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HUMAN INJURY INFORMATION
SYSTEM CONCEPT EXPLORATION

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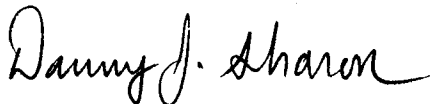
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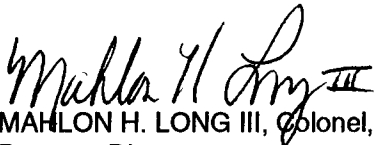**BROOKS AIR FORCE BASE, TEXAS**

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The Office of Public Affairs has reviewed this report, and it is releasable to the National Technical Information Service, where it will be available to the general public, including foreign nationals.

This report has been reviewed and is approved for publication.

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   This technical report documents efforts conducted to assess the feasibility of the concept of a human injury information system which provides data describing the effects of wartime hazards on individuals. It also provides general recommendations for implementing the concept. This information system will incorporate tables, graphs, and algorithms which describe the near-term effects of short-term exposure of a standard individual to various injury-causing mechanisms found in the wartime environment. These mechanisms are overpressure, penetration, acceleration, blunt impact, thermal energy, and toxic agents.

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EXECUTIVE SUMMARY

This technical report documents efforts conducted to assess the feasibility of the concept of a human injury information system which provides data describing the effects of wartime hazards on individuals. It also provides general recommendations for implementing the concept. This information system will incorporate tables, graphs, and algorithms which describe the near-term effects of short-term exposure of a standard individual to various injury-causing mechanisms found in the wartime environment. These mechanisms are overpressure, penetration, acceleration, blunt impact, thermal energy, and toxic agents.

The concept and system-level requirements for a human injury information system were developed primarily through interviews with key researchers and discussions with potential system users. Technical issues associated with producing the system from existing data also were identified from these discussions.

Results from an initial assessment of the current state of human vulnerability algorithms, models, and data suggest there are existing databases or data summaries of relevant research on the effects of single mechanisms. Although there are standard or accepted methodologies for predicting the effects of exposures to some aspects of wartime hazards, there are significant differences in definitions, terminology, and purposes among these separate research efforts. Standard formats and injury classifications are needed to pool the results of these individual studies into definitive system segments.

A method for developing the system segments was demonstrated in developing a sample segment on overpressure effects in the free field (included as an appendix to this report). To produce this sample segment, a working group of physicians, biomedical researchers, engineers, and analysts reviewed the overpressure research data produced by the Lovelace Foundation for Medical Education and Research. The group members identified the physical parameters which predict overpressure injury, described pathological conditions for different levels of injury, and identified probabilities of occurrence. This approach is proposed for producing the human injury information system once definitive user's requirements are identified. The segment for each mechanism would be developed by applying similar development steps (defining requirements, selecting an appropriate methodology, implementing the approach). Identifying a lead agency for human injury information system coordination, to direct the segment development and to propose future research to address human injury data gaps, is recommended. Identification of a lead agency for the technical content of each segment is also recommended.

An extensive bibliography of related research is also included at the end of this document.

A.   PURPOSE

This technical report documents efforts conducted to assess the feasibility of the concept for a human injury information system which provides data describing the effects of wartime hazards on individuals. It also provides general recommendations for implementing the concept.

The concept addresses a potential joint service human injury information system, which would be useful for casualty estimation, medical workload, and other analysis conducted by the individual services and other Department of Defense (DOD) agencies.

B.   BACKGROUND

The Air Force is developing more accurate determinations of personnel attrition through use of the Threat Related Attrition (THREAT) System, which estimates casualties based on a two-step process. First, the system specifies a physical environment for a particular weapon, to describe the acceleration, overpressure, penetration, and other human injury mechanisms expected due to structural response. This description of hazard environments is well understood, and numerous historical and test data exist.

Second, the model assesses personnel vulnerability to these mechanisms to estimate resulting casualties. The THREAT Program focused its initial efforts to determine personnel casualties and injury types by applying historical data from the London Blitz to estimate casualties in collapsed unprotected structures. As the system capabilities expand to include modern conventional munitions and protected structures, the historical data from World War II is not directly applicable for providing the casualty relationships.

The Air Force THREAT System is not alone in the need to link environments (insults) to human injury. The other services and Government agencies have similar requirements for accurate personnel attrition predictions, although the emphasis of one agency may be different from that of others.

C.   SCOPE

Activities under this delivery order include assessment and planning of the effort which would be necessary to identify and collect existing research results relating the hazards of the wartime environment with human response. The desired goal of subsequent phases is an information system to describe human injury resulting from exposure to the injury mechanisms associated with conventional weapons. These mechanisms are overpressure, penetration, acceleration, blunt impact, thermal energy, and toxic agents.

D.   DOCUMENT ORGANIZATION

In Section II, this report reviews the need for a human injury information system and the methodology for defining system-level requirements for its development. Section II also describes the human injury information system concept and identifies associated technical issues. Results from an initial assessment of the current state of human injury algorithms, models, and data are presented in Section III. Section IV presents conclusions and recommendations resulting from this effort. A sample system segment is included as Appendix A. An extensive bibliography of related research is also included at the end of this document (Appendix B).

SECTION II
SYSTEM-LEVEL REQUIREMENTS

A. REQUIREMENTS DEFINITION OVERVIEW

The human injury information system requirements definition process identified the capabilities necessary for a useful system. Analysts also addressed the system-level requirements for potential future application in the joint services community.

This task provided a high-level concept exploration. In this effort, analysts defined the need for the human injury information system and assessed the feasibility of developing such a system. The analysts met a number of potential users and members of the research community, and conducted a preliminary survey of available data and methods to describe human tolerance to injury-causing mechanisms. The results of this preliminary survey are included in Section III.

Analysts also proposed a preliminary concept, included in this section, for the system. A multidisciplinary panel met to develop the methodology and prepare the content for the sample segment on overpressure (Appendix A), which completed the concept exploration efforts.

B. PROBLEM DEFINITION AND FEASIBILITY ASSESSMENT

1. Discussions with Potential Users

The primary goals of these discussions were to define the need for the human injury information system, to explore experts' views of the feasibility of developing the system, and to determine top-level system requirements. The meetings also provided information about individuals and agencies that had conducted key research into the injury-causing mechanisms.

The first series of meetings involved members of the THREAT System development team. The group shared their experiences in casualty estimation methodology development. The human tolerance data requirements for the THREAT System Facility Model were emphasized. Many casualty relationship algorithms used in the preliminary model draw from historically based probabilities of certain types of injuries occurring once a building interior's hazard environment has been characterized. The historical data come from London Blitz surveys of damage and casualties in urban dwellings, which can be applied to unprotected facilities on airbases. The extension of historical data to casualty algorithms for protected structures is not well defined, nor are modern weapons and threats directly addressed by the London bombing data. The engineers involved in developing the Facility Model described the type of human injury data currently required for Threat System casualty estimation (Table 1). Note that specific data items are identified for conventional weapons, which are currently implemented in the Facility Model. Data required for nuclear, biological, and chemical weapons will be identified in the future.

The 1990 LFT Crew Casualty Assessment meeting provided contacts for key human vulnerability researchers. The meeting also provided system planners with a number of insights on this research community's need's. Representatives of the six working groups from the 1988 LFT Conference provided updates

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on recent research efforts on the injury-causing mechanisms addressed by their group (penetrating injuries, burns, toxic gases, blast/overpressure, directed energy, and blunt injury/acceleration). The LFT conference attendees participated in several sessions aimed at identifying research priorities for combinations of injury-causing mechanisms and weapon systems. The discussion from these sessions highlighted a wide range of priorities among the community. The conference participants observed that common terminology and methodologies do not exist across the casualty assessment community. Conference conclusions restated the need, first expressed at the 1988 LFT conference, for a human tolerance handbook (now viewed as an information system) to provide these common references.

System planners separately briefed the Joint Chiefs of Staff J-4 Casualty Study Coordination Work Group. The purpose of these briefings was to request Joint Staff direction for developing a joint services human tolerance handbook or information system. The work group expressed interest in the concept.

2. Discussions with Key Researchers

During this step, the staff also consulted key researchers, including Dr. Joseph Sperrazza, former director of the U.S. Army Materiel Systems Analysis Activity (AMSAA); Mr. David Neades, Dr. J. Terrence Klopcic, and Dr. Paul Deitz of USARL; Dr. Eugene Visco of the Office of the Deputy Undersecretary of the Army for Operational Research (DUSA(OR) Model Improvement and Study Management Agency (MISMA); Dr. Donald Richmond, formerly of the Lovelace Foundation for Medical Education and Research; LTC (Dr.) Garry Ripple, Walter Reed Army Institute of Research; and Dr. Ken Dodds, U.S. Army Medical Research & Development Command (USAMRDC).

Dr. Sperrazza developed criteria for incapacitation due to penetration while at AMSAA. In the discussions with system planners, he described the experiments conducted to develop the empirical relationships that formed the basis for the incapacitation criteria. These criteria, are described in Section III.

USARL has conducted numerous studies on penetrating injuries. Mr. Neades is the Joint Technical Coordinating Group for Munitions Effectiveness (JTCG/ME) focal point for research in this area. Dr. Klopcic and Mr. Neades were tasked by JTCG/ME to draft an implementation plan responding to the LFT Office's request that JTCG/ME hold future crew casualty assessment conferences. These researchers summarized the major points of the draft implementation plan, which included the preliminary cost and schedule if JTCG/ME assumed the crew casualty assessment tasking. Dr. Klopcic, Dr. Deitz, and Mr. Neades also described USARL's ongoing research in the area of penetration injuries.

Dr. Visco's research involves review of casualty assessment methodologies used by U.S. Army analysts. In discussions with human injury information system planners, Dr. Visco described the Improved Casualty Assessment Program (ICAP) methodology, which is currently being explored jointly with the Defense Nuclear Agency (DNA). This methodology addresses several injury-causing mechanisms (overpressure, thermal, ionizing radiation) and presents an approach for evaluating multiple effects.

Dr. Richmond was a principal investigator at the Lovelace Foundation and was involved in developing the overpressure survival curves which are widely used to evaluate human tolerance. He explained the

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TABLE 1. HUMAN TOLERANCE DATA NEEDED FOR THREAT
SYSTEM FACILITY MODELS

CONVENTIONAL WEAPONS

Overpressure
- peak pressure
- duration
- person's orientation to blast
- person's proximity to wall and reflections

Acceleration
- peak of force
- duration of force
- direction of force (x, y, z coordinates)
- posture at time of force
- position at rest (thrown into a brick wall or onto a featherbed)

Primary Fragment
- fragment shape
- fragment material
- velocity
- mass
- body region struck
- clothing/protective gear
- interdependence of hits

Secondary Fragments
- same as for primary fragments

Burns/Thermal (Future)

CHEMICAL WEAPONS (FUTURE)

NUCLEAR WEAPONS (FUTURE)

BIOLOGICAL WEAPONS (FUTURE)

interpretations of the animal data used to develop the curves for human lethality and incapacitation. These curves form the basic summary data for overpressure tolerance used in developing the sample system segment (Appendix A) of this report.

LTC Ripple reviewed the current state and direction of the medical evaluation of nonfragment injury effects in armored vehicle live fire tests and provided several reports pertaining to this general subject.

Dr. Dodd reviewed the current situation regarding the modeling of blast injuries and described the Walter Reed Army Institute of Research (WRAIR) blast casualty model Injury 3. Injury 3 treats the thorax as a mechanical structure and predicts injury as a function of blast induced chest wall velocity. The physiological injury database contained in the database is based on approximately 1000 animal experiments.

3.   Review of Published Research

The preliminary research assessment involved reviewing past efforts which studied a number of injury-causing mechanisms. The intent of this survey was to identify data sets and methods currently used by researchers and analysts studying human exposure to overpressure, penetration, acceleration, blunt impact, thermal, toxic, and ionizing radiation hazardous environments. The results, summarized in Section III, identify the most widely used methods. For each method, analysts identified the major parameters employed in determining human exposure limits, major research findings, and the limitations to applying the method.

4.   Observations

The results of the interviews and research assessment suggest that there is extensive human injury research documented in the literature that can be applied to developing this information system. Also, there are potential users for a joint human injury information system. An overall coordinating agency would be necessary to integrate the individual requirements of the participating agencies, establish common terminology and methodology, and evaluate the suitability and compatibility of the research in meeting the system requirements.

For system development, substantial resources must be invested to benefit from the rich data already in the literature. Each research undertaking was planned, executed, and documented as an individual effort, usually to answer very specific questions. Panels with expertise in the injury mechanisms would be essential in evaluating past research and in determining how compatible this research might be with related data. The panel would also determine whether or not there is a reasonable expectation for achieving compatibility with past research.

Based on these observations, the planners developed a preliminary concept for the information system. This concept addressed joint users' potential requirements, The concept exploration continued with the development of a sample segment for overpressure to explore the feasibility of adopting and enhancing existing research results to produce system segments.

C.   HUMAN INJURY INFORMATION SYSTEM CONCEPT

The planners defined a human injury information system concept to describe the common portion of processes that link wartime threats to human vulnerability, as applied by numerous users for various analyses (developing casualty streams, estimating personnel replacement rates, determining crew incapacitation, assessing

mission degradation). For this concept exploration only effects of conventional weapons are considered. The process for using human injury data to determine the incapacitation or mission degradation of personnel due to various threats (which is broader than the scope of this system) is depicted in Figure 1a and summarized below.

The user employs an appropriate model, specific to the analysis purpose, to apply the threat to a system, structure, or other surroundings, such as vehicles or free field. The model then determines the resulting injury-producing insult (such as fragments, overpressure, or toxic fumes). These effects are calculated for discrete points or local regions in the object being considered using standard parameters such as those shown in Table 2.

A human injury information system is consulted to determine individual injuries and probabilities of injury for personnel located at a point for which effects have been defined. The injury determination couples the individual and environment using the human injury information system to assign a particular injury and probability. The system defines the vulnerability in terms of a standard individual - by specific size, in particular clothing or uniform, and in a posture typical of that in which an individual might be exposed to a particular threat. For example, overpressure tolerance curves developed by the Lovelace Foundation express vulnerability for a 70kg man in certain postures to threshold lung damage in terms of pressure magnitude and duration.

The probabilities of one or more injuries for the population at risk are employed in the user's model to complete the specific analysis. Combined effects are evaluated in a subsequent step, following determination of injuries for each of the multiple causes.

D.   TECHNICAL ISSUES

Various discussions and review of past human vulnerability research highlighted a number of technical issues which must be addressed in developing a human injury information system.

1.   Suitability of Data

Some of the existing data can easily be adapted into a format that is compatible with the human injury database. For example, blast testing in which temperature data were measured within a structure can be used to determine nearby persons' vulnerability to burns. This assessment would apply published research relating temperature increase and energy loading to occurrence of burns of various degrees in humans.

Other research may not be suitable if appropriate data were not collected or if descriptions of test/model conditions are inadequate. For example, data on wounds produced by fragments are not useful for algorithm development unless details on the weapon type, victim's location relative to the weapon, victim's protective gear and posture, etc. are known. These data may, however, be useful in validating other models. A model might predict fragment injuries by postulating a particular distribution of number and sizes of particles over a certain distance from the weapon detonation. Comparing information from wartime casualty records on wounds produced, by particular size and fragment weight, can verify this model.

2.   Variability in Human Tolerance

The variability in how individuals tolerate wartime hazards complicates both the comparison of individual research results and the application to specific analyses. Some key parameters in variability include the individual's size (weight and height), age, gender, preexisting conditions or general health, posture during
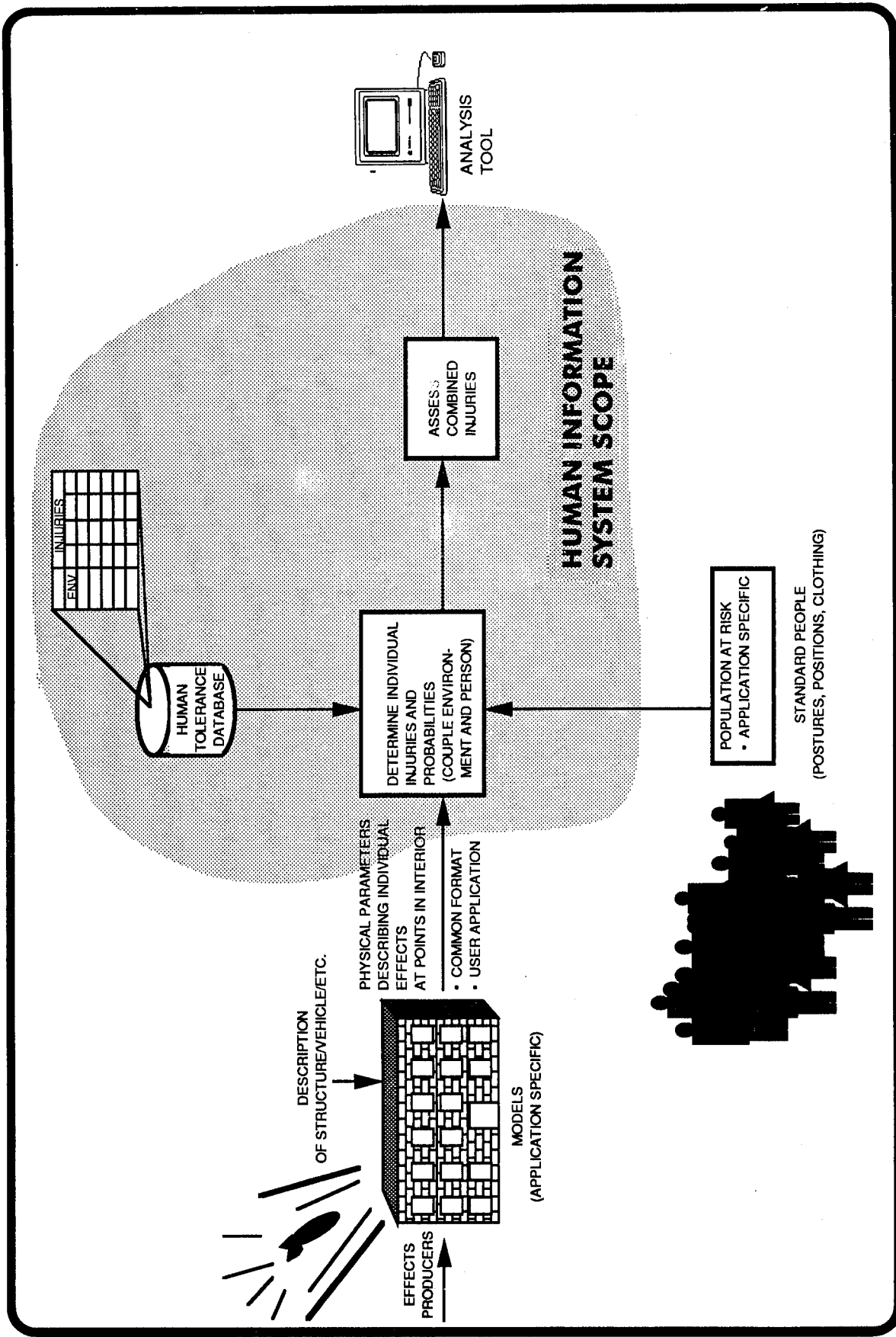
Figure 1. Human Tolerance Handbook Concept

ANALYSIS TOOL

HUMAN INFORMATION SYSTEM SCOPE

ASSESS COMBINED INJURIES

HUMAN TOLERANCE DATABASE

ENV. INJURIES

DETERMINE INDIVIDUAL INJURIES AND PROBABILITIES (COUPLE ENVIRON- MENT AND PERSON)

POPULATION AT RISK
• APPLICATION SPECIFIC

STANDARD PEOPLE
(POSTURES, POSITIONS, CLOTHING)

PHYSICAL PARAMETERS DESCRIBING INDIVIDUAL EFFECTS AT POINTS IN INTERIOR
• COMMON FORMAT
• USER APPLICATION

DESCRIPTION OF STRUCTURE/VEHICLE/ETC.

MODELS (APPLICATION SPECIFIC)

EFFECTS PRODUCERS

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Figure 1b. Crew Casualty Analysis Process

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TABLE 2. PARAMETERS FOR WEAPON-PRODUCED PHYSICAL ENVIRONMENTS

ENVIRONMENT	KEY PARAMETERS
OVERPRESSURE	• PEAK PRESSURE • DURATION (PRESSURE-TIME HISTORY)
PENETRATING FRAGMENTS	• FRAGMENT PATTERN (RANGES OF MASS AND VELOCITY)
ACCELERATION	• ACCELERATION - TIME HISTORY • PEAK ACCELERATION
THERMAL	• TEMPERATURE • EXPOSURE FIELD (TIME HISTORY)
TOXIC AGENTS	• CONCENTRATION OR DOSE • TIME HISTORY

exposure, type of uniform, use of protective gear, location relative to threat, and surroundings (free field, within shelter, etc.).

The two extremes in addressing this variability are to: (1) develop relationships only for an unclothed, unrestrained, standing, totally unprotected individual or; (2) develop relationships for individuals with all possible types and degrees of clothing, restraint, posture, and protection. The first extreme has very little direct applicability, and the second is impossible to achieve with finite resources. A small number of common human circumstances will therefore be defined (in detail) and injury prediction techniques and relationships will be developed for this limited set. The results will have direct practical applicability. Other circumstances can be related to the standard set by modeling the increase or decrease in insult which the human sustains due to the non standard environment.

3. Standard Circumstances for Human Injury Discussion

In addition to using the standard individual for establishing human vulnerability limits, an appropriate standard circumstance or circumstances should be considered for each of the various criteria. As described above, the criteria may be established as a series of tables/charts/etc., for each typical or reasonable combination of clothing, gear, posture, surroundings, etc. For example, burn tolerance criteria would consider personnel in standard battle dress, which affords bare skin some protection against injury. Penetrating injury criteria would consider personnel with and without body armor. Criteria for tolerance to chemical vapor agents should be developed for protected and unprotected personnel.

4. Notion of Time in Human Tolerance

The evaluation of human vulnerability to wartime threats involves consideration of time. One aspect of time, is the duration of exposure to the harmful environment. In the case of fragmentation any duration of exposure produces the full harmful result; however, the injury due to blast pressure, and most other weapon effects increases with increased duration of exposure. The time scales associated with different effects vary substantially. In the case of blast pressure the time scale is usually measured in milliseconds.

A second aspect of time is the delay between exposure and the manifestation of injury. In the case of fragments the manifestation of injury is immediate. In the case of detonation or combustion gases the manifestation of injury may not develop for some time.

Time from injury to medical diagnosis and treatment also influences the extent of wounding or injury for personnel exposed to many wartime threats. The anatomical and/or physiological changes occurring as a result of delayed treatment can profoundly alter the presenting condition. This would depend on the type of insult and the resulting wound.

In general, the discussion of human injury requires addressing time - to determine injuries upon exposure, to estimate whether the person must be replaced, to describe medical treatment requirements, or to evaluate mission degradation. For the human injury information system, the complexity associated with extended exposures or long-term effects limits reasonable discussion to immediate effects from short-duration exposures to hazards.

5.   Other Limitations

The effects of weather exposure, indigenous diseases, combat stress, or other threats which are produced by weapons are excluded. Otherwise, the scope of the information system would make achievement unattainable.

E.   SYSTEM REQUIREMENTS

Based on the concept exploration efforts, the analysts defined the system requirements.

1.   Input to the Human Injury Information System

The input necessary to use the human injury information system must be specified in a standard form. The input must be independent of the type of weapon or threat producing the hazard, and must define the environment in which a person may be at risk (i.e. the insult). For example, the input for the overpressure segment must define the wave shape (e.g. peak pressure and duration of exposure), regardless of what type of weapon produced the overpressure.

2.   Applicability of the Human Injury Data

The human injury information system segments must clearly indicate the conditions or assumptions used to develop the limits for human exposure. This clarity is needed so users may employ the data appropriately for modeling environments that directly correspond to the data.

Using the overpressure segment based on Lovelace Foundation survival curves as an example, it is noted that these data apply to single shock wave fronts that are characterized by instantaneous rise and exponential pressure decay (Figure 2). In the case of complex waves (Figure 3), where there are interactions due to reflections (as inside hardened facilities), the Lovelace data cannot be applied directly. However, other researchers (Reference 4 and 5) have proposed relationships to determine equivalent overpressure and duration values from the complex wave pressure-time history, so the Lovelace data can be applied.

3.   Injury-Causing Mechanisms

The information system will address the following injury-causing mechanisms:

a.   Overpressure

b.   Penetration

c.   Acceleration and Deceleration

d.   Blunt Impact and Crushing

e.   Thermal Energy

f.   Toxic Agents (e.g. Detonation and Combustion Products)

4.   Standard Individual

The system must describe limits for a standard individual. Addressing variability among individuals, as described above, is beyond the scope of this effort.

5.   Output From The Human Injury Information System

Each system segment will define the type and severity of injuries that will be caused and give the probabilities of each as a function of the exposure (i.e. the insult).
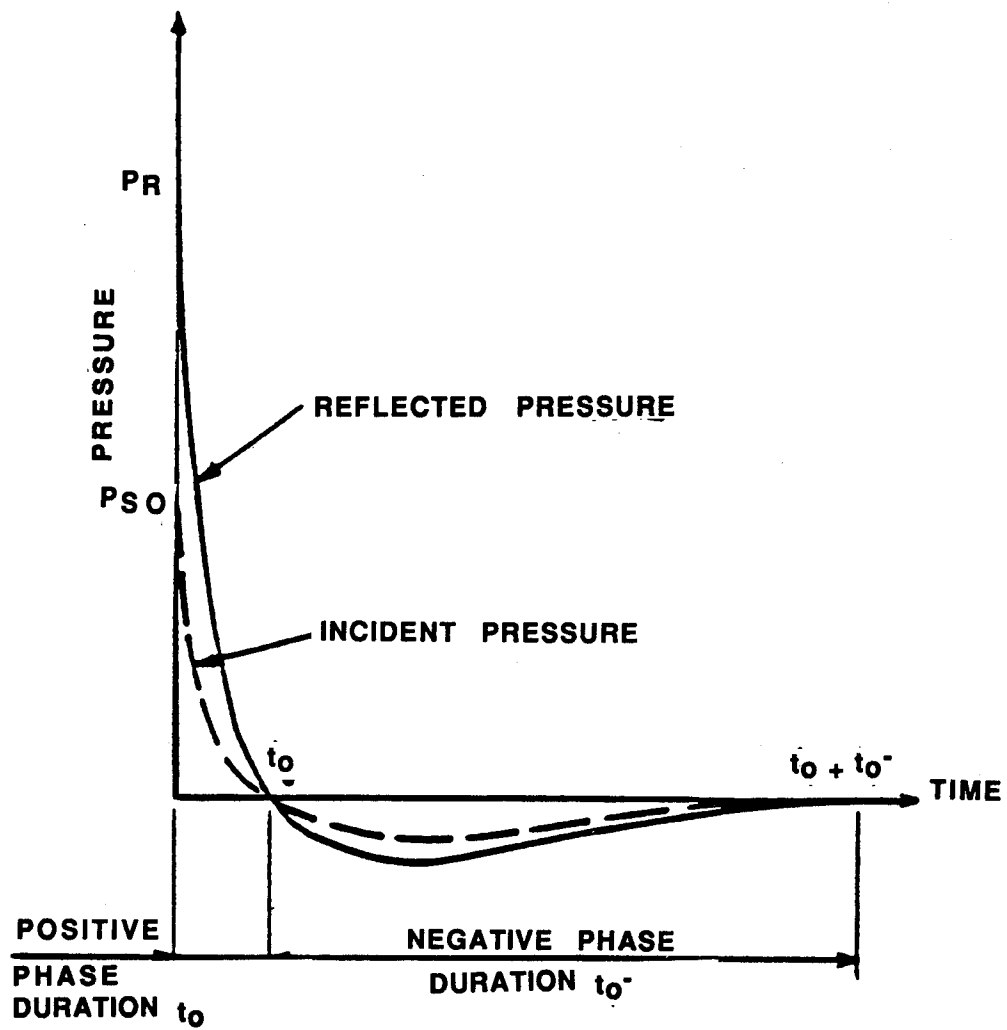
11

Figure 2. Representative Blast-Produced Pressure-Time Histories
(Single Shock Wave Front)
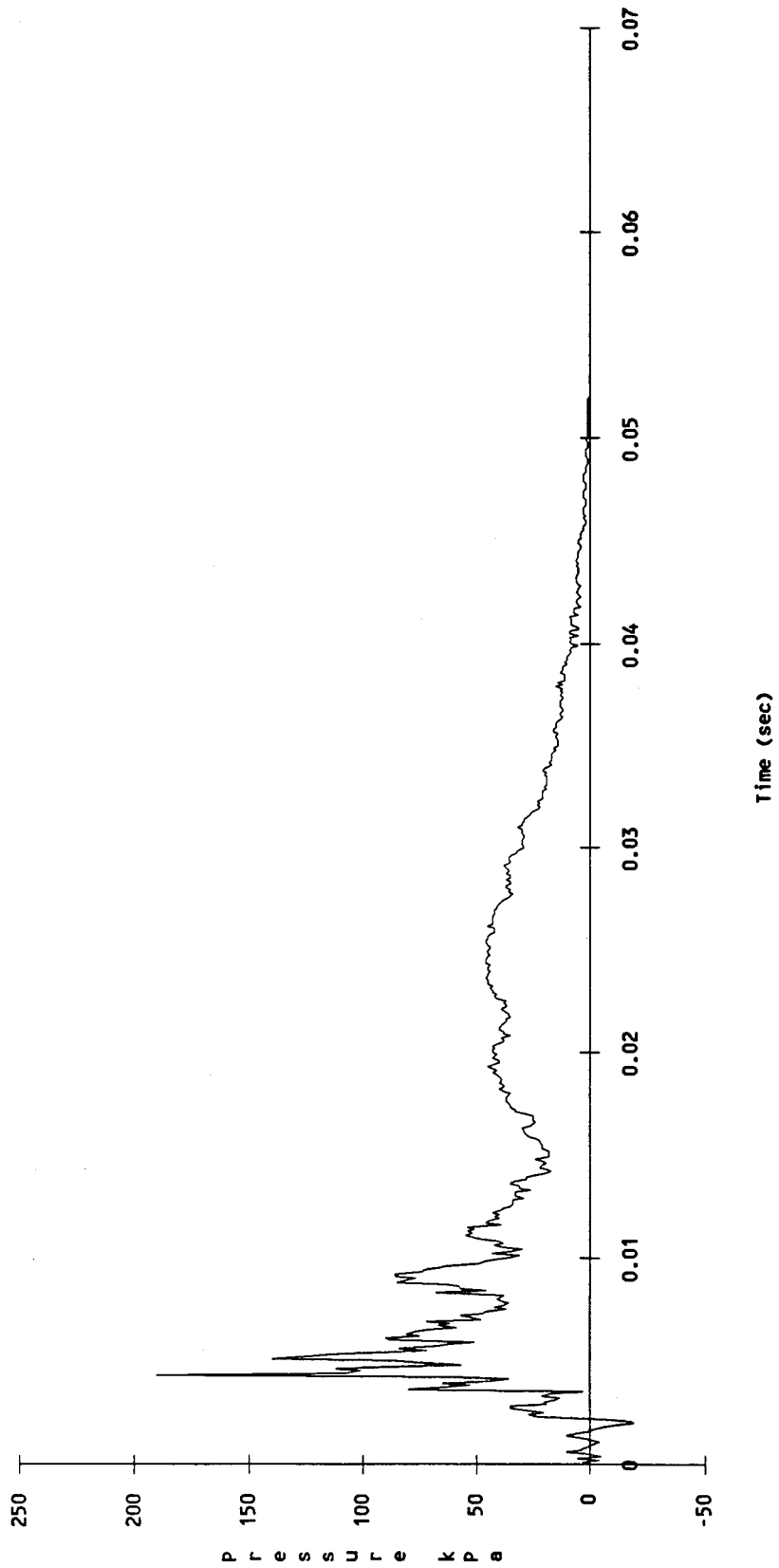
Figure 3. Representative Blast-Produced Pressure Time History
(Complex Wave Front)

SECTION III

ASSESSMENT OF HUMAN INJURY RESEARCH

As part of the concept exploration task, personnel conducted a preliminary assessment of relevant research. The assessment focused on identifying the methodologies that are currently accepted for assessing the results of human exposure to wartime hazards. For each methodology, analysts identified the major parameters, supporting research or experiments, major findings, definitions of lethality or injury thresholds, and limitations for using the method in the human injury information system. This section describes the categories of injury-causing mechanisms reviewed and summarizes the results of the preliminary assessment.

A.   INJURY-CAUSING MECHANISMS

The preliminary research assessment addressed six categories of injury-causing mechanisms:

1.   Overpressure: refers to the pressure increase caused by airblast produced from the detonation of conventional, fuel-air, or nuclear weapons, or by explosions in enclosed places.

2.   Penetration: includes bullets, flechettes, and other small arms, as well as the primary fragments from weapon casings, and secondary projectiles from debris.

3.   Blunt Impact: This category addresses injuries due to objects propelled by airblast or groundshock into persons but not penetrating the body.

4.   Acceleration/Deceleration: describes effects of whole-body acceleration or decleration from groundshock or blast, independent of pressure or impact effects.

5.   Thermal Energy: includes radiation and hot gas.

6.   Toxic Agents: addresses exposure to a variety of toxic agents, such as combustion products (from detonation of enhanced munitions or from fires), industrial products, and chemical warfare agents.

B.   ASSESSMENT OF RESEARCH

1.   Overpressure

The Lovelace Foundation developed the widely accepted methodology for determining man's tolerance to the effects of blast overpressure. Among the agencies and organizations which utilize this methodology are DNA, JTCG/ME, and Edgewood Arsenal.

a.   Lovelace Foundation Survival Curves

1)   Research Overview

Researchers at the Lovelace Foundation experimented with over 2000 animals from 13 different mammalian species by subjecting them to blast waves generated by either shock tubes or high-explosive charges. Based on a 24-hour postexposure time period, survival percentages for each species were determined, and the results were scaled to man according to body weight (70 kg). Several body orientations were considered. They were for cases when the body long axis was either parallel or perpendicular to the direction of the blast propagation and when the test subject was either located near a reflecting surface or in a free-field area.

2)   Major Findings

Experimentation revealed that mortality was most attributable to lung damage. Blast overpressures disrupts the lungs, causing air to enter the body's circulation, leading to an early death from coronary and cerebral air embolism (Reference 7). Furthermore, lethality was determined to be a function of both overpressure and duration, and would vary based upon lung volume and body orientation. Another significant injury associated with overpressure is eardrum rupture.

3) Lethality/Threshold Definitions

The survival curves were determined using the following fitting equation (Reference 8):

$$P = 61.5[1 + 6.76T^{-1.064}]e^{0.1788(5-z)}$$

P   :Scaled peak reflected overpressure, psi

T   :Scaled duration, msec

z   :Survival, probit units (i.e., 5 = 50% survival)

The scaling relationships developed for peak reflected overpressure and duration are (Reference 8):

$$P = p_r\left(\frac{61.5}{p_{sw}}\right)\left(\frac{14.7}{p_o}\right)$$
$$T = t_+ \left(\frac{70}{m}\right)^{1/3}\left(\frac{p_o}{14.7}\right)^{1/2}$$

p_r :Peak overpressure at the reflecting surface,

p_{sw}:   Square-wave p_r resulting in 50% survival with p_o = 14.7 psi (For man, P_{sw} = 61.5 psi)

p_o: Ambient pressure, psi

t_+:   Duration of positive overpressure at the reflecting surface, msec

m: Body mass of mammal, kg

Using the above relationships, the Lovelace Foundation developed survival curves for a 70 kg man at 14.7 psi ambient pressure. These curves are presented in Figures 4 through 6. Since the blast parameters are measured at a reflecting surface, relationships between exposures near the reflecting surface and those in a free field were formulated. In free field situations, where the long axis of the body is parallel to the direction of propagation, equivalent damage occurs if the incident overpressure in the free field case is the same as the reflected pressure in the reflecting surface case. For free field situations, where the long axis of the body is perpendicular to the direction of propagation, equivalent damage results provided that the incident
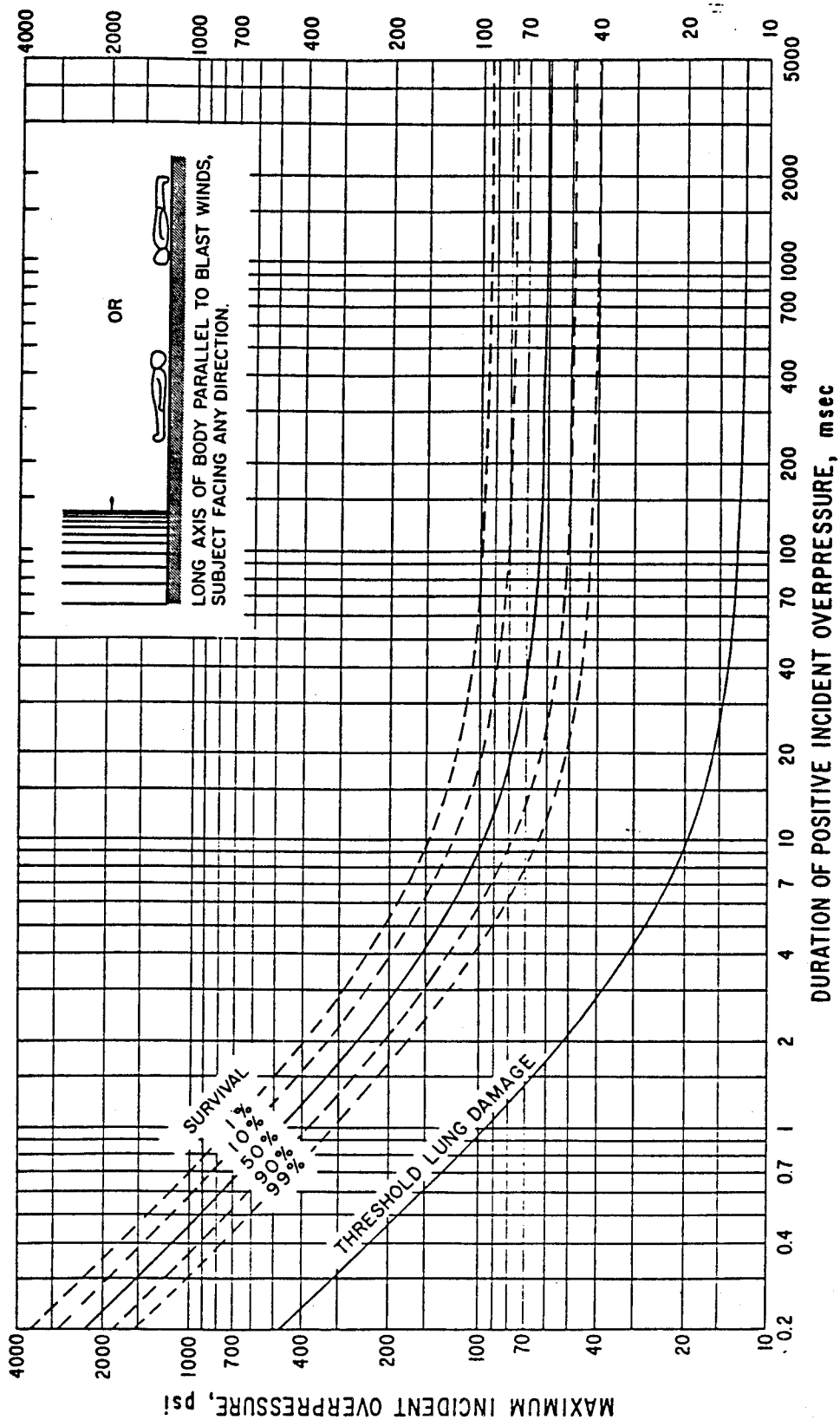
Figure 4. Survival Curves Predicted for 70-kg Man (Body Parallel to Direction of Wave Propagation)(Reference 8)

16
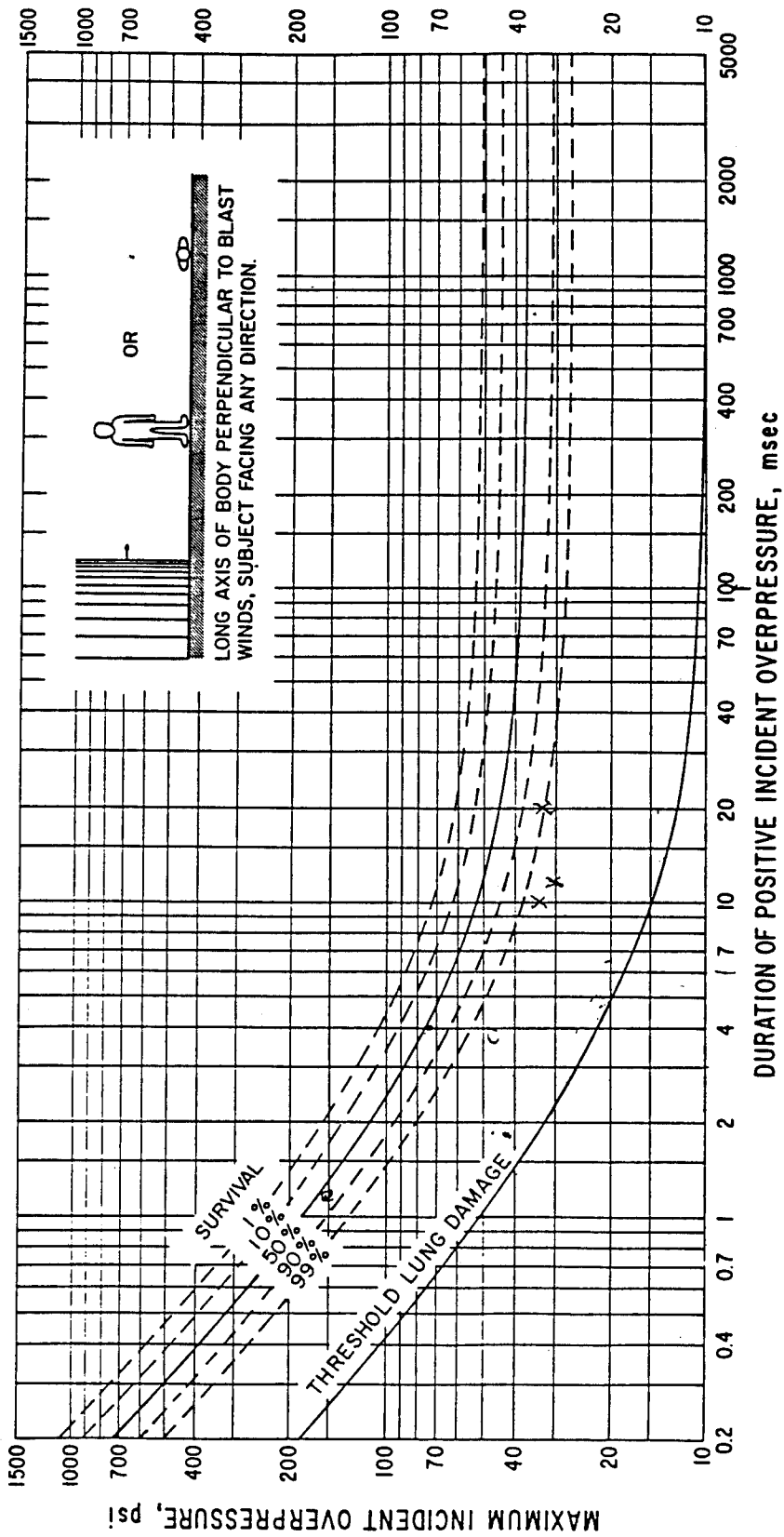
Figure 5.   Survival Curves Predicted for 70-kg Man (Body Perpendicular
to Direction of Wave Propagation)(Reference 8)

17
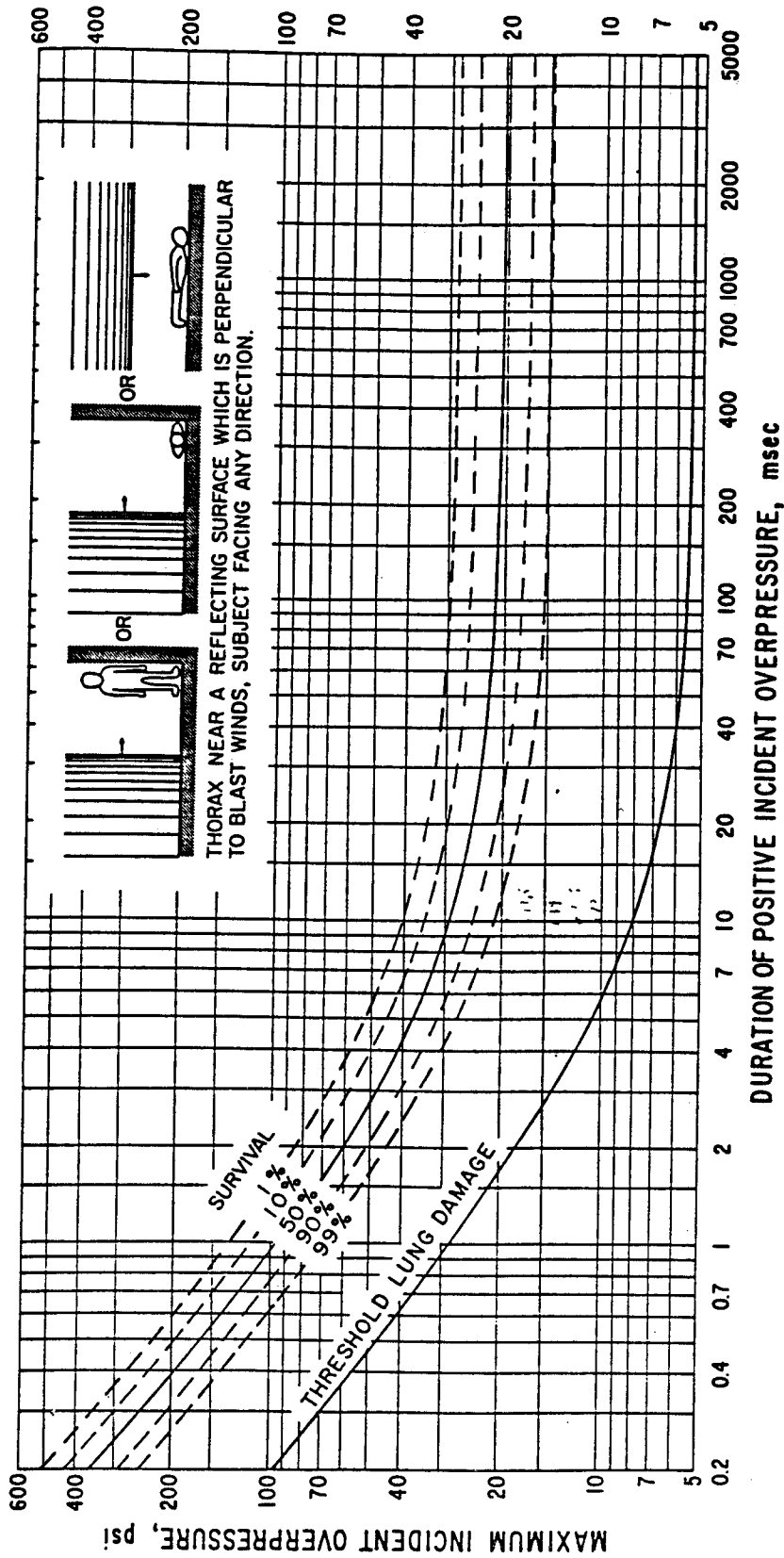
Figure 6. Survival Curves Predicted for 70-kg Man (Thorax Near Reflecting Surface)(Reference 8)

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overpressure plus the dynamic pressure for the free field exposure equals the reflected pressure in the reflecting surface case. The measured duration was considered the same for each case.

Threshold lung injury is defined as one-fourth the LD_{50} blast level, where LD_{50} is the lethal dose for 50 percent of the exposed population. This injury criterion is based upon postmortem examinations of various animal species used in lethality experiments. At threshold levels, petechial lung hemorrhaging occurs; however, this is not considered to affect respiration or blood gas concentrations which lead to severe lung damage and/or death (Reference 9).

Relationships for assessing the population subject to auditory system injury are shown in Figures 7 (Reference 10) and 8 (Reference 7).

4)   Major Data Parameters

The major data parameters considered in applying the Lovelace survival curves for overpressure are:

a)   Maximum incident overpressure

b)   Duration

c)   Body orientation to the blast wave

d)   Proximity to a reflecting surface

5)   Limitations

Since these results are based upon animal experimentation, some limitations exist when extrapolating the data to man. The newer Injury 3 Model under development by WRAIR might well replace the Lovelace work at sometime in the future. Injury 3 appears to offer the potential for providing a more detailed cause and effect relationship between blast and discrete physiological injury. Injury 3 relates a large animal injury database to the work done on the lung as a result of chest wall motion due to blast loading. The rationale for the model is based largely on finite element modeling of thorax movement under impulsive loading. The model has the advantage that it can accept a blast wave of any form as an input, and in the limiting case of an ideal blast wave the results are said to agree well with the Lovelace data.

2.   Penetration

A majority of the research on penetration effects due to impacting fragments was performed at Aberdeen Proving Ground by USARL and the Chemical Research and Development Laboratory (CRDL). The results of this joint effort are presented in various JTCG/ME weapons effectiveness manuals and are widely used by military planners. Furthermore, Reference 11 states that the USARL/CRDL research is primary in assessing human incapacitation due to penetrating fragments.

a.   Research Overview

USARL scientists conducted test firings with fragments and other projectiles, such as bullets and flechettes, to determine the depth and lateral extent of wound tracts. Experimentation involved firing fragments into animal tissue (usually goat tissue) and into gelatin simulant. Supplementary experiments involved
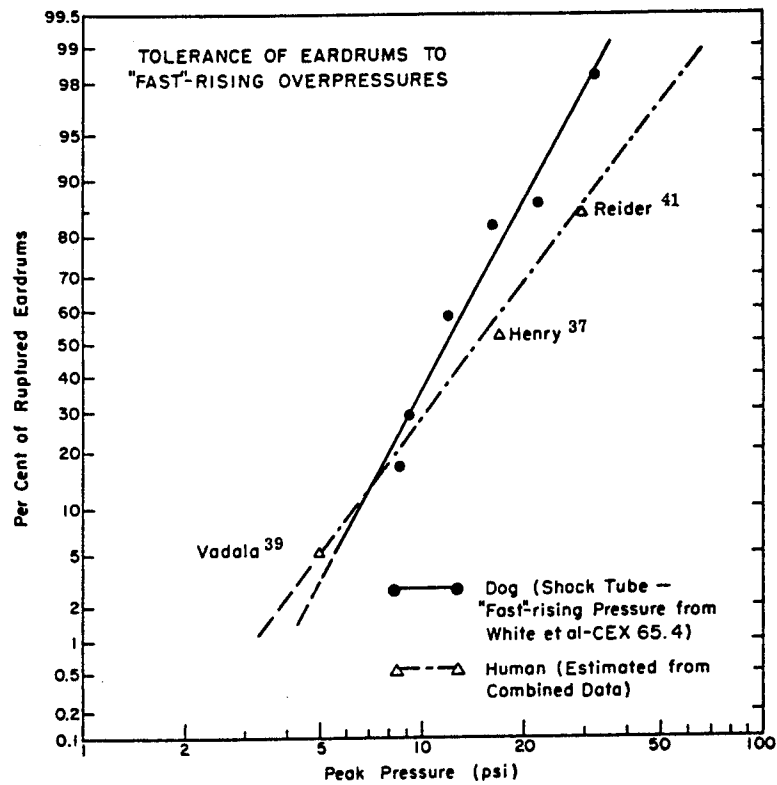
Figure 7.   Log-normal Plot of Data on Human Eardrum Ruptures
           (Reference 10)
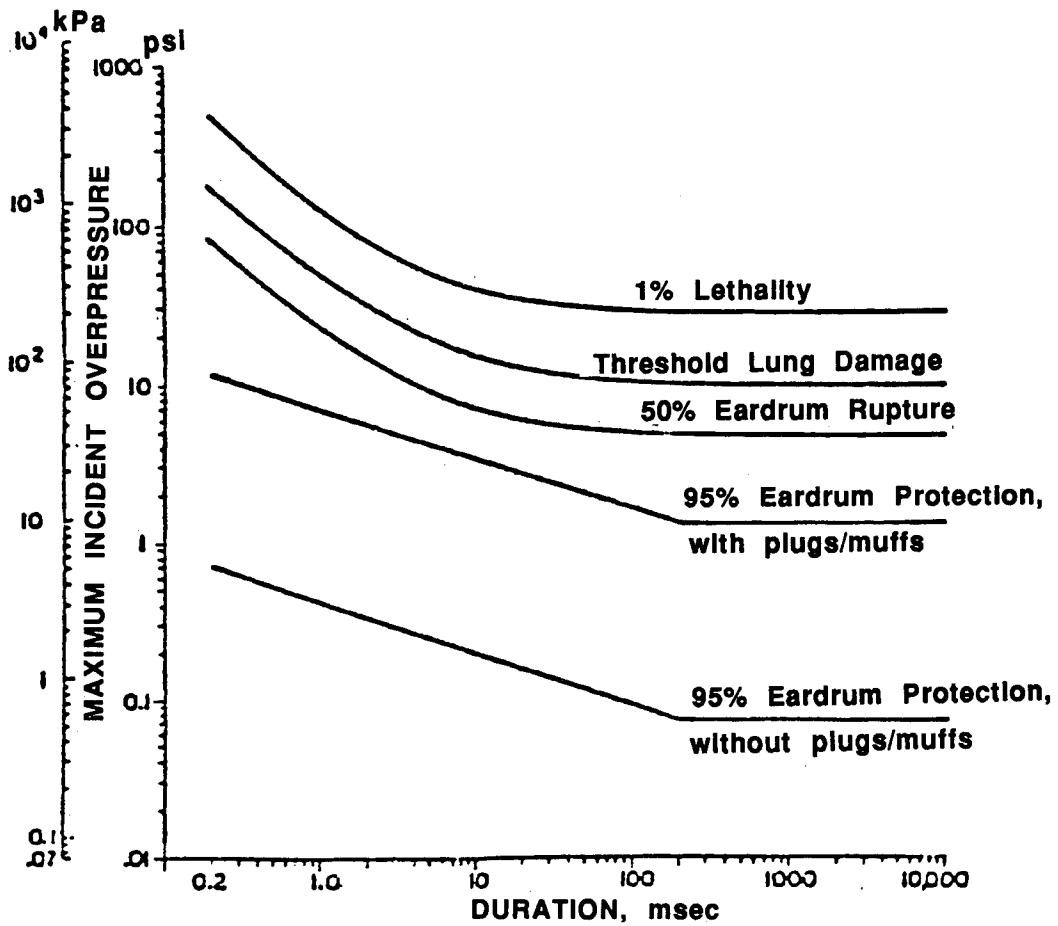
Figure 8.   Lethality and Damage/Injury Curves Predicted for Man
            (Reference 7)

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firing into human cadavers and live animals, with complete descriptions of each resulting wound tract obtained by autopsy. Factors varied in these experiments included fragment shape, mass, and striking velocities. Outputs of these experimental firings were wound depth, wound cross section along the wound tract, and velocity retardation for various anatomical components. In addition, test firings where also conducted on various types of clothing and body armor.

Based on these experimental data, specific shotlines were analyzed, and corresponding wound classes were determined by medical personnel at the Biophysics Division of CRDL. The shotline analysis was conducted using the Eycleshymer-Shoemaker body cross sections to identify the affected organs and body parts within the assumed straight line wound tract. The Eycleshymer-Shoemaker body cross sections depict 108 horizontal slices of an adult male human body measuring 69 inches tall and weighting 155 lbs. These slices are 1.2 cm thick in the head and neck region and 2.6 cm thick for the remainder of the body. The shotlines analyzed conformed to the cross sections' directionality, so all shotlines were considered horizontal. The retardation information obtained by experimentation for different tissue types was used to determine the overall shotline penetration depth and wound location. From this information, the wound type and severity were assessed, and wound classes were subsequently assigned to each shotline. In the wound class assignment process, wound width and indirect wound effects (e.g., a hit on the spine can incapacitate one or more extremities) were considered. Medical officers used their clinical and field experience when assigning wound classes to shotlines. Table 3 shows typical wound classes.

Based on the wound class, medical and military experts assigned a percent disability (PD) value for each combat role (i.e., assault, defense, supply, reserve) and postwounding time (i.e., 30 seconds, 5 minutes, 30 minutes, 12 hours, 24 hours, 5 days). An averaged PD value (i.e., $P_{k/h}$) given a particular fragment mass and velocity was determined for each major body subdivisions (i.e., head and neck, thorax, abdomen, pelvis, arms, legs) by analyzing all shotlines at 0-, 60-, 120-, 180-, 240-, and 300-degree angles measured from the body's anterior aspect. The whole body $P_{k/h}$ was determined as weighted average of the $P_{k/h}$ values for the individual body subdivisions.

b. Major Findings

Several factors influence wound class and severity. These are fragment penetration depth, shotline location, wound width, and deposited energy.

c. Lethality/Threshold Definitions (Reference 11)

Examples of the wound classes used in the analysis are shown in Table 3. The associated symbols indicate the parts of the body and degree of damage involved. In general, subscript numbers identify wound severity, with lower numbers indicating higher incapacitation. These wound classes are assigned to shotlines based upon penetration depth and shotline location. Reference 12 provides further information on this assignment process. The human incapacitation equations (i.e., $P_{k/h} = 1-\exp[-a(MV_s^{**}1.5-b)^{**}n])$ formulated from this methodology are for various combat roles and postexposure times. Because these are user-defined

TABLE 3. TYPICAL WOUND CLASSES (Reference 11)

SYMBOL	DESCRIPTION
B_2	SKULL: Severe Fragmentation or Depressed Fracture
$B_{a7}V_2$	BONE: With Concurrent Cardiovascular Wound
$B_{L1}V_1$	BONE: With Concurrent Cariovascular Wound
H_1	HAND: Any Wound at this Velocity
K_2	URETER, URETHRA, and URINARY BLADDER: Puncture Wound With Leakage
$N_a V_2$	NERVE: With Concurrent Cariovascular Damage
P_7	LUNG: Puncture With Small Blood Loss

incapacitation effects, they are considered beyond the scope of the human injury information system and will not be reviewed in this report The current version of the model can also output injury descriptions using the abbreviated injury scale (AIS) which is of greater value in the human injury context.

        d.   Major Data Parameters

              1)   Fragment mass

              2)   Fragment velocity

              3)   Wound track location

        e.   Limitations

In this methodology, human response is described in terms of average effects, with no allowance for differences among individuals. Expert medical opinion was used to develop wound classes and severity levels.

        3.   Blunt Impact

Data on this injury-causing mechanism appear to be limited. In some cases, the research on blunt impact effects was combined with the research on the other injury-causing mechanisms (i.e., overpressure, penetration, acceleration)

        a.   Edgewood Arsenal Projectile-Induced Blunt Trauma Methodology (Reference 13)

              1)   Research Overview

Blunt trauma data on three animal species (i.e., goats, pigs, dogs) were obtained by Edgewood Arsenal from several experimental sources. A lethality equation was formulated based upon this data. Army Materiel Command Applied Research, Land Warfare Laboratories (LWL), and the Lovelace Foundation were the test facilities for the experiments. The majority of these experiments involved impacts to the rib cage over the lung, with a few of the shots, as in the LWL experiments, impacting on the animal's sternum with the heart as the target organ. Lethality was assessed within a 24-hour holding period.

              2)   Major Findings

Lethality from projectile-induced blunt trauma can be determined by the projectile's mass, velocity, and diameter, and the animal/human mass.

              3)   Lethality/Threshold Definitions

The probability of death was determined by the following equation:

$$P = \left\{1 + e^{\left[34.90 - 4.39\,\ln\left(\frac{MV^2}{WD}\right)\right]}\right\}^{-1}$$

P: Probability of death

M: Projectile mass (grams)

V: Projectile velocity (meters/second)

D: Projectile diameter (centimeters)

W: Animal/Human mass (kilograms)

The curve-fitting parameters were determined by the principle of least squares, and a plot of this equation is shown in Figure 9.

4) Major Data Parameters

   a) Projectile mass

   b) Projectile velocity

   c) Projectile diameter

   d) Human mass

5) Limitations

This equation applies only to blunt trauma induced in the thorax region. Further experimentation would be needed to assess lethality from blunt impacts to other body regions. In addition, the results where based on animal extrapolation.

b. Debris and Fragments Lethality Model (Reference 14)

1) Research Overview

In this model, lethality was determined by considering both the debris impact location and the impact probability of a particular body part. The debris impact location was evaluated by dividing the body into several regions (i.e., head, thorax, abdomen, limbs) and assuming that human tolerance was equivalent for all points within one region. To determine the hit probability for each body region, the projected area of each body region onto a horizontal surface for various impact angles was calculated. Basic lethalities were established by evaluating various data from leading researchers of organizations such as USARL and the Lovelace Foundation. However, the model did not provide details on the derivation of the lethalities. An overall lethality of a single piece of debris hitting the body anywhere was then established, along with lethality percentages caused by multiple debris impacts.

2) Major Findings

Percent lethality is related to the debris energy striking the target at particular body locations.

3) Lethality/Threshold Definitions

Basic lethalities due to nonpenetrating debris are determined from Figure 10. These data are substituted into the following equation for calculating single debris impacting from any angle:

$$l_i = \frac{\sum\limits_{j=1}^{9} l_{ij} A_{ij}}{\sum\limits_{j=1}^{9} A_{ij}}$$

l_i: Percent lethality of single debris

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Figure 9. Continuous Probability Plot: Lethality as a Function of MV^2/WD Dose
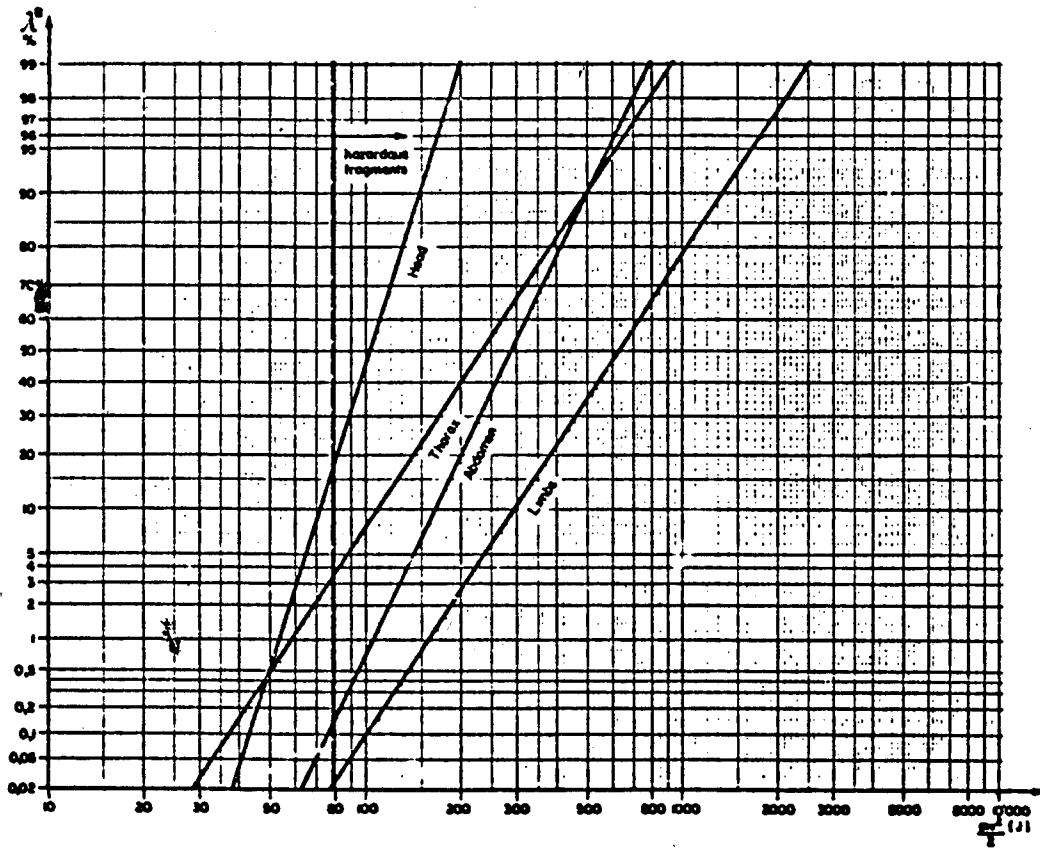
Figure 10. Basic Lethalities Due to Impacting (Non-penetrating) debris
Depending on Kinetic Energy

l_{ij}:   Percent lethality for a particular body region

A_{ij}:   Projected area of particular body region

For multiple impacting debris, the equation is:

$$1 = 1 - e^{\left\{ -d * \sum_{j=1}^{9} \left[\frac{y_i}{m_i} * \sum_{j=1}^{9} (l_{ij} * A_{ij}) \right] \right\}}$$

d: Debris mass density

y_i: Percentage of weight of debris group i

m_i: Average debris mass of group i

4)   Major Data Parameters

a)   Impact location

b)   Debris energy

5)   Limitations

Further information is needed to determine how the basic lethality percentages are calculated. The audit trail for justifying these percentages appears to be incomplete.

4.   Acceleration/Deceleration

The human tolerance data for this injury-causing mechanism has been developed primarily from experiments that examined acceleration effects on humans under various vehicle restraint systems and in the various moving vehicles (i.e. aircraft, cars, spaceships). Applicability of these data would be limited to acceleration effects that reproduce these particular conditions. In experiments that examined acceleration effects due to weapon blast, the Lovelace Foundation was a major investigating organization.

a.   Lovelace Foundation Experiments

1)   Research Overview:

The Lovelace Foundation conducted experiments to evaluate the translational effects produced by blast waves from nuclear and conventional explosions. A translation model was formulated to predict the complete time-displacement histories of objects bouncing along the ground. In its computations of acceleration, velocity, and displacement of the object, the model considers both aerodynamic drag and ground friction. Furthermore, the model was previously verified through experimentation with approximately 20,000 objects such as spheres, animals, anthropomorphic dummies, stones, concrete building blocks, window-glass fragments, and steel fragments (Reference 15). Criteria were formulated to determine the probability of serious injury (fracture or ruptured internal organ) as a function of maximum velocity, for personnel undergoing decelerative tumbling, or impact velocity for personnel at normal incidence against a nonyielding, flat surface (Reference 16).

2)   Major Findings

For a typical velocity-displacement history for a human, the maximum velocity or impact velocity could be computed. Furthermore, injury probability could be determined from these velocities based on whether the body either underwent decelerative tumbling or impacted against a nonyielding structure.

3)   Lethality/Threshold Definitions (Reference 16)

The criteria for assessing serious injury are shown in Table 4. No justification was provided for these criteria except that they agreed with results provided in Reference 17.

4)   Major Data Parameters

a)   Maximum velocity for decelerative tumbling over open terrain

b)   Impact velocity for normal incidence against a nonyielding flat surface

5)   Limitations

Some results involved extrapolating from animals to humans. In addition, the human tolerance data for blast-induced acceleration effects were sparse, particularly for the decelerative tumbling case (Reference 11).

b.   Joint Live Fire Program Acceleration Injury Criteria (Reference 18)

1)   Research Overview

These criteria were used for armored vehicle live fire tests to evaluate soldier injuries resulting from the acceleration effects due to high-intensity explosions. The human tolerance levels were based on automotive industry standards that are established experimentally.

2)   Major Findings

Human tolerance to acceleration effects is based on the magnitude of the acceleration and its duration. Automotive industry standards could be used as a criterion to assess human tolerance to acceleration effects presented by weapon detonations.

3)   Lethality/Threshold Definitions

For head injury tolerance levels, acceleration in excess of 150 g sustained for greater than 2 millisecond (msec) is expected to cause a concussion, with immediate and complete incapacitation for military tasks.

Neck shear moments of greater than 190 newton-meters (N-m) forward flexion, greater than 57 N-m rearward extension, or greater than 105 N-m lateral bending were predicted to cause immediate incapacitation. Any force to the neck greater than 1 kilonewton (kN) lasting greater than 30 msec is considered to cause immediate incapacitation.

Chest accelerations of 40 g sustained for more than 7 msec are assessed as having a high risk of thoracic trauma and are scored as completely and immediately incapacitating for military tasks.

For lower spinal injuries, forward (longitudinal) accelerations in excess of 40 g sustained for more than 7 msec or lateral or upward (vertical) accelerations in excess of 23 g lasting more than 7

TABLE 4. BIOLOGICAL CRITERIA (Reference 16)

Probability of Serious Injury, Percent	Impact Velocity, ft/sec, for Normal Incidence Against a Nonyielding, Flat Surface	Maximum Velocity, ft/sec, for Decelerative Tumbling Over Open Terrain
1	6.5 (4.5 - 8.2)	28.8 (12.7 - 37.8)
2.5	7.5 (5.4 - 9.2)	32.9 (16.7 - 41.4)
5	8.4 (6.3 - 10.1)	36.8 (21.1 - 44.8)
50	15.4 (13.5 - 17.3)	66.4 (58.2 - 82.9)
95	28.4 (24.8 - 34.7)	120 (91.8 - 268)
	$y = -2.384 + 6.211 \log x$	$y = -6.705 + 6.423 \log x$

y is the probability of injury in probit units.
x is the velocity.
95% confidence limits for the velocities are given in parentheses

msec are considered to cause immediate and complete incapacitation for military tasks. Assessment of spinal bending moments predicted lower spinal injury with forward flexion greater than 1,235 N-m, rearward extension greater than 370 N-m or lateral bending greater than 675 N-m.

Lower extremity injury predictions are based on the strength of the tibia and femur under various loading modes. Any axial compressive force greater than 1250 pounds for any length of time or 900 pounds acting for longer than 10 msec is evaluated as causing a fracture. Leg fracture predictions are assumed to affect both legs simultaneously and are, therefore, expected to cause complete and immediate incapacitation for military tasks.

4) Major Data Parameters

a) Acceleration

b) Duration

5) Limitations

Since this criterion is based on automotive industry standards, the applicability may be limited to individuals in certain body positions (i.e., seated).

5. Thermal

The primary area examined by researchers investigating thermal effects was skin burns. This was a particular concern because of the thermal radiation emission associated with nuclear weapons. Ongoing research is also examining burns to the upper respiratory tract.

a. Edgewood Arsenal Burn Study (References 11 and 13)

1) Research Overview

This study examined the impact of second and third degree burns on human functional capability. A questionnaire and interview survey of 41 surgeons or surgical residents was conducted. The survey concerned the disabling effects of burns on specified human body areas and the incapacitating effects produced by systemic responses over a selected set of postburn time intervals (i.e., 5 minutes, 30 minutes, 4 hours, 8 hours, 12 hours, 24 hours, 5 days). The specific body areas considered in the study were selected because of their criticality in effective limb functioning. These body areas were the periorbital area, elbow, hand, perineal area, knee, and ankle/foot. Disability ratings were measured in terms of none, moderate, severe, and complete. These ratings were subsequently transformed to a 0- to 100-percent scale.

The second part of the study involved determining the combat incapacitation for assault and defense roles based on these percent disability ratings. This determination is beyond the scope of the human tolerance handbook and will not be discussed in this report.

2) Major Findings

Percent disability is based upon burn severity, affected body area, and postburn time intervals.

3) Lethality/Threshold Definitions

Table 5 reproduces one of the survey outputs obtained by averaging over all the respondents. This table shows the percent disability for second-degree burns as a function of time and burn site. The issue of burn lethality was not addressed.

4)   Major Data Parameters

   a)   Burn degree

   b)   Burn site

   c)   Postburn interval

5)   Limitations

The study results relied primarily upon expert opinion to establish the connection between burns and performance. In addition, the study considered only second- and third-degree burns. The excluded burn cases were combined second- and third-degree burns, first-degree burns, and burn lethality. Furthermore, no allowance was made for individual human differences such as for various skin pigmentation types.

b.   DNA Manual (Reference 19)

  1)   Research Overview

DNA's EM-1 manual provides information on how to predict the severity of skin burns due to nuclear weapons. These predictions are based on radiant exposure in calories per square centimeter (cal/cm^2) and weapons yield in kiloton (kt). No specific references are given as to how these data are derived.

  2)   Major Findings

The severity of skin burns is based on the radiant exposure or radiant fluence at the target location, spectral distribution, and pulse intensity time history or duration. Warhead yield serves as the surrogate for pulse intensity, duration, and spectral distribution. In addition, skin pigmentation type will influence burn severity because of the different radiant absorption properties.

  3)   Lethality/Threshold Definitions

Figure 11 shows the radiant exposure required to produce skin burns for different skin pigmentation based on weapons yield.

Figure 12 indicates the unprotected skin burn probabilities for an average population based on weapon yield and radiant exposure.

  4)   Major Data Parameters

   a)   Radiant exposure

   b)   Warhead yield

   c)   Skin pigmentation

  5)   Limitations

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TABLE 5. SUMMARY OF LOCAL EFFECTS PRODUCED BY
SECOND-DEGREE BURNS (Reference 11)

SITE OF BURN	PERCENT DISABILITY ESTIMATED AT SEVEN TIME PERIODS						
	30 sec to 5 min	>5 min to 30 min	>30 min to 4 hr	>4 hr to 8 hr	>8 hr to 12 hr	>12 hr to 24 hr	>24 hr to 5 days
Periorbital Area	14	28	36	50	60	75	70
Elbow, Antecubitral Area	8	12	19	23	31	40	46
Elbow, Olecranon Area	7	13	18	20	28	36	43
Elbow, Circumferential	11	19	22	24	41	50	59
Knee, Patellar Area	8	13	18	20	28	40	45
Knee, Popliteal Area	8	15	21	23	32	45	49
Knee, Circumferential	10	19	25	27	42	53	61
Hand, Dorsal Surface	13	20	26	32	38	51	56
Hand, Volar Surface	17	33	33	40	50	63	70
Hand, Circumferential	21	41	42	54	59	70	75
Foot and Ankle (except sole of foot	13	22	29	35	43	53	58
Entire Foot and Ankle	20	33	43	46	54	66	76
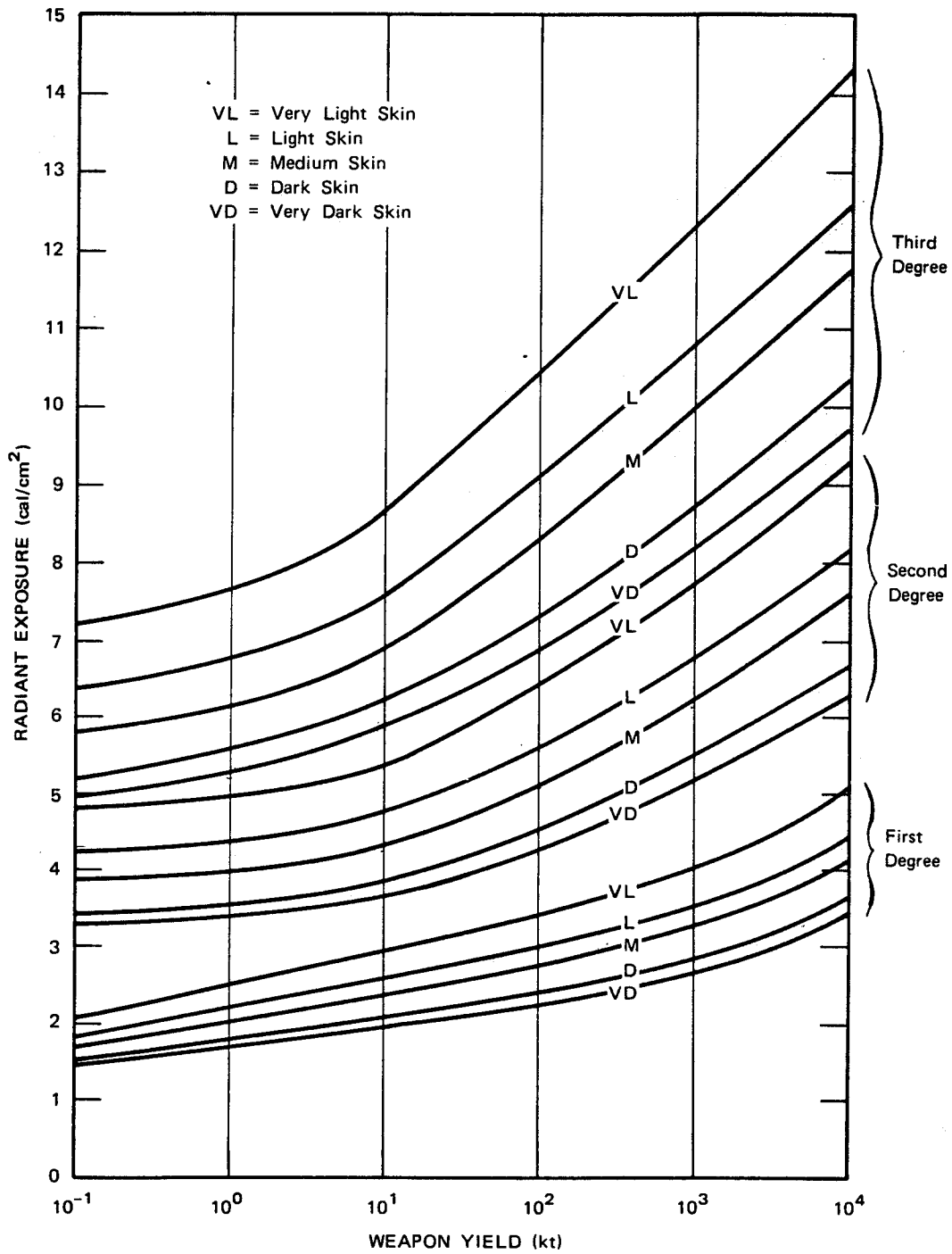
Figure 11. Radiant Exposure Required to Produce Skin Burns for
Different Skin Pigmentation (Reference 19)
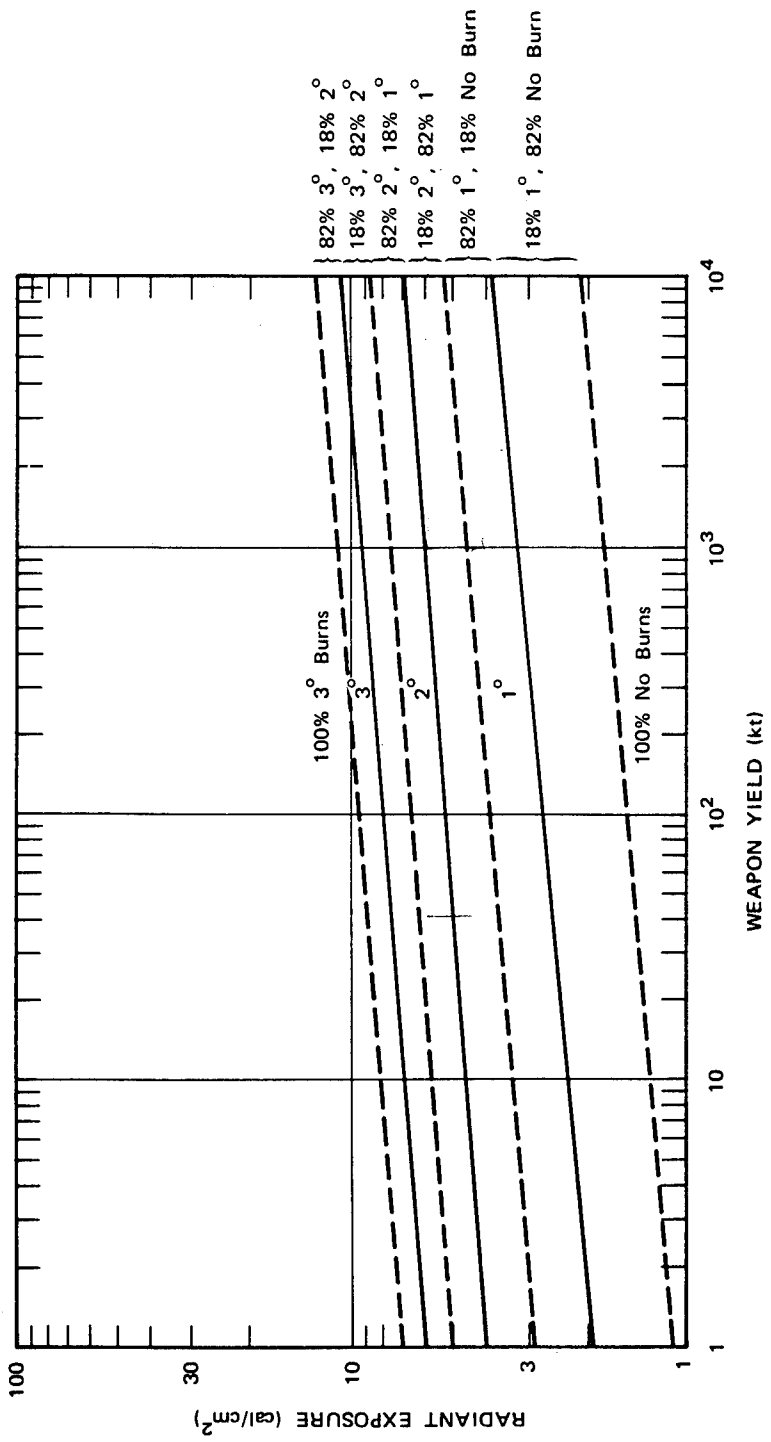
Figure 12. Skin Burn Probabilities for an Average Population Taking No Evasive Action (Reference 19)

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Data were provided only for the population probabilities for various burn degrees. Percentages of the human body burned and combination burns effects were not included in the results. In addition, the audit trail for these results was incomplete.

      c.   Harry Diamond Laboratories (HDL) Skin Simulant Study (Reference 11)

          1)   Research Overview

HDL at the White Sands Solar Facility experimented with simulant human skin to determine the incidence of skin burns under various uniform combinations.

          2)   Major Findings

The major finding of this study was that the thermal fluence criterion for burns under typical combat clothing protection is independent of warhead yield. Warhead yield would not be a factor as in the case of bare skin (Reference 19).

          3)   Lethality/Threshold Definitions

Table 6 indicates for various uniform combinations, the fluence required for first- and second-degree burns based on burn incidence and uniform type.

          4)   Major Data Parameters

          a)   Thermal fluence

          b)   Uniform type

          5)   Limitations

The results are applicable to only three uniform cases: battle dress uniform (BDU) over T-shirt; battle dress overgarment (BDO), a chemical protection uniform; and BDO over BDU/T-shirt. Also, the study did not test the effect of clothing color on burn severity or the effect of clothing ignition on burn severity.

      d.   U.S. Army Nuclear and Chemical Agency (USANCA) Geometric Skin Model

          1)   Research Overview

USANCA constructed a simplified model of a cylindrical man to roughly estimate the percent body area burned by thermal radiation. The model assumptions are:

          a)   Thermal radiation arrives along a fixed direction of propagation.

          b)   The shape of the target man is a cylinder, with its axis normal to the direction of propagation. The cylinder does not rotate or change orientation during this exposure.

          c)   The cylindrical man is uniformly clothed.

          2)   Major Findings

The percent body area burned is a function of thermal fluence and depends on the specific clothing configuration.

          3)   Lethality/Threshold Definitions

The fraction, Fi, of total skin area receiving a ith degree burn is given by:

TABLE 6. FLUENCE REQUIRED FOR INCIDENCE OF SKIN BURNS
UNDER VARIOUS UNIFORM COMBINATIONS (Reference 11)

UNIFORM	FLUENCE (cal/cm^2) FOR FIRST-DEGREE BURN INCIDENCE OF		FLUENCE (cal/cm^2) FOR SECOND-DEGREE BURN INCIDENCE OF	
	2.5-PERCENT	5-PERCENT	5-PERCENT	50-PERCENT
BDU/T-Shirt	3.3	3.5	5.1	7.1
BDU/T-Shirt with Spacer	7.0	7.6	10.9	15
Chemical Protection Uniform (BDO)	4.6	5.0	7.3	10
BDO with Spacer	7.4	8.1	11.7	16
BDO/BDU/T-Shirt	14.4	15.6	22.6	31
BDO/BDU/T-Shirt with Spacer	22.3	24.2	35.0	48

$$Fi = \frac{\cos^{-1}\frac{Qi}{Q}}{p}$$

or

$$Fi = 0 \qquad \text{if } Q < Qi$$

Q: Thermal fluence (cal/cm^2) at target location on an area normal to the direction of propagation

Qi: The deterministic thermal fluence (cal/cm^2) criterion for i^{th} degree burn

4)   Major Data Parameters

a)   Thermal fluence

b)   Thermal fluence criterion for i^{th} degree burn

c)   Clothing configuration

5)   Limitations

The model does not address clothing ignition, which would cause greater areas of skin to burn.

e.   Walter Reed Army Institute of Research (WRAIR) Medical Evaluation of Nonfragment Injury Effects in Armored Vehicle Live Fire Tests - Instrumentation Requirements and Injury Criteria.

1.   Research Overview

WRAIR developed this document to provide an injury determination standard for the Live Fire Test Program. The portion of the document that is most pertinent to the subject of thermal is intitled Thermal Injury criteria.

2.   Major Findings.

The major findings of the thermal casualty portion of the study included a determination that the thermal environment in the first 10 seconds after the initial penetration of a vehicle is critical to the risk of developing thermal injury and that the best measurable environmental correlate of burn potential is heat flux calorimetry. It was also found that burn criteria using free air temperature correlate loosely with heat flux criteria.

3.   Lethality/Threshold Definitions

Thermal energy of 3.9 cal/cm^2 delivered over a few seconds to unprotected skin will cause second degree burns.

Free air temperatures and exposure times are related to second degree burn predictions for exposed bare skin by using the time integral of measured air temperature (T_m) less body temperature according to the following equation:

$$T_i = \int_0^t (T_m - 37)\, dt \quad \text{(in degrees Centigrade)}$$

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Second degree burns to bare skins are predicted if the integral of temperature over 10 seconds exceeds 1315 °C-sec (2400 °F-sec). Since convective and conductive heat transfer are nearly linearly correlated with free air temperature, the temperature-time integral should also be linearly related to the measured heat flux.

4.   Major Data Parameters

a)   Thermal Energy (cal/cm^2)

b)   Air Temperature (as function of time).

5.   Limitations

The analysis focused on the thermal environment inside an armored vehicle after penetration of the hull by some kind of munition and does not seek to produce criteria for the full range of potential thermal exposure environments.

6.   Toxic Agents

Research conducted on weapons toxification effects focused on chemical agents, particularly nerve agents. The basic methodology used appeared to be consistent throughout the various research organizations and is outlined below.

a.   Research Overview

The mathematical tool frequently used in modeling the effects of toxic chemical agents is the log-probit model. The entire dose-response relationship is characterized by the lethal or incapacitating median effective dose and the probit slope, which are both determined through experimentation. Experimentation depends primarily on live animal testing and on carefully controlled low-dose experiments with live humans. Use of the available high-dose human data (from World War I, accidents, etc.) was limited because the actual doses or dosages were often unknown. To obtain estimates for humans at high dose levels, it was necessary to extrapolate results from animals to humans by body weight and from low dose to high dose regimes for humans. In addition, extrapolations were employed for various routes-of-entry and from agent to agent. The majority of the tests on chemical agents appeared to be for nerve agents GB and VX. GB is a high-volatility nerve agent designed to attack the body through inhalation. VX is a low-volatility nerve agents which attack the body via a percutaneous route.

b.   Major Findings

For inhalation exposure, dosage is a function of breathing volume rate, agent concentration, exposure time, and retention ratio. For percutaneous exposure, dosage is a function of skin penetration and agent concentration.

c.   Lethality/Threshold Definitions

The log-probit model for modeling the effects of chemical agents is:

$$P = F \left[s^{-1} \log \frac{D}{ED_{50}} \right]$$

D: dose level (mg) or Haber product C_t (mg-min/m3) for inhalation exposure

E: refers to an effect of interest (E=L lethality or E=I incapacitation)

P: the proportion of the population in which effect E appears

ED_{50}: the median dose (mg) (LD_{50}, ID_{50})

F: cumulative distribution function (cdf) of the normal distribution with mean = 0, standard deviation = 1.

s: curve probit slope

In the case of exposure to inhalation agents, humans or animals do not receive the entire dose at once, but receive it by breathing an agent over time. The Haber product C_t (concentration multiplied by exposure time) is:

$$C_t = \frac{D}{RV} * 1000 \frac{mg-min}{M^3}$$

D: Dose (mg)

R: Retention ratio

V: Breathing volume rate (liters/min)

Values of LC_{t50} and IC_{t50} for two exposure times due to GB agent inhalation are provided in Table 7. These values were based upon CWL experiments using the assumption of R = 1 and V = 10 liters/min. Symptoms associated with the varying levels of incapacitation are listed in Table 8. Given LC_{t50} and IC_{t50} and a probit slope of 0.137 for GB nerve agent inhalation, dose-response curves can be determined as illustrated in Figure 13. This figure presents curves for exposure times for two minutes and less. For exposure times greater than 2 minutes, a scaling relationship was used:

$$\log LC_{t50} = 0.274 \log t + 1.918$$

The median effective dosage values for VX by inhalation exposure were determined based on experimental evidence that VX is approximately twice as toxic as GB for both intravenous and inhalation routes of entry. Based on this result, LC_{t50} and IC_{t50} were identified as 50 and 25 mg-min/m^3, respectively.

In the case of percutaneous exposure, most studies examined VX in liquid form. The results were based on low-dose human skin tests using live volunteers and on animal testing. These studies led to the current whole-body LD_{50} estimate of 10 mg and ID_{50} = 50 percent of LD_{50}.

TABLE 7. VALUES OF LC_{t50} AND IC_{t50} FOR TWO EXPOSURE TIMES, INHALATION OF GB* (Reference 11)

EFFECTS LEVEL	DOSAGE, mg-min/m^3	
	2 min	10 min
DEATH (LC_{t50})	100	156
VERY SEVERE	70	109
SEVERE	55	85
MODERATE	40	62
MILD	15	23

INCAPACITATION IC_{t50}

* Breathing Volume Rate = 10ℓ/min

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TABLE 8. VARIOUS DEGREES OF INCAPACITATION IN MAN RESULTING FROM GB EXPOSURE
(REFERENCE 11)

MINIMAL (Minimal symptomatic exposure)	a.	EYE (24 hours) -- Some miosis, peripheral field dimness, retrobulbar pressure, and heaviness
	b.	RESPIRATORY SYSTEM (4-8 hours) -- Slight chest tightness, nasal discharge, and hyperemia
MILD (Mild symptomatic exposure)	a.	EYE -- Extreme miosis (3-14 days), aching in and behind eyes from ciliary spasm (worse in bright light or when attempting to focus), headache, twitching eyelids, and difficulty in accommodation (2-5 days)
	b.	RESPIRATORY SYSTEM -- More chest tightness, rhinorrhea (24 hours), and cough (1-2 days)
MODERATE (Mild systemic exposure)	a.	RESPIRATORY SYSTEM -- Moderate chest tightness, bronchial secretion, expiratory wheeze, cough, rhinorrhea, and salivation EYE -- Maximal miosis, etc., as above GASTROINTESTINAL TRACT -- Anorexia, nausea, and heartburn
	b.	NEUROMUSCULAR SYSTEM -- Easy fatigue, slight weakness (especially with exertion), muscle fasciculation, and twitching
	c.	CENTRAL NERVOUS SYSTEM -- Excess dreaming, insomnia (partly from eye pain), and anxiety
SEVERE (Moderate systemic exposure)	a.	EYE -- Same as moderate RESPIRATORY SYSTEM -- Severe chest tightness, lower sternal pain, etc. GASTROINTESTINAL TRACT -- Vomiting, cramps, diarrhea, and heartburn URINARY SYSTEM -- Frequent urination
	b.	NEUROMUSCULAR SYSTEM -- Muscular weakness, tremors, and dyspnea
	c.	CENTRAL NERVOUS SYSTEM -- Same as moderate plus jitteriness, emotional lability, giddiness, headache, memory impairment, slow recall, slow reaction, and ataxia
VERY SEVERE		CENTRAL NERVOUS SYSTEM -- The principal effects are convulsions, collapse, and paralysis
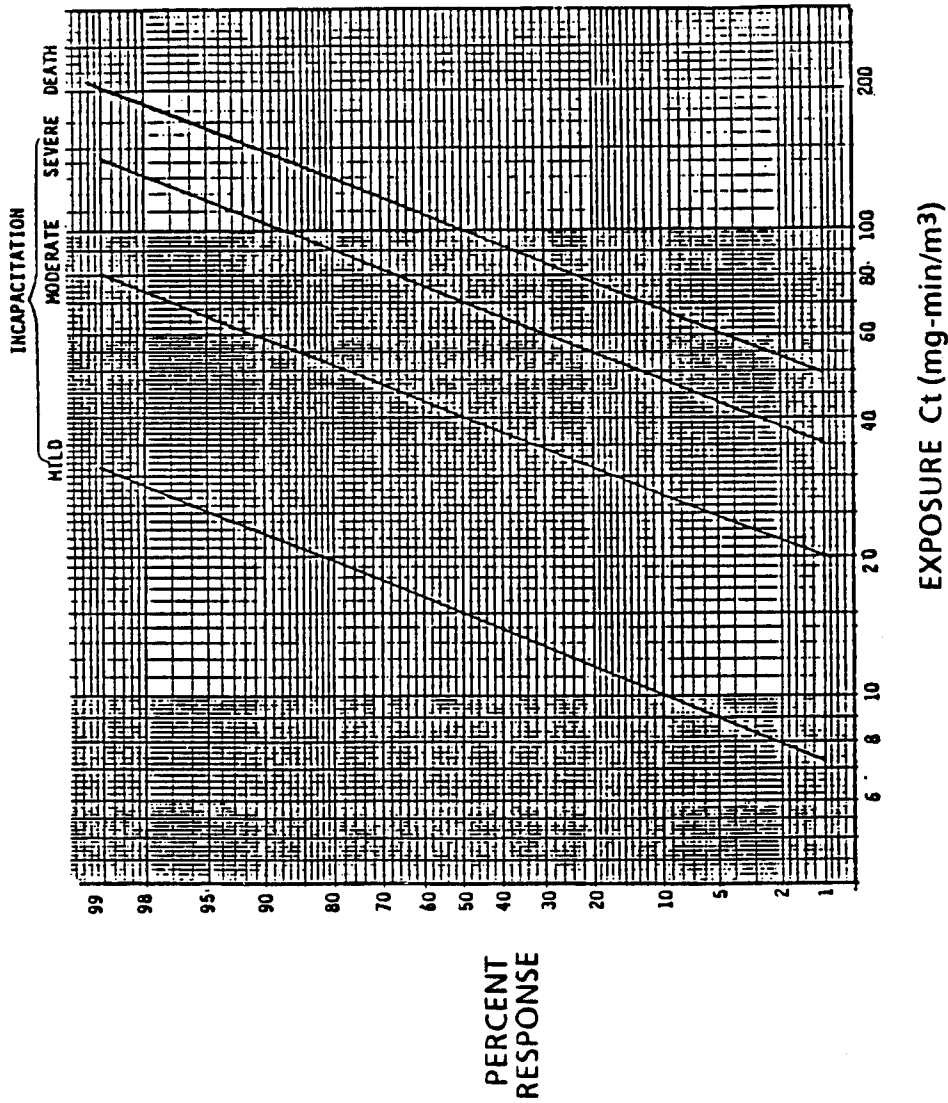
Figure 13. Dose-Response Curves for Inhalation of GB Vapor
(Reference 11)

Table 9 indicates various penetration factors. These factors would be used to assess human tolerance based on chemical protection gear worn. Lethal and incapacitation doses would be divided by these factors to determine dose levels under protection.

    d.   Major Data Parameters

        1)   Dose

        2)   Exposure Time

        3)   Type of Agent

        4)   Mission Oriented Protective Posture (MOPP) level

        5)   Post-exposure Time

    e.   Limitations

In cases where animal testing was conducted, extrapolation to humans was necessary. Furthermore, human judgement was used in relating symptoms exhibited in animals to incapacitation effects in humans. In some cases, audit trails leading to extrapolations for various chemicals were incomplete or inconsistent. The scaling relationship for LC_{t50} (i.e., log LC_{t50} = 0.274 log t + 1.918) requires further analysis because it is incompatible with the treatment of toxicity as measured by the Haber product (C_t) alone. For example, C = 50 mg/m3 for 2 minutes (C_t = 100 mg-min/m3) would lead automatically to C = 10 mg/m3 for 10 minutes. But the above scaling relationship shows that C = 15.6 mg/m3 for 10 minutes is necessary to achieve the same lethality. Detoxification by normal body processes is, of course, a possible explanation.

C.   SUMMARY

It is apparent that there is a diverse community of researchers who have worked for many years to study the effects of wartime threats to the human body. There exist a number of standard or accepted methods for evaluating the effects of single injury-causing mechanisms. There are a number of summary reports or databases for each mechanism. In most cases, the principal investigators or other knowledgeable experts are available to interpret the data and provide background information on the experiments conducted to produce the data. To accomplish the human injury information system development, little basic research would be required.

This diverse research, however, was generally intended to answer specific users' needs, usually to assess personnel incapacitation or mission degradation during wartime. This research did not focus on the pathological conditions. As a result, standard definitions or common classifications of wounds have not been established. Even among the various research, efforts studying one injury-causing mechanism, there are similar methods but subtle differences in format, purpose, and definitions. These differences will require some resolution effort before the results of the separate studies can be pooled into cohesive system segments.

TABLE 9. SOVIET TACTICAL CHEMICAL STUDY, VOLUME II (STACS-II)
PENETRATION FACTORS

ROUTE-OF-ENTRY	MOPP LEVEL				
	0	1	2	3	4
Eyes	1.	1.	1.	0.	0.
Inhalation	1.	1.	1.	0.	0.
Percutaneous Vapor	1.	0.120	0.120	0.070	0.
Percutaneous Liquid	0.095	0.095	0.095	0.025	0.

TABLE OF MISSION-ORIENTED PROTECTIVE POSTURES

MOPP LEVEL	DESCRIPTION
0	Baseline Clothing Posture with Fatigues Alone
1	Overgarment
2	Overgarment and Overboots
3	Overgarment, Overboots, and Mask with Hood
4	Overgarment, Overboots, Mask with Hood, and Gloves

SOURCE: (U) Soviet Tactical Chemical Study, (STACS-II), Volume II, 1 October 1983,
ATC-PD-1620-027-83

SECTION IV

CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The concept of developing a Human Injury Informtion System (HIIS) is feasible. The HIIS concept proposed here provides a robust approach to standardize data and methodologies for use in assessing the near-term effects of short-term exposure of a standard individual to various wartime hazards. Development of the HIIS provides needed data for casualty estimation tools, such as the THREAT System. The high-fidelity THREAT System Facility Model provides detailed descriptions of the structural damage and interior (or free field) hazards to which USAF personnel are subjected during wartime. Its accuracy can be greatly enhanced by expanding the data which support the relationships between these hazards and human injury through a realized HIIS. Similar considerations apply to models which evaluate injuries to personnel operating in other environments.

The preliminary assessment of the state of human vulnerability research suggests that there are numerous evaluation methods and data sources available for the injury-causing mechanisms of greatest interest. For each individual injury-causing mechanism, there are existing databases or data summaries and, frequently, an accepted methodology for assessing exposure effects. The separate research efforts, however, do not share standard definitions, formats, or wound classifications, as each study was undertaken to answer specific user questions. To maximize the potential benefit from these past studies and to direct future research priorities toward filling human injury data gaps, developers of the human injury information system should approach the undertaking in a systematic manner. The approach proposed in this development plan attempts to provide such a framework and minimize the risks associated with pooling large amounts of similar but different data from independently-conducted studies.

B. RECOMMENDATIONS

1.   The Human Injury Information System should be developed as a Joint Service product to provide a broader base of development resources. The additional resources can be used either to deepen the scope of data and algorithms, or accelerate its complete development.

2.   Specific user needs and a system specification should be developed.

3.   Each segment of the system should be developed as a separate entity which conforms to the standards established for the overall system.

4.   A lead agency should be designated for development, coordination and integration of the overall Human Injury Information System so that it has common assumptions and is internally consistent.

5.   A lead agency should be designated to develop the technical content of each individual segment of the system.

LIST OF REFERENCES

1. Fertal, M. J., <u>THREAT System Unprotected Facility Model, Version 1.00 (TH/UFM/1,00)</u>, HSD-TR-90-043, Operational Analysis Systems Division, Human Systems Division, Brooks Air Force Base, Texas, March 1991.

2. Fertal, M. J., <u>THREAT System Protected Facility Model of the NATO Semihardened Structure, Version 1.00 (TH/PFM-NATO/1,00), Technical Reference Manual</u>, Operational Analysis Systems Division, Human Systems Division, Brooks Air Force Base, Texas, October 1991.

3. Fertal, M. J., <u>THREAT System Protected Facility Model of the Survivable Collective Protective System, Version 1.00 (TH/PFM-SCPS/1,00), Vol II of III, Technical Reference Manual</u>, Operational Analysis Systems Division, Human Systems Division, Brooks Air Force Base, Texas, October 1991.

4. Richmond, D. R., J. T. Yelverton, W. Hicks, and Y. Y. Phillips, <u>Biological Effects of Complex Blast Waves from Explosions inside an Enclosure,</u> Los Alamos National Laboratory and Walter Reed Army Institute of Research, February 1987.

5. Dodd, K. T., G. R. Ripple, and T. G. Mundie, <u>Current Injury Assessment Techniques for Complex Waves</u>, Walter Reed Army Institute of Research.

6. <u>Deployable Medical System (DEPMEDS) Listing</u>, Materiel Assemblage Design and Development Branch, U.S. Army Academy of Health Sciences, Ft. Sam Houston, Texas, February 2, 1989.

7. Richmond, D. R., J. T. Yelverton and E. R. Fletcher, "New Airblast Criteria for Man", <u>Twenty-Second Explosives Safety Seminar: Vol.1</u>, August 1986.

8. Bowen, L. G., E. R. Fletcher and D. R. Richmond, <u>Estimate of Man's Tolerance to the Direct Effects of Air Blast</u>, DASA-2113, October 1968.

9. Berkowitz, Raymond S., <u>A Procedure for Computing Expectation and Variability of Casualties Achievable by an Attack with Airborne Agents</u>, DA-18-064-AMC-2757A, June 1967. (UNCLASSIFIED)

10. Hirsch, F. G., "Effects of Overpressure on the Ear - A Review", <u>Annals of the New York Academy of Science, Volume 152</u>, 1968.

11. Analysis and Simulation, Inc., <u>Lethality and Vulnerability Analysis (LAVA)</u> (U), 31 August 1988. (SECRET)

12. Joint Technical Coordinating Group on Munitions Effectiveness, <u>Target Vulnerability</u> (U), G1A1-3-1, 16 April 1990. (SECRET/NOFORN/WNINTEL)

LIST OF REFERENCES
(Concluded)

13. Edgewood Arsenal, <u>Handbook of Human Vulnerability Criteria</u> (U), EB-SP-76011, May 1976. (CONFIDENTIAL)

14. Janser, P. W., <u>Lethality of Unprotected Persons Due to Debris and Fragments</u>, August 1982

15. Fletcher, E. R. and I. G. Bowen, "Blast-Induced Translational Effects", <u>Annals of the New York Academy of Science</u>.

16. Lovelace Foundation for Medical Education and Research, <u>Probability from Airblast as a Function of Yield and Range</u>, DNA 3779T, October 1975.

17. Hirsch, F. G., "The Tolerance of Man to Impact", <u>Annals of the New York Academy of Science, Volume 152</u>, October 28, 1968.

18. Ripple, G. R. and T. G. Mundie, <u>Medical Evaluation of Nonfragment Injury Effects in Armored Vehicle Live Fire Test</u>, Walter Reed Army Institute of Research.

19. Defense Nuclear Agency, <u>Capabilities of Nuclear Weapons, Parts I and II</u> (U), DNA-EM-1, July 1972. (SECRET/RESTRICTED DATA)

20. Anno, G. H., M. A. Dore and D. B. Wilson, <u>Acute Radiation Effects on Crew Member Performance</u>, DNA-TR-85-52, August 1984.

21. Anno, G. H. and M. A. Dore, <u>Effects of Ionizing Radiation on the Performance of Selected Tactical Combat Crews</u>, 1989.

APPENDIX A

SAMPLE SYSTEM SEGMENT (OVERPRESSURE)

SAMPLE SYSTEM SEGMENT (OVERPRESSURE)

A.   PURPOSE

The overpressure sample segment illustrates the application of the human injury information system development methodology and explores the feasibility of the proposed concept. This appendix contains the sample segment on overpressure effects along with a description of the methodology used in its development.

B.   BACKGROUND

The human injury information system provides a common database of standard human reactions to various hazardous conditions (insults) found in the wartime environment. The system includes probabilities and descriptions of pathological/clinical conditions (i.e. injuries) based upon immediate effects of short-term exposures. With this information, a user could conduct various analyses, including wartime casualty estimation, crew incapacitation assessment, or mission effectiveness modeling.

The data for the system are derived from pooling results from key investigators in the various areas of human injury research. The system consists of separate segments with data on effects from each injury-causing mechanism (insult) (listed in Table A-1) and a segment on the methodology for assessing effects from multiple mechanisms.

C. METHODOLOGY

1.   General. Each segment will be developed using the approach depicted in Figure A-1.

2.   Step 1: Identify Physical Parameters Which Predict Injury

Researchers survey available relevant data on the injury-causing mechanism (insult) to identify the physical parameters which predict injury upon exposure. For overpressure, the physical parameters were identified as being the peak positive pressure (P) and the duration of the positive pulse (t).

3.   Step 2. Build A Table of the Catagories of Injuries Caused by the Insult

An expert working group consisting of the individuals listed in Table A-2 was convened in September 1991 to develop a table of injuries caused by free field blast overpressures.

The working group reviewed summary data on overpressure injuries (rather than the full set of raw experimental results), explored the feasibility of the proposed methodology, refined the concept of the human injury information system development approach, and identified technical issues which must be resolved in developing human injury information system segments.

The summary data used to develop this sample chapter resulted from years of research by the Lovelace Foundation for Medical Research and Education. Dr. Donald Richmond, a principal investigator for much of the experimentation, assisted the working group in interpreting the summary data. Based on Dr. Richmond's direction, the working group identified the four major classes of injury that are caused by blast overpressure as being; lung, gastrointestinal tract, upper airway, and auditory (ear) injuries. For each class of injury the working group defined pathological conditions of progressively increasing severity. The resultant injury tables are

TABLE A-1. HUMAN TOLERANCE HANDBOOK CHAPTERS
ON INJURY-CAUSING MECHANISMS

- Overpressure

- Penetration

- Acceleration

- Blunt Impact

- Thermal Radiation

- Toxic Agents

- Ionizing Radiation

```
        ┌─────────────────────────┐
        │      Characterize        │
        │   Physical Parameters    │
        │          Which           │
        │      Predict Injury      │
        └─────────────────────────┘
                    │
                    ▼
        ┌─────────────────────────┐
        │   Build Table of Wounds  │
        │      Caused by the       │
        │        Mechanism         │
        └─────────────────────────┘
                    │
                    ▼
   ┌───────────────────────────────────┐
   │  As Function of the Physical Parameters,  │
   │  Determine Probabilities of Occurrence    │
   │      for Each Wound in Table              │
   └───────────────────────────────────┘
                    │
                    ▼
   ┌───────────────────────────────────┐
   │   Calculate Probability of Occurrence     │
   │     for Each Collection of Wounds         │
   └───────────────────────────────────┘
                    │
                    ▼
```

OUTPUT USED BY OTHER ANALYSES:

- Casualty Determination
- Medical Workload
- Incapacitation

Figure A-1. Methodology for Developing Human Tolerance Handbook Chapters

TABLE A-2. WORKING GROUP MEMBERS OVERPRESSURE CHAPTER

WORKING GROUP MEMBERS

NAME	PANEL FUNCTION
HSD/YAO	
Maj. Russell J. Meiling	Panel Chairman
	THREAT Program Manager
Mr. Jack Wilson	HSD/YAO Technical Director
USAF/SGHR	
Maj. Steven P. Hellmann	Surgeon General Representative
BDM International	
Dr. James M. Whitehead	BDM Technical Director for THREAT
	THREAT Casualty Estimation
	Methodology
Ms. Elizabeth A. Godfrey	Sample Chapter Development
Ms. Paula A. Sydenstricker	Sample Chapter Development
Consultant	
Overpressure Researcher	
Dr. Donald R. Richmond	Lovelace Foundation Survival Curves
Biodynamic Research Corp.	
Dr. James H. Raddin*	Physician-Engineer
Dr. Whit McConnell	Physician-Engineer
USAF Medical Center	
Maj. Ken Kaylor	Military Medicine
Maj. Richard Roetger	Military Medicine
Maj. Dave Kissinger	Military Medicine
Maj. Jay Johanigman	Military Medicine

* REVIEWER

presented in Tables A-3 through A-6. The remainder of this section provides a further description of the blast overpressure injuries.

It should be noted that the blast overpressure segment refers to the injuries caused by exposure at standard ambient pressure (14.7 psi). The overpressure environment considered is that of a single shock wave front, characterized by an instantaneous rise and an exponential decay.

Primary blast injuries most often are accompanied with other forms of wounds resulting from other injury-causing mechanisms. However, there have been occasions where soldiers died in battles without visible external signs of injuries except for the bloody froth around the nose and mouth, associated with overpressure injuries. Primary blast injuries affect the hollow or gas-containing organs of the body (Reference 1). These organs are the lungs, the GI tract, upper airways, and the auditory system. Generally, casualties suffering overpressure effects exhibit respiratory distress, rapid shallow breathing, or slow labored breathing with difficulty in exhalation. In addition, they may be bleeding from the ears, the nose and mouth or may have bloody froth around the nose and mouth. If conscious, they may complain of tightness or pain in the chest, and may be clutching their abdomen. Furthermore, they may have no equilibrium or sense of direction, and may be convulsive. At a minimum, all overpressure causalities will be dazed and confused immediately following exposure (Reference 1).

The survival time for humans or animals exposed to a lethal dose of overpressure is short. In fact, the majority die within one hour after exposure from air embolism. The delayed deaths, typically within a few hours after exposure, are probably caused by suffocation from blood and fluids obstructing the airways and from intra-abdominal hemorrhaging. For GI tract injuries, the mortality rate is high within the first week following injury (Reference 1).

For use in developing the human injury information system methodology for overpressure injuries, a grading scheme similar to the one in use at Walter Reed Army Institute of Research (WRAIR) was incorporated using data provided by Dr. Richmond. This grading scheme categorizes primary blast injuries in terms of both pathological and clinical signs. The reader is cautioned that these injury levels are not equivalent between organs, nor do they infer dependence of injuries for one organ to another. For example, the fact that an injury to the gastrointestinal tract has been categorized as "severe" does not provide any information on whether the lungs have been spared or damaged. Furthermore, a "moderate" airway injury does not equate to a "moderate" lung injury.

The following sections describe the pathological and clinical signs associated with overpressure injuries to the lungs, GI tract, upper airway, and auditory system. A glossary of medical terms is included as Annex 4.

a.   Lung Injury

Observable overpressure damage to the lungs is hemorrhagic in nature. Damage may range from a few pin-head size hemorrhages (petechia) to confluent hemorrhages involving entire lobes. An illustration of typical lung hemorrhages is shown in Figure A-2. Five levels describe lung injury. In addition, since lung injury resulting in air embolism is the primary cause of death for overpressure casualities, a sixth level, lethal,

SOME CLINICAL SIGNS ASSOCIATED WITH LUNG INJURY LEVELS

Injury Levels	Pathological Signs	Clinical Signs
1 Trivial	Petchial hemorrhage	No Signs
2 Slight	Ecchymotic areas	Some shortness of breath
3 Moderate	Small isolated confluent hemorrhage, <30% of areas	Dyspnea; tachypnea, tachycardia and pain in chest; hypotension and some hemoptysis
4 Severe	Large confluent hemorrhage, 30-60% areas extending deep into the parenchyma	Air hunger, hemoptysis; tachypnea, tachycardia, and pain in chest; hypotension
5 Very Severe	Entire lobes with confluent hemorrhage, 60% of areas	Struggle to breathe, hemoptysis, leading to bradycardia, bradypnea, and cyanosis; livedo reticularis
6 Lethal	Massive arterial air embolism, disruption of lung alveoli with alveolarvenous fixtalae	Death

SOME CLINICAL SIGNS ASSOCIATED WITH
GI-TRACT INJURY LEVELS

Injury Levels	Pathological Signs	Clinical Signs
1 Trivial	Petechia or small area of discoloration	No signs
2 Slight	Small areas of light subserosal contusions	No signs
3 Moderate	Small area of submucosal contusions with little or no disruption of mucosal layer	Some abdominal pain possible
4 Severe	Large areas of submucosal contusions with disruption of mucosal membrane and bleeding extending into bowel lumen	Abdominal pain, involuntary guarding, and rebound tenderness; nausea and vomiting; tenesmus and gastrointestinal bleeding possible
5 Very Severe	Disruption of mucosal layer with hemorrhage into lumen or perforation into abdominal cavity and rupture of solid organs	Abdominal pain, involuntary guarding, and rebound tenderness; nausea and vomiting; tenesmus and gastrointestinal bleeding; hypotension; and syncope

TABLE A-5. INJURY LEVELS SELECTED FOR THE UPPER AIRWAYS

SOME CLINICAL SIGNS ASSOCIATED WITH UPPER AIRWAY INJURY LEVELS

Injury Levels	Pathological Signs	Clinical Signs
1 Trivial	Few submucosal petechiae	No signs
2 Slight	Petechiae and mild ecchymoses	No signs
3 Moderate	Mild submucosal contusions, non-elevated	Possible slight pain
4 Severe	Scattered areas of larger submucosal contusions, non-elevated	Slight Pain
5 Very severe	Confluent submucosal hemorrhage and hematomas that elevate the mucosal lining and reduce the cross sectional area of the airway	Pain and difficulty in breathing and swelling

TABLE A-6. INJURY LEVELS SELECTED FOR EAR DRUM RUPTURE

SOME CLINICAL SIGNS ASSOCIATED WITH EAR DRUM RUPTURE LEVELS

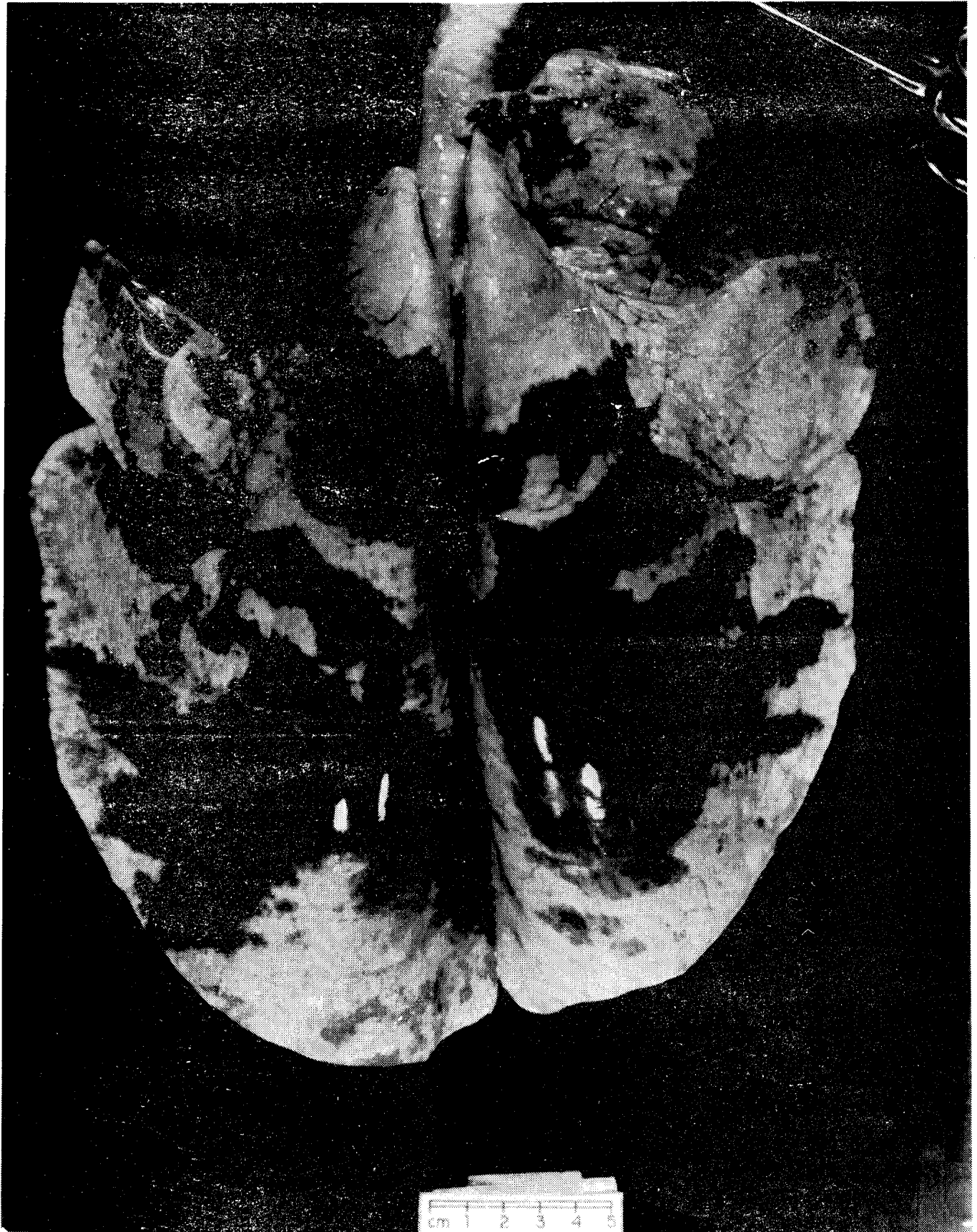| Injury Levels	Pathological Signs	Clinical Signs
Minor rupture	Minor slits and linear disruption of drum fibers	Transient tinnitus; 0-15 dB acute conductive hearing loss
Moderate rupture	Large tears or multiple small perforations	Tinnitus, pain; 10-40 dB acute conductive hearing loss
Major rupture	Total disruption of drum	Tinnitus, pain; 30-70 dB acute conductive hearing loss; disorientation

Figure A-2. Picture of Lung Hemorrhages

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was included. Table A-3 defines these injury level descriptors along with associated pathological and clinical signs.

Level 1 - Trivial

Casualties may provide no external clues to the extent of hemorrhagic damage. A stethoscope may confirm some localized rales.

Level 2 - Slight

Casualties may experience some shortness of breath. Ecchymotic (small light spots) areas on the surface of lungs (confluence of petechia) may be seen in a chest x-ray.

Level 3 - Moderate

Casualties may be obtunded or unconscious. Shortness of breath is evident, accompanied by increase in both respiratory and heart rates. In addition, there will be a marked decrease in blood pressure and some blood-stained sputum. Casualties may complain of chest pain and dyspnea.

Level 4 - Severe

Casualties will likely be unconscious, gasping for air, and coughing up blood. Their respiratory and heart rates will increase while blood pressure will decrease. Hemorrhages may involve entire lobes of the lungs, extending deep into the parenchyma and the surrounding bronchial tree.

Level 5 - Very Severe

Casualties may be unconscious, struggling to breath, and/or coughing up blood. Respiratory and heart rates will be significantly decreased. In addition, the casualty's skin may appear cyanotic or show signs of livedo reticularis. Chest x-ray may reveal entire lobes are confluently hemorrhagic.

Level 6 - Lethal

As the small air sacs (alveoli) closely surrounded by blood vessels are disrupted, air will enter the vascular system and travel throughout the body. Air embolism occurs when circulation is blocked by trapped air. Figure A-3 shows air trapped in the coronary arteries. Air embolism to the heart or brain is the major cause of deaths from blast (Reference 1). In fact, during animal tests, deaths which occurred within one hour from exposure to overpressure were due to air embolism. Air emboli were not found in surviving animals.

b.   GI Tract Injury

GI tract injuries are usually limited to those regions which contain large amounts of gas. However, overpressure injuries may occur throughout the GI tract. In severe cases, injuries may involve the liver, spleen, and kidneys, which are in close contact with the gas-containing regions of the stomach and large intestine (Reference 1).

GI tract damage ranges from light subserosal contusions to rupture of solid organs. Rupture can cause the GI tract's contents to spill into the abdominal cavity resulting in peritonitis. Figure A-4 shows an example of a typical GI tract injury. Table A-4 presents the pathological and clinical signs for the five injury levels used in the casualty estimation methodology.

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Figure A-3.   Picture of Air Embolism of the Coronory Arteries

Figure A-4. Picture of Gastrointestinal Tract Hemorrhages

Level 1 - Trivial

Casualties exhibit no outward signs of discomfort.

Level 2 - Slight

Casualties exhibit no outward signs of discomfort. Direct examination may show small areas of light subserosal contusions.

Level 3 - Moderate

Casualties may complain of some abdominal pain. Examination and x-ray may indicate submucosal contusions with hemorrhage into the lumen.

Level 4 - Severe

If conscious, casualties will likely complain of abdominal pain and involuntarily guard their abdomen. In addition, they may experience nausea, vomiting, or gastrointestinal bleeding. Examination and x-ray may show large areas of submucosal contusions with disruption of mucosal membrane and bleeding or blood clots extending into the bowel lumen.

Level 5 - Very Severe

Casualties may be unconscious. If not, they may complain of abdominal pain and involuntarily guard their abdomen. They will likely experience nausea, vomiting, and gastrointestinal bleeding. Examination and x-ray will show disruption of mucosal layer with hemorrhage into the lumen and/or perforation into the abdominal cavity and rupture of solid organs.

c.   Upper Airways Injury

Although not as potentially life threatening as the lungs, injuries to the upper airways are also a common characteristic of overpressure effects. As with the lungs, upper airway injuries are also hemorrhagic in nature and affect primarily the mucosal lining of the paranasal sinuses, nasopharynx, larynx, and trachea. The severity of injuries may vary from petechia and ecchymoses of the mucosal linings to hemorrhage beneath the mucosa. Figure A-5 illustrates an example of typical upper airways injury. In Table A-5, five severity levels associated with upper airways injuries are identified by their pathological and clinical signs.

Level 1 - Trivial

Casualties exhibit no outward signs of discomfort; however, an examination may reveal a few pin point red spots (petechie) in the airway mucosal lining.

Level 2 - Slight

Again, no outward signs of discomfort, but hemorrhagic spots may be larger in size.

Level 3 - Moderate

Casualties may complain of slight pain. Examination may reveal mild non-elevated submucosal contusions.

Level 4 - Severe

Casualties complain of slight pain and an examination may reveal scattered larger areas of non-elevated submucosal contusions.
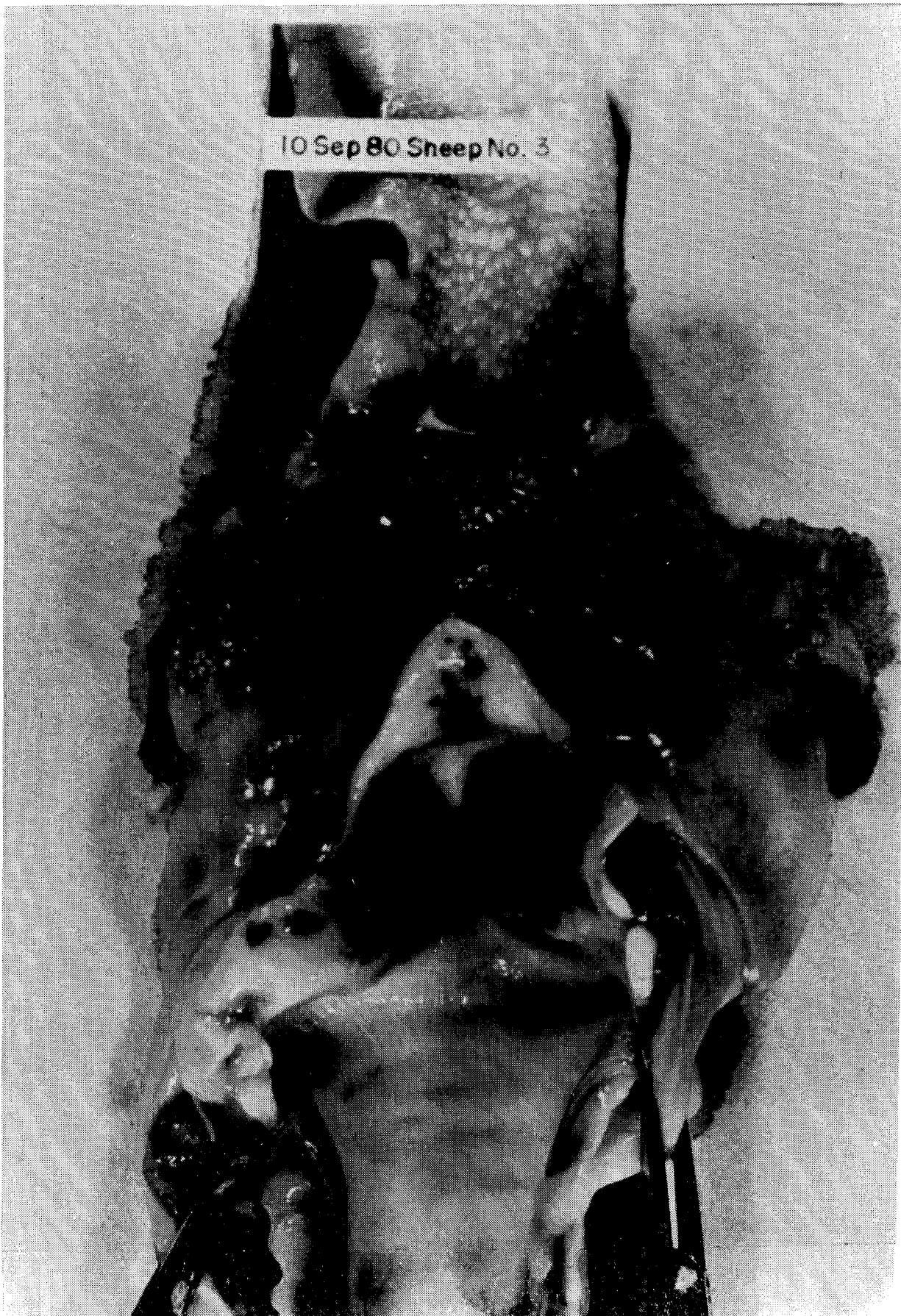
Figure A-5. Picture of Upper Airway Hemorrhages

Level 5 - Very Severe

Casualties experience pain, difficulty in breathing, and inter-airway areas of swelling. Examination shows confluent submucosal hemorrhage and hematomas which elevate the mucosal lining and reduce the airway's cross sectional area.

d.   Auditory System Injury

The auditory system consists of three regions: the outer ear which contains the pinnae and the external auditory canal; the middle ear which contains the ear drum (or tympanic membrane) and the ossicles which transmits sounds from the drum to the inner ear; and the inner ear region which has a conch-shaped area, the cochlea with its embedded hair cells, and endolymph fluid. The hair cells of the cochlea convert sound vibrations in the endolymph into nerve impulses which are transmitted to the brain by the auditory nerve. The inner ear also contains the vestibule and semicircular canals which have receptors for the sense of equilibrium and position. Overpressure type ear injuries will typically affect the tympanic membrane. In addition, hair cells in the cochlea may be also damaged causing temporary or permanent hearing loss. This may occur without any damage done to the tympanic membrane. Examples of ear injuries are shown in Figure A-6. Table A-6 presents the pathological and clinical signs for the three casuality prediction injury levels.

Level 1 - Minor Rupture

Casualties are ambulatory, alert, oriented and may complain of ringing and mild-moderate acute hearing loss. Ear examination with otoscope may reveal minor slits tearing the eardrum. Some hearing losss may be permanent.

Level 2 - Moderate Rupture

Casualties are ambulatory, alert, oriented, and will likely complain of moderate-severe acute hearing loss and pain. Ear examination reveal larger tears of the ear drum. Haircells in the cochlea may be damaged, causing hearing impairment.

Level 3 - Major Rupture

Casualties may be alert, but disoriented, with absent hearing, and possible hemorrhaging from the ear. The tympanic membrane has been massively damaged and the ossicles have been fractured or dislodged.

4.   Step 3. Determine Probabilities of Occurrance of Each Injury in the Injury Tables

a.   General Overview

This section outlines the basic methodology for predicting probabilities of injuries resulting from overpressure exposure. To automate this process, a computer program has been written and the program listing is provided in Annex 1. Manual procedures for making the calculations are provided in Annex 2.

b.   Characteristics of Blast Waves

The data used to predict overpressure casualities are based upon an "ideal" or "classical" airblast wave. Figure A-7 illustrates the pressure-time history of this airblast pulse. The wave is characterized by instantaneous rise after an arrival time, t_a, to a peak value, P_{so}, and then an exponential decay to the ambient value in time, t_o. After time $t_a + t_o$, the atmospheric pressure continues to decay until it reaches a value below the preshot ambient
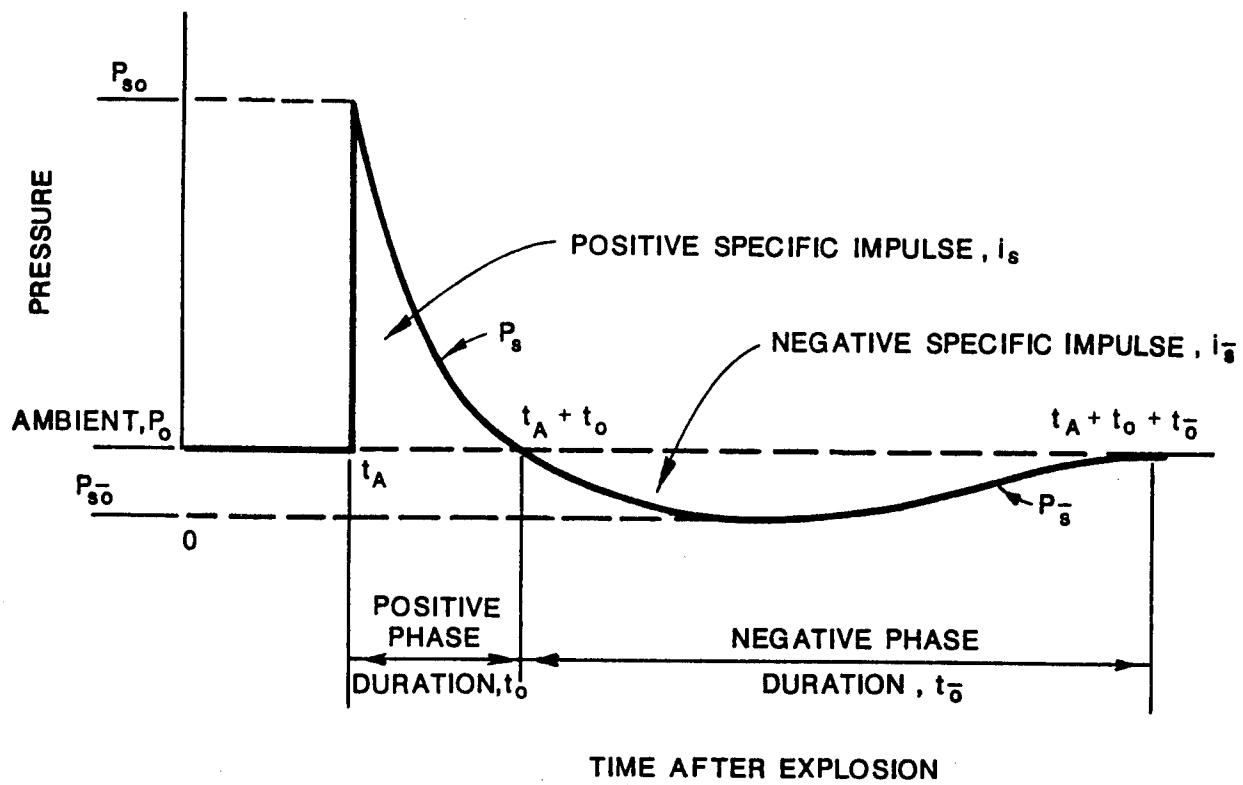
Figure A-6. Picture of Eardrum Rupture

Figure A-7.   Free-Field Pressure-Time Variation

pressure and then it returns to ambient pressure. This phase is identified as the negative phase. However, according to Reference 1, there is insufficient evidence to define the role, if any, played by the negative phase in blast injury. During the positive phase, the atmospheric particle flow or blast winds travel away from the explosive source, but reverse their direction during the negative phase.

Blast wave parameters which predict overpressure injuries are overpressure and duration of the positive phase. Depending on the person's orientation to a blast wave, dynamic pressure or reflected pressure may also be considered in determining injury probability. Dynamic pressure, q, is a measure of the blast flow and is determined by calculating the difference between the incident pressures measured face-on and side-on. If the shock wave impinges on a rigid surface oriented at an angle to the direction of wave propagation, a reflected pressure instantly develops on the surface and the resulting pressure is raised to a value in excess of the incident pressure. This reflected pressure is a function of the incident pressure and the angle formed between the rigid surface and the plane of the shock front. Section III.C describes the conditions when reflected pressure or dynamic pressure would be considered in assessing overpressure injuries.

Both conventional and nuclear weapons will produce shock waves similar to the wave form depicted in Figure A-7. For conventional explosions, the overpressure durations are on the order tens of milliseconds. For nuclear explosions, the durations are on the order of hundreds milliseconds to seconds.

This classical wave form describes freefield detonations. For detonations occurring near foxholes and inside structures or vehicles, the results in this chapter would not apply directly. These detonations follow complex wave patterns. Complex wave overpressure effects are being researched to determine relationships of suitable physical parameters (such as peak pressure and duration).

c.   Overpressure Exposure Conditions for Lungs, GI Tract and Upper Airway Injuries

The casualty predictions described in this sample segment are valid for a 70 kg male in a freefield condition with a standard (14.7 psi) ambient pressure. The body orientations considered in this chapter are for personnel:

o   Parallel To Blast Wave Direction Of Travel

o   Perpendicular To Blast Wave Direction Of Travel

o   Near Reflecting Surface

To determine casualties for these different body orientations, the peak overpressure used in the computations depends on the body orientations (Figure A-8). If the person is oriented parallel to the blast wave, the peak overpressure needed to calculate percent injuries is the incident overpressure. If the person is oriented perpendicular to the blast wave, the peak pressure would equal the sum of the incident overpressure and the dynamic pressure. For a person located near a reflecting surface, the reflected pressure would be needed to determine injuries.

For cases where the user wants to determine injury predictions based upon nonstandard conditions such as for a different body weight or ambient pressure, the following scaling relationships developed for scaled peak overpressure (P) and scaled duration (T) are available (Reference 2):

OVERPRESSURE EXPOSURE CONDITIONS

IF PERSON IS:

PEAK OVERPRESSURE EQUALS:

Parallel to Blast Wave

OR

LONG AXIS OF BODY PARALLEL TO BLAST WINDS, SUBJECT FACING ANY DIRECTION.
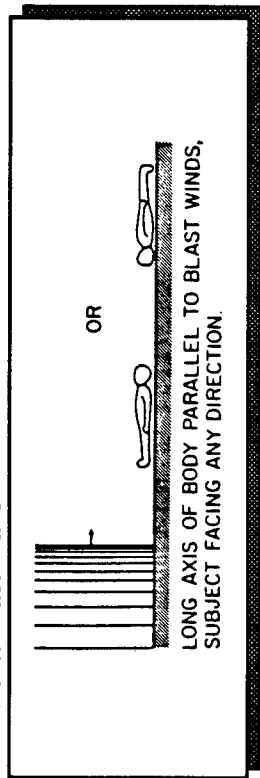
Incident Overpressure

Perpendicular to Blast Wave

OR

LONG AXIS OF BODY PERPENDICULAR TO BLAST WINDS, SUBJECT FACING ANY DIRECTION.
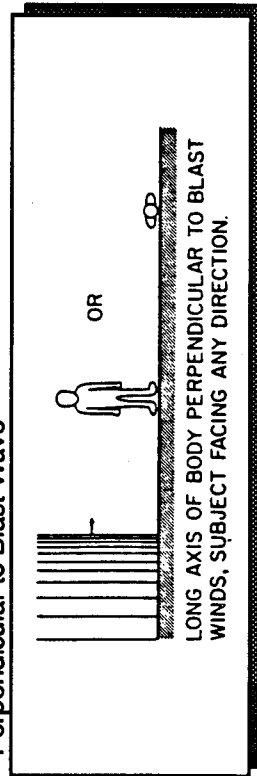
Incident Overpressure and Dynamic Pressure

Near Reflecting Surface

OR

OR

THORAX NEAR A REFLECTING SURFACE WHICH IS PERPENDICULAR TO BLAST WINDS, SUBJECT FACING ANY DIRECTION.
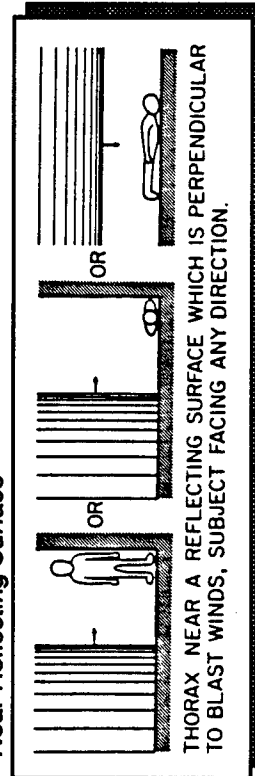
Reflected Overpressure

Figure A-8. Overpressure Exposure Conditions

$$P = \frac{14.7}{p_0} p \qquad \text{(A-1)}$$

$$T = t_+ \left(\frac{70}{m}\right)^{1/3} \left(\frac{p_0}{14.7}\right)^{1/2} \qquad \text{(A-2)}$$

where p_0:   Ambient pressure, psi

t_+:   Duration of positive overpressure, msec

m: Body Weight, kg

p: Peak overpressure, psi

The user first calculates the scaled overpressure and duration, then use these values to determine injury probability by using the equations developed in paragraphs d and e below.

d.   Interpretation of Injury Probabilities

The probability of injury numbers presented in the following paragraph e are the probability of sustaining "at least" the indicated level of injury severity. Figure A-9 shows a three dimensional representation of the relationship of the various probability of injury curves to one another, and to the basic physical parameters. In order to determine the probability of sustaining "exactly" the indicated level of injury it is necessary to subtract the included probability of more severe injury to the organ. The methodology is as follows:

Let $F_n(x)$ be the cumulative probability function and $f_n(x)$ be the probability mass function with n representing the injury type (i.e. n = 1 for lung, 2 for GI, 3 for upper airways, 4 for ears) and x representing the injury level (i.e. x = 0 for no injury, 1 for trivial, 2 for slight, 3 for moderate, 4 for severe, 5 for very severe, and 6 for lethal). So,

$$F_n(i) = \sum_{i\_j} f_n(j)$$

To determine $f_n(x)$, the relationships between $f_n(x)$ and $F_n(x)$ are established:

$F_n(0) = 1$

$F_n(N) = f_n(N)$

$f_n(x) = F_n(x) - F_n(x+1)$ for $0 \_ x < N$ \qquad (A-3)

where N is the maximum injury level. The sample problem below serves as an illustration of how to calculate probabilities.

To determine the probabilities corresponding to the following lung injury cumulative probabilities:

$F_1(0) = 1$, $F_1(1) = 1$, $F_1(2) = 1$, $F_1(3) = 1$

$F_1(4) = .5$, $F_1(5) = .25$, $F_1(6) = .01$

Using the cumulative probabilities above:
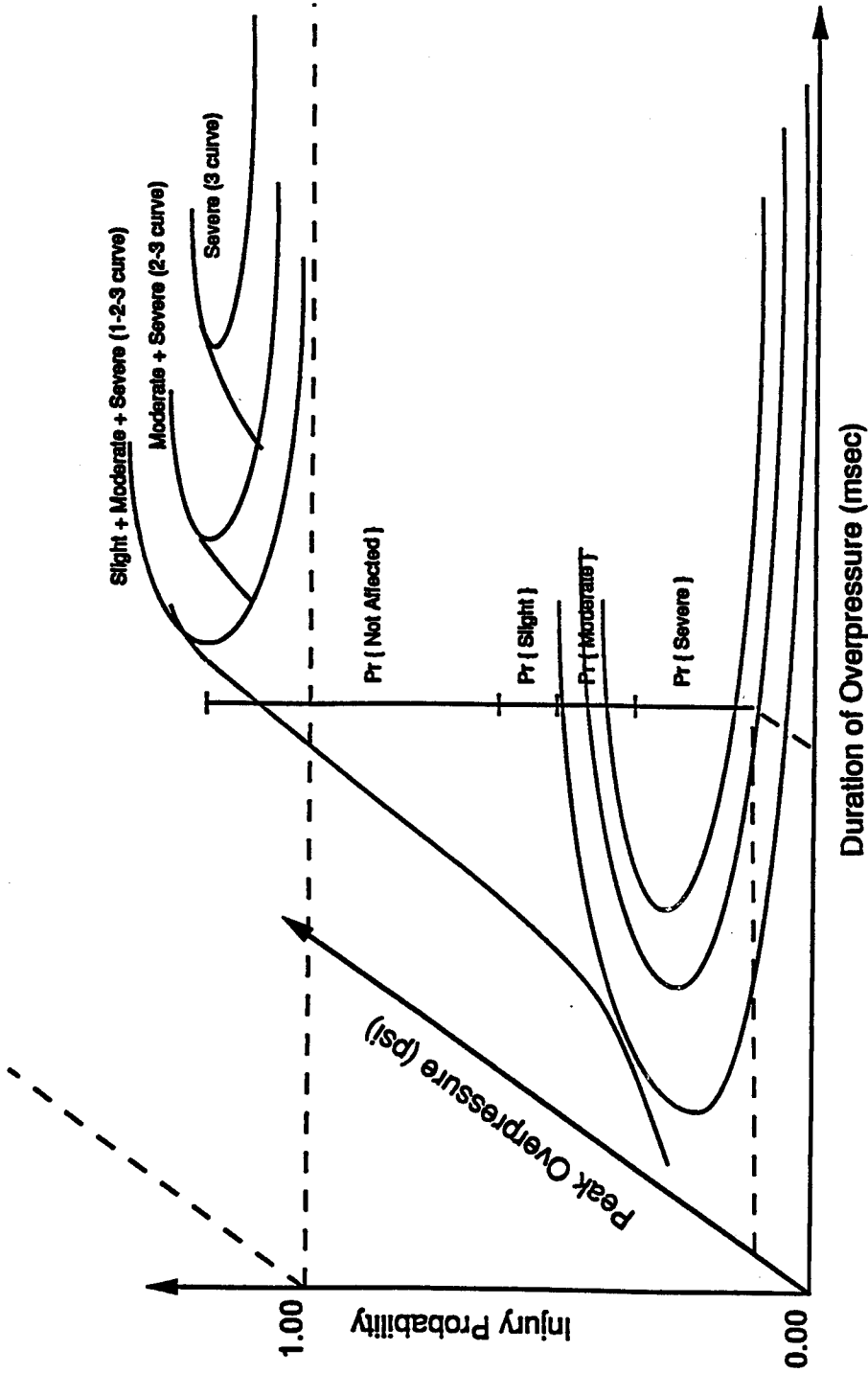
Figure A-9. Three-Dimensional Representation of Injury Curves

$f_1(6) = F_1(6) = .01$

$f_1(5) = F_1(5) - F_1(6) = .25 - .01 = .24$

$f_1(4) = F_1(4) - F_1(5) = .5 - .25 = .25$

$f_1(3) = F_1(3) - F_1(4) = 1 - .5 = .50$

$f_1(2) = F_1(2) - F_1(3) = 1 - 1 = 0$

$f_1(1) = F_1(1) - F_1(0) = 1 - 1 = 0$

$f_1(0) = F_1(0) - F_1(1) = 1 - 1 = 0$

e. Calculation of Probabilities of Blast Overpressure Injuries

(1) Lethality

The most comprehensive data pertaining to blast overpressure injuries are those pertaining to lethality; therefore, these are used as the basis for extrapolating the less comprehensive data for the other injuries, and will be considered first.

For overpressure, lethality results from air embolism caused by lung disruption (Reference 9). Therefore, injury level 6 (lethality) applies only to lung injuries (n=1). Curves used to calculate percent killed from overpressure injuries (or, alternately, probability of occurrence for lung injury level 6) were determined by using the following fitting equation from Reference 9:

$$P = 61.5[1+6.76T^{-1.064}]\exp^{0.1788(5-z)} \qquad \text{(A-4)}$$

where P: Scaled peak overpressure, psi   (i.e. scaled for body weight and ambient pressure)

T: Scaled duration, msec

z: Survival, probit units (i.e., 5 = 50% survival)

Equation A-4 is plotted in Figure A-10 for 1-, 25-, 50-, 75-, and 99-percent lethality. Equation A-4 is based upon the Lovelace Foundation's past overpressure experiments with over 2000 animals from 13 different mammalian species. These animals were subjected to blast waves generated by either shock tubes or high explosive charges. Based on a 24 hour post-exposure time period, percent survival rates for each species were determined and the results were scaled to man by body weight (70 kg).

To calculate probability using the above equation, the equation must be solved for z. Using algebraic manipulations, Equation A-4 becomes:

$$z = 5 - \frac{1}{0.1788} \ln \left\{ \frac{p}{61.5[1 + 6.76T^{-1.064}]} \right\} \qquad \text{(A-5)}$$

For determining probability from survival probit units, z, Table A-7 is provided. To use this table, the user subtracts 5 from the value of z calculated using Equation A-5. The new value of z is used

to enter Table A-7 to find the value of F(z), the cumulative distribution function. The first two digits of F(z) are read down the left hand side of Table A-7, and the last two digits are read across.

To determine probability of lethality (or, more generally, injury at any level), P_r:

$$P_r = 1 - F(z) \quad \text{if } z\_0 \tag{A-6}$$

$$P_r = F(z) \quad \text{if } z < 0 \tag{A-7}$$

For example, after scaling from a given pressure and duration, if the scaled z = 3.545, then 3.545 - 5 = -1.455. From Table A-7, then P_r = F(z) = 0.9265. If the scaled z = 7.44, then 7.44 - 5 = 2.44 and P_r = 1 - F(z) or 1 - 0.9927 = 0.0073.

(2)   Non Lethal Injuries

(a)   General

Relationships formulated for non-lethal lung, GI tract, and upper airways injuries are based primarily upon animal experimentation conducted by the Lovelace Foundation. As with the overpressure lethality predictions, the results were scaled to man based on body weight. Data on these injuries were obtained from Dr. Richmond. In cases where the data were unavailable for a particular severity level for some durations, pressure was scaled from known data using the following scaling relationship (Reference 1).

$$P_2 = P_1 \frac{1 + 6.76(t_2)^{-1.064}}{1 + 6.76(t_1)^{-1.064}} \tag{A-8}$$

where P_2 is the overpressure to be determined at t_2 duration, and (P_1, t_1) are the known overpressure and duration values for a particular injury, severity level, and probability of occurrence. For example, given a pressure and duration point, (for example, 16 psi and 200 msec) for a 50-percent occurrence of a Level 1 lung injury, Equation A-8 would be used to calculate the overpressure that would cause a 50-percent occurrence of a Level 1 lung injury given a duration of 2 milliseconds. By substituting these values into Equation A-8, P_2 would equal 66.1 psi.

Because Equation A-8 is used to scale results to other durations, injury curves for lung, GI tract, and upper airways were assumed to behave similarly to the lethality curves. A generalized equation for these curves would be:

$$P = x_1 [1 + 6.76 T^{-1.064}] \exp^{x_2(5-z)} \tag{A-9}$$

where x_1 and x_2 are the parameters to be determined by curve fitting techniques. These parameters were determined for each injury and severity level and are provided in paragraphs (b) through (e) below.

Injury predictions for ear injuries are based upon experimentation with cadavers and animals. The relationships between injury probability, peak overpressure, and duration follow a

TABLE A-7. TABLE OF PROBIT UNITS AND ASSOCIATED PROBABILITY

z	.00	.01	.02	.03	.04	.05	.06	.07	.08	.09
.0	.5000	.5040	.5080	.5120	.5160	.5199	.5239	.5279	.5319	.5359
.1	.5398	.5438	.5478	.5517	.5557	.5596	.5636	.5675	.5714	.5753
.2	.5793	.5832	.5871	.5910	.5948	.5987	.6026	.6064	.6103	.6141
.3	.6179	.6217	.6255	.6293	.6331	.6368	.6406	.6443	.6480	.6517
.4	.6554	.6591	.6628	.6664	.6700	.6736	.6772	.6808	.6844	.6879
.5	.6915	.6950	.6985	.7019	.7054	.7088	.7123	.7157	.7190	.7224
.6	.7257	.7291	.7324	.7357	.7389	.7422	.7454	.7486	.7517	.7549
.7	.7580	.7611	.7642	.7673	.7704	.7734	.7764	.7794	.7823	.7852
.8	.7881	.7910	.7939	.7967	.7995	.8023	.8051	.8078	.8106	.8133
.9	.8159	.8186	.8212	.8238	.8264	.8289	.8315	.8340	.8365	.8389
1.0	.8413	.8438	.8461	.8485	.8508	.8531	.8554	.8577	.8599	.8621
1.1	.8643	.8665	.8686	.8708	.8729	.8749	.8770	.8790	.8810	.8830
1.2	.8849	.8869	.8888	.8907	.8925	.8944	.8962	.8980	.8997	.9015
1.3	.9032	.9049	.9066	.9082	.9099	.9115	.9131	.9147	.9162	.9177
1.4	.9192	.9207	.9222	.9236	.9251	.9265	.9279	.9292	.9306	.9319
1.5	.9332	.9345	.9357	.9370	.9382	.9394	.9406	.9418	.9429	.9441
1.6	.9452	.9463	.9474	.9484	.9495	.9505	.9515	.9525	.9535	.9545
1.7	.9554	.9564	.9573	.9582	.9591	.9599	.9608	.9616	.9625	.9633
1.8	.9641	.9649	.9656	.9664	.9671	.9678	.9686	.9693	.9699	.9706
1.9	.9713	.9719	.9726	.9732	.9738	.9744	.9750	.9756	.9761	.9767
2.0	.9772	.9778	.9783	.9788	.9793	.9798	.9803	.9808	.9812	.9817
2.1	.9821	.9826	.9830	.9834	.9838	.9842	.9846	.9850	.9854	.9857
2.2	.9861	.9864	.9868	.9871	.9875	.9878	.9881	.9884	.9887	.9890
2.3	.9893	.9896	.9898	.9901	.9904	.9906	.9909	.9911	.9913	.9916
2.4	.9918	.9920	.9922	.9925	.9927	.9929	.9931	.9932	.9934	.9936
2.5	.9938	.9940	.9941	.9943	.9945	.9946	.9948	.9949	.9951	.9952
2.6	.9953	.9955	.9956	.9957	.9959	.9960	.9961	.9962	.9963	.9964
2.7	.9965	.9966	.9967	.9968	.9969	.9970	.9971	.9972	.9973	.9974
2.8	.9974	.9975	.9976	.9977	.9977	.9978	.9979	.9979	.9980	.9981
2.9	.9981	.9982	.9982	.9983	.9984	.9984	.9985	.9985	.9986	.9986
3.0	.9987	.9987	.9987	.9988	.9988	.9989	.9989	.9989	.9990	.9990
3.1	.9990	.9991	.9991	.9991	.9992	.9992	.9992	.9992	.9993	.9993
3.2	.9993	.9993	.9994	.9994	.9994	.9994	.9994	.9995	.9995	.9995
3.3	.9995	.9995	.9995	.9996	.9996	.9996	.9996	.9996	.9996	.9997
3.4	.9997	.9997	.9997	.9997	.9997	.9997	.9997	.9997	.9997	.9998

piecewise linear behavior so that the techniques for determining probability are different from that discussed for lung, GI tract and upper airways. Further details on ear injury are discussed in paragraph (e) below.

(b)   Lung Injuries

Figures A-10 through A-15 are the lung injury probability curves for the six severity levels. This includes the lethality probability curve (lung injury level 6) described earlier as well as the five non-lethal lung injury levels. Equations for these curves are as follows:

Level 6: $P = 61.5[1+6.76T^{-1.064}]\exp^{0.1788(5-z)}$ (A-4)

Level 5: $P = 46.9[1+6.76T^{-1.064}]\exp^{0.0359(5-z)}$ (A-10)

Level 4: $P = 42.0[1+6.76T^{-1.064}]\exp^{0.0501(5-z)}$ (A-11)

Level 3: $P = 33.2[1+6.76T^{-1.064}]\exp^{0.0509(5-z)}$ (A-12)

Level 2: $P = 21.5[1+6.76T^{-1.064}]\exp^{0.0872(5-z)}$ (A-13)

Level 1: $P = 15.6[1+6.76T^{-1.064}]\exp^{0.1100(5-z)}$ (A-14)

(c)   GI Tract Injuries

Figures A-16 through A-20 are the GI Tract probability curves for the five severity levels. Equations for these curves are as follows:

Level 5: $P = 40.1[1+6.76T^{-1.064}]\exp^{0.0422(5-z)}$ (A-16)

Level 4: $P = 33.2[1+6.76T^{-1.064}]\exp^{0.0638(5-z)}$ (A-17)

Level 3: $P = 27.4[1+6.76T^{-1.064}]\exp^{0.0619(5-z)}$ (A-18)

Level 2: $P = 17.6[1+6.76T^{-1.064}]\exp^{0.1067(5-z)}$ (A-19)

Level 1: $P = 11.7[1+6.76T^{-1.064}]\exp^{0.1490(5-z)}$ (A-20)

(d)   Upper Airway Injuries

Figures A-21 through A-25 are the upper airway probability curves for the five severity levels. Equations for these curves are as follows:

Level 5: $P = 30.3[1+6.76T^{-1.064}]\exp^{0.0467(5-z)}$ (A-21)

Level 4: $P = 22.5[1+6.76T^{-1.064}]\exp^{0.0756(5-z)}$ (A-22)

Level 3: $P = 13.7[1+6.76T^{-1.064}]\exp^{0.1261(5-z)}$ (A-23)

Levels 1,2: $P = 9.8[1+6.76T^{-1.064}]\exp^{0.1820(5-z)}$ (A-24)

(e)   Ear Injuries

The pressure and duration dependence for probability curves corresponding to ear injury is different from those of other overpressure injuries. First, dynamic pressure does appear to impact on the injury probability. Results indicate that an individual orientated either parallel or perpendicular to the blast wave would experience similar levels of injury. However, reflected overpressure would still be important in assessing ear injuries for an individual situated near a reflecting surface (Figure A-9).

Since the injury curves for the ear are piecewise linear representations, ear injury probability is determined by using interpolation methods as opposed to probit methods. A rough estimate of the injury probability can be obtained by visually interpolating the value from Figures A-26 to A-28 for each severity level. A more precise method would be to apply the following curve fitting technique:

First, assume that the injury probability curve can be divided into three regions, based on the value of peak pressure, P, at a given duration, t (Figure A-29). In Figure A-29, $P_{.01}$, $P_{.50}$, and $P_{.99}$ represent the peak pressures at a given duration for 1-, 50-, and 99-percent injury probabilities, respectively. $P_{.01}$, $P_{.50}$, and $P_{.99}$ are calculated using the following linear equations developed from curve fitting of injury data.

For t < 5 milliseconds

Level 3

$$P_{.01} = -0.83t + 11.2 \tag{A-25}$$

$$P_{.50} = -2.5t + 33.5 \tag{A-26}$$

$$P_{.99} = -7.7t + 101.5 \tag{A-27}$$

Level 2

$$P_{.01} = -0.42t + 5.9 \tag{A-28}$$

$$P_{.50} = -1.25t + 17.2 \tag{A-29}$$

$$P_{.99} = -3.75t + 52.8 \tag{A-30}$$

Level 1

$$P_{.01} = -0.31t + 4.4 \tag{A-31}$$

$$P_{.50} = -1.02t + 13.2 \tag{A-32}$$

$$P_{.99} = -2.92t + 39.6 \tag{A-33}$$

For t > 5 milliseconds

Level 3

$$P_{.01} = 7.0 \tag{A-34}$$

$$P_{.50} = 21.0 \tag{A-35}$$

$$P_{.99} = 63.0 \tag{A-35}$$

Level 2

$$P_{.01} = 3.8 \tag{A-37}$$

$$P_{.50} = 11.0 \tag{A-38}$$

$$P_{.99} = 34.0 \tag{A-39}$$

LETHALITY PREDICTION
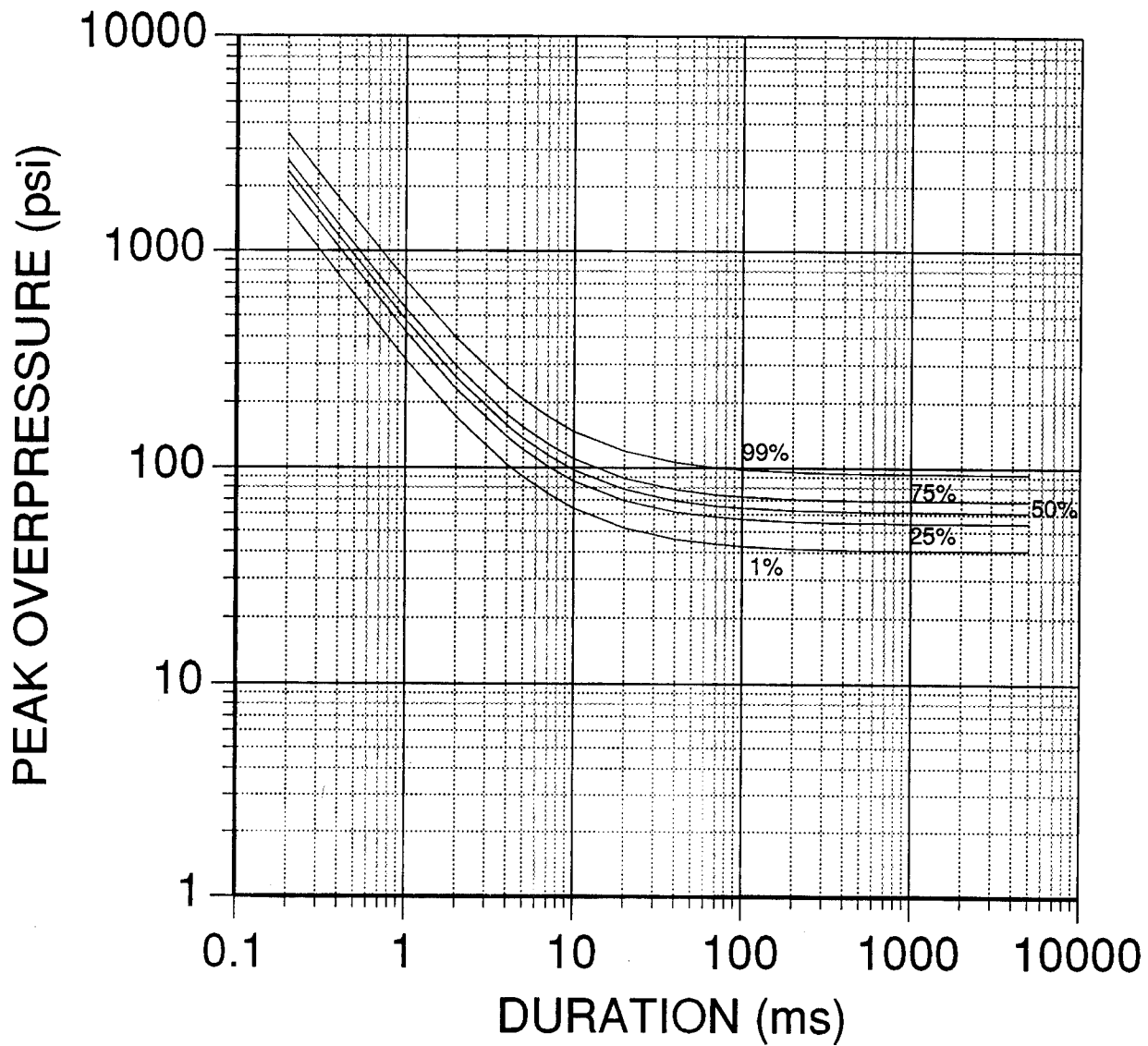
Figure A-10. Overpressure Lethality Prediction

LUNG INJURIES, LEVEL 5
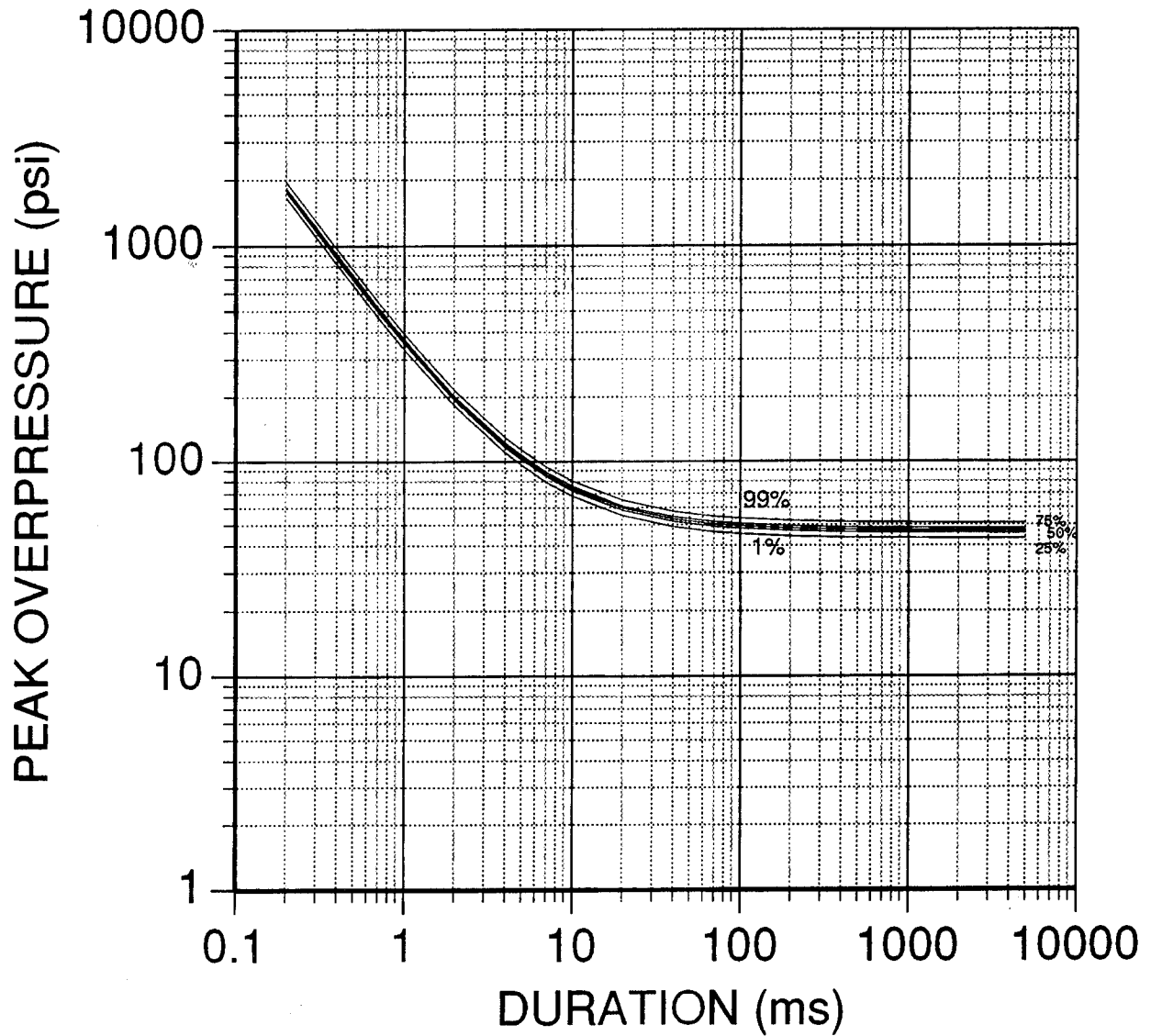
Figure A-11. Injury Curves for a Level 5 Lung Injury

LUNG INJURIES, LEVEL 4
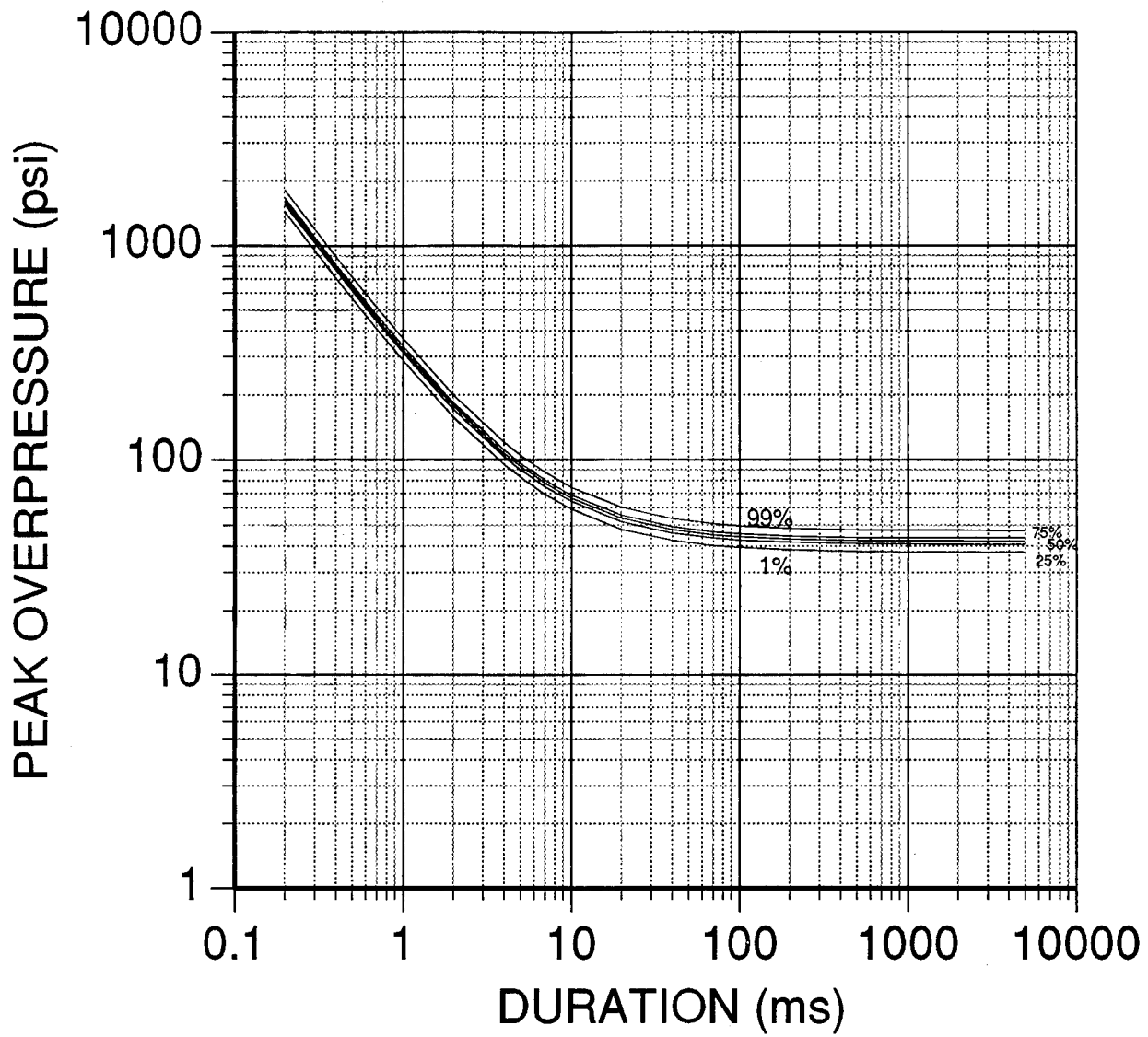
Figure A-12. Injury Curves for a Level 4 Lung Injury

LUNG INJURIES, LEVEL 3
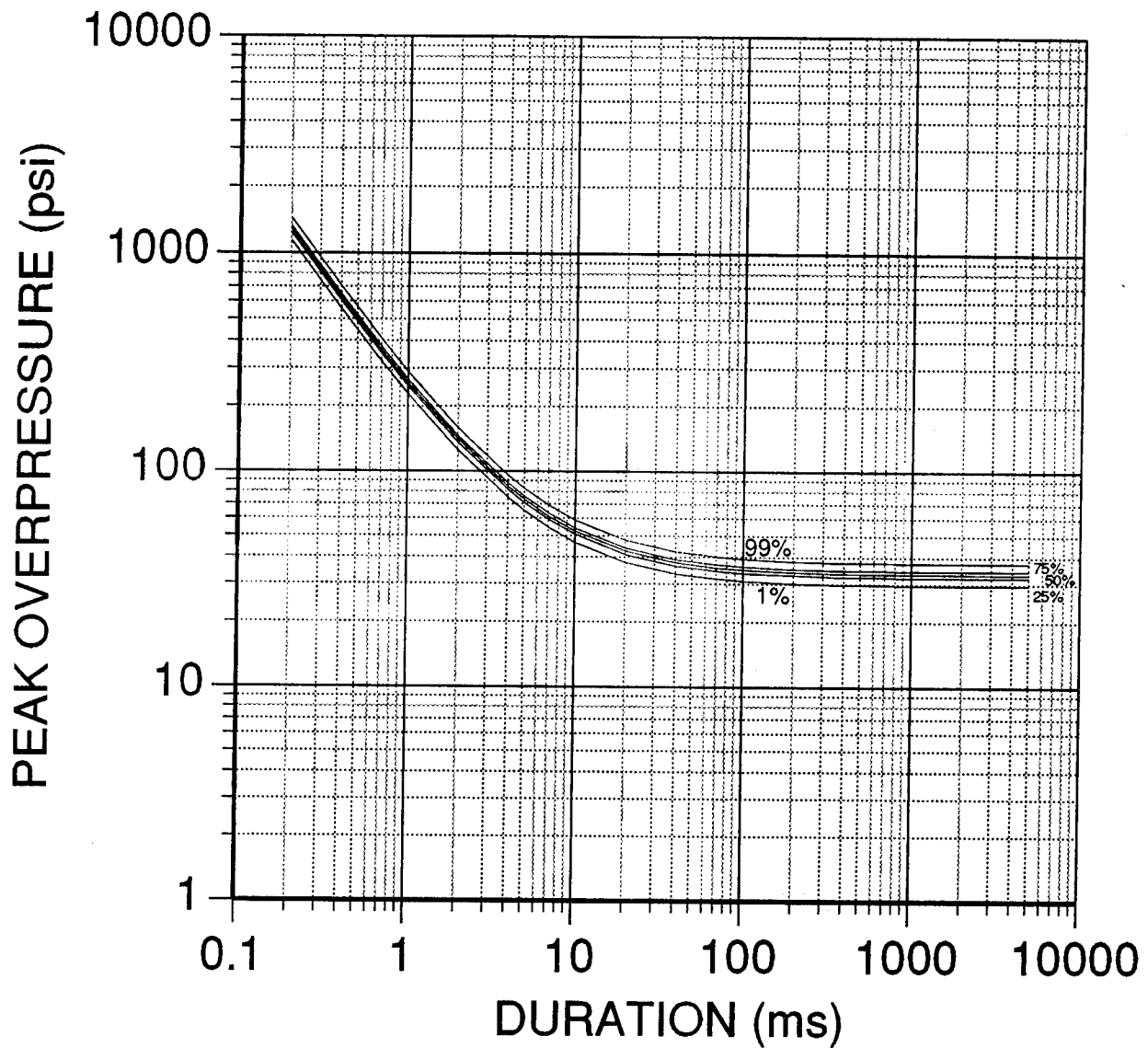
Figure A-13.   Injury Curves for a Level 3 Lung Injury

LUNG INJURIES, LEVEL 2
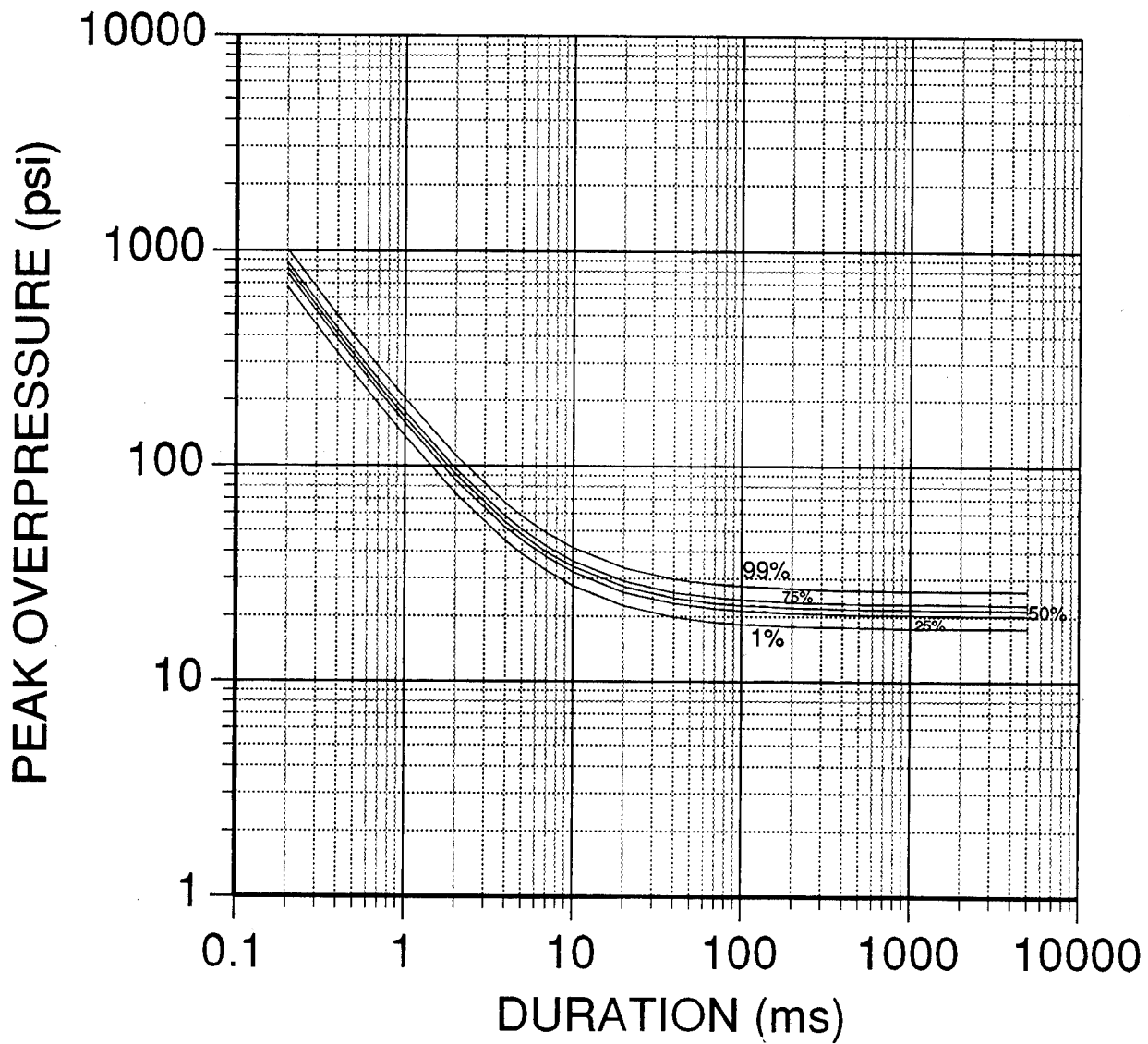
Figure A-14.   Injury Curves for a Level 2 Lung Injury

LUNG INJURIES, LEVEL 1
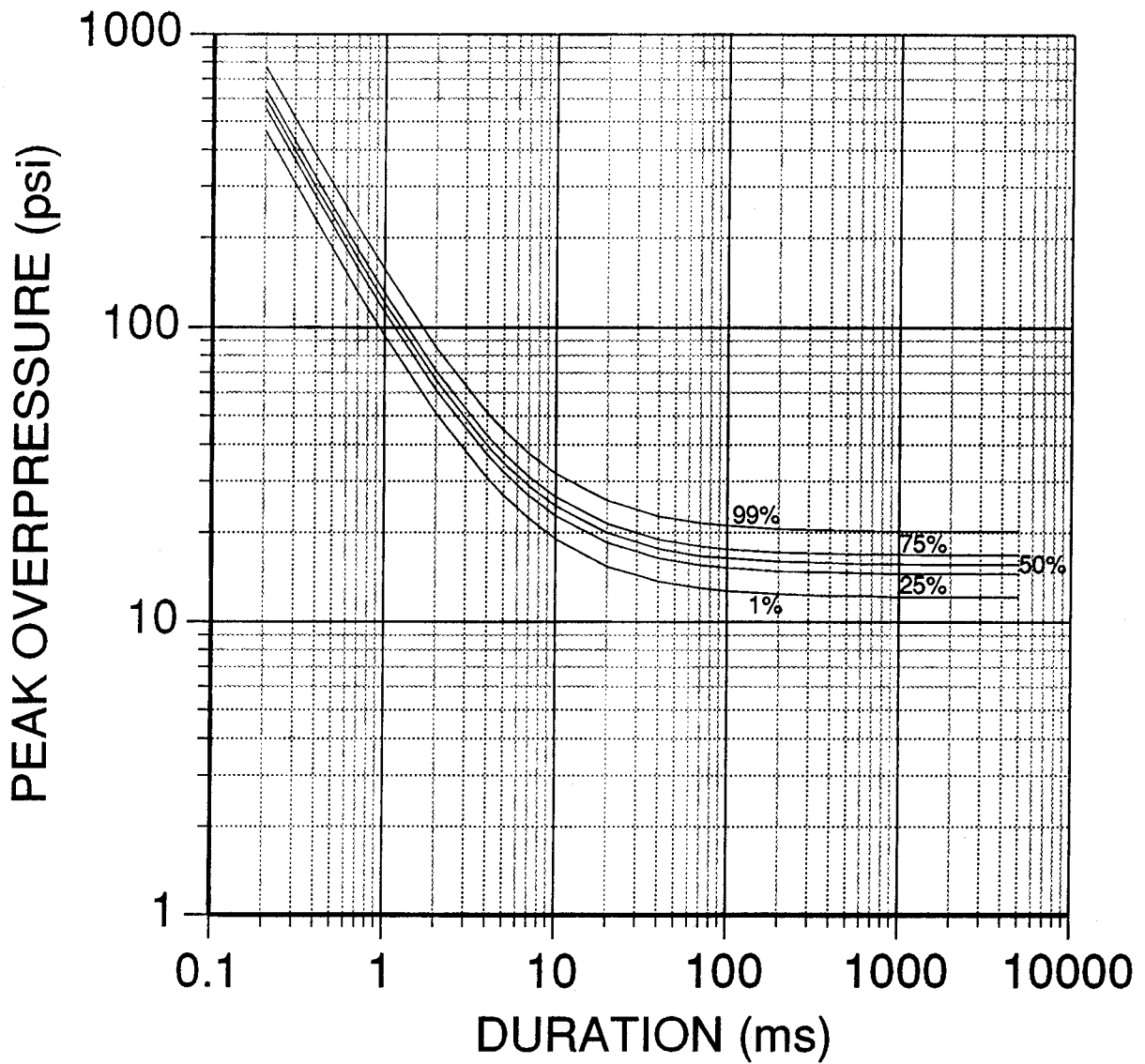
Figure A-15.   Injury Curves for a Level 1 Lung Injury

GI TRACT INJURIES, LEVEL 5
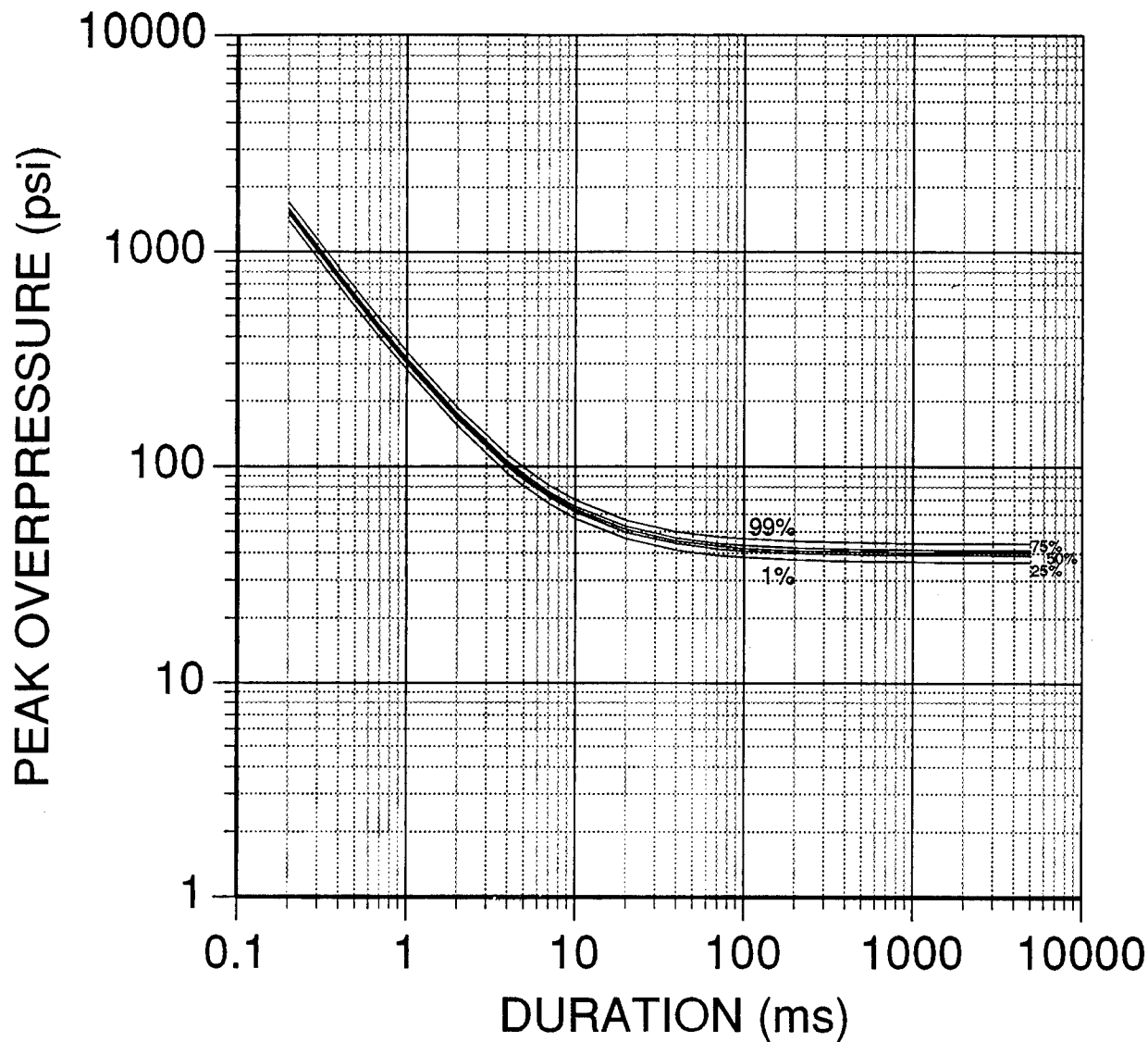
Figure A-16.   Injury Curves for a Level 5 GI Tract Injury

GI TRACT INJURIES, LEVEL 4
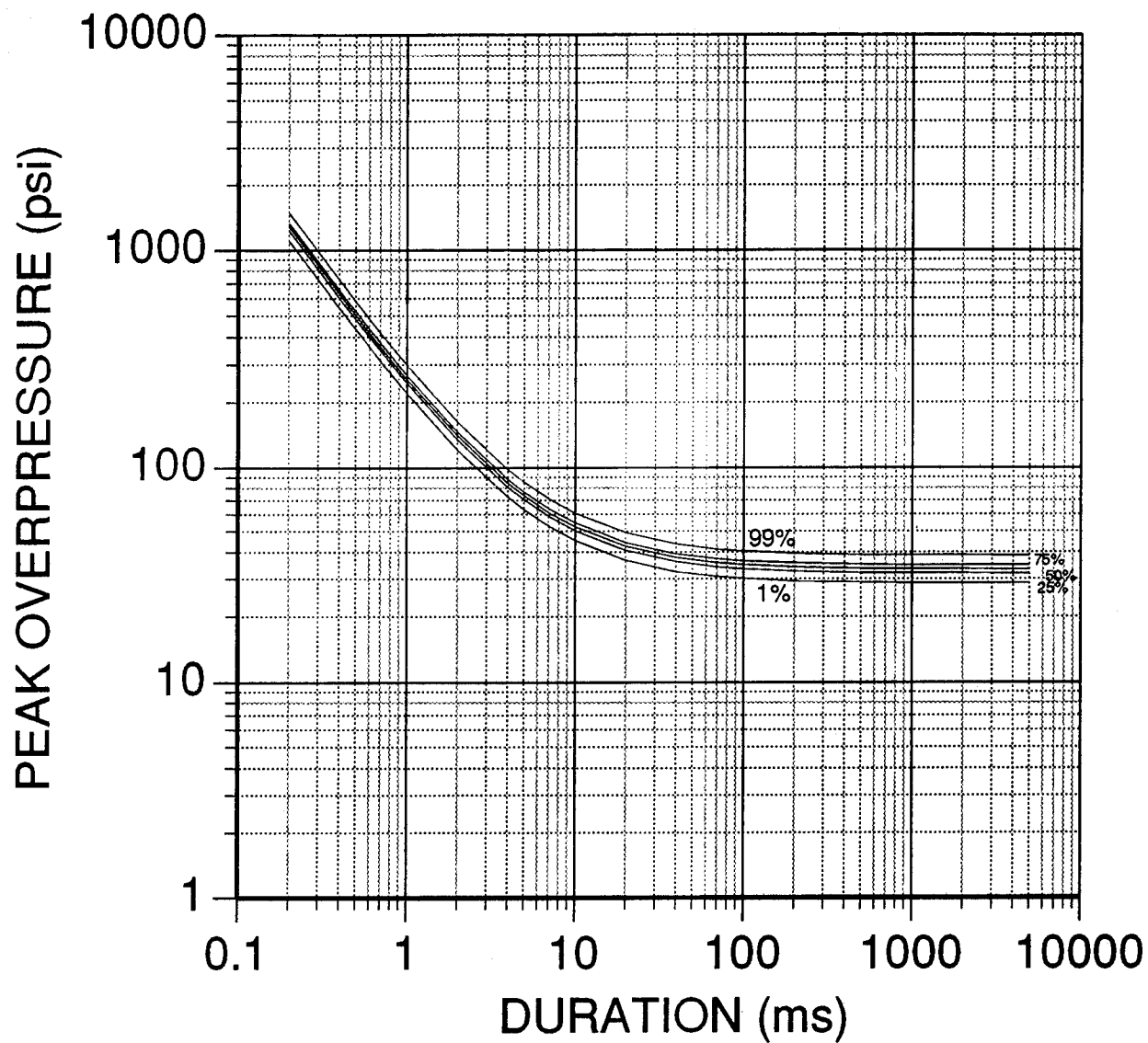
Figure A-17.   Injury Curves for a Level 4 GI Tract Injury

GI TRACT INJURIES, LEVEL 3
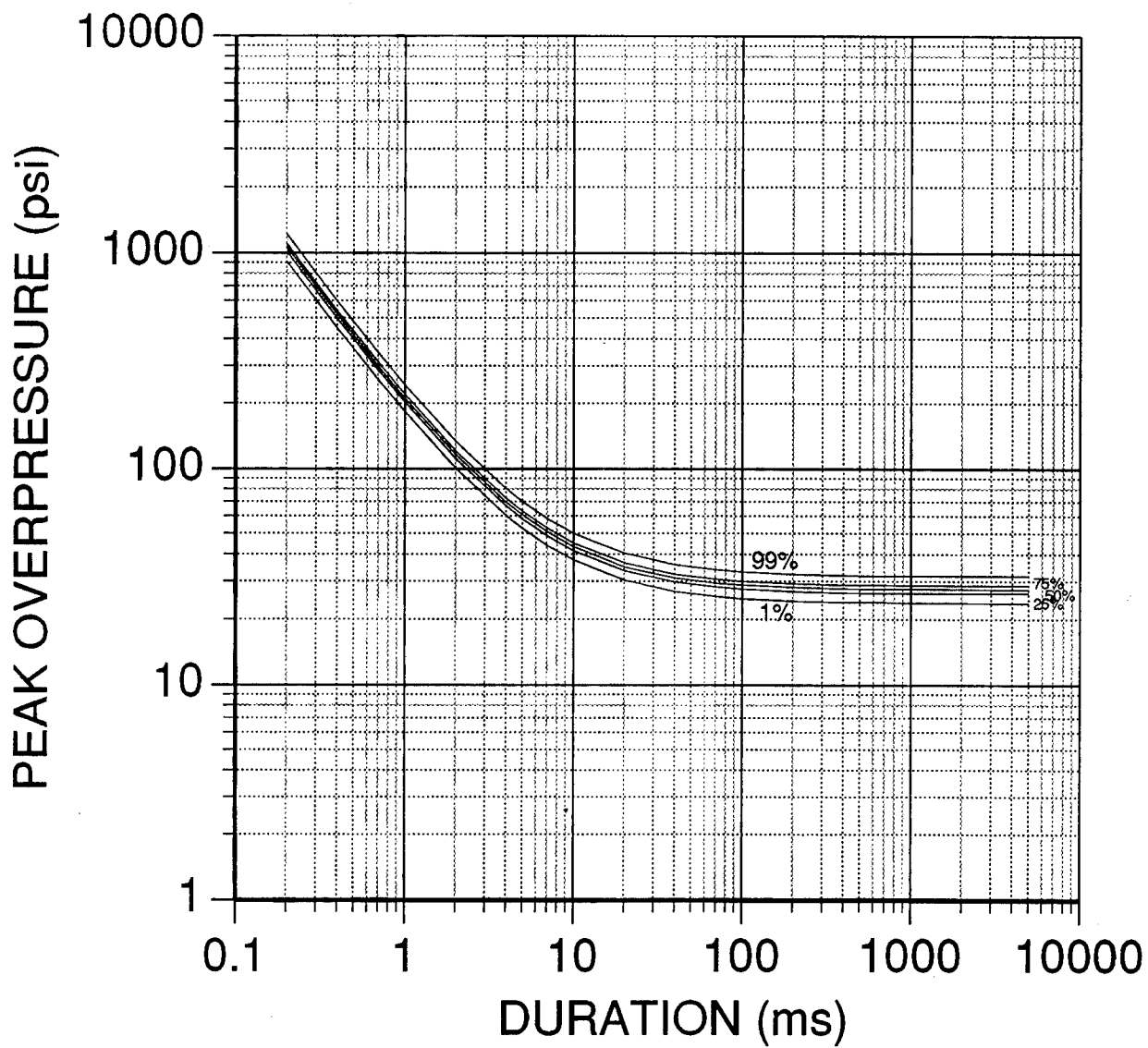
Figure A-18.   Injury Curves for a Level 3 GI Tract Injury

GI TRACT INJURIES, LEVEL 2
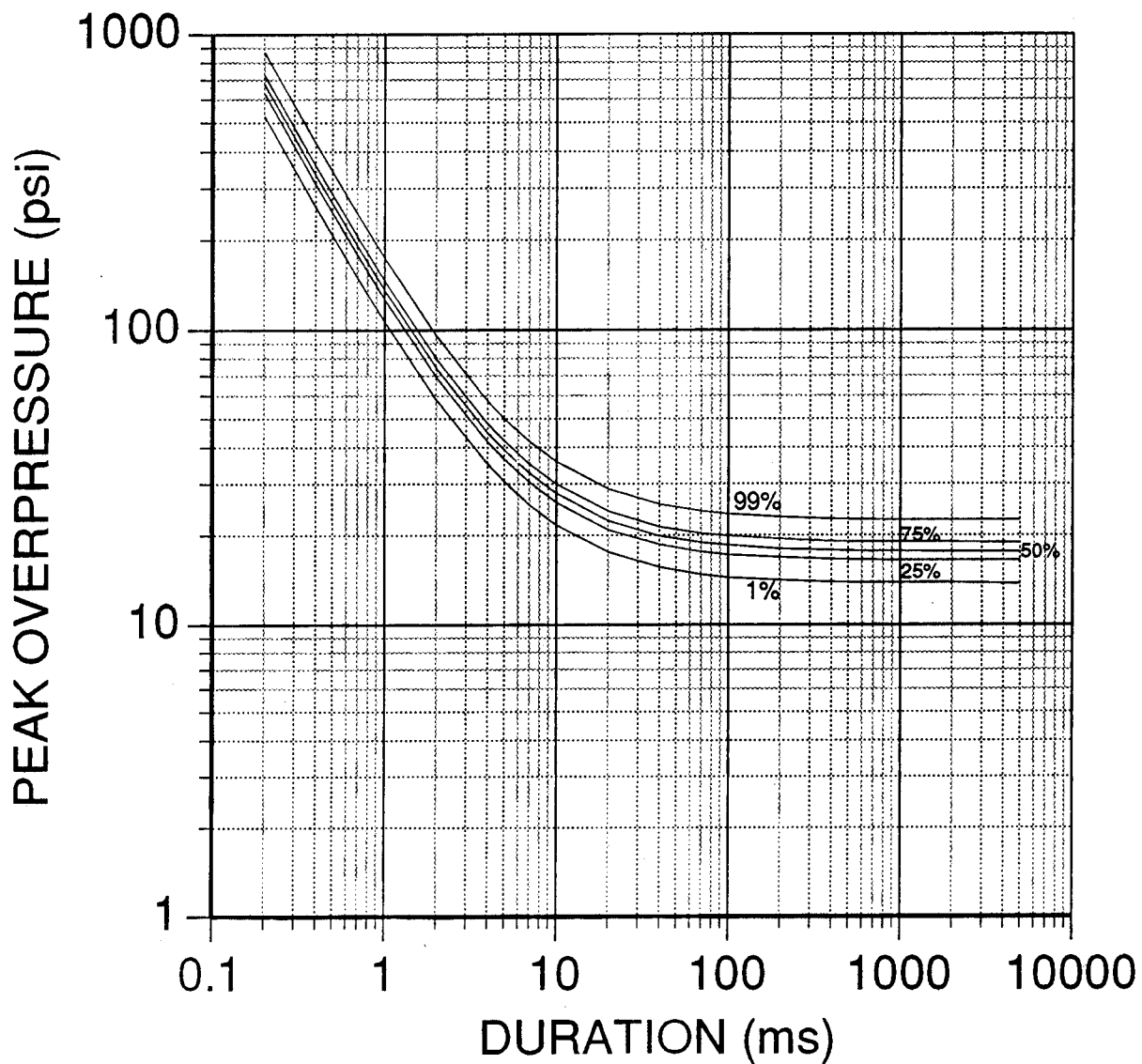
Figure A-19.   Injury Curves for a Level 2 GI Tract Injury

GI TRACT INJURIES, LEVEL 1
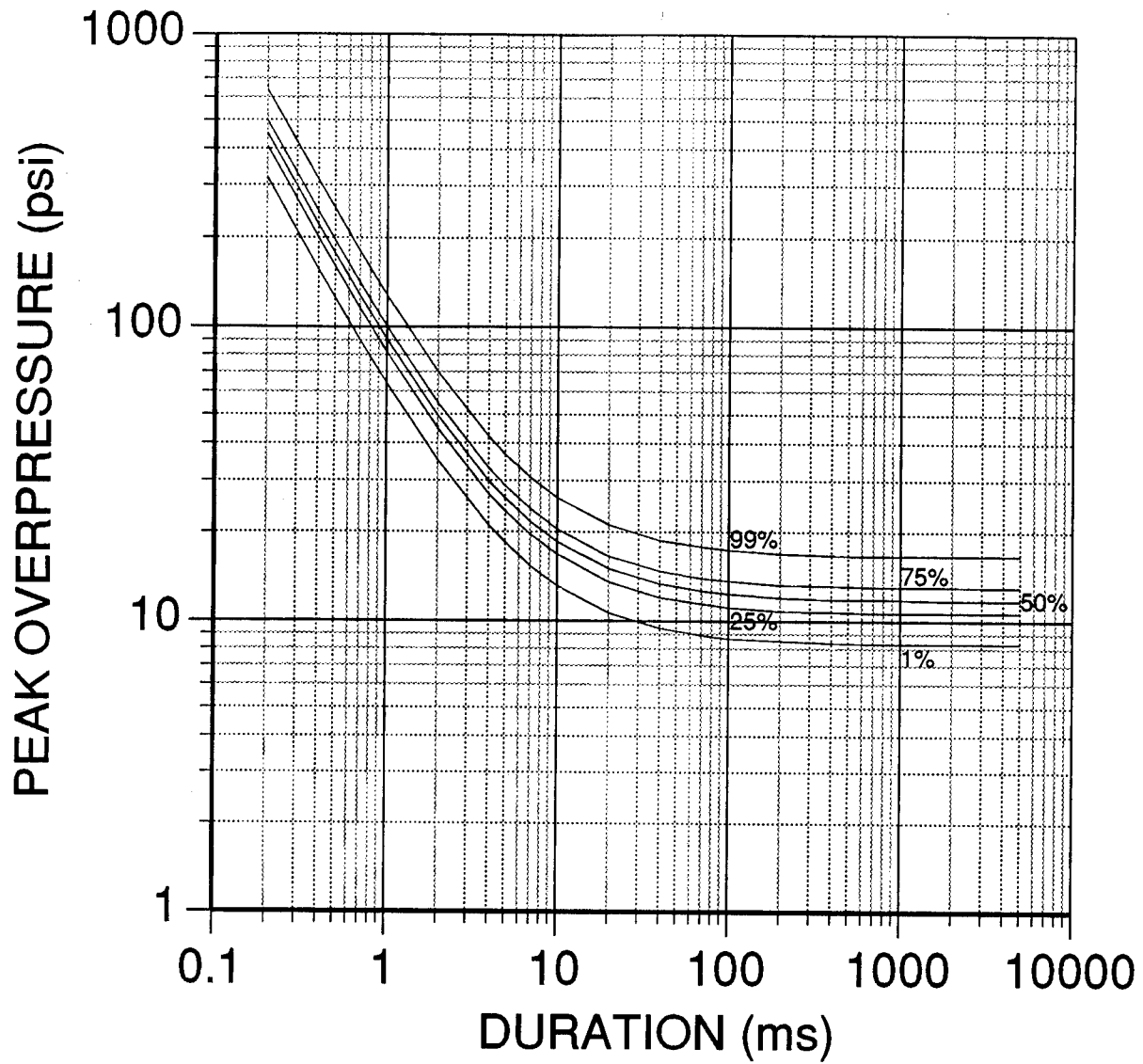
Figure A-20. Injury Curves for a Level 1 GI Tract Injury

UPPER AIRWAY INJURIES, LEVEL 5
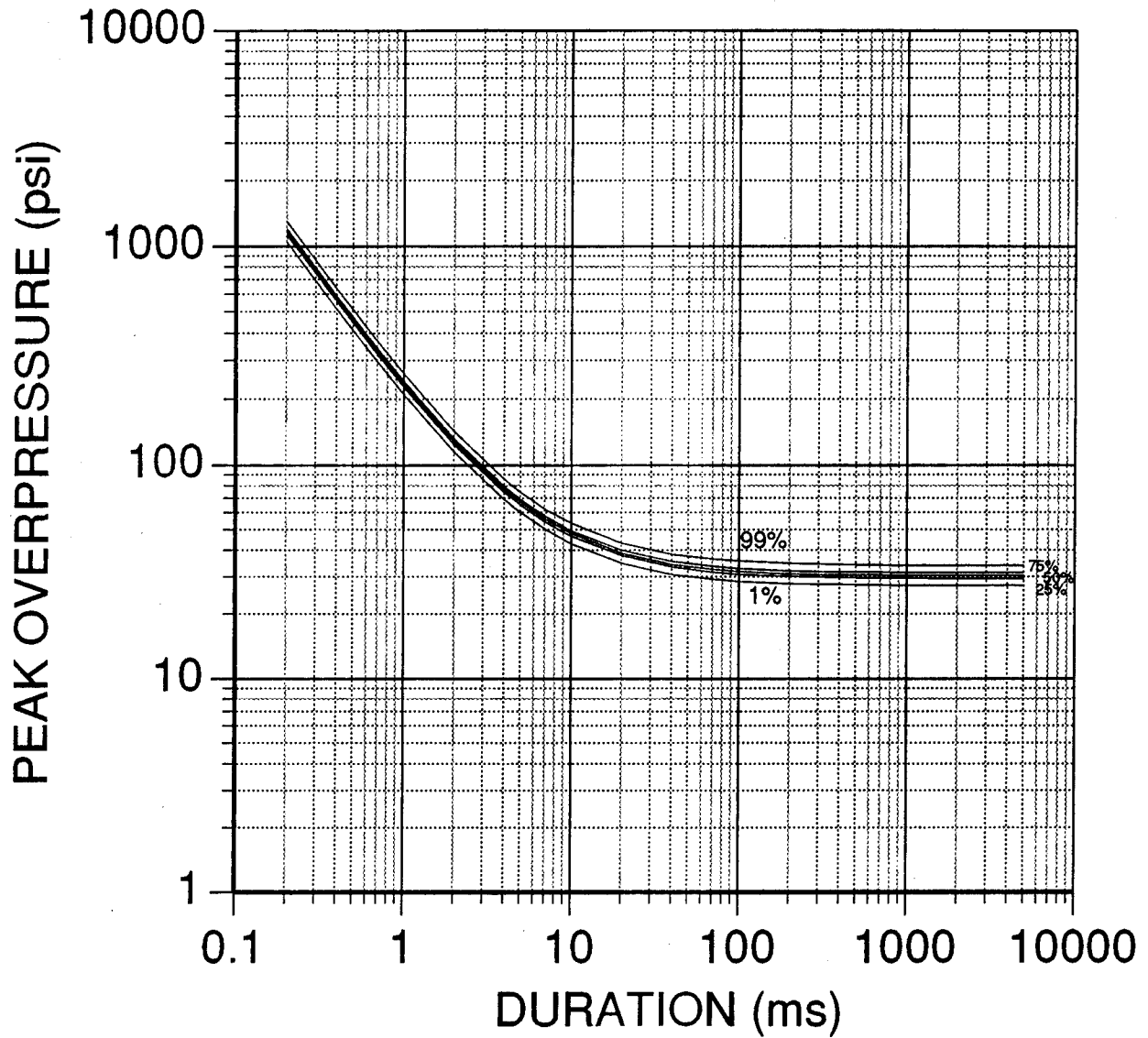
Figure A-21. Injury Curves for a Level 5 Upper Airway Injury

UPPER AIRWAY INJURIES, LEVEL 4
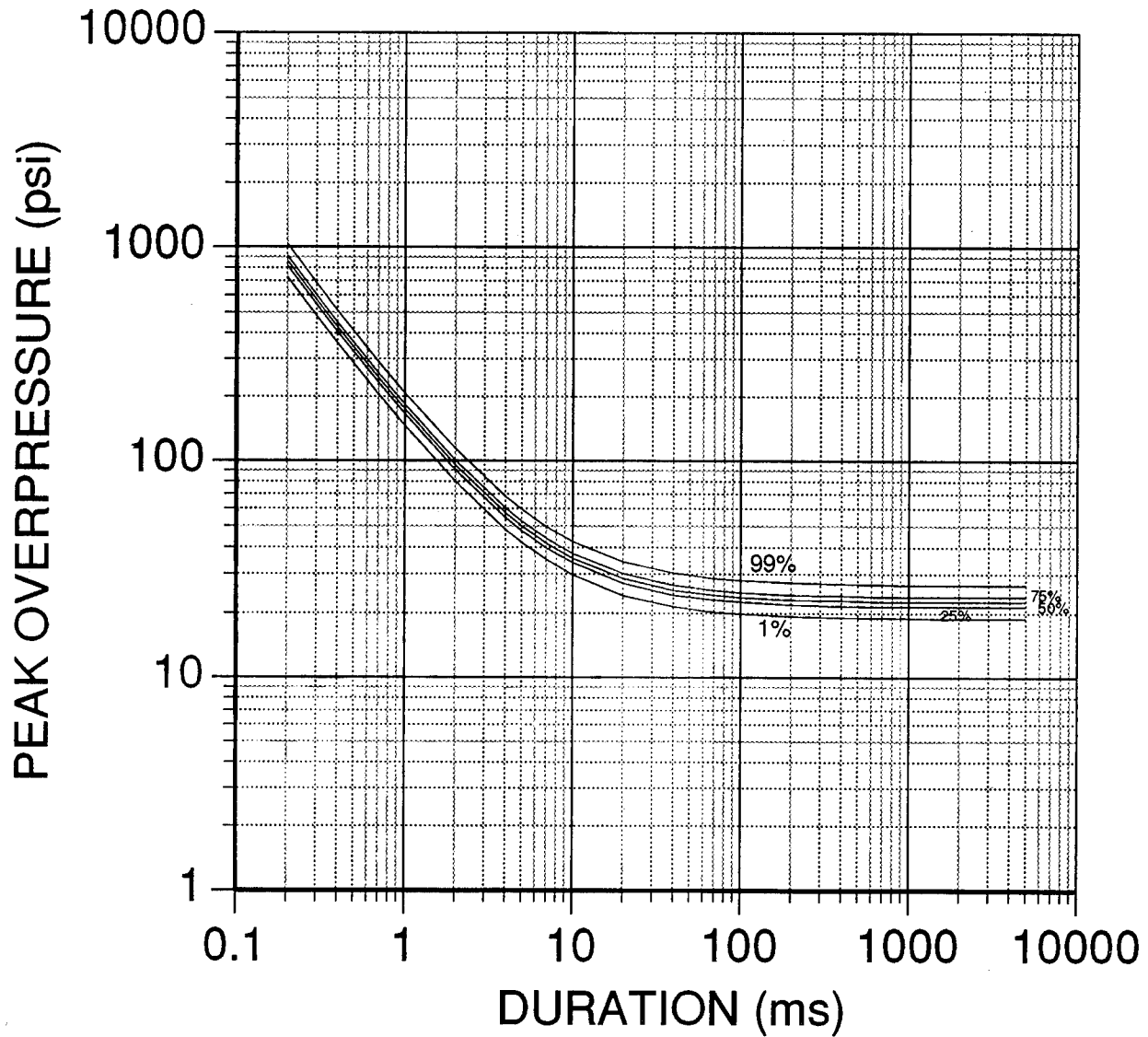
Figure A-22. Injury Curves for a Level 4 Upper Airway Injury

UPPER AIRWAY INJURIES, LEVEL 3
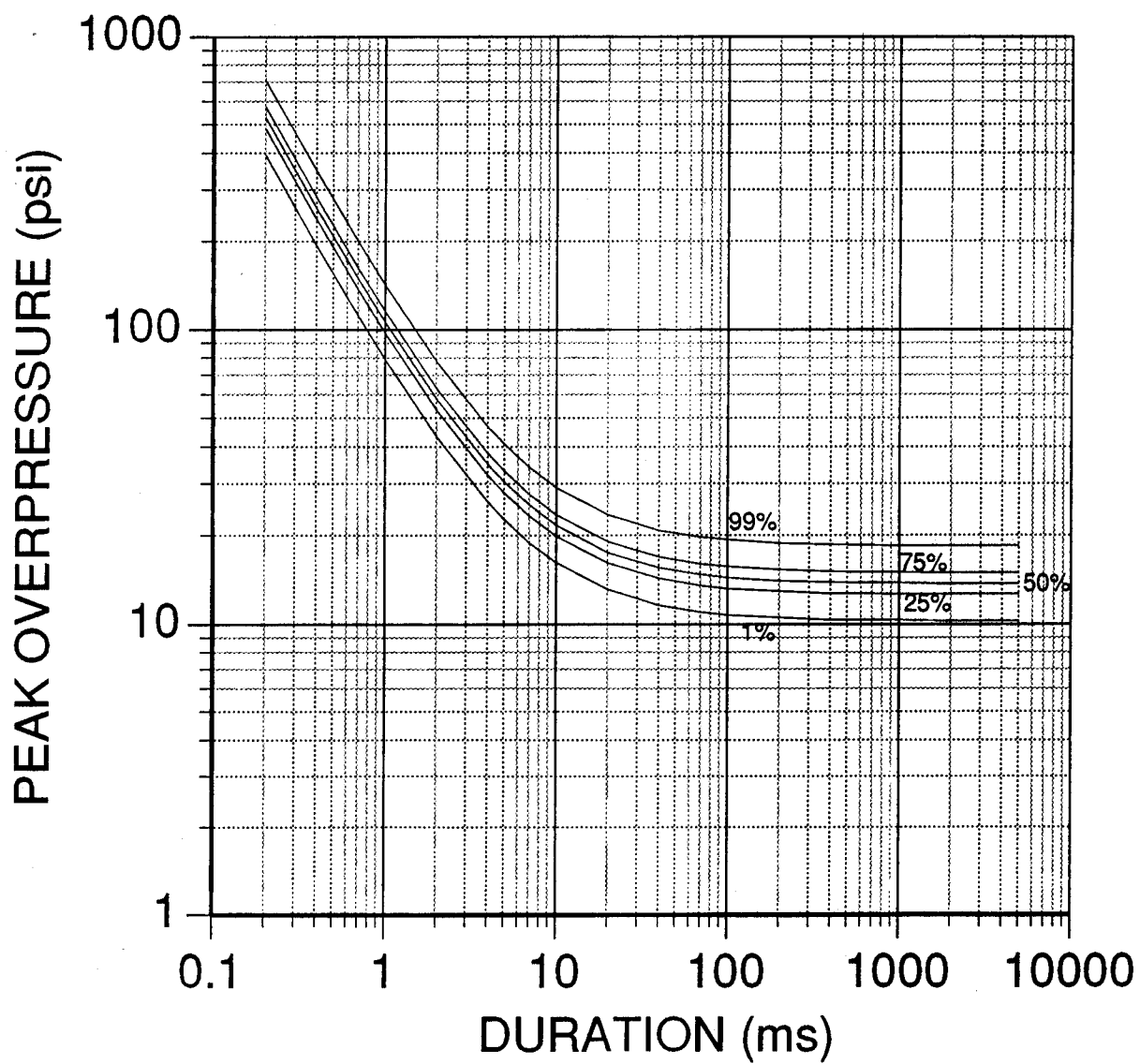
Figure A-23. Injury Curves for a Level 3 Upper Airway Injury

UPPER AIRWAY INJURIES,
LEVEL 2
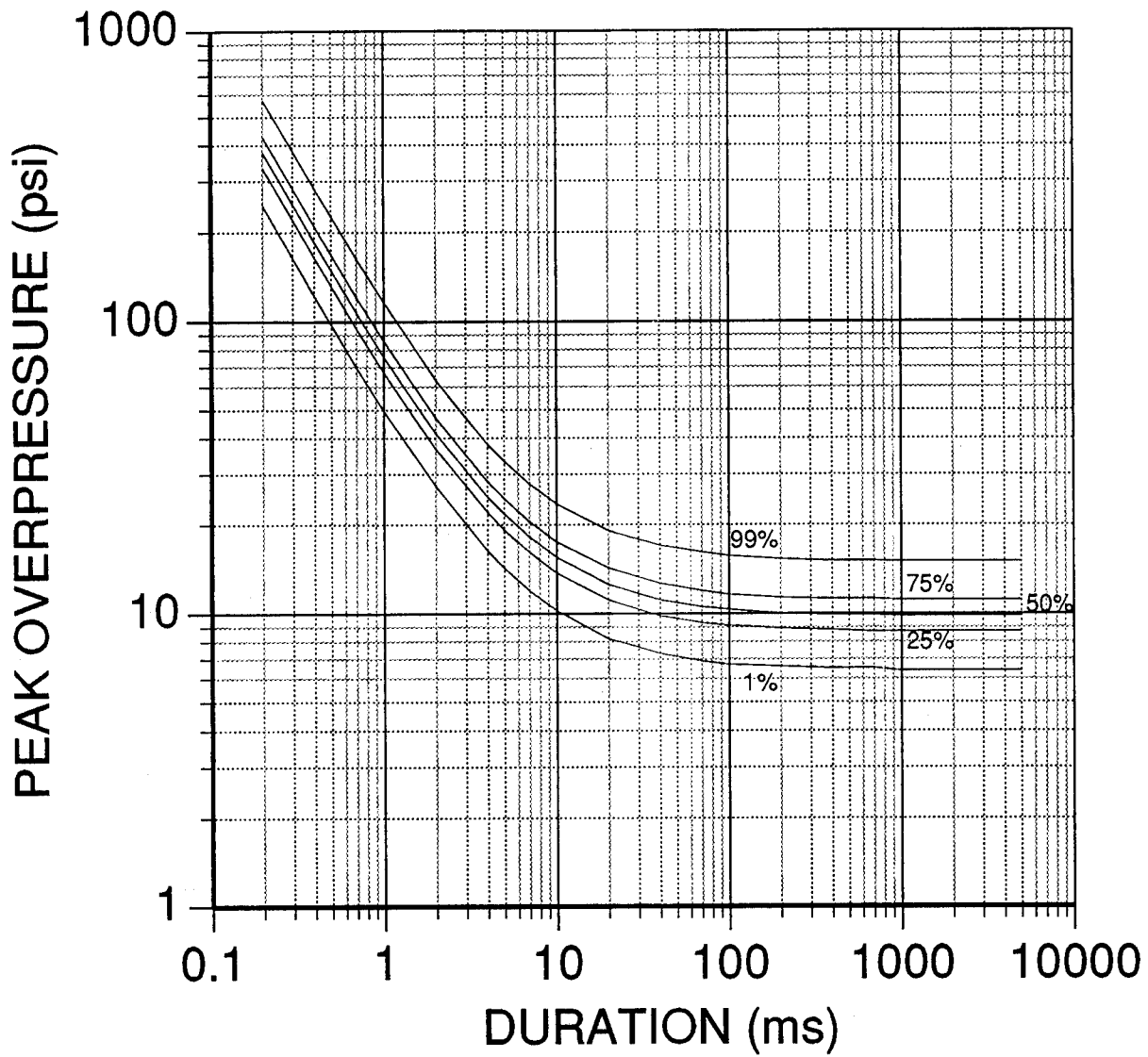
Figure A-24.   Injury Curves for a Level 2 Upper Airway Injury

UPPER AIRWAY INJURIES, LEVEL 1
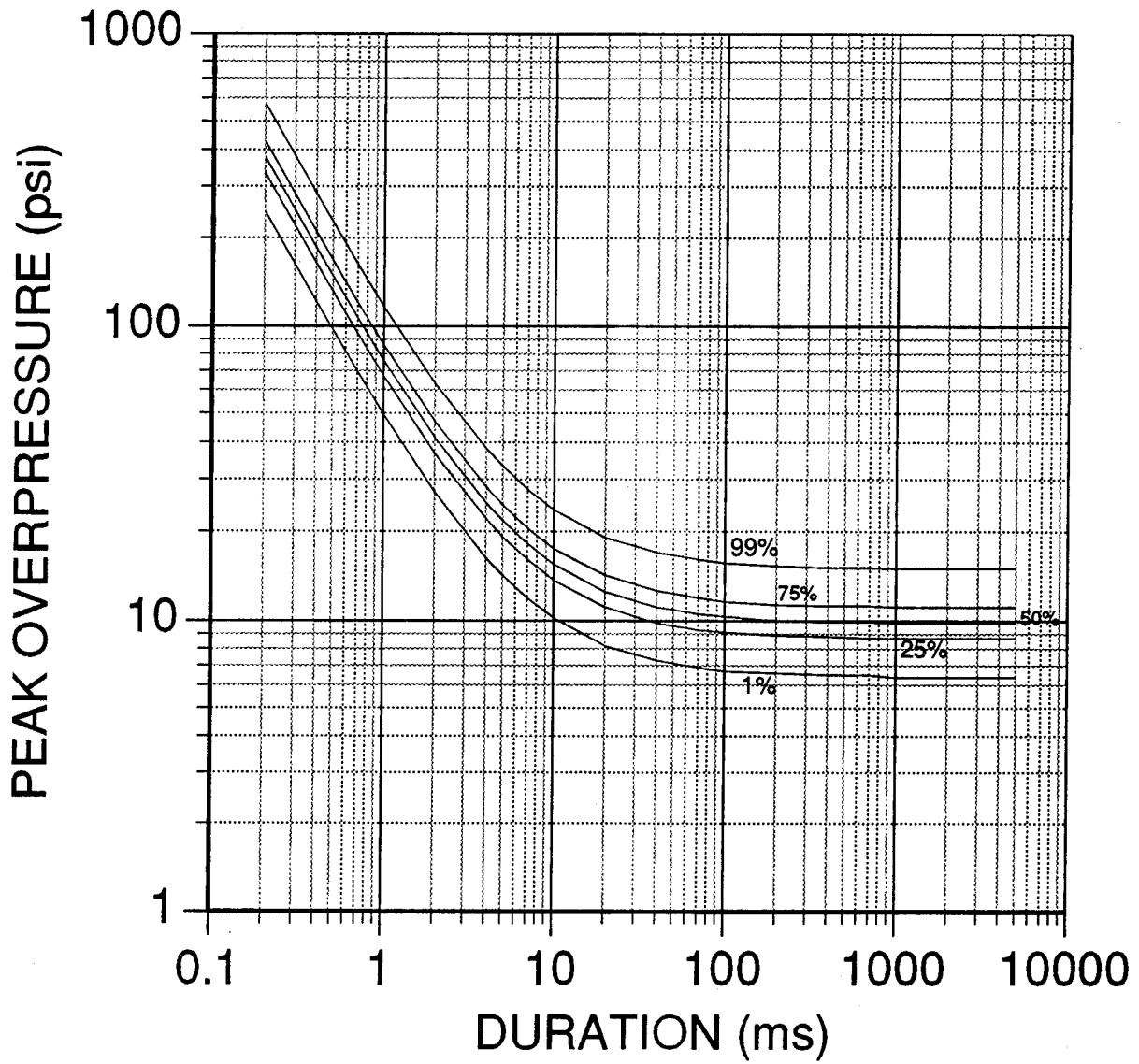
Figure A-25.   Injury Curves for a Level 1 Upper Airway Injury

EAR INJURY, LEVEL 3
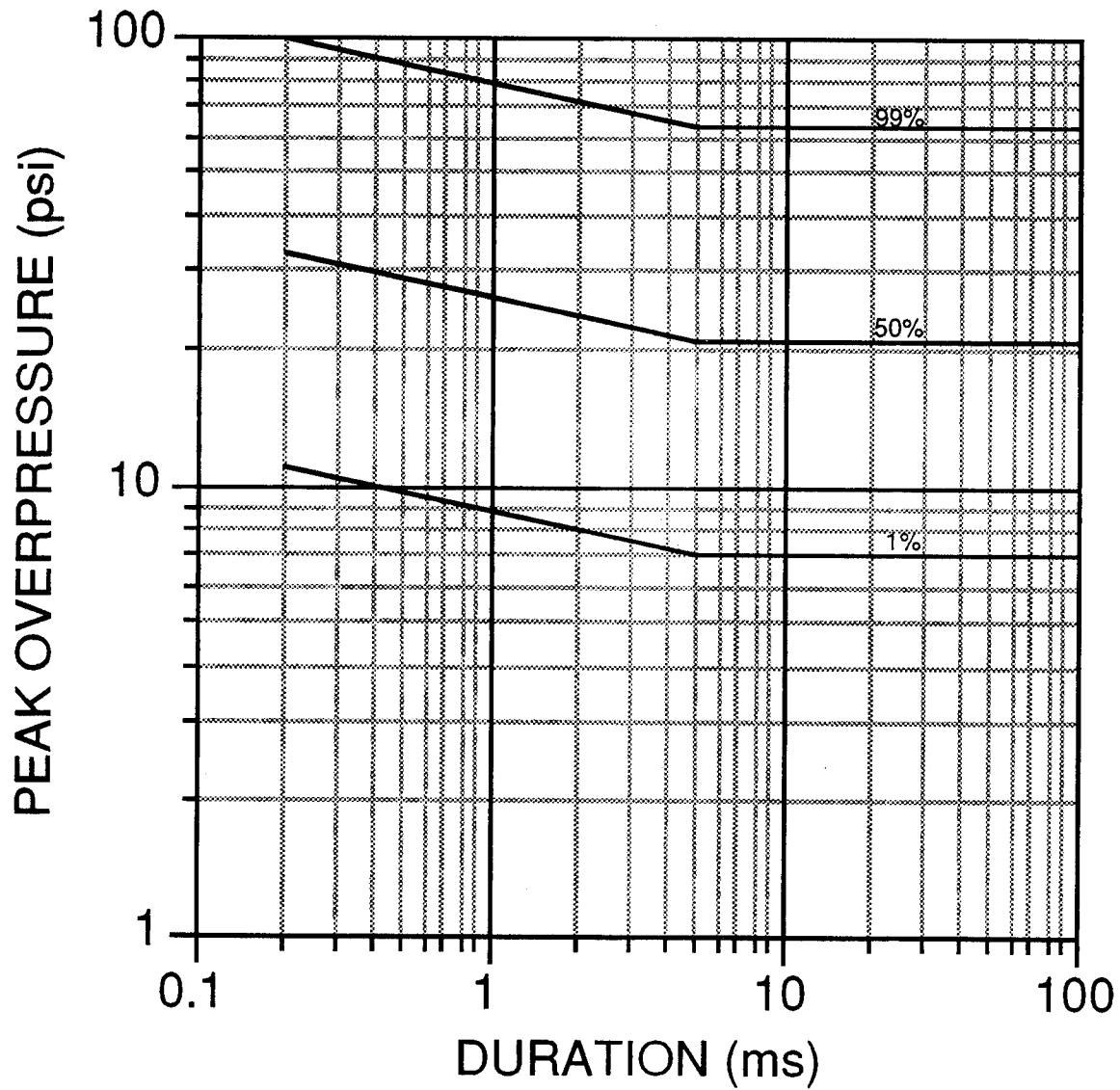
Figure A-26.   Injury Curves for a Level 3 Ear Injury

A-45
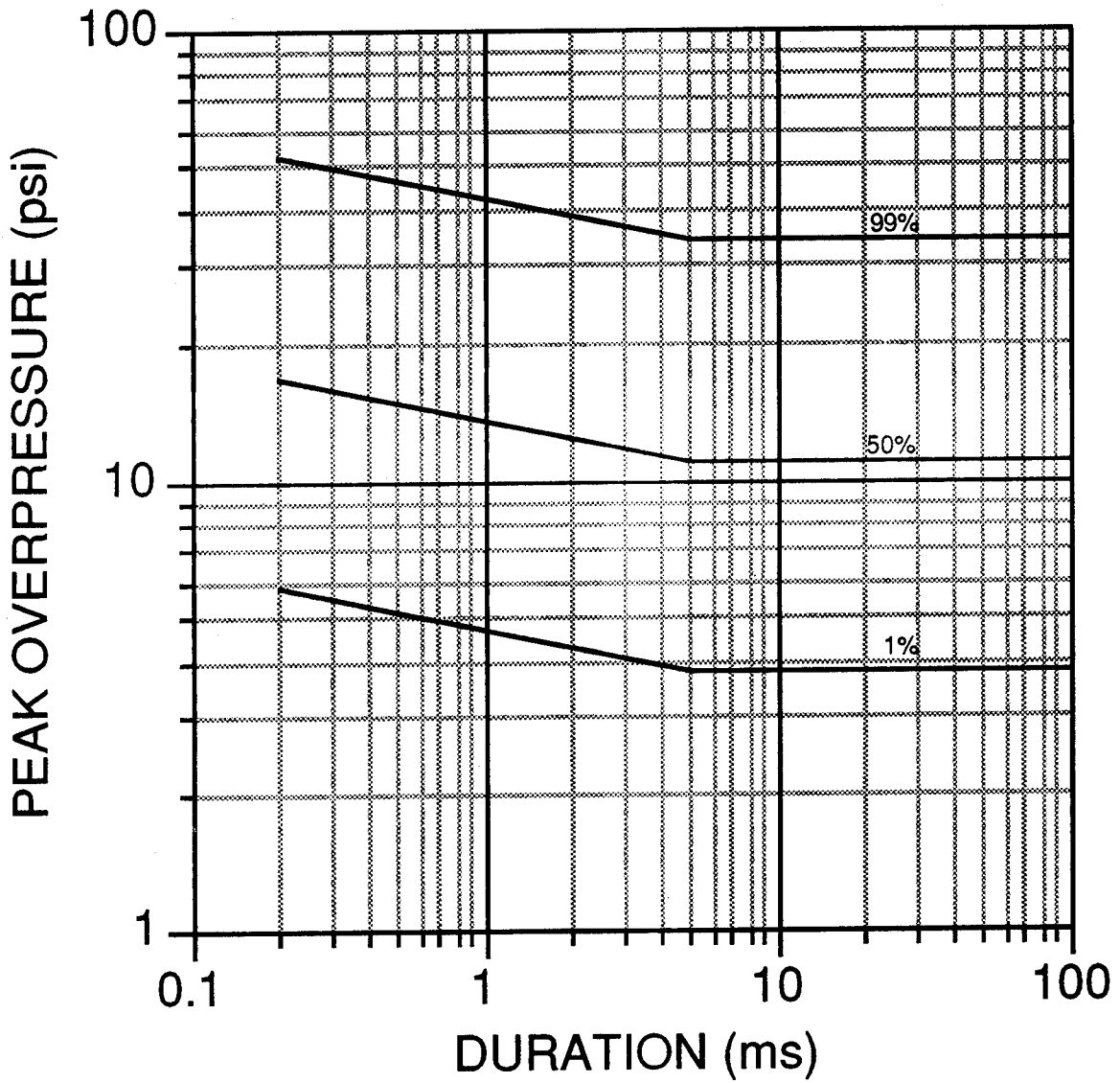
EAR INJURY, LEVEL 2

Figure A-27.   Injury Curves for a Level 2 Ear Injury

EAR INJURY, LEVEL 1
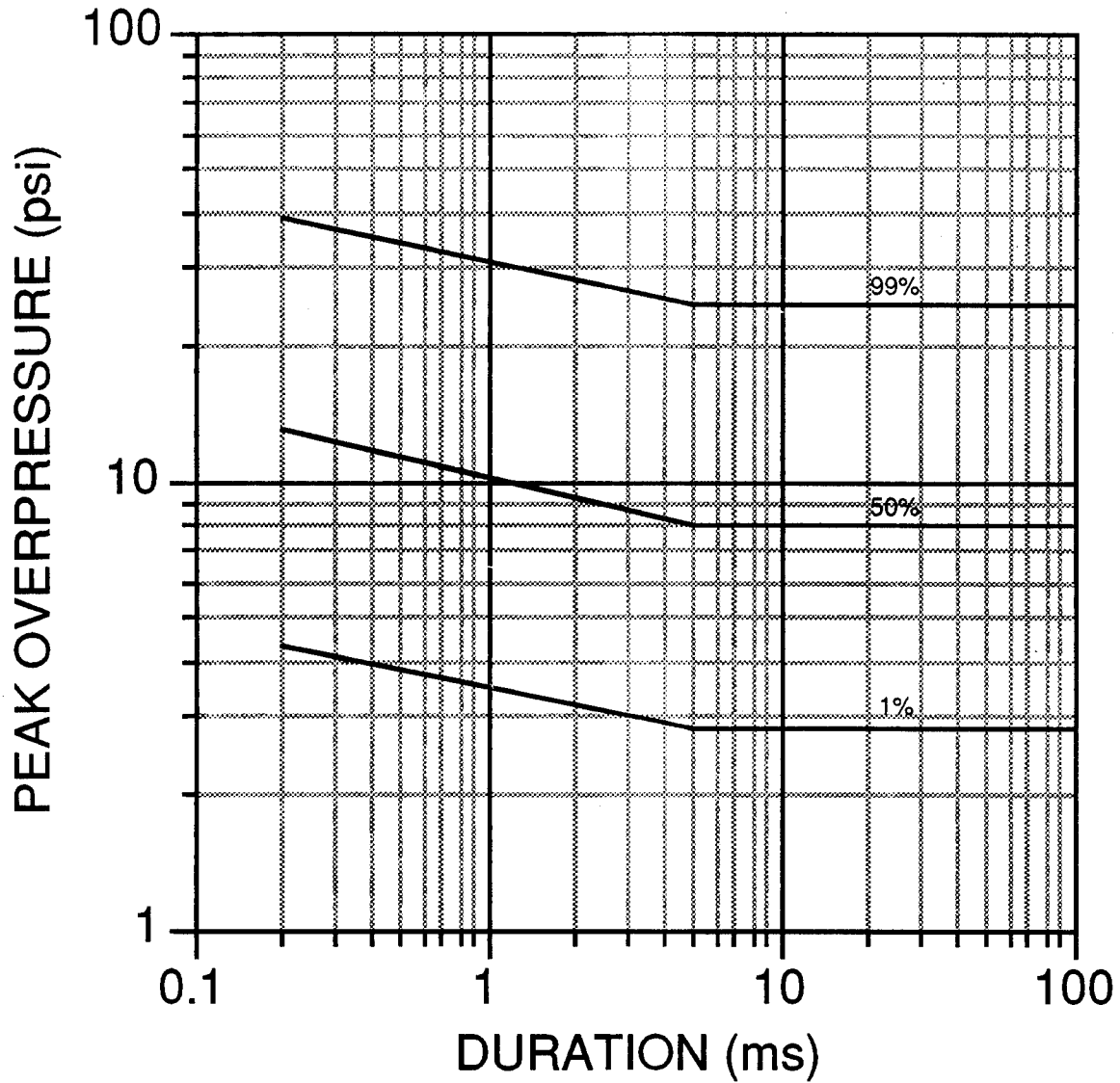
Figure A-28. Injury Curves for a Level 1 Ear Injury

A-47
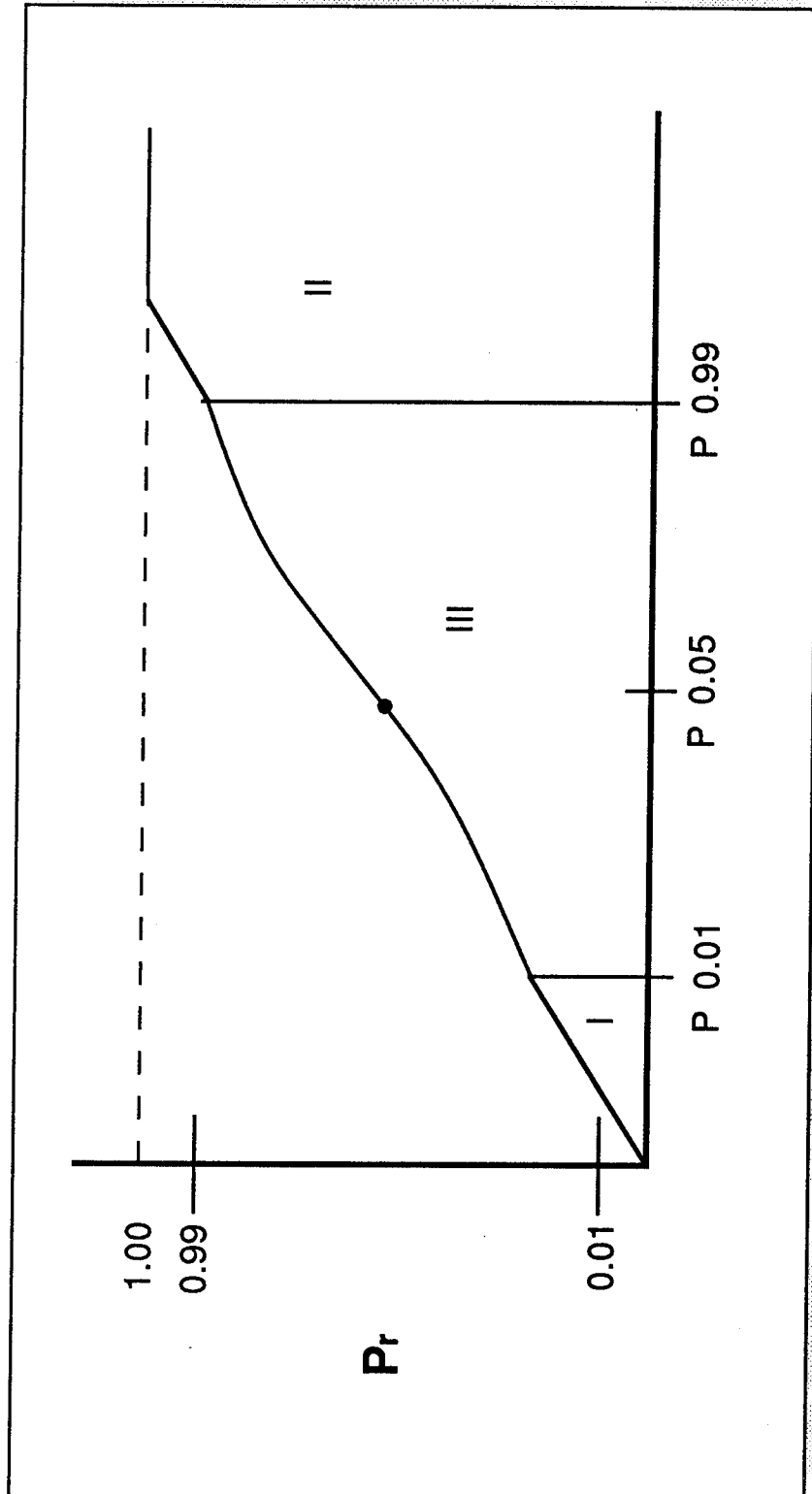
Figure A-29. Regions for Defining the Ear Injury Probability Curve

Level 1

$$P_{.01} = 2.8 \qquad \text{(A-40)}$$

$$P_{.50} = 8.1 \qquad \text{(A-41)}$$

$$P_{.99} = 25.0 \qquad \text{(A-42)}$$

A separate equation was developed for each region defined from the values of $P_{.01}$, $P_{.50}$, and $P_{.99}$ for a given duration.

For $0 < P < P_{.01}$, the following linear equation is used to represent Region I in Figure A-29:

$$P_r = \frac{.01}{P_{.01}} P \qquad \text{(A-43)}$$

where P_r is the injury probability.

For $P_{.99} < P < P_{.99} + (P_{.99} - P_{.50})$, Region II in Figure A-29 is defined by the following linear equation:

$$P_r = .99 + \frac{.01}{P_{.99} - P_{.50}} (P - P_{.99}) \qquad \text{(A-44)}$$

Additionally, if $P > P_{.99} + (P_{.99} - P_{.50})$, then $P_r = 1$.

For $P_{.01} < P < P_{.99}$, assume that the injury probability curve in Region III has a logistic functional form:

$$P_r = \frac{1}{1 + \exp(aP^2 + bP + c)} \qquad \text{(A-45)}$$

where P_r is the injury probability; P is the pressure at a particular duration, t; and a, b, c, are three parameters. Define a function Q:

$$Q = 1 - P_r = \frac{\exp(aP^2 + bP + c)}{1 + \exp(aP^2 + bP + c)} \qquad \text{(A-46)}$$

then,

$$\frac{Q}{P_r} = \exp(aP^2 + bP + c) \qquad \text{(A-47)}$$

and

$$\ln(\frac{Q}{Pr}) = aP^2 + bP + c \tag{A-48}$$

To solve for the unknown parameters, a, b, and c, it is noted that the curve defined by Equation A-28 passes through three points $(P_1, .01)$, $(P_2, .50)$, $(P_3, .99)$ where P_1, P_2, and P_3, are the pressure values for the 1-, 50-, and 99-percent probability curves at a given duration, t. Solving for the three unknown parameters is equivalent to finding the vector $(a,b,c)^T$ such that:

$$\begin{bmatrix} P_1^2 & P_1 & 1 \\ P_2^2 & P_2 & 1 \\ P_3^2 & P_3 & 1 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} \ln Q_1/Pr_1 \\ \ln Q_2/Pr_2 \\ \ln Q_3/Pr_3 \end{bmatrix} \tag{A-49}$$

A matrix representation of Equation A-29 is:

$$[A] [X] = [B] \tag{A-50}$$

and the solution X is readily obtainable as:

$$[X] = [A^{-1}] [B] \tag{A-51}$$

Once the values of a, b, and c are solved for a given duration t, the peak overpressure value, P, is substituted into Equation A-45 to calculate the injury probability for a particular level.

LIST OF REFERENCES

1.   Richmond, D. R. and Damon, E. G., "Primary Blast Injuries in the Open and in Foxholes Resulting from Nuclear Type Detonations", Technical Report, DNA-TR-90-212, Defense Nuclear Agency, Alexandria, VA, July 1991.

2.   Hirsch, F. G., "Effects of Overpressure on the Ear - A Review", Contract No DA-49-146-XZ-372, Defense Atomic Support Agency, Washington, D.C.

3.   Desaga, H. "Blast Injuries", Chap. 14 D in German Aviation Medicine, World War II, Vol. 2, pp. 1274-1293, U.S. Government Printing Office, Washington, D.C., 1950.

4.   Kokinakis, W., Rudolph, R. R., "An Assessment of the Current State-of-the-Art of Incapacitation by Air Blast", Ballistic Research Laboratory, Aberdeen Proving Ground, MD.

5.   Rossle, R., "Pathology of Blast Effects", Chap. 14-C in German Aviation Medicine, World War II, Vol. 2, pp. 1260-1273, U.S. Government Printing Office, Washington, D.C., 1950.

6.   Rusca, F., (1915) Deutsche Ztschr. f. Chir, CXXXII, 315.

7.   Bowen, I. G., Fletcher, E. R., Richmond, D. R., Hirsch, F. G. and White, C. S., "Biophysical Mechanisms and Scalling Procedures Applicable in Assessing Responses of the Thorax Energized by Air-Blast Overpressures or by Nonpenetrating Missiles", Defense Atomic Support Agency and U.S. Atomic Energy Commission, Washington, D.C.

8.   Richmond, D. R., and White, C. S., "A Tentative Estimation of Man's Tolerance to Overpressures from Air Blast", Technical Progress Report, DASA-1335, Defense Atomic Support Agency, Washington, D.C., November 7, 1962.

9.   Bowen, L. G., E. R. Fletcher and D. R. Richmond, Estimate of Man's Tolerance to the Direct Effects of Air Blast, DASA-2113, October 1968.

ANNEX 1

AUTOMATED OVERPRESSURE INJURY DETERMINATION COMPUTER PROGRAM

A FORTRAN computer program was developed to automate the procedures outlined in Section III for predicting overpressure injuries. The user inputs are peak overpressure (psi), duration (msec), ambient pressure (psi), and body weight (kg). Figure A1-1, illustrates the computer screen display for user inputs. In addition to showing the input values, the display indicates the location of output files.

A listing of a summary report is shown in Figure A1-2. Individual probabilities for each injury type by injury level are presented in the summary report along with a listing of the previous input values.

Another report that the program generates is a joint probability distribution report which calculates the joint probabilities of all (993) injury combinations. An example of a one page output of the report is shown in Figure A1-3. The first column respresents the injury combination number from 1 to 993. The second column lists the joint probabilities which are calculated by multipling the individual injury probabilities. The third through sixth columns indicates the particular injury and injury level. Column three is lung, column four is GI tract, column five is upper airways, and column six is ear injuries. The injury levels are numbered from zero to six with zero representing no injury and six representing lethal injuries. Figure A1-4 identifies the injury levels used for each particular injury.

The source code listing is included at the end of this annex, beginning on page A-57.

A. Output File Names:
   1. Joint Prob. Distribition: pmf.dat
   2. Summary report: summary.out
B. p0   weight
   14.7   70.
C. Peak Overpressure (psi) and Duration (msec.)
   50.   200.

Figure A1-1.   Computer Screen Display for Inputing Overpressure Variables

Summary Report

```
Peak Overpressure (psi):              50.00
Duration (msec.):                    200.00
Scaled Peak Overpressure (psi):       50.00
Scaled Duration (msec.):             200.00
Mean Psw (psi):                       61.50
Ambient Pressure (psi):               14.70
Average Weight (kg):                  70.00
Inputed weight (kg):                  70.00


Injury Type                     Probability

Lung
    Trivial                         .00000
    slight                          .00000
    Moderate                        .00079
    Severe                          .10504
    Very.Severe                     .79582
    Lethal                          .09835
    Not injured                     .00000
GI.Injury
    Trivial                         .00000
    slight                          .00000
    Moderate                        .00000
    Severe                          .00000
    Very.Severe                    1.00000
    Not injured                     .00000
Upper.Airway.Injury
    Trivial                         .00000
    slight                          .00000
    Moderate                        .00000
    Severe                          .00000
    Very.Severe                    1.00000
    Not injured                     .00000
Ear.Drum.Rupture
    Minor                           .00304
    Moderate                        .00647
    Major                           .99049
    Not injured                     .00000
```

Figure A1-2. Example Computer Output of Summary Report

```
 1     .000000   1  1  1  1
 2     .000000   1  1  1  2
 3     .000000   1  1  1  3
 4     .000000   1  1  1  0
 5     .000201   1  1  2  1
 6     .006061   1  1  2  2
 7     .004812   1  1  2  3
 8     .000088   1  1  2  0
 9     .009236   1  1  3  1
10     .278923   1  1  3  2
11     .221429   1  1  3  3
12     .004067   1  1  3  0
13     .000002   1  1  4  1
14     .000048   1  1  4  2
15     .000038   1  1  4  3
16     .000001   1  1  4  0
17     .000000   1  1  5  1
18     .000000   1  1  5  2
19     .000000   1  1  5  3
20     .000000   1  1  5  0
21     .000002   1  1  0  1
22     .000063   1  1  0  2
23     .000050   1  1  0  3
24     .000001   1  1  0  0
25     .000000   1  2  1  1
26     .000000   1  2  1  2
27     .000000   1  2  1  3
28     .000000   1  2  1  0
29     .000121   1  2  2  1
30     .003653   1  2  2  2
31     .002900   1  2  2  3
32     .000053   1  2  2  0
33     .005566   1  2  3  1
34     .168096   1  2  3  2
35     .133446   1  2  3  3
36     .002451   1  2  3  0
37     .000001   1  2  4  1
38     .000029   1  2  4  2
39     .000023   1  2  4  3
40     .000000   1  2  4  0
41     .000000   1  2  5  1
42     .000000   1  2  5  2
43     .000000   1  2  5  3
44     .000000   1  2  5  0
45     .000001   1  2  0  1
46     .000038   1  2  0  2
47     .000030   1  2  0  3
48     .000001   1  2  0  0
49     .000000   1  3  1  1
50     .000000   1  3  1  2
51     .000000   1  3  1  3
52     .000000   1  3  1  0
53     .000000   1  3  2  1
54     .000000   1  3  2  2
55     .000000   1  3  2  3
56     .000000   1  3  2  0
57     .000000   1  3  3  1
58     .000000   1  3  3  2
59     .000000   1  3  3  3
60     .000000   1  3  3  0
```

Figure A1-3.   Example of One Page Output of Joint
             Probability Distribution Report

```
Number of Types of Injuries:     4
(A)  Lung
     No. of Severity Levels:      6
       1       Trivial
       2       slight
       3       Moderate
       4       Severe
       5       Very.Severe
       6       Lethal
(B)  GI.Injury
     No. of Severity Levels:      5
       1       Trivial
       2       slight
       3       Moderate
       4       Severe
       5       Very.Severe
(C)  Upper.Airway.Injury
     No. of Severity Levels:      5
       1       Trivial
       2       slight
       3       Moderate
       4       Severe
       5       Very.Severe
(D)  Ear.Drum.Rupture
     No. of Severity Levels:      3
       1       Minor
       2       Moderate
       3       Major
```

Figure A1-4. Definition of Injury Levels Used in Computer Program

```
      program blast
c
c     Human Tolerance Handbook - Blast Overpressure Chapter
c     Estimation of Probabilities of Injuries Due to Blast
c     Overpressure

c     Version (1.0)
c     Designed and programmed by Dr. Kim L. Ong, BDM International

c     Global data (gloabl.dat)
c        input   filenm names
c           1. Global data - blast.dat
c           2. Injury Curves Data - injury.dat
c           3. Standard Normal CDF Data - cdfz.dat
c        output filenm names
c           1. Joint Probability Distributions
c           2. Casualty summary report

      common/epsln/epsln
      common/niter/niter
      character*30 filenm(7)
      common/filenm/filenm
      common/npar/npar
      common/pinjur/pinjur(4, 4)

      common/ntypes/ntypes
      common/ltotal/ltotal
      common/iflag/iflag

c     Mean Psw's
      common/avepsw/avepsw
c     Ambient Pressure at sea level, psi
      common/ambipr/ambipr
c     Average weight
      common/avewei/avewei

c     Initialization
      call initia

c     Read blast.dat
      call rdglob

c     Scale data
      call scale

c     Read curve data
      call rdcrvs

c     Output injury codes
      call codes

c     Read Standard Normal table
      call readz

c     Compute marginal probability distributions
      call comput

c     Compute joint probability distribution
      call joinpr
```

```
c       Produce summary report
        call report

        close (9)
        stop
        end


        subroutine initia
c       Initialization
c       Mean Psw's
        common/avepsw/avepsw
        common/pswp0/psw, p0, weight
c       Ambient Pressure at sea level, psi
        common/ambipr/ambipr
c       Average weight, kilogram
        common/avewei/avewei
        open(unit = 9, file = 'debug.out', status = 'new')
        rewind(9)
        psw     = 61.5
        avepsw = 61.5
        ambipr = 14.7
        avewei = 70.
        return
        end



        subroutine report
c       Produce summary report
        parameter(maxtyp = 4, maxlvl = 10, maxpmf = 2000)
        common/ntypes/ntypes
        common/nlevel/nlevel(maxtyp)
        common/level/level
        common/type/type
        common/ltotal/ltotal
        common/prob/prob(maxtyp, maxlvl)
        common/data1/peakp, scalpr, durat, scalt
        common/pswp0/psw, p0, weight
c       Mean Psw's
        common/avepsw/avepsw
c       Ambient Pressure at sea level, psi
        common/ambipr/ambipr
c       Average weight, kilogram
        common/avewei/avewei
        common/pmf/pmf(maxpmf)
        common/iflag/iflag
        common/severe/severe
        common/numpcs/numpcs(maxpmf)
        common/pcaray/pcaray
        integer severe(maxpmf)
        character*16 pcaray(maxpmf)

        character*20 type(maxtyp)
        character*20 level(maxtyp, maxlvl)

        common/curves/c1(maxtyp, maxlvl),
c                     c2(maxtyp, maxlvl),
c                     c3(maxtyp, maxlvl),
c                     c4(maxtyp, maxlvl)
```

```fortran
      character*30 filenm(7)
      common/filenm/filenm

      common/totalp/totalp(maxtyp)

      real probab(4)

c     Open report.out
      open(unit = 7, file = filenm(5), status = 'new')
      rewind(7)
      write(7, 11)
 11   format(30x, 'Summary Report', //)

      write(7, 12) peakp, durat, scalpr, scalt,
     c             avepsw, p0, avewei, weight
 12   format(2x, 'Peak Overpressure (psi):          ', f8.2,
     c    /, 2x, 'Duration (msec.):                 ', f8.2,
     c    /, 2x, 'Scaled Peak Overpressure (psi): ', f8.2,
     c    /, 2x, 'Scaled Duration (msec.):          ', f8.2,
     c    /, 2x, 'Mean Psw (psi):                   ', f8.2,
     c    /, 2x, 'Ambience Pressure (psi):          ', f8.2,
     c    /, 2x, 'Average Weight (kg):              ', f8.2,
     c    /, 2x, 'Inputed weight (kg):              ', f8.2,//)

      write(7, 13)
 13   format(2x, 'Injury Type                    Probability',/)
      do 1 i = 1, ntypes
         totalp(i) = 0.
         write(7, 2) type(i)
 2       format(2x, a20)
         do 3 j = 1, nlevel(i)
            write(7, 4) level(i, j), prob(i, j)
 4          format(5x, a20, 5x, f8.5)
            totalp(i) = totalp(i) + prob(i, j)
 3       continue
         write(7, 5) prob(i, nlevel(i)+1)
 5       format(5x, 'Not injured                   ', f8.5)
         totalp(i) = totalp(i) + prob(i, nlevel(i)+1)
 1    continue

      if (iflag .eq. 1) then
         do 14 i = 1, 4
            probab(i) = 0.
 14      continue
         do 15 i = 1, ltotal
            if (severe(i) .eq. 0) then
               probab(4) = probab(4) + pmf(i)
            else
               ilevel = severe(i)
               probab(ilevel) = probab(ilevel) + pmf(i)
            endif
 15      continue

         s = 0.
         do 20 i = 1, 4
            s = s + probab(i)
 20      continue
      write(7, 16) (probab(k), k = 1, 4), s
 16   format(//, 2x, 'Overall Probabilities: ', /,
```

```
c                2x, '      Pr{KIA}:                         ', f8.5,/,
c                2x, '      Pr{Seriously Injured}:           ', f8.5,/,
c                2x, '      Pr{Slightly Injured}:            ', f8.5,/,
c                2x, '      Pr{Not Injured}:                 ', f8.5,/,
c                2x, '      ------------------------------------',/,
c                2x, '      Total Probability:               ', f8.5)
      endif

      close (7)
      return
      end

      subroutine initv(v, nv)
c     Initialize a vector
      dimension v(nv)
      do 1 i = 1, nv
         v(i) = 0.
  1   continue
      return
      end

      subroutine comput
c     Compute the values of the parameters for injury curves
      parameter(maxtyp = 4, maxlvl = 10, maxpmf = 2000)
      common/ntypes/ntypes
      common/nlevel/nlevel(maxtyp)
      common/level/level
      common/type/type
      common/ltotal/ltotal
      common/prob/prob(maxtyp, maxlvl)
      common/data1/peakp, scalpr, durat, scalt

      character*20 type(maxtyp)
      character*20 level(maxtyp, maxlvl)

      common/curves/c1(maxtyp, maxlvl),
c                   c2(maxtyp, maxlvl),
c                   c3(maxtyp, maxlvl),
c                   c4(maxtyp, maxlvl)

      real w(maxlvl)

c     Find Lung, GI, and Airway injury probabilities
      do 1 i = 1, 3
         write(9, 15) type(i)
 15      format(a25)
         call initv(w, maxlvl)
         do 2 j = 1, nlevel(i)
            write(9, 15) level(i, j)
            z = probit(scalpr, scalt, i, j)
            write(9, *) ' j = ', j,  ' probit = ', z
            w(j) = phi(z - 5.)
            w(j) = 1. - w(j)
            write(9, *) ' j = ', j,  ' w(j) = ', w(j)
  2      continue
         prob(i, nlevel(i)) = w(nlevel(i))
         prob(i, nlevel(i)+1) = 1. - w(1)
         write(9, *) ' prob{no injuries} = ',
c           prob(i, nlevel(i)+1)
         do 3 k = 1, nlevel(i) - 1
```

```
            prob(i, k) = w(k) - w(k+1)
   3    continue
        do 4 k = 1, nlevel(i)
            write(9, 5) type(i), level(i, k), prob(i, k)
   5        format(2(1x, a25), 2x, f9.5)
   4    continue
   1 continue

c     Calculate eardrum injury probabilities:
      call earinj(scalpr, scalt)

      return
      end


      subroutine joinpr
c     Compute joint probability distribution
      parameter(maxtyp = 4, maxlvl = 10, maxpmf = 2000)
      common/ntypes/ntypes
      common/nlevel/nlevel(maxtyp)
      common/level/level
      common/type/type
      common/ltotal/ltotal
      common/prob/prob(maxtyp, maxlvl)

      common/nlvlp1/nlvlp1(maxtyp)
      common/pmf/pmf(maxpmf)

      character*20 type(maxtyp)
      character*20 level(maxtyp, maxlvl)

      character*30 filenm(7)
      common/filenm/filenm

      integer n(maxtyp)

      open(unit = 2, file = filenm(4), status = 'new')
      s = 0.
      do 1 m = 1, ltotal
         call map1tn(m, n)

c        compute the joint probability assuming independent
         p = 1.
         do 11 i = 1, ntypes
            p = p * prob(i, n(i))
  11     continue
         pmf(m) = p

         do 12 i = 1, ntypes
            if (n(i) .eq. nlvlp1(i)) n(i) = 0
  12     continue

         write(2, 2) m, p, (n(i), i = 1, ntypes)
   2     format(i5, 3x, f8.6, 10(1x, i2))
         s = s + p
   1 continue
      pnoinj = 1.
      do 13 i = 1, ntypes
         pnoinj = pnoinj * prob(i, nlvlp1(i))
  13 continue
      s = s - pnoinj
```

```fortran
      write(2, 15) s
15    format(' Overall Probability of being injured = ', f8.6)
      write(2, 14) s+pnoinj
14    format(' Total Probability =                    ', f8.6)
      close (2)

      return
      end


      subroutine rdglob
c     Read global data
      character*30 filenm(7)
      common/filenm/filenm
      common/iseed/iseed
      common/epsln/epsln
      common/niter/niter
      common/iflag/iflag
      common/npar/npar
      common/pswp0/psw, p0, weight

      common/data1/peakp, scalpr, durat, scalt

      open(unit = 1, file = 'blast.dat', status = 'old')

c     read output filenm names
      call skipln(1, 1)
      read(1, 2) filenm(4)
      read(1, 2) filenm(5)

2     format(32x, a30)

      call skipln(1, 1)
      read(1, *) p0, weight
      write(9, *) p0, weight

      call skipln(1, 1)
      read(1, *) peakp, durat
      write(9, *) peakp, durat

      close (1)
      return
      end


      subroutine skipln(ifile, nline)
c     Skip lines during reading
      character*90 line
      integer ifile, nline
      if (nline .eq. 0) return
      do 1 i = 1, nline
         read(ifile, 2) line
2        format(a90)
1     continue
      return
      end
```

A-62

```fortran
      subroutine mxinit(mx, nr, nc)

c     Initialize a real matrix mx with dimension nr x nc

c     Called from subroutines:

c     Parameters
c     Name          Comm.     Type       Description
c     mx            input     real       real matrix
c     nr            input     integer    row dimension of mx
c     nc            input     integer    column dimension of mx

c     Global Variables
c     Name                    Type       Description
c     (None)

c     Local Variables
c     Name                    Type       Description
c     i, j                    integer    loop control variables

      real mx(nr, nc)

c     Assign each element to zero and return
      do 1 i = 1, nr
         do 2 j = 1, nc
            mx(i, j) = 0.
2        continue
1     continue
      return
      end


      subroutine vmxmul(v1, mx, v2)

c     Premultiply a 4x4 real matrix mx by a vector v1

c     Called from subroutines:

c     Parameters
c     Name          Comm.     Type       Description
c     mx            input     real       a 4x4 real matrix
c     v1            input     real       a vector of dimension 4
c     v2            output    real       a vector of dimension 4

c     Global Variables
c     Name                    Type       Description
c     (None)

c     Local Variables
c     Name                    Type       Description
c     s                       real       sum
c     i, j                    integer    loop control variables

      real v1(4), v2(4), mx(4, 4)

c     Perform vector and matrix multiplication
      do 1 j = 1, 4
         s = 0.
         do 2 i = 1, 4
```

```
            s = s + v1(i) * mx(i, j)
    2       continue
c           Assign value to output vector and return
            v2(j) = s
    1 continue
      return
      end


      subroutine codes
c     Output injury codes
      parameter(maxtyp = 4, maxlvl = 10, maxpmf = 2000)
      integer n(maxtyp)
      common/ntypes/ntypes
      common/nlevel/nlevel(maxtyp)
      common/nlvlp1/nlvlp1(maxtyp)
      common/level/level
      common/type/type
      common/ltotal/ltotal
      character*20 type(maxtyp)
      character*20 level(maxtyp, maxlvl)

      open(unit = 2, file = 'code.dat', status = 'new')
      write(2, 4)
    4 format(3x,'No.    Severity Levels   Overall',12x,'DEPMEDS PCs')
      do 1 m = 1, ltotal
          call map1tn(m, n)

          do 3 i = 1, ntypes
              if (n(i) .eq. nlvlp1(i)) n(i) = 0
    3     continue

          write(2, 2) m, (n(i), i = 1, ntypes)
    2     format(i5, 3x, 10(1x, i2))
    1 continue
      close (2)
      return
      end


      subroutine map1tn(m, n)
c     Map injury code to an array of injury levels
      parameter(maxtyp = 4, maxlvl = 10, maxpmf = 2000)
      integer n(maxtyp)
      common/ntypes/ntypes
      common/nlevel/nlevel(maxtyp)
      common/nlvlp1/nlvlp1(maxtyp)
      common/level/level
      common/type/type
      common/ltotal/ltotal
      character*20 type(maxtyp)
      character*20 level(maxtyp, maxlvl)

      k = m
      do 1 i = 1, ntypes
          ncells = 1
          do 2 j = i+1, ntypes
              ncells = ncells * nlvlp1(j)
    2     continue
          no = k / ncells
          n(i) = no + 1
          if (k - no * ncells .eq. 0) n(i) = n(i) - 1
```

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```
                      nstart = (n(i) - 1) * ncells
                      k = k - nstart
              1 continue
                return
                end



                subroutine rdlvls
c       Read injury serverity level data
                parameter(maxtyp = 4, maxlvl = 10, maxpmf = 2000)
                character*30 filenm(7)
                common/filenm/filenm
                common/ntypes/ntypes
                common/nlevel/nlevel(maxtyp)
                common/nlvlp1/nlvlp1(maxtyp)
                common/level/level
                common/type/type
                common/ltotal/ltotal
                character*20 type(maxtyp)
                character*20 level(maxtyp, maxlvl)
                open(unit = 1, file = 'injury.dat', status = 'old')
                ltotal = 1
                read(1, 1) ntypes
                write(9, 1) ntypes
                do 2 i = 1, ntypes
                      read(1, 3) type(i)
                      write(9, 3) type(i)
              3       format(4x, a20)
                      read(1, 1) nlevel(i)
                      nlvlp1(i) = nlevel(i) + 1
c                     ltotal = ltotal * nlevel(i)
                      ltotal = ltotal * nlvlp1(i)
                      write(9, 1) nlevel(i)
                      do 4 j = 1, nlevel(i)
                            read(1, 5) level(i, j)
                            write(9, 5) level(i, j)
              5             format(10x, a20)
              4       continue
              2 continue
              1 format(30x, i2)
c       close (1)
                return
                end



                real function phi(x)
c       CDF of the standard normal distribition
                common/cdfz/cdfz(4000)
c       Error function


c       Called from subroutines:


c       Parameters
c       Name        Comm.    Type        Description


c       Function called
c       Name                 Type        Description
```

```fortran
c      Global Variables
c      Name                Type        Description
c      (None)

c      Local Variables
c      Name                Type        Description

       if (x .lt. 0.) then
          n = ifix(- x * 1000. + 0.5)
          if (n .eq. 0) then
             phi = 0.5
          elseif (n .gt. 4000) then
             phi = 0.
          else
             phi = 1. - cdfz(n)
          endif
       else
          n = ifix(x * 1000. + 0.5)
          if (n .eq. 0) then
             phi = 0.5
          elseif (n .gt. 4000) then
             phi = 1.
          else
             phi = cdfz(n)
          endif
       endif

       return
       end


       subroutine readz
c      Input CDF of the standard normal distribution


c      common/cnstnt/c1, c2, crit, epsiln, pi
       common/cdfz/cdfz(4000)
       character*30 filenm(7)
       common/filenm/filenm
       open(unit = 3, file = 'cdfz.dat', status = 'old')
       do 1 i = 1, 4000
          read(3, 2) z, cdfz(i)
    2     format(2(2x, f10.5))
    1  continue
       close (3)
       return
       end



       real function probit(p, t, i, j)
c      Compute the probit unit
c      p: scaled pressure
c      t: scaled duration
c      i: type  index
c      j: level index
       parameter(maxtyp = 4, maxlvl = 10, maxpmf = 2000)
       common/nset/nset
       common/ncurve/ncurve(maxlvl)
       common/curves/c1(maxtyp, maxlvl),
c                    c2(maxtyp, maxlvl),
```

```
c                       c3(maxtyp, maxlvl),
c                       c4(maxtyp, maxlvl)
      common/ntypes/ntypes
      v1 = c1(i, j)
      v2 = c2(i, j)
      v3 = c3(i, j)
      v4 = c4(i, j)
      write(9, *) ' i = ', i, ' j = ', j, ' p = ', p, ' t = ', t
      write(9, *) ' v1= ', v1, ' v2= ', v2, ' v3= ', v3, ' v4= ', v4
      v = exp(v3 * alog(t))
      write(9, *) ' exp(v3 * alog(t)) = ', v
      write(9, *) ' v2 = ', v2
      v = v2 * v
      write(9, *) ' v2 * exp(v3 * alog(t)) = ', v
      y = v1 * (1. + v2 * exp (v3 * alog(t)))
      write(9, *) ' y= ', y
      v = alog(p/y)
      write(9, *) ' alog(p/y) = ', v
      v = v / v4
      write(9, *) ' alog(p/y) / v4 = ', v
      probit = 5. - alog(p/y) / v4
      write(9, *) ' probit unit = ', probit
      return
      end



      subroutine rdcrvs
c     Input injury curves data
      parameter(maxtyp = 4, maxlvl = 10, maxpmf = 2000)
      common/ntypes/ntypes
      common/nlevel/nlevel(maxtyp)
      common/nlvlp1/nlvlp1(maxtyp)
      common/level/level
      common/type/type
      common/ltotal/ltotal
      character*20 type(maxtyp)
      character*20 level(maxtyp, maxlvl)
      call rdlvls
      call skipln(1, 1)
c     Read Lung, GI, and Airway injury curve data
      do 1 i = 1, 3
         do 2 j = 1, nlevel(i)
            read(1, *) itype, ilevel
            call calcul(itype, ilevel)
2        continue
1     continue
      call rdear
c     Read ear drum injury curve data
      close (1)
      return
      end



      subroutine calcul(itype, ilevel)
c     Compute injury probabilities
      parameter(maxtyp = 4, maxlvl = 10, maxpmf = 2000)
      common/curves/c1(maxtyp, maxlvl),
c                       c2(maxtyp, maxlvl),
c                       c3(maxtyp, maxlvl),
c                       c4(maxtyp, maxlvl)
```

```fortran
c      Working arrays
       real p(2), t(2), z(2), told(2), a(2, 2), b(2, 2),
      c      v(2), u(2)

c      Input type and level indices
       write(9, *) ' Type: ', itype, ' Level: ', ilevel
       do 1 i = 1, 2
           read(1, *) p(i), told(i), z(i)
           t(i) = 1. + 6.76 * told(i) ** (-1.064)
     1 continue

c      construct coefficient matrix
       do 2 i = 1, 2
        .  a(i, 1) = 1.
           a(i, 2) = 5. - z(i)
     2 continue

c      invert coefficient matrix
       det = a(1, 1) * a(2, 2) - a(1, 2) * a(2, 1)
       b(1, 1) = a(2, 2) / det
       b(1, 2) = - a(1, 2) / det
       b(2, 1) = - a(2, 1) / det
       b(2, 2) = a(1, 1) / det

c      Construct left hand side vector
       v(1) = alog(p(1)) - alog(t(1))
       v(2) = alog(p(2)) - alog(t(2))

c      Premultiply left hand side vector by the
c          inverted coefficient matrix

       u(1) = exp(b(1, 1) * v(1) + b(1, 2) * v(2))
       u(2) = b(2, 1) * v(1) + b(2, 2) * v(2)

c      Install solutions in common blocks
       c1(itype, ilevel) = u(1)
       c2(itype, ilevel) = 6.76
       c3(itype, ilevel) = -1.064
       c4(itype, ilevel) = u(2)

c      write to debug file
       write(9, *) ' i = ', itype, '    j = ', ilevel
       write(9, *) ' c1 = ', c1(itype, ilevel)
       write(9, *) ' c2 = ', c2(itype, ilevel)
       write(9, *) ' c3 = ', c3(itype, ilevel)
       write(9, *) ' c4 = ', c4(itype, ilevel)

       return
       end




       subroutine wrmtrx(a, m, n)
c      Output an m by n matrix
       real a(m, n)
       write(9, *)
       do 1 i = 1, m
           write(9, 2) (a(i, j), j = 1, n)
     2     format(10(1x, f12.5))
     1 continue
```

```
      return
      end


      subroutine scale
c     Compute scaled overpressure and duration
      common/data1/peakp, scalpr, durat, scalt
c     Mean Psw's
      common/avepsw/avepsw
c     Ambient Pressure at sea level, psi
      common/ambipr/ambipr
c     Average weight, kilogram
      common/avewei/avewei
      common/pswp0/psw, p0, weight
      write(9, *) ' psw, p0, weight '
      write(9, *) psw, p0, weight
      write(9, *) avewei, ambipr, avepsw
      write(9, *) ' avewei, ambipr, avepsw '
      scalt  = durat * exp(alog(avewei / weight) * (1. / 3.))
c                     * sqrt(p0 / ambipr)
      scalpr = peakp * (avepsw / psw) * (ambipr / p0)
      write(9, *) ' peakp = ', peakp
      write(9, *) ' durat = ', durat
      write(9, *) ' scalpr = ', scalpr
      write(9, *) ' scalt = ', scalt
      return
      end


      subroutine earinj(p, t)
c     Find the eardrum injury probabilities
c     p: scaled overpressure, phi
c     t: scaled duration, millisec
      parameter(maxtyp = 4, maxlvl = 10, maxpmf = 2000)
      common/ntypes/ntypes
      common/nlevel/nlevel(maxtyp)
      common/ear/pct(3, 3), xval(3, 2), yval(3, 2, 3), slope(3, 3)
      common/prob/prob(maxtyp, maxlvl)
      real x(3), y(3), pr(3)
      real crvfit
c     For each eardrum injury level, do the following:
      do 1 i = 1, 3
         write(9, *) ' Level ', i, ' and above: '
         do 2 j = 1, 3
            y(j) = pct(i, j)
2        continue
c        Find pressure values at duration = t on three lines
c        If (t, p) is in the short duration region
         if (t .lt. xval(i, 2)) then
            write(9, *) ' t = ', t, ' xval(i, 2) = ', xval(i, 2)
            write(9, *) ' Short duration '
            do 3 j = 1, 3
               x(j) = yval(i, 1, j) + slope(i, j) * (t - xval(i, 1))
               write(9, *) ' j = ', j, ' x(j) = ', x(j)
3           continue
         else
            write(9, *) ' t = ', t, ' xval(i, 2) = ', xval(i, 2)
            write(9, *) ' Long  duration '
            do 4 j = 1, 3
               x(j) = yval(i, 2, j)
```

```fortran
             write(9, *) ' j = ', j, ' x(j) = ', x(j)
4         continue
       endif
       pr(i) = crvfit(x, y, p)
       write(9, *) ' fitted value = ', pr(i)
1   continue
     prob(4, 1) = pr(1) - pr(2)
     prob(4, 2) = pr(2) - pr(3)
     prob(4, 3) = pr(3)
     prob(4, 4) = 1. - prob(4, 1) - prob(4, 2) - prob(4, 3)
     write(9, *) (prob(4, j), j = 1, 4)
     return
     end


     real function crvfit(x, y, p)
c    Curve fitting routine
     real x(3), y(3), p
     real v1(3), a(3, 3), b(3, 3), v2(3)

     write(9, *) ' Pressure = ', p
     do 1 i = 1, 3
        write(9, *) i, x(i), y(i)
1   continue

c    Find coefficient matrix A given vector X
     call lgcoef(x, a)
     write(9, *) ' Coeff matrix: '
     call wrmtrx(a, 3, 3)
c    Find left-hand side vector V1 given vector Y
     call lglhs(y, v1)
     write(9, *) ' Left hand side vector: '
     call wrvect(v1, 3)
c    Find the inverse of the matrix A
     call mxinvs(a, b)
     write(9, *) ' Inverse of the Coeff matrix: '
     call wrmtrx(b, 3, 3)
c    Find the product of B and V1
     call multip(b, v1, v2)
     write(9, *) ' Parameters: '
     call wrvect(v2, 3)

c    Read the probability from the fitted logistic curve
     crvfit = fitval(x, y, v2, p)
     write(9, *) ' fitted value = ', crvfit
     return
     end

     subroutine rdear
c    Read eardrum injury curve data
     common/ear/pct(3, 3), xval(3, 2), yval(3, 2, 3), slope(3, 3)
     do 1 i = 1, 3
        read(1, *) itype, ilevel
        read(1, *) (pct(ilevel, j), j = 1, 3)
        read(1, *) xval(ilevel, 1), (yval(ilevel, 1, k), k = 1, 3)
        read(1, *) xval(ilevel, 2), (yval(ilevel, 2, k), k = 1, 3)
        write(9, *) itype, ilevel
        write(9, *) (pct(ilevel, j), j = 1, 3)
        write(9, *) xval(ilevel, 1), (yval(ilevel, 1, k), k = 1, 3)
        write(9, *) xval(ilevel, 2), (yval(ilevel, 2, k), k = 1, 3)
```

```
          do 2 j = 1,  3
              slope(i,  j) = (yval(i,  2,  j) - yval(i,  1,  j)) /
c                             (xval(i,  2) - xval(i,  1))
              write(9,  *) ' i = ', i, ' j = ', j, ' s = ', slope(i, j)
2         continue
c         Extrapolation of the data
          if (xval(i,  1) .gt. 0.) then
              do 4 j = 1,  3
                  yval(i,  1,  j) = yval(i,  1,  j)
c                             - slope(i,  j) * xval(i,  1)
4             continue
              xval(i,  1) = 0.
          endif
1     continue
c     close (1)
      return
      end



      subroutine wrvect(v,  nv)
c     Output a vector v of length nv
      dimension v(nv)
      do 1 i = 1,  nv
          write(9,  2) v(i)
2         format(2x,  f10.5)
1     continue
      return
      end




      subroutine lgcoef(v,  a)
c     Construct the coefficient matrix for
c     solving logistic curve parameters
      dimension v(3),  a(3,  3)
      do 1 i = 1,  3
          a(i,  1) = 1.
          a(i,  2) = v(i)
          a(i,  3) = v(i) ** 2
1     continue
      return
      end

      subroutine lglhs(v1,  v2)
c     Construct the left hand side vector for
c     solving logistic curve parameters
      dimension v1(3),  v2(3)
      do 1 i = 1,  3
          v2(i) = alog((1. - v1(i)) / v1(i))
1     continue
      return
      end



      subroutine mxinvs(a,  b)
c     Invert a 3x3 matrix
      dimension a(3,  3),  b(3,  3)
      a11 = a(1,  1)
      a12 = a(1,  2)
```

```fortran
      a13 = a(1, 3)
      a21 = a(2, 1)
      a22 = a(2, 2)
      a23 = a(2, 3)
      a31 = a(3, 1)
      a32 = a(3, 2)
      a33 = a(3, 3)
      det = a11 * a22 * a33
c     + a12 * a23 * a31
c     + a13 * a21 * a32
c     - a13 * a22 * a31
c     - a11 * a32 * a23
c     - a12 * a21 * a33
c     write(9, *) ' det(A) = ', det

      b(1, 1) =   (a22 * a33 - a23 * a32) / det
      b(2, 1) = - (a21 * a33 - a23 * a31) / det
      b(3, 1) =   (a21 * a32 - a22 * a31) / det

      b(1, 2) = - (a12 * a33 - a13 * a32) / det
      b(2, 2) =   (a11 * a33 - a13 * a31) / det
      b(3, 2) = - (a11 * a32 - a12 * a31) / det

      b(1, 3) =   (a12 * a23 - a13 * a22) / det
      b(2, 3) = - (a11 * a23 - a13 * a21) / det
      b(3, 3) =   (a11 * a22 - a12 * a21) / det

      return
      end


      subroutine mxmult(a, b, c, n)
c     Matrix multiplication
      dimension a(n, n), b(n, n), c(n, n)
      do 1 i = 1, n
         do 2 j = 1, n
            s = 0.
            do 3 k = 1, n
               s = s + a(i, k) * b(k, j)
3           continue
            c(i, j) = s
2        continue
1     continue
      return
      end


      subroutine multip(a, v1, v2)
c     Post multiplication of a matrix by a vector
      dimension a(3, 3), v1(3), v2(3)
      do 1 i = 1, 3
         s = 0.
         do 2 k = 1, 3
            s = s + a(i, k) * v1(k)
2        continue
         v2(i) = s
1     continue
      return
      end
```

```fortran
      real function fitval(x, y, coef, v)
c     Find fitted probability on the logistic curve
c     coef: parameters of the fitted logistic curve
c     x: three percentiles
c     y: three percent values (0.01, 0.50. 0.99)
      dimension x(3), y(3), coef(3)
      if (v .lt. x(1)) then
          s1 = y(1) / x(1)
          fitval = s1 * v
      elseif (v .gt. x(3)) then
          s2 = (1. - y(3)) / (x(3) - x(2))
          fitval = y(3) + s2 * (v - x(3))
          if (fitval .gt. 1.) fitval = 1.
      else
          fitval = 1. + exp(coef(1) + coef(2)*v + coef(3)*v**2)
          fitval = 1. / fitval
      endif
      return
      end
```

ANNEX 2

MANUAL PROCEDURES FOR INJURY PREDICTION

A.   PROCEDURE

This annex outlines the basic procedures that a user would follow to calculate injury probabilities resulting from a given pressure and duration. First, peak pressure (incident, incident plus dynamic, or reflected) and duration are calculated by the user based upon the body orientation of the exposed population. If non-standard conditions are to be considered such as changes to the standard body weight of 70 kg or ambient pressure of 14.7 psi, then Equations A-1 and A-2, are used to calculate scaled pressure, P, and duration, T. The next step would be to determine the cumulative "at least" probabilities for each primary injury using the injury equations and injury curves identified in Appendix A, Paragraph C 4 e. Finally, individual injury level probabilities would then be calculated from the cumulative injury probabilities using the procedure described in Appendix A, Paragraph C 4 d. Examples to illustrate different aspects of this procedure are provided in the next section.

B.   EXAMPLE PROBLEMS

1.   Example 1:

a.   Problem

A surface burst nuclear artillery shell explodes in front 50 soldiers who are in prone positions. From the location and yield of the weapon, the peak incident overpressure and duration is calculated to be 80 psi and 1000 ms respectively. Find the percentages of individuals killed or experience lung injuries due to overpressure effects. Calculate using the equation method assuming standard body weight of 70 kg and standard ambient pressure of 14.7 psi.

b.   Solution

Using Equations A-4 and A-10 through A-14, after some algebraic manipulation, z is calculated by substituting for P and T for each injury level:

Level 6
$$z = 5 - \frac{1}{.1788} \ln \frac{80}{61.5[1+6.76(1000)^{-1.064}]} = 3.545$$

Level 5
$$z = 5 - \frac{1}{.0359} \ln \frac{80}{46.9[1+6.76(1000)^{-1.064}]} = .1849$$

Level 4
$$z = 5 - \frac{1}{.0501} \ln \frac{80}{42.0[1+6.76(1000)^{-1.064}]} = -7.775$$

Level 3

$$z = 5 - \frac{1}{.0509} \ln \frac{80}{33.2[1+6.76(1000)^{-1.064}]} = -12.193$$

Level 2

$$z = 5 - \frac{1}{.0872} \ln \frac{80}{21.5[1+6.76(1000)^{-1.064}]} = -10.019$$

Level 1

$$z = 5 - \frac{1}{.110} \ln \frac{80}{15.6[1+6.76(1000)^{-1.064}]} = -9.822$$

Following the procedure outlined in Appendix A, Paragraph C 4 e (1), 5 is subtracted from the value of z, and the resulting value is used to enter Table A-7. Applying equations A-6 and A-7 to the values from Table A-7, the cumulative probabilities suffering at least the specified lung injury level found to be:

Level 6 (Killed): .9279

Level 5:   1.000

Level 4:   1.000

Level 3:   1.000

Level 2:   1.000

Level 1:   1.000

These probabilities are identified by the following notation used in Appendix A, Paragraph C 4 d.

$F_1(0) = 1,$ $F_1(1) = 1, F_1(2) = 1, F_1(3) = 1$

$F_1(4) = 1,$ $F_1(5) = 1 \; F_1(6) = .9279$

Using Equation A-3, the resulting individual probabilities are calculated below:

$f_1(6) = F_1(6) = .9279$

$f_1(5) = F_1(5) - F_1(6) = 1 - .9279 = .0721$

$f_1(4) = F_1(4) - F_1(5) = 1 - 1 = 0$

$f_1(3) = F_1(3) - F_1(4) = 1 - 1 = 0$

$f_1(2) = F_1(2) - F_1(3) = 1 - 1 = 0$

$f_1(1) = F_1(1) - F_1(0) = 1 - 1 = 0$

$f_1(0) = F_1(0) - F_1(1) = 1 - 1 = 0$

2.   Example 2

   a.   Problem

   A general purpose (GP) bomb detonates above 100 people lying prone in an open field. The reflected pressure and duration is 11.6 psi and 1 ms. Using the injury curves, determine the number of ear injuries by injury level which would result.

   b.   Solution

   Given the scaled pressure and duration, determine the probabilities, $F_4(x)$, by interpolating from Figures A-26 through A-28.

$$F_4(0) = 1, \qquad F_4(1) = .55, F_4(2) = .45, F_4(3) = .10$$

   Using Equation A-3, the probabilities $f_4(x)$ of sustaining exactly each level of ear injury are calculated to be:

   Level 3: $f_4(3) = F_4(3) = .10$

   Level 2: $f_4(2) = F_4(2) - F_4(3) = .45 - .10 = .35$

   Level 1: $f_4(1) = F_4(1) - F_4(2) = .55 - .45 = .10$

   No Injury: $f_4(0) = F_4(0) - F_4(1) = 1 - .55 = .45$

   The number and type of ear injuries are:

   Level 3: 100 x .10 = 10

   Level 2: 100 x .35 = 35

   Level 1: 100 x .10 = 10

   No Injury: 100 x .45 = 45

3.   Example 3

   a.   Problem

   A ground burst GP bomb detonates in front of a group of airmen standing near a building. Based on the location and explosive weight of the weapon, the peak reflected overpressure and duration is calculated to be 50 psi and 1 ms respectively. Calculate the percentage of the various levels of ear injuries using the curve fitting techniques.

   b.   Solution

   First, calculate the peak pressures for each ear injury level for 1-, 50-, and 99-percent probabilities using equations A-25 through A-33.

   Level 3

$$P_{.01} = -.83(1) + 11.2 = 10.4$$

$$P_{.50} = -2.5(1) + 33.5 = 31.0$$

$$P_{.99} = -7.7(1) + 101.5 = 93.8$$

Level 2

$$P_{.01} = -.42(1) + 5.9 = 5.5$$

$$P_{.50} = -1.25(1) + 17.2 = 16.0$$

$$P_{.99} = -3.75(1) + 52.8 = 49.0$$

Level 1

$$P_{.01} = -.31(1) + 4.4 = 4.1$$

$$P_{.50} = -1.02(1) + 13.2 = 12.2$$

$$P_{.99} = -2.92(1) + 39.6 = 36.7$$

Next step is to calculate the probability $(F_4(x))$ functions for each injury levels. For Level 1, since P is in the interval of $P_{.99} < P < P_{.99} + (P_{.99} - P_{.50})$, then Equation A-44 is used to calculate the probability Pr:

$$Pr = .99 + \frac{.01}{36.7-12.2} (50-36.7) = .9954$$

For Level 2, P also falls within the interval $P_{.99} < P < P_{.99} + (P_{.99} - P_{.50})$ so Equation A-44 is again used:

$$Pr = .99 + \frac{.01}{49.0-16.0} (50-49.0) = .9903$$

For Level 3, P is in the interval $P_{.01} < P < P_{.99}$ so that Equations A-45 and A-49 are used.

$$Pr = \frac{1}{1+exp(a50^2+b50+c)}$$

$$\begin{bmatrix} (10.4)^2 & 10.4 & 1 \\ (31.0)^2 & 31.0 & 1 \\ (93.8)^2 & 93.8 & 1 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} \ln .99/.01 \\ \ln .50/.50 \\ \ln .01/.99 \end{bmatrix}$$

Using linear algebra techniques, Pr = .7955. The probabilities of suffering at least each of the levels of ear injury are:

$$F_4(0) = 1, \qquad F_4(1) = .7955, F_4(2) = .9903, F_4(3) = .9954$$

Using Equation A-3, the probabilities ($f_4(x)$) of sustaining exactly each level of ear injury are calculated to be:

Level 3: $f_4(3) = F_4(3) = .7955$

Level 2: $f_4(2) = F_4(2) - F_4(3) = .9903 - .7955 = .1948$

Level 1: $f_4(1) = F_4(1) - F_4(2) = .9954 - .9903 = .0051$

No Injury: $\quad f_4(0) = F_4(0) - F_4(1) = 1 - .9954 = .0046$

ANNEX 3

HISTORICAL PERSPECTIVE OF OVERPRESSURE RESEARCH

The potential for combat casualties resulting from primary blast has been the subject of extensive military medical research for over 200 years. As early as the middle of the 18th Century, Ravaton and Bilger postulated that air compressed around a flying projectile can produce a heavy jolt. However, it was Jars who, in 1788, initially described the phenomenon now called "blast injury"; and in 1897, Mach substantiated the existence of "grazing shots from air blast" by explaining the physical phenomena associated with a flying projectile (Reference 3).

In 1914, the Swiss were the first to systematically study blast injury in experimental animals. Their interest arose from examination of three soldiers without external injuries who were killed during the Balkan War by a bursting grenade (shell), and by accounts of soldiers and sailors injured by shells passing close to them. Rusca conducted extensive studies on the nature of death by air blast in rabbits and by water blast in fish. His findings parallel today's present conclusions on the effects of overpressure (Reference 1).

Although there are few post-World War I reports of blast injuries, there is little doubt that pulmonary injuries by air and water blast occurred. In studies from 1918 to 1919 at Sandy Hook Proving Grounds, New Jersey, dogs exposed to multiple muzzle blasts from 10-inch naval rifles with 280-psi peak pressure and from 12-inch mortars with blast pressures of 388 psi repeatedly suffered shock from the rifle blast. This prompted the suggestion that the critical factor for overpressure injury is the positive pressure phase duration, which was longer for the rifle than the mortar. Researchers, however, concentrated on comprehensive physiological measurements on the brain and the nervous system, partly because of the large number of "shell shock" casualties of World War I who showed a variety of psychophysiologic symptoms after prolonged exposures to heavy artillery barrages, and partly because of the speculation in the medical literature that blast affected the nervous system. These measurements were later determined to be inconclusive (References 1 and 4).

In German research after World War I, Hansemann, Dietrich, and Berger reported blast injuries, although they failed to mention pulmonary injuries, which are now known to be the primary overpressure-related injuries. Hanser was probably the first researcher to allude to pulmonary injuries caused by blast. In 1923, at Oppau, a disastrous explosion was followed a week later with a large number of victims affected with pneumonia, which was diagnosed as "contusion pneumonia". In England and France, though, interest in blast as a cause of injury was not aroused until some time after World War I (Reference 3).

World War II, with increased sophistication in weaponry, delivery, and targeting heightened the level of interest in blast injury. In the United Kingdom (UK) which experienced increased air bombardment on civilian population centers, interspecies studies were conducted to relate blast overpressure levels required to attain a 50% mortality relative to body weight. Mice, rabbits, guinea pigs, goats and monkeys were subjected to blast from 1-, 8-, and 66-lb charges (Reference 1). The nature of the blast injuries and the pathophysiological effects were carefully described by the UK group. The other reported findings were that the blast wave must impact the thorax

directly to produce lung hemorrhage and that sponge rubber may shield the body from some direct blast effects (Reference 1).

In Germany, also the target of increased air bombardment on civilian population centers, extensive studies on blast injuries were undertaken. Benzinger, Desaga, Rossle, and Schardin fully publicized their findings on blast injury. Published in 1950 and reprinted in 1971 by the U.S. Air Force in a book entitled "German Aviation Medicine, World War II", Vol. II, these researchers' appreciation of blast injury is best stated by Benzinger (Reference 1): "The blast wave is a shot without a bullet, a slash without a sword. It is present everywhere within its range. Blast would be as dreaded a weapon as chemical if its effects were not limited to small areas. However, it would be premature to believe that this situation will always remain the same."

The Germans first discovered that arterial air embolism was the cause of immediate death from blast injury. They reasoned that air entered the pulmonary venous circulation from the disrupted alveoli and was then distributed to the coronary vessels, the brain, and vascular beds in other organs of the body. They also observed that the nature of internal injuries produced by air and underwater blast were the same. Another significant finding of the German studies was the duration effect. They found that the fatal static or side-on overpressure for dogs decreased by a factor of three when the duration of the positive phase was increased from 1.8 to 12 milliseconds. As shown in Figure A3-1, the fatal peak overpressure decreases for larger charge weights (References 1, 3, 5, and 6).

Benzinger et al. also demonstrated that the blast wave strikes the thorax, rather than entering through the upper respiratory tract to inflict lung injury. Desaga found that placing foam rubber material about the thorax provided no protection from airblast. In fact, he showed that lung hemorrhage was intensified by this material covering; a conclusion supported by more recent findings (References 1, 3, and 7).

The devastating destruction witnessed at Hiroshima and Nagasaki intensified research efforts on the effects of blast from nuclear weaponry: Did the pressure duration curve of Desaga (Figure A3-1) continue significantly downward, thereby increasing the lethal zone from these type weapons? In 1953, the Atomic Energy Commission contracted the Lovelace Foundation for Medical Research and Education, Albuquerque, New Mexico, to study the biological effects of nuclear blast. The effort was under the direction of Clayton S. White. In studies of 13 animal species subjected to blast waves of various durations, the Lovelace Foundation substantiated the extension of the mortality curves of Desaga to overpressure durations of greater than 1000 milliseconds. The blast waves generated in these studies were produced either by high explosives in the open or in shock tubes. From these studies, lethality curves for humans were developed by scaling animal response by body weight (Figure A3-2) (References 1 and 8).

Ongoing overpressure research efforts have been concentrating in the following areas (Reference 1):

o Prognosis and treatment of blast injuries

o Mathematical modeling of body response to blast loading

o Repeated blast effects

o Definition of exposure variables for complex waves

o Protective garments for personnel

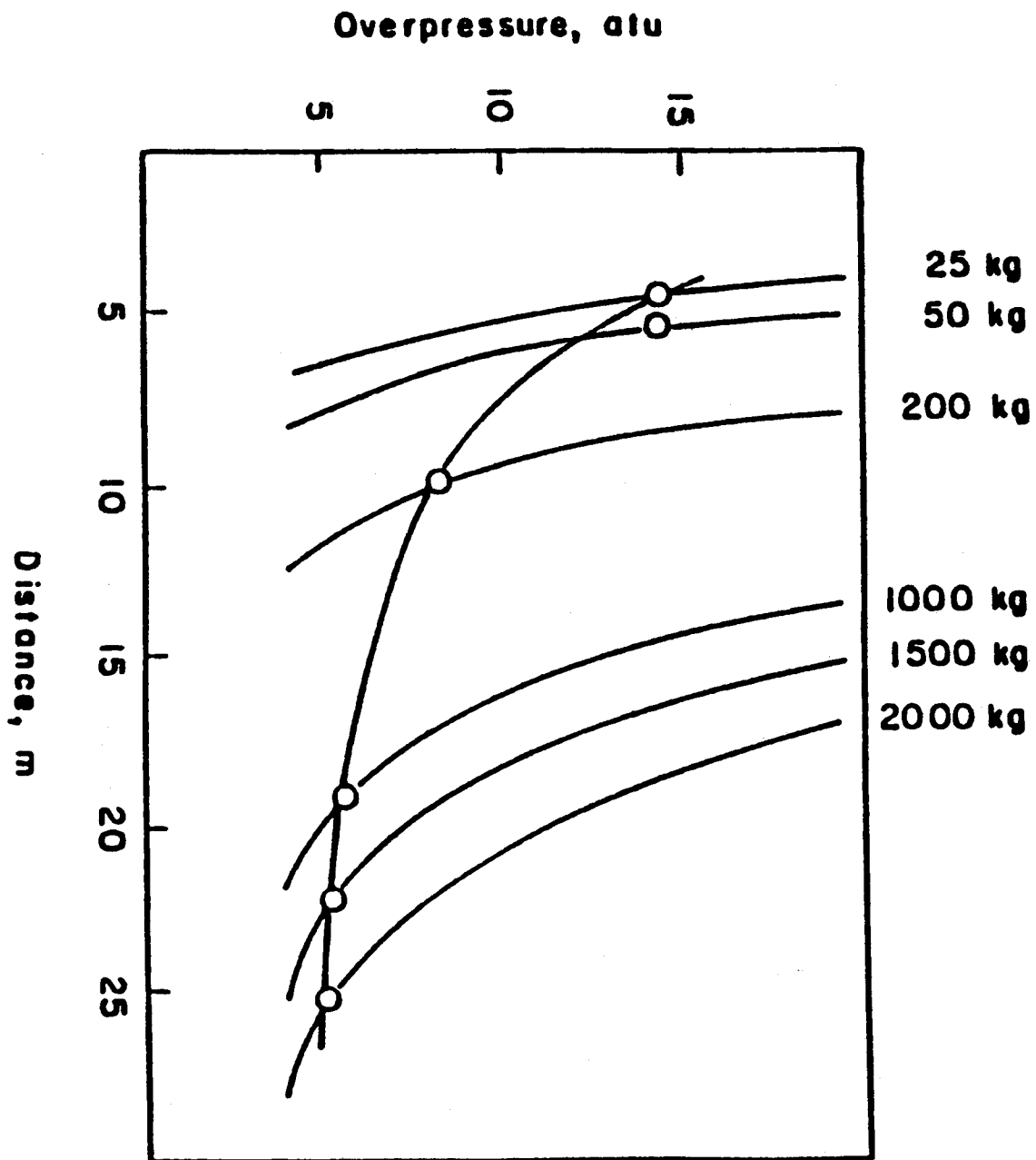o Enhanced blast munitions effects, such as fuel-air-explosives

Figure A3-1. Fatal Blast Overpressures for Dogs as a Function of Distance and Charge Weight (Overpressure-Duration Effect).
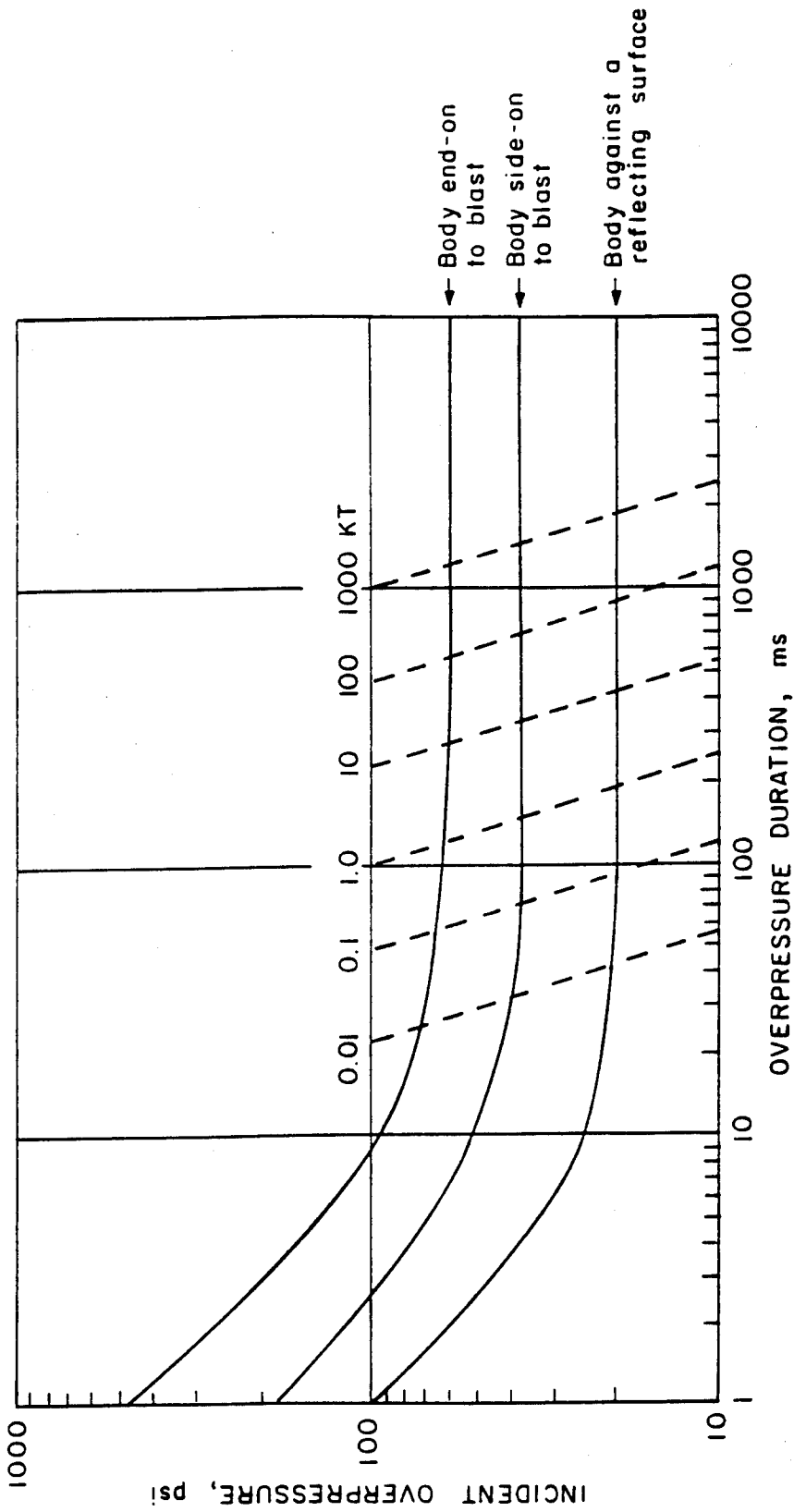
Figure A3-2. P_{50} Incident Overpressure for Man as a Function of Positive Overpressure and Body Orientation.

ANNEX 4
GLOSSARY OF TERMS

Alveolus: Small hollow or cavity. Air cell of the lungs. (Pl.alveoli)

Bradycardia: A slow heart beat characterized by a pulse rate that is under 60 beats per minute.

Bradypnea: Decrease in respiratory rate; abnormally slow breathing.

Cochlea: A winding cone-shaped tube forming a portion of the inner ear. It contains the organ of Corti, the receptor for hearing.

Confluent: Running together.

Corti: Organ of an elongated spiral structure running the entire length of the cochlea.

Cyanosis: Slightly bluish, grayish, slatelike, or dark purple discoloration of the skin due to presence of abnormal amounts of reduced hemoglobin in the blood.

Dyspnea: Air hunger resulting in labored or difficult breathing, sometimes accompanied by pain.

Ecchymoses: A form of macula (small spot or colored area) appearing in large irregularly formed hemorrhagic areas of the skin.

Ecchymotic: Resembling an ecchymosis.

Embolism: Obstruction of a blood vessel by foreign substances or a blood clot. An air embiolism is caused by air bubble.

Hematoma: A swelling or mass of blood (usually clotted) confined to an organ, tissue, or space and caused by a break in a blood vessel.

Hemoptysis: Expectoration of blood arising from the oral cavity, larynx, trachea, bronchi, or lungs.

Hypotension: Decrease of systolic and diastolic blood pressure below normal.

Larynx: The enlarged upper end of the trachea below the root of the tongue.

Lumen: The space within an artery, vein, intestine, or tube.

Mucosa: Mucous membrane.

Mucosal: Concerning any mucous membrane.

Parenchyma: The essential parts of an organ that are concerned with its function in contradistinction to its framework.

Petechiae: Small, purplish, hemorrhagic spots on the skin that appear in certain severe fevers and are indicative of great prostration. Similar spots occuring on mucous membranes or serous surfaces.

Pharynx: Passageway for air from nasal cavity to larynx, and food from mouth to esophagus.

Pinna: The auricle or projected part of the exterior ear.

Sinus: A canal or passage leading to an abscess. A cavity within a bone. Any cavity having a relatively narrow opening.

Submucosa: The layer of areolar connective tissue under a mucous membrane

Submucosal: Pertains to submucosa.

Subserous: Beneath a serous membrane.

Subserousal: Pertains to subserous.

Syncope: A transient loss of consciousness due to inadequate blood flow to the brain.

Tachycardia: Abnormal rapidity of heart action, usually defined as a heart rate over 100 beats per minute.

Tachypnea: Abnormal rapidity of respiration.

Tenesmus: Spasmodic contraction of anal or vesical sphincter with pain and persistent desire to empty

                   the bowel or bladder, with involuntary ineffectual straining efforts.

Tinnitus: A subjective ringing or tinkling sound in the ear.

Trachea: A cylindrical cartilaginous tube, 4 1/2 inches long, from the larynx to the bronchial tubes.

APPENDIX B

BIBLIOGRAPHY OF HUMAN INJURY RESEARCH

Albanese, Richard A. and John E. Pickering, AIRCREW VULNERABILITY IN NUCLEAR ENCOUNTERS, July 1974.

Anno, G. H., M. A. Dore and D. B. Wilson, ACUTE RADIATION EFFECTS ON CREW MEMBER PERFORMANCE, DNA-TR-85-52, August 1984.

Anno, G. H. and M. A. Dore, EFFECTS OF IONIZING RADIATION ON THE PERFORMANCE OF SELECTED TACTICAL COMBAT CREWS, 1989.

Berkowitz, Raymond S., A PROCEDURE FOR COMPUTING EXPECTATION AND VARIABILITY OF CASUALTIES ACHIEVABLE BY AN ATTACK WITH AIRBORNE AGENTS, DA-18-064-AMC-2757A, June 1967. (UNCLASSIFIED)

Bowen, L. G., A. Holladay, E. R. Fletcher, D. R. Richmond and C. S. White, A FLUID-MECHANICAL MODEL OF THE THORACO-ABDOMINAL SYSTEM WITH APPLICATIONS TO BLAST BIOLOGY, September 1965.

Bowen, L. G., E. R. Fletcher and D. R. Richmond, ESTIMATE OF MAN'S TOLERANCE TO THE DIRECT EFFECTS OF AIR BLAST, DASA-2113, October 1968.

Bruchley, William J. Jr. and Benjamin Cummings, A PROVISIONAL LETHALITY MODEL - 1974, Ballistics Research Laboratories, 1T762708A068, January 1974.

Burns, K.C., C. A. Mauro and D. E. Smith, FINAL REPORT: STATISTICAL RESEARCH ON PROBLEMS OF BIODYNAMICS, N00014-79-C-0128, August 15, 1985.

Clemedson, C. J. and A. Jonsson, DYNAMIC RESPONSE OF CHEST WALL AND LUNG INJURIES IN RABBITS EXPOSED TO AIR SHOCK WAVES OF SHORT DURATION, 1964.

Clemedson, C. J., G. Hellstrom and S. Lindgren, "The Tolerance of the Head, Thorax, and Abdomen to Blunt Trauma", ANNALS NEW YORK ACADEMY OF SCIENCES.

Clemedson, C. J., L. Frankenburg, A. Jonsson and A. B. Sundqvist, "Effects on Extra- and Intrathoracic Pressure Pattern and Lung Injuries of Rigid and Soft Protection of Thorax in Air Blast Exposed Rabbits".

Damon, E. G., C. S. Gaylord, J. T. Yelverton and D. R. Richmond, THE TOLERANCE OF CATTLE TO "LONG" - DURATION REFLECTED PRESSURE IN A SHOCK TUBE, Lovelace Foundation for Medical Education and Research, DA-49-146-XZ-372, August 1966.

Damon, E. G., C. S. Gaylord and W. Hicks, THE EFFECTS OF AMBIENT PRESSURE ON MAMMALS EXPOSED TO AIR BLAST, DA-49-146-XZ-372, AUGUST 1966.

Dodd, K. T., G. R. Ripple, and T. G. Mundie, CURRENT INJURY ASSESSMENT TECHNIQUES FOR COMPLEX WAVES, Walter Reed Army Institute of Research.

Draeger, R. H. and R. H. Lee, DIRECT AIR BLAST EXPOSURE EFFECTS IN ANIMALS, WT-744, December 1953.

Fletcher, E. R., D. R. Richmond and J. T. Yelverton, GLASS FRAGMENT HAZARD FROM WINDOWS BROKEN BY AIRBLAST, DNA IACRO-76-634, May 1980.

Fletcher, E. R. and I. G. Bowen, "Blast-Induced Translational Effects", ANNALS NEW YORK ACADEMY OF SCIENCES.

Heiser, R., THE EFFECT OF FRAGMENTATION AGAINST SOFT TARGETS, FSTC-HT-1111-80, March 1981.

Hirsch, F. G., "Effects of Overpressure on the Ear - A Review", ANNALS OF THE NEW YORK ACADEMY OF SCIENCE, VOLUME 152, 1968.

Hirsch, F. G., "The Tolerance of Man to Impact", ANNALS OF THE NEW YORK ACADEMY OF SCIENCE, VOLUME 152, October 28, 1968.

Holladay, M. S. and I. G. Bowen, A MATHEMATICAL MODEL OF THE LUNGS FOR STUDIES OF MECHANICAL STRESS, DA-49-146-XZ-055.

Janney, J. L. and R. N. Rogers, PREDICTIVE MODELS FOR THERMAL HAZARDS, Twenty-Second Explosives Safety Seminar: Vol.II, August 1986.

Janser, P. W., LETHALITY OF UNPROTECTED PERSONS DUE TO DEBRIS AND FRAGMENTS, August 1982.

Jonsson, A., E. Arvebo and B. Schantz, INTRATHORAIC PRESSURE VARIATIONS IN AN ANTHROPOMORPHIC DUMMY EXPOSED TO AIR BLAST, BLAST IMPACT, AND MISSILES, Vol. 28, DA-49-146-XZ-055, April 1965.

Labeeu, Fr., BLAST INJURIES, AFMIC-RT-068-83, March 1984.

Longinow, A., E. Hahn, A. Wiedermann and S. Citko, CASUALTIES PRODUCED BY IMPACT AND RELATED TOPICS OF PEOPLE SURVIVABILITY IN A DIRECT EFFECTS ENVIRONMENT, DAHC20-73-C-0196, August 1974.

Merkler, Jules M., A. P. Mickiewicz, Conrad L. Swann and A. V. Milholland, A CODE FOR PENETRATING AND BLUNT TRAUMA, BASED ON THE H-ICDA INDEX, ARCSL-TR-78054, October 1978.

Richmond, D. R. and C. S. White, A TENTATIVE ESTIMATION OF MAN'S TOLERANCE TO OVERPRESSURE FROM AIR BLAST, Lovelace Foundation for Medical Education and Research, DA-49-146-XZ-372, November 1962.

Richmond, D. R. and C. S. White, BIOLOGICAL EFFECTS OF BLAST AND SHOCK, Lovelace Foundation for Medical Education and Research, DA-49-146-XZ-055, April 1966.

Richmond, D. R., E. G. Damon, L. G. Bowes, E. R. Fletcher and C. S. White, AIR-BLAST STUDIES WITH EIGHT SPECIES OF MAMMALS, Lovelace Foundation for Medical Education and Research, August 1966.

Richmond, D. R., E. R. Fletcher, K. Saunders and J. T. Yelverton, INJURIES PRODUCED BY THE PROPAGATION OF AIRBLAST WAVES THROUGH ORIFICES, IACRO 81-832, March 1980.

Richmond, D. R., J. T. Yelverton and E. R. Fletcher, NEW AIRBLAST CRITERIA FOR MAN, Twenty-Second Explosives Safety Seminar: Vol.1, August 1986.

Richmond, D. R., J. T. Yelverton, W. Hicks, and Y. Y. Phillips, BIOLOGICAL EFFECTS OF COMPLEX BLAST WAVES FROM EXPLOSIONS INSIDE AN ENCLOSURE, Los Alamos National Laboratory and Walter Reed Army Institute of Research, February 1987.

Richmond, D. R., V. C. Coldizen, B. S. Clare, D. E. Pratt, F. Shpering, R. T. Sanchez, C. C. Fischer and C. S. White, "The Biological Response to Overpressure", AEROSPACE MEDICINE, Vol. 23, January 1962.

Ripple, G. R. and T. G. Mundie, MEDICAL EVALUATION OF NONFRAGMENT INJURY EFFECTS IN ARMORED VEHICLE LIVE FIRE TEST, Walter Reed Army Institute of Research.

Roberts, J. E., C. S. White and T. L. Chiffelle, EFFECTS OF OVER PRESSURES IN GROUP SHELTERS ON ANIMALS AND DUMMIES, September 1964.

Rudder, Earl, Wayne C. Hall and Sidney O. Brown, INCAPACITATION OF THE GOAT FOLLOWING MASSIVE DOSES OF MIXED NEUTRON AND GAMMA RADIATION, RTD-TDR-63-3077, December 1963.

Rudolph, Ronald R., AN ASSESSMENT OF THE CURRENT STATE-OF-THE-ART OF INCAPACITATION BY AIR BLAST, June 1982.

Shnider, R. W. and E. S. Shapiro, PREDICTION OF CASUALTIES FROM LAND SURFACE NUCLEAR DETONATIONS, USNRDL-TR-109, August 1956.

Silcox, L. E. and H. P. Schenck, BLAST INJURY OF THE EARS.

Stech, E. L. and P. R. Payne, THE EFFECT OF AGE ON VERTEBRAL BREAKING STRENGTH, SPINAL FREQUENCY, AND TOLERANCE OF ACCELERATION IN HUMAN BEINGS, Frost Engineering Development Corporation, AF 33(657)-9514, January 1963.

Strother, C. E. and R. M. Mahone, THE EFFECT OF DECK Deceleration ON THE RESPONSE OF SEATED MAN TO DECK MOTIONS INDUCED BY UNDERWATER EXPLOSIONS, August 1972.

Sturdivan, Larry M., A MATHEMATICAL MODEL OF PENETRATION OF CHUNKY PROJECTILES IN A GELATIN TISSUE STIMULANT, ARCSL-TR-78055, December 1978.

Taborelli, R. V., I. G. Bowen and E. R. Fletcher, TERTIARY EFFECTS OF BLAST- DISPLACEMENT, Lovelace Foundation for Medical Education and Research, February 1959.

Vanden Bosch, Peter M. and Arthur Woodrum, RADIATION DOSES FROM FLYING THROUGH NUCLEAR DEBRIS CLOUDS, USAFSAM-TR-85-86, April 1986.

Warkley, P. G., EFFECT OF UNDERWATER EXPLOSIONS ON THE HUMAN BODY, June 1945.

White, C. S., I. G. Bowen and D. R. Richmond, BIOLOGICAL TOLERANCE TO AIR BLAST AND RELATED BIOMEDICAL CRITERIA, Lovelace Foundation for Medical Education and Research, April 1965.

White, C. S., "The Scope of Blast and Shock Biology and Problem Areas in Relating Physical and Biological Parameters", ANNALS NEW YORK ACADEMY OF SCIENCES.

Woodward, A. A., THE USE OF MODELS IN THE STUDY OF WOUND BALLISTICS, AMRL-TR-71-29, December 1971.

Young, A. J., J. J. Jaeger, Y. Y. Phillips, J. T. Yelverton and D. R. Richmond, THE INFLUENCE OF CLOTHING ON HUMAN INTROTHORACIC PRESSURE DURING AIRBLAST, June 1985.

Yu, J. H. and E. J. Vasel, GI TRACT EXPERIMENTAL STUDY, U. S. Army Medical Research and Development Command, DAMD17-83-C-3067, July 1983.

AIR BLAST INDUCED LUNG INJURY - A MATHEMATICAL MODEL, June 1978.

Analysis and Simulation, Inc., LETHALITY AND VULNERABILITY ANALYSIS (LAVA) (U), 31 August 1988. (SECRET)

Defense Nuclear Agency, CAPABILITIES OF NUCLEAR WEAPONS, PARTS I AND II (U), DNA-EM-1, July 1972. (SECRET/RESTRICTED DATA)

Edgewood Arsenal, HANDBOOK OF HUMAN VULNERABILITY CRITERIA (U), EB-SP-76011, May 1976. (CONFIDENTIAL)

Joint Technical Coordinating Group on Munitions Effectiveness, TARGET VULNERABILITY (U), G1A1-3-1, 16 April 1990. (SECRET/NOFORN/WNINTEL)

Lovelace Foundation for Medical Education and Research, PROBABILITY OF INJURY FROM AIRBLAST AS A FUNCTION OF YIELD AND RANGE, DNA 3779T, October 1975.

MATHEMATICAL MODELING BIODYNAMIC RESPONSE TO IMPACT, ADA040351, June 1977.