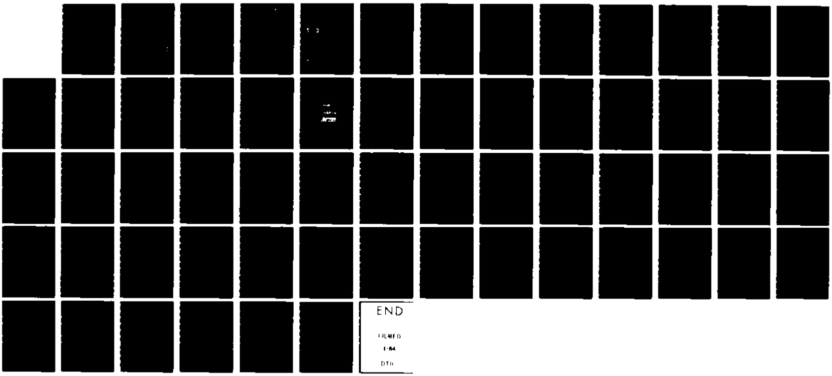
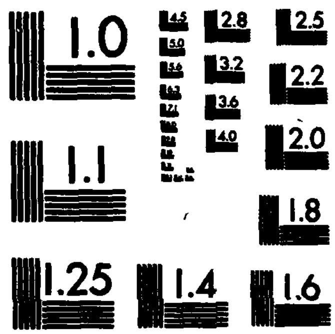
AD-A135 540 TEST PROGRAM FOR ASSESSING VULNERABILITY OF INDUSTRIAL EQUIPMENT TO NUCLEAR AIR BLAST(U) LAWRENCE LIVERMORE NATIONAL LAB CA J V ZACCOR ET AL. OCT 83 UCRL-15558 1/1

UNCLASSIFIED EMW-E-0883 F/G 18/3 NL





MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

(13)

SSI 8302-8

UCRL-15558
P.O. 9652901

AD-A135 540

TEST PROGRAM FOR ASSESSING VULNERABILITY OF INDUSTRIAL EQUIPMENT TO NUCLEAR AIR BLAST

FINAL REPORT
OCTOBER 1983

DTIC
ELECTE
DEC 8 1983
S D
B

for
FEDERAL EMERGENCY MANAGEMENT AGENCY
WASHINGTON, D.C. 20472

DTIC FILE COPY

Approved for public release;
distribution unlimited

Contract No. EMW-E-0883
Work Unit 1124F

SCIENTIFIC SERVICE, INC.

83 12 08 017

Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: UCRL-15558
2. GOVT ACCESSION NO.: A135 540
3. RECIPIENT'S CATALOG NUMBER:
4. TITLE (and Subtitle): TEST PROGRAM FOR ASSESSING VULNERABILITY OF INDUSTRIAL EQUIPMENT TO NUCLEAR AIR BLAST
5. TYPE OF REPORT & PERIOD COVERED: Final Report
6. PERFORMING ORG. REPORT NUMBER: SSI 8302-8
7. AUTHOR(s): J.V. Zaccor and G. Selvaduray
8. CONTRACT OR GRANT NUMBER(s): EMW-E-0883
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Scientific Service, Inc., 517 East Bayshore, Redwood City, CA 94063
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: Work Unit 1124F
11. CONTROLLING OFFICE NAME AND ADDRESS: Federal Emergency Management Agency, Washington, D.C. 20472
12. REPORT DATE: October 1983
13. NUMBER OF PAGES: 53 pages
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 24550
15. SECURITY CLASS. (of this report): Unclassified
15a. DECLASSIFICATION/DOWNGRADING SCHEDULE:
16. DISTRIBUTION STATEMENT (of this Report): Approved for Public Release; Distribution Unlimited
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report):
18. SUPPLEMENTARY NOTES:
19. KEY WORDS (Continue on reverse side if necessary and identify by block number): design; test program; vulnerability; industrial equipment; air blast; nuclear weapons; scale models; selection procedure; tradeoffs; damage mechanism; communications/electronics
20. ABSTRACT (Continue on reverse side if necessary and identify by block number):

The report discusses the design of a test program to develop technical data on the vulnerability of industrial equipment to air blast from nuclear weapons (1 megaton weapons size in the overpressure region up to 20 psi). To achieve the experimental objective, scale models, full size models, and actual equipment may be used for different facets of the program under specific circumstances.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

Block 20. (contd)

A selection procedure is identified for choosing equipment for testing, and for making technical versus economic tradeoffs in selecting a given level of vulnerability or for verifying the representativeness of a selection or tradeoff to achieve a general level of vulnerability. Damage mechanisms likely to affect equipment subjected to a blast wave are identified and a flow chart identifies test types and major parameters affecting outcome. A minimum experimental program is proposed to provide reference equipment-vulnerability-data for the communications/electronics industry for four different air blast damage mechanisms as the first stage in the eventual development of data on hardening.

Accession For	
NTIS GRA&I	☑
DTIC TAB	☐
Unannounced	☐
Justification	
By	
Distribution/	
Availability Codes	
Dist	Avail and/or Special
A-1	

SSI 8302-8 Final Report
October 1983

UCRL-15558

TEST PROGRAM FOR ASSESSING VULNERABILITY OF INDUSTRIAL EQUIPMENT TO NUCLEAR AIR BLAST

by

J.V. Zaccor and G. Selvaduray

for

Lawrence Livermore National Laboratory
Livermore, CA 94550

Purchase Order No. 9652901

and

Federal Emergency Management Agency
Washington, D.C. 20472

Contract No. EMW-E-0883, Work Unit 1124F

Approved for public release; Distribution unlimited

FEMA REVIEW NOTICE:

This report has been reviewed by Lawrence Livermore National Laboratory for the Federal Emergency Management Agency and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the Federal Emergency Management Agency.

Scientific Service, Inc.
517 East Bayshore, Redwood City, CA 94063

SUMMARY

The report discusses considerations pertinent to the design of a test program to develop technical data on the vulnerability of industrial equipment to air blast from nuclear weapons (1 megaton weapons size in the overpressure region up to 20 psi).

Information is provided on the appropriate use of scale models, full size models, and actual equipment to achieve the experimental objective, and it is concluded that all three are appropriate to the program for different facets; the specific circumstances for each are identified.

A procedure is identified for selecting equipment for testing, and for making technical versus economic tradeoffs in selecting a given level of vulnerability or for verifying the representativeness of a selection or tradeoff to achieve a general level of vulnerability.

Damage mechanisms likely to affect equipment subjected to a blast wave are identified and a flow chart identifies test types and major parameters affecting outcome, which must be addressed in any comprehensive effort to develop data intended to isolate overpressure, drag, and missile effects.

A minimum experimental program is proposed to provide reference equipment-vulnerability-data for the communications/electronics industry for four different air blast damage mechanisms as the first stage in the eventual development of data on hardening. A total of 525 separate tests are proposed, involving 186 units of four different types of equipment and 6 scale models.

ACKNOWLEDGEMENTS

This report describes an exploratory experimental program to establish reference data for communications and communications related equipment vulnerability to air blast from megaton size nuclear weapons. The authors would particularly like to thank the many individuals who have helped them assemble information on communications equipment, communications systems, and typical environments.

We especially wish to thank Mr. W.L. Edwards of AT&T Long Lines for his generous support in the form of reports, photographs, and information supplied, and for arranging for us to visit telephone switching facilities of the 4ESS and the 4A types located in our vicinity.

We also wish to extend our thanks to Mr. C.D. Mead and Mr. M. Kelly and to Ms. Rebecca Gonzales and Ms. Maureen Kluska for the time and consideration accorded us in providing tours of their respective facilities and for their efforts to provide a clear description of how these switching systems function.

The report review guidance of Robert Hickman of Lawrence Livermore National Laboratory has been of considerable benefit, is much appreciated, and gratefully acknowledged.

Finally, the authors would like to acknowledge the support of A.B. Willoughby and Theodore Zsutty, consultants, and of the SSI staff: B.L. Gabrielsen, M. Ineich, E.P. Kaplan, and L. Wilton.

INDUSTRIAL EQUIPMENT VULNERABILITY ASSESSMENT

1. INTRODUCTION

This report represents the first step in a program to develop comprehensive technical information on the vulnerability of industrial equipment to nuclear attack, propose expedient cost-effective countermeasures to protect critical equipment, and develop an experimental plan to assess the efficacy of these countermeasures. The overall program is a prerequisite to ensure the **survival** of industrial capability during, and **recovery** after, a nuclear attack; both these factors are fundamental to the nation's ability to provide logistic support for the surviving population and to enable the nation to recover as an international power. The industrial survival information developed will be provided to industry to apply as a self-help program in the event of a crisis so that industry may protect itself. The effort reported here is on the design of an experimental program to develop the necessary data on equipment vulnerability.

For the past 20 years the Federal Emergency Management Agency (FEMA) and its predecessor agencies have sponsored a variety of research programs dealing with various aspects of industrial protection. During the latter part of this period, the Defense Nuclear Agency (DNA) and other organizations have also sponsored studies in this general area. Such efforts have included studies to determine those industries and business establishments that would be most vital for national defense and postattack recovery (Ref. 1), in-depth studies of specific vital facilities and industries (Refs. 2 - 6), and most recently, a program on industrial protection conducted by Scientific Service, Inc. (Refs. 7 - 9). The latter program included a review (1977) of past research efforts relating to industrial protection, analytical and laboratory studies to develop viable protection techniques, some field testing of the technical merit of the techniques (Ref. 10), incorporation of these techniques into a planning guide for industry, and testing of their practical merit by means of demonstrations to assess the application of the planning guide by industry.

Unfortunately, virtually all studies to date on industrial equipment vulnerability to blast effects of nuclear weapons have been concentrated within a narrow range: machine shop equipment, within a typical plant environment (i.e., "inside" a frangible structure), and without any protection provided to avoid impact damage due to missiles, debris, or overturning (Ref. 11). Clearly, if a nuclear attack were to occur, many more industries than machine shops would be critical to survival and recovery. Consequently, the current effort has been to design the initial phase of a test program that will establish reference vulnerabilities for a range of industrial equipment as a framework for the real task of evaluating and demonstrating industrial hardening alternatives.

From the standpoint of the vast variation in types of equipment and their characteristics, no test program can be sufficiently comprehensive. However, this problem might be overcome by suitable design of the test program. Such a design must not only yield actual data on the specific equipment tested, but must also yield sufficient basic data that will permit inferences regarding vulnerabilities of untested equipment within the industry group and do this with a quantified reliability. An effective approach is to establish procedures for equipment selection, select representative equipment, identify the damage mechanisms and select the appropriate test methods, and then design a test program to assess not only the vulnerability of the "representative" equipment selected, **but also its representativeness.** Figure 1 summarizes the input requirements.

The resulting experimental program designed constitutes just the first element of an ambitious comprehensive multi-element program. In this first element, the end objective has been limited to the design of experiments to acquire pertinent technical information on the vulnerability of industrial equipment and the adequacy of the method for establishing representativeness. As requested in the Invitation For Proposal (IFP), this has been accomplished by considering the relative importance, or ranking of the industry groups specified and:

A. Selecting equipment for testing using a documented detailed selection criterion.
B. Identifying the damage mechanisms resulting from nuclear blast waves.
C. Identifying where:
   - Full-size models are required
   - Scale models can be used or are required.
D. Developing a testing program plan to determine the vulnerability of the test items or models, to combine effects of overpressure, drag, and missiles that are characteristic of a 1.0 Mt yield explosive.

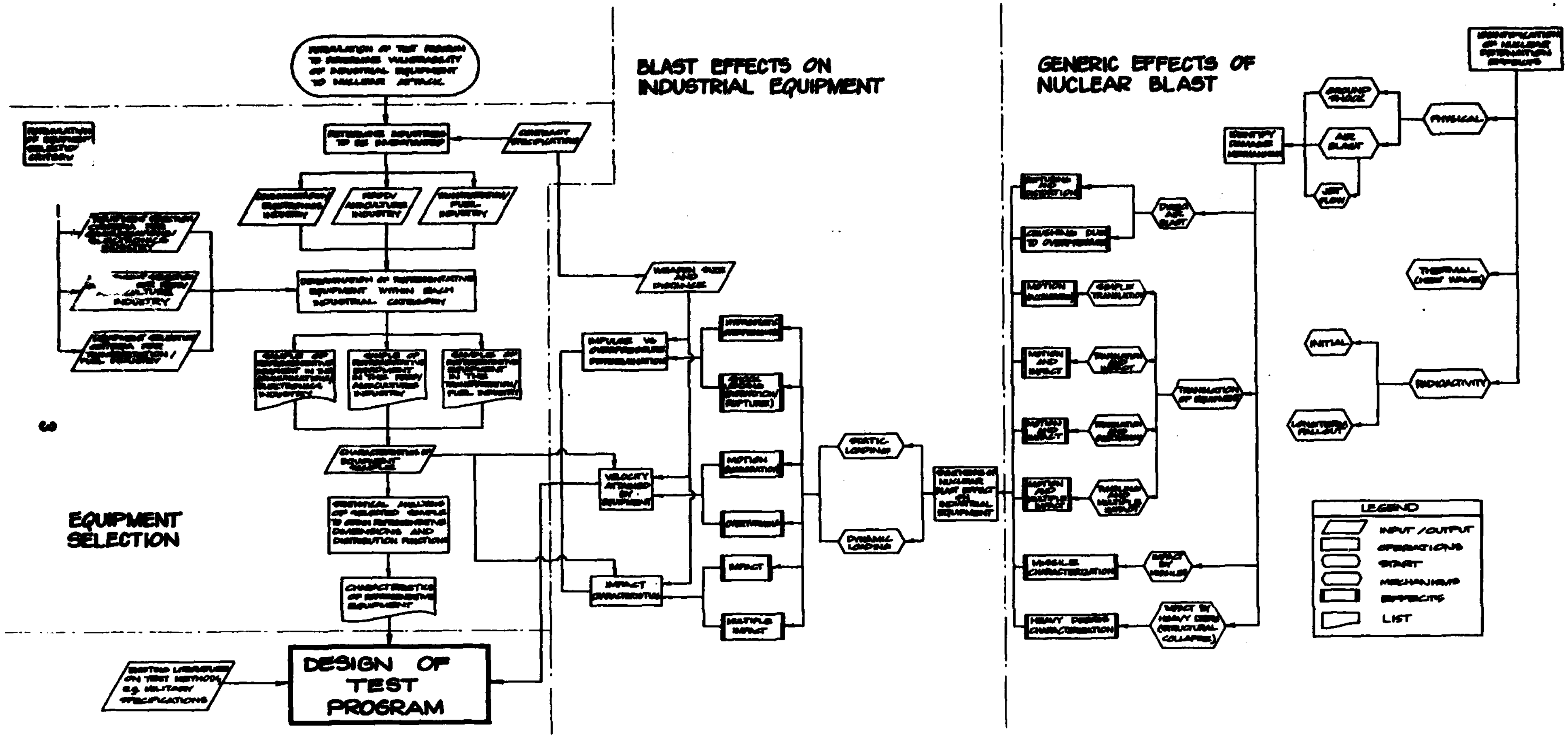


Fig. 1. Decision Analysis Flowsheet for Equipment Selection and Damage Mechanism Identification.

In completing this first element, it was important to keep in mind that overpressures of interest range from 5 psi to 20 psi, and that the tests will eventually be conducted with and without "hardening" to protect the test objects.

The effort under A considered:

1. Three pairs of related industry groups and ranked them as follows:
   a. Communications/electronics
   b. Fuel/transportation
   c. Food/agriculture
2. The communications/electronics industry to:
   a. Identify types of equipment required immediately postattack
   b. Develop a critical equipment list
   c. Define a selection procedure for equipment to test
3. The role played by equipment characteristics on the damaging effects of blast waves.

The effort under B considered:

1. Identifying the basic mechanisms by which industrial equipment can be damaged by blast waves
2. Determining the effect these mechanisms, singly and jointly, could have on the equipment selected, and how equipment characteristics would influence these effects.

The effort under C considered:

1. Technical constraints pertinent to testing full-size versus scale models
2. Economic constraints pertinent to testing full-size versus scale models.

The effort under D required attention be given to:

1. Methods to isolate damage mechanisms: overpressure, drag, and missile effects on test objects
2. Scaling requirements necessary to predict response at 1 Mt
3. Methods to measure drag coefficients and friction coefficients of industrial equipment.

2. EQUIPMENT SELECTION

In order to ensure that the information gathered is pertinent to a wide range of critical equipment in key industries, important questions to consider were:

- o Which are key industries and how would they be identified?
- o What constitutes critical equipment and how does the damage occur?

Ref. 1 is perhaps the most comprehensive study reported to date on industry essentiality. It discusses twelve studies to identify key industries, points out the difficulty of arriving at a consensus, and shows that only **five** industrial sectors (groups) out of a list of **seventy eight** qualified as "essential" by consensus (i.e., over six votes) of the twelve assessors. It should be noted that these five fall within the more general categories of two of the three target groups specified in the IFP to be considered in this study - **agriculture/food** and **fuel/transportation** (two classes of transportation, railroads and trucking, were among the five consensus key industries in Ref. 1). However, **communications/electronics** (the third group identified in the IFP) was far down on the list of rankings in Ref. 1, with only two out of twelve possible votes. Nevertheless, as communications is clearly at the heart of organization and reorganization (which is precisely what will be needed for recovery), the practice of attempting to develop a **key industries** list through a **consensus** might not be all that serviceable. A better approach would be to consider the general disaster scenario and identify more **definitive factors** for answering the above questions in order to rank priorities of industries that need to be operating immediately, and the equipment required for this. The factors considered were:

1. How soon in the disaster scenario the industry becomes a key factor
2. Diversity of industry locations and proximities to strategic or tactical targets
3. Mobility of industry's equipment (easy, or impossible, to move on short notice)
4. Equipment that is uncommon or specialized and critical to operation in critical industries
5. Relative vulnerabilities of equipment, dependent on:
    - o damage mechanisms and their ranking for major damage
    - o packaging
    - o nature of construction
    - o materials of construction.

Starting with the general disaster scenario, the first critical demand that will worsen the situation if it is not met is for communications, one of the industry groups specified in the IFP and a representative subset of the electronics industry. Mobility is likely to be the next most critical demand (i.e., fuel/transportation, another industry pair specified in the IFP). Clearly, if resources cannot be mobilized when a requirement is communicated, effective response may be precluded, or slowed drastically. However, it will not be very soon in the unfolding disaster scenario that hunger becomes a serious general concern and the food/agriculture industry group critical, so food/agriculture would rank third among the industry pairs considered, though distant as far as the requirement for immediacy of operation is concerned.

If we now consider items 2 and 3 in the above list, the relative importance of the industries to be evaluated can be spread much farther along the criticality continuum. For example, the agricultural industry is among the most disperse industries in the nation, and generally remote from strategic or tactical targets. This already amounts to an ideal choice among hardening options so that further study of this industry with the intent to develop hardening alternatives can be set aside in favor of more pressing needs. The food industry is a derivative of the agricultural industry with many processors near the source of supply, so that the same condition applies to a portion of this industry as applies to agriculture. An added factor to consider is that the food industry is one in which the production output is normally heavily stockpiled - another option in the arsenal of hardening alternatives - and most of the food processing plants at risk are involved primarily in cosmetic upgrading and packaging, processes that are superfluous in time of emergency. Overall, the food/agriculture industry group, though critical to survival in the long term, is far down the continuum of industries needing industrial hardening attention.

Because of the need for mobility from early times postattack, based on item 1 of our definitive factors list, the fuel/transportation industry ranks only just below the communications/electronics category. However, because of the diversity and mobility of transportation equipment, a great deal of the transportation rolling stock will be movable on short notice to disperse locations - making this industry considerably less vulnerable than communications, based on items 2 and 3. Studies have already been made of the vulnerability of the petroleum industry (Refs. 12 and 13), but it does not take a study to realize that this industry is considerably more vulnerable than its transportation counterpart. This is because major refineries will likely be targets, refineries (equipment) are not so disperse as to preclude targeting them, and all are unmovable. On the other hand, a great deal of refinery end product is very well dispersed with some of this located underground - in pipelines and at retail sites. It appears the fuel/transportation group will not be as important for early consideration as the communications/electronics group, but it will rank high for consideration of hardening (or production) alternatives insofar as petroleum fuels are concerned.

With regard to specific items of equipment to test, for purposes of this study what seems most desirable is to be assured that whatever items are selected for testing be representative of real equipment, and have vulnerabilities (to the various damage mechanisms that arise from blast loadings) bounding the extremes of such equipment. The point here is that if the most vulnerable items can be hardened to 20 psi, then probably the majority can; and if the least vulnerable can survive 20 psi, unhardened, then there may be no need to expend resources to harden them when other equipment might more profitably be given attention. As we do not yet know the vulnerabilities of industrial equipment to air blast, there is the problem to face of how to select items representative of vulnerability extremes. This will require some consideration of damage mechanisms to establish an index for comparison. These are discussed in greater detail in Section 3, DAMAGE MECHANISMS, and additional facets of the selection process are discussed in Section 4, PRIORITY CONSIDERATIONS.

A major problem encountered in the course of this investigation has been the magnitude of the population size. The number of different pieces of equipment used currently in just the industry groups specified in the IFP to be considered would literally run into the millions. There are hundreds of thousands to millions in just the communications/electronics industry. Selecting a truly "statistically representative" sample of equipment is not simple: damage can occur in a variety of ways with a different variance for each way and each type and class of item. Factors important to the selection process are how the sample and data might be used; it is far more important to the credibility of the end result that the equipment eventually selected be functionally representative than that it be abstractly representative of the various industrial categories.

In the first attempt to cut the task to size, the relative importance of the industry groups was ranked in order to select one on which to concentrate. As has been shown earlier, the communications/electronics group was thus selected. In general, communications industry equipment vulnerability will be indicative of the general vulnerability of the electronics industry. The next step was to examine several organizations/companies that were aware of, and had made preparations against, disasters. These were interviewed, and the communications equipment they would value in a postattack environment identified. Among the organizations, industries, and businesses surveyed for communications preparedness in an emergency situation, two types of equipment emerged as being of greatest value functionally:

1. Two-way radios for organizations interested only in **intra-plant** communications.

2. Microwave radios for organizations interested in **inter-plant** communications.

While the equipment identified above is representative of the type(s) of communications equipment that industries would employ, it does not include the main communication industry of the country: the telephone network. In view of the facts that:

a. It is the telephone network that is the major communication link of the country, and

b. From a national security and coordination viewpoint the effort of reconstruction must be nationally coordinated,

the equipment that constitutes the heart of the telephone system, a complex switch, must be included in the analysis here. The switching system of primary interest is the 4 Type (Network Type Machine), which could be either electromechanical or electronic.

Once a range of functionally representative equipment for the industry was identified, came the task of actually obtaining physical test data to analyze to obtain a statistical assessment of the distribution of established (and apparent) vulnerabilities (e.g. acceleration sensitivities, drop heights - hence velocities - leading to damage, crush strengths). Because it was not always possible to obtain the appropriate information from both manufacturers and users, an alternative approach was taken based on an analysis of the damage mechanisms.

3. DAMAGE MECHANISMS

The four basic mechanisms by which industrial equipment can be damaged by a blast wave are:

- o **Translation** of equipment under blast loading including subsequent **impact** on another surface with or without overturning
- o **Impact by missiles** accelerated (and developed) by the blast loading
- o **Impact by heavy debris** resulting from a structural collapse
- o **Direct air blast damage** by crushing, deforming, rupturing of equipment

The primary mechanism for **translation** of equipment is acceleration by the drag force of the blast wave. An important early study of drag effects (e.g., Ref. 14) defined the maximum velocities and the displacements at maximum velocities for items accelerated under an essentially "airborne" condition, where frictional resistance was not a factor. However, more recent studies (Ref. 15) have indicated "anomalous" behavior for some object shapes, which signifies these objects not only fail to become airborne, but the static overpressure helps to hold them in place against the dynamic pressure drag. In any case, the drag force is given by:

$$F_D = (C_D A_D)q \qquad (1)$$

where
F_D = drag force
C_D = drag coefficient
A_D = drag area, area of the object presented to flow*
q = dynamic pressure

For the case where frictional resistance does not come into play (e.g., for objects with shape characteristics that give lift in a flow field), a stepwise numerical solution is required to chart the most **general** case, in order to take into account the object velocity changes as it accelerates **within** the flow field. However, for the special case of **impulsive** loading where the object does not move significantly before the blast wave passes, then:

$$F_D \, dt = m \, dv \qquad (2)$$

or

$$(C_D A_D)q \, dt = m \, dv \qquad (2a)$$

where v = the object velocity and m = the object mass

---

* An effective drag area, based on time-dependent reorientation.

Integrating, we obtain,

$$v = (C_D A_D/m)\ I_q \tag{3}$$

where $I_q = \int q\ dt$, the dynamic pressure impulse

This form will apply where the weapon size is small and/or the peak object velocities are less than 50 ft/s. Also,

$$v = (\alpha)\ I_q \tag{4}$$

where $\alpha = C_D A_D/m$ is the acceleration coefficient

Two important factors in the above equations are the drag coefficient, C_D, and the cross sectional area, A_D. Experimental evaluation of these two factors must be among the objectives of the experimental test program. Additionally, the role that a friction force introduced into Equation (2) would play on object response (which will necessitate evaluation of friction coefficients, as well) also needs to be empirically determined.

A secondary mechanism for translation of equipment is acceleration by jet flow (Refs. 16, 17), which may be formed behind an opening in a non-failing wall. Under certain circumstances (see Figure 2, from Ref. 16), the dynamic pressure in a jet can be ten times that in the free field. For example, a 5.0 psi static overpressure at normal incidence on a non-failing wall with a frangible opening will result in formation of a jet with a flow velocity (u jet) equivalent to that in the free field (u free field) at a static overpressure of 20 psi. (Note that the difference in magnitude between dynamic pressures in jet flow, q_{jet}, compared with the normal flow causing it, $q_{free\ field}$, increases with decreasing overpressures.) The calculation of equipment velocities under jet flow are similar to those for drag flow with the dynamic pressure impulse replaced by the jet flow impulse. Whichever the cause, the velocity attained by the object is the key parameter to determining the extent of damage when impacts occur.

Translation of equipment can lead to impact with other surfaces in the following ways:

- o Overturning and impact with the ground surface
- o Tumbling and multiple impact with the ground surface

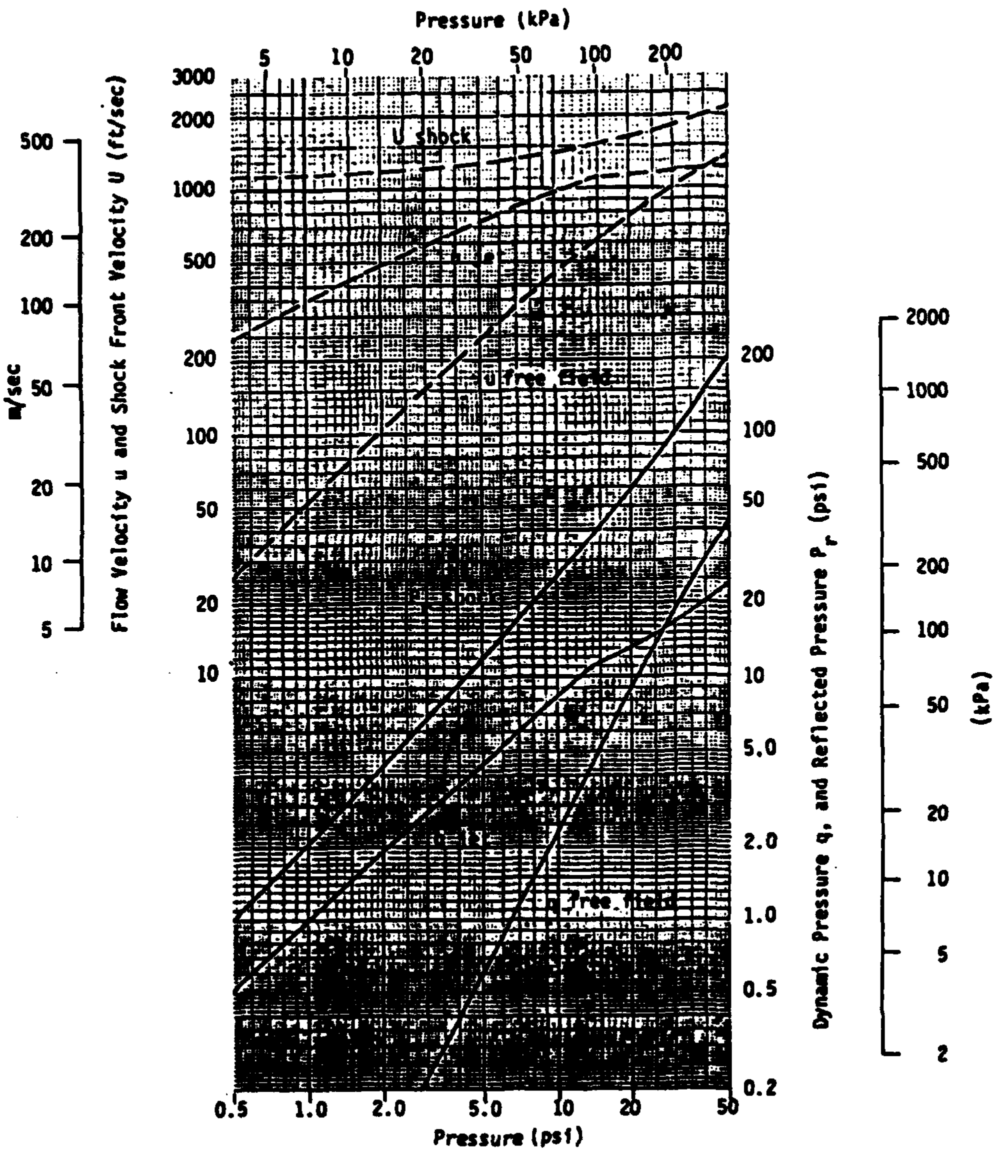


Fig. 2. Shock Wave and Jet Parameters: Dynamic Pressure q, Flow Velocity u, Shock Front Velocity U, Reflected Shock Pressure P_r.

Source: Kenneth Kaplan and Paul D. Price, Accidental Explosions and Effects of Blast Leakage into Structures, ARLCD-CR-79009, U.S. Army Armament Research and Development Command, Dover, New Jersey, June 1979.

- Sliding and/or tumbling followed by impact with a vertical surface - including the case of ejection through a frangible wall of a building and subsequent impact on the ground surface

Procedures for calculating the minimum velocity required for overturning (as well as the start of tumbling) and expected translation distances as a function of equipment properties have been given in Ref. 18.

Impact by missiles can occur as a result of three mechanisms. Two of these are the same as already discussed for accelerating the equipment (free field drag force and jet flow). These two mechanisms will apply to loose materials such as building contents, fixtures, fragments of broken equipment.

The third mechanism is applicable to fragments of the walls of a structure. On a wall facing the blast, the loading initially will be peak reflected overpressure, decaying to the stagnation pressure during the front face clearing time and remaining at this level until the wall has fragmented sufficiently to permit pressure relief. When this latter occurs, the loading will drop back to the drag level and drag forces will start to operate. Impact by wall fragments is expected to be the ranking source of damage to equipment by missiles and was the principal damage mechanism studied at NTS (Ref. 19). This third acceleration mechanism, as a result of high early time loading, is considered the major source of damaging impacts by missiles because it generally results in higher velocities for larger missiles than the other two mechanisms. That is, at the 20 psi overpressure range, the dynamic pressure, q, which results in normal drag loading acceleration of missiles is 8.9 psi; jet flow could accelerate missiles corresponding to a loading of q_{jet} = 13 psi; and the peak reflected pressure, p_r, that will cause structural walls to fail will accelerate the resulting missiles under a loading of 60 psi (see Figure 2).

Impact by heavy debris can occur inside a structure when the structure or portions thereof collapse on the equipment, or it can occur with equipment located outdoors but in the vicinity of a structure; the greatest concern would be for equipment in the immediate vicinity of high rise buildings that topple over onto the equipment.

Even without high rise buildings, at the 5 psi overpressure range, falling debris could easily be the most severe, as a fall from a height of 22 feet onto a 6-ft high piece of equipment would correspond to an impact velocity of 35 ft/s, while, as will be shown later assuming a drag coefficient $C_D = 1.0$, less than 55% of the generally lightweight communications equipment might be expected to be accelerated to this velocity.

Direct air blast damage can cause differential motions of various parts of equipment leading to permanent deformation or to rupture. It also includes the collapse of structures under a sudden differential in static overpressure between the inside of an enclosed space and the outside. This "crushing" effect is analogous to the equipment package being subjected to sudden hydrostatic overpressure. Within the context of this study, however, there is a critical difference between the "crushing" effect of a blast wave, and the same effect caused by applying hydrostatic overpressure. Because of the inherently slow rise time in hydraulic loaders, to conduct a test using a hydrostatic loading, it is necessary that the equipment be hermetically sealed, so that the overpressure applied will act on the equipment only from the outside. Actual equipment, and especially telecommunications equipment, are generally not hermetically sealed. Consequently, for air blast loadings there is a finite buildup of pressure within the equipment itself while the blast wave is engulfing it, but because of the shock front, it does not build up fast enough to neutralize the "crushing" effect. Note that the term direct air blast damage does not imply damage **only** from crushing under the static overpressure; many items of communications equipment (antennas, power poles) will **not** respond to the static overpressure but **will** succumb to deformation and fracture under the drag loading **alone**.

It is for the direct air blast damage case that the only known detailed study was made of a statistically significant population of similar artifacts. That is, direct air blast damage to **trees** was studied under drag loading (Refs. 20, 21, 22, 23, 24), where there is essentially a **single mode of failure**. (Circumstances will not be so simple for the industrial equipment problem.) The tree damage prediction model used a blending of deterministic calculations for failure, with statistical variations (e.g., height, girth, of the test articles) in the sample populations for a variety of species studied by the U.S. Forestry Service to determine probability of failure versus species. However, in applying the information, one must take account of the fact that in any given forest area the **entire** population under consideration will consist of **different combinations** of species in **different quantities**.

In a somewhat parallel technique, catalogs of communications equipment were used to acquire sufficient data on dimensions and weights to make deterministic calculations of maximum velocities and of threshold velocities for overturning (using Equation 3 herein and the procedure described in Ref. 18, respectively). The data are listed in Tables 1 - 4, and Figure 3 shows the cumulative distribution curves for the velocities presumed to be attained by members of this sample (i.e., for this selection of species) of communications equipment at each of three overpressures: 5, 10, and 20 psi from a 1 Mt weapon at one value of the drag coefficient, $C_D = 1.0$. The statistical aspect of the assessment here corresponds only to variation among the **individual species** of equipment **on the list** (which we have taken to be adequate to our purposes for now). It cannot take cognizance of relative frequency of occurrence of each species because this will be different in each population of communications equipment at each facility or site (and the list does not begin to cover all species). Note that the curve in Figure 3 for 5 psi provided the basis for the statement (on page 13) that less than 55% of the equipment (types) **might** be expected to exceed a velocity of 35 ft/s. Further note that the abscissa for Figure 3 is really just the cumulative percentage of the (13) types (on the list) that are expected **not** to exceed the indicated velocity, and the 5 psi curve cannot be construed to indicate that 55% of the communications equipment at a given site will not exceed 35 ft/s. *Any attempt to make such a statement would first have to take* into account the actual makeup of the entire population at that facility. One further note: there are considerably more species of equipment than there are of trees - and the vulnerability of even one species has not yet been documented nor any selection procedure tested for representativeness in any way; hence, the need for an initial experimental program that is principally exploratory.

4. PRIORITY CONSIDERATIONS

Although the experimental program will concentrate on communications equipment (and be limited to very few items in order to keep costs for equipment tests reasonable), one important program objective is to make extrapolation to electronic equipment in general, as well as within the communications equipment subset. Another factor to keep in mind in the consideration of priorities for testing is that the longer range objective of the program is to find ways to **protect** communications/electronic equipment (not part of the current effort). The first requirement has been to develop both a rational selection procedure for choosing a

TABLE 1: BLAST INDUCED TRANSLATION VELOCITY (v ft/sec) AS A FUNCTION OF ACCELERATION COEFFICIENT (α)
[1 Mt weapon, 5 psi overpressure]

Equipment Name	α (C_D=0.25)	v ft/sec	α (C_D=0.5)	v ft/sec	α (C_D=0.75)	v ft/sec	α (C_D=1.0)	v ft/sec	α (C_D=1.25)	v ft/sec	α (C_D=1.5)	v ft/sec
AFM 601A	.0057	13	.0114	23	.0142	27	.0228	39	.0285	47	.0342	53
FM 603	.0030	7	.0060	13	.0076	16	.0121	24	.0152	29	.0182	34
AM 725	.0052	12	.0104	21	.0130	26	.0208	37	.0260	44	.0312	50
AM 705C	.0047	11	.0095	20	.0119	24	.0191	35	.0239	38	.0287	47
MWR 70F3	.0253	43	.0507	68	.0634	77	.1015	96	.1269	107	.1523	115
MWR 2.1GHz	.0041	10	.0082	18	.0103	21	.0165	31	.0206	37	.0247	42
Micro 2.1GHz	.0041	10	.0082	18	.0103	21	.0165	31	.0206	37	.0247	42
Starpoint	.0025	6	.0050	11	.0062	14	.0100	21	.0125	25	.0150	29
Multiplex	.0064	15	.0129	26	.0162	30	.0259	44	.0324	52	.0389	58
TV	.0098	21	.0196	36	.0245	42	.0392	58	.0491	67	.0589	74
Mobil Radio	.0156	30	.0312	50	.0390	58	.0625	76	.0781	86	.0937	94
Citicom	.0106	22	.0212	37	.0265	45	.0424	61	.0530	70	.0636	77
Tempus	.0046	11	.0093	19	.0116	23	.0186	34	.0233	40	.0280	46

TABLE 2: BLAST INDUCED TRANSLATION VELOCITY (v ft/sec) AS A FUNCTION OF ACCELERATION COEFFICIENT (α)
[1 Mt weapon, 10 psi overpressure]

Equipment Name	α (C_D=0.25)	v ft/sec	α (C_D=0.5)	v ft/sec	α (C_D=0.75)	v ft/sec	α (C_D=1.0)	v ft/sec	α (C_D=1.25)	v ft/sec	α (C_D=1.5)	v ft/sec
AFM 601A	.0057	39	.0114	66	.0142	77	.0228	105	.0285	120	.0342	132
FM 603	.0030	23	.0060	40	.0076	48	.0121	68	.0152	80	.0182	91
AM 725	.0052	36	.0104	62	.0130	72	.0208	99	.0260	112	.0312	125
AM 705C	.0047	34	.0095	58	.0119	68	.0191	94	.0239	107	.0287	120
MWR 70F3	.0253	112	.0507	163	.0634	178	.1015	210	.1269	228	.1523	240
MWR 2.1GHz	.0041	29	.0082	52	.0103	61	.0165	85	.0206	98	.0247	110
Micro 2.1GHz	.0041	29	.0082	52	.0103	61	.0165	85	.0206	98	.0247	110
Starpoint	.0025	20	.0050	35	.0062	41	.0100	60	.0125	70	.0150	80
Multiplex	.0064	43	.0129	72	.0162	84	.0259	112	.0324	128	.0389	141
TV	.0098	59	.0196	95	.0245	110	.0392	142	.0491	160	.0589	172
Mobil Radio	.0156	82	.0312	127	.0390	142	.0625	178	.0781	193	.0937	207
Citicom	.0106	62	.0212	100	.0265	114	.0424	150	.0530	165	.0636	180
Tempus	.0046	33	.0093	56	.0116	66	.0186	92	.0233	106	.0280	118

TABLE 3: BLAST INDUCED TRANSLATION VELOCITY (v ft/sec) AS A FUNCTION OF ACCELERATION COEFFICIENT (α)
[1 Mt weapon, 20 psi overpressure]

Equipment Name	α (C_D=0.25)	v ft/sec	α (C_D=0.5)	v ft/sec	α (C_D=0.75)	v ft/sec	α (C_D=1.0)	v ft/sec	α (C_D=1.25)	v ft/sec	α (C_D=1.5)	v ft/sec
AFM 601A	.0057	93	.0114	152	.0142	178	.0228	235	.0285	265	.0342	285
FM 603	.0030	57	.0060	98	.0076	115	.0121	160	.0152	185	.0182	205
AM 725	.0052	87	.0104	144	.0130	165	.0208	220	.0260	250	.0312	275
AM 705C	.0047	82	.0095	136	.0119	158	.0191	212	.0239	240	.0287	265
MWR 70F3	.0253	245	.0507	340	.0634	375	.1015	430	.1269	450	.1523	470
MWR 2.1GHz	.0041	72	.0082	122	.0103	142	.0165	195	.0206	220	.0247	245
Micro 2.1GHz	.0041	72	.0082	122	.0103	142	.0165	195	.0206	220	.0247	245
Starpoint	.0025	49	.0050	84	.0062	100	.0100	140	.0125	163	.0150	182
Multiplex	.0064	103	.0129	165	.0162	192	.0259	250	.0324	280	.0389	305
TV	.0098	138	.0196	213	.0245	242	.0392	310	.0491	340	.0589	365
Mobil Radio	.0156	187	.0312	275	.0390	305	.0625	370	.0781	400	.0937	420
Citicom	.0106	145	.0212	225	.0265	255	.0424	320	.0530	350	.0636	375
Tempus	.0046	79	.0093	132	.0116	158	.0186	210	.0233	238	.0280	260

TABLE 4: EQUIPMENT CHARACTERISTICS AND OVERTURNING VELOCITY (v_o)

Equipment Name	Depth (D) ft	Width (W) ft	Height (H) ft	Weight lb	Density (lbs/ft^3)	F	DF	f (D/H)	Area	v_o ft/sec
AFM 601A	2.50	2.92	6.25	800	17.53	.04	.09	.40	18.25	6.05
FM 603	2.50	2.92	6.25	1500	32.88	.07	.16	.40	18.25	6.05
AM 725	2.50	11.67	6.25	3500	19.19	.04	.10	.40	72.94	6.05
AM 705C	2.50	5.83	6.25	1900	20.86	.04	.10	.40	36.44	6.05
MWR 70F3	1.31	1.58	1.02	16	7.50	.01	.02	1.29	1.61	4.09
MWR 2.1GHz	1.50	1.58	.44	42	40.38	.08	.12	3.42	0.70	3.93
Micro 2.1GHz	1.50	1.58	.44	42	40.38	.08	.12	3.42	0.70	3.93
Starpoint	1.92	1.58	.73	115	51.93	.10	.20	2.63	1.15	4.60
Multiplex	1.25	1.58	7.50	457	30.84	.06	.08	.17	11.85	4.39
TV	1.17	1.58	.92	37	21.76	.04	.05	1.27	1.45	3.86
Mobil Radio	.14	.25	.46	2	114.29	.23	.03	.30	.12	1.45
Citicom	.54	.90	.23	5	43.66	.09	.05	2.35	.21	2.47
Tempus	1.04	.65	.23	8	51.45	.10	.11	4.52	.15	3.15

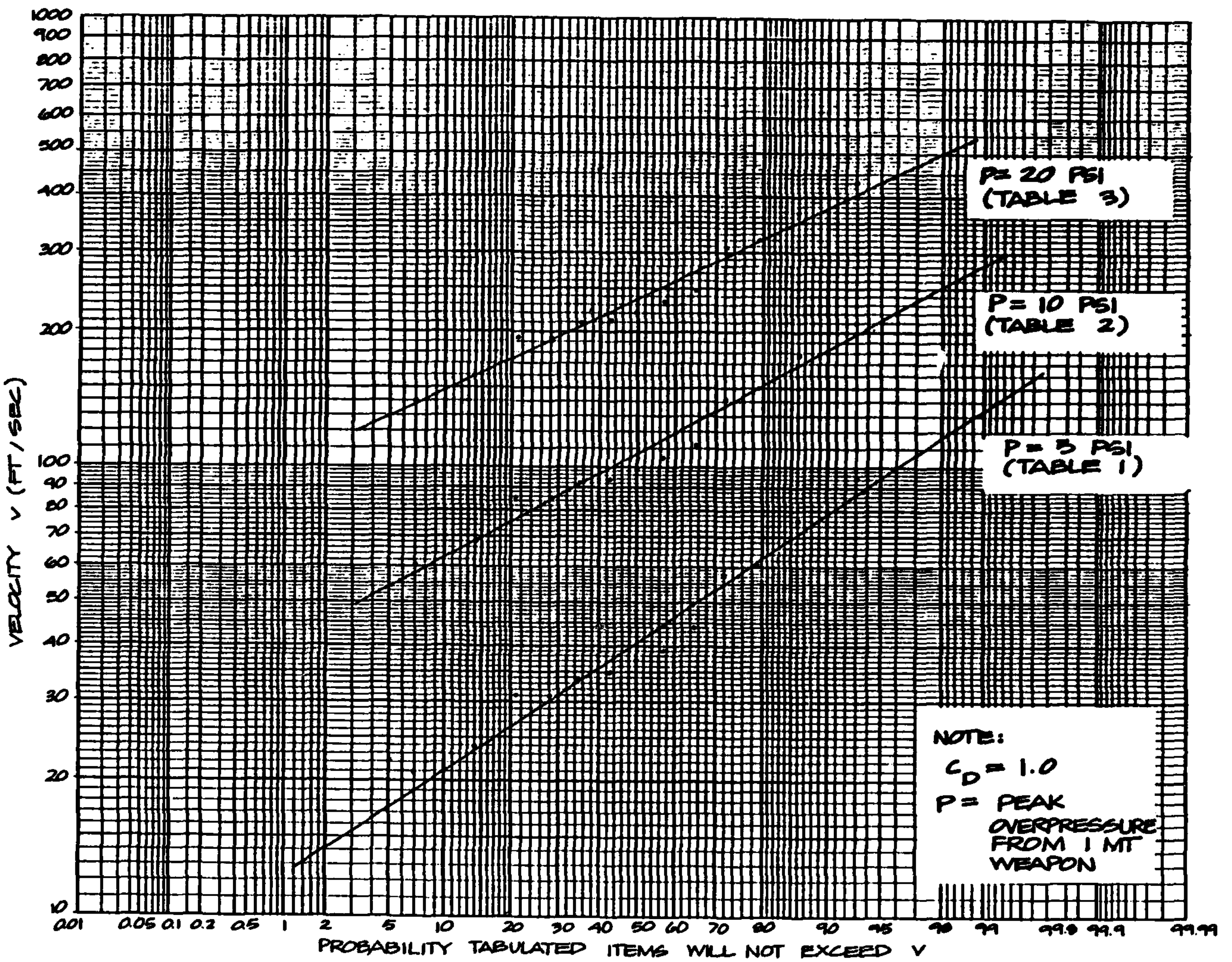


Fig. 3. Cumulative Distribution Curves Showing Percent of Objects in Tables 1, 2, and 3 Expected to Attain the Indicated Velocities as a Function of Applied Peak Overpressure.

representative sample and a method to test it. Thereafter, major interest will be in the greatest threat in terms of vulnerability (so that means for expedient protection might be developed).

Greatest vulnerability will result from objects free to move in the blast wave; **impact** of two objects can lead to generation of stresses that exceed the **yield** or the **failure** strengths of even the strongest materials. (We are interested in both of these; the former should be indicative of the onset of failure, the latter indicative of final mechanical collapse.) As the highest stresses for a given velocity at impact are generated when steel impacts steel, this can be used to set a bound on velocities it would be desirable not to exceed. As an example, for the weakest common structural steel, say an A36 steel, this would be about 30 ft/s to preclude exceeding the yield stress.

For **homogeneous solid** bodies, impact velocities likely to cause damage depend on object particle velocity, v, on shock impedances (product of density, ρ, and shock velocity, U), and on stress-strain (σ-ε) characteristics of the impacting items. The governing equation for impulsive loading that relates sudden changes in stress to those in object particle velocity is:

$$\Delta\sigma = \rho U \Delta v \qquad (5)$$

For propagating plastic shocks, U is the velocity of propagation of the step change in particle velocity change, Δv. (That is, the wave propagation velocity defines the mass involved in the momentum transfer process.) To find the particle velocity for a steel-on-steel collision indicative of the **threshold** between elastic and plastic response (assuming the colliding objects are initially stress free), the velocity of sound, C, can be substituted for U and the yield point stress substituted for $\Delta\sigma$, to compute the Δv on impact that will generate the yield stress. Thus, Equation (5), enables the change in stress $\Delta\sigma$ that is sufficient to exceed the yield strength (determined from the material's stress-strain relationship) to be related to the shock impedance (also inherent in the material's stress-strain relationship) and the particle velocity change in the object that would generate such a stress.

Unfortunately, the objects of interest to us are neither solid nor homogeneous and methods for dealing with impact damage to complex composite structures are essentially non-existent, hence extremely simplified methods are desirable initially, as well as some idea of where to start. Equation (5) can be useful to identify "ballpark" velocities for damage and will also enable rough estimates to be made of expected changes in damage threshold velocities for a shift in basic construction materials (e.g., to plastic from Aluminum) once the vulnerability is determined for one material - but a simpler approach is needed. Moreover, in view of the paucity of quantitative data on vulnerabilities of equipment to different shock and impact conditions, it would be desirable to have this simple alternative keyed to readily obtained tabular data on object parameters, e.g., dimensions and weights.

Ref. 18 describes a form of the impulse-momentum equation that fits the practical requirement because the input data can be acquired from equipment catalogs. It can be used to evaluate final velocities of non-solid heterogeneous real objects accelerated by a blast wave and simplifies making comparisons. However, for our particular application — equipment selection — vulnerability is not solely dependent on an object's maximum velocity on impact, but also on how it is brought to a halt (which Equation 5 has the capability to resolve, but for simpler configurations). Consequently, our **selection** procedure does not at this time take into consideration two factors: the variations in wave propagation velocities among different items (because of different materials and geometries) or the variation in yield strengths and in ultimate strengths. The former omission is not a major one as the variation in elastic wave propagation velocities (indicative of the first threshold of interest) is expected to introduce less than a ±25% uncertainty in the end result for a very wide range of typical equipment construction materials.

Omission of the second factor in the selection procedure might well be a major shortcoming. Once some threshold damage and failure data are obtained, it will be simple to test whether it is necessary (and effective) to normalize the data in Tables 1 - 4 using the yield stress of the major structural material in the package to make the selection procedure more suitable. It is imporant to note here that it is in the **selection** process where this concession to the complexity of material and structural differences is made; in the test program there is no way these effects can be left out, as they will naturally affect the results (including the assessment of how effective this approach taken to select representative equipment for test might be).

The alternative form of Equation (5) used as a practical expedient in the selection procedure makes use of the transformation:

$$A_D/m = 32.2/D\rho_e \qquad (6)$$

where D is the depth of the equipment normal to the blast in feet, 32.2 is the acceleration of gravity in ft/s^2, and ρ_e is the equivalent density of the equipment package in lb/ft^3. By substituting 500F for ρ_e, where F is the ratio of density of the equipment to that of steel (ρ_{steel} = 500 lb/ft^3), the velocity of the object generated by an impulsive load I_q can be written as:

$$v = 9.3\ C_D I_q/DF \qquad (7)$$

To provide conservative estimates of maximum velocity, v, in Tables 1 - 4, D was taken as the shortest dimension on the test item in the horizontal plane.

Also pertinent to our priorities is that, generally when equipment impacts occur, the bulk of them are likely to involve concrete because concrete is found so frequently in the environment. For impact of concrete on steel, the ballpark estimate using Equation (5) indicates the upper bound on relative velocity to preclude exceeding the yield strength of a solid piece of an A36 steel on impact would be 45 ft/s, while for plastic on concrete an upper bound for elastic response would be about 12 ft/s. Thus, for our objects (which are neither solid nor homogeneous) damage thresholds may be expected at lower object velocities than these.

A very critical priority in the program is that vulnerabilities to blast effects from megaton yield weapons are the main objective (vulnerabilities to a 1 kt weapon could be obtained directly in field tests). Naturally, this objective is more difficult to achieve now that there is no longer access to weapons tests of megaton size. (To make matters worse on this subject, none of the facilities designed, or being designed, as simulators for megaton yield weapons will be able to be used to study free object response to drag forces because their test chambers are all designed for tethered test objects.) Hence, understanding of equipment vulnerability to 1 Mt blast loadings that involve equipment motions necessarily must be pieced together and built up out of studies of portions of the response. Credibility for this understanding must then be tested through experiments that evaluate predictions at extreme conditions that are possible to achieve and for which effects can be measured. One technique that has been used is to test the item of interest at considerably higher overpressures from smaller weapons. Such techniques have been applied to assess expected damage to below grade shelters (Ref. 25). Naturally, it is also necessary to demonstrate that the equivalency condition holds.

With the limitations and reservations outlined, Tables 1 - 4 can be used to select the item that is most vulnerable, least vulnerable, or anything in between (with variations in yield strength accounting for the larger error in this selection scheme). At this stage of development of a data base on equipment vulnerability, it is impossible to know relative importances of all the variables involved; testing will be required to rank these. The efficacy of the selection procedure can be tested initially by choosing two items representative of the extremes of vulnerability and a third item with an indicated vulnerability as close as possible to one of the extremes selected. The efficacy of the method can be considered tested if velocities leading to damage are widely disparate in the case of the pair selected to represent the opposite extremes and are approximately the same in the case of the pair selected to represent the same extreme. Whether the procedure can be improved with an additional (normalizing) step to account for material property differences to make it more suitable can also be tested. But some method must be accepted as it will be impossible ever to include more than a tiny fraction of all the items of equipment in such an assessment.

Subsequently, it is hoped development of similar tables for other types of equipment will enable appropriate selections to be made among a minimum of types to establish vulnerabilities to blast loadings (with a minimum of air blast tests). Assuming the procedure is effective, it will also enable items of the same approximate vulnerability, but perhaps less expensive, to be selected and substituted, with an eye to cost control.

5. MODELING AND SCALING CONSIDERATIONS

Reiterating from the DAMAGE MECHANISMS section (p. 9) there are three types of experiment indicated by the four types of damaging events: Translation involving acceleration; translation involving impact; impact by other items of equipment or debris; and direct air blast damage that excludes damage from other sources. The event likely to be most damaging of all involves acceleration of test objects to high velocity and subsequent impact on another object (most likely structural in nature). For this type of experiment and assessment of object vulnerability, it is possible to divide the study into two parts, dealing with motion and with impact.

The motion studies lend themselves to rough computation and to scaling to establish effective drag areas, A_D, drag coefficients, C_D, and overturning velocities. Note that the effective drag area, A_D, can be affected by the friction coefficient, C_f, and the weight distribution as the object reorients in the flow field, so attention must be given this in scaling.

The impact portion of the study, because it must deal with vulnerability to damage, does not lend itself to scaling. Scaling can only be applied when the failure modes are so well known that all the appropriate parameters can be scaled to produce exact similarity. If we knew this much we should not need the tests. Moreover, the failure of interest is whether the item is operational. Some mechanical failures that do occur may not even be of concern. Thus, it is precisely because we do not know the levels where damage is likely to occur, the failure modes, how many, or their consequences to equipment function, that these tests are needed. Hence, we shall never find the answer with scale models when we do not know what to scale; the actual article needs to be impacted to find what velocities lead to damage. For the testing program, these damaging translational velocities can be developed in any convenient way - and related to overpressures that cause them, through the scaling studies and related computations.

On weapon scaling, 1 Mt pulses will not be necessary to conduct experiments to assess missile and debris damage to test-objects; rather it is only necessary to achieve the appropriate velocity at impact. For the most part, wall fragments or falling roofs will be the most likely source of damage to industrial equipment for this type of event. Here, initial fragment velocities and velocities at impact are essentially the same (because the items of equipment will generally not be far from walls or ceiling, so there would not be time to accelerate fragments for more than a fraction of a second before impact). Once walls have failed, initial fragment velocities are a result of acceleration under the influence of the peak reflected pressure. Subsequently, additional increments of velocity may be added by the effects of the stagnation pressure and finally the dynamic pressure drag, but the peak reflected pressure is so dominant (see Figure 2) that any contribution by the others may be ignored.

Suitable wall fragment velocities for heavy debris missile experiments (i.e., those appropriate to a given incident overpressure) may be expected to be generated in the Lawrence Livermore National Laboratory/Federal Emergency Management Agency shock tunnel facility developed in the 1960's by Scientific Service, Inc. staff. Provided the wall fails at the overpressure of interest, pulse duration will not otherwise be a factor in determining fragment velocities. Ref. 26 shows failure of walls, in studies conducted in the shock tunnel on sheetrock, clay tile and concrete block walls, occur in less than 50 ms after the peak overpressure arrives - even at overpressures less than 4 psi. (This is the first 1.5% of a 1 Mt pulse.) Displacement time data for these same wall studies indicates approximately constant velocity after the first 20 ms for sheetrock walls and after the first 40 ms for clay tile and concrete block walls (displacements are 2 to 4 feet in 100 ms for the more massive wall materials, and 5 to 6 feet in 50 ms for the sheetrock walls).

For the experiments to assess damage from direct air blast, the principal damage mechanism will be the sudden pressure change as the item "passes through the shock front.*" Generally speaking, the major damage will be from collapse of the casing or structural support package under the sudden differential pressure. Again (based on the observed displacements of 2 to 4 feet in the case of massive wall panels), assessing the vulnerability of (lightweight) equipment-package wall panels to static overpressures is not expected to require simulation of an entire 1 Mt pulse but, perhaps, only the first 2% of it. A 1 kt pulse may or may not prove adequate, depending on the competing processes of rate of buildup of pressure inside the package due to air flow into it versus the rate of falloff of the pulse. Any uncertainty about this aspect may be avoided simply by using the shock tunnel loading pulse, which has the slower falloff rate characteristic of a 1 Mt pulse for the first 50 milliseconds.

In general, then, for purposes of the experimental program, the major use of scale models should be to obtain information that determines the physical motions of industrial equipment. Specifically, that is to determine the drag coefficients, maximum velocities attained, frictional forces involved (including the effect of static

---

* Note that some communications equipment, e.g., antennas, will be principally sensitive to dynamic pressure forces, which cannot be simulated full scale using existing shock tunnels or with high explosives. This kind of equipment is not typical of electronics, but theoretically such equipment could be tested in a wind tunnel.

overpressure to cause anomalous friction on some surfaces, Ref. 15), distance of translation, potential for overturning, and effects of initial orientation on some of these parameters.

Both **full scale models** and **actual equipment** will be required for the vulnerability studies. Primarily, models can be used for initial assessment of vulnerability to missile and structural debris impact; i.e., to establish the threshold where the casing (or packaging) is likely to survive without crushing or being "holed"; then an actual piece of equipment can be tested just below the threshold to see if it remains functional. At a higher level where missiles do significant damage to the model casing, then possibly damage to the internals of an actual unit may be inferred; where it cannot be, some missile impact tests with actual equipment may be required. Although actual equipment is recommended for the studies to determine threshold velocities for damage to accelerating equipment when it impacts stationary objects, to find where damage to the casing initially occurs, tests with full-scale models can be used; then actual equipment can be tested starting at a slightly lower velocity to see if internals are damaged before the casing is.

From an economics point of view, the use of scaling, models, and artifacts wherever possible is highly desirable. It is entirely possible that enough can be learned from the early experiments to enable more of the later studies (including hardening) to be conducted with models and/or artifacts, and such opportunity should be sought as part of the first experimental study.

In summary, technical constraints require that the motion studies under blast be scaled because of limitations on blast simulations (and simulators). On the other hand, the impact studies cannot be scaled because one needs to know failure modes and processes to do it, and the reason the tests are being done in the first place is to discover those failure modes and processes. Table 5 provides a summary of the critical scaling considerations. Table 6 lists the ideal scaling factors for several variables of interest.

TABLE 5: SCALING REQUIREMENTS SUMMARY

Information Required	Scaling Required	Governing Factors	Air Blast Shock Front Required	Reason	Alternative Means of Measurement	Condition
I_q	max I_q possible	available I_q is $0.1 \times I_q$ (1 Mt)	yes	Preserve P_s/q, Needed to define C_f*, C_D, v	none	n.a.
C_f	no	n.a.	maybe	May be affected by lift	Inclined plane for static and dynamic C_f	Appropriate surface; and lift not a factor
C_f*	unknown	P_s increases normal force	yes	Preserve ratio of P_s to q for anomalous friction on some surfaces	none	n.a.
C_D	maybe	available I_q	yes	Drag and friction interact on some surfaces	none	n.a.
A_D*	maybe	available I_q	yes	Object will reorient based on C_D, C_f, P_s, q	none	n.a.
v	$v_p/v_m = 1$	$I_p/I_m = n$; so $A_p/A_m = n^2$ $M_p/M_m = n^3$	yes	Object velocity may depend on P_s/q	none	n.a.
Impact damage	full scale	$v_p/v_m = 1$	no	1 Mt maximum velocity must be matched	drop, slide wire rocket sled, etc.	Any that match v
Direct air blast damage	Need first 5% to 10% of 1 Mt	P_s (square wave)	yes	Response is to sudden differental pressure	none	n.a.

I_q = unit impulse (see Table 6 for scaling symbol definitions)
C_f = Coefficient of static $C_f(s)$ and of dynamic $C_f(d)$ friction
C_f* = Anomalous coefficient of friction
C_D = drag coefficient
A_D* = Preferred orientation area normal to air blast stream flow
v = Actual object velocity to be expected from 1 Mt air blast at appropriate overpressure

TABLE 6: COMPUTATIONS OF IDEAL SCALES (Ref. 27)

Quantity	Symbol	Typical Units	Ideal Scale
Length	L	ft	$L_p/L_m = n$
Depth	D	ft	$D_p/D_m = n$
Area	A	ft^2	$A_p/A_m = n^2$
Mass	M	$lb\text{-}sec^2/ft$	$M_p/M_m = n^3$
Unit Resistance	w	$lb/in.^2$	$w_p/w_m = 1$
Total Resistance	R	lb	$R_p/R_m = n^2$
Weapon	W	lb	$W_p/W_m = n^3$
Distance	r	ft	$r_p/r_m = n$
Scaled Distance	Z	$ft/lb^{1/3}$	$Z_p/Z_m = 1$
Unit Impulse	I	$lb\text{-}ms/in.^2$	$I_p/I_m = n$
Scaled Impulse	I	$lb\text{-}ms/in.^2\text{-}lb^{1/3}$	$I_p/I_m = 1$
Pressure	p	$lb/in.^2$	$p_p/p_m = 1$
Kinetic Energy	KE	ft-lb	$KE_p/KE_m = n^3$
Density	ρ	$lb\text{-}sec^2/ft^4$	$\rho_p/\rho_m = 1$
Elastic Modulus	E	$lb/in.^2$	$E_p/E_m = 1$
Deflection	δ	in.	$\delta_p/\delta_m = n$
Moment	M	ft-lb	$M_p/M_m = n^3$
Moment/ft	$\overline{M}$	lb	$\overline{M}_p/\overline{M}_m = n^2$
Shear	V	lb	$V_p/V_m = n^2$
Shear/ft	$\overline{V}$	lb/ft	$\overline{V}_p/\overline{V}_m = n$
Stress	σ	$lb/in.^2$	$\sigma_p/\sigma_m = 1$
Strain	ε	–	$\varepsilon_p/\varepsilon_m = 1$
Velocity	v	ft/sec	$v_p/v_m = 1$
Time	t	sec	$t_p/t_m = n$
Moment of Inertia	I	$in.^4$	$I_p/I_m = n^4$
Frequency	f	cycles/sec	$f_p/f_m t = 1/n$

6. TEST PROGRAM

The flow chart shown in Figure 4 identifies the test types required under each of two categories, and the corresponding parameters. The first category, Testing Program to Obtain Basic Data, deals with basic motion mechanics, and the second category, Testing Program to Determine Vulnerabilities to Nuclear Blast Damage Mechanisms, deals with the mechanics of the damaging response. The studies required of basic motion mechanics are non-destructive tests to discover dynamic behavior and properties of the test items and interfaces that control behavior (e.g., test objects/flow field, test objects/interfacing surface of support). Among other things, experiments are needed to illuminate such things as: reorientation process for test objects in blast waves, including time required to do so relative to the pulse duration; subsequent drag forces that apply; whether overturning and tumbling occur, or just sliding; approximate thresholds of velocity where sliding frictional resistance is sufficient to cause overturning, etc. As very little information has ever been developed on these subjects, high speed photography is required to find out just what does happen. Many parameters that will be factors in the behavior of interest for whatever samples are taken from the population of interest can be identified now, but there is currently no information extant regarding sampling schemes to achieve desired objectives, so none either on sample means, sample variances, magnitudes of difference in means that might prove important between samples, or any rationale for estimating population mean or variance.

When specific experimental objectives move from establishment of "simple" behavior processes affecting motion, which are "fairly well" understood (e.g., drag forces induced by blast waves), to finding thresholds for incipient functional damage, we cannot even begin to make a decent guess as to an objective description of the **dependent** variable, let alone what might be a suitable measure of it until we run some experiments. In any case, we are looking for **failure thresholds**. Therefore, our interests are **not** those that relate to a population mean, but rather we are particularly interested in **extremes**. Moreover, besides wanting items of equipment representative of extremes of the population, for any sample we might select we are primarily interested in extremes of **its** behavior — that is, where a governing relationship **suddenly changes** (e.g., from elastic response to a plastic or a brittle failure). Finally, for future use we wish to learn enough to be able to identify a particular member species from among any population of species (e.g., those comprising communication equipment) that best represent the extremes of

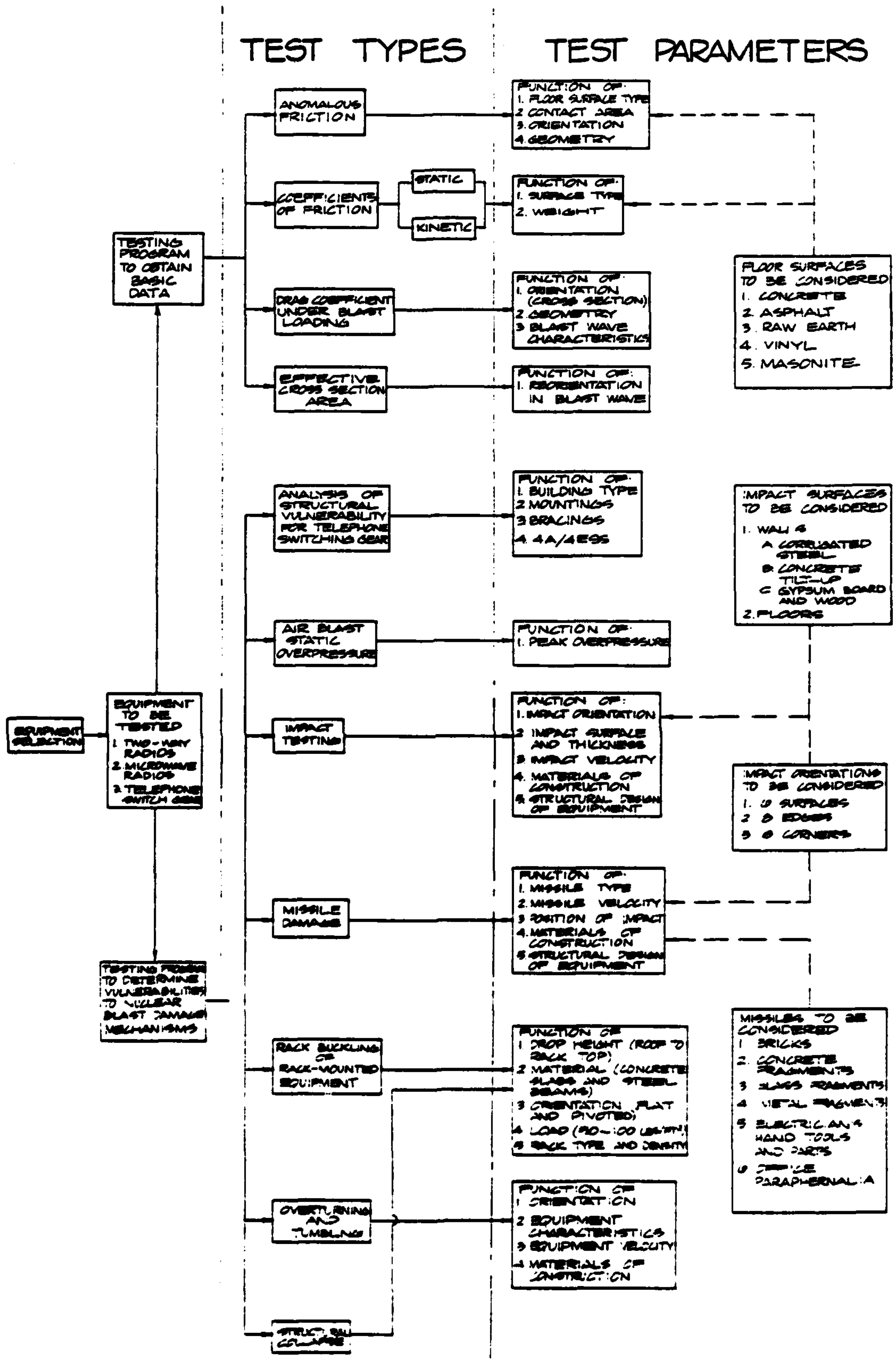


Fig. 4. Test Program to Determine Vulnerabilities of Communication Equipment to Nuclear Blast.

vulnerability (i.e., where the sudden change in the governing impact/response relationship that is of interest to us occurs at the lowest or the highest threshold value for the population).

To keep the cost of real equipment required for the damage evaluation tests to a minimum, it is recommended that a Bayesian statistical approach be used (Ref. 28) wherein repeated tests are made with the same piece of equipment at increasing impact velocities until a light degree of physical damage is incurred.* Then the equipment should be repaired and subjected to successively higher impact levels until it fails functionally. If this can also be repaired readily, the process should be continued up to the judged level of irrepairability (i.e., easier to build a new one). Such a series of tests will give a first approximation to the threshold values for these various damage ratings (i.e., light physical, minor functional, and heavy).

From this point two directions would ordinarily be available. One is to repeat the above sequence with n-1 pieces of other identical equipment so that we have n estimates of the impact velocity for the threshold of light physical damage; n estimates for the threshold of minor functional damage; and n estimates for heavy damage with only n total items and 3n (or more) tests. This way lies information (confounded to be sure) that provides the least expensive preliminary estimate of threshold values for the dollars expended, and to which we can apply statistical methods to obtain a first estimate of sample means and variances (to provide input for design of a later test program that presumably will be conducted eventually to assess hardening schemes intended to find ways to shift thresholds for damage - once these thresholds have been found). The other alternative is to use new equipment for subsequent tests (which avoids the confounding of prior damage with the damage of interest) so that 3n (or more) pieces of equipment are tested in 3 (or more) tests. The second approach is typical of test design but could be much more expensive than the former depending on relative costs to purchase equipment versus costs to conduct a test. In this second approach, the velocity levels obtained for the various damage levels from the first sequence become the basis for a test series of m pieces of new equipment at each velocity level. This would give a probability of achieving the specified damage level, but for that specific impact velocity. To obtain the probability of damage vs impact velocity at a desired percentile rank (say, 90% or

---

* Light physical damage might be defined as the equipment is damaged but working correctly, minor functional damage as being easily repaired on the spot; and heavy damage as not worth fixing.

95% of the time this is the threshold velocity for this item of equipment), these tests would then have to be repeated at five or six additional velocity levels in the vicinity of each threshold. It is estimated that this second approach would require up to 4 to 6 times as many tests and up to 12 times as many new pieces of equipment. Because failure processes are involved, the statistics of extremes (Ref. 29) should be applied to the data. Generally, something on the order of twenty datum are desirable. However, in an application to the study of probability of failure of wall panels (Ref. 30), as few as ten datum have been used (see Figure 5, from Ref. 30), and the single worst smog day condition of the year for as few as six years of records have been applied to predict the 20-year event. (Where the random variable of concern is the extreme value, then it is much better to have a small sampling of clearly identifiable extremes from different independent samples than to infer what those extremes might be from a large sample size taken from the general population.) That is, the half dozen points in the tail of a normal distribution curve containing 2190 points are overwhelmed by the other data, whereas plotted on extreme probability paper (e.g., as in Figure 5), they can be used to make valid estimates of the probability of an extreme value occurrence.

Again, from the standpoint of establishing a fixed program (set number of tests) with pre-established measures of reliability for contracting purposes, it is not possible to establish in advance the exact number of tests required without more information than is now available. However, a program to acquire some initial data should enable a reasonable estimate to be made of the additional tests required to establish a given reliability, and the relative importance of parameters to be identified. But at least part of that relative importance will be obscured by leaving considerations of practical (things industry will really do) hardening schemes out of the initial program.

Testing Program to Obtain Basic Data (Motion Mechanics)

Anomalous Friction

Experiments demonstrating anomalous friction were conducted as part of the MILL RACE tests at White Sands Missile Range in September, 1981. Interest in the subject stems from the observation that drums standing on soil surfaces are significantly less vulnerable than many other objects and can be used as anchors in a blast environment. Moreover, drums are plentiful in the normal environment and a great deal of communications and electronic equipment will fit into them; it may

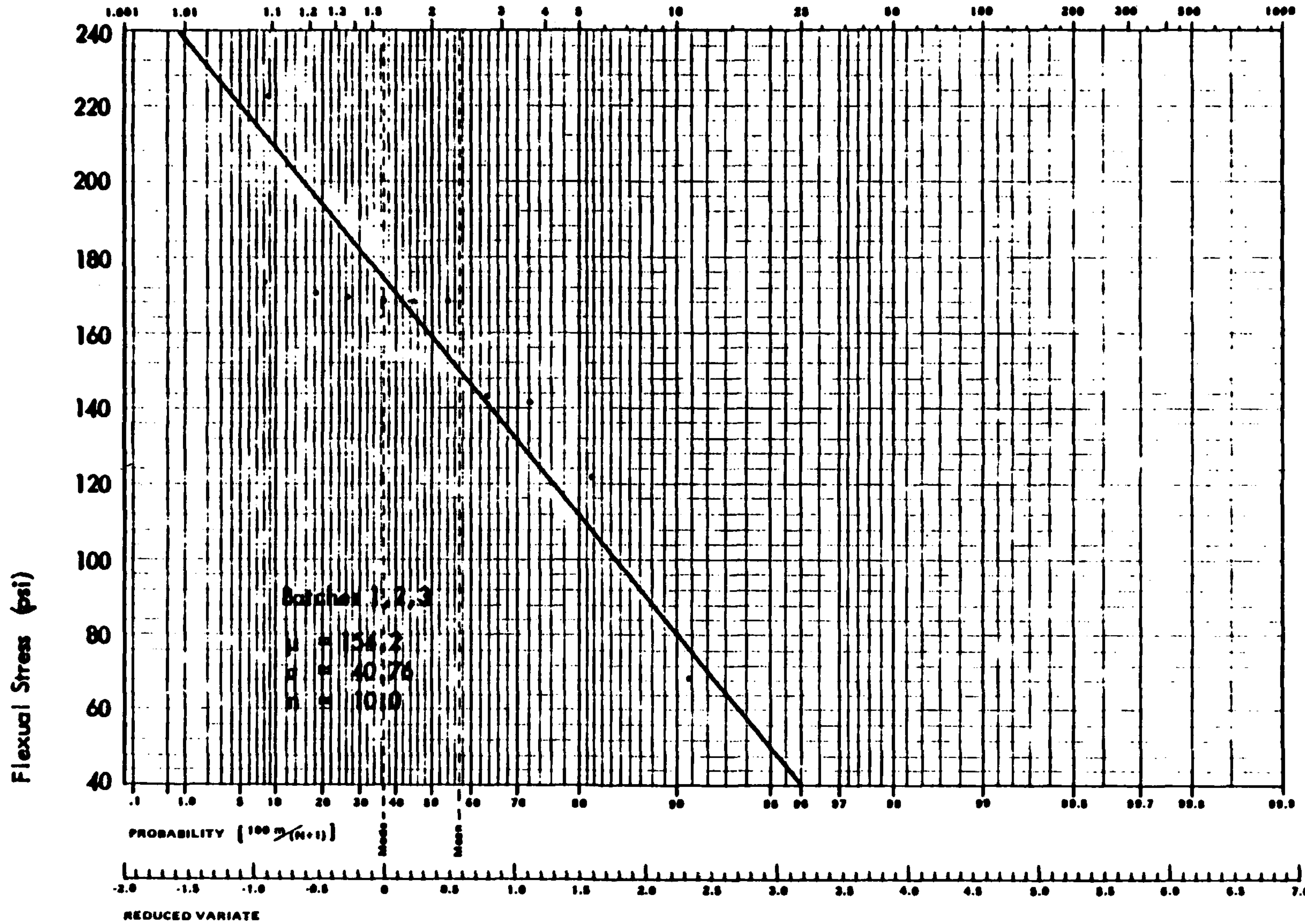


Fig. 5. Low Extreme Probability Plot of Flexural Stress (μ_t) From Brick Beam Tests.

even be possible to ensure the phenomenon of anomalous friction as a hardening option for other items and other than soil surfaces. In view of the fact that equipment hardening is a long range objective of the program, and this initial phase is intended to aquire reference data that will enable progress in the development of industrial hardening to be measured quantitatively (versus cost of implementing) for decision purposes, the subject has been introduced here so that some reference data might be otained. If this first experimental effort is to preclude any aspect of hardening (not required by the IFP) then this experimental effort may be deleted.

Anomalous friction refers to the case where resistance to motion of an object sliding along a surface does not follow the conventional relationship of:

$$F_f = \mu N \quad (8)$$

where N is the normal force due to gravity. F_f is the friction force and μ is the proportionality constant, which depends on the properties of the interfacing surfaces. When an air blast wave passes over an extensive surface and engulfs an object on it, generally the static overpressure impinges all around the object, and all the object's surfaces are affected by drag forces. Under special circumstances, the static overpressure may be sealed off from the interfacing surfaces so that two things occur:

a. There is no drag force acting on the interfacing surface of the object, and
b. The static overpressure acts to force the object to maintain contact at the interface.

The first of these effects is less significant than the second one, and the two together have an effect overwhelmingly greater than normal friction forces. For example, a single drum standing upright on its cylindrical base of area 415.5 $in.^2$ and sealed from an applied static overpressure of 20 psi will experience an added normal force of 415.5 x 20 psi = 8,310 lb. For typical contents, this increases the apparent normal force 1500% or more over that due to gravity alone (550 lb for drum and contents typically found) and leads to an anomalous friction force as a result. In such a case:

$$F'_f = \mu N + A_i p_s \quad (9)$$

where F'_f is the total friction force, A_i is the interface area, and p_s is the static overpressure. The anomalous friction portion is $A_i p_s$.

The anomalous friction forces, including whether they would play a role or not, would therefore be dependent on:

a. Floor surface type (for μ and for sealing at the interface)
b. Contact Area, A_i
c. Orientation (whether object loses contact with surface before anomalous friction is established)
d. Geometry (needed to obtain normal force at the interface)
e. Static overpressure, p_s

Coefficients of Friction

Both static and kinetic coefficients of friction are of interest in this study. The static coefficient of friction is vital not only in assessing the threshold loading required to cause a piece of equipment to move, but may also determine whether the piece of equipment would slide or overturn. (Note that obstructions on the surface in the normal environment are also likely to cause overturning.) Once the equipment is in motion, kinetic friction determines the frictional forces acting against the motion and the distance moved.

The parameters of concern here are:

a. Floor surface type(s)
b. Weight of equipment

Drag Coefficient Under Blast Loading

From Equation (2a) the parameters that would therefore determine the value of the drag coefficient are:

a. Orientation (cross-sectional area) and geometry of the equipment (which determine the cross-sectional area presented to the flow field, and flow conditions around the object), and
b. Characteristics of the blast wave, which will determine the total impulse, i.e., overpressure, dynamic pressure, clearance time, and subsequent drag pressure.

In order to avoid confusion, it needs to be mentioned here that while there might be some common facets to the relationship between drag coefficients under blast loading and drag coefficients obtained in a wind tunnel, there will be important (even critical) differences because: (1) the objects are not fixed, and (2) the flow field in a blast wave varies with time. This makes it mandatory that the drag coefficients be determined under blast conditions. (See Effective Cross-Sectional Area also.)

Effective Cross-Sectional Area

This variable is significant because the effective cross-sectional area of the equipment that the blast wave "sees" determines the exact amount of loading on the equipment itself. The exact area presented would be dependent not just on the geometry, but equally important, also on the orientation of the equipment vis à vis the blast wave. The manner in which the piece of equipment "faces" the blast wave will determine the initial interaction. However, as it is picked up and moved by the wave, the equipment will reorient itself (depending on all the forces acting), and this reorientation may be the major determinant of the drag area, depending on time of reorientation relative to the blast wave. That is, the value of A_D in Equation (2a) is really a function of time, for equipment that is not fixed, so that blast wave studies are required to define the single value A_D equivalent to the integrated $A_D(t)$ to establish the effective cross-sectional area.

Testing Program to Determine Vulnerabilities to Nuclear Blast Damage Mechanisms

The mechanisms via which nuclear blast waves can damage equipment have been identified in Figure 1 and discussed earlier in Section 3. Parameters whose effects must be assessed are listed in Figure 4. The discussion here will therefore be limited to identifying the measurements that must be made and the variables upon which these values will be dependent.

Analysis of Structural Vulnerability for Telephone Switching Gear

Not only because of the size and unique nature of telephone switching gear, but also because construction of telephone exchanges appear to have been standardized by the telephone company to a large extent, a substantial portion of the information can be obtained by calculations.

There are two major types of telephone switches in current use:

a. The 4A type, which is electromagnetic, and
b. The 4ESS type, which is electronic.

Though the latter is slowly replacing the former, there are still a sufficient number of 4A type switches around the country to justify analysis of both types. In the authors' estimation there would be sufficient data available or obtainable to permit calculation of not only how a blast wave would affect the building, but also how this would be transferred to the equipment assemblies contained within the building. This analytical study would be sufficient to eliminate the necessity of scaled models for determining the overall vulnerability of the special buildings that house telephone exchanges.

While the above would be sufficient to identify the vulnerability(ies) of the building and equipment racks, the damage that the individual modules would suffer from missiles, buckling, etc., would have to be tested separately. This is covered below under the respective subsections.

The parameters of interest and the information that would be required for this analysis are:

a. Switch type (4A or 4ESS) and detailed design data of the mountings and bracings.
b. Building type and detailed design data.

Air Blast Static Overpressure

This is in effect a dynamic situation not simulated accurately by standard hydrostatic overpressure tests on sealed equipment. The key factor here is the peak overpressure of the blast wave and competing process of filling time of internal volume versus pressure falloff.

The effect of this peak overpressure on the equipment casing and on the internal contents must be measured.

Impact Testing

As has been described earlier, equipment can be expected to be "lifted" up by a blast wave and moved until it hits some other object. In an industrial environment, this will be primarily the walls and floor of the building. The exact manner and force with which the impact occurs will depend on the reorientation of the equipment while being moved by the blast wave and on the characteristics of the blast wave itself. The factors that will affect the damage a piece of equipment will thus suffer will be determined by:

a. Impact orientation
b. Impact surface and its thickness
c. Impact velocity
d. Materials of construction of the piece of equipment
e. Structural design of the piece of equipment

As far as communications equipment go, the vast majority are cuboid, but with anisotropic properties. Though this can lead to an infinite number of impact orientations to be considered, these can be boiled down to:

a. 6 surfaces
b. 12 edges
c. 8 corners

Although 26 orientations is a greatly reduced number compared to infinity, from a practical standpoint, it still calls for a very large number of tests. Consequently, it seems reasonable to treat orientation as a secondary parameter, to use random orientations of impact for testing, and to take high speed photographs to note the orientation condition on impact in order to test the data for significant differences between surface, edge, and corner results.

The impact surfaces that one would encounter in an industrial environment would be walls and floors. While the floors are primarily reinforced concrete, the walls can be divided into the following categories:

a. Corrugated steel
b. Concrete tilt-up
c. Gypsum board and wood frame

The thickness of these walls will determine the amount of resistance offered to the impacting equipment, and thus the damage.

The values to be measured here are therefore the damage thresholds as a function of the various parameters, orientations and materials stated above.

Missile Damage

The factors governing the generation of missiles, as well as the manner in which they can damage equipment has also been discussed earlier, and will therefore be omitted here.

Definition of missile characteristics is extremely important, and this should be part of the test program before actual testing for missile damage. The following types of missiles can be expected in an industrial environment where communications equipment is used:

a. Bricks
b. Concrete fragments
c. Glass fragments
d. Metal fragments
e. Electrical hand tools and parts
f. Office paraphernalia

The characteristics of the above missile types that need further definition are their sizes, weights, and, if possible, shapes.

Besides the missile type, other parameters that would govern the extent of damage caused by missiles are:

a. Missile velocity
b. Position of impact
c. Materials of construction of equipment
d. Structural design of equipment.

The damage caused by missiles is therefore to be measured as a function of the missile types and parameters stated above.

Rack Buckling of Rack-Mounted Equipment

Most communications equipment today are mounted in standardized racks that are 19 inches wide. The rack itself could serve as a protection mechanism, and as such ought to be evaluated for its vulnerability. The main concern is buckling of the racks due to structural collapse. Of interest here are the loads that an assembled rack can withstand without yielding to the point that the equipment in the rack are damaged. The aspect being tested here is the vulnerability of rack-mounted equipment to structural collapse. The factors that will affect this vulnerability are:

a. Drop height (roof to rack top)
b. Materials (concrete slabs and steel beams)
c. Orientation (flat and pivoted)
d. Loading (50 - 100 lb/ft^2)
e. Rack type, orientation and density of mounted equipment

The results from this test group will establish the vulnerability thresholds of rack-mounted assemblies as a function of the above variables.

Overturning and Tumbling

Even if the blast wave does not "crush" or "carry away" the equipment, depending upon the latter's configuration, it could be simply overturned. In this case the equipment impacts the floor, which will in most cases be a reinforced concrete slab (but could be asphalt in a parking lot, if equipment were moved out to avoid building collapse). Subsequent translation would be either simple translation or tumbling. Translation, its consequences, and the major controlling parameters have been dealt with under Impact Testing. Tumbling involves several impacts and rotation primarily around the edges and the corners. The damage the equipment would suffer, as a result of overturning and tumbling will be governed by:

a. Orientation of equipment
b. Equipment characteristics
c. Equipment velocity
d. Materials of construction
e. Structural design

Structural Collapse

The damage mechanism described in Rack Buckling of Rack-Mounted Equipment is from structural collapse.

Minimum Test Program

The foregoing sections have discussed the factors relevant to designing a comprehensive test program to determine the vulnerabilities of industrial equipment in general and communications equipment in particular. The formulation in Figure 4 is already an attenuated program (a minimum selection of test objects), and it contains no estimates of numbers of tests, confidence intervals, etc., and cannot for the reasons discussed — until some preliminary data are obtained. Even so, it is evident that conducting even this comprehensive a test program for a single group of industrial equipment - communications equipment in this case - would be extremely expensive, hence unrealistic. Further condensation is required.

Table 7 is such a condensation of the test program outlined in Figure 4. This table represents a **minimum test program** with emphasis being placed on minimizing

TABLE 7: MINIMUM TEST PROGRAM(1)

Test Type	Test Sequence	Test Parameters	Number of Tests	Test Items Required	Remarks
Anomalous Friction	1	Equipment type Floor surface type Contact area Overpressure	9	6 models (3 types, reusable)	2 surfaces: concrete and raw earth Fixed A_D's; 1 A_i 3 overpressures (p = 5, 10, 20 psi) 2 repetitions
Coefficients of Friction	1	Equipment type Floor surface type Equipment surface Weight	$12\Sigma n_i$(2)	3 units (3 types)	2 surfaces: concrete and raw earth 2 A_j n_i repetitions for ith condition (1)
Drag Coefficient Under Blast Loading	1	Equipment type Orientation Geometry Dynamic pressure	24	6 models (3 types, reusable)	3 overpressures (p = 5, 10, 20 psi) 5 repetitions 2 A_D (2 geometry)
Effective Cross-Sectional Area	1	same as for C_D above	n.a.	n.a.	Photograph drag coefficient tests with high speed camera to obtain re-oriented cross-sectional areas
Structural Vulnerability of Telephone Switches	n.a.	n.a.	n.a.	n.a.	Theoretical analysis
Air Blast Static Overpressure	2	Equipment type Peak overpressure	n.a.	18 units (3 types)	1 overpressure (20 psi)(1) 5 repetitions

(1) See text entitled **Table 7 Amplification.**
(1) Sufficient tests to obtain C_f with expectation it is $\pm 10\%$ of true mean for the population with 90% confidence.

TABLE 7: MINIMUM TEST PROGRAM (contd)

Test Type	Test Sequence	Test Parameters	Number of Tests	Test Items Required	Remarks
Impact Testing	6	Equipment type Impact surface Impact velocity	216[3]	36 units (3 types)	Random orientation 2 surfaces: concrete/masonry wood/gypsum board 6 velocities[3] 5 repetitions
Missile Damage	5	Equipment type Missile type Missile velocity Position of impact	36	36 units (3 types)	2 orientations Mix of missiles 1 velocity (20 psi wall failure) 5 repetitions
Buckling of Rack-Mounted Equipment	*(4)	Drop height Material Orientation Load Equipment density	24	24 racks	1 rack 1 height 1 load (concrete) 2 orientations 2 densities 5 repetitions
Overturning & Tumbling	4	Equipment type Surface type Velocity	108	36 units (3 types)	2 surfaces: concrete and asphalt 3 velocities 5 repetitions
Structural Collapse	3	Equipment type Drop height Material Orientation Load	36	36 units (3 types)	1 height 1 load (concrete) 2 orientations 5 repetitions

(3) The actual velocities (and hence, total number of tests) is a guess. At this time there are no data to provide any rational estimate of threshold velocity for any kind of damage, let alone those suggested for the test program.

(4) Not part of sequence.

financial outlay for purchase of test items consonant with obtaining data to make estimates of pertinent mean values, variances, significant differences in damage thresholds, drag coefficients, etc., where such are of value, and for assessing behavior of extremes. To achieve this, the test types were arranged in a sequence so that one test item could be utilized for more than one test, with more damaging tests coming later in the program, even though damage may be confounded.

The proposed test program may or may not be able to provide the desired level of confidence. However, some number is required for planning. This really cannot be determined until: the different increments of damage level are defined; estimates of variance are determined; and the appropriate levels of dependent variables in any test series are established. In fact, until this first exploratory phase of experimentation is performed to generally establish "damage levels" and identify the various important factors related to damage, it is really not possible to set up experiments according to the principles of experimental design: inclusive of factorial designs; identification of factor levels; use of the Hadamard matrix for the design of the level of arrangements of test variables and corresponding data analyses; and recognition of interaction and confounding of independent factors (Refs. 31 and 32). In these proposed beginning tests, sample sizes and factors and their levels have been set up according to judgment and the available general experience from past field test results. The numbers of tests and items given are examples of this judgment process. Once these exploratory test results are available, then the specific experimental design and analysis techniques will definitely be employed.

Table 7 Amplification

Anomalous Friction:

Under "Test Parameters" only the short descriptor, overpressure, is not self explanatory. Overpressure here is an indicator for the real blast parameter of interest, i.e., the ratio of static overpressure to dynamic pressure. Number of tests is determined by the requirement for 3 overpressures and 3 replications (using 3 pairs of models in each test with one of each pair on a concrete surface and the other on a raw earth surface).

Coefficient of Friction:

The floor surfaces are the same as for the Anomalous Friction tests. Tests are with real units, rather than models, and are nondestructive. Enough repetitions for each of the 3 different types of items are required at each condition of interfacing surface to obtain C_f with the expectation the sample valuee is $\pm10\%$ of true mean for the population, with 90% confidence at each condition. (Thus each n is different for the ith condition.) Weight enters as a variable in this study only implicitly by virtue of the 3 different types of unit to be tested. The two interfacial areas, A_i under remarks, are indications of equipment surface, under Test Parameters; each unit to be turned on the side that gives maximum A_i (for a side). Number of tests is determined by the requirement for 3 types of unit (equipment package) on 2 interfacing surfaces for 2 faces of the units with n_i replications for each of the ith conditions (12 total) to achieve the desired value within $\pm10\%$ of the population area with the desired confidence.

Drag Coefficient:

Under Test Parameters, orientation relates to drag area, A_D, and geometry relates to the variation in flow conditions (which is implicit in orientation). Thus, these two independent variables change with A_D, as indicated under remarks. Though the pressure test parameter of interest is the dynamic pressure, it is generally keyed to the common descriptor, overpressure; hence this entry under remarks. In the shock tunnel, incident peak overpressures are limited to 9 psi so that to get 20 psi peak static overpressure, a reflected pressure pulse must be applied (see Figure 2). To get peak dynamic pressure that corresponds to that at 10 and 20 psi peak static overpressure in the free field, part of the tunnel must be closed off and jet flow applied. In these two cases there is less room for test objects, hence only 4 items per test. The specification of 9 tests at each of these 2 overpressures is to obtain 6 values for the drag coefficient for each of the 3 different unit types at 2 values of A_D. As 6 items can be placed in the tunnel at 5 psi (where it does not need to be partly closed off), only 6 tests are needed at this overpressure level for a total of 6 + 9 + 9 = 24 tests. Note that the Air Blast Static Overpressure tests can be conducted at the same time as the third series by placing the test units directly in front of the portion of the tunnel that is blocked (to cause jet flow).

Effective Cross-Sectional Area:

This requires only that high speed photographs be taken in the previous series of tests to observe the reorientation conditions in the flow, and the time required. Thus no "additional" tests are required in the shock tunnel.

Air Blast Static Overpressure:

These tests will be done only at the maximum peak overpressure (20 psi) and simultaneously with the 20 psi tests to determine Drag Coefficient under Blast Loading.

Impact Testing:

There are 3 types of units to be impacted on 2 surfaces in a series involving sequential increases in velocity with 6 replications. Thirty-six units are needed, and the estimate of the total number of tests is based on a guess of 6 velocity levels in each series.

Missile Damage:

A conglomerate of the debris listed in Figure 4 under "Missiles to be considered" will serve for missiles. The velocity will correspond to that for wall failures at a 20 psi peak reflected overpressure loading. There will be 3 types of unit to be impacted at 2 orientations (head-on and obliquely) with 6 replications for a total of 36 tests.

Buckling of Rack Mounted Equipment:

Drop height will be typical for a 4A or 4ESS telephone switching installation. The material (of the ceiling) will be concrete with 2 orientations at impact (one nearly parallel with the original roof plane, the other a pivoted, hinge type failure) on racks with 2 densities of equipment and 6 replications, for a total of 24 tests.

Overturning and Tumbling:

There are 3 types of unit to set in motion on 2 surfaces at 3 velocities (characteristic of those expected at overpressure levels of 5, 10, and 20 psi) with 6 replications, for a maximum of 108 tests. Only 36 items are indicated as the tests will be conducted sequentially starting at the lowest velocity and terminated when the unit is non-functional.

Structural Collapse:

There are 3 types of unit impacted from 1 "typical ceiling" height by 1 ceiling material (concrete) with 2 orientations at impact (one nearly parallel with the original roof plane the other a pivoted, hinge type of failure) and 6 replications, for a total of 36 tests.

7. REFERENCES

1. Leavitt, Jane, **Analysis and Identification of Nationally Essential Industries Volume I: Theoretical Approach**, Paper P-972, Work Unit 731-24, Institute for Defense Analyses, Arlington, VA, March 1974.

2. Fisher, R., et al., **Emergency Sewage Procedures During Crisis Relocation**, Report No. SSI 7728-4 (Also published by DCPA as RS 2-8-30), Scientific Service, Inc., Redwood City, CA, November 1978.

3. Edsall, H., **Essential Facilities Chart**, Defense Civil Preparedness Agency, U.S. Department of Defense, April, 1973.

4. Block, E., et al., **Critical Industry Repair and Reclamation Study: U.S. Rubber Industry**, Science Applications, Inc., Huntsville, AL, November 1979.

5. Van Horn, W.H., et al., **Process Control Instrumentation: Vulnerability & Manufacturer/User Response to Nuclear Attack**, Work Unit 3311F, AD No. 010 804, URS Research Company, San Mateo, CA, February 1975.

6. York, E.N., et al., **Industrial Plant Hardness-Phase II**, DNA 4549F, Boeing Aerospace Co., Seattle, WA, April 1978.

7. Zaccor, J. et al., **Industrial Protection Guide**, SSI 8011, Scientific Service, Inc., Redwood City, CA, June 1981.

8. Zaccor, J.V., et al., **Industrial Hardening Demonstration**, Report No. SSI 7828-8, Scientific Service, Inc., Redwood City, CA, September 1980.

9. Zaccor, J.V., et al., **Industrial Hardening: 1980 Technical Report**, Report No. SSI 8011-6, Scientific Service, Inc., Redwood City, CA, June 1981.

10. Tansley, R.S., and J.V. Zaccor, **Testing of Shelter Design and Industrial Hardening Concepts at the MILL RACE Event**, SSI 8115-4, Scientific Service, Inc., Redwood City, CA, January 1982.

11. Sparks, L.N., **Nuclear Effects on Machine Tools**, WT-1184, U.S. Atomic Energy Commission, December 1956.

12. Walker, F.E., **Estimating Production and Repair Effort in Blast-Damaged Petroleum Refineries**, Stanford Research Institute, Menlo Park, CA, July 1969.

13. Miller, C.F.,and S.D. Stratton, **Expedient Measures in Postattack Industrial Recovery: Petroleum Refining**, Center for Planning and Research, Inc., Palo Alto, CA, December 1980.

14. Bowen, I.G., et al., **A Model Designed to Predict the Motion of Objects Translated by Classical Blast Waves**, CEX-58.9, U. S. Atomic Energy Commission, June 1961.

15. "FEMA Work Unit 1128D, Construction, Instrumentation, and Testing of Shelter Design and Industrial Hardening Concepts at the MILL RACE Event," **Proceedings of the 1982 Asilomar Conference: Fire and the Related Effects of Nuclear Explosions**, S. Martin and R. Alger (eds.), SRI International, Menlo Park, CA, November 1982, p.III-17.

16. Kaplan, K., and P.D. Price, **Accidental Explosions and Effects of Blast Leakage into Structures**, ARLCD-CR-79009, U. S. Army Armament Research and Development Command, Dover, NJ, June 1979.

17. Peterson, R.E., et al., **Damage Function Rating Procedure for Flat Slab Basement Shelters**, SSI 8143-9, Scientific Service, Inc., Redwood City, CA, December 1982.

18. Zaccor, J.V., et al., **Industrial Hardening: 1981 Technical Status-Report**, SSI 8145-7, Scientific Service, Inc., Redwood City, CA, September 1982.

19. Glasstone, S. (ed), **The Effects of Nuclear Weapons**, Superintendent of Documents, U.S. Government Printing Office, Washington, D.C., 1977.

20. Fons, W.L., F.M. Sauer, and W. Y. Pong, **Blast Effects on Forest Stands by Nuclear Weapons**, TR-AFSWP-971, Division of Fire Research, Forest Service, U.S. Department of Agriculture, Washington, D.C., December 1957.

21. Fons, W.L., and W.Y. Pong, **Tree Breakage Characteristics Under Static Loading - Ponderosa Pine**, TR-AFSWP-867, Division of Fire Research, Forest Service, U.S. Department of Agriculture, Washington D.C. November 1957.

22. Sauer, F.M., W.L. Fons, and K. Arnold, **Experimental Investigation of Aerodynamic Drag in Tree Crowns Exposed to Steady Wind - Conifers**, Division of Fire Research, Forest Service, U.S. Department of Agriculture, Washington D.C., December 1951.

23. Sauer, F.M., W.L. Fons, and T.G. Storey, **Blast Damage to Coniferous Tree Stands by Atomic Explosions**, Operation Upshot-Knothole, WT-731, Division of Fire Research, Forest Service, U.S. Department of Agriculture, Washington, D.C. January 1954.

24. **Operation Distant Plain Preliminary Report,** DASA 1876-3, Volume III, Event 4, Project 7.01, Defense Atomic Support Agency Information and Analysis Center, General Electric, TEMPO, Santa Barbara, CA, January 1968.

25. Kiger, S.A., and J.P. Balsara, **Response of Shallow-Buried Structures to Blast Loads,** U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS (undated).

26. Gabrielsen, B., C. Wilton, and K. Kaplan, **Response of Arching Walls and Debris From Interior Walls Caused by Blast Loading**, URS 7030-23, URS Research Company, San Mateo, CA, February 1975.

27. Dobbs, N., and E. Cohen, **Model Techniques and Response Tests of Reinforced Concrete Structures Subjected to Blast Loads**, Paper SP24-17, ACI Publication No. 24, American Concrete Institute, Detroit, MI, June 1980.

28. Benjamin, Jack R., and C. Allin Cornell, **Probability, Statistics and Decision for Civil Engineers**, McGraw-Hill Inc., New York, NY, 1970.

29. Weibull, W., **A Statistical Theory of the Strength of Materials**, Royal Swedish Institute for Engineering Research, 1938.

30. Willoughby, A.B., C. Wilton, B.L. Gabrielsen, and J.V. Zaccor, **A Study of Loading, Structural Response, and Debris Characteristics of Wall Panels**, URS 680-5, URS Research Company, Burlingame, CA, July 1969.

31. Montgomery, Douglas C., **Design and Analysis of Experiments**, John Wiley & Sons, New York, NY, 1976.

32. Diamond, William J., **Practical Experiment Designs**, Lifetime Learning Publications, Belmont, CA 1981.

DISTRIBUTION LIST

(One copy unless otherwise specified)

Federal Emergency Management Agency
Attn: Assistant Associate Director
for Research
National Preparedness Programs
Directorate
Washington, D.C. 20472 (3)

Mr. David W. Bensen
Office of Research
National Preparedness Programs
Federal Emergency Management Agency
Washington, D.C. 20472 (45)

Defense Technical Information Center
Cameron Station
Alexandria, VA 22314 (12)

Assistant Director
Energy & Natural Resources
Office of Science and Technology Policy
Executive Office Building
Washington, D.C. 20500

Mr. Carl Wiehle
Defense Intelligence Agency
Attn: CKW DB-4C2
Washington, D.C. 20301

Director, Defense Nuclear Agency
Attn: Michael Frankel
Washington, D.C. 20305

Command and Control Technical Center
Department of Defense
The Pentagon
Washington, D.C. 20301

Chief of Engineers
Department of the Army
Attn: DAEN-RDZ-A
Washington, D.C. 20314

Director, Army Materials and Mechanics
Research Center
Attn: Technical Library
Watertown, MA 02172

Assistant Secretary of the Army (RD&A)
Attn: Deputy ASA for (RD&S)
Washington, D.C. 20310

U.S. Army Training and Doctrine Command
Fort Monroe
Hampton, VA 23651

Director, U.S. Army Ballistic Research
Laboratory
Attn: Document Library
Aberdeen Proving Ground, MD 21005

Mr. William Taylor
Ballistic Research Laboratory
Aberdeen Proving Ground, MD 21005 (2)

Director, U.S. Army Engineer
Waterways Experiment Station
Attn: Document Library
P.O. Box 631
Vicksburg, MS 39180

Mr. W.L. Huff
USAE Waterways Experiment Station
P.O. Box 631
Vicksburg, MS 39180

U.S. Army Combined Arms Combat
Development Activity
Fort Leavenworth, KA 66027

Civil Engineering Center AF/PRECET
Attn: Technical Library
Wright-Patterson Air Force Base
Dayton, OH 45433

Air Force Weapons Laboratory
Attn: SUL Technical Library
Kirtland Air Force Base
Albuquerque, NM 87117

Air Force Weapons Laboratory
Civil Engineering Division
Kirtland Air Force Base
Albuquerque, NM 87117

Mr. Lewis V. Spencer
National Bureau of Standards
Center for Radiation Research
Room C313 - Building 245
Washington, D.C. 20234

Mr. Samuel Kramer,
National Bureau of Standards
Room B-124, Bldg 225
Washington, D.C. 20234

Mr. William Parker
National Bureau of Standards
Building 224 - Room A-345
Washington, D.C. 20234

Fire Research Library
National Bureau of Standards
Building 224 - Room A-246
Washington, D.C. 20234

Dr. John Rockett
National Bureau of Standards
Center for Fire Research
Building 224 - Room B-260
Washington, D.C. 20234

Dr. Craig Chandler, Director
Forest Fire & Atmospheric Science Research
U.S. Forest Service
Department of Agriculture
Washington, D.C. 20013

U.S. Forest Service
Attn: Dr. A. Broido
P.O. Box 245
Berkeley, CA 94710

Director
Department of Military Application
Department of Energy
Washington, D.C. 20545

Los Alamos Scientific Laboratory
Attn: Document Library
Los Alamos, NM 87544

Chief Robert G. Purington
Lawrence Livermore National Laboratory
University of California
Box 808, L-519
Livermore, CA 94550

Mr. Norman J. Alvares
Lawrence Livermore National Laboratory
University of California
Box 808, L-442
Livermore, CA 94550

R.G. Hickman
Lawrence Livermore National Laboratory
University of California
Box 808, L-140
Livermore, CA 94550

Oak Ridge National Laboratory
Attn: Librarian
P.O. Box X
Oak Ridge, TN 37830

Emergency Technology Division
Oak Ridge National Laboratory
Attn: Librarian
Oak Ridge, TN 37830

Dr. Conrad Chester
Oak Ridge National Laboratory
P.O. Box X
Oak Ridge, TN 37830

Dr. Clarence R. Mehl
Division 7112
Sandia National Laboratories
Box 5800
Albuquerque, NM 87185

Mr. A.P. Brackebush
Forest Fire Research
Northern Forest Fire Laboratory
Missoula, MT 59801

National Council on Radiation Protection and Measurements
7910 Woodmont Avenue
Bethesda, MD 20014

President, International Association of Fire Fighters
1750 New York Avenue, N.W., 3rd Floor
Washington, D.C. 20006

National Fire Protection Association Library
Batterymarch Park
Quincy, MA 02269

Mr. C. Wilton
Scientific Service, Inc.
517 East Bayshore
Redwood City, CA 94063 (2)

Dr. William Christian
Underwriters' Laboratories, Inc.
333 Pfingsten Road
Northbrook, IL 60062

Dr. Donald Drzewiecki
Calspan Corporation
P.O. Box 400
Buffalo, NY 14225

Mr. Raymond Alger
SRI International
333 Ravenswood
Menlo Park, CA 94025

Dr. Jana Backovsky
SRI International
333 Ravenswood
Menlo Park, CA 94025

Mr. Clay P. Butler
SRI International
333 Ravenswood
Menlo Park, CA 94025

Mr. Dick Foster
SRI International
333 Ravenswood
Menlo Park, CA 94025

Dr. Fred Offensend
SRI International
333 Ravenswood
Menlo Park, CA 94025

Hudson Institute
Quaker Ridge Road
Croton-on-Hudson, NY 10520

Mr. Fred Sauer
Physics International Company
2700 Merced Street
San Leandro, CA 94577

Mr. Laurence Pietrzak
Mission Research Corporation
P.O. Drawer 719
Santa Barbara, CA 93102

The Dikewood Corporation
1613 University Blvd, N.E.
Albuquerque, NM 87102

Dr. Anatole Longinow
IITRI
10 West 35th Street
Chicago, IL 60616

Mr. Thomas E. Watermann
IITRI
10 West 35th Street
Chicago, IL 60616 (2)

Mr. Leo A. Schmidt
Institute for Defense Analyses
Program Analysis Division
1801 N. Beauregard Street
Alexandria, VA 22311

The RAND Corporation
Attn: Document Library
1700 Main Street
Santa Monica, CA 90401

Director,
Lovelace Foundation
5200 Gibson Blvd, S.E.
Albuquerque, NM 87108

Dr. Donald Sachs
Kaman Sciences Corp.
1911 Jefferson Davis Highway
Arlington, VA 22202

Mr. Peter S. Hughes
Los Alamos Technical Associates, Inc.
P.O. Box 410
Los Alamos, NM 87544 (2)

Center for Planning and Research
2483 E. Bayshore, Suite 104
Palo Alto, CA 94303

Mr. Richard Laurino
Center for Planning and Research
2483 E. Bayshore
Palo Alto, CA 94303

Mr. John Rempel
Center for Planning and Research
2483 E. Bayshore
Palo Alto, CA 94303

Mrs. Ruth Schnider
Center for Planning and Research
2483 E. Bayshore
Palo Alto, CA 94303

Mr. Walmer Strope
Center for Planning and Research
5600 Columbia Pike - Suite 101
Bailey's Crossroads, VA 22041

Factory Mutual Research Corporation
Attn: Dr. Ray Friedman
1151 Boston-Providence Turnpike
Norwood, MA 02062

Dr. Dennis Holliday
R&D Associates
P.O. Box 9695
Marina del Ray, CA 90291

Research Triangle Institute
Attn: Mr. Ed. L. Hill
P.O. Box 12194
Research Triangle Park,
North Carolina 22709

Mr. Robert Fristrom
Johns Hopkins Applied Physics
Laboratory
Johns Hopkins Road
Laurel, MD 20707

Dr. John Cockayne
Senior Scientist
Science Applications, Inc.
1710 Goodridge Drive
P.O. Box 1303
McLean, VA 22101

Mr. Marvin Drake
Science Applications, Inc.
1200 Prospect Street
La Jolla, CA 92037

Mr. Harvey G. Ryland
Ryland Research, Inc.
5266 Hollister Avenue, Suite 324
Santa Barbara, CA 93111

Department of Fire Technology
Southwest Research Institute
P.O. Drawer 2851D
San Antonio, TX 78284

Technology & Management Consultants
330 Washington Street
Suite 613
Marina del Ray, CA 90291

Dr. Matthew Gibbons
5424 Lawton Avenue
Oakland, CA 94618

Mr. Kenneth Kaplan,
30 White Plains Court
San Mateo, CA 94402

H.L. Murphy Associates
Box 1727
San Mateo, CA 94401

Mr. Stanley B. Martin
Stan Martin & Associates
860 Vista Drive
Redwood City, CA 94062

Dr. Don Scheuch
430 Golden Oak Drive
Portola Valley, CA 94025

Dr. Francis E. Fendell
R1/1038
TRW
One Space Park
Redondo Beach, CA 90278

Dr. Michael A. Pachuta
4563 Braeburn Drive
Fairfax, VA 22032

Dr. Forman Williams
Department of the Aerospace and
Engineering Sciences
University of California San Diego
La Jolla, CA 92037

Professor A. Murty Kanury
Department of Aerospace and
Mechanical Engineering
University of Notre Dame
Notre Dame, IN 46556

Dr. Joseph E. Minor, Director
Institute for Disaster Research
Department of Civil Engineering
Box 4089
Lubbock, TX 79409

Professor R.K. Pefley
University of Santa Clara
Santa Clara, CA 95053

The Information Center
Forest Fire Research Institute
331 Cooper Street
Ottawa, Ontario KIA 043
CANADA

Dr. Ing. P.G. Seeger
Forschungsstelle fuer Brandschuetztechnik
University of Karlsruhe (TH)
75 Karlsruhe 21
Postfach 63380
WEST GERMANY

Dr. Vilhelm Sjolin
Director of BRANDFORSK
The Swedish Fire Research Board
S-115 87 Stockholm
SWEDEN

Secretaire d'Administration
Ministere de l'Interieur
Direction Generale de la
Protection Civile
rue de Louvain, 1
1000 Brussels, Belgium

Canadian Defence Research Staff
Attn: Dr. K.N. Ackles
2450 Massachusetts Ave, N.W.
Washington, D.C. 20008 (4)

Director, Civilforsvarsstyrelsen
Stockholmsgade 27
2100 Copenhagen 0
DENMARK

Direction de la Securite Civile
Ministere de l'Interieur
18 Rue Ernest Cognac
92 Levallois (Paris) France

Bundesministerium des Innern
Graurheindorfer Strasse 198
5300 Bonn 1
WEST GERMANY

Ministry of Social Service
11 Spartis Street
Athens, Greece

Almannavarnir Rikisins
Reykavik, Iceland

Stato Maggiore Difesa Civile
Centro Studi Difesa Civile
Rome, Italy

Civil Emergency Planning Directorate
North Atlantic Treaty Organization
1110 NATO, Belgium

Jefe, Seccion de Estudios y Planification
c/Evaristo San Miguel, 8
Madrid-8
Spain

Ministero dell Interno
Direzione Generale della
Protezione Civile
00100 Rome, Italy

Directeur de la Protection Civile
Ministere de l'Interieur
36 Rue J.B. Esch
Grande-Duche de Luxembourg

Directeur Organisatie
Bescherming Bevoling
Ministry of Interior
Schedeldoekshaven 200
Postbus 20011
2500 The Hague, Netherlands

The Head of Sivilforsvaret
Sandakerveien 12
Postboks 8136
Oslo dep
Oslo 1, Norway

Servico National de Proteccao Civil
Rua Bela Vista a Lapa, 57
1200 Lisbon, Portugal

Civil Defense Administration
Ministry of Interior
Ankara, Turkey

Home Office
Scientific Advisory Branch
Horseferry House
Dean Ryle Street
London SW1P2AW
ENGLAND

END

FILMED

1-84

DTIC