactants promise to minimize losses in manpower, facilities and material.

INTRODUCTION

There are several ways to initiate and communicate undesirable ordnance detonations. This paper addresses explosive communication through heat, or more specifically, the control of petroleum, oils and lubricants (POL) fires involving pyrotechnics and ordnance in an open area.

On July 29, 1967 -- fire broke out on the deck of the carrier , USS Forrestal. The crew was unable to control the blaze. Within minutes, aircraft-mounted ordnance begin to explode - 134 men died; 21 aircraft are destroyed. It happened again - on the USS Enterprise, January 14, 1969 - accidental missile warhead detonation and fire. Before the flames could be brought under control, nine ordnance devices on the flight deck detonated; 27 men died. And again, May 26, 1981 - this time on board the Nimitz, an aircraft crashed while landing; 14 men died and another 48 were injured in the fire fighting operation. The challenge is to design a reliable, responsive and personnel-safe system capable of dealing with the ever-present danger of catastrophic aircraft fire at sea.

Aerojet picked up this challenge three years ago and dedicated itself to designing a system that would eliminate the threat of catastrophic fire on aircraft carriers. We did, in fact, design, build and demonstrate such a system in our Sacramento facility. This paper will review our analysis, describe the hardware, and show you a demonstration of the system in operation. It will also identify various application concepts for a fire elimination capability of this type.

Aircraft carrier fires, train fires, and other accidents that have produced violent explosive reaction have pointed out the need for less vulnerable munitions and improved control of fires. The services have been working for 20 years developing new types of explosives which demonstrate good vulnerability behavior compared to conventional TNT-based explosives. Significant progress has been made; However, the bunkers and depots are storing thousands of tons of TNT-based ordnance, and that is the material we will be warehousing, transporting and using for a long, long time. The question is then, how do we protect this material, the facilities, and personnel involved in handling this ordnance?

ANALYSIS

We performed a detailed analysis of every major POL and ordnance fire we could find, and reviewed all pertinent historical records and reports. A summary of the results of that effort are shown in Figure 1. These considerations set the criteria for the system.

Figure 1

System Considerations

• Rapid response:	• Reliable prime movers • Simple controls
• Remove the human element:	• Adequate range • Remote control equipment
• Eliminate the fire:	• Adequate water • Control the footprint • Chemical additive capability
• Cool the area:	• Massive capability

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Rapid response requires the system to be available and reliable. Ideally, the system should be running in a standby mode during operations that could spawn a catastrophic incident. Controls should be as automatic as reliability will allow to simplify operation under stress. POL fires quickly reach temperatures of 1000°C, and ordnance cook-off can be expected in as short a time as one minute in this environment. Rapid response is an absolute necessity.

The human element must be removed from the fire site to safeguard personnel in an ordnance fire. Quantity distance data requires a system capable of delivering water at least 300 feet from the pumping unit. The greater the distance between the firefighters and the potential explosion, the better. This requires high flow rates and pressures. Additional personnel isolation could be provided by making the system mobile and remotely controllable.

Historically fire fighting has been restricted by the capacity of the system to deliver water. Consequently, elimination of the fire has been accomplished by isolating small sections of a large fire, controlling it, then moving to the next section until the fire is out. This procedure takes precious time when there are people in the vicinity of cooking ordnance. Using DoD fire standards, we decided to design a system that was capable of attacking the largest anticipated fire: a system that would not fight a fire piece by piece but would overwhelm it; a system that would deluge the fire, absorb all the energy generated by combustion, and extinguish it. To do this, the water would have to be delivered where it was needed and in the quantity and spray required. Fire suppressant chemicals would also be required to prevent re-ignition from hot spots.

There were cases on record involving running fuel fires where it was desirable to let the fire burn as a means of eliminating the volatile material. In cases like this, adjacent structures, aircraft or ordnance required protection from the heat to prevent escalation of the fire and minimize collateral damage. This cooling requirement dictated the delivery of massive quantities of water at safe standoff range. This included providing spray coverage of personnel who may be required to enter the fire zone. These considerations required the design and development of new pumps, monitors and nozzles.

HARDWARE

The 8x8x20-feet portable pumping module shown in Figure 2 is powered by a 2100 horsepower diesel engine, selected for its reliability and economy goals. The diesel drives a new pump designed to operate over a wide range of flows and pressures. This pump is capable of moving up to 16,000 gallons of water a minute at a discharge pressure capable of providing water ranges over 600 feet. The module shown is self-contained, except for water, and weighs approximately 40,000 pounds. It was designed to meet and comply with all existing international marine and firefighting regulations and certification standards.

A smaller 6000 gpm air transportable unit, weighing 4000 pounds, is in the design stages now and will be available for testing in the near future.

Controlling the placement of water with a monitor of reasonable size resulted in the design of the Aero-Safe monitor. As you may suspect by noting the difference in the size of the two monitors shown in

Figure 2

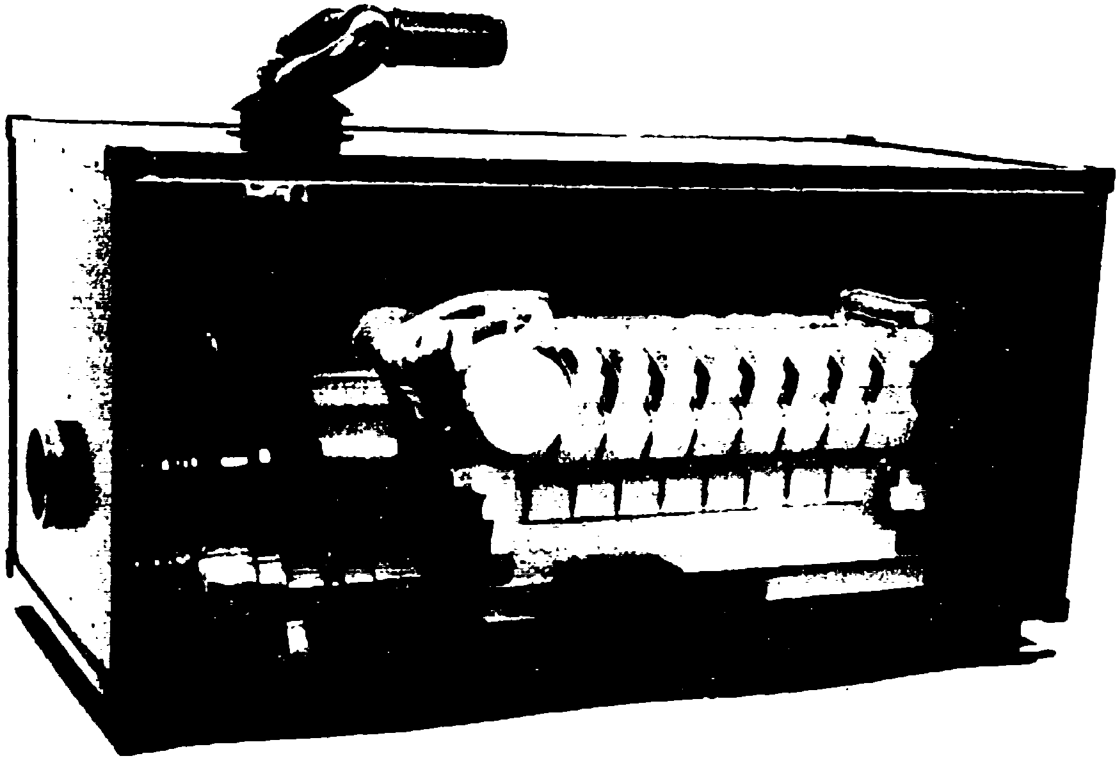

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Figure 3, there is more to a compact monitor than just a bent pipe. We have incorporated turning vanes and flow straighteners in such a manner to produce a nonturbulent stream of liquid at the monitor/nozzle interface which will result in a cohesive, manageable stream when it exits the nozzle. The monitor is also remotely controllable in azimuth and elevation.

The requirement to provide a controlled footprint on the fire site at flow rates up to 16,000 gpm necessitated the development of a new remotely controlled nozzle. A nozzle was needed that could provide variable control of the water flow from a cohesive, solid stream for maximum range to a full fog discharge for maximum droplet dispersion. The result was a nozzle that is 30% more efficient than any commercial nozzle we could find. The research and subscale testing required to develop this nozzle produced the data shown in the range/pressure/volume family of curves (Figure 4).

A single injector in the pump inlet under the control of a solenoid valve provided a simple and reliable system for controlling and mixing fire suppressant chemicals on demand. This design provided a method for

Figure 3

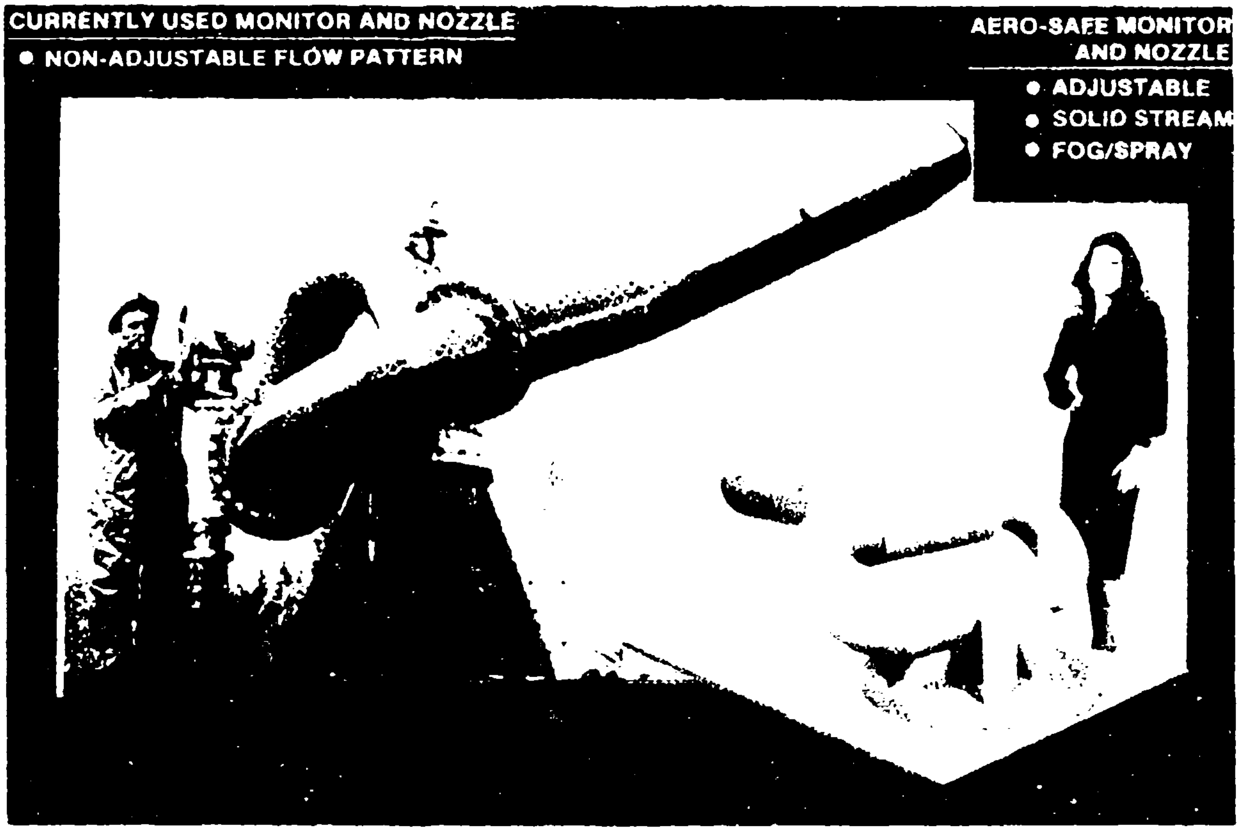
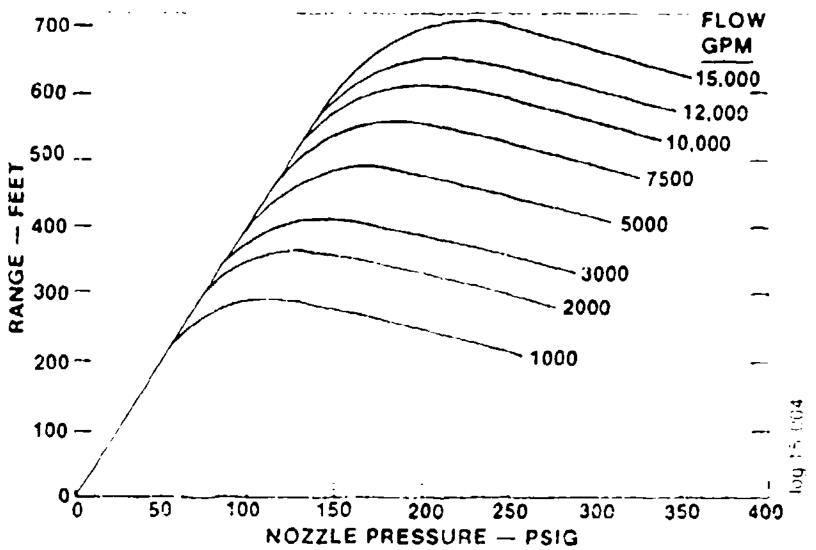


Figure 4

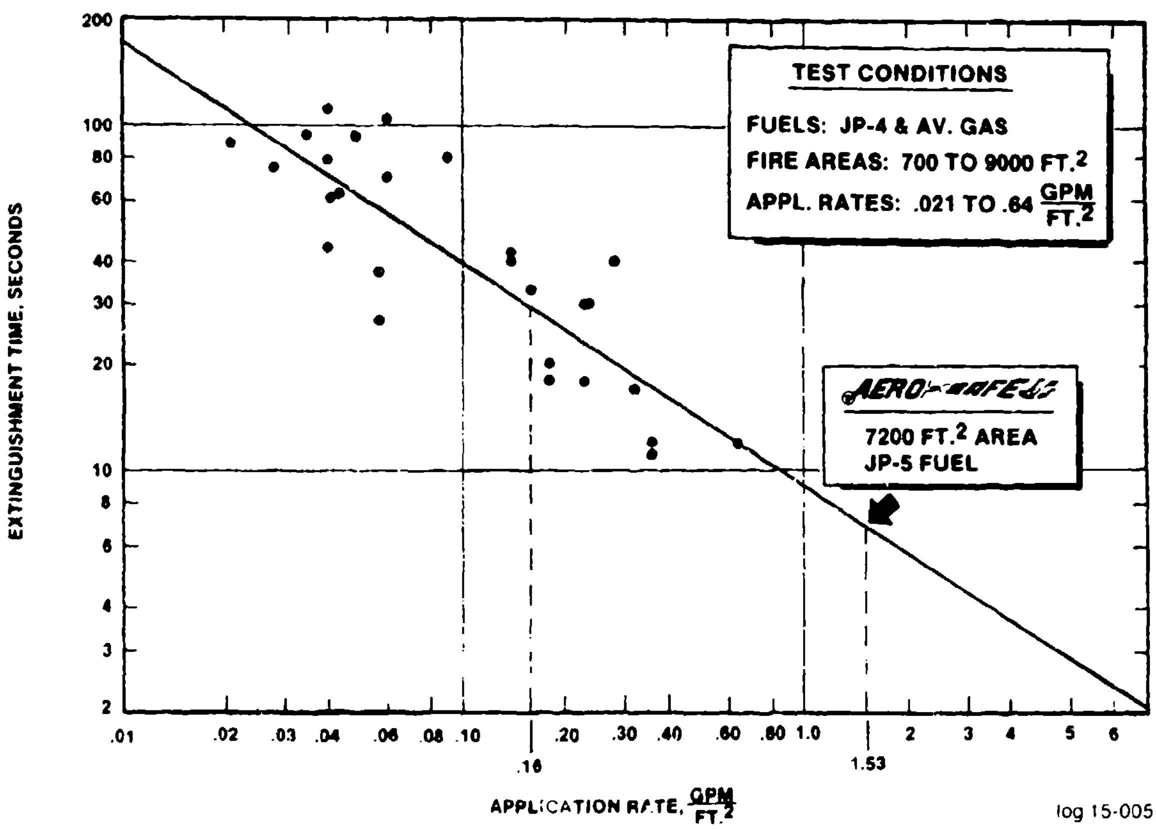


depositing aqueous film forming foam (AFFF) on a fire site at great distances without requiring re-aiming of the nozzle or monitor. One of the objectives of our design was to reduce the amount of foam required to put out a fire. This objective was satisfied in that Aero-Safe only uses 25% of the foam used in other fire fighting systems.

PERFORMANCE

It was Aerojet's belief from the start of this project that by increasing the water and foam application in a given period of time to a given area, a fire would be extinguished in a shorter period of time (due to the absorption of the energy of combustion). After running our tests in Sacramento, we compared our results with Navy test data. The graph in Figure 5 shows the results of this comparison. The vertical axis of the graph is the time of extinguishment and the horizontal axis is the application rate (in gallons per minute per square foot of surface). The dots on the upper left of the chart show the results of many tests conducted by the Navy using water and a 6% solution of foam. The arrow at the lower right shows the results of the Aerojet tests using water and a 1-1/2% solution of foam. We

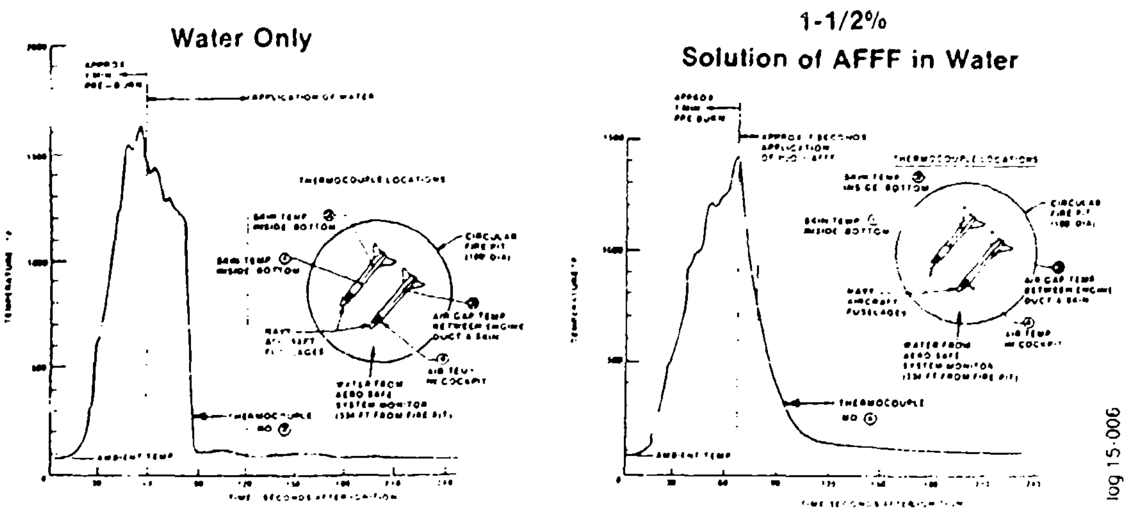
Figure 5



believe that the test results shown prove that our original premise was indeed correct, i.e., the Aero-Safe system concept is superior to others because it effectively applies water and foam in greater quantity and in a controlled manner, at greater stand off distances than other systems. That results in faster control of the fire.

A significant product of our performance testing was the cooling data recorded. We ran many tests with water only and others with water and foam (at 1-1/2% solution) for the sole purpose of collecting such data. In these tests, we placed two aircraft fuselages in the fire pit and instrumented them with thermocouples. Figure 6 shows the actual traces of two such tests and are typical of all the test results. In both cases, the fire was allowed to develop for approximately one minute. Temperatures rose to 1500°F before we applied our water and/or water and foam. In both cases, the temperatures were reduced to almost ambient in 20 to 30 seconds. This is an extremely important point when one considers ordnance cook-off. You will note that the temperatures on both charts decreased to ambient in about 30 seconds, however, the slope of each curve is different. The reason for this difference is that, in the water-only test, our goal was to determine how much control we had over temperature, not to eliminate the fire. Consequently, the stream of water remained on the fire and provided continual cooling, and rapid return to ambient temperature. But in the foam tests, the fire was extinguished in seven seconds and the water (and AFFF spray) was moved off the fire site. The slope of this curve is more gradual because it reflects unassisted cooling to the ambient temperature.

Figure 6



The Aero-Safe system has been designed as a unique, highly efficient means of protecting and defending personnel, material, and facility assets. It does what no other system can do. Aero-Safe offers a choice. Fires that previously had to be allowed to burn out can be eliminated. Critical areas vulnerable to heat can be more effectively cooled and protected.

Within seconds an Aero-Safe system can deliver 3,000 to 16,000 gallons of water per minute directly into fire areas hundreds of yards away, providing both fire elimination and cooling. Structures and equipment, ordnance storage, tank cars or hazardous chemical pressure vessels can be protected from the intense heat of a fire. In tests at a distance of 350 ft, water flowing at 12,000 gallons per minute, surface temperatures are reduced by more than 1500°F within 20 seconds of water coverage. The spread of the fire was contained, the area was cooled, effectively preventing failure of critical equipment and further explosion of combustible material. The system with a flow capacity of up to 16,000 gallons per minute can project water and fire suppressant chemicals over 700 ft horizontally (Figure 7). In a 30-knot crosswind, the horizontal reach is over 400 feet. Aero-Safe's vertical reach is more than 500 ft from the moni-

Figure 7

log 15-007

tor (Figure 8).

Figure 8

log 15-008

Adjustments of the nozzles between a solid cohesive stream, insensitive to wind, and a fog or spray can provide controlled coverage of a large fire area (Figure 9). Fail-safe design of the control system automatically adjusts the nozzle flow to a full fog, preventing accidental damage to valuable equipment and personnel. Aero-Safe's unique articulating monitors and adjustable nozzles can be operated from a remote location, safely away from hazardous areas. Water and fire suppressant delivery can be accurately directed without requiring personnel to approach the vicinity of the fire site. However, spray delivery from adjustable nozzles can provide substantial protection in hazardous areas where personnel activity may be necessary.

Figure 9

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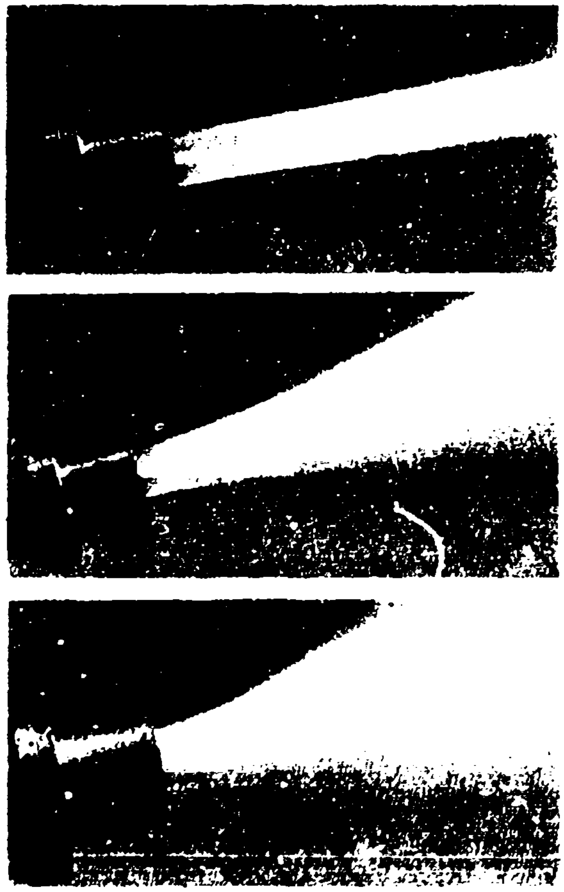
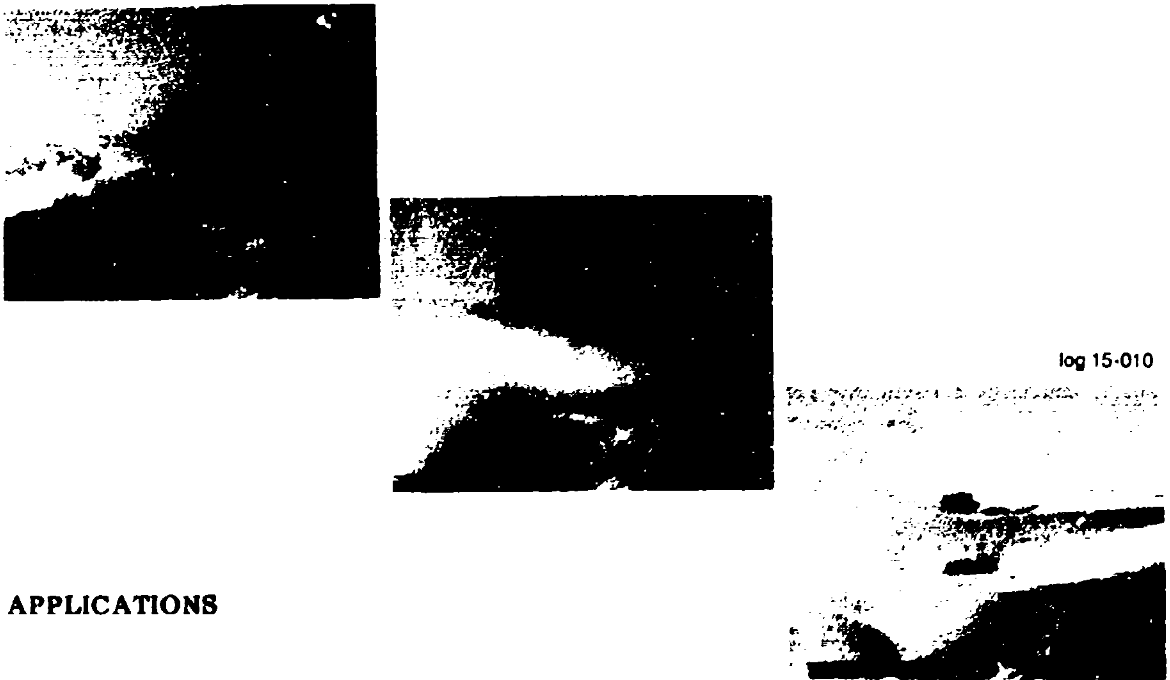


Test after test at Aerojet's marine test facility in Sacramento, California have proven Aero-Safe's effectiveness and reliability. In tests for the United States government, a fire burning in a 100-ft diameter arena, containing debris and 2,500 gallons of jet fuel (Figure 10) was eliminated by an Aero-Safe system from a distance of 380 ft with the addition of a 1.5% solution of chemical suppressant. Elimination was complete in 7 to 10 seconds and required less than 45 gallons of the foam suppressant.

Figure 10



log 15-010

APPLICATIONS

Systems can be modularized for fixed or mobile installations, integrated into existing systems, or they can be installed as part of unique, stand-alone, customized systems. Munitions staging, particularly during mobilization, presents a high likelihood of accident. Transportion and storage of chemicals such as toluene, and solvents used in the production of explosives also present a significant potential hazard. Protection could be provided with an Aero-Safe system mounted on a railroad flat car, supported by a few tank cars of water (Figure 11). The pumping unit could be shielded from the conflagration by other rail equipment, or it could be pushed into an open danger area at the end of a long string of cars and operated remotely. This same rail system could be used to protect docks and wharves by taking advantage of the rail system generally in existence at these facilities. Systems installed on road-transportable trailers are also practical if advanced planning identified water sources (Figure 12). In both cases, the Aero-Safe capability is not tied to a facility, but free to move with the material being transported.

Fire fighting support in harbors (Figure 13) as well as nuclear, biological, chemical wash down at sea (Figure 14) can also be provided from a safe distance, with sufficient quantity of water and foam or chemical neutralizers to be effective.

Last, but not least, the aircraft carrier. Unfortunately, the U.S. Navy has not moved forward with the installation of an Aero-Safe-type system (Figure 15). Instead, they have decided to undertake a detailed and protracted study to investigate and explore all the potential alternatives available. The result is that essentially the same conditions exist on U.S. Navy carriers today that resulted in the incidents described at the beginning of this paper.

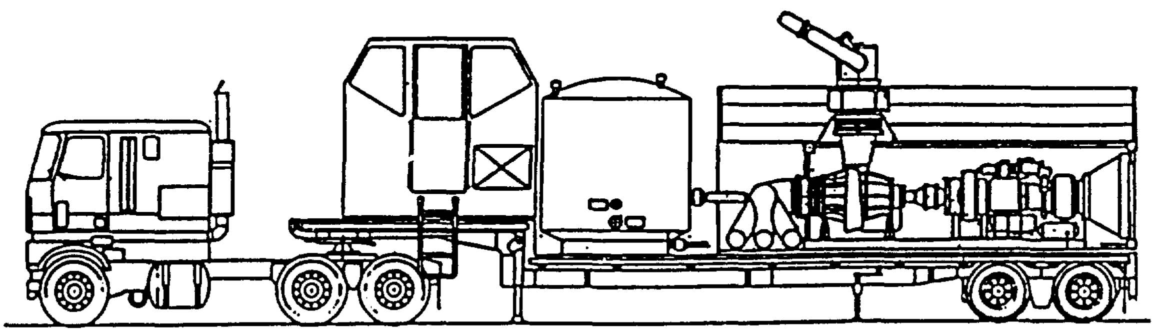
CONCLUSIONS

The capability to control catastrophic fire is now available and application analysis can identify optimum hardware installation. Protection can be by mobile equipment or a fixed installation; the system provides reduced damage, permits earlier facility start-up and return to production/operation and readiness is preserved by minimizing personnel, materiel, and facility losses.

Figure 11

log 15-011

Figure 12



log 15-012

Figure 13

log 15-013

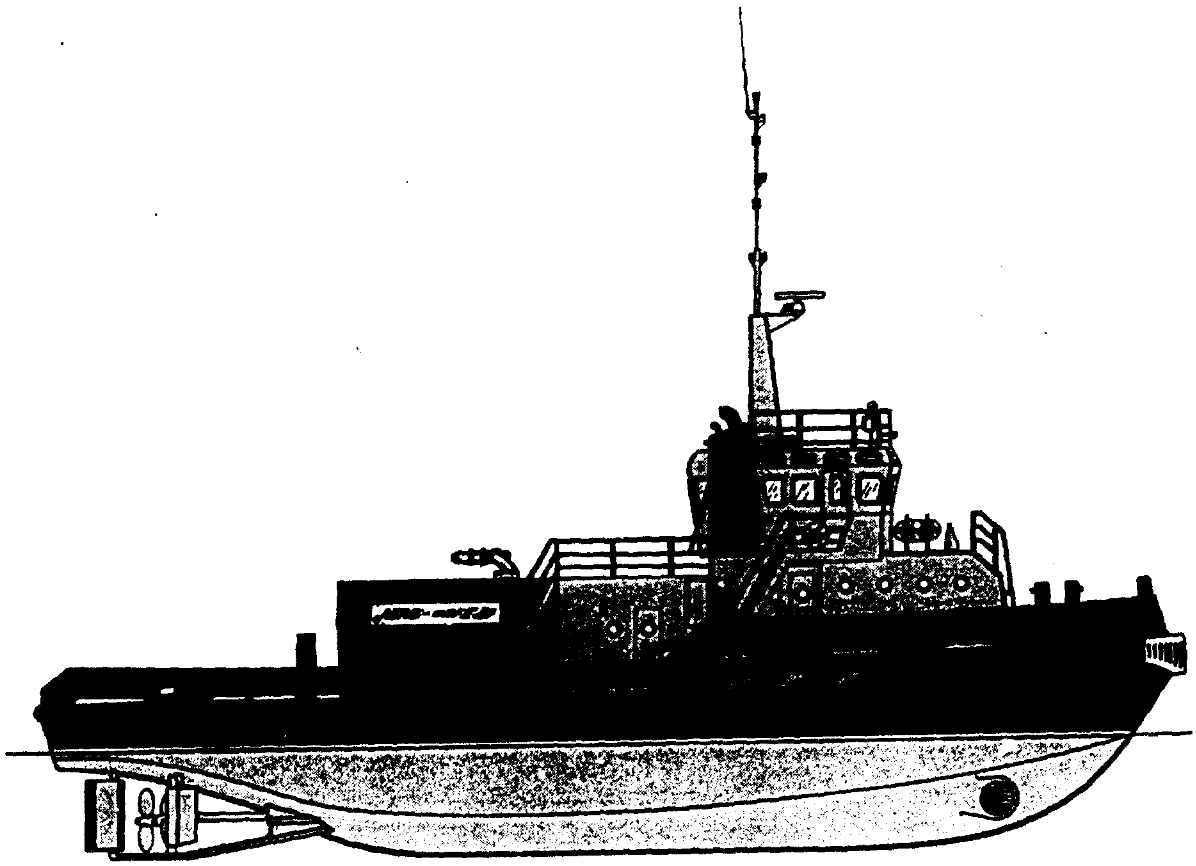


Figure 14

log 15-014

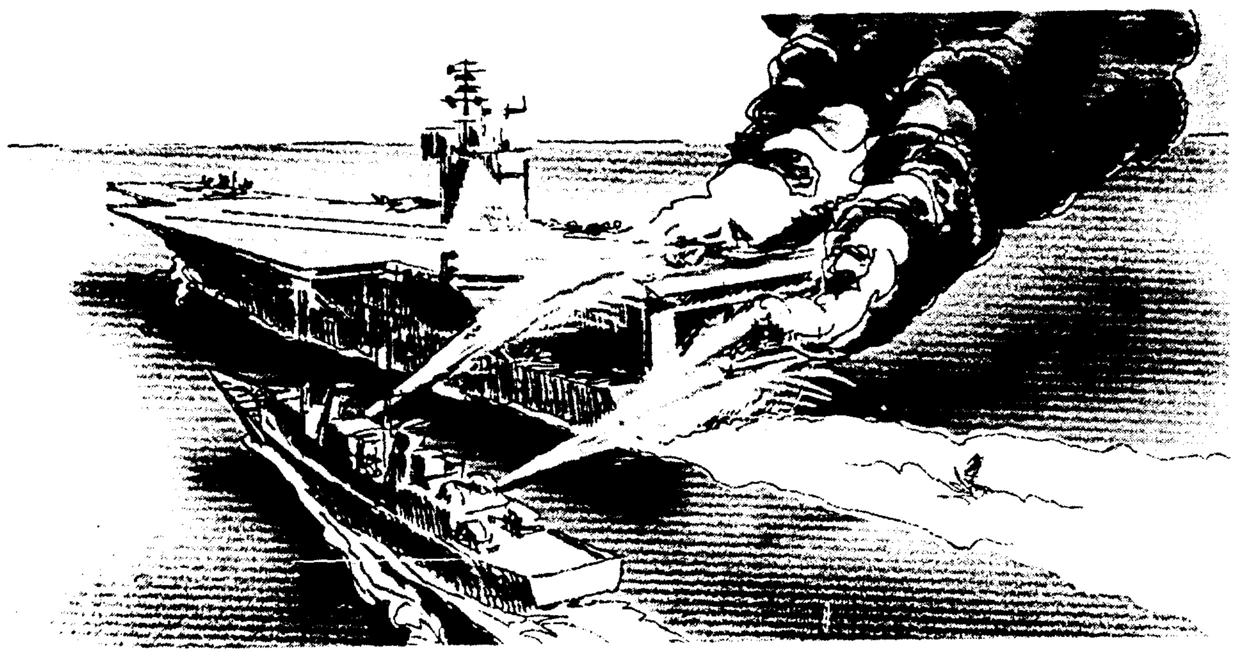


Figure 15

log 15-015