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A NEW SIMULATION FACILITY FOR ATOMIC EXPLOSIONS-PROJECT FAX

Phase II–Definition and Design of Experimental Facility

McMillan Science Associates, Inc.
1100 Glendon Avenue, Suite 901
Los Angeles, California 90024

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R. B. Morrison R. W. Oliver

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This study defines the user requirements for a fuel-air explosive test facility for nuclear blast simulation. It details an experimental program and provides the design for an initial experimental fuel-air explosive facility with a capacity of 10,000 pounds of fuel which, by making use of its design as a basic cell, may be expanded to a full 1-KT nuclear blast simulation facility with a 200,000-pounds fuel capacity.

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PREFACE

This Study was conducted for the Defense Nuclear Agency as Phase II of a two-phase effort. The Study was sponsored by the Shock Physics Directorate of DNA as a part of its nuclear blast simulation program.

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1. INTRODUCTION

1.1 BACKGROUND

The 1963 Limited Test Ban Treaty included among its provision the prohibition of atmospheric testing of nuclear devices. Having previously conducted only limited testing to determine the effects of nuclear weapons on U.S. forces and their equipment, the United States found itself in a precarious position from this lack of knowledge. The survivability--or means to improve the survivability--of U.S. forces and their equipment in nuclear war was not known.

Responsibility for generating nuclear weapons effects information lies with the Defense Nuclear Agency (DNA--until 1971 the Defense Atomic Support Agency). DNA is tasked not only with nuclear weapons effects research but also with the construction and management of nuclear weapons effects simulation facilities as well as field experiments which simulate nuclear weapons effects phenomena using non-nuclear sources.*

DNA has conducted extensive nuclear effects simulation tests. For air blast wave simulation, two primary explosives have been employed: TNT and Ammonium Nitrate/Fuel Oil (ANFO). These explosives--with quantities up to 500 tons of TNT and 600 tons of ANFO--have provided useful information on air blast wave effects but have demonstrated serious shortcomings and deficiencies: safety; long set-up time; expense; unpredictable asymmetries; non-reproducibilities; excessive ground shock; difficulty in tailoring effects; and uncontrollable ejecta. These deficiencies have had

* *U.S. Government Manual*, (1974-75), p. 208.

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adverse effects on many test results which--considering the immense cost of instrumentation, provision of equipment and personnel--have made a more satisfactory method of nuclear blast simulation most desirable.

DNA has recognized that the explosion resulting from an explosive mixture of some type of fuel--such as methane--with oxygen or air might have application for blast simulation. Tests were conducted using large balloons (125-foot-diameter hemispheres and 110-foot-diameter spheres) filled with gaseous explosive mixtures. Many hours were required to fill the balloons during which time weather conditions were most critical. Static electricity commonly caused premature ignition or detonation. The balloons were expensive. This effort to make use of confined fuel-oxygen explosives simply proved impractical.

With this background DNA sponsored a Study* to determine the feasibility of a simulation facility making use of unconfined fuel-air explosive mixtures. Such unconfined fuel-air clouds had proven practical in small weapons (containing 80 pounds of ethylene oxide fuel) developed by the Navy during the Viet Nam War.** In this weapon application the fuel, contained in a small metal canister, was explosively dispersed into the surrounding air where, 125 milliseconds later, an initiator caused this now explosive mixture in this fuel-air cloud to detonate. The resulting explosions were reliable, reproducible, caused no ejecta and were cost effective. Could practical use be made of this phenomenon for nuclear blast simulation?

The results of the Phase I Study established without doubt that such a fuel-air explosive simulation facility was feasible. Detailed calculations showed that upwards of 100 tons of fuel can be dispersed into the air (in 3 to 5 seconds) without being confined and can, when detonated, provide the air blast effects of a one-kiloton nuclear weapon. Smaller or larger quantities of fuel are equally feasible for simulation.

* McMillan Science Associates, Inc., *A New Simulation Facility for Atomic Explosions (Project FAX); Phase I, Preliminary Engineering Feasibility*, Prepared for the Defense Nuclear Agency, 30 August 1975.

**Weapons containing 1000 and 2000 pounds of fuel are now under development.

As a result of the recommendations contained in the Phase I Study,* this follow-on Study, Phase II, was sponsored by DNA with the following tasks:

I Experimental Program Definition

II Definition of User Requirements

III Equipment Identification and Selection

IV Design of Experimental Facility

V Data Bank and Information Collection

The overall program embraces three different-sized "facilities." The first, the Sector Facility, is intended for the basic experimentation in determining the optimum design/arrangement for dispersing the fuel. Probably only about 1000 pounds of fuel/water would be used in this experimentation. Based upon the results from the Sector Facility, the Experimental or Pilot Facility addressed in this Study constitutes the next step. This facility, in which up to 10,000 pounds of fuel may be used, will provide confirmation testing as well as testing of various cloud configurations to optimize/tailor the explosive effects. This facility will also be useful by itself as a (small) simulation facility and is, in fact, designed somewhat as an independent and prototype modular "Cell." Finally, the eventual full-scale FAX Simulation Facility --with its 100 tons of fuel to simulate a one-kiloton nuclear weapon-- may be constructed using the 10,000-pound modular cells as its basic building blocks.

1.2 STUDY OVERVIEW

This Study uses the Tasks specified in the Work Statement as a logical sequence for presentation of the material. Beginning with Task I --The Experimental Program Definition--a program is developed leading from initial single-nozzle fuel dispersal through to the design of the Experimental Pilot Facility.

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* To avoid needless repetition little of the information contained in the Phase I Study has been repeated herein. It is recommended that the Phase I Study be consulted for additional background information.

Task II--Definition of User Requirements--presents the overpressure regions of interest for field equipment testing in previous nuclear/HE blast tests. This presentation confirms the usefulness of the fuel-air explosion in producing overpressures--and more importantly, static and dynamic impulses--as desired by the User. Additionally it is shown that even the small ($\sim$10,000-pound) Experimental Facility will have lasting potential for testing quickly, easily and inexpensively in the regions of User interest.

Task III--Equipment Identification and Selection--provides identification of establishments/personnel who, because of their expertise, are recommended as participants in the testing program. Applicable equipment is identified. One of the many advantages of the 10,000-pound Experimental Facility is that the equipment necessary consists primarily of standard off-the-shelf hardware.

Task IV--Design of the Experimental Facility--builds on the results of the first three Tasks in providing a basic design for the Facility. As the ultimate implementation of the Experimental Plan (Task I) progresses in establishing nozzle locations/patterns/angles/head types, some fine tuning of the Experimental Facility design will likely be necessary.

Task V--Data Bank and Information Collection--gathers and collates general background information pertinent to this program, and provides a readily assimilated understanding of the fuel-air explosion phenomena and their application to the nuclear blast simulation efforts of DNA.

Following the analyses conducted under each of the Tasks, the Results, Discussion and Recommendations are presented. Thereafter Appendices contain additional amplifying/background information.

Phase I of this two-part Study established the feasibility of a FAX Blast Simulation Facility. The present Phase II of the Study provides the required design details and experimental plan to proceed with the construction of the FAX Experimental Pilot Facility (10,000 pounds of fuel) and ultimately the one-kiloton equivalent full-scale FAX Facility (200,000 pounds of fuel).

2. EXPERIMENTAL PROGRAM DEFINITION--TASK I

2.1 GENERAL

Phase I of the FAX Feasibility Study concluded that the detonation of a hydrocarbon fuel-air cloud of suitable shape would meet the requirements for nuclear blast wave simulation. The primary purpose of Task I is the determination of an experimental plan that could be used expeditiously for the development of a new Simulation Facility for Nuclear Explosions. It is envisioned that the ultimate Facility would simulate the blast effects of a one-kiloton nuclear explosion.

The Phase I Study recommended that a small-scale Pilot Facility be employed initially as the means of providing a "test bed" for testing fuel dispersal techniques, detonation initiation techniques, cloud shaping, et cetera. In this Study, Phase II, a 1000-pound fuel Pilot Facility was considered initially. An overall test plan was outlined around this size of facility in order to delineate possible sites, costs, and interests for such a Pilot Facility. It was determined that this 1000-pound fuel facility size was not only too small for future use but would also be difficult or impossible to scale-up to large sizes with credibility for performance and costs.

Accordingly, a 10,000-pound fuel Pilot Facility Plan was developed around a "cell approach" (see 2.2) which would accommodate off-the-shelf, commercially available, and non-exotic types of equipment. This 10,000-pound fuel cell was further divided into six *sectors* of 60° (total 360°) wherein pertinent tests could be performed in one sector initially to establish fuel dispersal patterns and cloud shapes.

The single (60°) sector tests would be conducted first with water, then followed with hydrocarbon fuels. The advantages of early water tests are numerous, i.e.:

- Safe
- Flexible
- Inexpensive

* Readily available equipment
* Available data for water
* Drop size and mass distribution data from an essentially non-vaporizing liquid
* Rapid testing (no post-test clean-up)
* Backlog of experience (industry, government, etc.)
* Provides a base line for fuel tests.

The philosophy of the single (60°) sector testing is twofold:

1) Establish steady-state cloud patterns for several injection/discharge pressures that can be used for the time unsteady programming of the injection/discharge pressures.
2) Provide the basis for the full six-sector 10,000-lb Pilot Facility which would be equivalent to one cell of the ultimate facility.

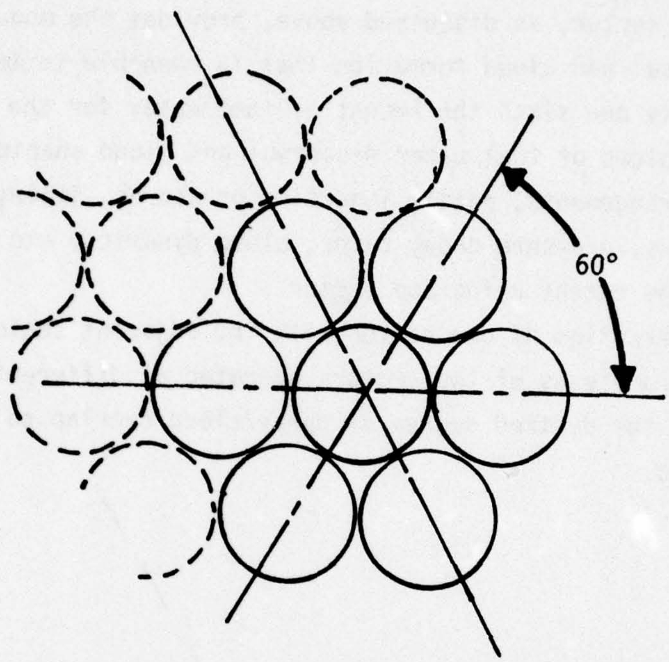
2.2 THE FAX CELL CONCEPT

The cell concept is illustrated in Figure 1. It is noted in the arrangement of cells around the central cell that 60° sectors are naturally formed.

Two cell sizes were considered: one for 1200 pounds of fuel, and the other for 10,000 pounds of fuel. It requires approximately 200 1200-pound fuel cells or approximately 20 10,000-pound fuel cells (utilizing two rings of cells around the central cell) to provide a one-kiloton nuclear blast simulation.

One 10,000-pound fuel cell was selected as the appropriate size for the Pilot FAX Facility for the following reasons:

* Appropriate size for scaling, i.e., adding rings of cells
* 60° sectors provide the logical means for both testing and growth
* Existing equipment and hardware are commercially available in this size range
* One cell/pilot facility useful in itself for blast testing
* Provides for modular construction of the full-scale facility
* Fuel/water pressures required are nominal.



1200 lbs. FUEL
(0.006 KT)

Nominal Cell Size of 100 Ft. $D_{(HS)}$
for F/A ≅ 0.06 (Stoichiometric)

10,000 lbs. FUEL
(0.05 KT)

Nominal Cell Size of 200 Ft. $D_{(HS)}$
for F/A ≅ 0.06 (Stoichiometric)

Size Progression (Number of Cells) 1-6-12/Ring

1-7-19 (Total)

FIGURE 1. FAX CELL CONCEPT

2.3 THE FAX SECTOR CONCEPT

The 60° sector, as discussed above, provides the module for fuel/water dispersal and cloud formation that is amenable to testing while requiring only one sixth the amount of fuel/water for the full cell.

The problems of fuel/water dispersal and cloud shaping for various nozzle(s) arrangements, nozzle injection pressures, impingement geometries, spray patterns, pressure decay rates, cloud dynamics, etc., can be worked out to a large extent using one sector.

The interaction of one sector with the adjacent sectors would be determined from tests of two sectors operated at different test conditions to establish the desired degree of spray/cloud overlap to produce a homogeneous cloud.

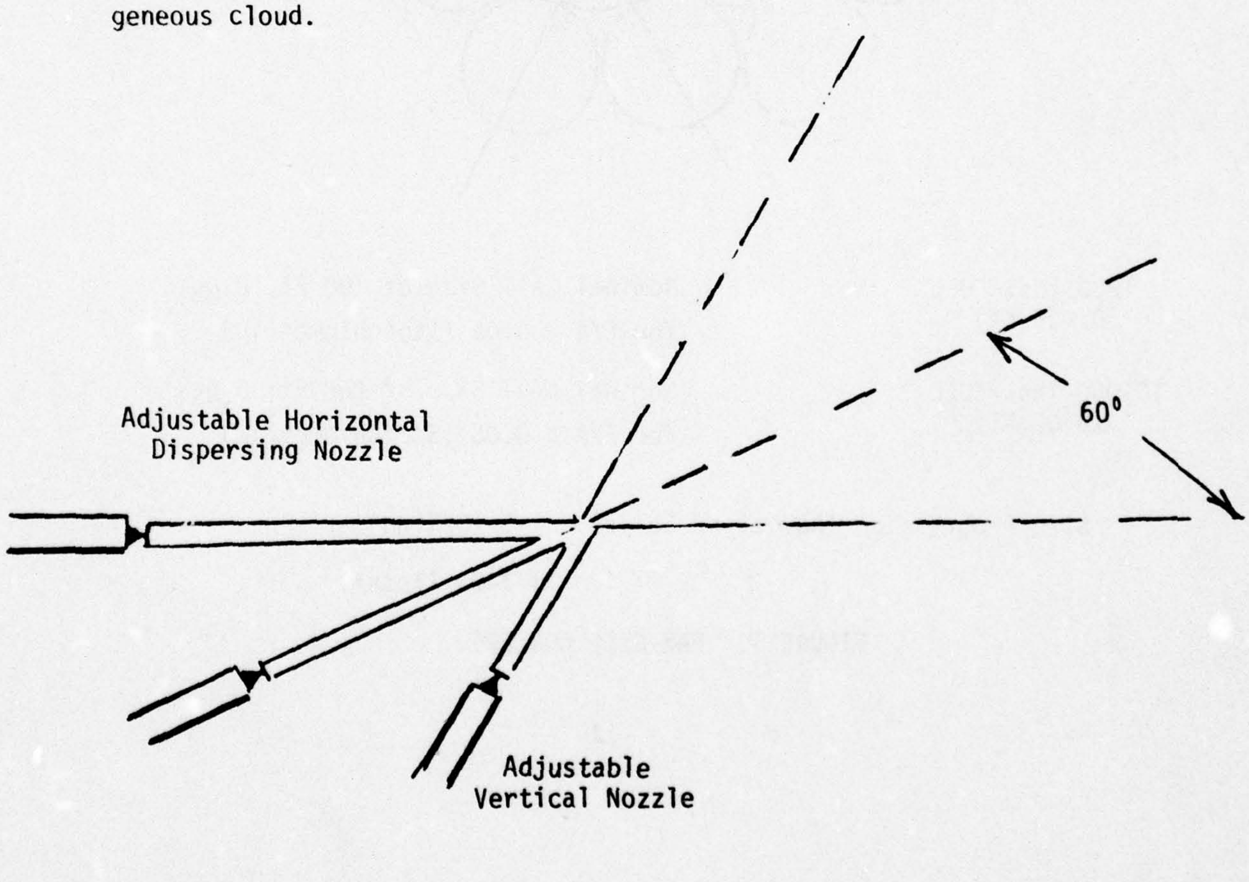


FIGURE 2. 3-NOZZLE IMPINGING ARRAY

Figure 2 shows a 3-nozzle impinging array of fuel/water streams/sprays/jets that could be used to produce large variations in flow/spray patterns by varying the nozzle type, locations, angles and injection pressures. Versatile nozzle units, completely swivelable in both elevation and azimuth, are commercially available. Differing types of nozzle heads can also be used in these units: i.e., solid stream, spray or fog. Figure 3 shows a Santa Rosa Manufacturing Company's M3-DS Monitor Unit which is characteristically available on the commercial market and meets all the requirements for the 60° sector of a 10,000-pounds fuel cell.

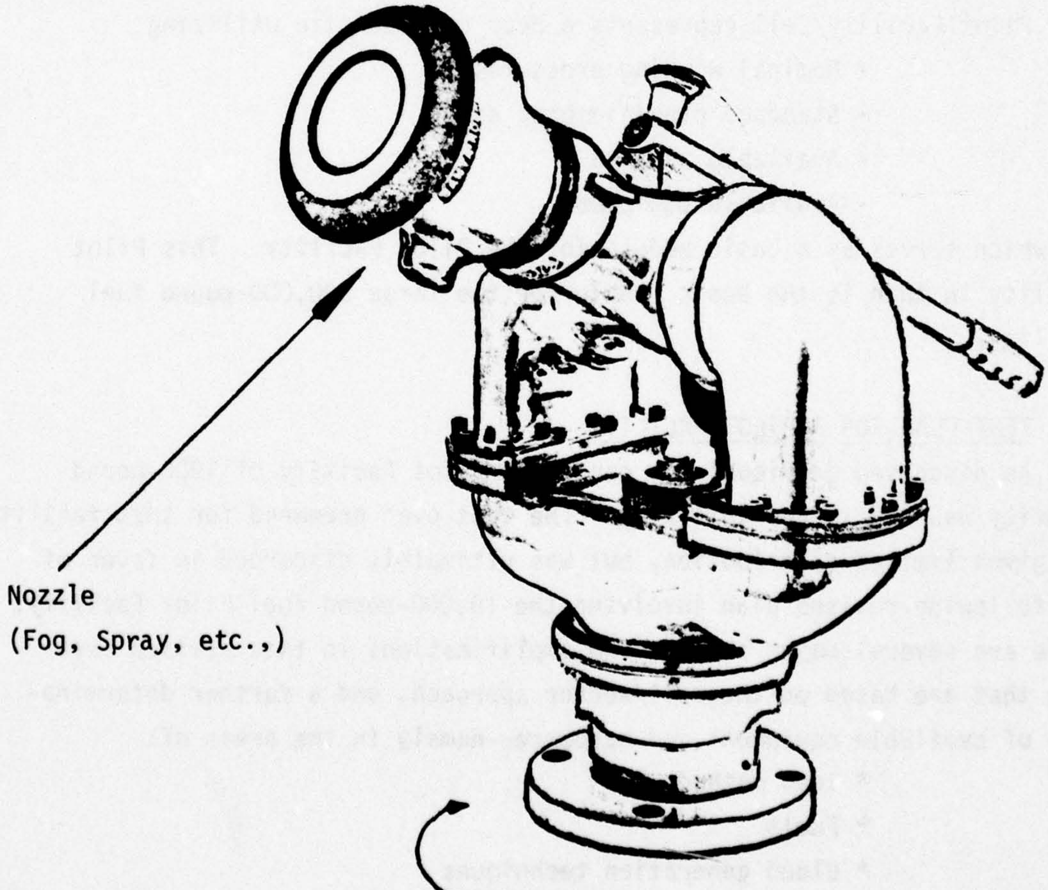


FIGURE 3. SANTA ROSA M3-DS MONITOR UNIT

Although such nozzle units are designed primarily for fire-fighting and fire protection these units are also employed extensively for general industrial purposes such as:

- ° Washing tanks
- ° Earth moving
- ° Water filtration (in plants)
- ° Cleaning railroad cars
- ° Placer mining
- ° Dredging harbors
- ° Clearing ski runs (snow geysers)

It is to be emphasized that the 60° sector of the 10,000-pound fuel size Pilot Facility/Cell represents a near optimum size utilizing:

- Nominal working pressures
- Standard pipe/plumbing sizes
- Available tankage
- Available equipment

and which serves as a basic module for the Pilot Facility. This Pilot Facility in turn is the basic module for the large 200,000-pound fuel Facility.

2.4 TEST PLAN FOR A PILOT FACILITY

As discussed previously, a candidate Pilot Facility of 1000-pound capacity was considered initially. The test plan prepared for that facility was given limited distribution, but was ultimately discarded in favor of the following revised plan involving the 10,000-pound fuel Pilot Facility. There are several major changes and amplifications in this revised test plan that are based on the cell/sector approach, and a further determination of available equipment and hardware--namely in the areas of:

- * Test methods
- * Fuels
- * Cloud generation techniques
- * Nozzles
- * Other

The overall objective of the FAX program is to provide a simple, cost-effective, and flexible test facility that will provide reproducible blast waves with known properties of a) peak overpressure; b) static impulse ($\int p\,dt$); and c) dynamic impulse $[\int(\rho/2)v^2 dt]$.*

The detonation of a fuel-air cloud of proper dimensions and distribution of fuel can be made to produce blast waves that closely approximate those obtained from nuclear explosions in air. It is this technique that is preferred as the means of obtaining this simulation objective.

Fuel-oxygen detonations are well researched and yield well-understood phenomena for gaseous mixtures in confined volumes. Far less understood are unconfined detonations of fuel-air mist-aerosol clouds consisting of vaporizing fuel droplets.

Successful fuel-air unconfined detonations have centered around the hydrocarbon fuels: ethylene oxide, propylene oxide, methane, propane, and MAPP gas. The quantities of fuel employed have ranged from approximately 5 pounds to 1,000 pounds. Fuel dispersal into the air has usually been accomplished by means of small explosive charges centrally located within a cylindrical fuel container.

Ignition (detonation initiation) is usually accomplished from a very small charge in a "detonator" that is precisely timed and located in the fuel-air cloud. It is to be noted that these small detonators are usually used only for gaseous fuel-air mixtures and that fuel-air mists require substantially larger charges.

The Defense Nuclear Agency (DNA) has conducted several large-scale nuclear blast simulation tests using HE and ANFO.† While such explosions produce blast waves comparable to those from nuclear explosions of similar yield, there are several disadvantages in their use:

- ° Cratering
- ° Ejecta
- ° Relatively high explosive costs
- ° Damage to site and instrumentation systems
- ° Propensity for instabilities in the detonation of the solid charge.

For these reasons, DNA is considering the utilization of

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* p = pressure; t = time; ρ = density; & v = material speed.

† ANFO = Ammonium Nitrate/Fuel Oil

large-scale fuel-air detonations as a means of eliminating these disadvantages and to provide reliable reproducible and tailored blast waves to meet both the defense and industrial user requirements.

Large-scale fuel-air detonations will require large quantities of fuel to be dispersed in a short period of time if a proper fuel-air cloud of known properties is to be formed. It is probable that the explosive fuel-expulsion technique will not supply a large fuel-air cloud that meets DNA's needs of flexibility and cost effectiveness. Fuel expulsion/dispersal from spray nozzles is therefore the preferred method for producing fuel-air clouds.

Prior to initiation of a full-scale facility, small-scale pilot tests will need to be made to determine and select the most appropriate technology, techniques and hardware that can be extrapolated to full-scale tests. This plan addresses the small-scale pilot tests--i.e.,:

- 60° Sector tests
- 10,000-pound fuel Cell plan.

The FAX Pilot Test Plan is based upon the availability of a test site capable of handling fuel-air detonations produced from 10,000 pounds of fuel (0.05-kiloton equivalent). The functional elements of the overall system to be considered are shown schematically in Figure 4.

Liquid Fuel	→	Pressurization	→	Fuel Dispersal by Nozzles	→	Cloud	→	Detonation	→	Blast Wave of Interest
10,000 pounds		50-500 psi		1-5 sec		F/A Distribution		300 psi max. Initiation & Propagation		0.5-100 psi

FIGURE 4. FUNCTIONAL ELEMENTS OF THE OVERALL FAX SYSTEM

System hardware components include fuel tankage, fuel transfer equipment, plumbing, valves, pumps/pressurization equipment, nozzles, initiators, instrumentation and control equipment. The test pad area is circular with a radius of a nominal 100 ft. (∿30.5 m.). This area will contain all the equipment for generating the fuel-air clouds and be so arranged to accomplish safe and rapid testing.

Outside the test pad area, from ∿100-175 ft. (∿30.5-53.3 m.), the area into which the detonated fuel-air mixture expands, is a primary measurement zone for evaluation of the transition from detonation waves to shock waves. The zone from 175 ft. outward is the pure blast wave evaluation area, and most pertinently, the location wherein the objectives of the FAX program are to be satisfied.

2.5 BASIC CLOUD GEOMETRIES

The nuclear or HE detonation may be considered as a point source of energy release insofar as the generated blast waves are concerned. The fuel-air detonation is a distributed source of energy release, however, making cloud geometry and manner of detonation initiation most important. To exactly duplicate or closely approximate nuclear or HE blast wave effects would require a spherical or hemispherical cloud with detonation initiated at the center.

However, though useful for comparison purposes, generation of a spherical or hemispherical fuel-air cloud is not the purpose of the FAX pilot facility. The main purpose of the facility is to produce blast waves possessing known characteristic properties of overpressure, static impulse, and dynamic impulse which can be controlled and adjusted by means of cloud shape and fuel-air ratios.

The cloud geometries to be considered here focus on cylindrical clouds with height-to-diameter (H/D) ratios of 0.5 (approximating a hemisphere), 0.4, 0.3, 0.2 and 0.1 . Table 1 shows the resulting approximate cloud dimensions obtained by evenly distributing 10,000 pounds of fuel throughout the cloud at a fuel-air mass ratio (F/A) of 0.06. Fuel-air ratios other than 0.06 would correspondingly change the dimensions given in Table 1. One 60° sector will require ∿1700 lbs. of fuel. Initial sector tests are based upon this amount of fuel or an equal mass of water.

TABLE 1. F/A CLOUD DIMENSIONS FOR PILOT FAX FACILITY
(0.06 F/A ratio, 10,000 lbs. fuel)

	Cloud Diameter (D)		Cloud Height (H)	
H/D	ft.	m.	ft.	m.
0.1	302	92.0	30	9.1
0.2	241	73.5	48	14.6
0.3	210	64.0	53	16.2
0.4	191	58.2	76	23.2
0.5	177	53.9	89	27.1

Figure 5 illustrates the initial 60° sector cloud geometry.

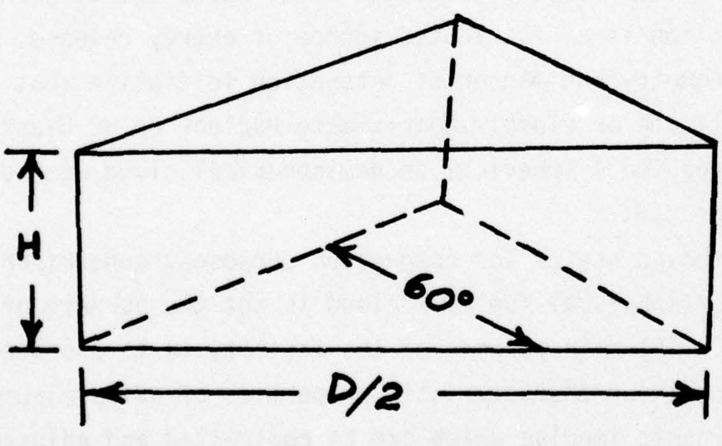

FIGURE 5. INITIAL 60° CLOUD GEOMETRY

2.6 FUELS

The gross detonative properties of common hydrocarbon-air mixtures in stoichiometric proportions are shown in Figure 6 for the case of an average specific heat for air equal to 0.24 Btu/lb. °F with the mass of fuel in the mixture neglected.

It is noted, with the exception of methane, that the detonation Mach number is constant and approximately equal to five. Methane possesses a detonation Mach number of approximately six.

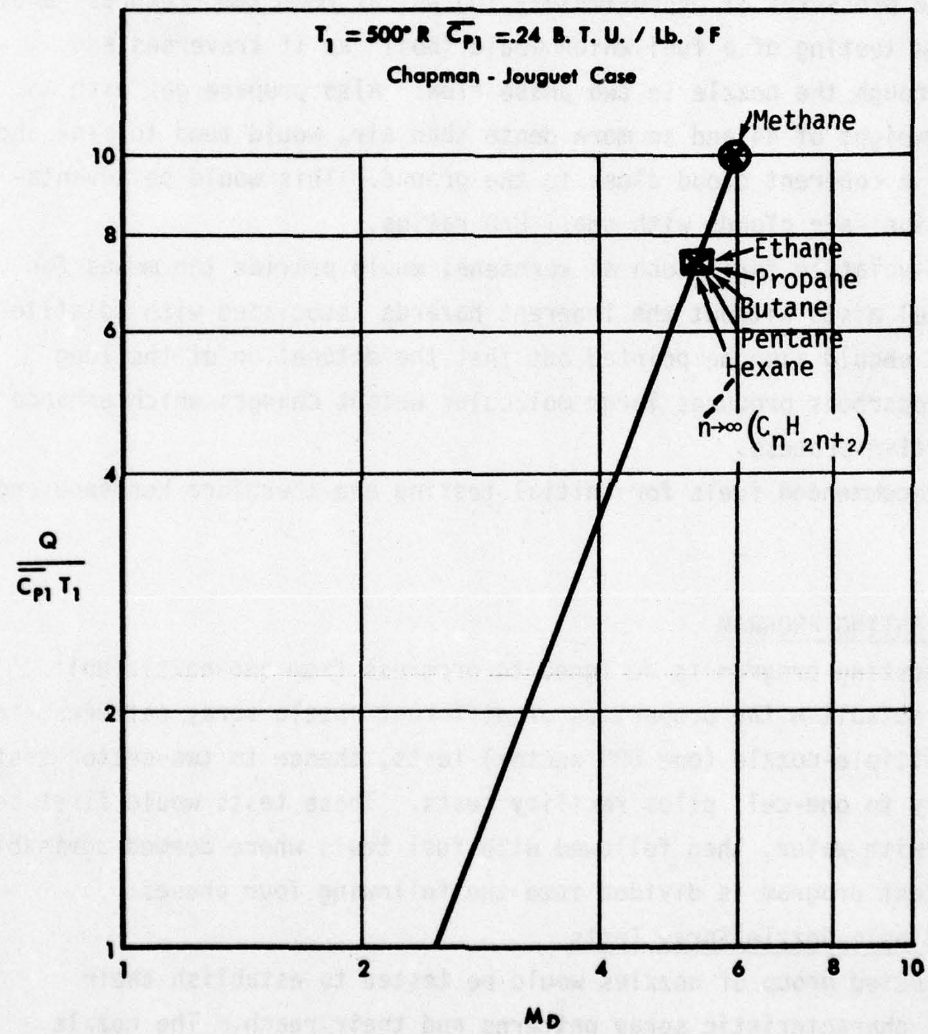

FIGURE 6. EFFECT OF HYDROCARBON FUEL SELECTION (C_nH_{2n+2}) UPON THE DETONATION MACH NUMBER OF STOICHIOMETRIC HOMOGENEOUS F/A MIXTURES

Although methane would ideally deliver overpressures approximately 40% higher than those from the other C_nH_{2n+2} hydrocarbons it is highly cryogenic in liquid form and requires high pressures for reasonable sized containment in gaseous form. For these reasons methane is not recommended as a fuel for early tests although it may prove to be an excellent candidate for later tests.

Propane would be an excellent substitute for methane. It is liquid at moderate pressures of approximately 100 psi at room temperatures, and would allow testing of a fuel which would "boil" as it traverses and expands through the nozzle in two phase flow. Also propane gas with a molecular weight of 44 and so more dense than air, would tend to sink and to provide a coherent cloud close to the ground. This would be advantageous for fuel-air clouds with small H/D ratios.

A non-volatile fuel, such as kerosene, would provide the means for testing fuel mists without the inherent hazards associated with volatile fuels. It should also be pointed out that the detonation of the long chain hydrocarbons produces large molecular weight changes which enhance the detonative process.

The recommended fuels for initial testing are therefore kerosene and propane.

2.7 THE TESTING PROGRAM

The testing program is designed to progress from one-nozzle unit tests (to establish the properties of different nozzle spray patterns) to that of multiple-nozzle (one 60° sector) tests, thence to two-sector tests, and finally to one-cell pilot facility tests. These tests would first be performed with water, then followed with fuel tests where deemed advisable.

The test program is divided into the following four phases:

Phase I--Single-Nozzle/Spray Tests

A selected group of nozzles would be tested to establish their individual characteristic spray patterns and their reach. The nozzle types would include but not be limited to:

- Fog nozzles
- Solid-stream nozzles
- Spray nozzles
- Fire nozzles

Steady-flow tests would be conducted first with water for a range of nozzle injection pressures extending from approximately 20 psi to 300 psi. The range of elevation angles utilized would extend from 0°-90°.

Spray patterns and/or cloud characteristics would be determined from photographic coverage and suitable drop size measuring equipment.

Pertinent nozzles would be tested selectively on fuels. The two fuels recommended are kerosene and propane, as was discussed previously.

Phase II--Multiple-Nozzle/Spray Sector Tests

The nozzles selected from the Phase I single-nozzle tests are to be arrayed in combinations of 2, 3 or 4 to determine which will produce the desired 60° sector coverage. The testing would be initiated with a doublet of impinging nozzles, a triplet of impinging nozzles, etc.

As in the single-nozzle tests these tests would first be conducted with water through a range of injection pressures and elevations to establish the steady-state spray patterns. The data from these tests would be used to establish the nozzle injection pressure build-up and/or decay rates required for the fuel-air cloud.

Spray patterns and/or cloud characteristics would be determined from photographic coverage and suitable drop-size measuring equipment.

The nozzle arrays determined to be the most satisfactory would then be tested on fuels in order to determine optimum settings for the various 60° sector cloud H/D ratios.

Phase III--Sector Interaction Tests

The object of Phase III is to determine the interaction between one sector and the adjacent sector and to make the minor adjustments of the nozzle angles and nozzle injector pressures required at the sector interfaces. These tests would be run primarily on water with measurements being made primarily at the interface. A check with the fuels would follow the above water tests.

Phases I, II and III sector testing can all be carried out separately and remotely from the Pilot Facility itself. Sector testing requires that small amounts of fuel/water be used and should proceed rapidly. The results from these sector tests would then be used to determine the final FAX Cell/Pilot Facility configuration/design.

Phase IV--FAX Cell/Pilot Facility Tests

The FAX Cell/Pilot Facility tests are mostly a matter of inspection, assembly, calibration, and checkout of the FAX Cell components (equipment, hardware, plumbing, wiring, etc.) which finally culminates in combined systems tests on water and fuels.

Phase IV must be accompanied with a Detailed Test Plan (DTP) that is supplied by the contractor(s)/agency(s) involved in the construction of the Pilot Facility. The DTP should also be designed around the total system and incorporate the requirements and specifications at all system, subsystem, component, part, etc., levels.

The Phase IV combined systems tests would be performed first using water for cloud H/D ratios of 0.5, 0.4, 0.3, 0.2 and 0.1 (see Table 1). The above water tests would be followed by stoichiometric tests for a cloud H/D ratio of 0.25 (the midrange H/D).

At the discretion of DNA, these fuel tests could also be regarded as the facility acceptance tests. DNA should further determine the advisability of detonating the fuel-air cloud during these fuel tests. If it is decided to detonate the cloud, this fact should be reflected in the DTP and provisions made to evaluate the blast wave measurement system.

2.8 MEASUREMENTS OF DETONATION/BLAST PHENOMENA

Measurement of the propagation rate(s) of the detonation blast wave should concentrate upon the spatial velocities (amplitude and direction) attained by these waves as a function of distance and time. High speed photographic techniques coupled with accurate high response pressure/time-of-arrival gauges, etc., are required as a minimum to adequately describe wave shapes and wave intensities.

Determination of static and dynamic impulse (at ground level) requires additional accurate information with time and distance of static and dynamic pressure in the flow regions corresponding to overpressures of 0.5 to 100 psi.

The blast initiation of detonation waves requires that a certain minimum critical blast energy be supplied or detonation will not occur. Primarily involved is the ignition delay of the explosive mixture. Large ignition delay times result in long ignition delay distances and hence require large blast energies in order to detonate. These large ignition delay times, which are associated with very lean or very rich mixtures, establish the detonation limits for the mixture.

The manner in which the detonation is initiated is also important to the critical energy required, i.e., initiation of planar or one-dimensional detonation waves requires less energy than the initiation of spherical detonations. The initiation energy for cylindrical detonation waves lies between that of the planar and spherical waves.*

Detonation initiation in unconfined fuel-air mixtures has been studied by P. M. Collins of the Eglin Air Force Base, Florida,** wherein the critical energy threshold was "measured as a function of fuel concentration for high explosive blast wave initiation of a gaseous hydrocarbon fuel MAPP, mixed in air, and also for MAPP fuel sensitised with 6% by volume n-propyl nitrate." (MAPP is a welding fuel produced by Dow Chemical Company consisting of approximately 37% methylacetylene, 25% propadiene, 20% propane, 9% propylene, and 9% C_4 compounds by volume.) Collins found that propylene oxide was detonable in a much wider mixture range than either the hydrocarbon or hudrocarbon/n-propyl nitrate fuels.

J. A. Nicholls, et. al., of the University of Michigan studied unconfined explosions for Eglin, wherein both gaseous fuels and kerosene mists were investigated. The experimental work concentrated upon cylindrical detonation waves wherein the kerosene drop size was carefully controlled through a range of 200μ to 600μ. The University of Michigan work most pertinent to this program is listed in Chapter 6 of this report (see Tables 14, 15 and 16, Section 6.7).

The detonation initiation tests would involve the following:

- Initiation techniques
- Gaseous fuels
- Liquid fuels
- Sensitizing agents

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* James Bowen, Naval Weapons Center, China Lake, California, has successfully detonated near-stoichiometric propane-air mixtures using a rule of thumb that 1% of the propane weight is the weight of the HE initiator.

**Patrick M. Collins, "Detonation Initiation in Unconfined Fuel-Air Mixtures," *Acta Astronautica*, Vol. I, (Permagon Press, 1974), pp. 259-266.

These tests, as with the nozzle tests of Phase I, Phase II and Phase III, can be carried out separately from the Pilot Facility. It would be advisable to also carry out these tests concurrently with Phase I and II tests and possibly at the same site so that the nozzle tests could be combined with the initiation tests.

2.9 SCHEDULE FOR DEVELOPMENT

Figure 7 shows a proposed schedule for the development of the Pilot FAX Facility for 10,000 pounds of fuel in separable phases each of which leads to the following phase in a synergistic manner.

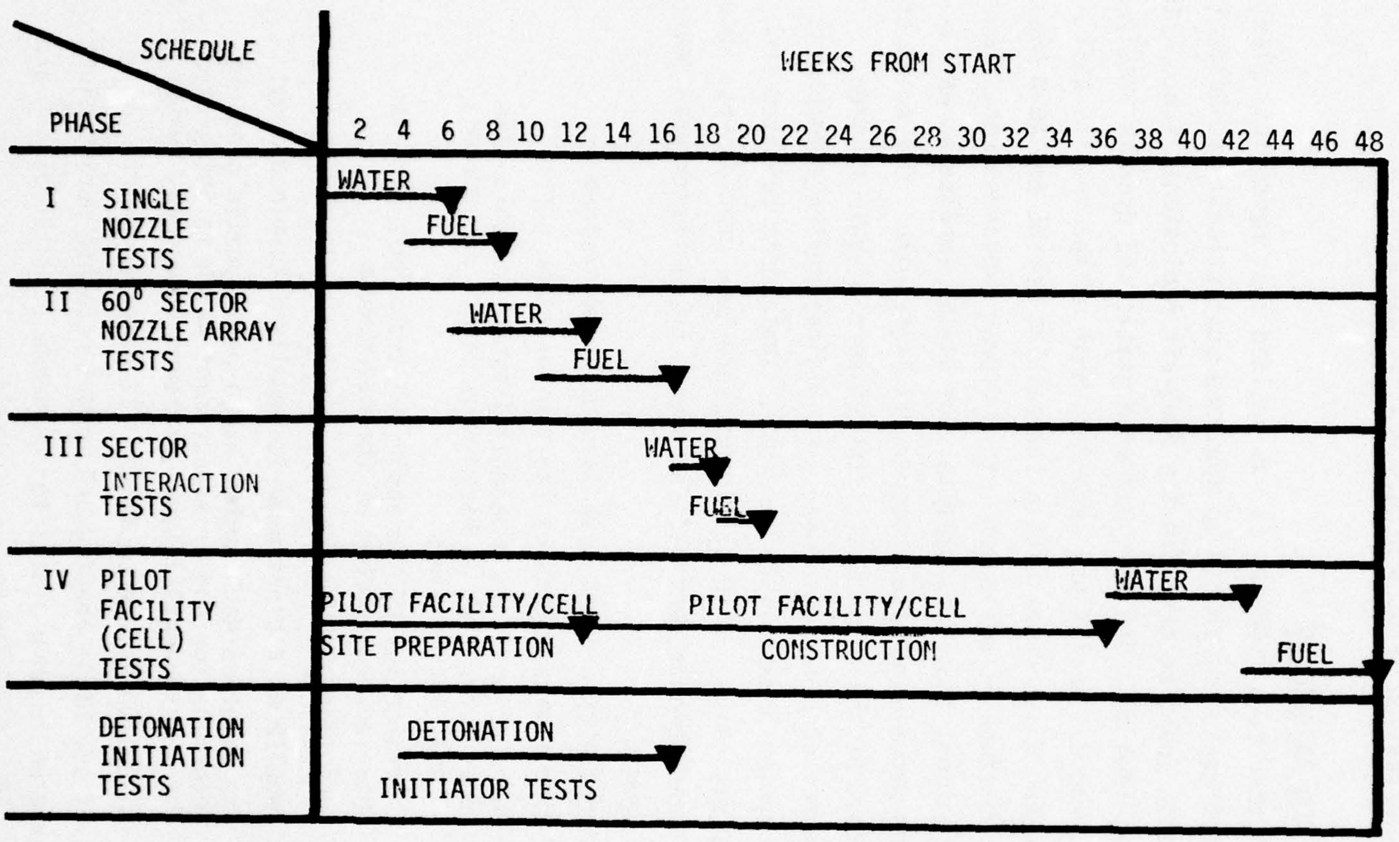

FIGURE 7. PROPOSED SCHEDULE FOR DEVELOPMENT OF PILOT FAX FACILITY (10,000 lb. FUEL)

3. DEFINITION OF USER REQUIREMENTS--TASK II

3.1 METHODOLOGY AND BACKGROUND

To determine user requirements, it was decided that historical blast wave tests on field equipment should be analyzed statistically to determine if such requirements could be met with the fuel-air explosions, i.e., with peak overpressures less than 300 psi, and with static and dynamic impulses in the ranges of from 0.1 to 1.8 psi-seconds. Most of the results available were for nuclear blast waves with a few results for HE and ANFO blast waves. The data obtained is quite complete for peak overpressures. There is adequate information, though incomplete, for static impulse as well. The information on dynamic impulse, however, is inadequate. One point of concern is that most of the equipment(s) tested were of WWII vintage.

The major source of blast wave data was obtained during atmospheric nuclear tests conducted between 1946 and 1957. These data resulted from measurements made exclusively with static pressure-type transducers. Direct dynamic pressure measurements were made in these nuclear tests with several dynamic pressure gauges.*

The static impulse of a blast wave is usually determined by:

° Direct integration of the pressure-time curve

° Integration of an exponential-type, pressure-time decay curve that is based upon direct measurement of peak overpressure

° A combination of the above two techniques with the observed Mach number of the blast wave

° DASA 1200 prepared charts.

The dynamic impulse of a blast wave is usually determined from:

- The observed Mach number and a peak dynamic pressure determination and/or measurement which is integrated for an exponential-type, pressure-time decay curve.
- DASA 1200 Reference Volume III prepared charts.

The effects of air blast loading and target response during blast wave tests are treated in an unclassified government publication** and

* Reference DASA 1200, Appendix 6B, pp. 6-131 to 6-147.

***The Effects of Nuclear Weapons*, (Government Printing Office, 1964).

many classified reports exist for blast wave effects on specific items of equipment. These air blast effects are usually considered under the two general headings of:

1) loading--forces that result from the action of the blast pressure; and
2) response--the distortion of the structure due to the pressure loading.

Under the heading of loading are in turn two subheadings--namely:

a) diffraction loading--the force which exists while the blast wave is being diffracted around the target; and
b) drag (dynamic pressure) loading--the drag force which results from the convective flow around the target.

The general properties of blast waves for the variation of overpressure and dynamic pressure with time at a fixed location in the low pressure region are shown in Figure 8 below. The integration of the overpressure curve from shock-arrival time to the time when the overpressure is equal to the ambient pressure, is defined as the static (pressure) impulse. The corresponding integral for dynamic pressure is defined as the dynamic (pressure) impulse.

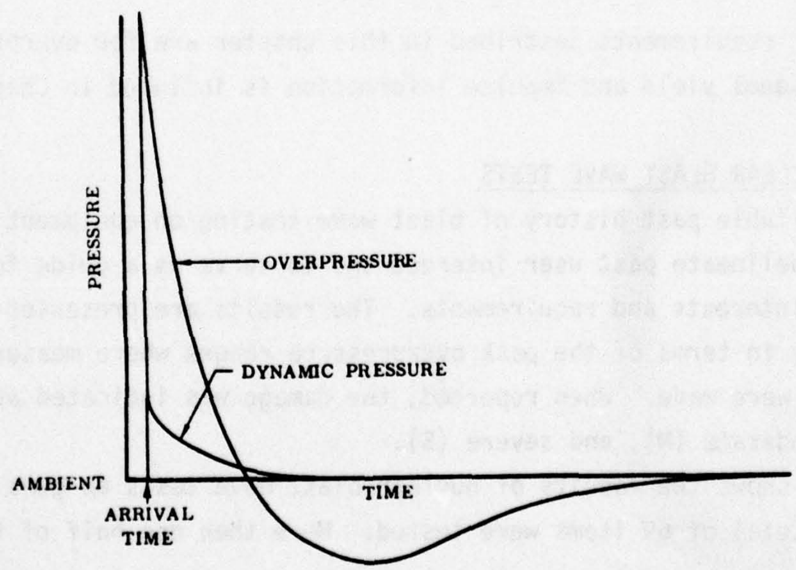

FIGURE 8. THE GENERAL PROPERTIES OF BLAST WAVES

There are several general comments to be made regarding user requirements that relate to the loading and response of targets:

- Diffraction loading analyses usually neglect the reflected shock wave pressures and use only the pressure behind the incident shock, called "side-on pressure."
- Past attention has focused upon peak overpressure and to a lesser extent upon static impulse with little attention given to dynamic impulse.
- The concurrent combined effects of static and dynamic pressures and impulses upon target response need further understanding.
- The current damage classification* of severe, moderate, and light is most insufficient.
- Specification of required peak overpressure without specification of required static and dynamic impulse is almost meaningless inasmuch as the impulse is directly related to yield.

The user requirements described in this chapter are for overpressures only. Additional yield and impulse information is included in Chapter 6.

3.2 PAST NUCLEAR BLAST WAVE TESTS

The available past history of blast wave testing on equipment was surveyed to delineate past user interest and to serve as a guide for future user interests and requirements. The results are presented statistically in terms of the peak overpressure ranges where measurements on equipment were made. When reported, the damage was indicated as light (L), moderate (M), and severe (S).

Table 2 shows the results of nuclear blast wave tests on guns and mortars. A total of 69 items were tested. More than one half of the

* *The Effects of Nuclear Weapons*, (Government Printing Office, 1964), Chapter 4.

items were tested at peak overpressures in excess of 20 pounds per square inch. Light damage was incurred for peak overpressures less than 15 to 20 pounds per square inch. Moderate damage was incurred as overpressures were increased up to a peak overpressure of approximately 40 pounds per square inch. Higher peak overpressures produced severe damage. These results indicate that guns and mortars possess user requirements in the peak overpressure range above 15 pounds per square inch.

TABLE 2. NUCLEAR BLAST WAVE TESTS ON GUNS AND MORTARS[1]

Test Item: Guns/Mortars	No. of Items Tested	[2]Range of Peak Overpressure Measurements (psi) 0-5	5-10	10-20	Over 20
155mm G	9	0	5	0	0
105mm G	9	2	0	1	6
90mm G	16	4	4	2	6
40mm AA	4	2	0	0	2
81mm M	4	2	0	0	2
57mm G	27	0	2	3	22
TOTAL	69	10	11	6	38

[1] Tests conducted from 1946 to 1955.

[2] Summary of resulting damage incurred by peak overpressures:
0 psi < (L) < 15 psi < (M) < 40 psi < (S).

Table 3 shows the results of nuclear blast wave testing on vehicles and trucks. A total of 395 items were tested with the results as shown in this table. Less than 20% of the tests were performed at peak overpressures exceeding 20 pounds per square inch. The range of peak overpressures extending from 5 to 20 pounds per square inch is of most interest in these tests. The data indicated that light damage usually was incurred by peak overpressures under 10 psi and that severe damage was likely to be incurred by peak overpressures greater than 20 psi. These tests indicated the importance of vehicle orientation, ground-surface conditions, and dynamic impulse. It should be noted that 62% of the vehicles and trucks tested were jeeps (listed in Table 3 as 1/4 ton truck).

TABLE 3. NUCLEAR BLAST WAVE TESTS ON VEHICLES AND TRUCKS[1]

Test Item: Vehicles/Trucks	No. of Items Tested	Range of Peak Overpressure Measurements (psi)[2] 0-5	5-10	10-20	Over 20
1/4 ton truck	246	16	86	79	45
2/3 ton truck	5	0	5	0	0
3/4 ton truck	5	2	0	2	0
2 1/2 ton truck	86	4	28	36	8
5 ton truck	9	0	3	6	0
amphib. & auto repair truck	8	4	0	0	4
APC	8	0	4	4	4
LVT	12	0	4	4	4
Light-Armored Car	4	2	0	0	2
ONTOS	12	-	-	-	-
TOTAL	395	28	126	131	65

[1] Tests conducted from 1946 to 1956.

[2] Summary of resulting damage incurred by peak overpressures:
0 psi < (L) < 10 psi < (M) < 20 psi < (S).

Table 4 shows the results of tests conducted on 68 tanks, wherein about one third were tested at peak overpressures exceeding 20 psi. No damage estimates resulting from these tests are available. Except for very large overpressures though, damage to the tank would most likely be light; however, crew injury could be severe for overpressures of more than 10 psi. Injury to tank crews would depend heavily upon the static impulse and the overpressures realized inside the tank from this static impulse, and the "leak" rate into the tank from the outside overpressure.

TABLE 4. NUCLEAR BLAST WAVE TESTS ON TANKS

Test Item: Tanks	No. of Items Tested	Range of Peak Overpressure Measurements (psi) 0-5	5-10	10-20	Over 20*
M46	6	0	1	0	5
M48	35	2	12	10	2
M4A3	1	0	1	0	0
M24	9	2	1	1	5
M4	3	0	0	0	3
M26	14	2	2	2	6
TOTAL	68	6	17	13	21

* 45-700 psi.

Nuclear blast wave tests on 27 aircraft in flight are listed in Table 5. It should be noted that while a total of 214 tests were carried out at peak overpressures known to be under 5 psi, no explicit overpressure measurements listed exceeded 2.7 psi.

Aircraft in flight are very sensitive to dynamic impulse and to aircraft orientation to the blast wave. Aircraft need not be tested for damage while actually in flight, however, to obtain the necessary stress-strain data for calculation of blast wave effects which would occur under more severe conditions: the advanced state of air-frame design permits the use of key stress-strain measurements on spars and skin which can be interpreted in terms of probable aircraft damage. Results of the tests listed in Table 5 indicate that damage was none to slight for the pressure range of 0-2.7 psi. Most in-flight aircraft requirements could likely be met in this range using key stress-strain measurements.

Nuclear blast wave tests were also conducted on parked aircraft, as is shown in Table 6. As with aircraft in flight, the dynamic impulse and aircraft orientation to the blast wave are most important. The use of tie-downs in the proper orientation can greatly enhance the aircrafts' survivability.

TABLE 5. NUCLEAR BLAST WAVE TESTS ON AIRCRAFT IN FLIGHT

Test Item: Aircraft	No. of Items Tested	No. of Tests	**Range of Peak Overpressure Measurements (psi)
A4D	2	30	0.3 to 2.7
B-17	1	5	0 to 5*
XB-47	1	2	0 to 5*
T-33	1	2	0 to 5*
B-36	1	8	0 to 5*
B-47	1	12	0.2 to 0.8
B-66	1	7	0 to 5*
B-50D	3	8	0 to 5*
B-52	3	19	0.2 to 0.88
B-57B	1	28	0.3 to 1.28
F-84	4	26	0.1 to 1.7
F-89D	1	14	0.2 to 0.5
F-100	1	1	0.4
F-101A	1	9	0.3 to 1.2
FJ-4	2	23	0.3 to 1.95
HSS-1(Hel)	1	8	0.18 to 1.1
AD (Drone)	1	5	0.3 to 2.7
A3D-1	1	7	0.12 to 0.67
TOTAL	27	214	

* Tests fell into 0-5 psi range, but no explicit range measurement was given.

** There were no test measurements over 5 psi.

The results of nuclear blast wave tests on parked aircraft are shown in Table 6 which follows.

TABLE 6. NUCLEAR BLAST WAVE TESTS ON PARKED AIRCRAFT

Test Item: Aircraft	No. of Items Tested	No. of Tests for Ranges of Peak Overpressure Measurements (psi)*			
		0-5	5-10	10-20	Over 20
B-29	7	7	0	0	0
B-17	6	20(0.5-4.8)	0	0	0
B-45	1	0	1(6.7)	0	0
F-47	5	23	21	3	2
F-86	2	4	2	2	0
F-90	1	1	2	0	0
TOTAL	22	55	24	5	2

* Summary of resulting damage incurred by peak overpressures:
0 psi < (L) < 2.5 psi < (M) < 4 psi < (S).

Twenty-two aircraft were subjected to 86 tests through a range of peak overpressures from under 1 psi to over 20 psi. Approximately two thirds of the tests were conducted for peak overpressures under 5 psi. Light to moderate damage occurred in the peak overpressure range of 0 to 4 psi, with severe damage to the aircraft occurring at higher peak overpressures.

User interest indicates a requirement in the peak overpressure range of 0 to 10 psi for parked aircraft.

3.3 PAST HIGH EXPLOSIVE BLAST WAVE TESTS

The results of high explosive blast wave tests carried out with TNT upon seven items (APCs and guns) are shown in Table 7. Two measurements were made in the 5 to 10 psi range of peak overpressure and two measurements were made in the 10 to 20 psi range. No damage estimates were available.

The results of the high explosive blast wave tests on tanks are shown in Table 8. Major user interest in these tests appears to be in the over 20 psi peak overpressure range. Again no damage estimates were available.

TABLE 7. HIGH EXPLOSIVE BLAST WAVE TESTS ON APCs AND GUNS

Test Item: APCs/Guns	Explosive: Tons of TNT	No. of Items Tested	Range of Peak Overpressure Measurements (psi) 0-5	5-10	10-20	Over 20
M113A1	500	1	0	0	0	0
M113A1	500	1	0	0	0	0
XM163	500	1	0	1	0	0
XM167	500	1	0	0	0	0
XM198	500	1	0	0	0	0
M109	500	1	0	0	1	0
M110	500	1	0	1	0	0
TOTAL		7	0	2	2	0

TABLE 8. HIGH EXPLOSIVE BLAST WAVE TESTS ON TANKS

Test Item: Tanks	Explosive: Weight	Type	No. of Items Tested	Range of Peak Overpressure Measurements (psi) 0-5	5-10	10-20	Over 20
M48C1	500 lbs.	50/50 pentolite	1	0	1	0	0
M60	20 tons	TNT	1	0	0	0	1
M60	500 tons	TNT	1	0	0	0	1
TOTAL			3	0	1	0	2

The results of high explosive blast wave tests on 23 vehicles and trucks are shown in Table 9. As with the nuclear blast wave tests on vehicles and trucks, tests on jeeps constituted about two thirds of the tests conducted. It would appear that the major user interest of these tests was in the over 20 psi peak overpressure range.

TABLE 9. HIGH EXPLOSIVE BLAST WAVE TESTS ON VEHICLES AND TRUCKS

Test Item: Vehicles/Trucks	Explosive: Weight	Explosive: Type	No. of Items Tested	Range of Peak Overpressure Measurements (psi) 0-5	5-10	10-20	Over 20
1/4 ton jeep	100 tons	TNT	15	0	2	4	9
1/4 ton jeep	.25 tons & 5 tons	TNT TNT	3		NO DATA		
3/4 ton truck	500 tons & 15 M117s	TNT	2?	1	0	0	0
2 1/2 ton cargo carrier	100 tons	TNT	1	0	0	0	2
3 ton Bedford	500 tons	TNT	1	0	1	0	0
M113	500 tons	TNT	1?	0	0	1	2
TOTAL			23	1	3	5	13

3.4 SUMMARY OF TEST RESULTS

The results reported in Tables 2 through 9 above are more appropriately presented as histograms where the statistical distributions are more apparent. These histograms constitute Figures 9 through 14 which are included at the end of this chapter.

Past user interest/requirements for equipment are tabulated in Table 10 according to:

° Prime interest
° Secondary interest
° Tertiary interest
° Some interest
° No interest (none).

This was determined from the number of test item measurements performed in each range of peak overpressures. This table indicates that for all equipment tested, prime interest exists in the 0-5 psi range; secondary interest lies in the 5-10 psi range; and tertiary interest is in the 10-20 psi range. The prime interest for guns, mortars and tanks is in the over 20 psi range.

When all the aircraft tests are excluded from this statistical tabulation, prime interest is noted in the 5-10 psi range; secondary interest is in the 10-20 psi range; and tertiary interest is in the over 20 psi range. Only some interest exists in the 0-5 psi range.

TABLE 10. PAST USER INTEREST/REQUIREMENTS FOR EQUIPMENT

Items Tested	Peak Overpressure Range 0-5 psi	5-10 psi	10-20 psi	Over 20 psi
Guns/Mortars	Tertiary	Secondary	Some	Prime
Vehicles/Trucks	Some	Secondary	Prime	Tertiary
Tanks	Some	Secondary	Tertiary	Prime
Aircraft (in-flight)	Prime	None	None	None
Aircraft (parked)	Prime	Secondary	Tertiary	Some
TOTAL OF ALL EQUIPMENT:	PRIME	SECONDARY	TERTIARY	SPECIFIC*
TOTAL OF EQUIPMENT W/O AIRCRAFT:	SOME	PRIME	SECONDARY	TERTIARY

* Prime interest range for guns, mortars and tanks.

Presentation of these data upon a peak overpressure versus distance plot for a one-kiloton nuclear blast (100 tons of fuel equivalent) is shown in Figure 15, included at the conclusion of this chapter. Also shown there, in Figure 16, are the scaled distances for the 10,000-pound fuel FAX Pilot Facility. The spatial dispersion of interests indicate the adequacy of such a proposed facility. Hardening of equipment for higher overpressures would compact the testing areas toward shorter ranges and tighter test conditions.

These results have been presented in terms of peak overpressure measurements for tests performed on selected equipment. It should be noted that no data has been analyzed for C^3 equipment and that the targets have not been characterized according to their sensitivity to overpressure/static impulse/dynamic impulse. The Naval Weapons Center at China Lake, California, feels that impulse sensitive targets are of first priority for future blast wave testing.* It should also be noted that no data have been analyzed for surface structures.

Table 11, taken from *The Effects of Nuclear Weapons*, shows that the interest for most structural type blast wave testing would be in the 0-5 psi peak overpressure range.

TABLE 11. CONDITIONS OF FAILURE OF PEAK OVERPRESSURE SENSITIVE ELEMENTS**

Structural Element	Failure	Side-on Blast Overpressure[1]
Glass windows, large & small	Shattering usually, occasionally frame failure	0.5-1.0 psi
Corrugated asbestos siding	Shattering	1.0-2.0 psi
Corrugated steel or aluminum paneling	Connection failure followed by buckling	1.0-2.0 psi
Brick wall panel, 8 in. or 12 in. thick (not reinforced)	Shearing and flexure failures	7.0-8.0 psi
Wood siding panels, standard house construction	Usually failure occurs at the main connections allowing a whole panel to be blown in	1.0-2.0 psi
Concrete or cinder-block wall panels, 8 in. or 12 in. thick (not reinforced)	Shattering of the wall	2.0-3.0 psi

[1] Side-on blast overpressures listed are approximate.

The histograms comprising Figures 9-16 previously referred to in this chapter follow.

* Conversation with Mr. James Bowen, Director of Fuel-Air Developments, Naval Weapons Center, China Lake, California.

***The Effects of Nuclear Weapons*, U.S. Government Printing Office, Feb. 64.

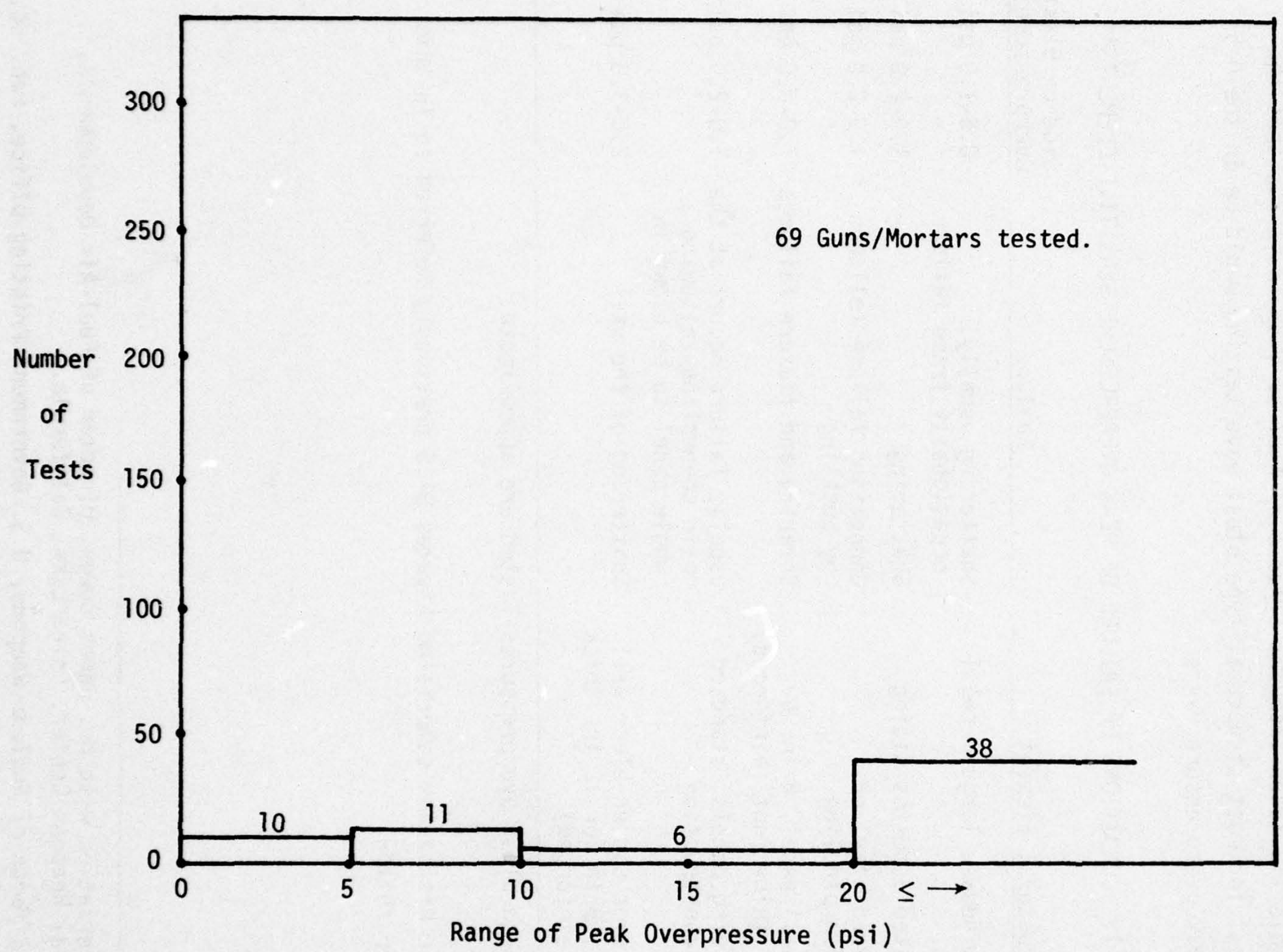

FIGURE 9. HISTOGRAM OF NUCLEAR BLAST WAVE TESTS ON GUNS/MORTARS

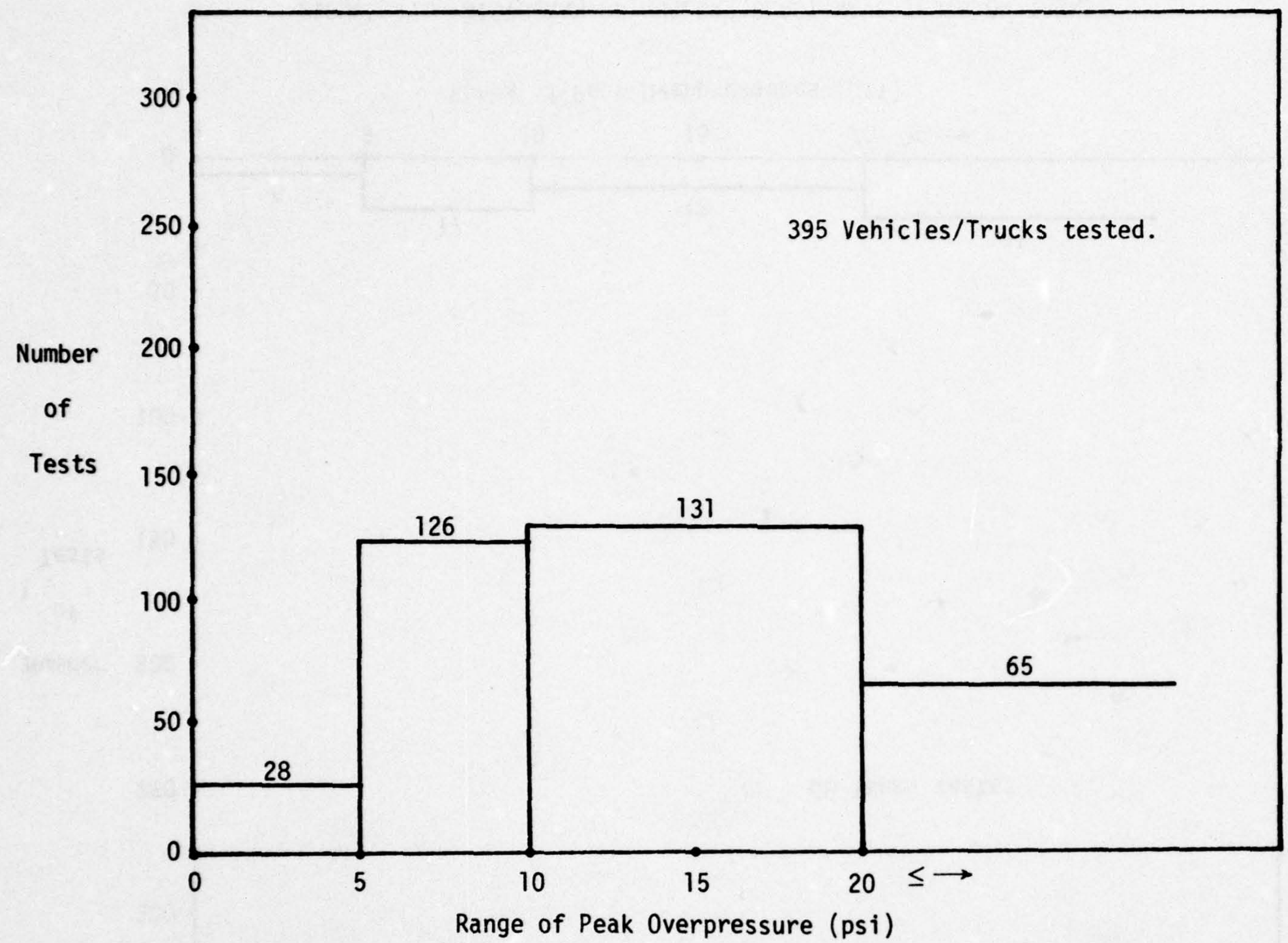

FIGURE 10. HISTOGRAM OF NUCLEAR BLAST WAVE TESTS ON VEHICLES/TRUCKS

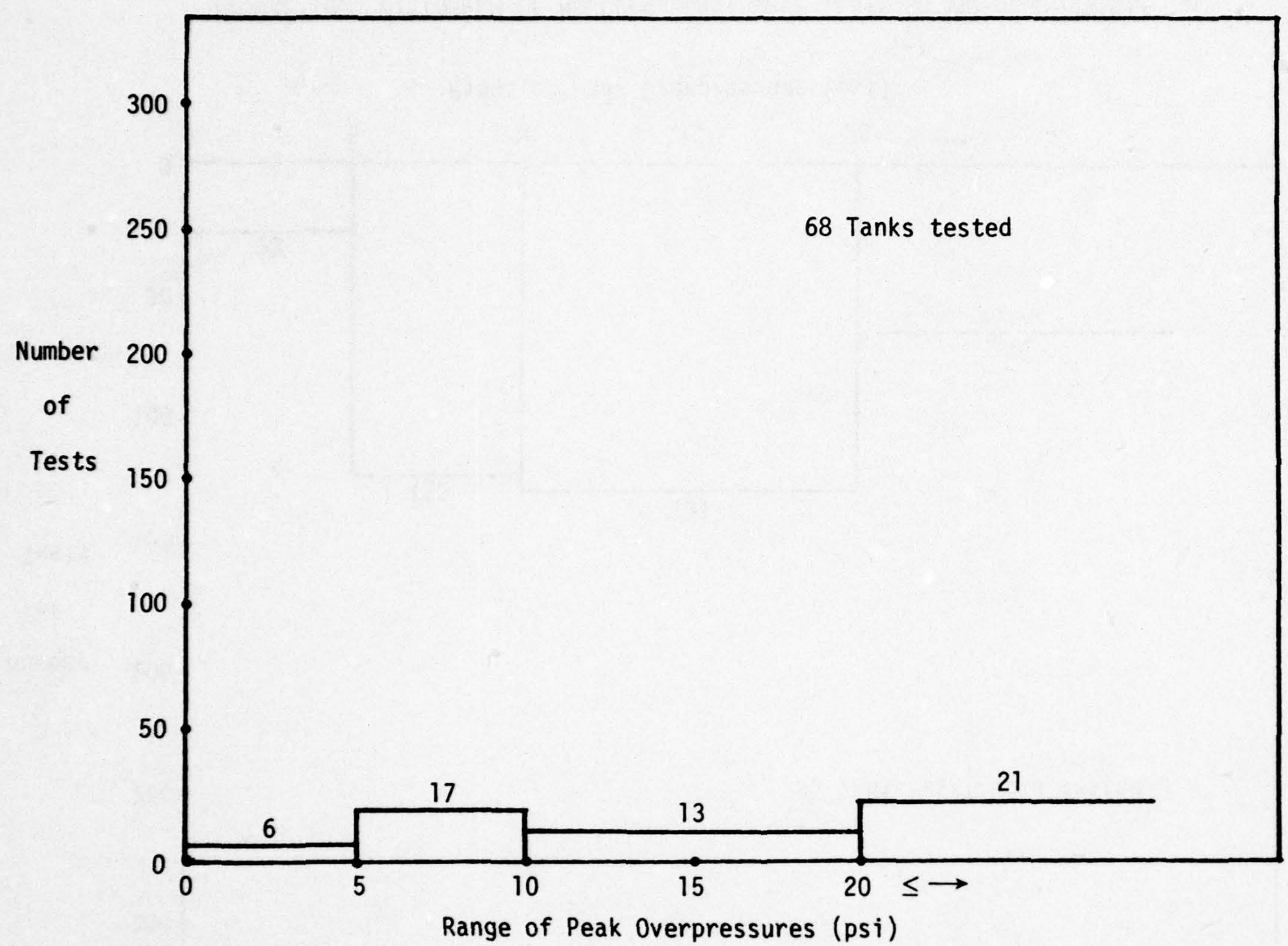

FIGURE 11. HISTOGRAM OF NUCLEAR BLAST WAVE TESTS ON TANKS

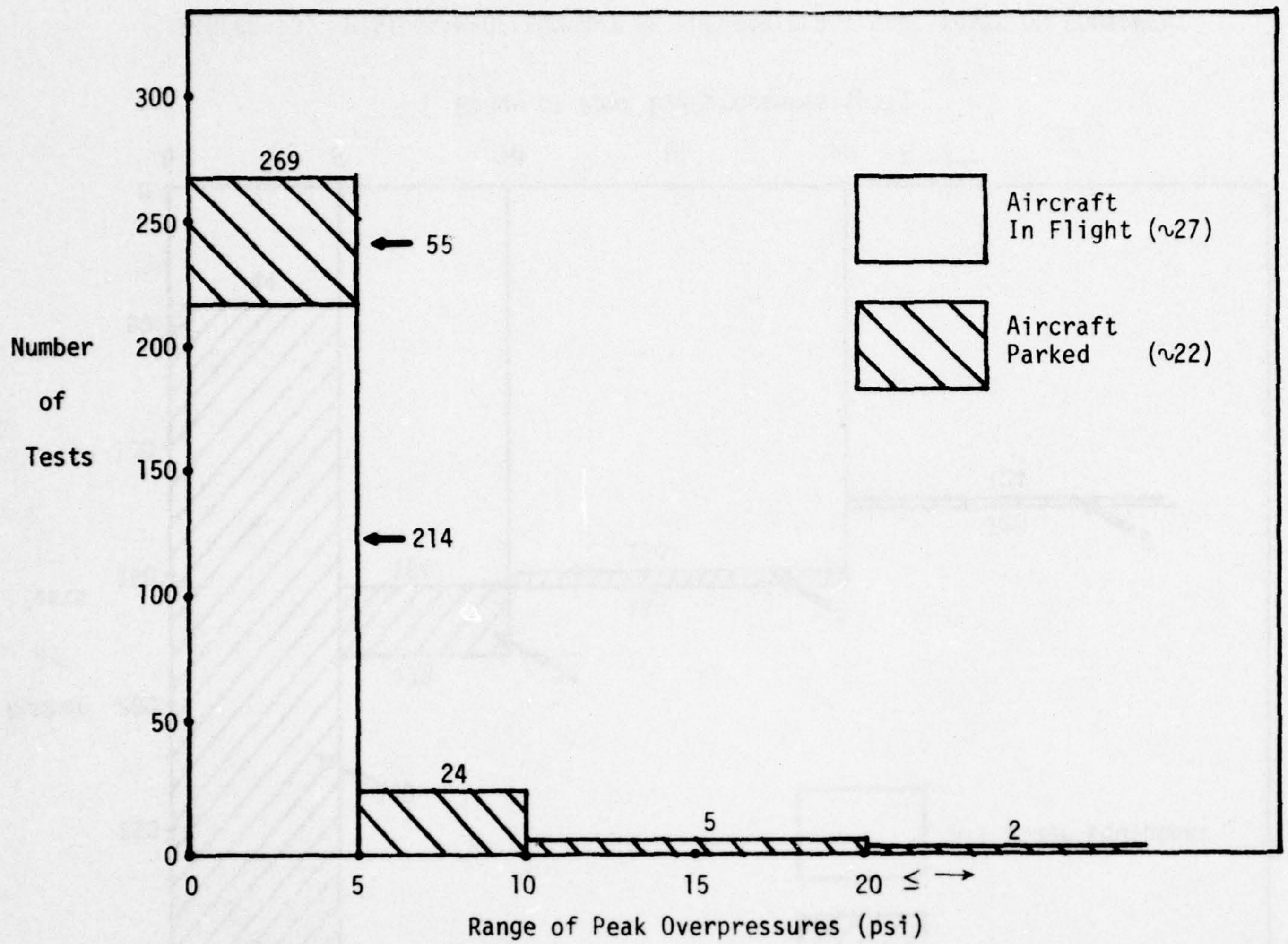

FIGURE 12. HISTOGRAM OF NUCLEAR BLAST WAVE TESTS ON AIRCRAFT

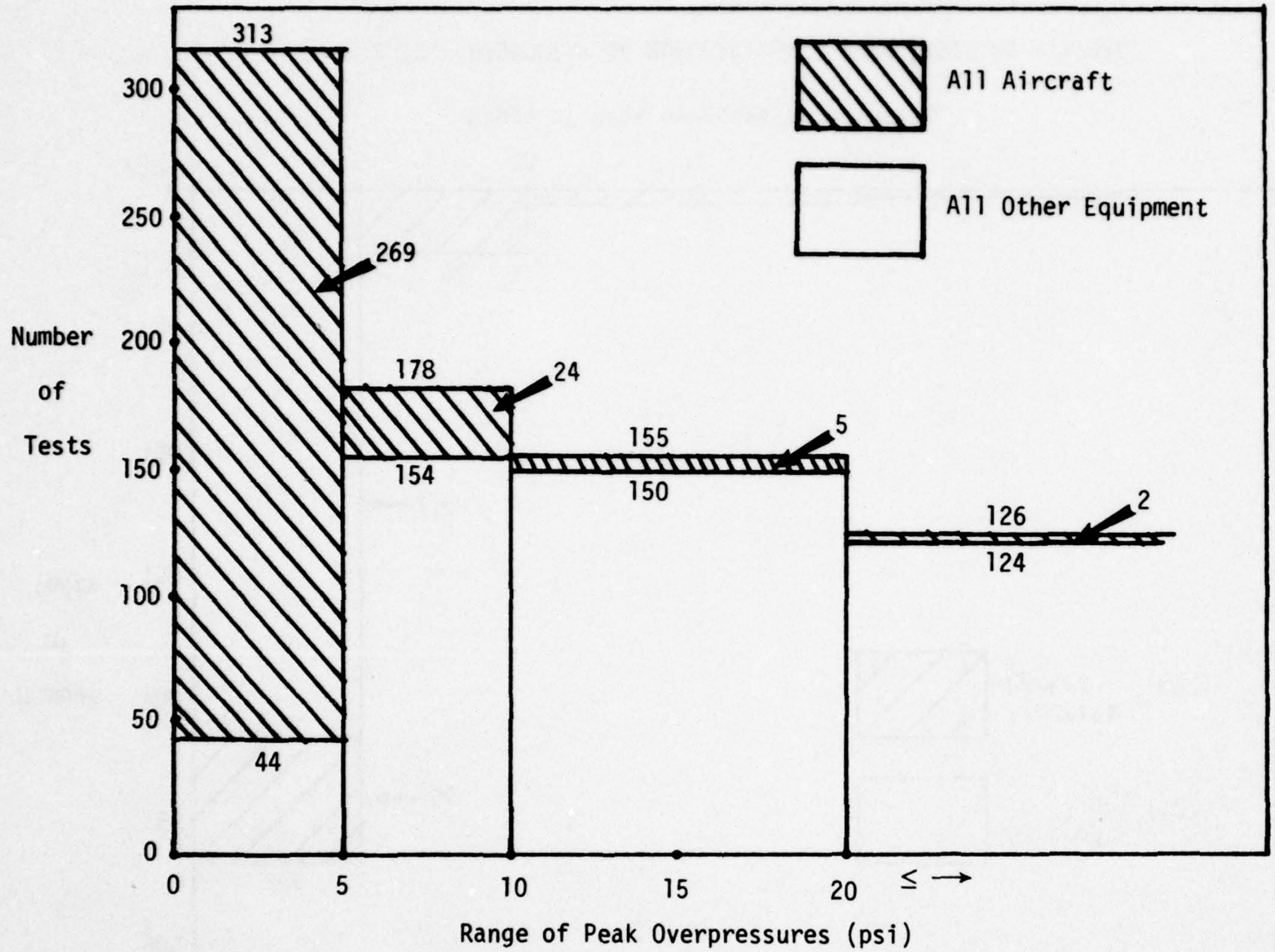

FIGURE 13. HISTOGRAM OF SUMMARY OF NUCLEAR BLAST WAVE TESTS ON EQUIPMENT

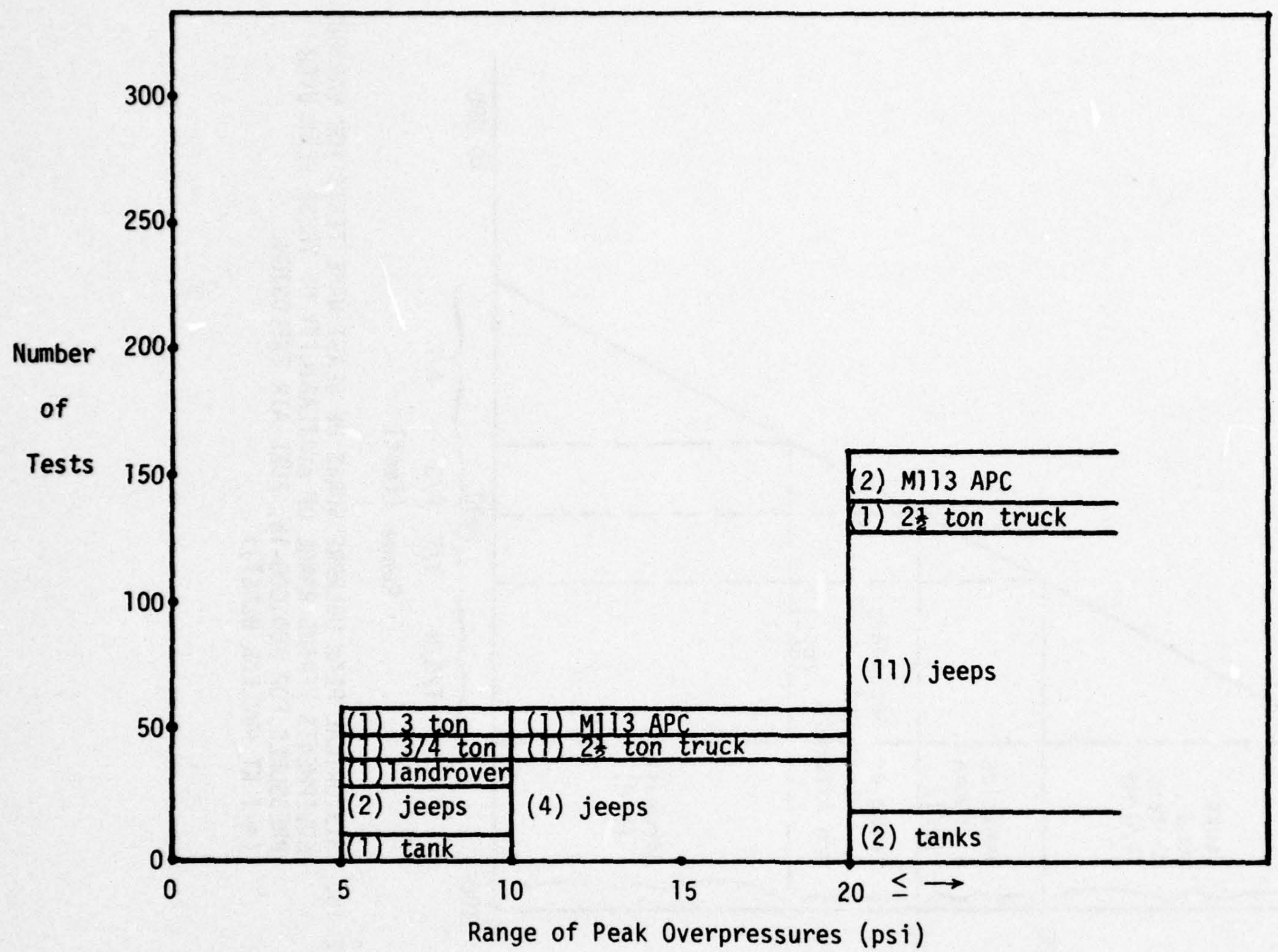

FIGURE 14. HISTOGRAM OF HE/ANFO BLAST WAVE TESTS ON VEHICLES/TANKS

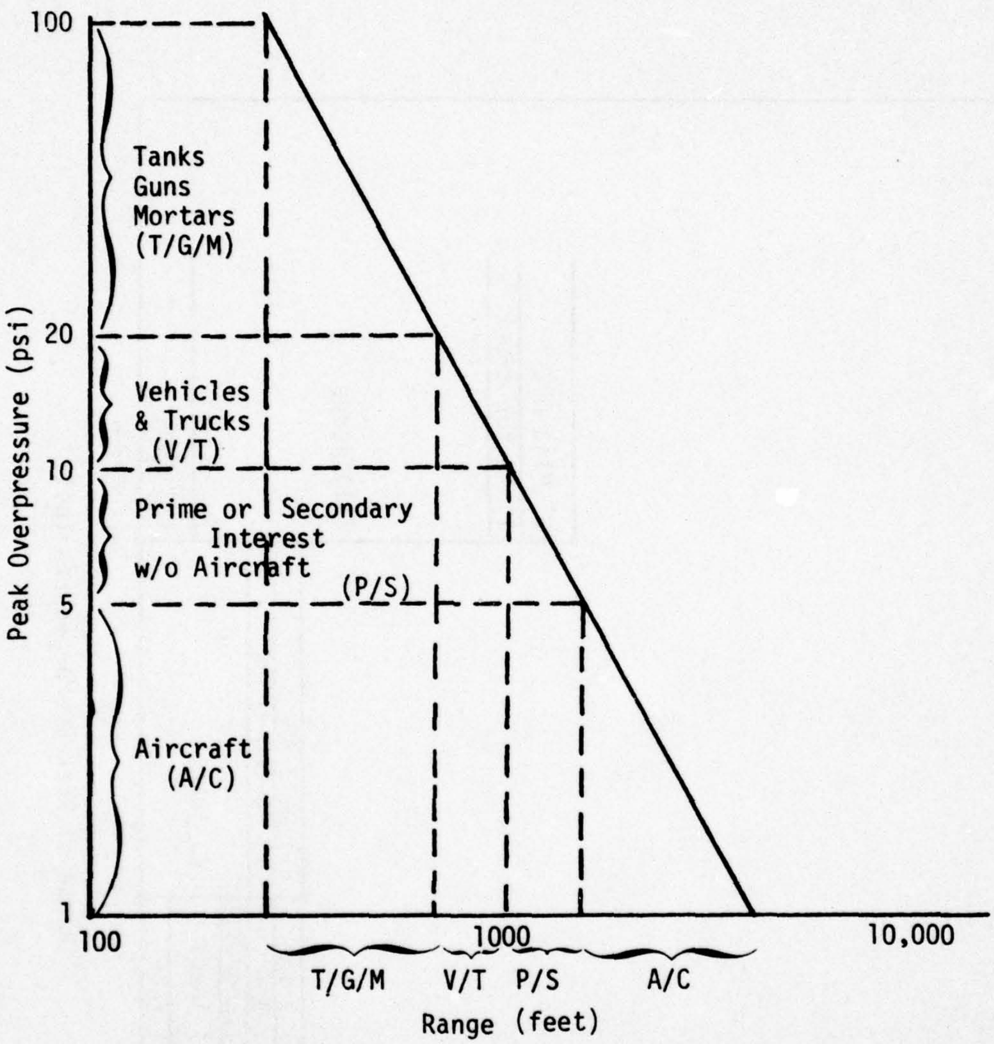

FIGURE 15. HISTORICAL PEAK OVERPRESSURES OF BLAST WAVE TESTS FOR VARIOUS EQUIPMENTS VERSUS RANGE OF AVAILABILITY OF THESE PEAK OVERPRESSURES FOR 200,000-lb. FUEL-AIR EXPLOSION. (≈1 KT NUCLEAR BLAST).

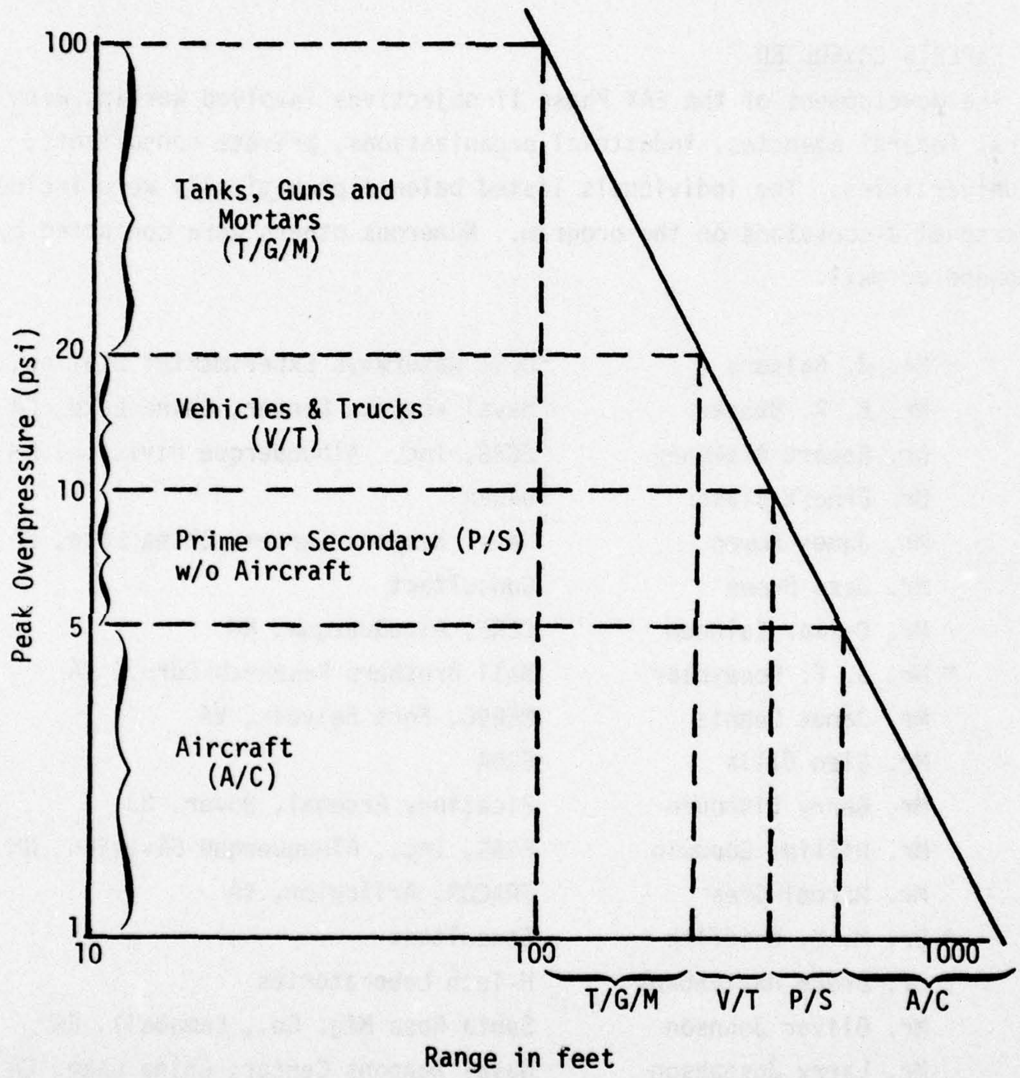

FIGURE 16. HISTORICAL PEAK OVERPRESSURES OF BLAST WAVE TESTS FOR VARIOUS EQUIPMENTS VS. RANGE OF AVAILABILITY OF THESE PEAK OVERPRESSURES FOR 10,000-lb. FUEL-AIR PILOT FACILITY EXPLOSION.

4. CONTRACTOR/AGENCY/EQUIPMENT IDENTIFICATION--TASK III

4.1 EXPERTS CONSULTED

The development of the FAX Phase II objectives involved working with several federal agencies, industrial organizations, private consultants, and universities. The individuals listed below alphabetically were included in personal discussions on the program. Numerous others were contacted by telephone or mail.

Mr. J. Balsara	U.S. Waterways Experimental Station, MI
Mr. B. R. Bessee	Naval Weapons Center, China Lake, CA
Dr. Robert Blakeney	EG&G, Inc., Albuquerque Division, NM
Dr. Ernest Blase	DARPA
Mr. James Bowen	Naval Weapons Center, China Lake, CA
Mr. Jess Brown	Consultant
Mr. Delmar Calhoun	CERF, Albuquerque, NM
* Mr. J. F. Coneybear	Ball Brothers Research Corp., VA
Mr. James Dennis	MERDC, Fort Belvoir, VA
Mr. Glen Ellis	ERDA
Mr. Barry Fishburn	Picatinny Arsenal, Dover, NJ
Mr. William Goodwin	EG&G, Inc., Albuquerque Division, NM
Mr. Marcel Gres	TRACOR, Arlington, VA
* Dr. M. E. Griffith	Consultant
Dr. Bruce Hartenbaum	H-Tech Laboratories
Mr. Oliver Johnson	Santa Rosa Mfg. Co., Campbell, CA
Mr. Larry Josephson	Naval Weapons Center, China Lake, CA
Mr. John Keefer	Aberdeen Proving Ground, Aberdeen, MD
Dr. C. N. Kingery	Aberdeen Proving Ground, Aberdeen, MD
Mr. William Kurth	Santa Rosa Mfg. Co., Campbell, CA
* Mr. C. C. Lutman	Ralph M. Parsons Co., Washington, D.C.
Dr. Edward Marram	Geocenters
* Mr. Cord Mounkes	EG&G, Inc., Albuquerque Division, NM
Dr. J. A. Nicholls	University of Michigan

Mr. A. H. Piantes	Aerojet Liquid Rocket Co.
Lt. Dennis Rawley, USN	NATC, Patuxent River, MD
Mr. William Reniecke	AVCO
Mr. Kenneth Reusser	Universal Systems, Inc.
Dr. D. R. Richmond	Lovelace Foundation
* Mr. C. F. Riley, Jr.	TRACOR, Arlington, VA
Mr. James Rowe	Aerojet Liquid Rocket Co.
Mr. R. T. Sedgwick	Systems, Science & Software, La Jolla, CA
Mr. George Sisson	DCP
Dr. Norman Slagg	Picatinny Arsenal, Dover, NJ
Mr. H. D. Smith	Ball Brothers Research Corp., VA
Dr. Martin Summerfield	Princeton Combustion Laboratories

4.2 FAX ADVISORY GROUP

An advisory group[1] was formed of senior-type personnel with extensive experience in the operation and construction of facilities of the type represented in the ultimate 200,000-pound fuel FAX facility. This advisory group met several times during the preparation of this Study and the results of these meetings were reported in MSA's Bimonthly Reports to DNA for the periods of 23 February-25 June and 25 June-2 September, 1976. The FAX advisory group's conclusions and recommendations are summarized below.

- The use of a fuel-air detonation facility is recommended as the best and most cost-effective means for simulation of nuclear blast waves in the range of peak overpressures of 0-100 psi.
- The use of the 10,000-pound fuel experimental facility is recommended as the means for developing weapons in the intermediate-size range between the iron bomb and small nuclear weapons.
- A better definition of user requirements is needed which would be based on static and dynamic impulse as well as peak overpressure.

[1] Those individuals designated with (*) in the above list attended the initial meeting held 23 March 1976.

- A step-wise approach is recommended in the development of the facility, i.e., 1) the nozzle pilot tests, followed by 2) the 10,000-pound fuel experimental facility, and 3) the design of the 200,000-pound fuel facility.
- The application of the expertise and technology needed for Project FAX is recommended--as it already exists, is well-developed and could thus be used immediately to to advantage.

4.3 SITE EVALUATION

A cursory telephone survey was made of possible U.S. locations that could accommodate a fuel-air detonation using 1,000 pounds of fuel, which is approximately equivalent to 5,000 pounds of HE/ANFO. Several possibilities were found, but of course no attempt was made at this early stage to elicit any commitment. This search narrowed down to two leading candidates: The Naval Weapons Center at China Lake, and Kirtland Air Force Base. Both of these facilities were visited by MSA to evaluate capabilities as well as the supporting industry. The results of these visits delineated the following:

Naval Weapons Center, China Lake:

1) No practical limits on the size of fuel-air detonation
2) Currently engaged in instrumented FAE bomb tests
3) Currently engaged in large LP fuel spill tests with the USCG
4) All instrumentation, data collection, photographic, etc., available and being used.

Kirtland Air Force Base, Albuquerque, NM:

1) Probable limit on the size of fuel-air detonations (i.e., under 1,000 pounds of fuel). ERDA facilities are being erected close to existing fuel-air detonation facilities.
2) Not currently engaged in larger fuel-air detonation work. Lovelace, being primarily interested in the biological aspects of explosions, uses small charges.

3) There is good in-house technical support.

4) There is little outside industrial support--except for instrumentation and EMP expertise, which is excellent.

MSA was impressed with the enthusiasm and positive approach to the FAX concept encountered at the Naval Weapons Center in China Lake. The Naval Weapons Center, with its outside industrial support, may well be the most appropriate site for the FAX Pilot Facility and possibly for the Full-Scale Facility as well.

4.4 CONTRACTOR INFORMATION

Of the many prospective agencies/contractors which provided information on their capabilities, the Santa Rosa Manufacturing Co.* was of particular interest to MSA. The Santa Rosa Mfg. Co. had recently delivered over 50 nozzle units to China Lake to be used on their fire fighting trucks. These nozzles are identical with those considered here for FAX application. A visit to the company to determine the applicability of their fire nozzles for use in FAX testing revealed that they carry a complete line of equipment which meets the requirements for a FAX sector and cell facility design.

O. M. Johnson, Inc.,** the parent company of Santa Rosa Mfg. Co., was also visited to determine their capabilities for the manufacturing of other components of the FAX facility. Their capabilities were found to be complete. O. M. Johnson, Inc. has been in the business for more than 50 years supplying missile, aircraft, and ordnance fields with machine work. These companies comprise some of the outside industrial support, cited in the previous section, which is available to the Naval Weapons Center and was a contributing factor in MSA's recommendation of China Lake as the most appropriate site for the FAX Pilot Facility.

Numerous other corporate qualification brochures and various individual resumes obtained by MSA from parties interested in the FAX facility are being provided to DNA under separate cover.

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* The Santa Rosa Manufacturing Co., 715 McGlincey Lane, Campbell, CA, 95008.

** O. M. Johnson, Inc., 320 W. San Carlos, San Jose, CA, 95110.

5. EXPERIMENTAL FACILITY DESIGN--TASK IV

5.1 GENERAL

The experimental facility design is based on 10,000 pounds of fuel being discharged into the air in approximately 5 seconds to produce a detonable fuel-air cloud with a nominal radius of 100 feet (∿30 m.). The facility should be hardened to withstand the maximum overpressures produced in the detonation of the cloud, i.e., 300 psi. This facility would be operated from a remote site approximately 1,000 feet (∿305 m.) distant from the cloud center and, if possible, upwind of the prevailing winds. This "control room" would also serve as the communications and data gathering center. Although the nominal one pound per square inch peak overpressure point would occur at a radius of 250 feet (∿76 m.), this remote "control room" should be hardened to withstand peak overpressures of 10 psi.

5.2 PAD AREA SPECIFICATIONS

The pad area requires a fourteen-foot (∿four-meter) diameter circular pit, which is thirteen feet deep and meets the following specifications:

- Two-foot (∿60 cm.) reinforced concrete walls.
- A two-foot reinforced concrete apron extending into the pit.
- A six-foot (∿two-meter) apron extending outward from the pit.
- Two below-grade access ways into the pit.
- A one-foot thick (∿30 cm.) reinforced concrete floor with a sump drain to the outside.
- Twelve one-foot diameter thimbles located around the pit with two thimbles per 60° sector.
- Multiple 110/220/440 volt electric current outlets with fastenings/hangers, such as Unistrut, for mounting equipment, meters, instrumentation, etc., in the pit.
- Lighting around the pit perimeter and apron areas.

5.3 TANK SPECIFICATIONS

The fuel tank, which also serves as the pressure vessel, has the following specifications:

- A 300 cubic-foot capacity for a normal working pressure of 500 psi.
- All-steel construction.
- A top-mounted flange of approximately six-inch diameter to accommodate gas generators.
- Top and bottom flange connections to accommodate a twelve-inch standpipe and bottom access.
- A top flange connection to accommodate a burst diaphragm.
- A top flange to receive the pressure relief valve.
- A two-inch pneumatic connection (to be used for charging).
- Four mounting legs.

5.4 PRIMARY FUEL DISTRIBUTION MANIFOLD SYSTEM

The primary fuel distribution manifold provides the connection between the standpipe and the six secondary fuel distribution manifolds. Although an abrupt right angle turn is shown in the drawing (bottom of Figure 17, at the end of this chapter), a more gentle turn will be required to reduce the pressure losses. Listed below are the specifications for this manifold:

- Made of light-weight aluminum or magnesium alloy for 500 psi service.
- A bottom flange mounted to standpipe.
- Six radial outlets on 60° centers of 3½-inch size.
- Six 3½-inch, quick-opening, shut-off valves--500 psi service.
- Six 3½-inch throttling valves--500 psi service.
- Six male fire hose connectors.
- Six connecting lines approximately five feet long to mate the secondary distribution system.

5.5 SECONDARY FUEL DISTRIBUTION MANIFOLD SYSTEM

The secondary fuel distribution manifold system provides the connection between the primary distribution system and the sector nozzles. In the drawing (see Figure 18 at the end of this chapter), a three-nozzle array is shown. However, provision should be made to accommodate four or five. The specifications for one 60° sector are:

- Manifold to be made of light-weight aluminum or magnesium alloy for 500 psi service.
- Pedestal mounted on the pad apron.
- 3½-inch inlet connector.
- Five 3½-inch flange outlets.
- Three to five connecting lines to mate with the nozzle units.
- A two-inch top access flange (to be used when charging the system with fuel).
- Three to five nozzle units of the type illustrated in Figure 3 (shown on page 19) of a Santa Rosa Mfg. Co. M3-DS MONITOR.
- Three to five adjustable pedestals providing a vertical three-inch pipe flange mount.

5.6 GAS PRESSURIZATION SYSTEM

Although the eventual experimental facility may possess a separate gas pressurization or gas generator system, the original mode of operation will utilize the provided tank head-space/volume to contain the compressed gas for the blowdown tests of the nozzle arrays (see Figure 17).

Charging with air or nitrogen would be accomplished on-site by mobile compressor units and/or tankers.

5.7 REMOTE FACILITY

The remote facility "control room" is to be located approximately 1,000 feet from the experimental facility and should meet the following general specifications:

- Have 1,000 square feet of floor space.
- Be hardened to withstand 10 psi peak overpressure.
- Provide a service tunnel or trench extending 1,000 feet to the experimental facility which would contain remote control lines, hardware, instrumentation lines, communication lines, etc.
- Be equipped to supply water, electrical, toilet, emergency shower, etc., services for ten people.
- Contain floor service tunnels/trenches for easy connection to control, instrumentation, and communication panels.
- Provide a fenced-in parking and storage area of approximately 15,000 square feet.

5.8 ESTIMATED CONSTRUCTION COSTS

The following over-all estimate was made of construction costs for the FAX experimental facility:

Basic Pad Facility--including the manifolds, valves, nozzles, electrical service, etc.	$107,000
Remote Site Control Center--including connecting instrumentation, tunnel/trench, electrical, mechanical services, etc. (No furnishings, test panels, etc, were included in this estimate.)	$115,000
Total estimate of constuction costs.	$222,000

5.9 GENERAL LAYOUT

Figures 17 and 18 provide rough schematics of the general layout of the 10,000-pound fuel experimental FAX facility. As was previously discussed in Chapter 2, the exact locations/angles, etc., of the nozzles will be determined during the experimental program. The pure simplicity of the facility, however, should be noted.

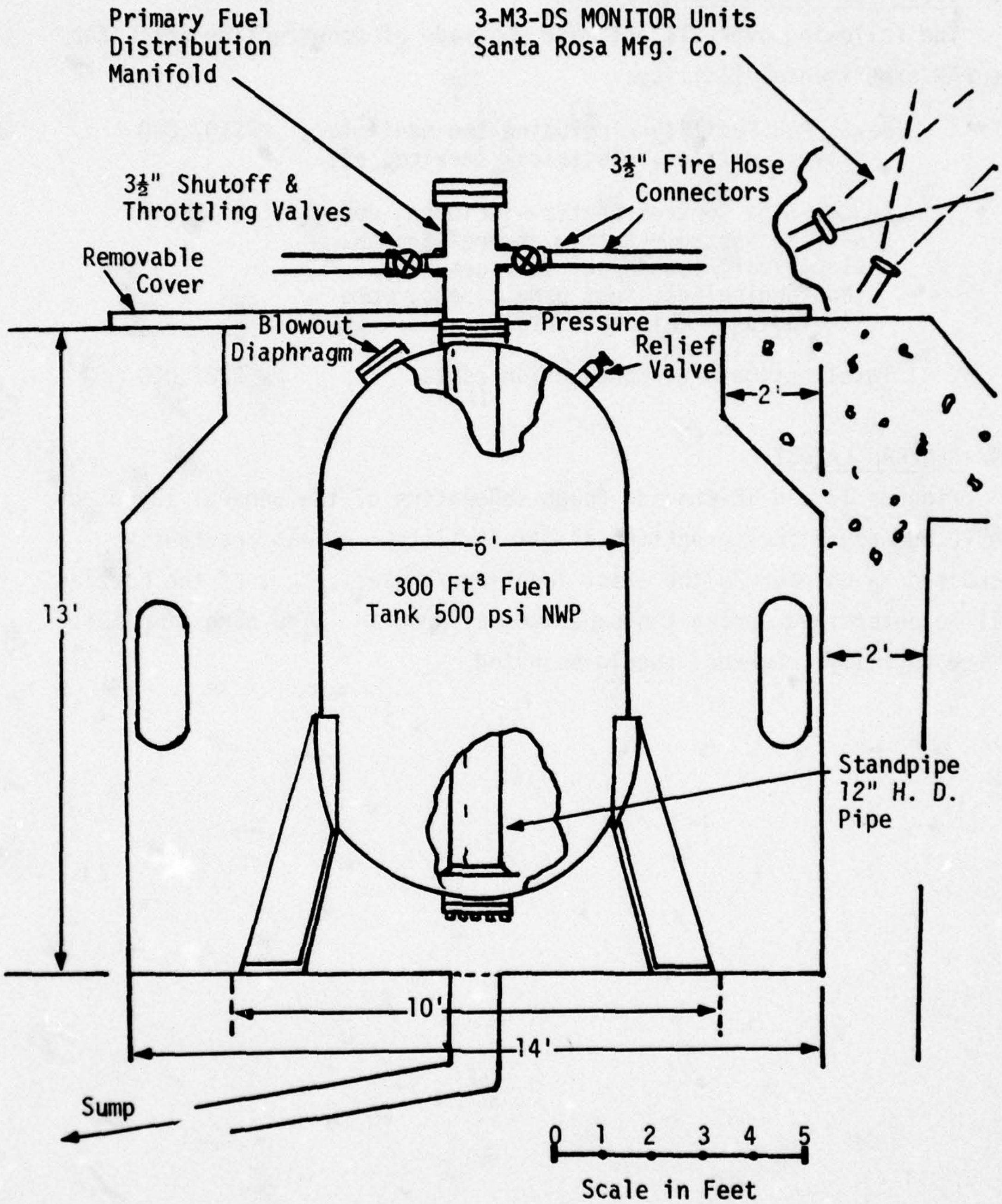

FIGURE 17. ROUGH SCHEMATIC SECTION VIEW OF EXPERIMENTAL FACILITY PAD

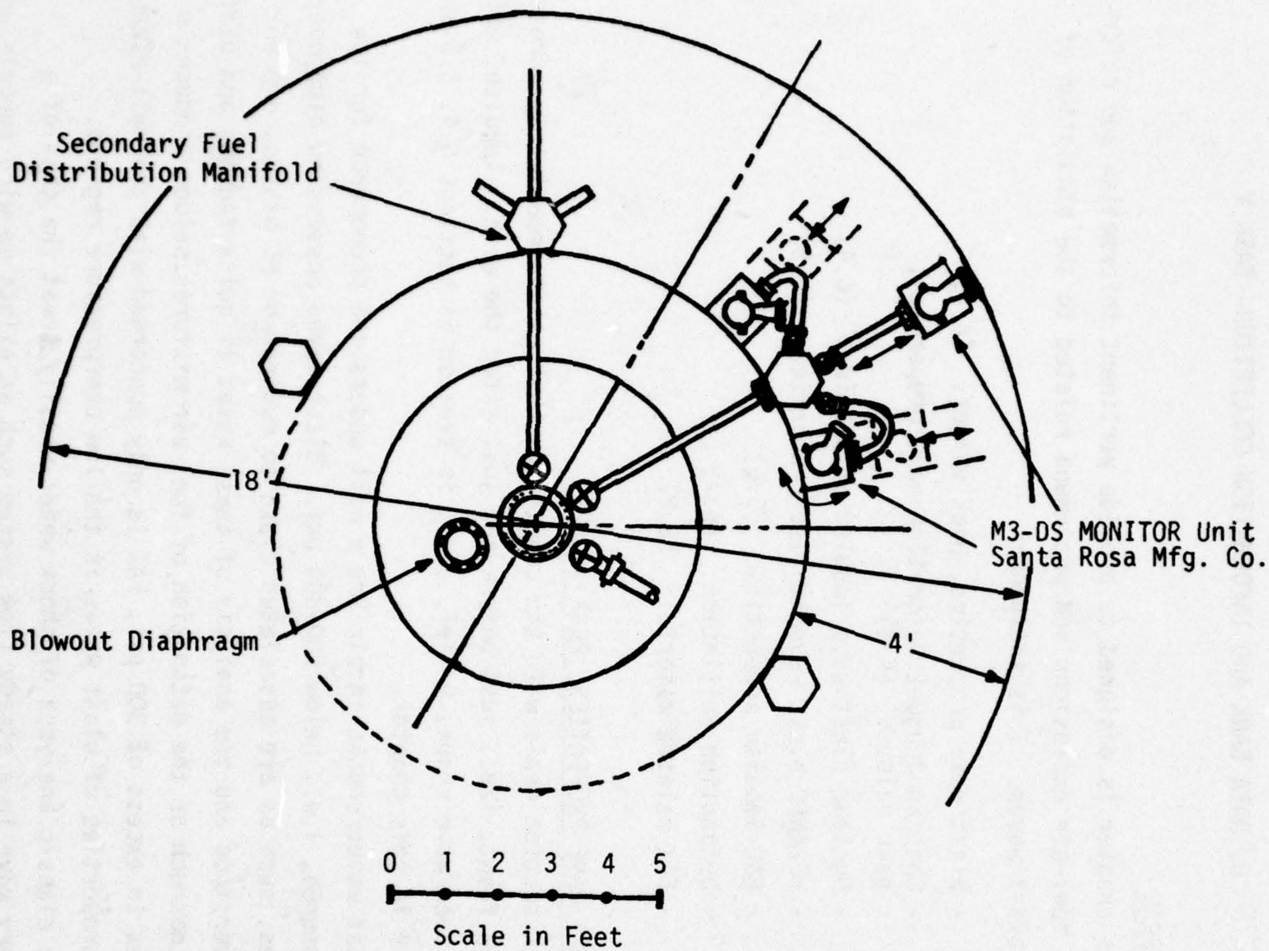

FIGURE 18. ROUGH SCHEMATIC PLAN VIEW OF EXPERIMENTAL FACILITY PAD

6. DATA BANK AND INFORMATION COLLECTION--TASK V

6.1 GENERAL

This chapter is designed to provide pertinent information and references on fuel-air explosions and phenomena related to the simulation of nuclear blast waves. This includes:

- Blast wave properties, peak values. (6.2)
- Chapman-Jouguet detonation wave properties, peak values. (6.3)
- Nuclear blast wave impulse properties. (6.4)
- HE/ANFO blast wave impulse properties. (6.5)
- FAE impulse properties. (6.6)
- Detonation Initiation. (6.7)
- FAX related material. (6.8)

6.2 BLAST WAVE PROPERTIES, PEAK VALUES

This section deals with the conditions that exist immediately across the shock front, i.e., just before and just after the wave. Impulse, which depends upon wave shape, relief, etc., is treated in sections 6.4, 6.5 and 6.6 later in this chapter.

Blast waves/shocks in air are a well understood phenomenon for low overpressures, i.e., below 200-300 psi. Blast waves possessing high overpressures, such as are associated close to nuclear or HE blasts, are not as well understood and the analysis of these waves is quite tedious and difficult. Inasmuch as the detonation of fuel-air mixtures seldom produces overpressures in excess of 300 psi, FAX is only concerned with the well-established properties of blast waves in the low overpressure regions.

The classic analyses of shock waves usually treat the case of a stationary wave in a steady flow system such as exists in wind tunnels and in the flow around aircraft, i.e., an Eulerian system of coordinates. It is more appropriate for the case of blast waves that result from explosions to treat a "traveling" wave in a Lagrangian system of coordinates. Furthermore, it would be desirable if all wave properties could be related to one variable such as the wave Mach number.

One such set of solutions* that treated "traveling" waves is summarized below.

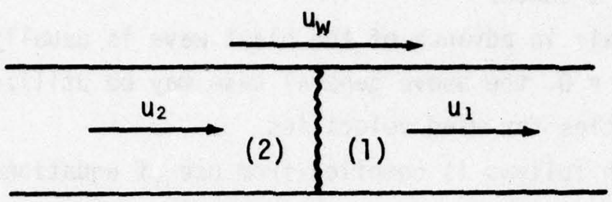

FIGURE 19. TRAVELING ONE-DIMENSIONAL WAVE

Figure 19 shows a one-dimensional wave traveling at a velocity of u_w, traversing a gas moving at the velocity of u_1, with the gas following the wave moving at a velocity of u_2.

Solution of the conservation equations in conjunction with the perfect gas-state equation gives the following relations for shock/blast waves:

$$\frac{p_2}{p_1} = 1 + \frac{2\gamma}{\gamma+1}\left(M_{S1}{}^2-1\right) \qquad [6.2\text{-}1]$$

$$\frac{\rho_2}{\rho_1} = \frac{1}{1 - \dfrac{2}{\gamma+1}\,\dfrac{\left(M_{S1}{}^2-1\right)}{M_{S1}{}^2}} \qquad [6.2\text{-}2]$$

$$\frac{T_2}{T_1} = \left\{1 + \frac{2\gamma}{\gamma+1}\left(M_{S1}{}^2-1\right)\right\}\left\{1 - \frac{2}{\gamma+1}\,\frac{\left(M_{S1}{}^2-1\right)}{M_{S1}{}^2}\right\} \qquad [6.2\text{-}3]$$

$$M_{21S} \equiv \frac{u_2-u_1}{a_1} = \frac{2}{\gamma+1}\left(M_{S1} - \frac{1}{M_{S1}}\right) \qquad [6.2\text{-}4]$$

Where: p = pressure $\quad \rho$ = density $\quad \gamma$ = ratio of specific heats

T = temperature $\quad a$ = speed of sound $\quad M_{S1}$ = Mach number of the blast wave relative to the air at (1)

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* "Combustion", Alexander Weir, Jr., Richard B. Morrison, and Thomas C. Adamson, University of Michigan, 1956.

and: (1) denotes conditions immediately in front of the wave,

(2) denotes conditions immediately behind the wave,

(s) denotes a shock.

Although the air in advance of the blast wave is usually considered to be at rest, $u_1 = 0$, the above general case may be utilized to correct blast wave properties for wind velocities.

Table 12 which follows is compiled from use of equations [6.2-1] through [6.2-4] for air at standard temperatures and pressures. These values have been checked, where possible, against available test data, and are in good agreement.

TABLE 12. BLAST WAVE PROPERTIES

Peak Over-pressure P_{ov} (psi)	Blast Wave Velocity u_W ft/sec (a = 1116 ft/sec)	Convective Velocity u_C ft/sec (a = 1116 ft/sec)	Peak Dynamic Pressure P_D (psi)	Peak Dynamic Pressure P_D (psf)	Mach Number of Blast Wave M
0.1	1119	5.4	0.00026	0.037	1.003
0.2	1122	10.8	0.00103	0.149	1.006
0.3	1126	16.1	0.00233	0.335	1.009
0.4	1129	21.5	0.00415	0.597	1.012
0.6	1135	32.0	0.00835	1.203	1.017
0.8	1142	42.4	0.0153	2.208	1.023
1.0	1148	52.7	0.0245	3.528	1.029
2.0	1179	103.0	0.0964	13.88	1.057
3.0	1210	150.0	0.2128	30.64	1.084
4.0	1239	195.0	0.3776	54.38	1.111
5.0	1268	239.0	0.5752	82.82	1.136
6.0	1297	280.0	0.8282	119.3	1.162
7.0	1324	320.0	1.119	161.1	1.187
8.0	1351	358.0	1.443	207.8	1.211
9.0	1378	395.0	1.796	258.7	1.234
10.0	1404	431.0	2.211	318.3	1.258
15.0	1527	596.0	4.766	686.3	1.369
20.0	1643	737.0	8.144	1173.0	1.472
30.0	1850	981.0	16.92	2437.0	1.658
50.0	2208	1371.0	40.90	5890.0	1.979
70.0	2516	1685.0	70.82	10198.0	2.254
100.0	2917	2076.0	123.1	17728.0	2.613

Figure 20 presents Table 12 in graph form.

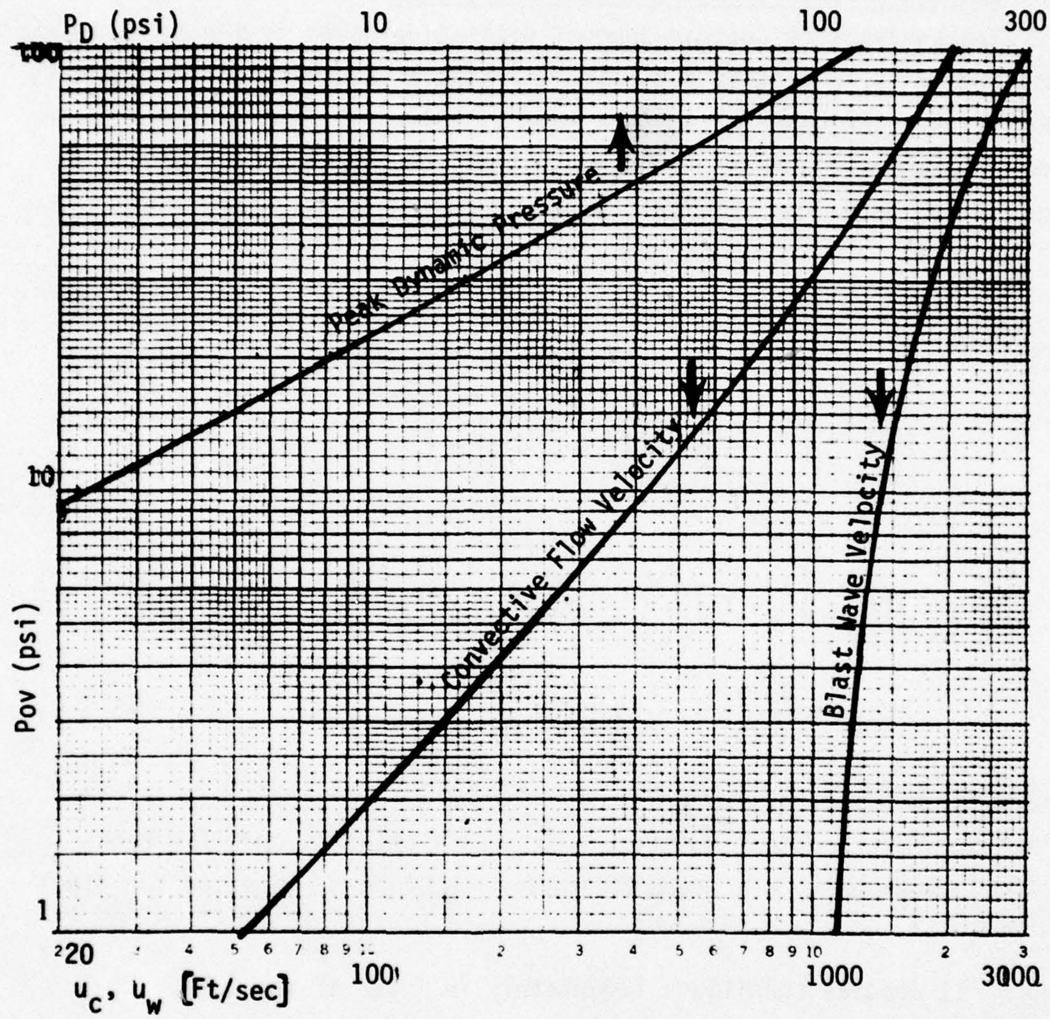

FIGURE 20. PEAK OVERPRESSURE, Pov, FOR BLAST WAVES IN AIR AT STP vs. PEAK DYNAMIC PRESSURE, P_D, CONVECTIVE FLOW VELOCITY u_c, AND BLAST WAVE VELOCITY u_w.

6.3 CHAPMAN-JOUGUET DETONATION WAVE PROPERTIES

The analysis of Chapman-Jouguet detonation waves is identical to that just presented in section 6.2, with the single exception of the boundary conditions. The case for a shock wave is adiabatic, and the case of the Chapman-Jouguet detonation wave is that of limiting heat addition. The descriptive equations for the Chapman-Jouguet detonation are given below.

$$\frac{p_2}{p_1} = 1 + \frac{\gamma}{\gamma+1}\left(M_{D_1}{}^2 - 1\right) \qquad [6.3\text{-}1]$$

$$\frac{\rho_2}{\rho_1} = \frac{1}{1 - \frac{1}{\gamma+1}\frac{\left(M_{D_1}{}^2-1\right)}{M_{D_1}{}^2}} \qquad [6.3\text{-}2]$$

$$\frac{T_2}{T_1} = \left\{1 + \frac{\gamma}{\gamma+1}\left(M_{D_1}{}^2-1\right)\right\}\left\{1 - \frac{1}{\gamma+1}\frac{\left(M_{D_1}{}^2-1\right)}{M_{D_1}{}^2}\right\} \qquad [6.3\text{-}3]$$

$$M_{21D} \equiv \frac{u_2 - u_1}{a_1} = \frac{1}{\gamma+1}\left(M_{D_1} - \frac{1}{M_{D_1}}\right) \qquad [6.3\text{-}4]$$

Where, as before:

p = pressure ρ = density γ = ratio of specific heats

T = temperature a = speed of sound M_{D_1} = Mach number of the blast wave relative to the air at (1)

and: (1) denotes conditions immediately in front of the wave,

(2) denotes conditions immediately behind the wave, and

(D) denotes a detonation.

The above equations for detonation waves assume that specific heats remain constant across the wave (as for shock waves), and therefore makes no allowance for the high temperatures behind the wave which result from combustion. These shock relations are in good agreement with measured values; however, the detonation relations do not agree as well with measured values. Inasmuch as this program is primarily concerned with the blast effects which occur outside the fuel-air cloud, in the pressure region of 0-100 psi, equations [6.3-1] through [6.3-4] are adequate for descriptive purposes.

Table 13 is compiled from use of these equations.

TABLE 13. CHAPMAN-JOUGUET DETONATION WAVE PROPERTIES FOR FUEL-AIR MIXTURES AT STP WITH a = 1116 Ft/Sec.

Peak Overpressure Pov (Atm)	(psi)	Wave Velocity u_W (Ft/Sec)	Convective Velocity u_C (Ft/Sec)	Peak Dynamic Pressure P_D (Atm)	(psi)	M-Mach Number	Density ρ_2 (Slugs/Ft^3)
4	58.8	3128	1137	2.282	33.55	2.803	0.00374
5	73.5	3453	1288	2.973	43.70	3.094	0.00379
6	88.2	3749	1424	3.673	53.98	3.359	0.00383
7	102.9	4024	1548	4.374	64.31	3.606	0.00386
8	117.6	4280	1662	5.073	74.58	3.836	0.00389
9	132.3	4523	1770	5.782	85.00	4.053	0.00391
10	147.0	4753	1871	6.486	95.35	4.259	0.00392
11	161.7	4973	1968	7.197	105.8	4.456	0.00394
12	176.4	5183	2060	7.911	116.3	4.645	0.00395
13	191.1	5385	2148	8.621	126.7	4.826	0.00396
14	205.8	5580	2232	9.328	137.1	5.000	0.00396
15	220.5	5768	2313	10.03	147.5	5.169	0.00397
16	235.2	5950	2392	10.75	158.0	5.332	0.00398
17	249.9	6127	2468	11.46	168.4	5.490	0.00398
18	264.6	6299	2542	12.17	178.9	5.644	0.00399
19	279.3	6466	2614	12.88	189.4	5.794	0.00399
20	294.0	6629	2684	13.60	199.9	5.940	0.00400
21	308.7	6788	2752	14.31	210.3	6.083	0.00400
22	323.4	6944	2819	15.03	220.9	6.222	0.00400
23	338.1	7096	2884	15.74	231.4	6.358	0.00401
24	352.8	7245	2947	16.45	241.8	6.492	0.00401
25	367.5	7391	3009	17.16	252.2	6.622	0.00401
26	382.2	7534	3070	17.87	262.7	6.751	0.00401
27	396.9	7674	3130	18.59	273.2	6.876	0.00402
28	411.6	7812	3189	19.30	283.8	7.000	0.00402
29	426.3	7948	3246	20.01	294.1	7.121	0.00402
30	441.0	8081	3303	20.73	304.7	7.241	0.00402

Table 13 is shown in graph form in Figure 21.

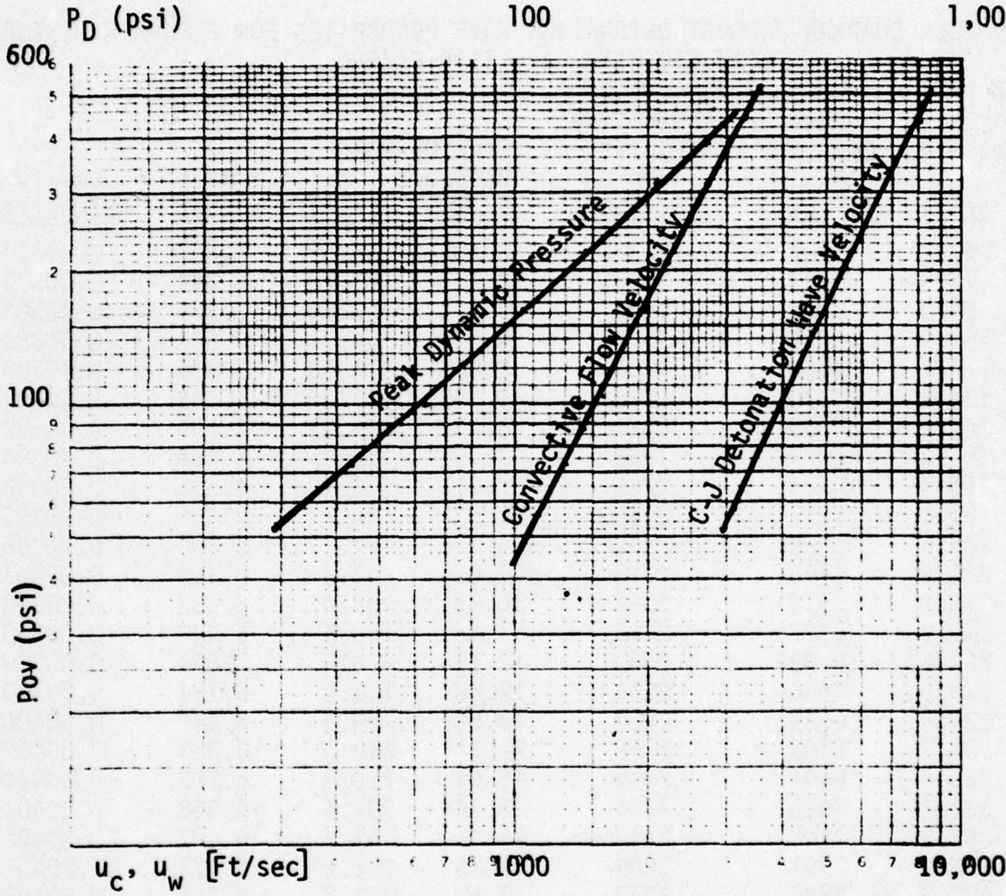

FIGURE 21. PEAK DYNAMIC PRESSURE, P_D, CONVECTIVE FLOW VELOCITY, u_c, AND CHAPMAN-JOUGUET DETONATION WAVE VELOCITY, u_W, vs. PEAK OVERPRESSURE, Pov, FOR FUEL-DETONATIONS IN AIR.

6.4 NUCLEAR BLAST WAVE, IMPULSE PROPERTIES

Nuclear explosions at low altitudes distribute their energy to the atmosphere in the following manner:

- Blast and shock 50%
- Thermal radiation 35%
- Residual nuclear radiation 10%
- Initial nuclear radiation 5%

It is the nuclear blast and shock energy portion of the nuclear yield (50%) that is of concern to the FAX Simulation Facility.

The distribution of this blast/shock energy from a nuclear explosion depends upon the ratio of the yield to the height of the burst (HOB). From the numerous nuclear tests conducted, optimum HOB's have been established to maximize blast wave effects on targets located at ground levels. In broad terms, the above involves consideration of peak overpressures and peak dynamic pressures in conjunction with a combination of static and dynamic impulses to produce maximum damage on targets.

A surface nuclear burst, HOB = 0, produces surface blast waves that are not optimum for soft targets and therefore would seldom be used against distributed surface targets such as structures and most equipments. The advantage of the air burst comes from the reflected wave and/or the Mach effect which reinforces/increases the overpressures and impulses.

Figure 22, taken from *The Effects of Nuclear Weapons**, shows the values of peak overpressures and peak dynamic pressures to be expected from a one-kiloton nuclear surface burst. The impulse information to match Figure 22 was not given. Estimation of impulse requires then the use of empirical equations in the form of:

$$p(t) = p\left(1 - \frac{t}{t+}\right) e^{-t/t+} \qquad [6.4\text{-}1]$$

$$q(t) = q\left(1 - \frac{t}{t+}\right)^2 e^{-2t/t+} \qquad [6.4\text{-}2]$$

Where: p(t) is the overpressure at time, t; p is the peak overpressure; q(t) is the dynamic pressure at time, t; q is the peak dynamic pressure; and t+ is the duration of the positive phase.

* *The Effects of Nuclear Weapons*, (Government Printing Office, 1964).

Equations [6.4-1] and [6.4-2], however, are only valid for low peak overpressures, i.e., below 10 psi.

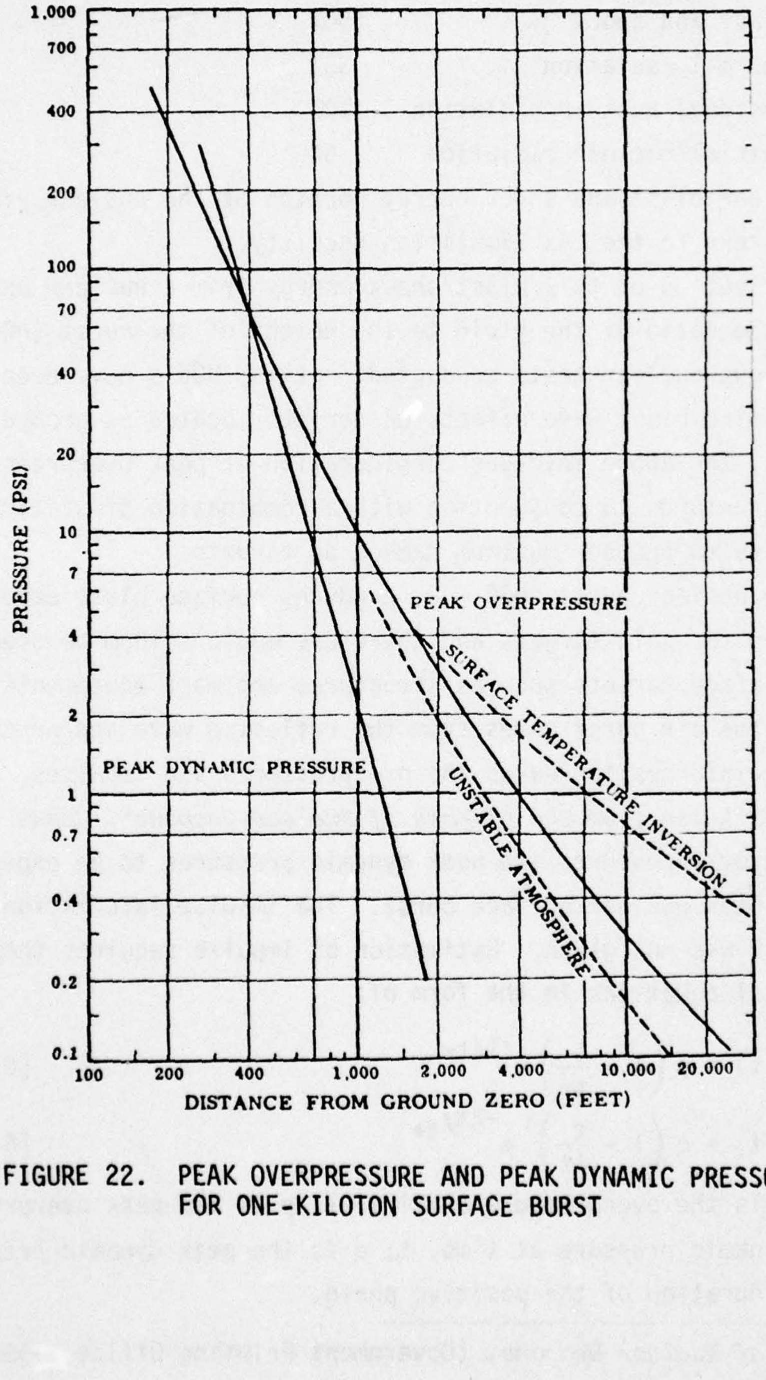

FIGURE 22. PEAK OVERPRESSURE AND PEAK DYNAMIC PRESSURE FOR ONE-KILOTON SURFACE BURST

Figure 23 represents a more realistic one-kiloton standard for the FAX simulation of nuclear bursts. It should be noted that the shape of peak overpressure versus distance curve is determined by the yield and the HOB, hence determining the ultimate character of the blast effects upon targets. In Figure 23, the data are plotted against range. Of prime interest to this simulation are the variables of peak overpressure, static impulse, and dynamic impulse.

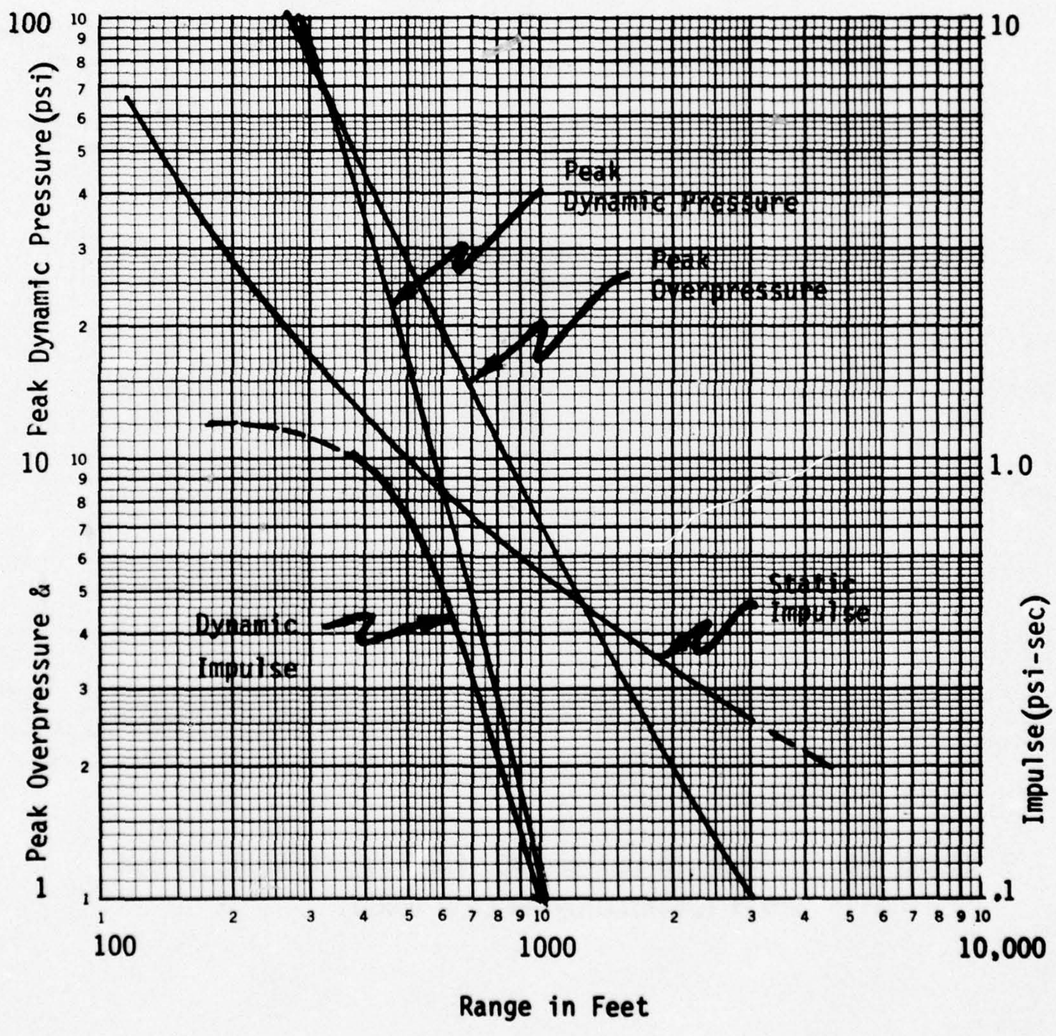

FIGURE 23. ONE-KILOTON STANDARD

Figure 24 is a cross-plot from Figure 23 of static and dynamic impulse versus peak overpressure for a one-kiloton nuclear burst. It should be noted that dynamic impulse contributes little to the overall impulse at peak overpressures below 5 psi.

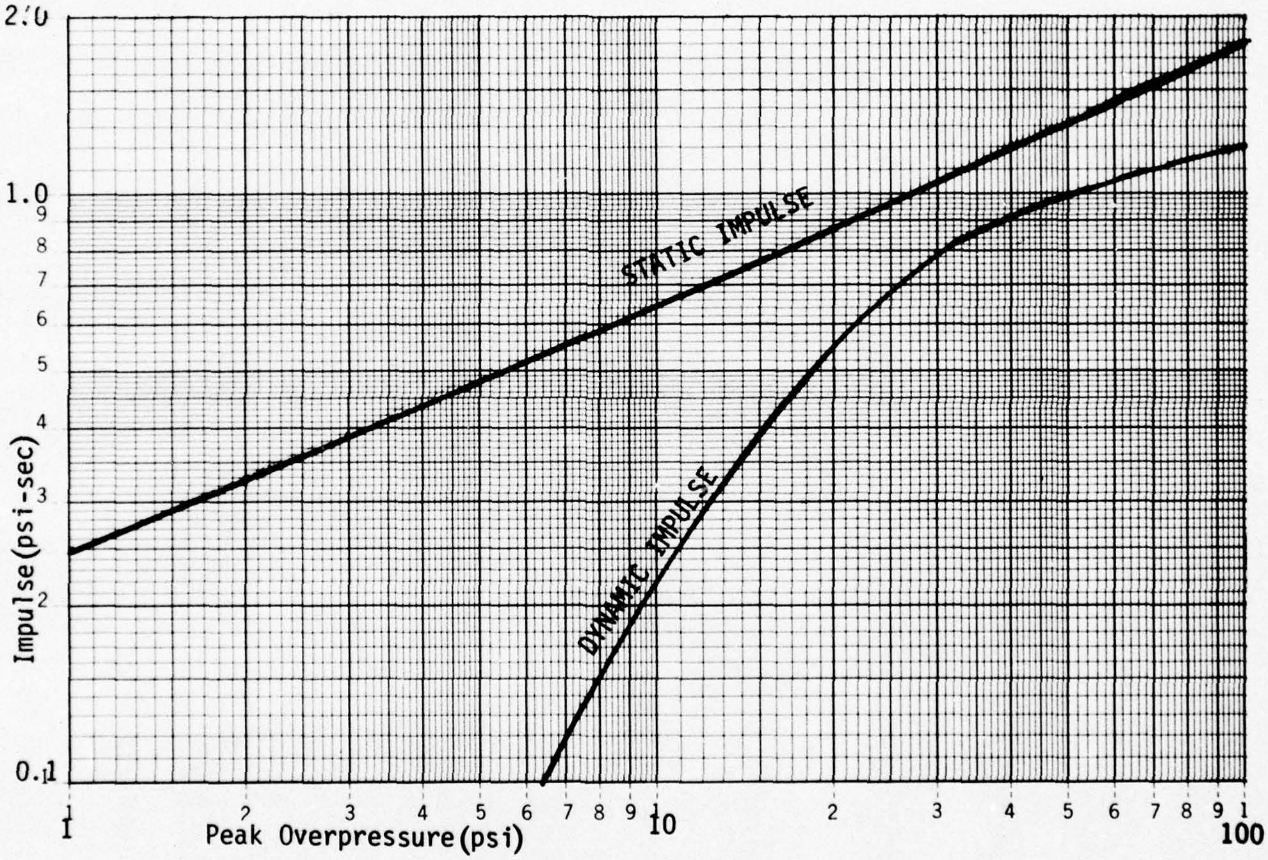

FIGURE 24. IMPULSE IN psi-sec VS. PEAK OVERPRESSURE IN psi FOR A ONE-KILOTON NUCLEAR BURST.

6.5 HE/ANFO BLAST WAVE IMPULSE PROPERTIES

The blast wave properties resulting from the detonation of a HE/ANFO charge are very similar to those obtained from a nuclear burst. This is particularly true at ranges wherein the peak overpressures are below 100 psi.

Figure 25, a graph of peak overpressure and static impulse versus range, shows the blast wave results obtained from the detonation of 500 pounds of TNT, "Suffield." It should be noted that the actual static impulses obtained lie below those predicted.

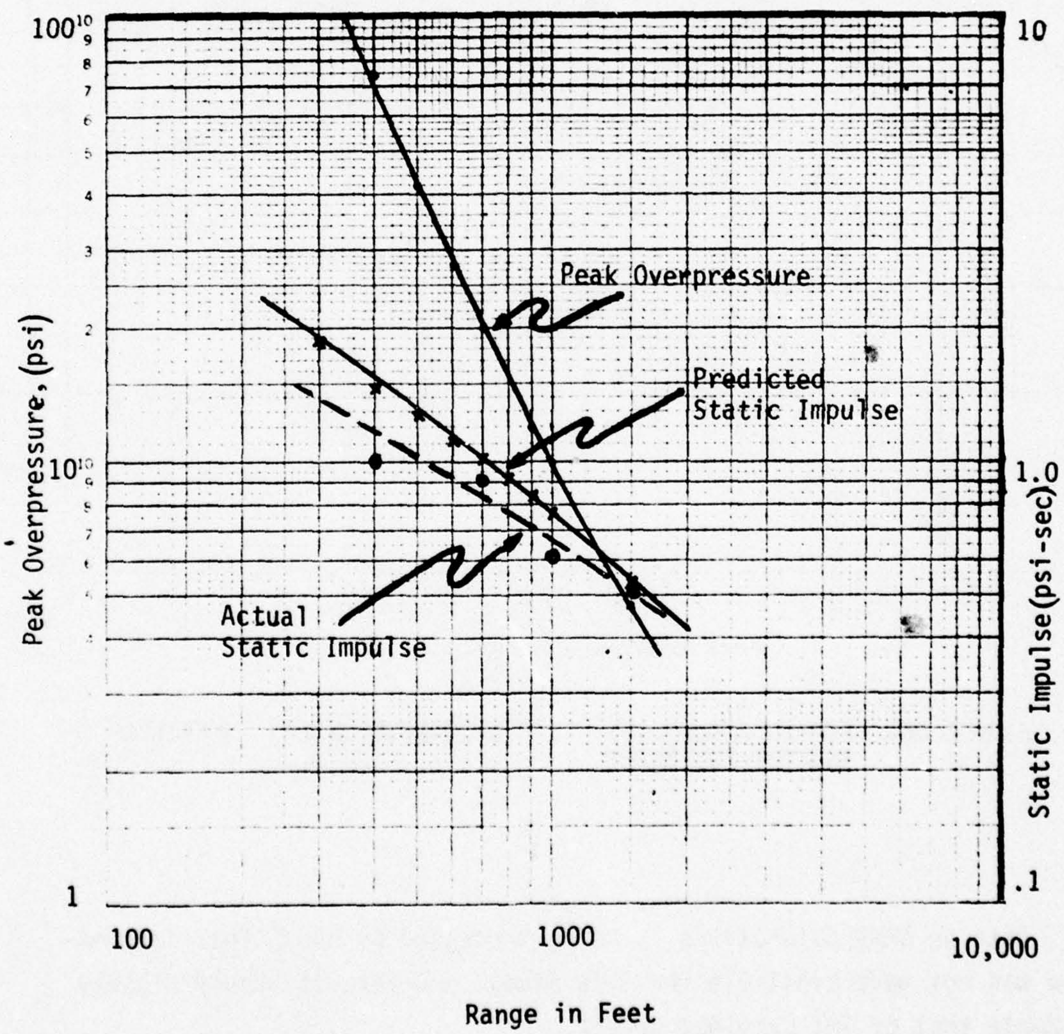

FIGURE 25. PEAK OVERPRESSURE AND STATIC IMPULSE VS. RANGE FOR "SUFFIELD" 500-TON TNT BLAST.

Figure 26 is the cross-plot of static impulse versus peak overpressure.

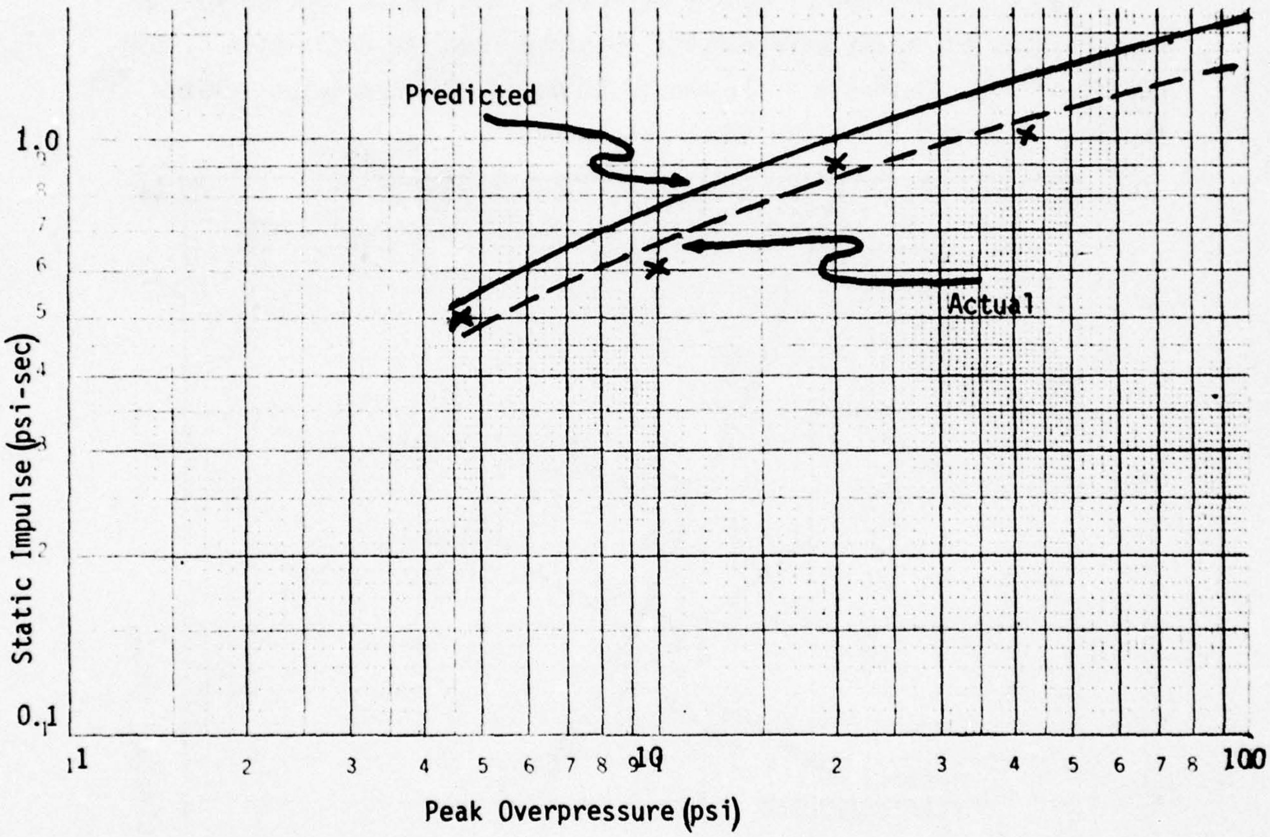

FIGURE 26. STATIC IMPULSE VS. PEAK OVERPRESSURE FOR "SUFFIELD" 500-TON TNT BLAST.

Data on ANFO detonations is being processed by BRL.* This information was not made available for this Study; however, it should closely resemble that of TNT provided herein.

* The Army's Ballistics Research Laboratory, Aberdeen Proving Ground, MD.

6.6 FAE BLAST WAVES, IMPULSE PROPERTIES

The blast waves resulting from the detonation of a fuel-air cloud differs from that of the detonation of a HE/ANFO charge in that the fuel-air cloud occupies a large volume of space and therefore can not be regarded as a point source of energy. Also, the detonative process, though rapid (5,000 to 6,000 feet per second), progresses over large ground areas and never develops the very large pressures associated with either nuclear or HE/ANFO explosions.

The dynamics of blast wave generation are shown in Figure 27. In (a), a hemispherical fuel-air cloud has been generated at ground level. In (b), detonation has been initiated from the center and the detonation wave is proceeding through the cloud. The unburned portion of the cloud remains undisturbed until the passage of the detonation wave. In (c), the detonation has progressed through the combustible mixture, collided with the air interface, transmitted a shock into the air, and reflected a wave back into the combusted region. As a rule of thumb, the expanded, burned cloud will possess a radius that is approximately 1.75 times that of the original, unburned cloud.

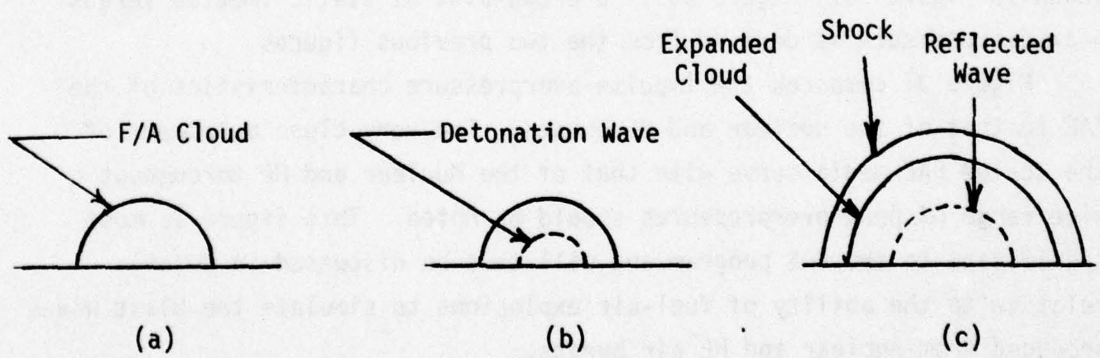

FIGURE 27. DETONATION OF A F/A CLOUD

Blast wave properties produced from the detonation of fuel-air mixtures depend upon several variables, the most important of which are:

- Cloud shape
- Fuel-air mixture distribution

• Initiation location(s)

• Constraint and/or relief

The best data available for unconstrained fuel-air detonations come from the weapons-testing of FAE devices such as:

• 75 pounds ethylene oxide BLU-73/B

• 85 pounds propylene oxide SLU/FAE

• 300 pounds ethylene oxide

• 940 pounds MAPP

All the above tests utilized explosive expulsion wherein a small charge of HE, located centrally within the fuel tank, was detonated. Characteristically-similar clouds are generated by this techniques; these have an approximately toroidal shape with an approximate height to diameter ratio of 0.25.

These data have been scaled to an equivalent one-kiloton size (200,000 pounds of fuel) to serve as a common basis of comparison. Figure 28 delineates the peak overpressure dependence upon range for several FAE bursts scaled to a one-kiloton nuclear equivalent of 200,000 pounds of fuel. The dependence of static impulse upon range is then shown in Figure 29. Figure 30 is a cross-plot of static impulse versus peak overpressure as derived from the two previous figures.

Figure 31 compares the impulse-overpressure characteristics of the FAE to that of the nuclear and HE bursts. The very close agreement of the scaled FAE media curve with that of the Nuclear and HE throughout a wide range of peak overpressures should be noted. This figure is most significant to the FAX program and will thus be discussed in detail relative to the ability of fuel-air explosions to simulate the blast waves produced from nuclear and HE air bursts.

The three properties of blast waves that are required to characterize the waves, as was previously stated, are :

• Peak overpressure,

• Static impulse, and

• Dynamic impulse.

Peak overpressure is independent of the explosive yield in the nondimensional sense that, at some scaled distance, the peak overpressure will

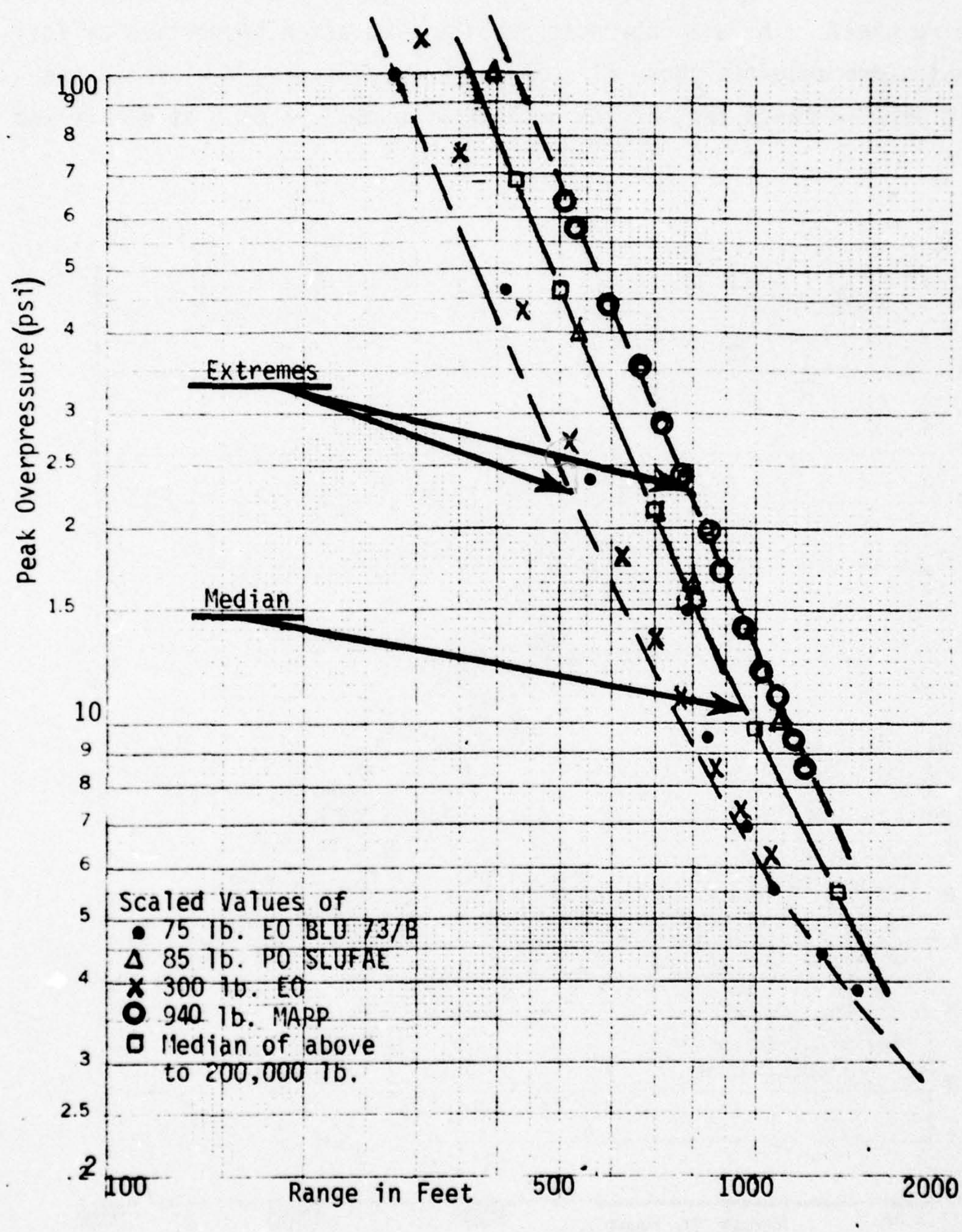

FIGURE 28. PEAK OVERPRESSURE VS. RANGE FOR 200,000-lb. FAE DETONATION AS SCALED FROM PAST TESTS

occur. Static and dynamic impulse, however, are directly dependent on the explosive yield. To fully characterize the simulation properties of fuel-air explosions requires that, at some peak overpressure, the static and dynamic impulse match that of the nuclear HE burst. A plot of static and

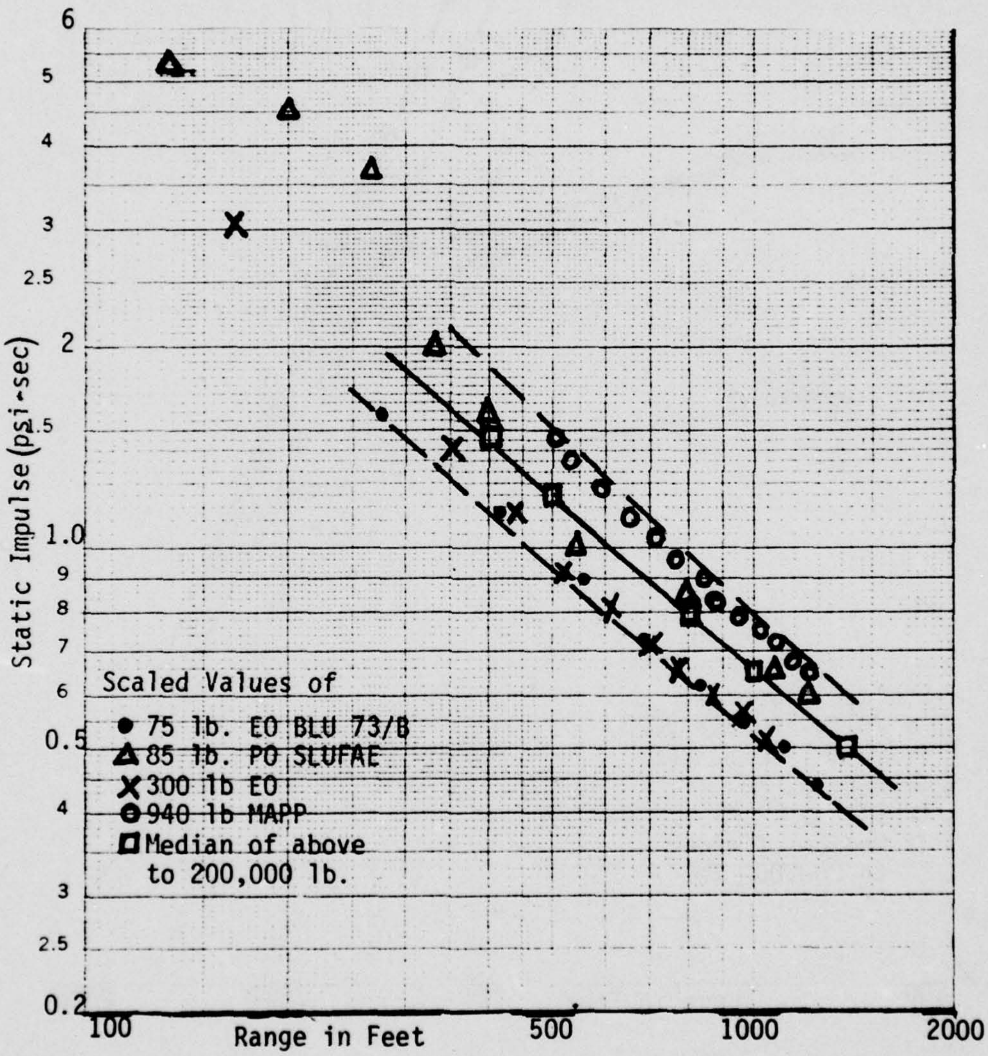

FIGURE 29. STATIC IMPULSE VS. RANGE FOR 200,000-lb. FAE DETONATIONS AS SCALED FROM PAST TESTS.

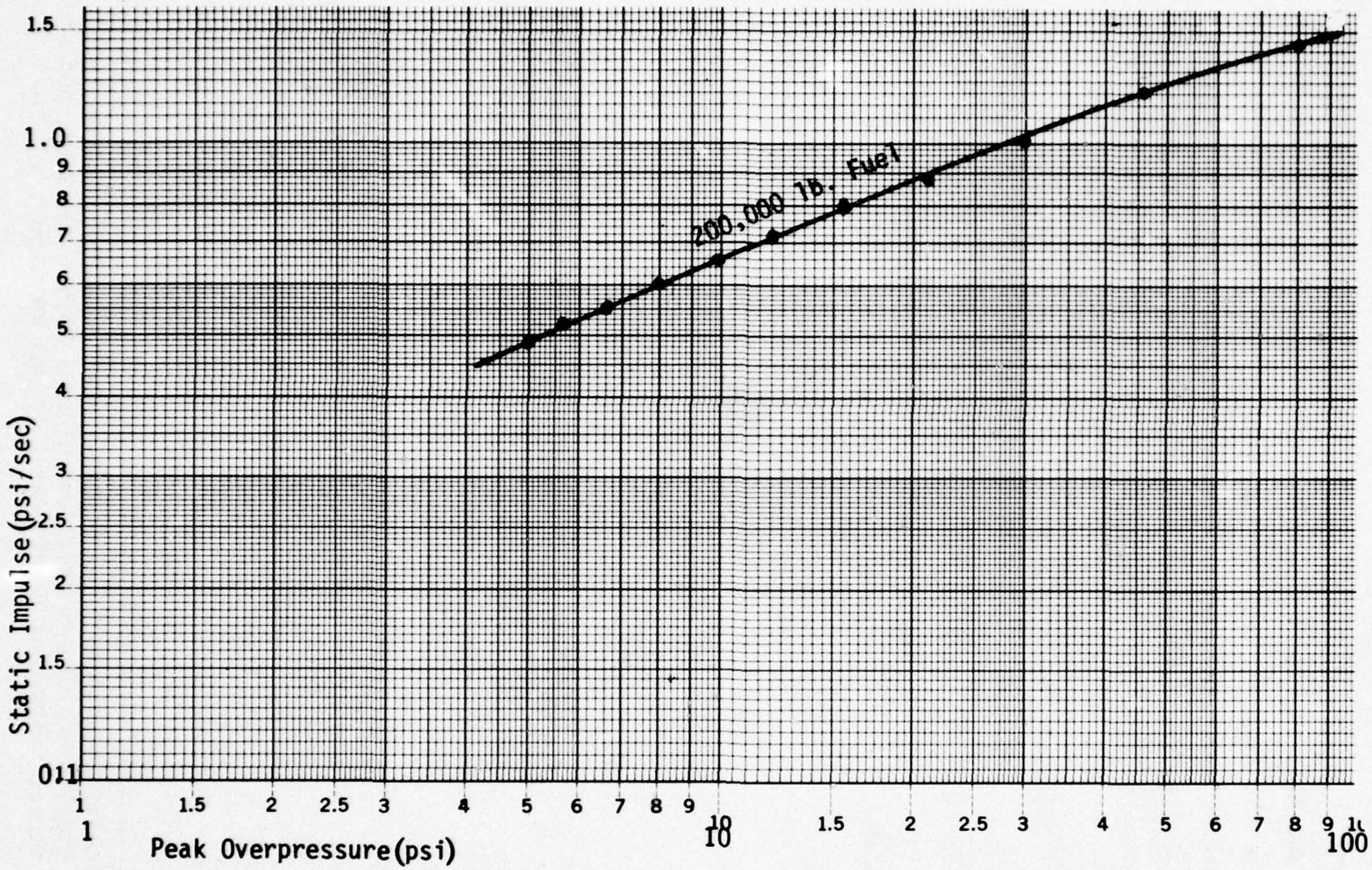

FIGURE 30. STATIC IMPULSE VS. PEAK OVERPRESSURE FOR SCALED FAE BURSTS

dynamic impulse (explosive yield dependent) versus peak overpressure (independent of explosive yield) provides an excellent comparison technique.

This was done in Figure 31, which illustrates the excellent match obtained for the fuel-air explosion to that of the nuclear and HE bursts for peak overpressure and static impulse. Although direct and consistent experimental data for dynamic impulse was not obtained for this Study, it is to be expected that the dynamic impulse match would equal that of static impulse.*

It is conclusive that fuel-air explosions can produce blast waves with characteristics that match those of nuclear explosions exceptionally well. To match the yield of a one-kiloton nuclear explosion would require 200,000 pounds of fuel. The HE equivalent would require 500 tons of TNT. The equivalence between HE and FAE is approximately five pounds of HE to one pound of fuel.

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* Analytically (equations 6.4-1 & 6.4-2, page 78), both dynamic and static impulse are direct functions of peak values and time, and should bear a direct functional relationship to one another.

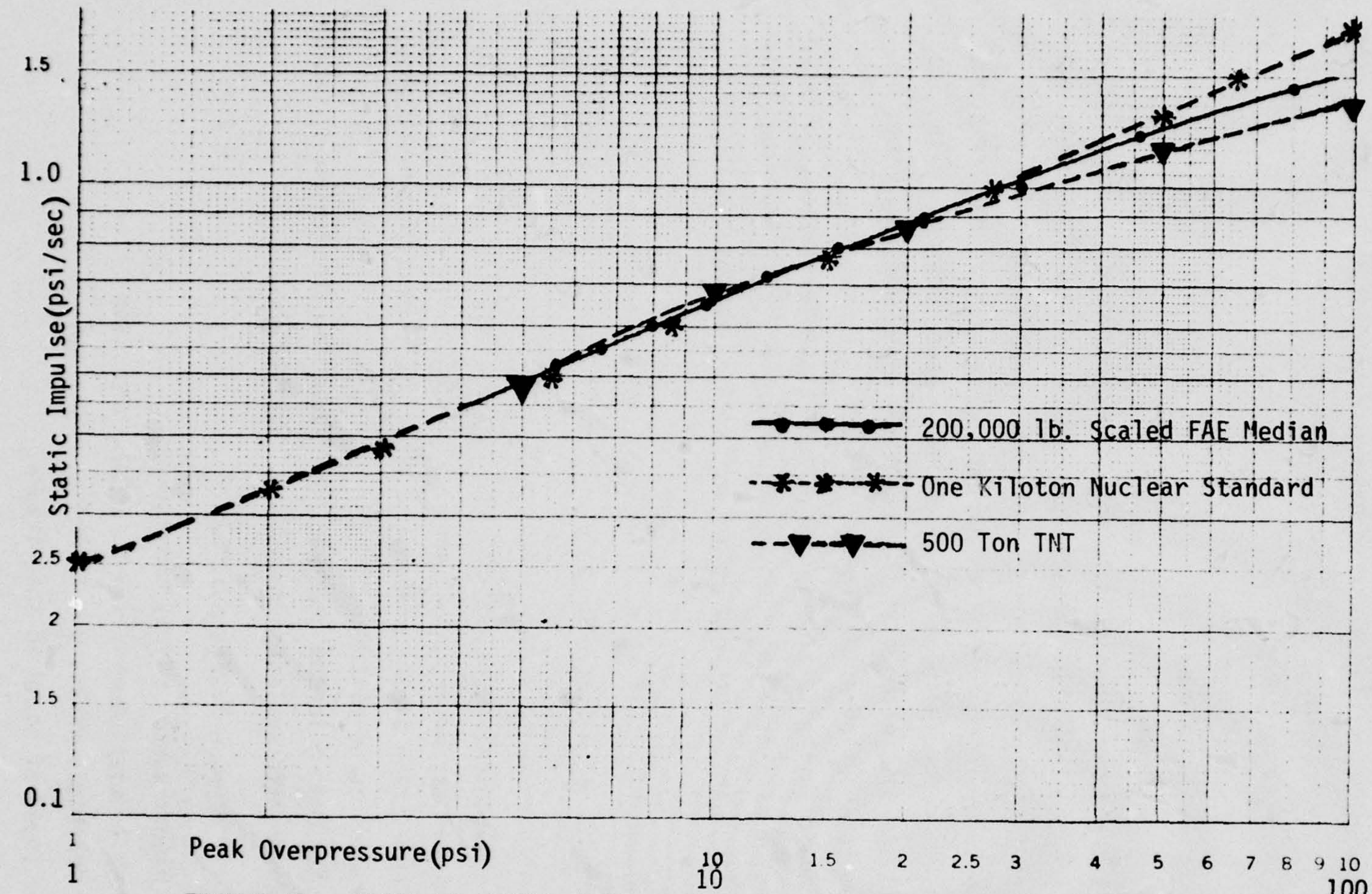

FIGURE 31. GRAPH OF STATIC IMPULSE IN psi-sec. VS. PEAK OVERPRESSURE IN psi FOR (a) 200,000-lb. FAE (SCALED MEDIA VALUES), (b) ACTUAL 500-TON TNT BLAST ("SUFFIELD"), AND (c) ONE-KILOTON "STANDARD" BURST.

6.7 DETONATION INITIATION

Initiation of detonation waves in gaseous combustible mixtures can be accomplished in several ways, i.e., by use of:

- Flame tubes
- Shock waves
- HE charges
- Other

Normally, all the above techniques involve the creation of shock waves of sufficient strength that the combustible gases behind the shock will react rapidly (short ignition delay times) enough to support the shock wave. Long ignition delay times allow the shock to be separated from the combustion zone which, depending upon the shock wave shape (planar, cylindrical, or spherical), permits attenuation of the shock wave, and consequently the reversion to a deflagration wave.

It is usual, in the treatment of the detonation initiation, to introduce the concept of a critical blast wave radius, r_*, such that the available combustion energy contained within r_* is equal to the blast wave energy, E_0.

The equation for r_* is:

$$r_* = (\nu E_0/\sigma_\nu Q \rho_1)^{1/\nu} \qquad [6.7\text{-}1]$$

Where: for planar waves, $\nu = 1$, and $\sigma_\nu = 2$;
for cylindrical waves, $\nu = 2$, and $\sigma_\nu = 2\pi$; and
for spherical waves, $\nu = 3$, and $\sigma_\nu = 4\pi$;
Q = combustion energy per unit mass of the fuel-oxidizer mixture;
and ρ_1 = density of mixture.

It is also common in the treatment of detonation initiation to introduce a characteristic explosion length, r_0, defined as:

$$r_0 = [E_0/(k_\nu \rho_1 a_1^2)]^{1/\nu} \qquad [6.7\text{-}2]$$

Where: for planar waves, $\nu = 1$, and $k_\nu = 1$;
for cylindrical waves, $\nu = 2$, and $k_\nu = 2\pi$; and
for spherical waves, $\nu = 3$, and $k_\nu = 4\pi$; and
a_1 = speed of sound in the mixture.

Bach et al.[1] found that with a finite reaction zone thickness, transition to a Chapman-Jouguet detonation occurs only when the blast energy, E_0, exceeds a certain critical initiation value in accordance with experimental observations. In terms of equation [6.7-2], blast initiation of a Chapman-Jouguet detonation occurs only when the ratio of the reaction zone thickness to r_0 is less than a certain critical value.

Figure 32, taken from the work of R. S. Fry and J. A. Nicholls[2] of the University of Michigan, shows the threshold energies required to initiate detonations in MAPP gas-air mixtures for the case of a cylindrical wave.

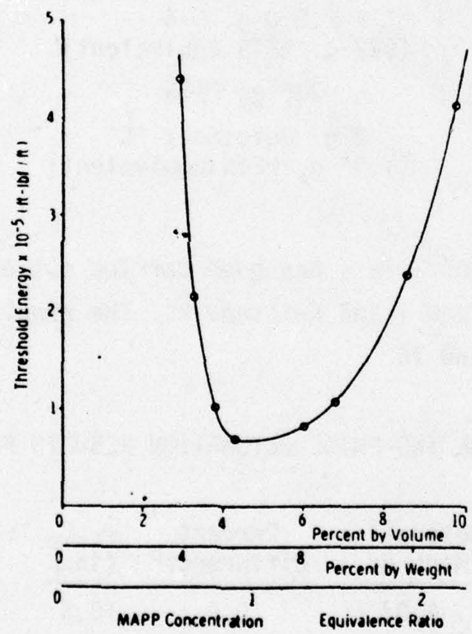

FIGURE 32. CRITICAL THRESHOLD ENERGY FOR DETONATION INITIATION AS A FUNCTION OF MAPP CONCENTRATION IN AIR.

[1] F. G. Bach, R. Knystautas and J. H. Lee, "Initiation Criteria for Diverging Gaseous Detonations," *13th International Symposium on Combustion*, (The Combustion Institute, Pittsburgh, PA, 1971), pp. 1097-1110.

[2] R. S. Fry and J. A. Nicholls, "Blast Initiation and Propagation of Cylindrical Detonations in MAPP-Air Mixtures," *AIAA Journal*, (Vol. 12, No. 12, December 1974), pp. 1703-1780.

Table 14, taken from the same reference[1], shows the detonation limits of MAPP gas from selected HE initiators. In general, it follows that a few grams of HE, such as PETN, is sufficient to detonate MAPP gas-air mixtures if one stays well within the detonation limits.

TABLE 14. DETONATION LIMITS OF MAPP-AIR MIXTURES BY VOLUME

Method	Initiator	Lower Limit	Upper Limit
Crawshaw-Jones apparatus	1 g. PETN	4.1	7.8
Crawshaw-Jones apparatus	10 g. PETN	2.4	13.7
Crawshaw-Jones apparatus	100 g. PETN	---	≧ 30
Bag test	800 g. C-4 (672 g. PETN equivalent)	2.9	10.2
Bag test	386 g. PETN	2.9	9.1
Sectored chamber	2 g. Detasheet 'C' (1.57 g. PETN equivalent)	2.9	10.5

Detonation of fuel-air mists has been carried out at the University of Michigan[2] using Kerosene 1 and Kerosene 2. The results of these tests are given in Tables 15 and 16.

TABLE 15. EXPERIMENTAL TWO-PHASE DETONATION RESULTS FOR KEROSENE 1.

Explosive Charge (grams)	Detonation Velocity (ft/sec)	Detonation Mach No.	Percent Difference[a]	$r_0$exp (in.)	$r_0$theo[b] (in.)	Percent Difference
2.5	4625	4.07	9.5	18.5	18.44	-0.33
1.5	4400	3.87	13.9	17.3	16.36	-5.74

[a] Based upon theoretical two-phase detonation velocity of 5110 ft/sec.

[b] Computed using energy adjusted by energy efficiency factors.

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[1] Ibid.

[2] J. A. Nicholls, M. Sichel, R. Fry and D. R. Glass, "Theoretical and Experimental Study of Cylindrical Shock and Heterogeneous Detonation Waves," *Acta Astronautica*, Vol. I (Permagon Press, 1974), pp. 385-404.

TABLE 16. EXPERIMENTAL TWO-PHASE DETONATION RESULTS FOR KEROSENE 2.

Explosive Charge (grams)	Detonation Velocity (ft/sec)	Detonation Mach No.	Percent Difference[a]	$r_0$exp (in.)	$r_0$theo[b] (in.)	Percent Difference
3.5	5106	4.50	0.30	20.3	20.3	0.0
3.0	5090	4.48	0.60	19.2	19.31	0.57
2.5	4900	4.32	4.30	18.2	18.44	1.30
2.0	4800	4.23	6.30	17.2	17.51	1.77
1.5	4800	4.23	6.30	15.8	16.41	3.72

[a] Based upon theoretical two-phase detonation velocity of 5120 ft/sec.

[b] Computed using energy adjusted by energy efficiency factors.

[References most pertinent to FAX and the detonation of unconfined fuel-air clouds, taken from the AIAA Journal* article, are included as Appendix B to this Report.]

From Tables 15 and 16, it is noted that a few grams of HE is all that is required to initiate detonation in kerosene-air mixtures for the cylindrical wave case.

6.8 FAX-RELATED MISCELLANY

This section consists of miscellaneous information relative to the properties of, and simulation of, nuclear blast waves.

Figure 33 contains plots of static impulse versus peak overpressure for various fuel weights that can be obtained from fuel-air explosions. These curves were derived from the cube root scaling of the values of static impulse shown in Figure 30 (page 89). It should be noted that the fuel weight employed in fuel-air explosions merely translates the curves up and down and does not "tilt" the curves.

* R. S. Fry et al. op. cit.

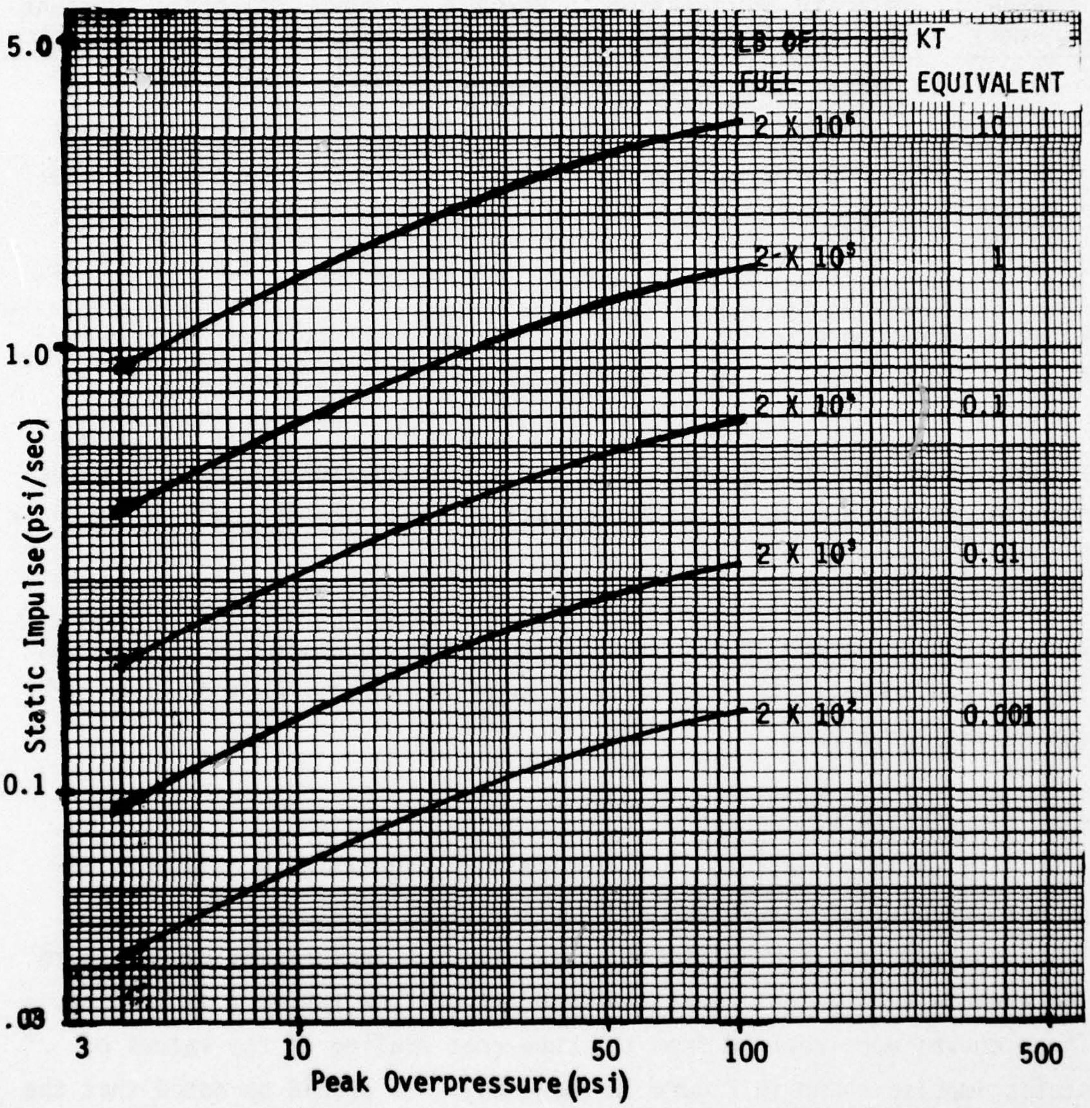

FIGURE 33. EXPECTED STATIC IMPULSE VS. PEAK OVERPRESSURE FOR SCALED FUEL-AIR DETONATIONS

A cross-plot of fuel weight versus static impulse for various peak overpressures is shown in Figure 34. This plot allows one to select the required fuel weight to meet a given peak overpressure and static impulse match. For example, to match a peak overpressure of 10 psi to a static impulse of 0.5 psi-sec. would require 80,000 pounds of fuel in a fuel-air explosion. To match a peak overpressure of 10 psi to a static impulse of 0.2 psi-sec. would require 5200 pounds of fuel. The ability to tailor peak overpressure to a desired static impulse is apparent.

The effect of cloud shape upon the peak overpressure versus static impulse curve is shown in Figure 35, as taken from the Systems, Science and Software (S^3) document SS-R-76-2932. The clouds were cylindrical and h/D represents the height to diameter ratio. Small given h/D's produce small static impulses at any given peak overpressure. Large h/D's produce large static impulses at any given peak overpressure.

In general then:

Fat clouds--large static impulses;

Thin clouds--small static impulses.

Figure 36, taken from DASIAC ES75-1 Draft Report, summarizes the empirical data from previous high explosive field tests.

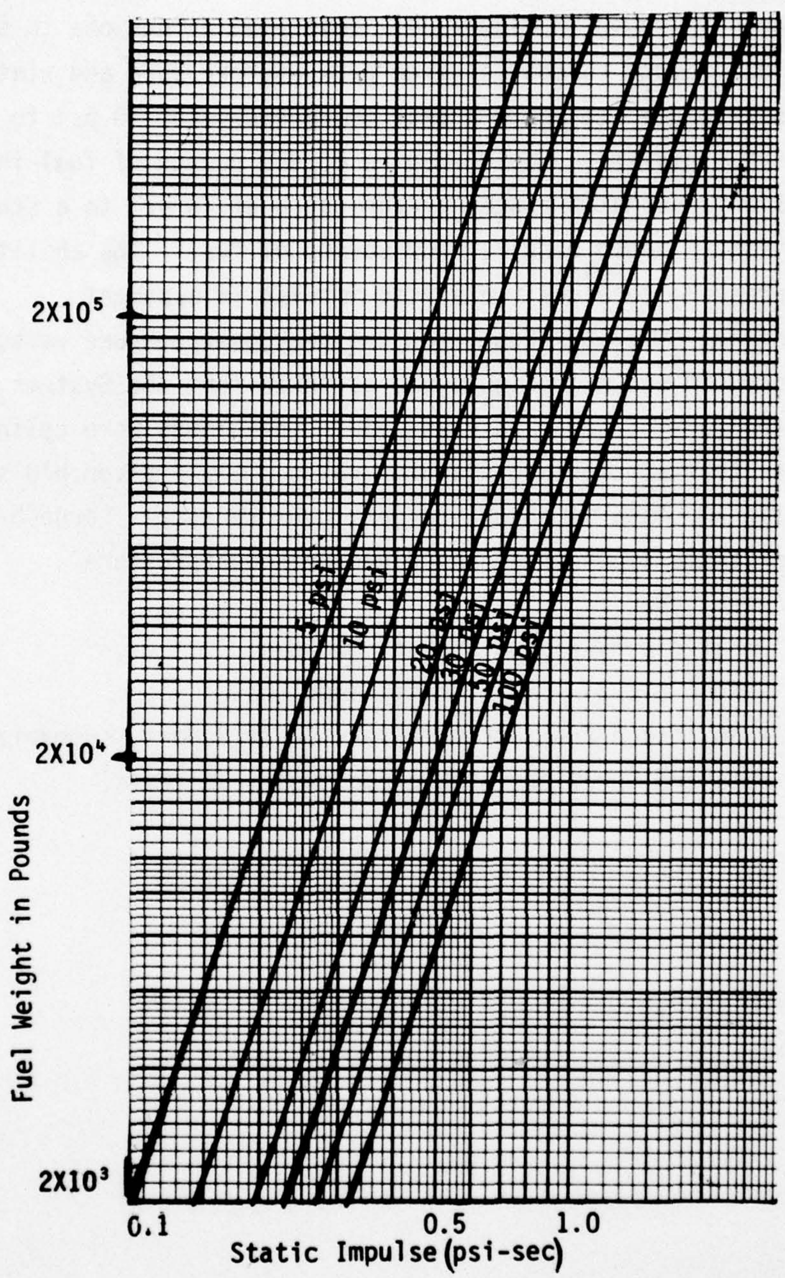

FIGURE 34. FUEL WEIGHT IN POUNDS REQUIRED FOR MATCHING PEAK OVERPRESSURES TO STATIC IMPULSE

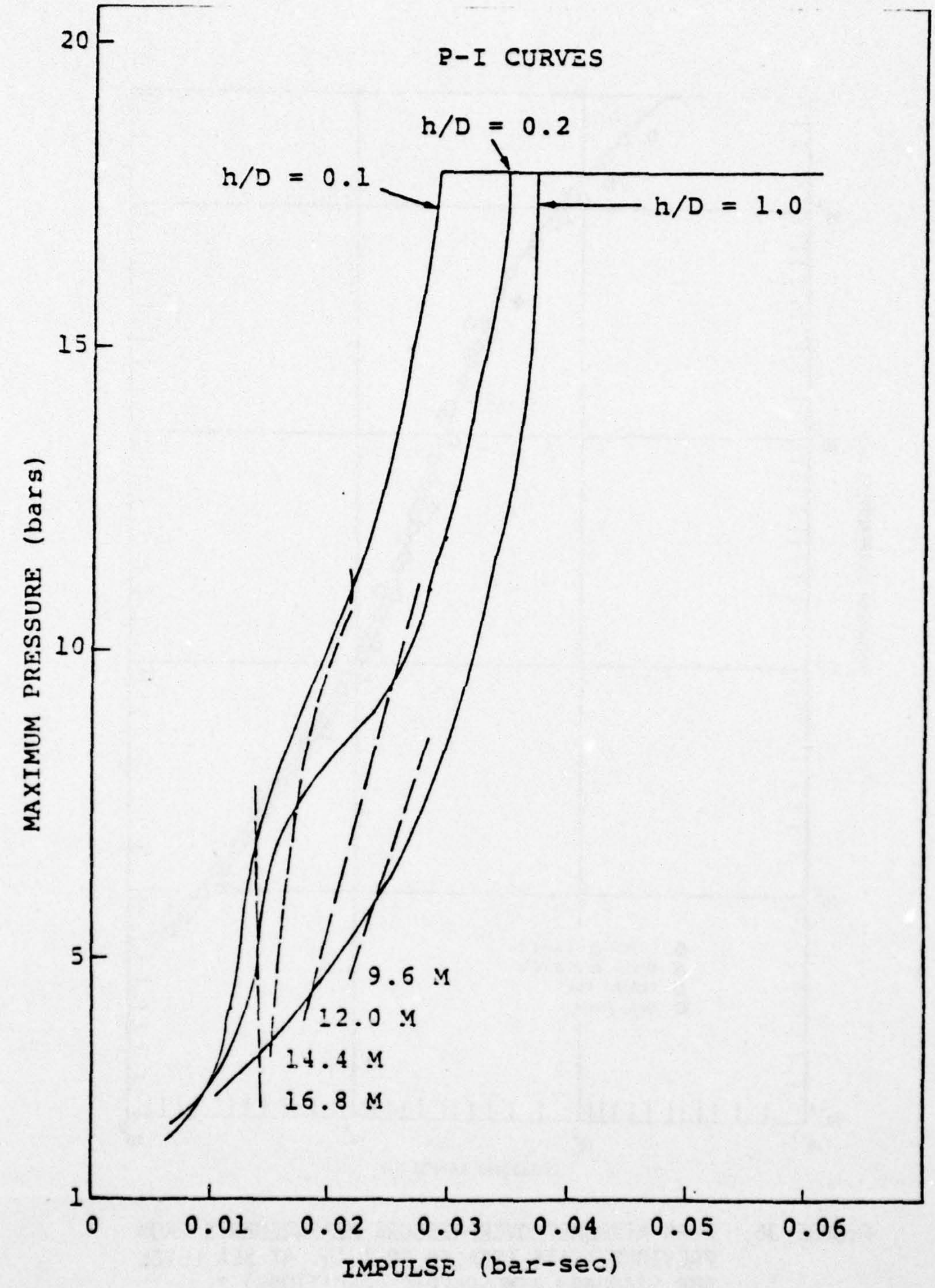

FIGURE 35. PLOT OF PREDICTED MAXIMUM PRESSURE VS. IMPULSE FOR THE THREE CLOUD CONFIGURATIONS.* ISO-RADII ARE SHOWN BY DASHED LINES

* Taken from Systems, Science and Software (S^3) document, SS-R-76-2932.

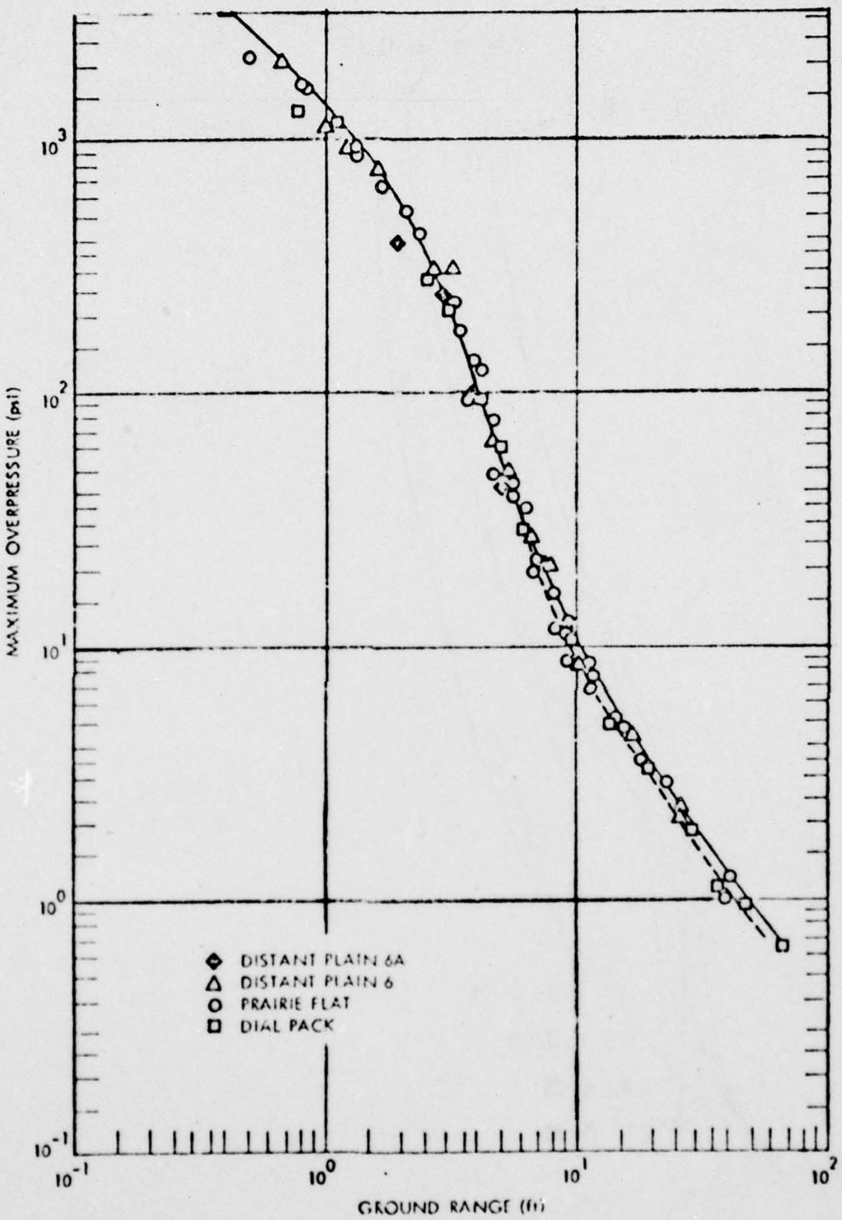

FIGURE 36. PEAK AIRBLAST OVERPRESSURE MEASUREMENTS FROM PREVIOUS TESTS (SCALED TO 1 lb. AT SEA LEVEL AND STANDARD ATMOSPHERIC CONDITIONS) *

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* Taken from DASIAC ES75-1 Draft Report.

7. RESULTS AND RECOMMENDATIONS

7.1 RESULTS

The results of this project, *Investigation and Development of a New Simulation Facility for Atomic Explosions (Project FAX), Phase II*, are presented by Task Statement as follows:

Task I. EXPERIMENTAL PROGRAM DEFINITION--The experimental program was defined and a test plan developed for a 1,000-pound fuel facility. This size was too small for scaling purposes and did not adequately match the availability of existing "off-the-shelf" equipment and hardware. Accordingly, a revised experimental program was defined and a new test plan developed for a 10,000-pound fuel facility. The principal features of this program definition and test plan are:

- Initial 60° sector testing of nozzle arrays with 1700 pounds of water/fuel,
- Cell testing of multiple 60° sectors of nozzle arrays using 10,000 pounds of water/fuel,
- Proceeding to the one-kiloton facility consisting of 19 cells arranged concentrically around a center cell--all of which are equal in size to those proposed for the FAX experimental facility.

The program is designed to proceed step-wise from a 60° sector module using water first and fuel second, to a basic cell module (made up of sector modules) that could then be used as the building block for larger facilities. Only off-the shelf hardware and equipment are needed for the moderate pressures utilized in this system.

Task II. USER REQUIREMENTS DEFINITION--User requirements have been defined for equipment in terms of past user interests in peak overpressure. The combined effects of peak overpressure, static impulse and dynamic impulse, and the needs of future users are projected.

Task III. CONTRACTOR/AGENCY IDENTIFICATION--Many contractors/agencies were identified with suitable capabilities for construction and operation of a FAX facility. (See Chapter 4.)

Task IV. EXPERIMENTAL FACILITY DESIGN--The experimental facility design, discussed in Chapter 5, is for a 10,000-pound fuel facility. The overall specifications for this facility have been delineated and a preliminary cost estimate for the facility (not including instrumentation) has been presented.

Task V. DATA BANK AND INFORMATION COLLECTION--Data and information on blast waves and blast wave effects have been collected for the following:

- Nuclear blasts,
- HE/ANFO blasts, and
- Fuel-air detonations.

The information collected concentrated on peak overpressures, static impulse data, and dynamic impulse data (little of which was available).

7.2 RECOMMENDATIONS

There are many recommendations that have been suggested throughout this report which should be pursued further--the two most important being:

1) The FAX Simulation Facility Program has demonstrated that fuel-air explosions produce blast waves that closely match those of a nuclear burst, and therefore this program should be continued through the construction of the experimental facility as a minimum.
2) The Naval Weapons Center, China Lake, should be given serious consideration as the site for the pilot facility testing and for the construction and subsequent testing of the experimental facility.

Another recommendation is that user requirements be defined in the more realistic terms of static and dynamic impulse. But although these recommendations are considered of value one other seems to be particularly timely in light of present budget constraints. While the objective of Project FAX was to utilize pure blast waves outside the cloud to simulate nuclear bursts, a secondary objective presents itself if detonation properties inside the cloud are noted. These detonation properties are most pertinent to the weapon development of highly effective devices. Therefore, it is recommended that the DNA consider a joint program with the Navy and DARPA to solicit their interest, support, and utilization of the FAX Facility as a true multi-purpose facility.

The future success of the FAX Program will depend to a large extent on its management. The program is multi-faceted and requires expertise from government, industry and universities. In this regard, it is recommended that a systems-oriented contractor--preferably, but not necessarily, a non-hardware producer--be contracted for the technical direction and coordination duties associated with the construction and operation of the facility.

It is strongly recommended that this program be carried forward as a means of providing a much-needed cost-effective multi-purpose facility with suitable flexibility for meeting a wide range of requirements.

APPENDIX A
SELECTED BIBLIOGRAPHY

Bach, G. G., Knystautas, R., & Lee, J. H. *Initiation Criteria for Diverging Gaseous Detonations*, 13th International Symposium on Combustion, 1971 The Combustion Institute, Pittsburgh, PA.

Berning, W. W. *Predicted Effects of Atomic Weapons Upon Ordnance Equipment*, AD # L17 046, BRL Report # 847, Aberdeen Proving Ground, MD, July 1953.

This 1953 Report outlines the semi-theoretical and emperical methods for estimating the effects of an atomic weapon upon items of ordnance equipment. It is pointed out that nuclear and thermal radiation effects appear to be of minor importance as compared to that resulting from the blast wave.

Bigoni, Robert A. *Preliminary Report on Project Gas Explosive Simulation Technique*, Prepared for Defense Nuclear Agency by Air Force Weapons Laboratory, October 1974.

This document is a preliminary report on Project GEST which consisted of a series of tests to simulate late-time, low altitude nuclear fireball phenomenology. Methane-oxygen mixtures were utilized in near-stoichiometric proportions. The entainment of bomb debris in the form of hot metal oxides were utilized to radiate in the 10-12 μ wave length region.

Blast Simulation with Balloons Containing Detonable Gas, General American Transportation Corp., Draft Final Technical Report, GARD Project 1539-6000, Niles, IL, June 1974.

This Final Report summarizes the experimental data on air blast generation by detonable gas in balloons conducted by the staff of the General American Research Division for various projects for the Defense Nuclear Agency. Blast parameters, including peak overpressure, shock wave arrival times, positive phase durations and positive phase overpressure impulse data were gathered from these sources and are condensed and presented together with descriptions of the balloons and the field operation.

Brode, Harold L. *A Calculation of the Blast Wave from a Spherical Charge of TNT*, USAF RAND Research Memorandum, RM-1965, Doc. # AD 114302, August 1957.

This Research Memorandum is a numerical solution of the partial differential equations of hydrodynamic motion for the case of a center-detonated spherical charge of TNT that was accomplished on a high speed computer. Results are mainly presented in graph form and illustrate the formation of a series of shock waves that results from the inward rarefaction into the TNT gases.

Brode, Harold L. *Numerical Solutions of Spherical Blast Waves*, Journal of Applied Physics, Vol. 26, No. 6, RAND JAP 26.766.775, December 1954.

This Journal of Applied Physics article addresses the numerical integration technique of solving spherical blast wave equations using the Von-Neumann and Richtmeyer technique employing artificial viscosity. The solutions were carried from two thousand atmospheres to less than one-tenth of an atmosphere peak overpressure.

California Research & Technology, Inc. Packet--"Investigation of Effects of Fuel-Air Cloud Variables upon Blast Pressures and Impulses," Proposal.

Much of the information presented in this packet can be found in the preliminary report, CRT 2000-1. (See Rosenblatt entry.)

Civil Engineering Research Facility, University of New Mexico--"Statement of Qualifications."

This is a statement of qualifications of the University of New Mexico Civil Engineering Research Facility to engage in fuel-air explosion work.

Collins, Patrick M. *Detonation Initiation in Unconfined Fuel-Air Mixtures*, Acta Astronautica, Vol. I, pp. 259-266, Permagon Press, 1974.

DASA 1200, Appendix 6B, pp. 6-131 to 6-147. (See Kriebel entry.)

Department of the Army US Army Test & Evaluation Command Environmental Impact Assessment, Dice Throw High-Explosive Field Test Program, White Sands Missile Range, DASIAC, General Electric Co.--TEMPO, Santa Barbara, CA, February 1975.

This document is an environmental impact assessment for the Dice Throw High-Explosive Field Test Program. It contains some excellent data on blast wave effects upon the biological environment, ejecta, cratering, etc.

The Effects of Nuclear Weapons, U.S. Government Printing Office, Feb. 1964.

EG&G, Inc.--Packet, "Statement of Capabilities for Engineering Services in Connection with a Facility for Simulation of Nuclear Effects."

This packet is a statement of EG&G's capabilities and experience relative to a fuel-air facility for the simulation of nuclear blast effects.

Ethridge, Noel *Blast Overturning Model for Ground Targets*, BRL Report # 1889, Aberdeen Proving Ground, MD, June 1976.

This report provides information pertinent to conditions that lead to the overturning of ground targets. It is a model based on empirical determination of "Blast & Loading Parameters" that are specific in terms of designated targets, such as vehicles. The necessity for target information, such as drag coefficients, center of pressure, target orientation, etc., is pointed out, along with the necessity for accurate dynamic impulse information.

Fishburn, Barry D. *Some Aspects of Blast from Fuel-Air Explosives*, Abstract, Feltman Research Laboratory, Picatinny Arsenal, Dover, NJ.

This document reports the results obtained from numerical solutions for (1) centrally initiated, self-similar Chapman-Jouguet detonation, (2) edge initiated spherical implosion, and (3) constant volume energy release followed by sudden venting to the environment. The unsteady equations governing the inviscid, adiabatic flow of perfect gases in one dimension were solved using the well-known artificial viscosity technique of Von-Neumann and Richtmeyer (1950) as employed by Oppenheim (1973).

Fry, R. S. & Nicholls, J. A. *Blast Wave Initiation of Gaseous & Heterogeneous Cylindrical Detonation Waves*, 15th Symposium on Combustion, Tokyo, Japan, August 1974.

This paper given at the 15th Symposium on Combustion in Tokyo is a summary paper on the work done at the University of Michigan on blast wave initiation of gaseous and heterogeneous cylindrical detonation waves. A summary of blast source energies and their effect upon wave Mach number are presented.

Fry, R. S. & Nicholls, J. A. *Blast Initiation and Propagation of Cylindrical Detonations in MAPP-Air Mixtures*, Reprint from AIAA Journal, Vol. 12, No. 12, December 1974, pp. 1703-1780.

This AIAA Journal article presents the results of an experimental investigation of the initiation, transition and quasi-steady propagation of blast-initiated cylindrical detonations in MAPP-Air mixtures. A sectored shock tube was used in this experimental investigation which delineated three wave propagation regimes that determine initiation.

Green Farm Test Site, Brochure, Systems, Science & Software (S^3), La Jolla, CA. (no date)

This brochure describes the Green Farm Test Site and its capabilities for testing up to 300 pounds of high explosives.

Kriebel, A. R. *Air Blast in Tunnels & Chambers*, DASA 1200-II, Supplement 1, DDC # AD 906986L, October 1972.

This is a detailed summary report of the propagation of shock waves penetrating into and propagating through tunnels and chambers based upon both theoretical and experimental analysis.

AD-A048 794 MCMILLAN SCIENCE ASSOCIATES INC LOS ANGELES CALIF F/G 19/4
A NEW SIMULATION FACILITY FOR ATOMIC EXPLOSIONS-PROJECT FAX. PH--ETC(U)
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Lovelace Foundation, "FAE Bibliography"--Packet.

This packet contains an FAE Bibliography and data for peak overpressures and impulses obtained from the fuel-air explosion of small charges.

Mayerhofer, Robert D. *Response to Blast of Parked Aircraft (Event Dial Pack) (U)*, BRL MR 2267, DDC # AD 524930, Aberdeen Proving Ground, MD, January 1973.

In this report, the results of an experiment to determine the structural and component response of two types of helicopters and two types of fixed-wing aircraft parked at various blast intensity levels are presented. Included are the damage descriptions, damage photographs, aircraft displacements, and a comparison of the results with those predicted based upon current methodologies.

McMillan, W. G., Oliver, R. W., & McMillan, N. C. *A New Simulation Facility for Atomic Explosions (Project FAX); Phase I--Preliminary Engineering Feasibility*, McMillan Science Associates, Inc., Final Report to DNA, DNA 4101F, 30 August 1975.

This Study investigates the feasibility of using unconfined fuel-air explosions to simulate the blast effects of up to one kiloton nuclear explosions. The detailed theoretical physico-chemical calculations of this Study along with experimental observations from other sources show the feasibility of such simulation. Substantial savings in the cost of nuclear blast simulation as well as improved predictability are indicated by using a fuel-air explosion in lieu of HE or Ammonium Nitrate-Fuel Oil (ANFO). Preliminary engineering and hydrodynamic calculations for a re-usable fuel-air explosion facility are presented along with recommendations for further engineering design developments in the several methods described which will achieve the desired fuel-air explosion. This Study is Phase I of a two-phase project for which the present Study serves as the second phase.

Needham, Charles, E., et al. *Nuclear Blast Standard (1 kt) (U)*, Air Force Weapons Laboratory, Final Report, Kirtland AFB, NM, April 1975.

This technical report involves the computer modeling of a one-kiloton nuclear blast standard to update past one-kiloton blast standards using advances made in the last 25 years in hydrodynamic calculation.

Nicholls, A. J., Fry, R. S., Glass, D. R., Sichel, M., Vander Schaff, J., & Sternstein, A. J. *Fundamental Aspects of Unconfined Explosions*, University of Michigan, Technical Report to Air Force Armament Test Laboratory, Eglin AFB, (AFATL) TR-72-49, DDC # AD 902582, March 1972.

This report is the first year report of a three-year program to study the fundamental aspects of unconfined explosions. The theoretical aspects of cylindrical, strong blast waves and Chapman-Jouguet detonations are treated in detail. The experimental equipment used to test the propagation of cylindrical detonation waves through two-phase clouds of fuel-air is described. A modified computer program for calculating detonation velocities of complex hydrocarbon fuels is discussed.

Nicholls, A. J., Sichel, M., Fry, R. S., Hu, C., Glass, D. R., Desaro, R., & Kearney, K. *Fundamental Aspects of Unconfined Explosions*, University of Michigan, Technical Report to AFATL, Eglin AFB, FL, TR-37-125, DDC # AD 913443, June 1973.

This report is the second year report of a three-year program to study the fundamental aspects of unconfined explosions. The propagation of detonation waves through fuel mists is studied, both theoretically and experimentally, and many excellent results from the testing of kerosene-air mixtures are presented.

Nicholls, A. J., Sichel, M., Fry, R. S., & Glass, D. R. *Theoretical and Experimental Study of Cylindrical Shock and Heterogeneous Detonation Waves*, Acta Astronautica, Vol. 1, No. 3-4, March-April 1974, pp. 385-404.

This Acta Astronautica Journal article presents both the theo-

retical and experimental verification for cylindrical shock and heterogeneous detonation waves. Data are presented for the propagation of detonation waves through a mono-disperse spray of 400 μ kerosene droplets in air. A sectored shock tube was used in these investigations. Much valuable information exists relative to the initiation and detonation of fuel mists.

A Preliminary Report on the British Participation in the 500-Ton Trial at Suffield in 1964 (U), TEMPO # 43395, DASIAC # 3366.

Project "Suffield," with 500 tons of TNT, provides a comprehensive source of data for HE blast testing since excellent test measurements were made for determination of blast parameters. The peak overpressure-static impulse match to a one-kiloton nuclear standard is very good in the 0-50 psi range and close (but lower) in the 50-100 psi range.

Rosenblatt, M., et al. *DICE--FAE Analysis of Fuel Dispersal and Detonation from a Fuel-Air-Explosive Device*, CRT 2000-1, Eglin AFB, FL, March 1976.

This is a preliminary report of a cloud dispersal analysis carried out by California Research & Technology, Inc. (CRT), using a two-dimensional, implicit, Eulerian, finite difference code which treats fuel-air mixtures, fuel droplet break-up, fuel phase changes, and fuel-air detonation dynamics. The analysis of the results is not complete.

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