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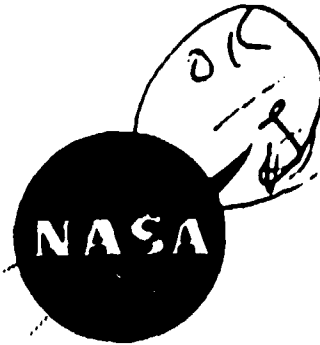
WORKBOOK FOR PREDICTING PRESSURE WAVE AND FRAGMENT EFFECTS OF EXPLODING PROPELLANT TANKS AND GAS STORAGE VESSELS

By W. E. Baker, J. J. Kulesz, R. E. Ricker, R. L. Bessey,
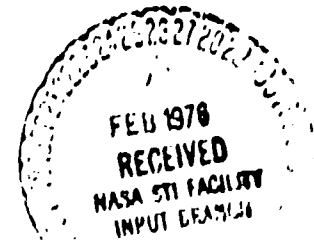P. S. Westine, V. B. Parr, and G. A. Oldham

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16. Abstract
This workbook is intended to provide the designer and the safety engineer with the best available technology that they need to predict damage and hazards from explosions of propellant tanks and bursts of pressure vessels, both near and far from these explosion sources. The information is presented in the form of graphs, tables, and nomographs to allow easy calculation without resource to difficult mathematical manipulation or the use of extensive computer programs. When complex methods have been used to develop simple prediction aids, they are fully described in appendices.

Topics covered in various chapters are:

1) Estimation of explosive yield
2) Characteristics of pressure waves
3) Effects of pressure waves
4) Characteristics of fragments
5) Effects of fragments
6) Risk assessment and integrated effects.

Short chapters giving discussion of results, conclusions and recommendations for further work are also included.

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FOREWORD

Many staff members at Southwest Research Institute in addition to the authors contributed substantially to the work reported here. The authors gratefully acknowledge the special contributions of the following:

- Mr. M. A. Sissung, for organization and editing of the workbook,

- Miss C. A. Hajovsky, for extensive data reduction and curve plotting.

The technical support of our project manager at NASA-Lewis Research Center, Dr. Robert D. Siewert, contributed materially to the success of this work. In particular, he provided excellent technical guidance throughout the contract, and was also able to obtain for us the needed input data for all of the example cases presented in Chapter VI, and references to other related work.

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SUMMARY

This workbook is intended to provide the designer and the safety engineer with the best available technology that they need to predict damage and hazards from explosions of propellant tanks and bursts of pressure vessels, both near and far from these explosion sources. The information is presented in the form of graphs, tables, and nomographs to allow easy calculation without recourse to difficult mathematical manipulation or the use of extensive computer programs. When complex methods have been used to develop simple prediction aids, they are fully described in appendices.

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(5)   Effects of fragments
(6)   Risk assessment and integrated effects.

Short chapters giving discussion of results, conclusions, and recommendations for further work are also included.

INTRODUCTION

Nature of the Hazards

The likelihood of accidental explosions, in the various activities that involve liquid propellants for space vehicles, can best be decreased by improvements in design practices and operating procedures. Over the years, the frequency of occurrence of accidental explosions in the space programs has decreased with advances in technology. Nevertheless, the possibility of space vehicle fuel/oxidizer explosions or pressure bursts will always exist, especially with reusable propulsion systems that must be more reliable compared with those in the "one-shot" space vehicle. Excessive cyclic stresses, wear of moving parts and the accumulation of contaminants are some of the factors that could contribute to component malfunctions or material failures during the lifetime use of such systems. These malfunctions or failures could, in turn, contribute to accidental explosions with risk of damage to facilities and hazards to people. Thus, it becomes important to predict the explosive yield and the effects of pressure wave and fragments in a quantitative manner.

It is the intent here to provide the designer and the safety engineer with the best available technology that they need to predict damage and hazards from explosions of propellant tanks and bursts of pressure vessels in the near and far fields of interest.

In a launch configuration within tankage in a rocket motor, liquid propellants and nonreacting gases are initially contained within vessels of various sizes, geometries, and strengths. Various modes of failure of these vessels are possible, from either internal or external stimuli. If the vessel is pressurized with static internal pressure, one possible mode of failure is simply fracture, instituted at a critical size flaw and propagated throughout the vessel. A similar kind of failure can occur if the vessel is accidentally immersed in a fire, and pressure increases internally because of vaporization of the internal propellant. Some launch vehicles have the liquid fuel and oxidizer separated by a common bulkhead. Accidental over-pressurization of one of these chambers can cause rupture of this bulkhead, and subsequent mixing and explosion of the propellant. External stimuli that can cause vessel failure include high-speed impact by foreign objects, accidental detonation of the warhead of a missile, dropping of a tank to the ground (as in toppling of a missile on the launch pad), as well as many other external sources. Vessel failure can result in an immediate release of energy or it can cause subsequent energy release because of mixing of propellant and oxidizer and subsequent ignition. Other modes of failure which have resulted or could result in violent explosions are fall-back immediately after launch due to loss of thrust, or low-level failure of the guidance system after launch resulting in impact

into the ground at several hundred feet per second.

Failure of a vessel containing liquid propellants or compressed gas can result in various levels of energy release, ranging from negligible to the full heat value of the combined propellant and oxidizer, or full value of stored energy in the compressed gas. Toward the lower end of the scale of energy release might be the failure of a pressurized vessel due to ductile crack propagation. Here, the stored pressure energy within the compressed propellant or gas in an ullage volume above the propellant could split the vessel or generate a weak blast wave. In the intermediate range of energy releases could lie vessel failure by external stimulus and ignition, either very rapidly or at very late times, so that only small proportions of mixed propellant and oxidizer contribute to the energy release. In this intermediate range could also lie the rapid fracture of gas storage vessels after heating or very rapid crack propagation. At the upper end of the scale could be the explosion in a vessel wherein a pre-mixed propellant and oxidizer detonate in much the same fashion as a high explosive, and explosions resulting after violent impact with the ground. In past studies of possible blast and fragmentation effects from vessel rupture, a critical problem has been to accurately assess the energy release as a result of the accident or incident. A common method of assessment of possible energy release or correlation of the results of experiments has been to assess the energy release on the basis of equivalent pounds of TNT. This method is used because a large body of experimental data and theoretical analyses exist for blast waves generated by TNT or other solid explosives (refs. 1 and 2). Although the comparison with TNT is convenient, the correlation is far from exact. Specific energies which can be released, i.e., energy per unit volume or mass of material, differ quite widely between TNT, various liquid propellants or mixtures of liquid propellants and oxidizers, and gases stored in pressure vessels. The characteristics of damaging blast waves from explosions which can occur in flight vehicle accidents can therefore be quite different from blast waves from TNT explosions. The accidental explosions usually generate waves with lower amplitudes (peak overpressures) and longer durations than equivalent energy TNT explosions, at least close to the explosion source. Reference 3 discusses in some detail the blast waves from accidental explosions of the classes covered in this handbook.

Dependent on the total energy release and the rate of this energy release, the sizes and shapes of fragments generated by bursting liquid propellant vessels and their appurtenances, and bursting gas vessels, cover a very wide spectrum. At one extreme is the case of a vessel bursting because of seam failure or crack propagation from a flaw wherein only one "fragment" is generated, the vessel itself. This fragment, from a very slow reaction, can be propelled by releasing the contents of the vessel. At the other extreme is the conversion of the vessel and parts near it into a cloud of small fragments by an explosion of the contents of a vessel at a

very rapid rate, similar to a TNT explosion (refs. 4 and 5). For most
accidental vessel failures, the distribution of fragment masses and shapes
undoubtedly lies between these two extremes. The modes of failure of the
vessel may be dependent upon details of construction and the metallurgy
of the vessel material. Some of the masses and shapes are dictated by the
masses and shapes of attached or nearby appurtenances. In any event,
assessment and prediction of these parameters is much more difficult than
is true for the better understood phenomenon of shell casing fragmentation.

Once the masses, shapes, and initial velocities of fragments from
liquid propellant vessels or bursting gas vessels have been determined in
some manner, then the trajectories of these fragments and their losses in
velocity due to air drag or perforation or penetration of various materials
must be computed. This problem is primarily one of exterior ballistics.
It differs from conventional exterior ballistic studies of trajectories of
projectiles, bombs, or missiles in that the body in flight is invariably very
irregular in shape and can be tumbling violently. Exact trajectories cannot
be determined then in the same sense that they can be for well-designed
projectiles. Only approximate trajectories can be estimated, usually by
assuming relatively simple geometric shapes, such as spheres, discs or
cylinders, for which exterior ballistic data and techniques exist. But,
in some fashion, one can predict the ranges and impact velocities for
fragments which were initially projected in specified directions from the
bursting vessel with specified initial velocities.

This problem is not complete until one can assess the effects of
blast waves and fragments from the accident on various "targets." For
a proper assessment of hazards, one should consider a wide variety of
targets, including human beings, various classes of buildings, vehicles,
and perhaps even aircraft. Problems of fragment damage are exceedingly
complex, not only because of the inherent statistical nature of the charac-
teristics of the impacting fragments but also because the terminal ballistic
effects for large irregular objects impacting any of the targets described
are not very well known. In most past studies of fragment damage from
accidents, the investigators have been content to simply locate and approxi-
mate the size and mass of the fragments in impact areas and have ignored
the important problem of the terminal ballistic effect of these fragments.
Prediction of blast damage is also not simple, but much more work has
been done and reasonable estimates can be made for most structures and
for humans, provided the characteristics of the blast waves can be defined
(refs. 6 and 7).

Means for Assessment of Risk

This handbook is directed toward estimation of blast and fragmentation
effects of accidental explosions in flight vehicles. It is not intended to
encompass the entire problem of risk assessment for launch and operation

of these vehicles. This more comprehensive task includes the estimation of the probability of occurrence of various types of failures or accidents, and must employ methods such as failure mode analysis or fault-tree analysis to obtain such probabilities. In this handbook, it is assumed that a specific explosive accident has occurred, and the hazardous effects of that accident are predicted. A brief discussion of methods of risk assessment is given in Chapter 6.

Scope and Significance of Material Presented

The material presented in the handbook is based on a previous study of fragmentation from bursting propellant vessels (ref. 8) and on the literature on characteristics and effects of blast waves and fragment impact. Methods are given for predicting the damage to facilities and hazards to people from exploding liquid propellant tanks or bursting gas storage bottles. Various chapters present material which allows estimation of explosive yield or energy for a variety of propellant explosions and gas vessel bursts, give predictions of characteristics of pressure waves from these explosions, and present techniques for making damage estimates for structures and facilities, and mortality or injury to people subjected to the blast waves. Other chapters include estimates of fragment initial velocities and the statistics of mass and shape, terminal velocities and impact conditions, and effects of such impact on facilities, structures and people. Throughout the workbook, presentations are made in the form of scaled graphs, equations, nomographs or tables which allow easy calculation without recourse to difficult mathematical manipulation or use of extensive computer programs. When such methods have been used to develop simple prediction aids, they are fully described in appendices.

It is believed that this workbook is the first to provide safety engineers with relatively simple yet comprehensive methods for estimating blast and fragment hazards for accidental explosions in liquid-propellant fueled flight vehicles. Some methods for estimating blast yield for classes of liquid propellant accidents are given in ref. 9, and ref. 10 discusses blast and fragmentation from such explosions. But, neither of these references allows estimation of fragment characteristics and effects for liquid propellant explosions, nor do they treat gas vessel bursts. Special features not seen elsewhere are the prediction of blast wave characteristics for gas vessel bursts, effects of fragment impact on structures and facilities, and extensive application of the pressure-impulse (P-I) damage concept to a wide variety of structures and to humans.

Intended Purpose and Limits of Use

The purpose of the workbook is to provide typical safety engineers, with training at the bachelor's degree level in some engineering specialty, with methods for rapid estimation of blast and fragment hazards from accidental explosions in flight vehicles. It should require only a desk or pocket calculator or slide rule to perform any of the needed calculations. There are, of course, a number of limits to the calculations and their applicability which the user should observe. Because almost all of the data he will use are graphical, these limits will often be self-evident from the extreme values on the graphs. In general, one should not extend or extrapolate these graphs, but should instead merely report that prediction is not possible if input parameters fall outside the range of the plot.

Factors of safety are included in the prediction methods in various ways. When curves are based on experiments, error bands are usually given. Use of average curves through the data will give most probable values for such loading parameters as blast overpressure and impulse; use of the upper limits of the error band will assure conservatism by encompassing all of the extreme values in the measured data rather than the most probable. Most of the fragment data must be presented statistically. The user is often given a choice of several regression lines through the data. Choice of such a line with a very high probability of, say, predicting that all fragments less than a certain mass will fall to earth within a given distance, will assure a high factor of safety in estimating exclusion distances for possible fragment damage. In estimating effects of blast and fragments, factors of safety are included by estimating different degrees of damage given blast envelopment or fragment impact. For structures, estimates can be made for lower limits to damage (threshold of no damage at all) through quite severe structural damage to buildings, vehicles, etc. For people, estimates can be made for threshold of ear damage through 1% chance of mortality to 99% chance of mortality. For estimation methods which are based on sparse data or analysis, we have large bands of uncertainty--the user should apply upper limits of these bands, if in doubt.

Applications to Areas Other Than Aerospace Rocket Launch and Research Facilities

This workbook was prepared primarily for use by safety engineers and site planners at aerospace rocket launch and research facilities. It emphasizes the blast and fragment hazards which could occur at such sites, and the prediction of their damaging effects. The prediction of blast and fragment hazards is specific for liquid propellant explosions and gas bottle bursts. The common use in explosive safety circles of conversion to TNT equivalency is nearly completely avoided, so the workbook cannot be easily used to predict hazards from detonations of condensed explosives such as TNT. On the other hand, the methods given in Chapters III, V and VI for

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prediction of damaging *effects* are quite independent of the methods for estimating the *hazards*. Blast damage predictions could as easily be made for TNT or nuclear explosions as for propellant explosions, provided the blast wave characteristics were defined. Similarly, fragment damage predictions are independent of the sources of the fragments, and only depend on a knowledge of the impact conditions. Indeed, the treatment of damage effects is much more extensive than one would be apt to find in any other single document, and could find much wider use than for damage prediction near aerospace test and launch facilities.

Additional Areas of Research

The bases for the prediction methods given in this workbook range from a firm foundation of extensive testing and analysis, through analyses supported by limited testing or accident reporting, to some predictions which are quite speculative because of little corroborating evidence. Predictions in the latter case could often be improved by additional research.

Areas in which we feel there is a pressing need for additional study are:

(1)   Definition of fragmentation characteristics for bursting gas storage bottles. Existing data consist of only five tests for one bottle geometry and material, and one gas.

(2)   Definition of blast wave characteristics for burst of cylindrical gas storage vessels, either analytically or experimentally. Present methods are limited to essentially spherically sym. ... -ic cases.

(3)   Better definition of fragment impact effects on a variety of structures and facilities, for fragments typical of those occurring in aerospace vehicle explosions. Most fragment impact data or methods developed to date are related to high velocity, small mass penetrators which are not typical of accidentally produced fragments.

(4)   Extension of the present work to accidental explosions in thick-walled storage vessels typical of ground transport and storage vessels. The current work is directed toward explosions of flight-weight hardware. Blast and fragmentation characteristics can be drastically different for heavier vessels.

In Chapter IX, we discuss these and other areas for further work in more detail.

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ESTIMATES OF EXPLOSIVE YIELD

1-1   Explosive Yield as a Function of Propellant Type and Accident
Conditions

1-1.1   General Discussion of Propellant Explosives

Accidents involving liquid propellant rockets, both during static
firing on a test stand and during launch, have shown that liquid propel-
lants can generate violent explosions. These explosions "drive" air blast
waves, which can cause direct damage and can accelerate fragments or
nearby objects. In fact, the specific energies of liquid rocket propel-
lants, in stoichiometric mixtures, are significantly greater than for TNT
(specific energy is energy per unit mass).[1] The estimation of explosive
yield, the energy released during the explosion, is a prerequisite to the
determination of expected damage resulting from the explosion. Before
delving into the method of calculating explosive yield, however, a general
discussion of the characteristics of propellant explosions will help the
reader understand the complexities involved in the determination of ex-
plosive yield.

One extremely important fundamental fact concerning liquid pro-
pellants is that their potential explosive yield is very high, but their
actual yield is much lower. This situation occurs because the propellant
and oxidizer are never intimately mixed in the proper proportions before
ignition. The degree of confinement of propellant and oxidizer can also
seriously affect the actual explosive yield of liquid propellants. For
example, a liquid propellant mixture could conceivably explode inside a
storage vessel or could leak out of a containment vessel and form a
shallow pool of large lateral extent before detonation. Each case produces
different values for explosive yield. Presently, there are at least four
methods for estimating yield from liquid propellant explosions which,
unfortunately, do not necessarily give the same predictions: One method
is based on Project PYRO results, [2-4] and two of the others are the
"Seven Chart Approach" and the "Mathematical Model" of Farber and
Deese.[5] The fourth approach, which is really based on the previous
three methods, was developed by Baker, et al.,[1] and is easy to use and
readily adaptable to the calculation of explosive yield. For further in-
formation concerning the development of this method, Reference 1 is
recommended.

From the test results reported in Reference 2 and 6 through 8, a
number of observations can be made regarding blast yields from liquid

propellant explosions.[1]

(1) Yield is quite dependent on the particular fuel and oxidizer being mixed.

(2) The yield is very dependent on the mode of mixing of fuel and oxidizer, i.e., on the type of accident which is simulated. Maximum yields are experienced when intimate mixing is accomplished before ignition.

(3) On many of the liquid hydrogen/liquid oxygen (LH_2/LO_2) tests (regardless of investigators), spontaneous ignition occurred very early in the mixing process, resulting in very low percentage yields.

(4) Yield is very dependent on time of ignition, even ignoring the possibility of spontaneous ignition.

(5) Blast yield per unit mass of propellant decreases as total propellant mass increases.

(6) Variability in yields for supposedly identical tests was great, compared to variability in blast measurements of conventional explosives.

1-1.2   Scaled Curves for Explosive Yield for Various Propellants and Types of Accidents

If a blast source is placed on or near a reflecting surface, such as the ground, then the initial shock is very quickly reflected and the reflected wave merges with the incident wave so rapidly that a single, strengthened blast wave is formed. The characteristics of this single wave are often almost identical with the characteristics of blast waves in free-air experiments, except that the blast source appears to have greater energy than for free-air tests. The proportion of energy reflected from the ground is a function of how perfect a ref...tor it is, that is, how little energy is imparted to the ground in cra ring, ground shock, and so forth. If the ground were a perfectly rigid surface, then the equivalent free-air energy driving the air blast wa... would be $E' = 2E$. The other extreme case is that of a perfect absorber, for which $E' = E$. All actual tests will have equivalent free-air energies lying between these limits.

All of the PYRO experiments, on which the prediction curves in this section are based, were conducted on the ground surface, with no cratering. When the curves are used to predict blast yields for explosions occurring in flight or far enough above the ground that the imme-

1-2

diate reflection discussed does not occur, one must account for the absence of the "perfect" reflecting surface. This is done by <u>dividing</u> the blast yields calculated from curves in this chapter by a factor of <u>two</u>.

1-1.2.1 Terminology

In this document, three types of fuel and oxidizer combinations and three different modes of mixing will be considered. The three types of propellants are:

(1) The hypergolic propellant which is in widest use. A fuel of 50% N_2H_4 - 50% UDMH and an oxidizer of N_2O_4 in a mass ratio of 1/2.

(2) <u>Liquid Oxygen-Hydrocarbon</u> - This propellant uses kerosene (RP-1) as a fuel and liquid oxygen (LO_2) as the oxidizer in stoichiometric mass ratio of 1/2.25.

(3) <u>Liquid Oxygen-Liquid Hydrogen</u> - This propellant is an entirely cryogenic combination of liquid hydrogen (LH_2) fuel and liquid oxygen (LO_2) oxidizer in stoichiometric mass ratio of 1/5.

The three modes of mixing (failure modes) discussed are:

(1) Confinement by Missile (CBM) - This type of accident consists of failure of an interior bulkhead separating fuel and oxidizer in a missile stage.

(2) Confinement by Ground Surface (CBGS) - This type of accident includes impacts at various velocities (e.g., fall back on the launch pad) of the missile on the ground, with all tankage ruptured, and subsequent ignition.

(3) High Velocity Impact (HVI) - This type of accident involves high velocity impact of a missile after launch.

1-1.2.2 Methods for Calculating Explosive Yield

Some parameters which become important in determining explosive yield are the type of propellant, the failure mode and in some cases, ignition time, impact velocity, and type of surface impacted. It is important to keep in mind, however, that blast yield as a percent or fraction of energy available decreases as total combined mass of propellant and oxidizer increases. Figure 1-1, which is a normalized plot for
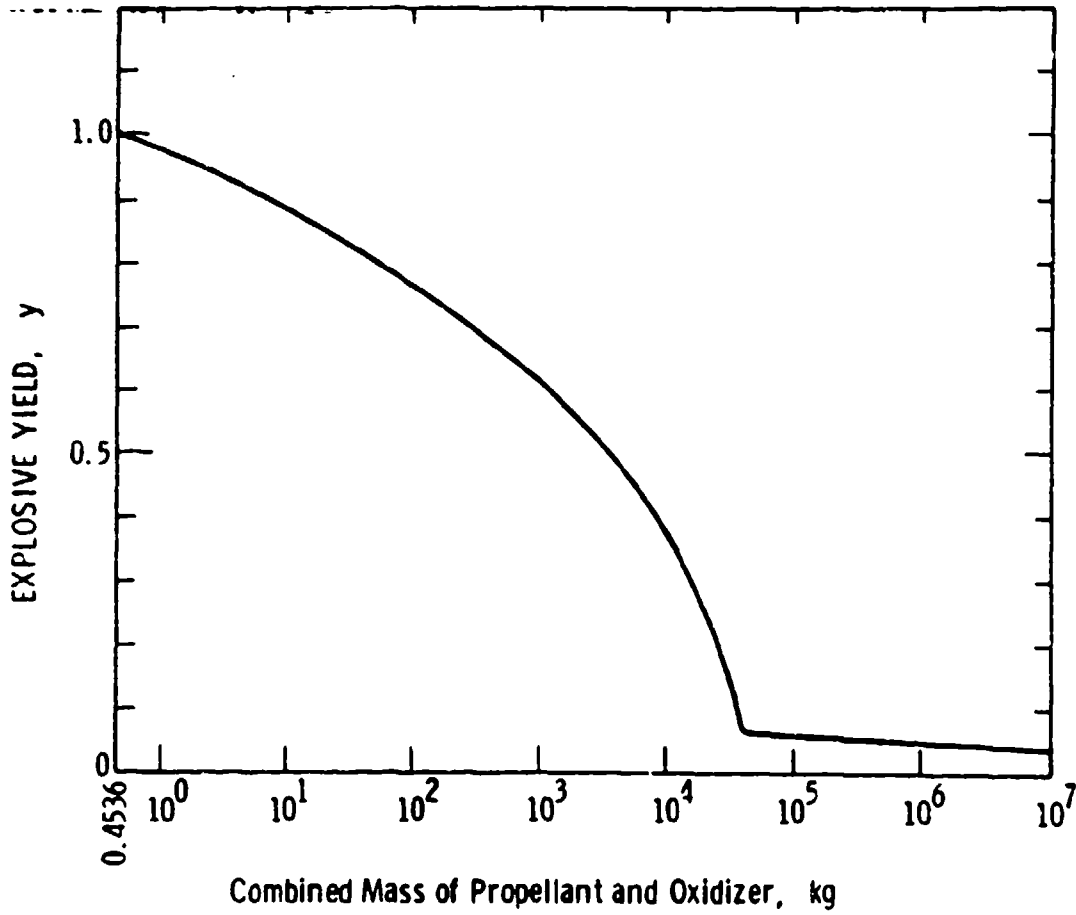
Multiplier Factors:

    (1) Hypergolic - 240%

    (2) LO_2/RP-1 - 125%

    (3) LO_2/LH_2 - 370%

    (lb_m = kg X 2.2)

Figure 1-1. Estimated Terminal Yield as a Function of
Combined Propellant and Oxidizer Mass (Ref. 9)

all propellants, depicts this relationship and should be used as an upper limit for percent explosive yield. Since this is a normalized plot, the percent yield for a particular propellant can be determined by obtaining the normalized fractional value from the graph and multiplying by the multiplier factor for the particular propellant under investigation. These multiplier factors, shown on the figure, are:

Hypergolic (50% N_2H_4 - 50% UDMH fuel and N_2O_4 oxidizer in mass ratio of 1/2) - 240%)[10]

Liquid oxygen-hydrocarbon (RP-1 fuel LO_2 oxidizer in mass ratio of 1/2.25) - 125%[6]

Liquid oxygen-liquid hydrogen (LH_2 fuel and LO_2 oxidizer in mass ratio of 1/5) - 370%[6]

Careful examination of Figure 1-1 and the multiplier factors indicate that explosive yield can be greater than 100 percent. Also, in certain cases, explosive yield will be greater than 100 percent when calculated by other methods. This anomaly occurs because explosive yield, as it is used here, is really terminal yield, or yield based on "TNT equivalence". Since the specific energies of the liquid propellants involved are greater than the specific energy of TNT, terminal (TNT equivalent) yield can be greater than 100 percent. Calculations were done in this manner to correlate with other methods discussed in subsequent paragraphs. Whenever the value of percent explosive (terminal) yield determined by these other methods exceeds the value of percent explosive (terminal) yield determined by using Figure 1-1, the value from Figure 1-1 is the correct choice.

(1)   Hypergolic materials, by definition, ignite spontaneously on contact, so it is not possible to obtain appreciable mixing before ignition unless the fuel and oxidizer are thrown violently together. Ignition time is therefore not an important determinant of blast yield for hypergolics, but impact velocity and degree of confinement after impact are important factors. If a CBM or CBGS failure mode is being considered, percent explosive yield can be acquired from Table 1-1. If a HVI failure mode is assumed, then percent explosive yield can be determined from Figure 1-2. The percent yield determined by any one of these methods must then be compared to the percent yield determined from the weight of the propellant (Figure 1-1). The smaller of the two is the correct choice.
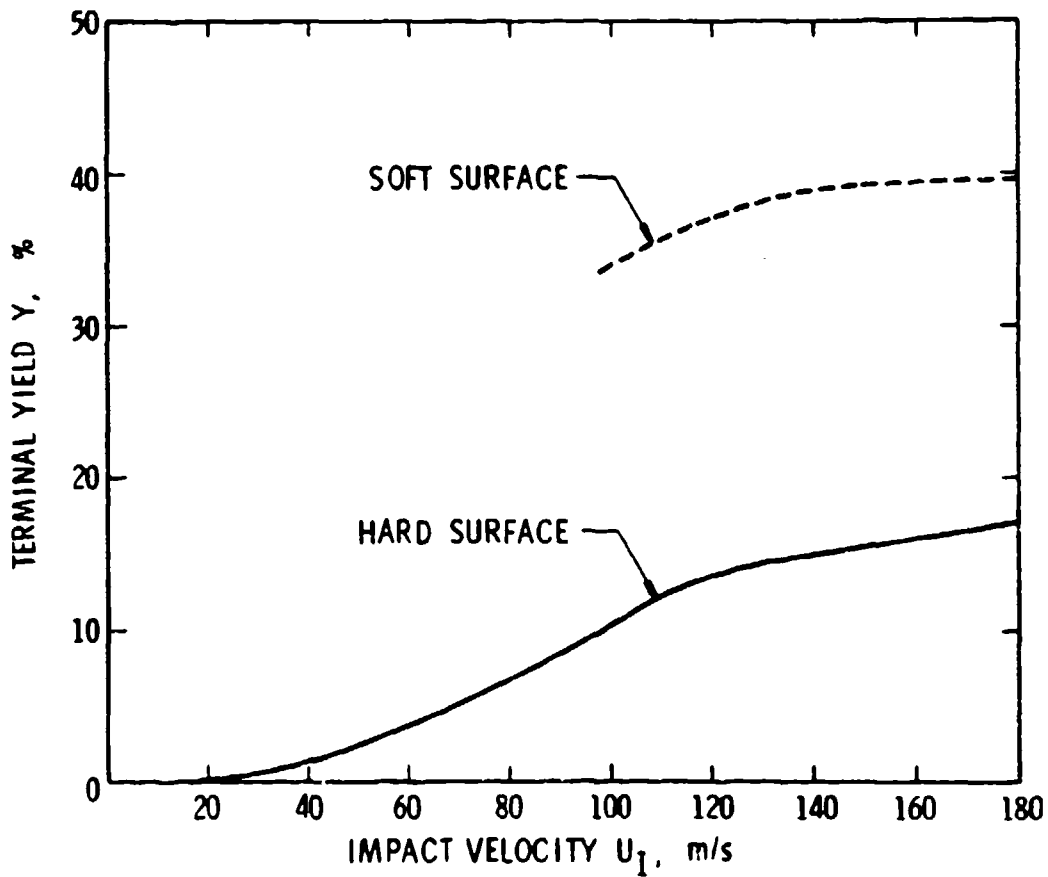
(ft/sec = m/s X 3.281)

Figure 1-2. Terminal Yield Vs Impact Velocity
for Hypergolic HVI (Ref. 3)

TABLE 1-1. ESTIMATE OF TERMINAL YIELD FOR HYPERGOLIC CBM AND CBGS (REF. 3)

Failure Mode	Terminal Yield Range (%)	Estimated Upper Limit
Diaphragm rupture (CBM)	0.01 - 0.8	1.5
Spill (CBGS)	0.02 - 0.8	0.5
Small explosive donor	0.8 - 1.2	2
Large explosive donor	3.4 - 3.7	5
Command destruct	0.3 - 0.35	0.5
310-ft drop (CBGS)	1.5	3

(2)   Because liquid oxygen/hydrocarbon propellants are not hypergolic, considerable mixing can occur in various types of accidents, and time of ignition after onset of mixing is an important determinant of blast yield. For the case of mixing and an explosion within the missile tankage (CBM), percent explosive yield can be determined by assuming an ignition time and then examining Figure 1-3.[*] For simulated fall-back on the launch pad (CBGS), impact velocity as well as ignition time are important parameters in estimating blast yield. A two-step approach has been developed to calculate blast yield. [1] After assuming an impact velocity, maximum percent yield Y_m can be determined for Equation (1-1):

$$Y_m = 5\% + \frac{(6.82\%)}{(m/s)} U_I, \quad 0 \le U_I \le 16.8 \text{ m/s} \qquad (1-1)$$

---

[*] A word of explanation will help clarify the meaning of the central solid line and shaded area of this graph and similar subsequent graphs. The shaded portion represents an area in which data from actual propellant blasts was found. The central solid line is an estimate of the most likely occurrence and, for most cases, is the recommended choice. Conservative estimates of explosive yield can be made by choosing the uppermost boundary of the shaded area. The vertical depth of the shaded area at any abscissa indicates the total range of data, and therefore the total uncertainty in the estimate.
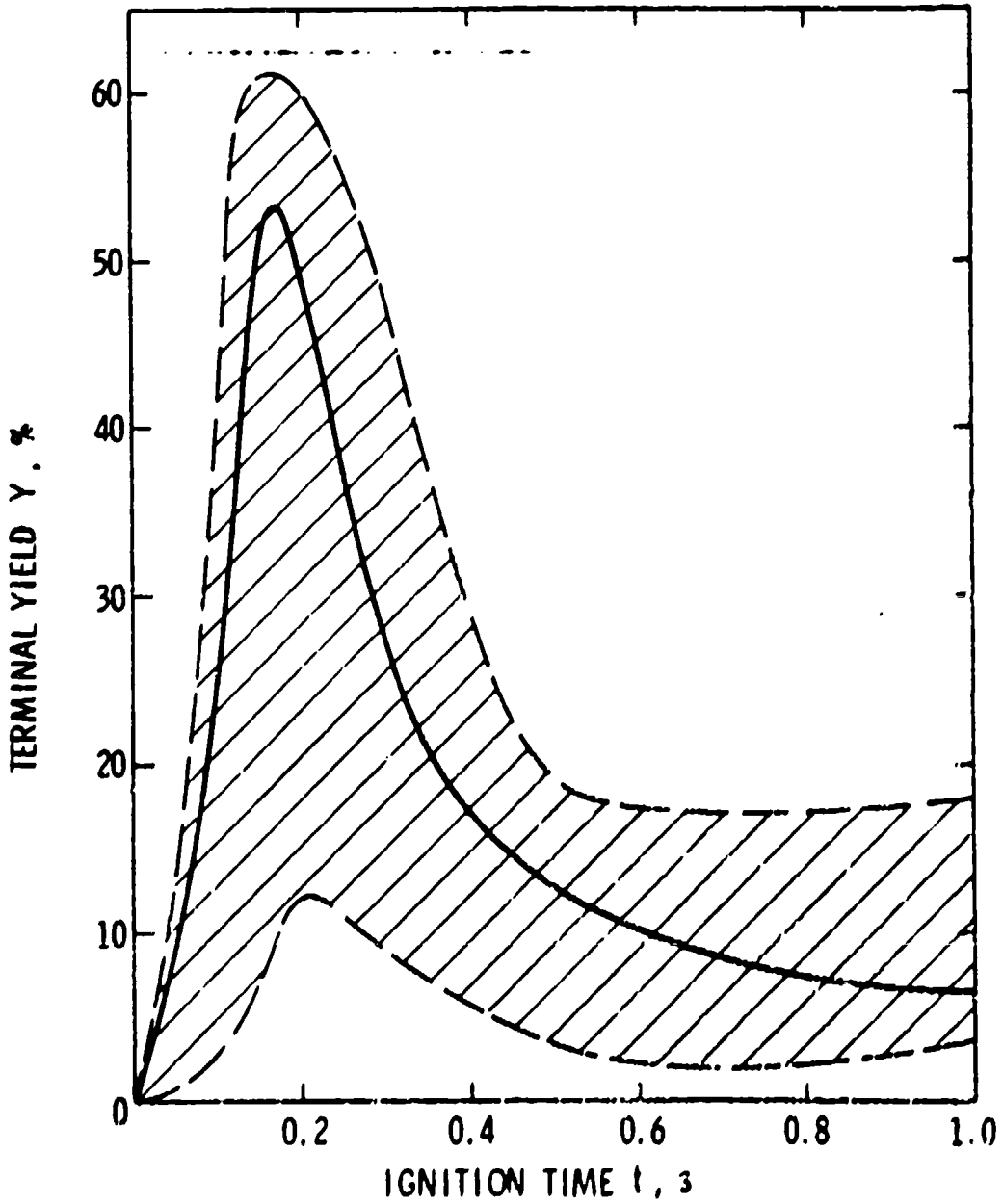
Figure 1-3. Terminal Yield Vs Ignition Time
for LO_2/RP-1 CBM

where Y_m is expressed in percent and U_I is in meters per second. Percent explosive yield can then be determined from Y_m, an estimate of ignition time, and Figure 1-4. The determination of explosive yield for the HVI failure mode is somewhat simpler because there is little ignition delay and therefore only impact velocity affects yield. Thus, blast yield can be acquired by using Figure 1-5 directly. The percent yield determined by any one of these methods must then be compared to the percent yield determined from the weight of the propellant (Figure 1-1). The smaller of the two is the correct choice.

(3)   The determination of explosive yield, for the entirely cryogenic combination of liquid hydrogen (LH_2) fuel and liquid oxygen (LO_2) oxidizer is similar to that of liquid oxygen-hydrocarbon propellants. For the CBM case, it is necessary for one to assume an ignition time and then use Figure 1-6 to find explosive yield. For the CBGS case, an impact velocity is assumed and maximum percent yield Y_m can be determined from Equation (1-2):

$$Y_m \quad = \quad 10\% \; + \; \frac{(13\%)}{(m/s)} \; U_I, \quad 0 \; \le \; U_I \; \le \; 24.4 \; m/s \qquad (1-2)$$

where Y_m is expressed in percent and U_I is in meters per second. Percent explosive yield can then be determined from Y_m, an estimate of ignition time and Figure 1-7. For high velocity impact (HVI) of this propellant, the blast yield is dependent only on the impact velocity and can be acquired from Figure 1-8 directly. The percent yield determined by any one of these methods must then be compared to the percent yield determined from the weight of the propellant (Figure 1-1). The smaller of the two is the correct choice.

    Table 1-2 has been prepared to alleviate the necessity of rereading the preceding presentation each time a value of explosive yield must be determined. To use the table, all one needs to do is identify the type of propellant and type of accident. Then the proper sequence in "Part 1" should be followed after making the necessary assumptions (e.g., ignition time or impact velocity and type of surface impacted) to arrive at a value for explosive yield. Explosive yield should then be determined by using the method depicted in "Part 2" which involves the use of Figure 1-1 and multiplier factors (see page 1-4). The smaller value for explosive yield
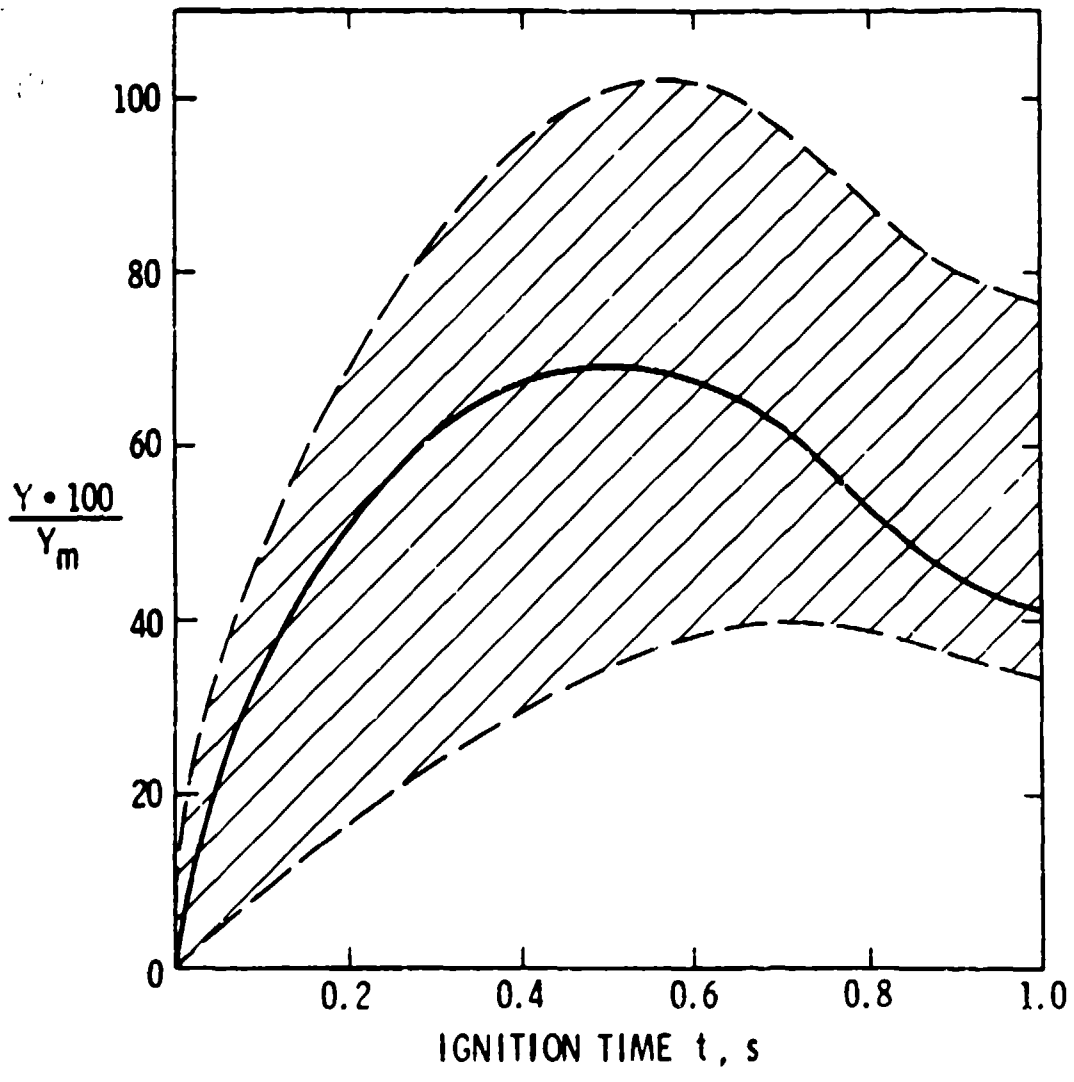
Figure 1-4. Normalized Terminal Yield Vs Ignition
Time for $LO_2/RP-1$ CBGS
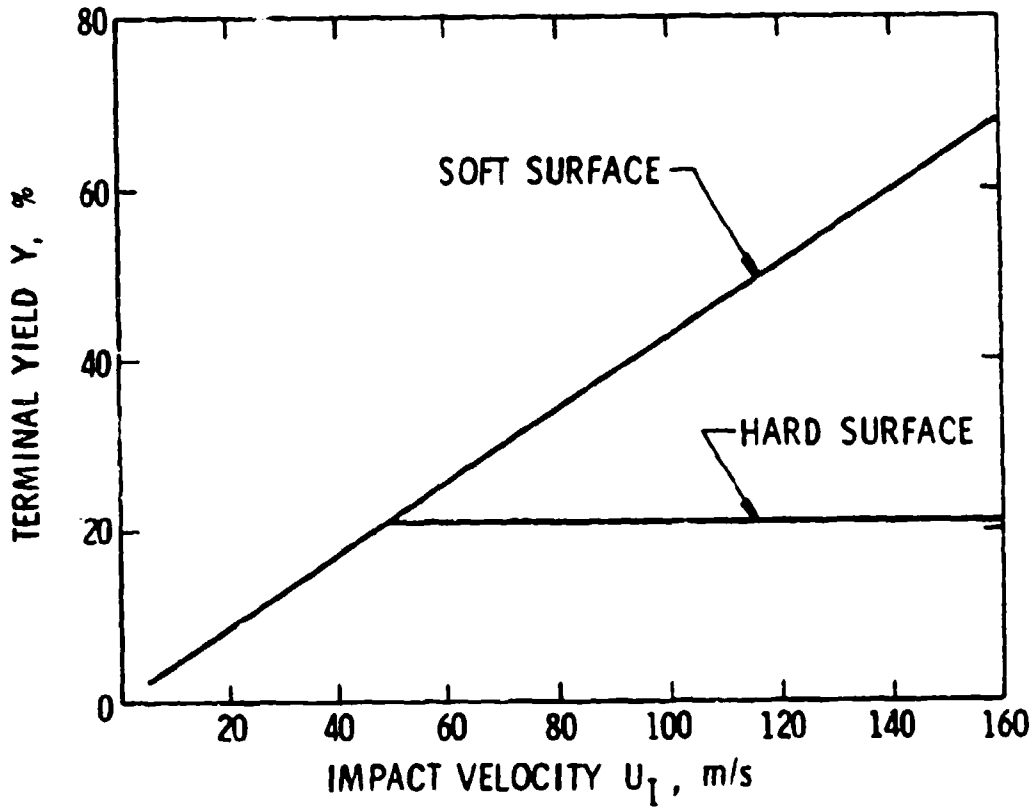
(ft/sec = m/s X 3.281)

Figure 1-5. Terminal Yield Vs Impact Velocity
for LO_2/RP-1 HVI (Ref. 3)
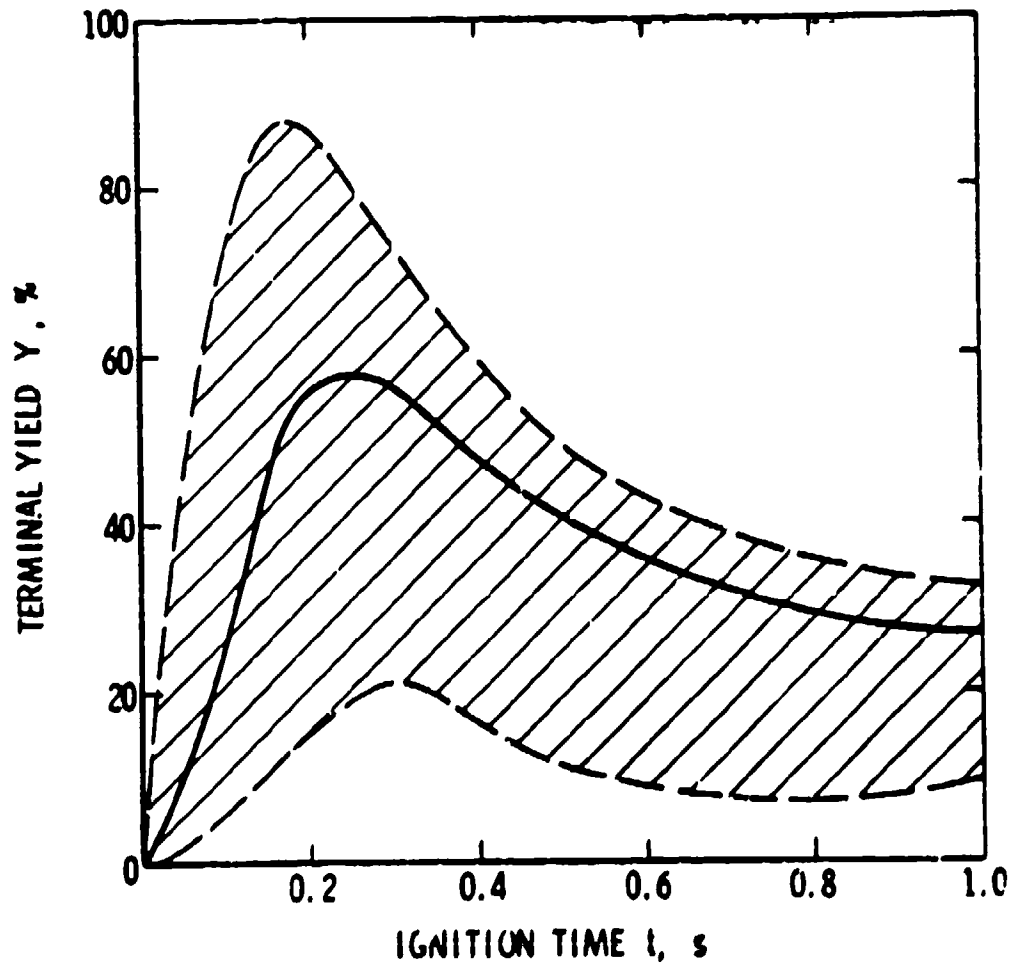
Figure 1-6. Terminal Yield Vs Ignition Time
for LO_2/LH_2 CBM
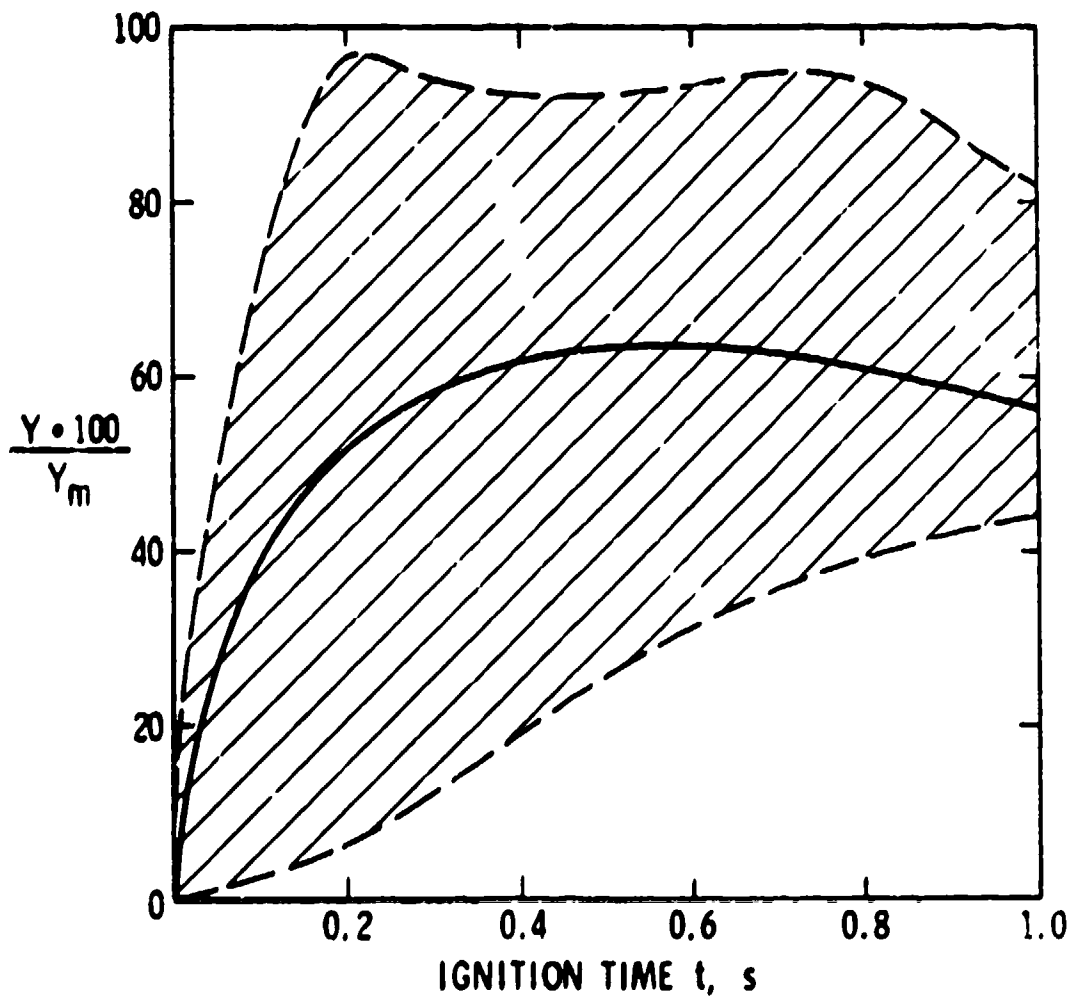
Figure 1-7. Normalized Terminal Yield Vs Ignition Time for LO_2/LH_2 CBGS
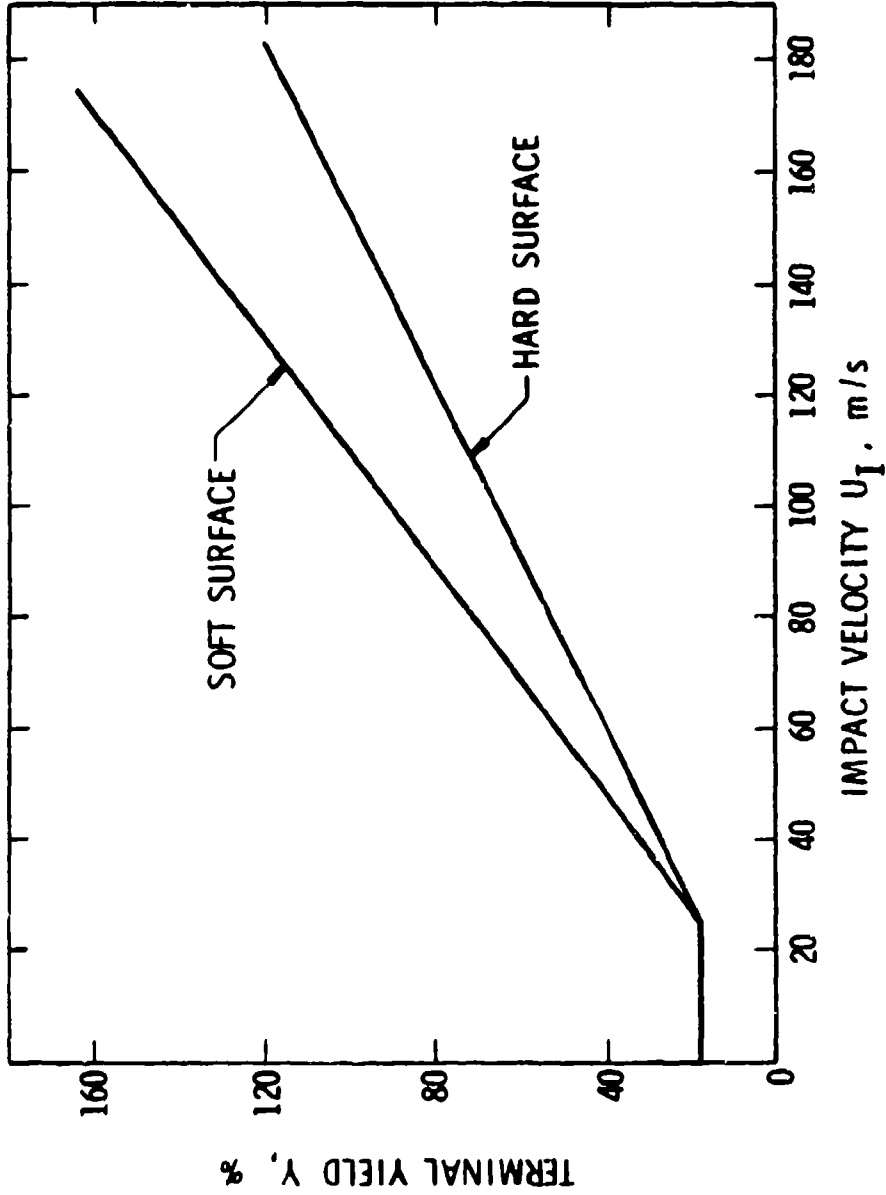
Figure 1-8. Terminal Yield Vs Impact Velocity for LO_2/LH_2 HVI (Ref. 3)

(ft/sec = m/s X 3.281)

IMPACT VELOCITY U_I, m/s

TERMINAL YIELD Y, %

HARD SURFACE

SOFT SURFACE

determined in "Part 1" and "Part 2" is the correct value. This value can then be used to determine an effective weight of propellant, and pressure and impulse at scaled distances using the methods demonstrated in a subsequent chapter.

1-1.3   Examples for Determining Explosive Yield

Example 1:

Propellant-Hypergolic
Combined mass of propellant and oxidizer-10, 000 kg (22, 000 lb_m)
Failure mode - CBM

Solution: Examine Table 1-2 for "Part 1" and "Part 2" solution sequences.

Part 1: Table 1-1 implies that for the CBM failure mode,

$Y = 0.01 - 0.8\%$

Using the higher portion for safety reasons,

$Y = 0.8\%$

Part 2: Figure 1-1 implies that for a combined mass of propellant and oxidizer of 10, 000 kg,

$Y = (24\%) (0.37) = 88.8\%$

where 240% is the hypergolic multiplier factor,

$Y = 0.8\%$, the smaller value, is the correct choice.

Example 2:

Propellant-Hypergolic
Combined mass of propellant and oxidizer-1000 kg (2200 lb_m)
Failure mode - HVI
Impact velocity (assumption) - 140 m/s (459 ft/sec)
Type of surface impacted - hard

Solution: Examine Table 1-2 for "Part 1" and "Part 2" solution sequences.

Part 1: Figure 1-2 implies that for an impact velocity of 140 m/s (459 ft/sec) onto a hard surface, $Y = 15\%$.

TABLE 1-2. SEQUENCE FOR DETERMINATION OF EXPLOSIVE YIELD [*]

Type of Propellant & Oxidizer	Type of Accident Failure Mode	Sequence[†] Part 1[‡]	Part 2 (check)
Hypergolic (50% N_2H_4 - 50% UDMH/N_2O_4)	CBM	Table 1-1	Figure 1-1
	CBGS	Table 1-1	Figure 1-1
	HVI	Figure 1-2	Figure 1-1
Liquid Oxygen - Hydrocarbon (LO_2/RP-1)	CBM	Figure 1-3	Figure 1-1
	CBGS	Eq. (1-1) Figure 1-4	Figure 1-1
	HVI	Figure 1-5	Figure 1-1
Liquid Oxygen- Liquid Hydrogen (LO_2/LH_2)	CBM	Figure 1-6	Figure 1-1
	CBGS	Eq. (1-2) Figure 1-7	Figure 1-1
	HVI	Figure 1-8	Figure 1-1

---

[*] For explosions occurring far above the ground ($H/W^{1/3} > 10$ m/kg$^{1/3}$ where H is height above the ground), blast yields calculated from curves in this section should be divided by two.

[†] Correct choice is the smaller of Part 1 and Part 2.

[‡] See footnote on page 1-7.

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Part 2: Figure 1-1 implies that for a combined mass of propellant and oxidizer of 1000 kg (2200 lb_m)

$$Y = (240\%) (0.6) = 144\%$$

where 240% is the hypergolic multiplier factor.

$Y = 15\%$, the smaller value, is the correct choice.

Example 3:

Propellant and oxidizer - $LO_2/RP-1$
Combined mass of propellant and oxidizer- 10,000 kg (22,000 lb_m)
Failure mode - CBM
Ignition time (assumption) - 0.2 seconds

Solution: Examine Table 1-2 for "Part 1" and "Part 2" solution sequences.

Part 1: Figure 1-3 implies that for an ignition time of 0.2 seconds,

$$Y = 52\%$$

Part 2: Figure 1-1 implies that for a combined mass of propellant and oxidizer of 10,000 kg (22,000 lb_m)

$$Y = (125\%) (0.37) = 46\%$$

where 125% is the $LO_2/RP-1$ multiplier factor.

$Y = 46\%$, the smaller value, is the correct choice.

Example 4:

Propellant and oxidizer - $LO_2/RP-1$
Combined mass of propellant and oxidizer - 150,000 kg
    (330,000 lb_m)
Failure mode - CBGS
Impact velocity (assumption) - 10 m/s (32.8 ft/sec)
Ignition time (assumption) - 0.5 seconds

Solution: Examine Table 1-2 for "Part 1" and "Part 2" solution sequences.

Part 1: Equation (1-1) implies that for an impact velocity of 10 m/s, (32.8 ft/sec)

$$Y_m = 5\% + \frac{(6.82\%)}{(m/s)} \, (10 \text{ m/s})$$

$$Y_m = 5\% + 68.2\%$$

$$Y_m = 73.2\%$$

Figure 1-4 implies that for an ignition time of 0.5 seconds

$$\frac{Y \cdot 100}{Y_m} = 70$$

or

$$Y = \frac{(70)}{(100)} \, Y_m$$

$$Y = \frac{(70)}{(100)} \, (73.2\%) = 51.2\%$$

Part 2: Figure 1-1 implies that for a combined mass of propellant and oxidizer of 150,000 kg (330,000 lb_m),

$$Y = (125\%)(0.05) = 6.25\%$$

where 125% is the $LO_2/RP-1$ multiplier factor.

Y = 6.25%, the smaller value, is the correct choice.

Example 5:

Propellant and oxidizer - LO_2/LH_2
Combined mass of propellant and oxidizer - 10,000 kg (22,000 lb_m)
Failure mode - HVI
Impact velocity (assumption) - 40 m/s (131 ft/sec)
Type of surface impacted - hard

Solution: Examine Table 1-2 for "Part 1" and "Part 2" solution sequences

Part 1: Figure 1-9 implies that for an impact velocity of 40 m/s (131 ft/sec),

$$Y = 30\%$$

Part 2: Figure 1-1 implies that for a combined mass of propellant and oxidizer of 10,000 kg (22,000 lb$_m$),

$$Y = (370\%)(.37) = 137\%$$

where 370% is the LO_2/LH_2 multiplier factor.

$Y = 30\%$, the smaller value, is the correct choice.

1-2 Explosive Yield as a Function of Fluid Type and Initial Conditions for Gas Vessel Bursts

1-2.1 General Discussion of Gas Vessel Explosions

When a pressurized gas-filled vessel bursts, a shock wave in many ways similar to that which results from a TNT explosion propagates from the source. The overpressure behind this shock wave may be quite large and capable of causing damage. The specific impulse associated with this shock wave is also important for the prediction of damage from a gas vessel burst. These two parameters vary with distance from the source.

In the analysis that was used for the overpressure and specific impulse calculations, the effects of the containing vessel and its fragments were ignored, that is, all of the energy of the gas in the vessel was put into the flow field, rather than into the fragments as kinetic energy. For a spherical vessel, the flow field was assumed spherically symmetric. Also, the surrounding atmosphere was assumed to be air.

To determine the overpressure and impulse, one must know the initial conditions of the gas in the vessel. The pressure p_1, temperature T_1, and ratio of specific heats of the gas γ_1 must be known.

The conditions of the atmosphere into which the shock wave propagates also must be known. These are the atmospheric pressure p_a, the speed of sound a_a, and the ratio of specific heats γ_a. The latter value will be a constant for all explosions in air.

1-2.2 Discussion of Energy

The energy contained in a pressurized gas vessel can be obtained by

$$E = \left(\frac{p_1 - p_a}{\gamma_1 - 1}\right) V_i$$

where

V_i is the volume of the vessel before it bursts[11] and

p_i indicates <u>absolute</u> pressures.

The overpressure and impulse are graphed versus a dimensionless scaled distance:

$$\bar{R} = \frac{r \; p_a^{1/3}}{E^{1/3}}$$

A scaled specific impulse is used:[12]

$$\bar{I} = \frac{I \; a_a}{p_a^{2/3} \; E^{1/3}}$$

Note that there is no need to calculate a TNT equivalent for gas vessel bursts.

1-2.3   Example Calculations

<u>Example 1. Calculation of Energy</u>

Let p_a = 1.013×10^5 Pa (1 standard sea level atmosphere) (14.7 psi)

p_1 = 41.013×10^5 Pa (595 psi)

γ_1 = 1.4 (diatomic gas)

V_i = $1.0 \; m^3$ (35.3 ft^3)

$$E = \frac{(p_1 - p_a)}{\gamma_1 - 1} V_i = \frac{(41.013 \times 10^5 \; Pa - 1.013 \times 10^5 \; Pa) \; 1 \; m^3}{1.4 - 1}$$

$$= 1.00 \times 10^7 \; J \; (1.34 \times 10^6 \; ft\text{-}lb_f)$$

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Example 2. Calculation of Scaled Distance

Using the same conditions as in the previous example.

$$\bar{R} = \frac{r\, P_a^{1/3}}{E^{1/3}} = \left[\frac{r}{\dfrac{(p_1/P_a - 1)\, V_i}{\gamma_1 - 1}}\right]^{1/3} = \left[\frac{r}{\dfrac{\left(\dfrac{41.013 \times 10^5\ Pa}{1.013 \times 10^5\ Pa} - 1\right) 1\ m^3}{1.4 - 1}}\right]^{1/3}$$

$$= 0.216\ r\ (r\ in\ m)\ \ [0.0658\ r\ (r\ in\ ft)]$$

Example 3. Calculation of Scaled Impulse

Let $a_a = 331$ m/s (speed of sound at standard sea level conditions) (1086 ft/sec).

For the conditions used in the previous examples,

$$\bar{I} = \frac{I\, a_a}{P_a^{2/3}\, E^{1/3}} = \frac{I\ (331\ m/s)}{(1.013 \times 10^5\ Pa)^{2/3}\ (1.00 \times 10^7)^{1/3}} =$$

$$7.070 \times 10^{-4}\ I\ \ (I\ in\ Pa \cdot s)$$

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CHAPTER II

CHARACTERISTICS OF PRESSURE WAVES

2-1   General

Explosions from liquid rocket propellant accidents "drive" air blast waves, which can in turn cause direct damage and can accelerate fragments or nearby objects. The launch pads at the Air Force Eastern Test Range (ETR) have for a number of years been instrumented with air blast recorders to measure the overpressures generated during launch pad explosions, so some data are available on the intensities of the blast waves generated. Such measurements, and the common practice in safety circles of comparing explosive effects on the basis of blast waves generated by TNT, have led to expression of blast yields of propellant explosions in equivalent "pounds of TNT." (Although a direct conversion of pounds of TNT to energy can easily be made -- 1 lb_m of TNT equals 1.4 x 10^6 ft-lb_f -- this is seldom done).

Liquid propellant explosions differ from TNT explosions in a number of ways, so that the concept of "TNT equivalence" quoted in pounds of TNT is far from exact. Some of the differences are described below.

(1)   The specific energies of liquid propellants, in stoichiometric mixtures, are significantly greater than for TNT (specific energy is energy per unit mass).

(2)   Although the potential explosive yield is very high for liquid propellants, the actual yield is much lower, because propellant and oxidizer are never intimately mixed in the proper proportions before ignition.

(3)   Confinement of propellant and oxidizer, and subsequent effect on explosive yield, are very different for liquid propellants and TNT. Degree of confinement can seriously affect explosive yield of liquid propellants, but has only a secondary effect on detonation of TNT or any other solid explosive.

(4)   The geometry of the liquid propellant mixture at time of ignition can be quite different than that of the spherical or hemispherical geometry of TNT usually used for generation of controlled blast waves. The sources of compiled data for blast waves from TNT or Pentolite invariably rely on

measurements of blasts from spheres or hemispheres of explosive. The liquid propellant mixture can, however, be a shallow pool of large lateral extent at time of detonation.

(5) The blast waves from liquid propellant explosions show different characteristics as a function of distance from the explosion than do waves from TNT explosions. This is undoubtedly simply a manifestation of some of the differences discussed previously, but it does change the "TNT equivalence" of a liquid-propellant explosion with distance from the explosion. Fletcher (Reference 1) discusses these differences and shows them graphically (see Figures 2-1 and 2-2). These differences are very evident in the results of the many blast experiments reported in Project PYRO (References 2-4). They have caused the coinage of the phase "terminal yield", meaning the yield based on blast data taken at great enough distance from the explosion for the blast waves to be similar to those produced by TNT explosions. At closer distance, two different yields are usually reported; an overpressure yield based on equivalence of side-on peak overpressures, and an impulse yield based on equivalence of side-on positive impulses.

Accidents with bursting gas storage vessels also can generate damaging blast waves. The characteristics of the blasts from these and other accidental explosions are reviewed in Reference 5, and rather complete descriptions given of the theory of such "non-ideal" explosions. Again, these sources generate blast waves which can differ significantly from blast waves generated by condensed explosives such as TNT, with the differences being greatest close to the source. The trend is similar to that for propellant explosions, i.e., peak overpressures are less and impulses are greater than for "equivalent" TNT explosions. But, the potential maximum yield or blast energy from gas vessel bursts is much more apt to be realized than for liquid propellant explosions. The high pressure gas already contains the necessary energy and can be rapidly released without the prior mixing and ignition required for the propellants.

However, let us for the moment ignore the differences between accidental explosions and planned ones, and discuss instead the general characteristics of the blast waves generated by any explosion. References 6-8 are good general source references on air blast waves and their behavior.

As a blast wave passes through the air or interacts with and loads a structure or target, rapid variations in pressure, density, temperature and particle velocity occur. The properties of blast waves which are
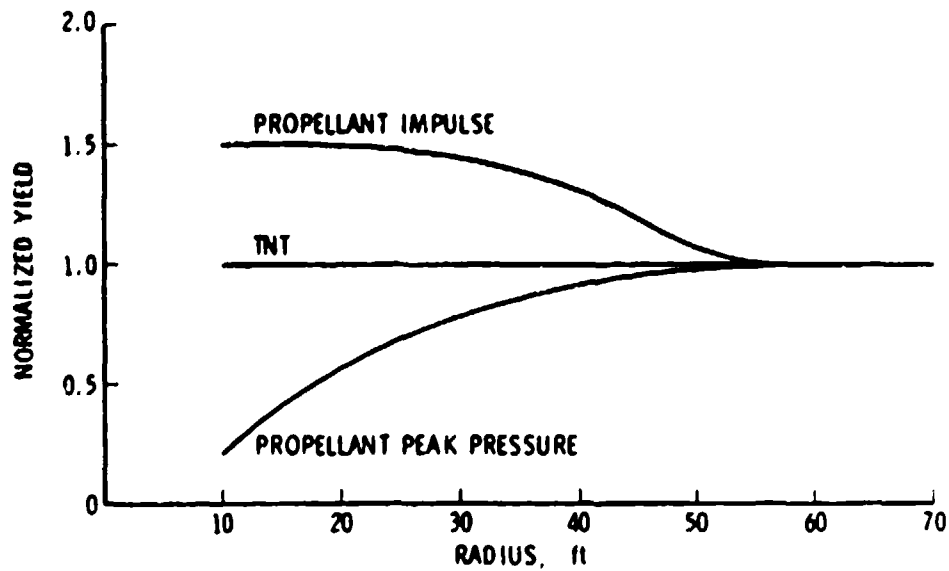
Figure 2-1. Normalized Pressure and Impulse Yields from
Explosion of N_2O_4/Aerozine 50 (Ref. 1)
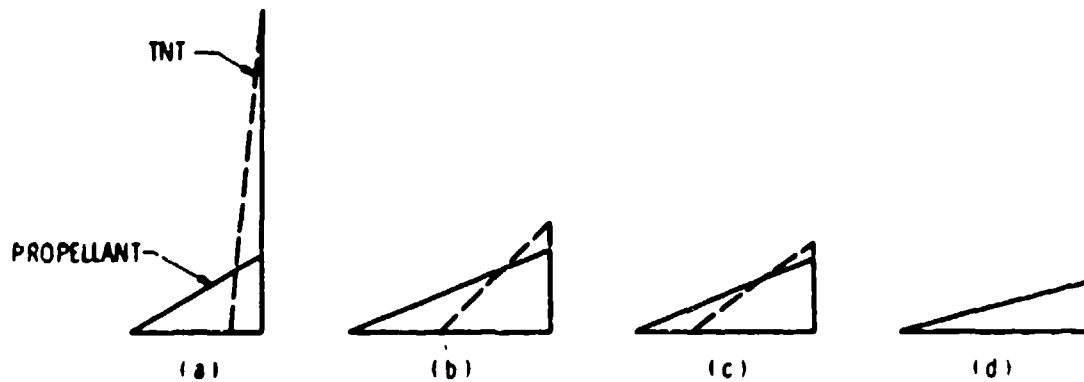
Figure 2-2. Representative Shock Impulses Showing Coalescence
of Shock Waves from Dissimilar Sources [Stages (a) Through (d)]
(Ref. 1)

usually defined are related both to the properties which can be easily measured or observed and to properties which can be correlated with blast damage patterns. It is relatively easy to measure shock front arrival times and velocities and entire time histories of overpressures. Measurement of density variations and time histories of particle velocity are more difficult, and no reliable measurements of temperature variations exist.

Classically, the properties which are usually defined and measured are those of the undisturbed or side-on wave as it propagates through the air. Figure 2-3 shows graphically some of these properties in an ideal wave (Reference 6).
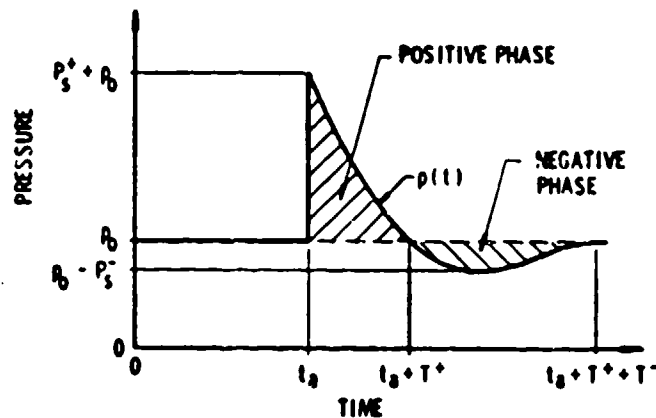
Figure 2-3. Ideal Blast Wave

Prior to shock front arrival, the pressure is ambient pressure p_0. At arrival time t_a, the pressure rises quite abruptly (discontinuously, in an ideal wave) to a peak value $P_s^+ + p_0$. The pressure then decays to ambient in total time $t_a + T^+$, drops to a partial vacuum of amplitude P_s^-, and eventually returns to p_0 in total time $t_a + T^+ + T^-$. The quantity P_s^+ is usually termed the peak side-on overpressure, or merely the peak overpressure. The portion of the time history above initial ambient pressure is called the positive phase, of duration T^+. That portion below p_0, of amplitude P_s^- and duration T^- is called the negative phase. Positive and negative impulses, defined by

$$I_S^+ = \int_{t_a}^{t_a + T^+} \lfloor p(t) - p_0 \rfloor \, dt \qquad (2-1)$$

2-4

and

$$I_S^- = \int_{t_a + T^+}^{t_a + T^+ + T^-} [\, p_o - p(t)\,]\, dt \qquad (2\text{-}2)$$

respectively, are also significant blast wave parameters.

In most blast studies, the negative phase of the blast wave is ignored and only blast parameters associated with the positive phase are considered or reported. (The positive superscript is usually dropped). The ideal side-on parameters almost never represent the actual pressure loading applied to structures or targets following an explosion. So a number of other properties are defined to either more closely approximate real blast loads or to provide upper limits for such loads.

An upper limit to blast loads is obtained if one interposes an infinite, rigid wall in front of the wave, and reflects the wave normally. All flow behind the wave is stopped, and pressures are considerably greater than side-on. The peak overpressure in normally reflected waves is usually designated P_r. The integral of this pressure over the positive phase, defined similarly to Equation (2-1), is the reflected impulse I_r. Durations of the positive phase of normally reflected waves are designated T_r. The parameter I_r has been measured closer to high explosive blast sources than have most blast parameters.

In certain instances, damage estimates involve P_r and I_r instead of P_s and I_s. This situation can occur when one is examining the effect of an air burst on ground structures. The ground, in this case, acts as the most significant reflecting surface. Reflected pressures and impulses are also used in analyzing face-on loading of windows and structures. Fortunately, reflected pressure and impulse can be calculated directly from side-on pressure and impulse. For values of $\overline{P}_r \leq 3.5$ where $\overline{P}_r$ is P_r/p_o (p_o is atmospheric pressure),

$$\overline{P}_r = 2\overline{P}_s + \frac{(\gamma + 1)\,\overline{P}_s^{\,2}}{(\gamma - 1)\,\overline{P}_s + 2\gamma} \qquad (2\text{-}3)$$

where $\overline{P}_s = P_s/p_o$ and γ is the ratio of specific heats which equals 1.4 for air. For values of $\overline{P}_s > 3.5$, $\overline{P}_r$, and subsequently P_r, can be determined from Figure 2-4.

Over the range $0.00141 \leq \overline{P}_s \leq 1.38$, $\overline{I}_r$ $(= I_r\, a_o/p_o^{1/3} E^{1/3})$ can be calculated from

$$\overline{I} = \overline{I}_s \frac{\overline{P}_r}{\overline{P}_s} \qquad (2\text{-}4)$$

where $\overline{I}_s = I_s a_o / p_o^{1/3} E^{1/3}$. For values of $\overline{P}_s < 0.00141$,

$$\overline{I}_r = 2\overline{I}_s \qquad (2\text{-}5)$$

A real target feels a very complex loading during the process of diffraction of the shock front around the target. Figure 2-5 shows schematically, in three stages, the interaction of a blast wave with an irregular object. As the wave strikes the object, a portion is reflected from the front face, and the remainder diffracts around the object. In the diffraction process, the incident wave front closes in behind the object, greatly weakened locally, and a pair of trailing vortices is formed. Rarefraction waves sweep across the front face, attenuating the initial reflected blast pressure. After passage of the front, the body is immersed in a time-varying flow field. Maximum pressure on the front face during this "drag" phase of loading is the stagnation pressure.
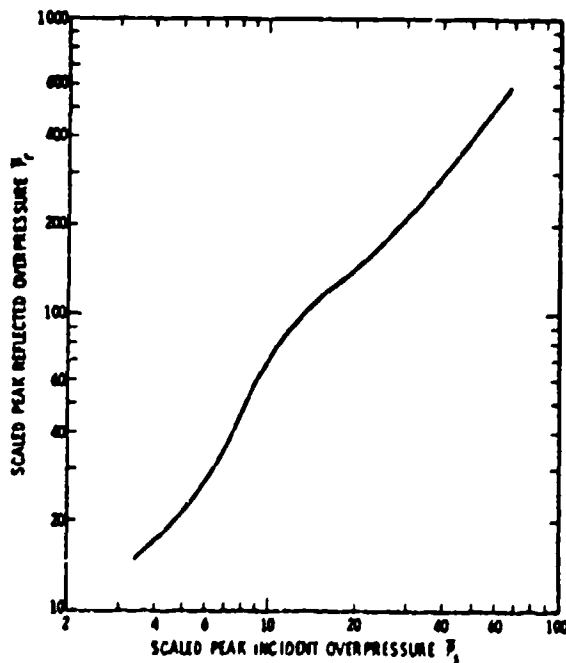
Figure 2-4. Scaled Reflected Overpressure Vs Scaled Side-on Overpressure

We are interested in the net transverse pressure on the object as a function of time. This loading, somewhat idealized, is shown in Figure 2-6 [details of the calculation are given by Glasstone (Reference 7)]. At time of arrival t_a, the net transverse pressure rises linearly from zero to maximum of P_r in time $(T_1 - t_a)$ (for a flat-faced object, this time is zero). Pressure then falls linearly to drag pressure in time $(T_2 - T_1)$, and then decays more slowly to zero in time $(T_3 - T_2)$. This time history of drag pressure q is a modified exponential, with a maximum given by

$$C_D Q = C_D \cdot (1/2) o_s u_s^2 \qquad (2-6)$$

where C_D is the steady-state drag coefficient for the object, Q is peak dynamic pressure, and o_s and u_s are peak density and particle velocity respectively for the blast wave. The characteristics of the diffraction phase of the loading can be determined if the peak side-on overpressure P_s or the shock velocity U is known, together with the shape and some characteristic dimension D of the object. The peak amplitude of the drag phase of the loading can be determined if the peak side-on overpressure P_s or the shock velocity U is known, together with the shape and some characteristic dimension D of the object. The peak amplitude of the drag phase, $C_D Q$, can also be determined explicitly from P_s or u_s.
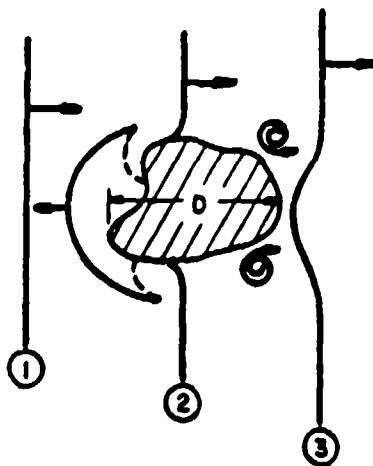
Figure 2-5. Interaction of Blast Wave with
Irregular Object
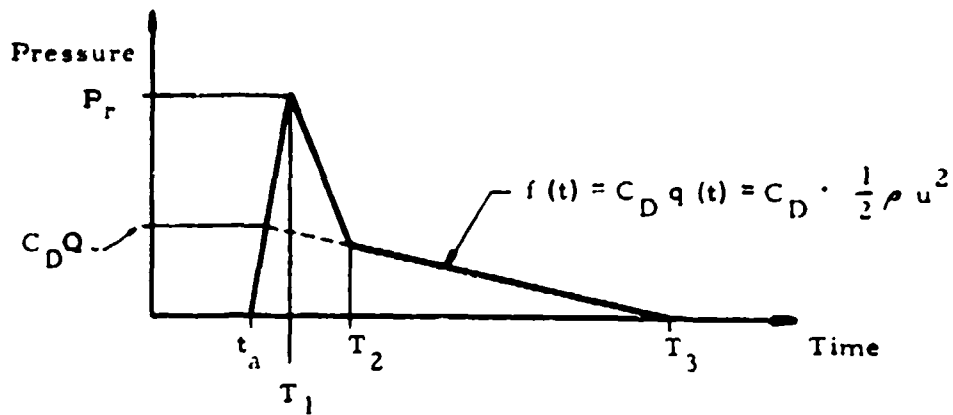
Figure 2-6. Time History of Net Transverse Pressure
on Object During Passage of a Blast Wave

Because of the importance of the dynamic pressure q in drag or
wind effects and target tumbling, it is often reported as a blast wave
property. In some instances drag impulse I_d, defined as

$$I_d = \int_{t_a}^{t_a + T} q \, dt = (1/2) \int_{t_a}^{t_a + T} {}_o u^2 \, dt \qquad (2-7)$$

is also reported.

Although it is possible to define the potential or kinetic energy in
blast waves, it is not customary in air blast technology to report or
compute these properties. For underwater explosions, the use of
"energy flux density" is more common (Reference 9). This quantity is
given approximately by

$$E_f = \frac{1}{{}_o c_o} \int_{t_a}^{t_a + T} [p(t) - p_o]^2 \, dt \qquad (2-8)$$

Blast waves from real accidental explosions can differ in a number
of ways from the essentially clean spherical waves considered in most
theoretical treatments, and in many field or laboratory experiments. As
an example, any explosion source which is not spherical in free air or

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hemispherical in contact with a reflecting plane will generate a blast wave which is, at least in its early stages, non-spherical. The wave may well have an axis of symmetry, but requires definition in at least two space coordinates and time. Analytically, the treatment of non-spherical waves requires more mathematical complexity, and experimentally, measurement requires many more tests than for spherical waves.

The simplest type of non-spherical behavior probably results from elevation of a spherical explosion source above a reflecting plane (usually the ground). The resulting reflection process is described in Baker (Reference 6) and Glasstone (Reference 7). A structure or target on the ground feels a double shock if it is in the region of regular reflection close to the blast source, or a single strengthened shock if it is in the region of Mach reflection. Even this "simplest" case of non-spherical behavior is quite complex.

The second type of asphericity is that caused by sources which are not spherical. Most real blast sources are non-spherical, and can be of regular geometry such as cylindrical or block-shaped, or can be quite irregular in shape. Few analyses or experiments have been done for other than cylindrical geometry of solid explosive sources. For cylinders, the wave patterns are quite complex. The pressure-time histories exhibit multiple shocks, and decay in a quite different manner in the near field than do spherical waves. Fortunately, asymmetries smooth out as the blast wave progresses, and "far enough" from most real sources, the wave will become a spherical wave.

Other effects which can significantly alter blast wave properties are:

(1)   Effect of partial or total confinement.

(2)   Atmospheric propagation effects.

(3)   Absorption of energy by ground shock or cratering.

(4)   Transmission over irregular terrain.

These effects are often ignored or roughly approximated in safety studies because they are quite variable or can be adequately accounted for by use of simple safety factors or energy multipliers. They are discussed in some detail in References 5 and 6.

2-2 Pressure Waves From Propellant Explosions

2-2.1 Introduction

The characteristics of pressure waves, particularly peak side-on overpressure and specific impulse, are used extensively in developing damage estimates from propellant explosions. This portion of this chapter is therefore devoted to the calculation of pressures and specific impulses at varying distances from a propellant explosion based on methods given by Baker, et al[10].

The same terminology used in Chapter I, Section A for propellant types and failure modes is used in this chapter. Three different types of propellant-oxidizer combinations are considered. These are hypergolic (50% N_2H_4 - 50% UDMH fuel and N_2O_4 oxidizer in a mass ratio of 1/2), liquid oxygen-hydrocarbon [Kerosene (RP-1) fuel and liquid oxygen (LO_2) oxidizer in a mass ratio of 1/2.25], and liquid oxygen-liquid hydrogen [cryogenic combination of liquid hydrogen (LH_2) fuel and liquid oxygen (LO_2) oxidizer in stoichiometric mass ratio of 1/5]. Three types of failure modes are considered; namely, confined by missile (CBM), confined by ground surface (CBGS), and high velocity impact (HVI). If needed, Chapter I should be consulted for a more complete explanation of types of propellants and failure modes.

2-2.2 Determination of Peak Side-On Overpressure and Specific Impulse

Throughout the PYRO (2-4) work, blast yield is expressed as percent yield, based on an average of pressures and impulses measured at the farthest distance from the source when compared to standard reference curves (Reference 11) for TNT surface bursts (terminal yield). Hopkinson's blast scaling is used when comparing blast data for tests with the same propellants and failure conditions, but different mass of propellant. So, the blast parameters P (peak side-on overpressure) and $I/W^{1/3}$ (scaled impulse) are plotted as functions of $R/W^{1/3}$ (scaled distance), after being normalized by the fractional yield. This procedure is equivalent to determining an effective mass of propellant for blast from:

$$W = W_T \times \frac{Y}{100} \tag{2-9}$$

where W_T is total mass of propellant and oxidizer, Y is terminal blast yield in percent and W is effective mass of propellant. Because the data are normalized by comparing to TNT blast data, the effective blast energy E can be obtained by multiplying W by the specific detonation energy of

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TNT, 4.18×10^6 J/kg (1.4×10^6 ft lb_f/lb_m). Baker's[10] smoothed curves through the scaled PYRO blast data, and Equation (2-9) will be used to obtain blast wave properties for particular combinations of propellants and simulated accidents.

Table 2-1 contains the different propellant failure mode combinations under consideration and the figure numbers of the graphs (following Table 2-1) needed to determine peak side-on overpressure and scaled specific impulse as a function of scaled distance for each accident situation. The procedure for finding peak side-on overpressure and specific impulse are as follows:

(1)   Calculate terminal yield Y using methods discussed in Chapter I, Section A.

(2)   Determine W, effective mass of propellant and oxidizer, from Equation (2-9).

(3)   Choose a specific standoff distance R from the center of the anticipated blast and calculate scaled distance $R/W^{1/3}$.

(4)   Examine Table 1 and acquire the proper figure numbers for finding peak side-on overpressure P and scaled impulse $I/W^{1/3}$ for the particular propellant/oxidizer and failure mode under consideration.

(5)   Determine P from the appropriate Pressure versus Scaled Distance curve and the predetermined scaled distance.

(6)   Determine $I/W^{1/3}$ from the appropriate Scaled Positive Impulse versus Scaled Distance curve* and the predetermined scaled distance.

(7)   Calculate specific impulse I from scaled positive impulse $I/W^{1/3}$.

---

*A word of explanation will help clarify the meaning of the central solid line and shaded area of the graphs. The shaded portion represents actual data from propellant blasts. The central solid line is an estimate of the most likely occurrence and, for most cases, is the recommended choice. The vertical distance between the two dashed lines at any abscissa is a measure of the data spread, or uncertainty in a prediction from the solid line.

That is

$$I = \left(\frac{I}{W^{1/3}} \right) (W^{1/3}) \qquad\qquad (2-10)$$

TABLE 2-1. GUIDE TO SELECTION OF PROPER GRAPHS FOR THE
DETERMINATION OF PRESSURE AND SPECIFIC IMPULSE

Type of Propellant & Oxidizer	Type of Accident (Failure Mode)	Peak Side-On Overpressure (P)	Scaled Impulse $(I/W^{1/3})$
Hypergolic (50% N_2H_4 50% UDMH/N_2O_4)	CBM	Figure 2-7	Figure 2-8
	CBGS	Figure 2-7	Figure 2-8
	HVI	Figure 3-9	Figure 2-8
Liquid Oxygen-Hydrocarbon (LO_2/RP-1)	CBM	Figure 2-10	Figure 2-11
	CBGS	Figure 2-12	Figure 2-12
	HVI	Figure 2-12	Figure 2-13
Liquid Oxygen-Liquid Hydrogen (LO_2/LH_2)	CBM	Figure 2-14	Figure 2-15
	CBGS	Figure 2-16	Figure 2-17
	HVI	Figure 2-16	Figure 2-17

PEAK OVERPRESSURE P, pascal

SCALED DISTANCE R/W$^{1/3}$, m/kg$^{1/3}$

(psi = Pa X 1.450 X 10^{-4})

(ft/lb$_m^{1/3}$ = m/kg$^{1/3}$ X 2.521)

Figure 2-7. Pressure vs Scaled Distance. Hypergolic
Propellant; CMB and CBGS Failure Modes.

Figure 2-8. Scaled Positive Impulse vs Scaled Distance.
Hypergolic Propellant; CBM, CBGS and HVI
Failure Modes.
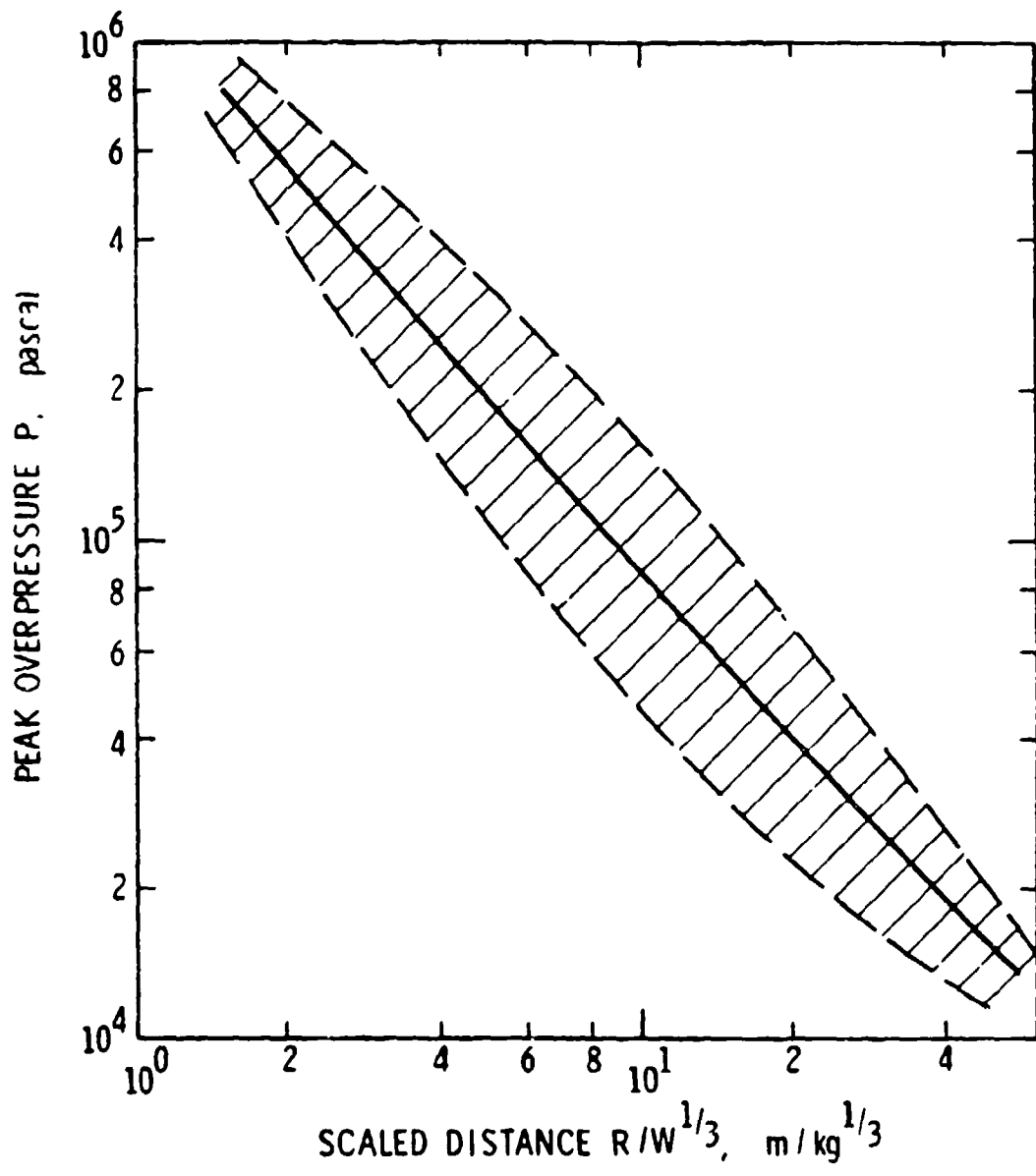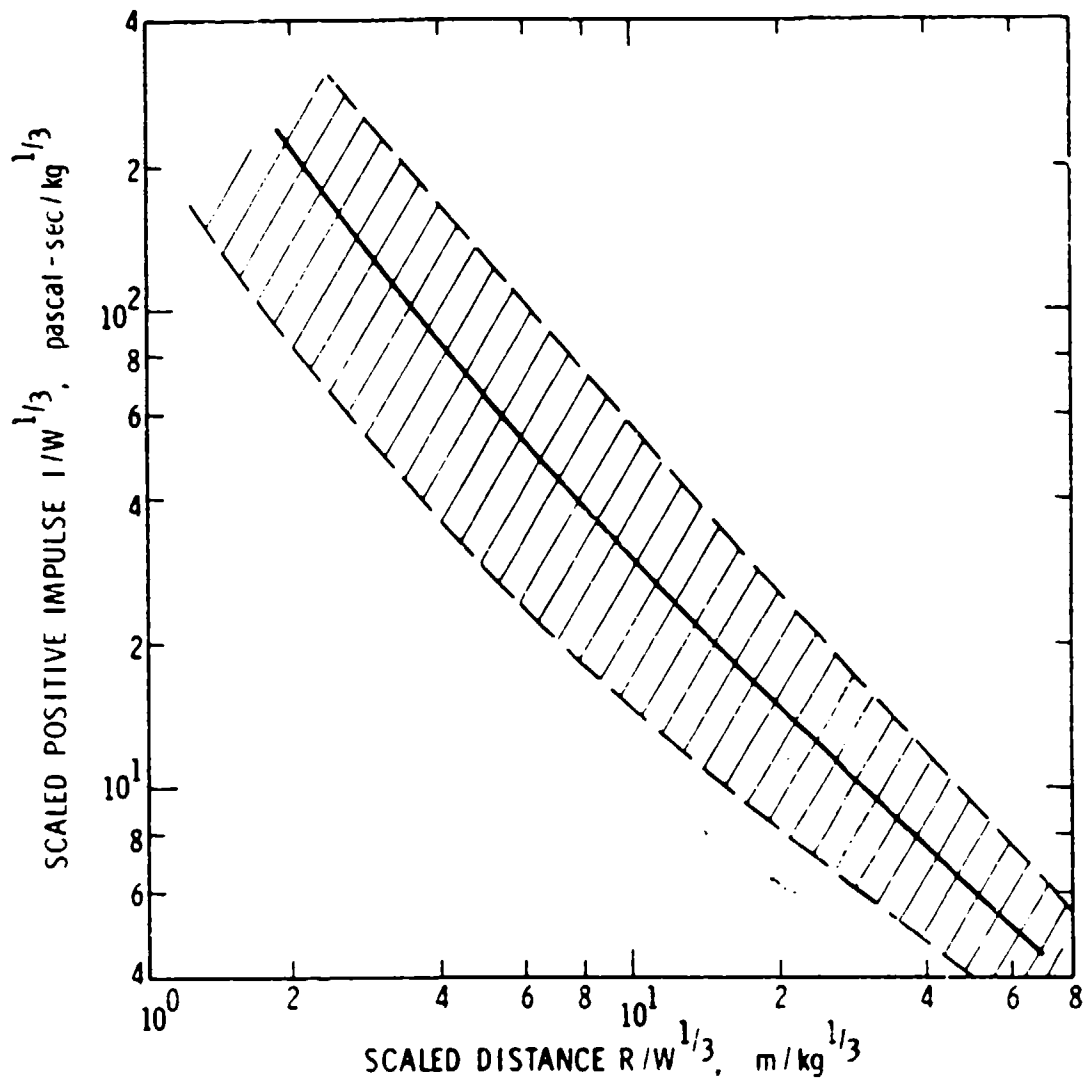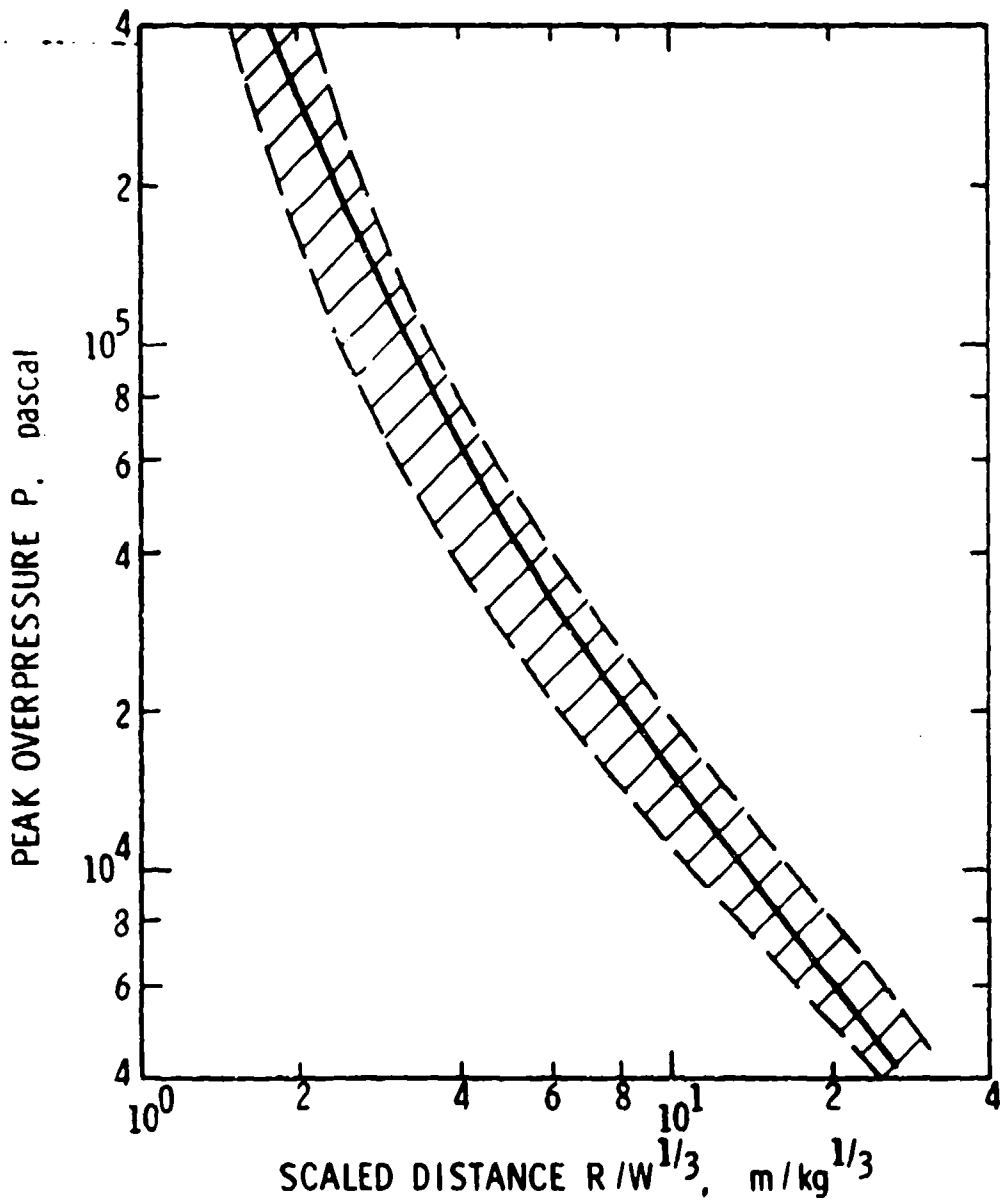
$(psi-sec/lb_m^{1/3} = Pa \cdot s/kg^{1/3} \times 1.114 \times 10^{-4})$

$(ft/lb_m^{1/3} = m/kg^{1/3} \times 2.521)$

Figure 2-9. Pressure vs Scaled Distance. Hypergolic
Propellant; HVI Failure Mode.

The axes and annotations of the figure:

PEAK OVERPRESSURE P, pascal (vertical axis)

SCALED DISTANCE $R/W^{1/3}$, $m/kg^{1/3}$ (horizontal axis)

(psi = Pa X 1.450 X 10^{-4})

($ft/lb_m^{1/3}$ = $m/kg^{1/3}$ X 2.521)
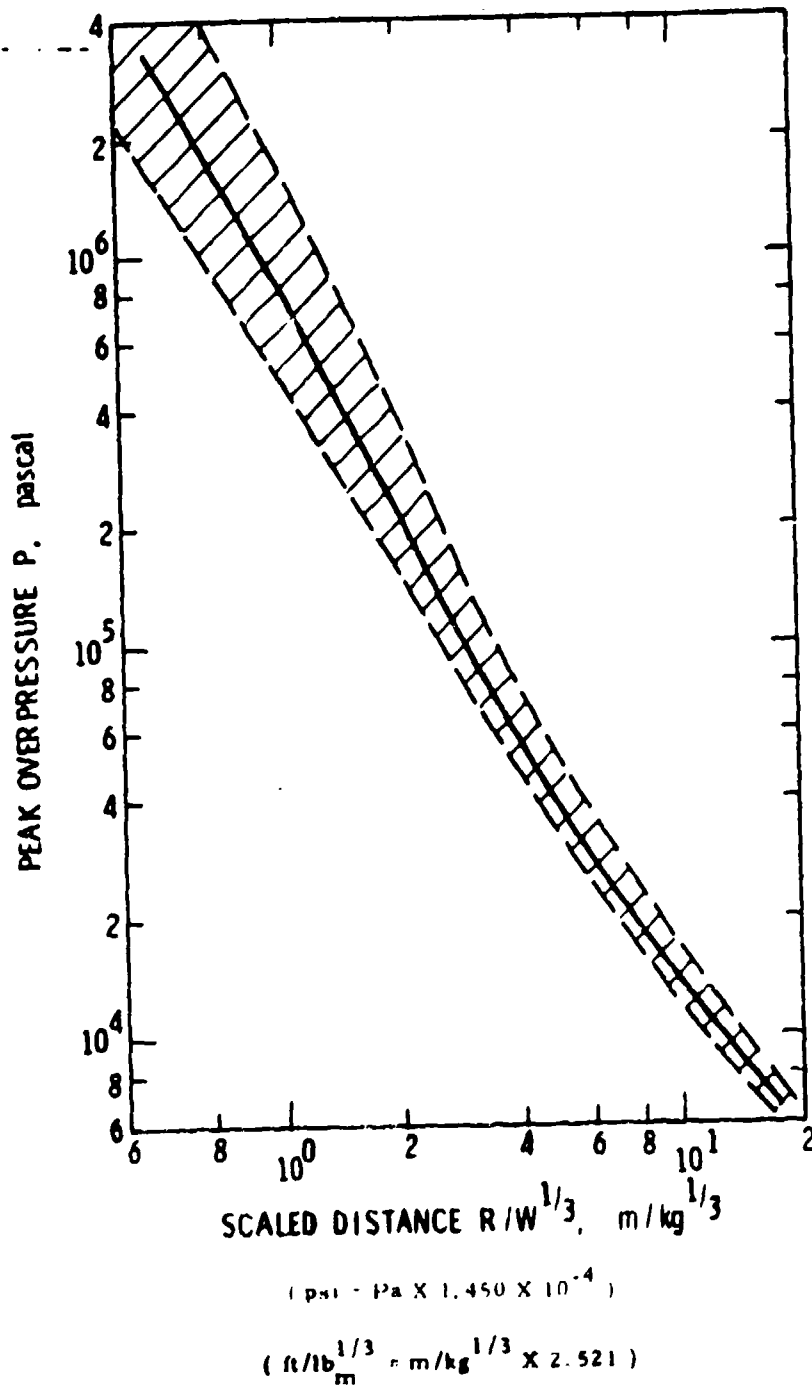
Figure 2-10. Pressure vs Scaled Distance. $LO_2/RP-1$ Propellant; CBM Failure Mode.

PEAK OVERPRESSURE P, pascal (vertical axis)

SCALED DISTANCE $R/W^{1/3}$, $m/kg^{1/3}$ (horizontal axis)

(psi - Pa X 1.450 X 10^{-4})

($ft/lb_m^{1/3} = m/kg^{1/3}$ X 2.521)

Figure 2-11. Scaled Positive Impulse vs Scaled Distance.
LO$_2$/RP-1 Propellant; CBM Failure Mode.

The axes and conversion notes of the figure read:

SCALED POSITIVE IMPULSE I/W$^{1/3}$, pascal-sec/kg$^{1/3}$

SCALED DISTANCE R/W$^{1/3}$, m/kg$^{1/3}$

(psi-sec/lb$_m^{1/3}$ = Pa · s/kg$^{1/3}$ X 1.114 X 10^{-4})

(ft/lb$_m^{1/3}$ = m/kg$^{1/3}$ X 2.521)

Figure 2-12. Pressure vs Scaled Distance. $LO_2/RP-1$ Propellant; CBGS and HVI Failure Modes.

(psi = Pa X 1.450 X 10⁻⁴)
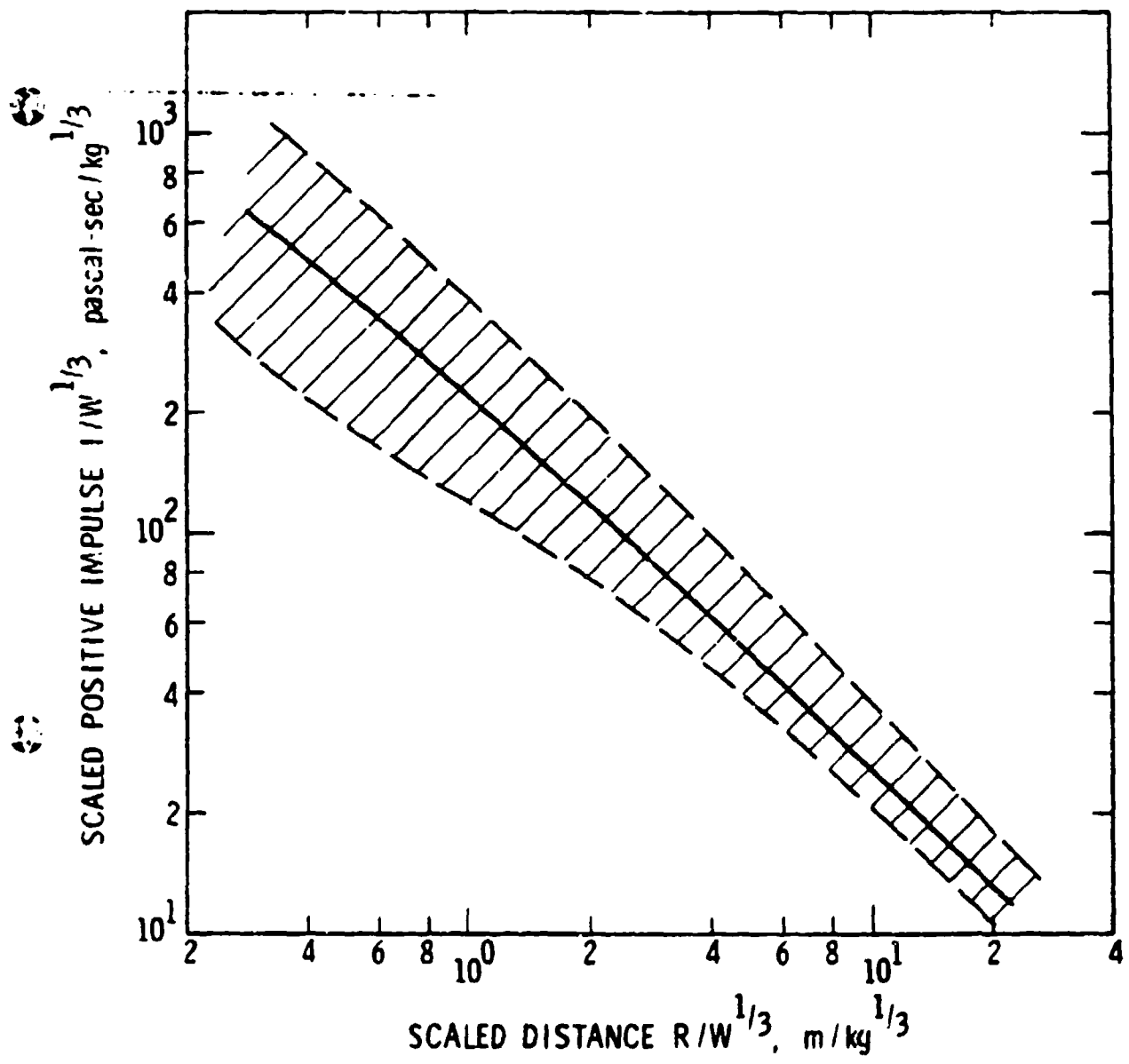
(ft/lb$_m^{1/3}$ = m/kg$^{1/3}$ X 2.521)

Figure 2-13. Scaled Positive Impulse vs Scaled Distance.
LO$_2$/RP-1 Propellant; CBGS and HVI Failure Modes.

(psi-sec/lb$_m^{1/3}$ = Pa · s/kg$^{1/3}$ X 1.114 X 10^{-4})

(ft/lb$_m^{1/3}$ = m/kg$^{1/3}$ X 2.521)

PEAK OVERPRESSURE P, pascal

SCALED DISTANCE R/W$^{1/3}$, m/kg$^{1/3}$

(psi = Pa X 1.450 X 10^{-4})

(ft/lb$_m^{1/3}$ = m/kg$^{1/3}$ X 2.521)

Figure 2-14. Pressure vs Scaled Distance, LO$_2$/LH$_2$
Propellant; CBM Failure Mode.

(psi-sec/lb$_m^{1/3}$ = Pa · s/kg$^{1/3}$ X 1.114 X 10^{-4})

(ft/lb$_m^{1/3}$ = m/kg$^{1/3}$ X 2.521)

Figure 2-15. Scaled Positive Impulse vs Scaled Distance.
LO$_2$/LH$_2$ Propellant; CBM Failure Mode.
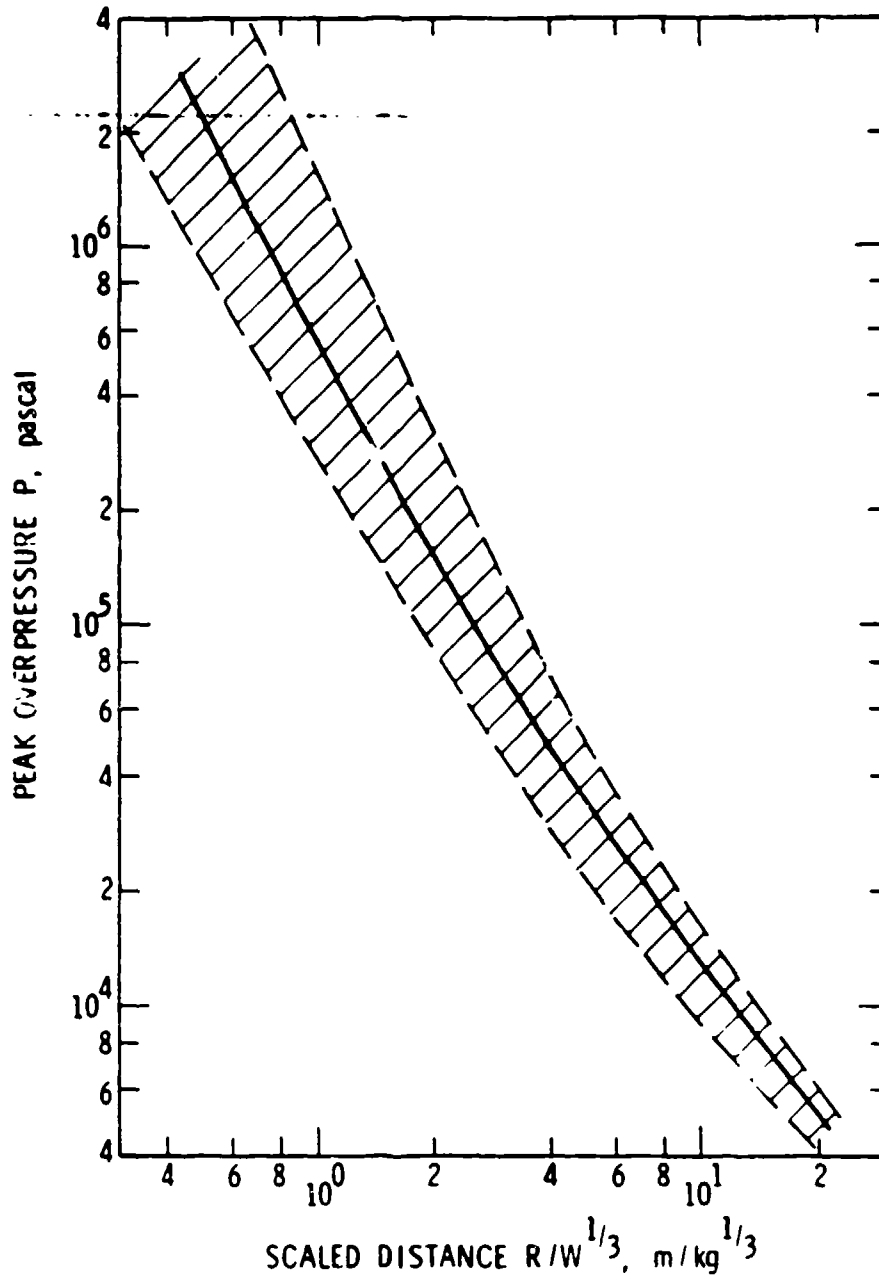
Figure 2-16.   Pressure vs Scaled Distance. LO_2/LH_2
Propellant; CBCS and HVI Failure Modes.

(psi = Pa X 1.450 X 10^{-4})

($ft/lb_m^{1/3} = m/kg^{1/3}$ X 2.521)

Figure 2-17. Scaled Positive Impulse vs Scaled Distance.
LO$_2$/LH$_2$ Propellant: CBGS and HVI Failure Modes.

The axes of the figure are labeled:

SCALED POSITIVE IMPULSE I/W$^{1/3}$, pascal-sec/kg$^{1/3}$ (vertical)

SCALED DISTANCE R/W$^{1/3}$, m/kg$^{1/3}$ (horizontal)

(psi-sec/lb$_m^{1/3}$ = Pa · s/kg$^{1/3}$ X 1.114 X 10^{-4})

(ft/lb$_m^{1/3}$ = m/kg$^{1/3}$ X 2.521)

2-2.3   Examples for Determining Peak Side-On Overpressure and
        Specific Impulse

The problems which follow are continuations of some of the example
problems started in Chapter I, Section A.

Example 1:   (Continuation of Example 1 of Chapter I, Section A)

Propellant-Hypergolic
Combined mass of propellant and oxidizer-10, 000 kg (22, 000 lb_m)
Failure mode - CBM
Standoff distance R (assumption) - 50 m (164 ft)

Solution:

(1)   Terminal yield y = 0.8% (See Example 1 of Chapter I,
        Section A for calculations)

(2) $W = W_T \times \frac{1}{100\%}$

        $W = 10,000 \text{ kg} \times \frac{0.8\%}{100\%}$

        $W = 80 \text{ kg} (176 \text{ lb}_m)$

(3)   Scaled distance $R/W^{1/3} = 50 \text{ m}/(80 \text{ kg})^{1/3} = 12 \text{ m/kg}^{1/3}$

(4)   Table 2-1 indicates:

        Acquire P, peak pressure, from Figure 2-7.

        Acquire $I/W^{1/3}$, scaled impulse, from Figure 2-8.

(5)   From Figure 2-7, $P = 8.2 \times 10^4$ Pa (11.89 psi)

(6)   From Figure 2-8, $I/W^{1/3} = 27$ Pa·s/kg$^{1/3}$

(7) $I = \left(\dfrac{I}{W^{1/3}} \right) (W^{1/3}) = 116$ Pa·s $(1.682 \times 10^{-2}$ psi/sec)

Example 2:   (Continuation of Example 4 of Chapter I, Section A)

Propellant and oxidizer = LO_2/RP-1
Combined mass of propellant and oxidizer-150, 000 kg
        (330, 000 lb_m)

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Failure mode - CBGS
Impact velocity (assumption) - 10/ms (32.8 ft/sec)
Ignition time (assumption) - 0.5 seconds
Standoff distance (assumption) - 100 m (323 ft)

Solution:

(1)   Terminal yield y = 6.25% (See Example 4 of Chapter I,
       Section A for calculations).

(2) $W = W_T \times \dfrac{y}{100\%}$

       $W = 150,000 \text{ kg} \times \dfrac{6.25\%}{100\%}$

       $W = 9375 \text{ kg } (20,600 \text{ lb}_m)$

(3)   Scaled distance $R/W^{1/3} = 100 \text{ m}/(9375)^{1/3} = 4.7 \text{ m/kg}^{1/3}$

(4)   Table 2-1 indicates:

       Acquire P, peak pressure from Figure 2-12.

       Acquire $I/W^{1/3}$, scaled impulse from Figure 2-13.

(5)   From Figure 2-12, $P = 3.8 \times 10^4 \text{ Pa } (5.5 \text{ psi})$

(6)   From Figure 2-13, $I/W^{1/3} = 55 \text{ Pa·s/kg}^{1/3}$

(7) $I = \left(\dfrac{I}{W^{1/3}}\right)(W^{1/3}) = 1160 \text{ Pa·s } (0.168 \text{ psi/sec})$

Example 3: (Continuation of Example 5 of Chapter I, Section A)

   Propellant and oxidizer - LO_2/LH_2
   Combined mass of propellant and oxidizer - 10,000 kg (22,000 lb_m)
   Failure mode - HVI
   Impact velocity (assumption) - 40 m/s (131 ft/sec)
   Type of surface impacted - hard
   Standoff distance (assumption) - 100 m (328 ft)

Solution:

(1)   Terminal yield y = 30% (See Example 5 of Chapter I,
       Section A for calculations)

(2) $W = W_T \times \dfrac{Y}{100\%}$

       $W = 10,000\ kg \times \dfrac{30\%}{100\%}$ .. -- --

       $W = 3000\ kg\ (6600\ lb_m)$

(3)   Scaled distance $R/W^{1/3} = 100\ m/(3000\ kg)^{1/3} = 6.9\ m/kg^{1/3}$

(4)   Table 2-1 indicates:

       Acquire P, peak pressure, from Figure 2-16.

       Acquir $i/W^{1/3}$, scaled impulse, from Figure 2-17.

(5)   From Figure 2-16, $P = 2.2 \times 10^4\ Pa\ (3.19\ psi)$

(6)   From Figure 2-17, $I/W^{1/3} = 45\ Pa \cdot s/kg^{1/3}$

(7) $1 = \dfrac{I}{W^{1/3}}$ $(W^{1/3}) = 649\ Pa \cdot s\ (9.41 \times 10^2\ psi/sec)$

2-3   Pressure Waves From Gas Vessel Bursts

Application to spherical vessels will be discussed first.

2-3.1   Overpressures for Various Gases and Initial Conditions

The overpressure versus distance relationship for a bursting gas vessel is strongly dependent upon the pressure, temperature, and ratio of specific heats of the gas in the vessel. For high pressures and temperatures, relative to the air outside the vessel, the overpressure behavior is much like that of a blast wave from a high explosive. On the $\overline{P}_s$ versus $\overline{R}$ graph (Figure 2-18), the curves for higher pressures and temperature are located near the high explosive curve. The curves for lower pressures and temperatures lie farther from the high explosive curve.

The procedure for relating overpressures and distance from the source of a gas vessel burst is the following: Determine the starting overpressure and distance. Locate this point on a $\overline{P}_s$ versus $\overline{R}$ graph. (Figure 2-18). Follow the nearest curve on this graph for the overpressure versus distance behavior. Choose the $\overline{R}$ of interest, and read $\overline{P}_s$ from the proper curve. Alternatively, one can choose a value for $\overline{P}_s$ and locate the corresponding $\overline{R}$. For $\overline{R}$ greater than about 2, Figure (2-19), $\overline{P}_s$ versus R
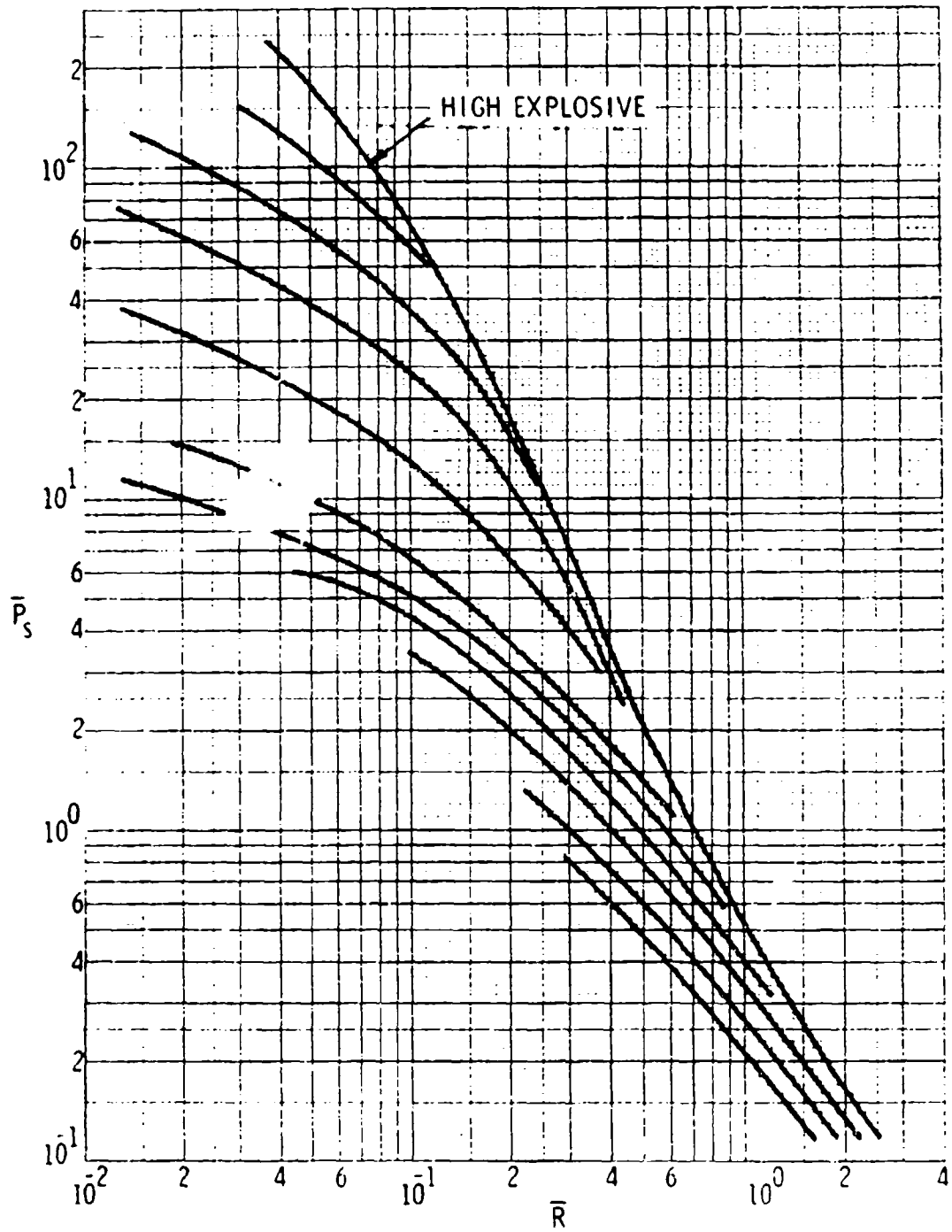
Figure 2-18. $\overline{P}_s$ vs $\overline{R}$ for Overpressure Calculations.
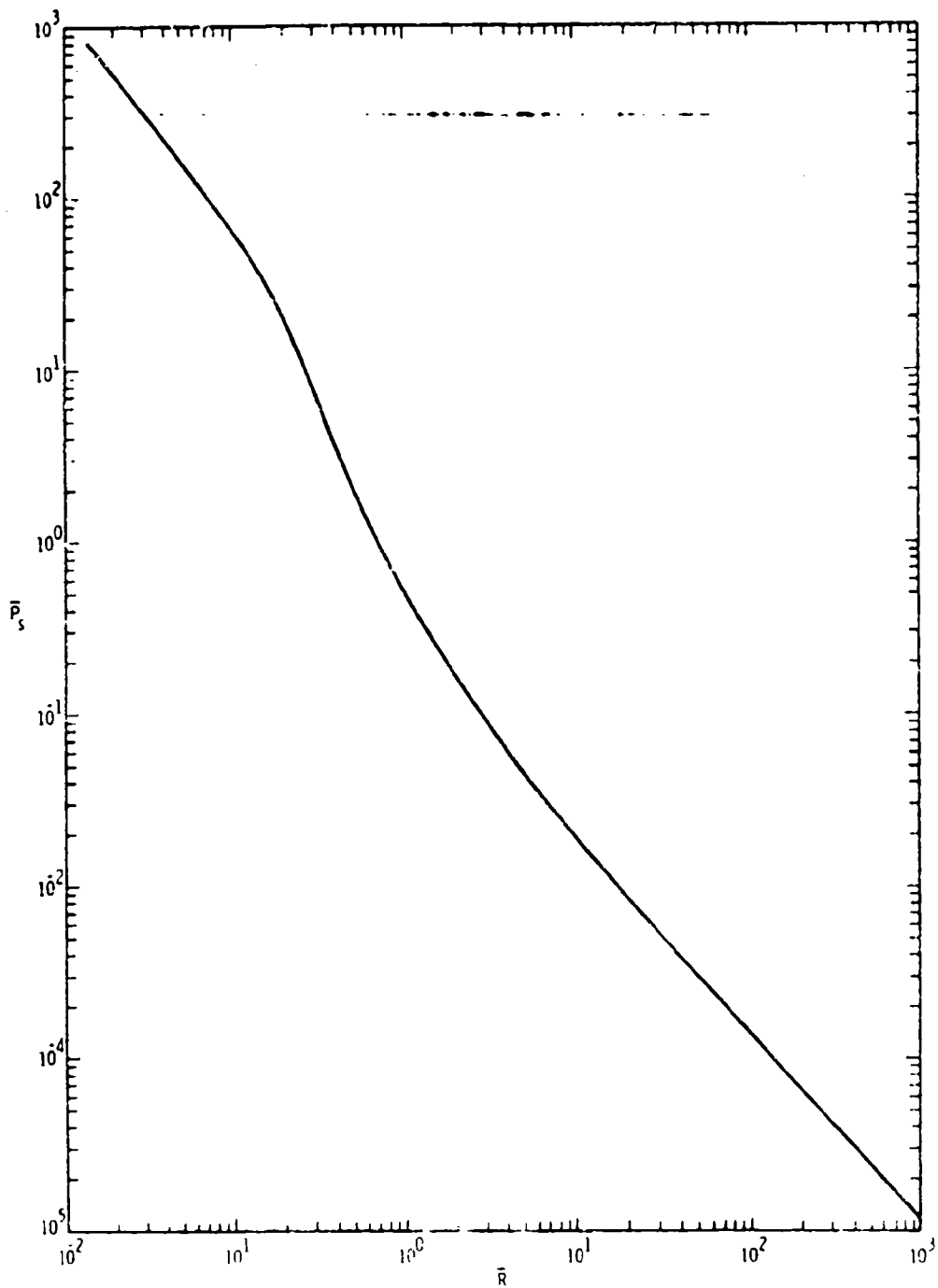
Figure 2-19. $\bar{P}_s$ vs $\bar{R}$ for Pentolite

for pentolite (a high explosive)[6] can be used as an upper limit for $\overline{P}_s$.
For a given p_1/p_a, T_1/T_a, and γ_1, $\overline{P}_{so}$, the nondimensional starting
shock overpressure can be read from one of the graphs in Figure 2-20
and 2-21. For diatomic gases, such as air, O_2, and H_2, let γ_1, equal
1.4. For monatomic gases such as He, let γ_1, = 1.667. The nondimen-
sional starting distance $\overline{R}_o$ is

$$\overline{R}_o = \frac{1}{\left[\frac{4}{3}\left(\frac{\frac{p_1 - 1}{p_a}}{\gamma_1 - 1}\right)\right]^{1/3}} \tag{2-11}$$

Locate $\overline{R}_o$ and $\overline{P}_{so}$ on the graph of $\overline{P}_s$ versus $\overline{R}$ as in Figure 2-22.
This is the starting point. Follow the nearest curve for the $\overline{P}_s$ versus $\overline{R}$
behavior. The $\overline{P}_s$ versus $\overline{R}$ curves in Figure 2-18 are accurate to
about ± 20%.

To determine the overpressure at a given distance, first compute
$\overline{R}$.

$$\overline{R} = \frac{r}{\left[\left(\frac{\frac{p_1 - 1}{p_a}}{\gamma_1 - 1}\right) V_i\right]^{1/3}} \tag{2-12}$$

where r is the distance from the center of the vessel, and V_i is the
volume of the vessel before it bursts.

Then, read $\overline{P}_s$ from the proper curve. Compute the overpressure:

$$\overline{P}_s = \frac{p_s - p_a}{p_a}, \text{ then } p_s - p_a = \overline{P}_s p_a. \text{ The quantity } p_s p_a \text{ is}$$

the overpressure.

To determine the distance at which a given overpressure will be ob-
served, compute $\overline{P}_s$ from the given $p_s - p_a$:
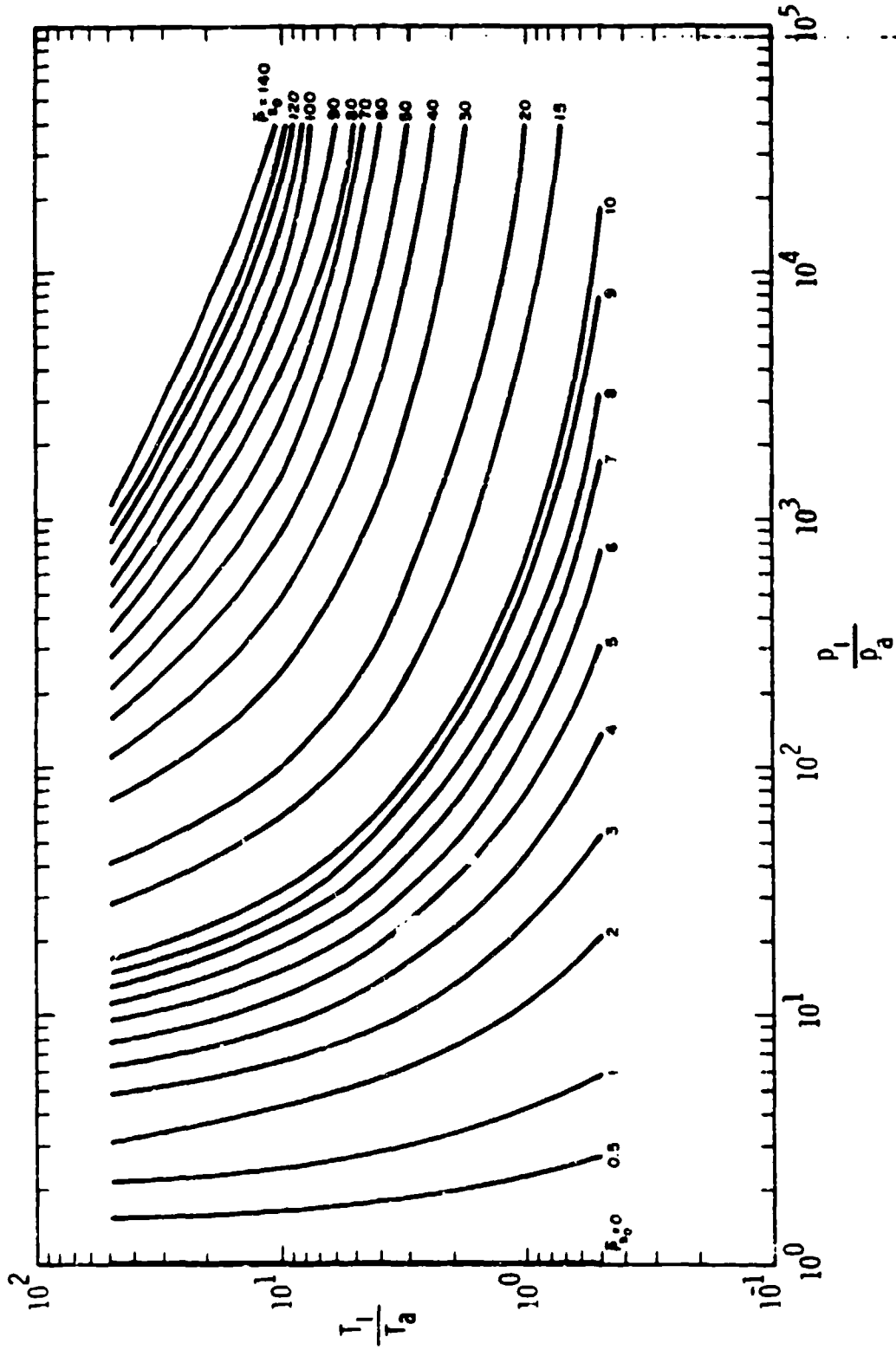
Figure 2-20. Kernel Temperature vs Kernel Pressure for Constant P, $\gamma_1 = 1.4$
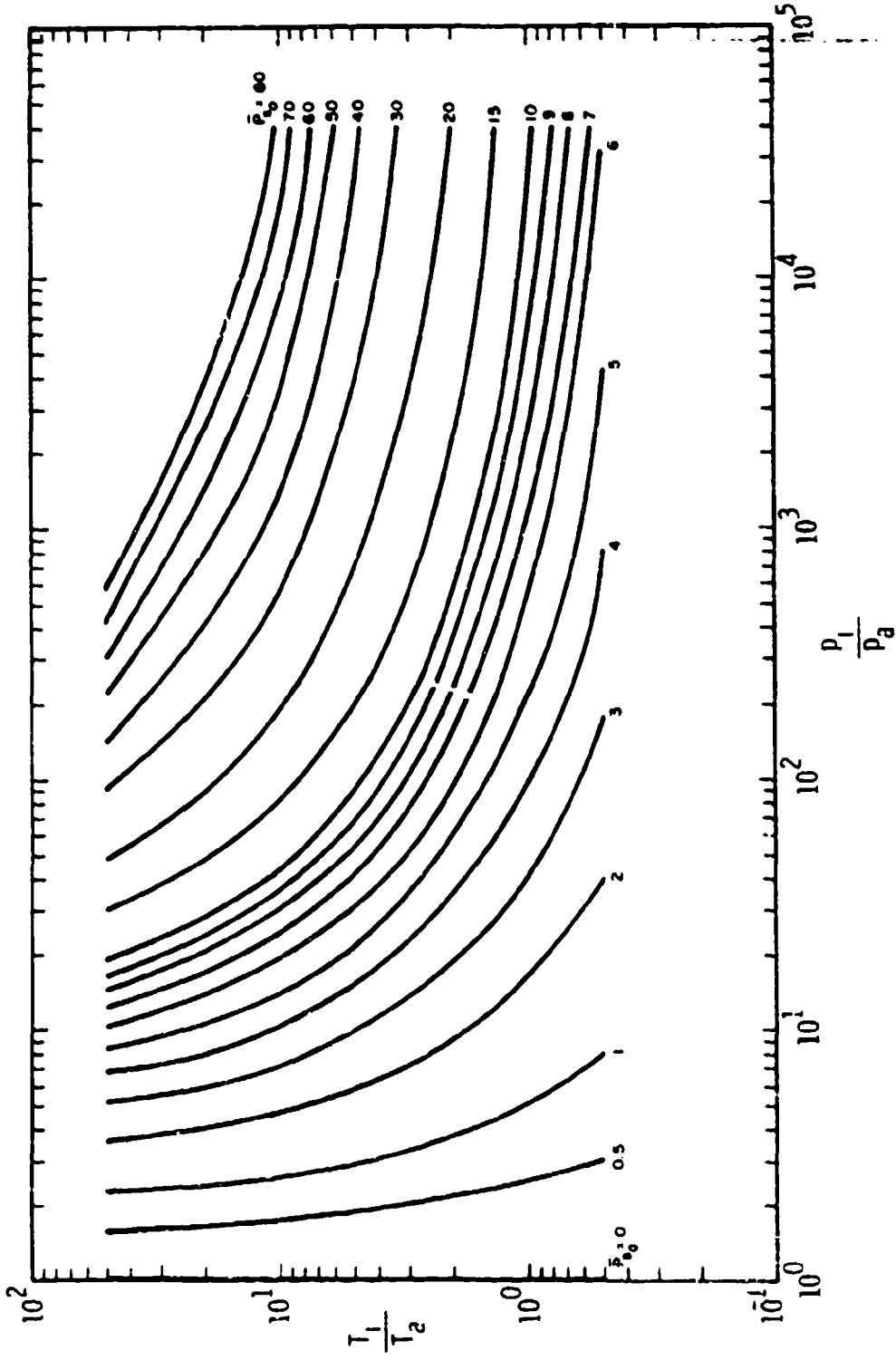
Figure 2-21. Kernel Temperature vs Kernel Pressure
for Constant Values of $\bar{P}$, $Y_1 = 1.667$
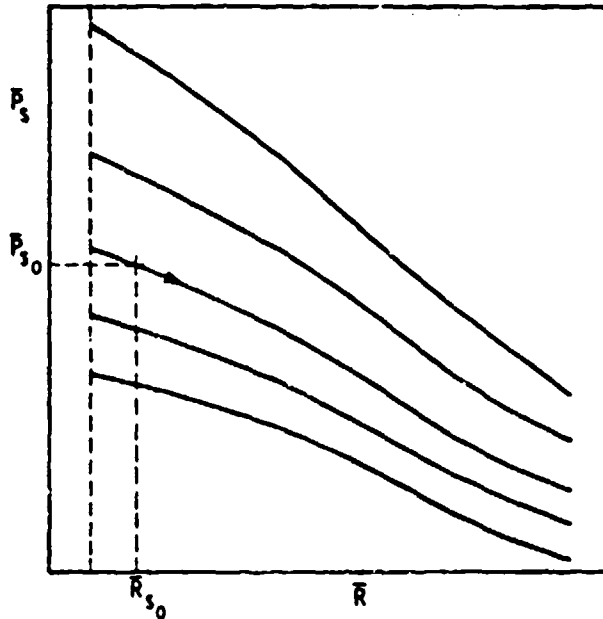
Figure 2-22. Location of Starting Point on Graph of $\bar{P}_s$ vs $\bar{R}$

$$\bar{P}_s = \frac{P_s - P_a}{P_a} \qquad (2\text{-}13)$$

Read $\bar{R}$ from the proper curve, and calculate r:

$$\bar{R} = \frac{r}{\left[\frac{\left(\frac{P_1}{P_a} - 1 \right) V_i}{\gamma_1 - 1} \right]^{1/3}} \qquad \text{then} \qquad (2\text{-}14)$$

$$r = \bar{R} \left[\frac{\left(\frac{P_1}{P_a} - 1 \right) V_i}{\gamma_1 - 1} \right]^{1/3} \qquad (2\text{-}15)$$

2.3.2 Specific Impulses for Various Gases and Initial Conditions

For the burst of a pressure vessel, the $\overline{I}$ versus $\overline{R}$ relationship in Figure 2-23 or 2-24 should be used. For $\overline{R}$ in the range of 10^{-1} to 10^0, the $\overline{I}$ versus $\overline{R}$ curve in Figure 2-24 is more convenient. This is an enlargement of part of Figure 2-23. These curves are accurate to about $\pm 25\%$. For a given distance, $\overline{R}$ is calculated, and $\overline{I}$ is read from Figure 2-23 or 2-24. Then I is calculated. Alternatively, one can choose a maximum acceptable specific impulse and find the minimum distance at which the specific impulse is less than this value.

<u>Example:</u>

A spherical pressure vessel of radius 1.0 m (3.3 ft) containing air ($\gamma_1 = 1.4$) bursts in a standard sea level atmosphere. The inside gas pressure is 1.013×10^6 Pa (147 psi) and the temperature is 300 K 80°F). There are no reflecting surfaces nearby. Find the peak overpressure and specific impulse at a distance of 5.0 m (16.4 ft) from the source.

Solution for peak overpressure:

$\overline{R}_o$ and $\overline{R}$ for the distance of interest are calculated, $\overline{P}_{so}$, the starting peak overpressure is obtained from Figure 2-20. The correct curve is located in Figure 2-18 and P_s is read from the graph for the $\overline{R}$ of interest.

$$\overline{R}_o = \cfrac{1}{\left[\cfrac{\dfrac{4\pi}{3}\left(\dfrac{P_1}{P_a} - 1\right)}{\gamma_1 - 1} \right]^{1/3}} =$$

(2-16)

$$\cfrac{1}{\left[\cfrac{\dfrac{4\pi}{3}\left(\dfrac{1.013 \times 10^6 \text{ Pa}}{1.013 \times 10^5 \text{ Pa}} - 1\right)}{1.4 - 1} \right]^{1/3}} = 0.2197$$

2-33
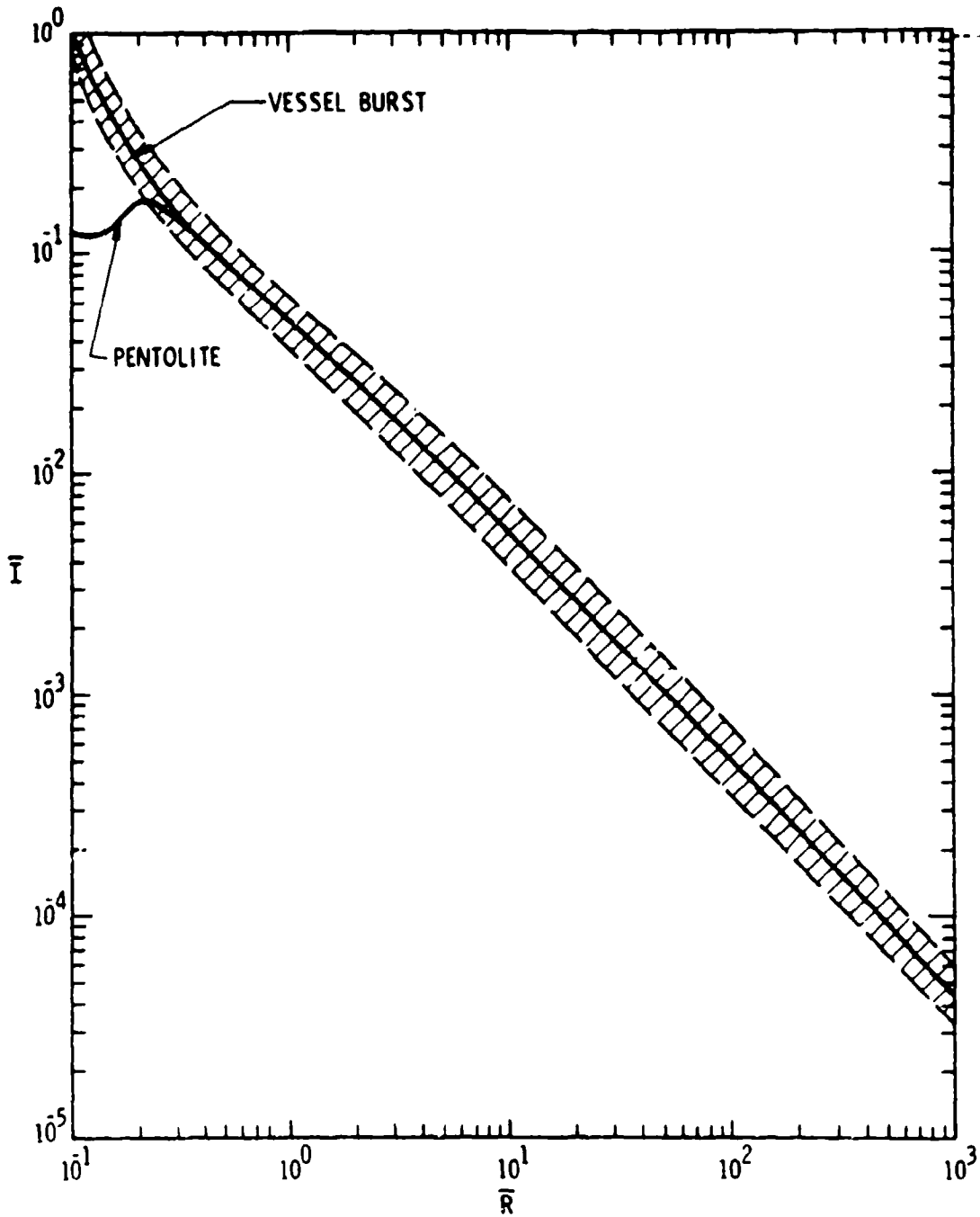
Figure 2-23. $\overline{I}$ vs $\overline{R}$ for Pentolite and Gas Vessel Bursts

2-54
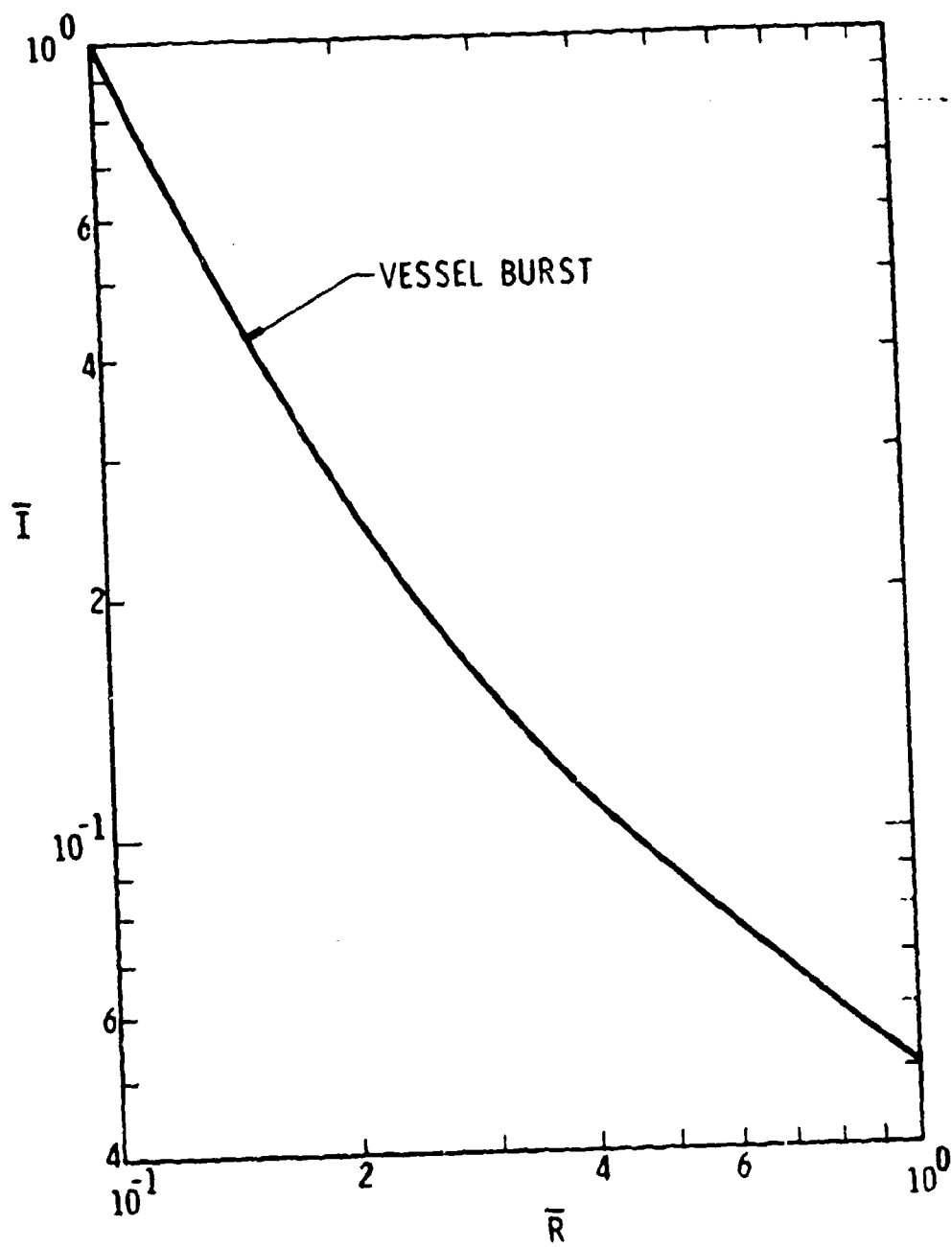
Figure 2-24. $\bar{I}$ vs $\bar{R}$ for Gas Vessel Bursts, Small $\bar{R}$

$$\overline{R} \ (\text{at } r = 5.0 \text{ m}) = \cfrac{r}{\cfrac{4\pi r_o}{3}\left[\cfrac{\left(\cfrac{P_1}{P_a} - 1\right)}{\gamma_1 - 1}\right]^{1/3}} =$$

$$(2-17)$$

$$\cfrac{\cfrac{5.0 \text{ m}}{1.0 \text{ m}}}{\left[\cfrac{4\pi}{3}\cfrac{\left(\cfrac{1.013 \times 10^6 \text{ Pa}}{1.013 \times 10^5 \text{ Pa}} - 1\right)}{1.4 - 1}\right]^{1/3}} = 1.099$$

For $P_1/P_a = 10$ and $T_1/T_a = 1$, $\overline{P}_{S_o} \cong 1.7$ (Figure 2-20). Looking at Figure 2-18, this point $(\overline{R}_o, \overline{P}_{S_o})$ falls near the third curve from the bottom. Following this curve, for $\overline{R} = 1.099$, $\overline{P}_s = 0.26$. Since $\overline{P}_s = \cfrac{P_s - P_a}{P_a}$, $P_s - P_a = \overline{P}_s P_a = (0.26)(1.013 \times 10^5 \text{ P}_a) = 2.6 \times 10^4$ Pa (3.77 psi).

Solution for specific impulse:

The $\overline{R}$ of interest has been calculated above. Read $\overline{I}$ for this $\overline{R}$ from Figure 2-23.

For $\overline{R} = 1.099$, $\overline{I} = 0.046$ (Figure 2-23).

Since $\overline{I} = \cfrac{I \, a_a}{P_a^{2/3} E^{1/3}}$, $I = \overline{I} \cfrac{P_a^{2/3} E^{1/3}}{a_a}$ $(2-18)$

$$E = \left(\cfrac{P_1 - P_a}{\gamma_1 - 1}\right) V_i = \left(\cfrac{1.013 \times 10^6 \text{ Pa} - 1.013 \times 10^5 \text{ Pa}}{1.4 - 1}\right)$$

$$(2-19)$$

$$\times \frac{4\pi}{3} (1.0 \text{ m})^3 = 9.55 \times 10^6 \text{ J}$$

$$I = \frac{(0.046)(1.013 \times 10^5 \text{ Pa})^{2/3}(9.55 \times 10^6 \text{ J})^{1/3}}{331 \text{ m/s}} = 64 \text{ Pa·s}$$

(2-20)

$(9.28 \times 10^{-3} \text{ psi·sec})$

2-3.3   Cylindrical Vessel

For a cylindrical vessel, given the length L and the diameter D, use its volume ($V_i = \frac{\pi D^2}{4} L$) in the equations above, performing the calculations as for a spherical vessel. After $\overline{P}_s$ and $\overline{I}$ have been determined, further corrections are necessary. For $\overline{R}$ less than about 0.3, the calculated overpressure should be multiplied by a factor of 4 or 5. For $\overline{R}$ near 1.0, the factor is 1.6. For $\overline{R}$ greater than about 3.5, multiply the calculated overpressure by about 1.4. For $\overline{R}$ less than about 0.3, the calculated specific impulse should be doubled. For $\overline{R}$ near 1.0, the factor is about 1.1. For $\overline{R}$ greater than about 1.6, no correction to the specific impulse is necessary. The difference between spherical and cylindrical vessel bursts is only known qualitatively. Therefore these corrections are very crude.

2-3.4   Ground Burst

The method described above is to be used for gas vessel bursts far from any reflecting surfaces. If there is a reflecting surface adjacent to the gas vessel, such as with a gas vessel on the ground, multiply V_i, the volume of the vessel, by a factor of 2. Use this new V_i in the calculations. Also, once $\overline{P}_s$ has been calculated, increase it by 100% for $\overline{R}$ less than about 1, and by 10% for $\overline{R}$ greater than 1. After $\overline{I}$, has been calculated, increase it by 60% for $\overline{R}$ less than about 1. There is little effect for longer distances. Only qualitative effects are known, and therefore these corrections are very crude.

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APPENDIX II.A

GAS VESSEL BURST

2A-1. Nondimensional Parameters

A model analysis was perfo... for the pressurized gas-filled vessel burst. The following dimensionless parameters were obtained: [1]

$$\bar{I} = \frac{I \, a_a}{p_a^{2/3} E^{1/3}} \qquad \text{specific impulse} \qquad (2A-1)$$

$$\bar{P}_b = \frac{P_s - P_a}{P_a} \qquad \text{peak shock overpressure} \qquad (2A-2)$$

$$\bar{R} = \frac{r \, p_a^{1/3}}{E^{1/3}} \qquad \text{distance} \qquad (2A-3)$$

2A-2. Sources of Data

The data which were used in the shock overpressure and specific impulse calculations are generated numerically by a finite-difference computer program in which the one-dimensional (spherical coordinates) unsteady equations of conservation of mass, momentum, and energy in Lagrangian form are solved for a perfect gas. Artificial viscosity is used to smooth the shock waves. [2]

Previously, other investigators have used numerical methods to calculate the flow field variables after the burst of a pressurized sphere. Huang and Chou used the Hartree method of characteristics with Rankine-Hugoniot jump conditions across the shocks. [3] Boyer, et al., used a numerical program similar to the one used here and compared their results to experimental data obtained by breaking glass spheres pressurized with air, He, and SF$_6$. [4] Their values of nondimensional impulse versus distance fit in well with those calculated here.

... 2A ... gives the initial conditions of the cases that were run to gene... ... ta used in the ... ly ...

TABLE 2A-1. INITIAL CONDITIONS FOR PRESSURE SPHERE BURSTS

Case	$\dfrac{P_1}{P_a}$	$\dfrac{T_1}{T_a}$	γ_1
1	5	0.5	1.4
2	5	2.5	1.4
3	5	10	1.4
4	5	50	1.4
5	10	0.5	1.4
6	10	50	1.4
7	100	0.5	1.4
8	100	50	1.4
9	150	50	1.4
10	500	50	1.4
A	94.49	1.0	1.4
B	94.49	1.167	1.2
C	94.49	0.84	1.667
11	37000	0.5	1.4
12	37000	5	1.4
13	37000	10	1.4
14	1000	1	1.4
15	1000	4	1.667
16	1000	0.5	1.4
17	5	5	1.4
18	22	1	1.4 (Ref. 4)

2A-2.   Overpressure Calculation

The $\bar{P}_s$ versus $\bar{R}$ data were plotted for several sets of initial conditions, and it was found that the $\bar{P}_s$ versus $\bar{R}$ curves for high pressure bursts pass through the curves for lower pressures (see Figure 2A-1). (There is some crossing of the curves, but some of this is due to inaccuracy in the computer program). Therefore, if a number of curves were generated for high vessel pressures and various temperatures, the $\bar{P}_s$ versus $\bar{R}$ behavior for bursts at lower pressures could be determined by finding the starting point $(\bar{R}_{so}, \bar{P}_{so})$ of a lower pressure burst and following the nearest $\bar{P}_s$ versus $\bar{R}$ curve.[5] The curves in Figure 2-1 of the text were drawn based upon the curves in Figure 2A-1 of the appendix. Their uncertainty should not be assumed to be less than about ±20%.
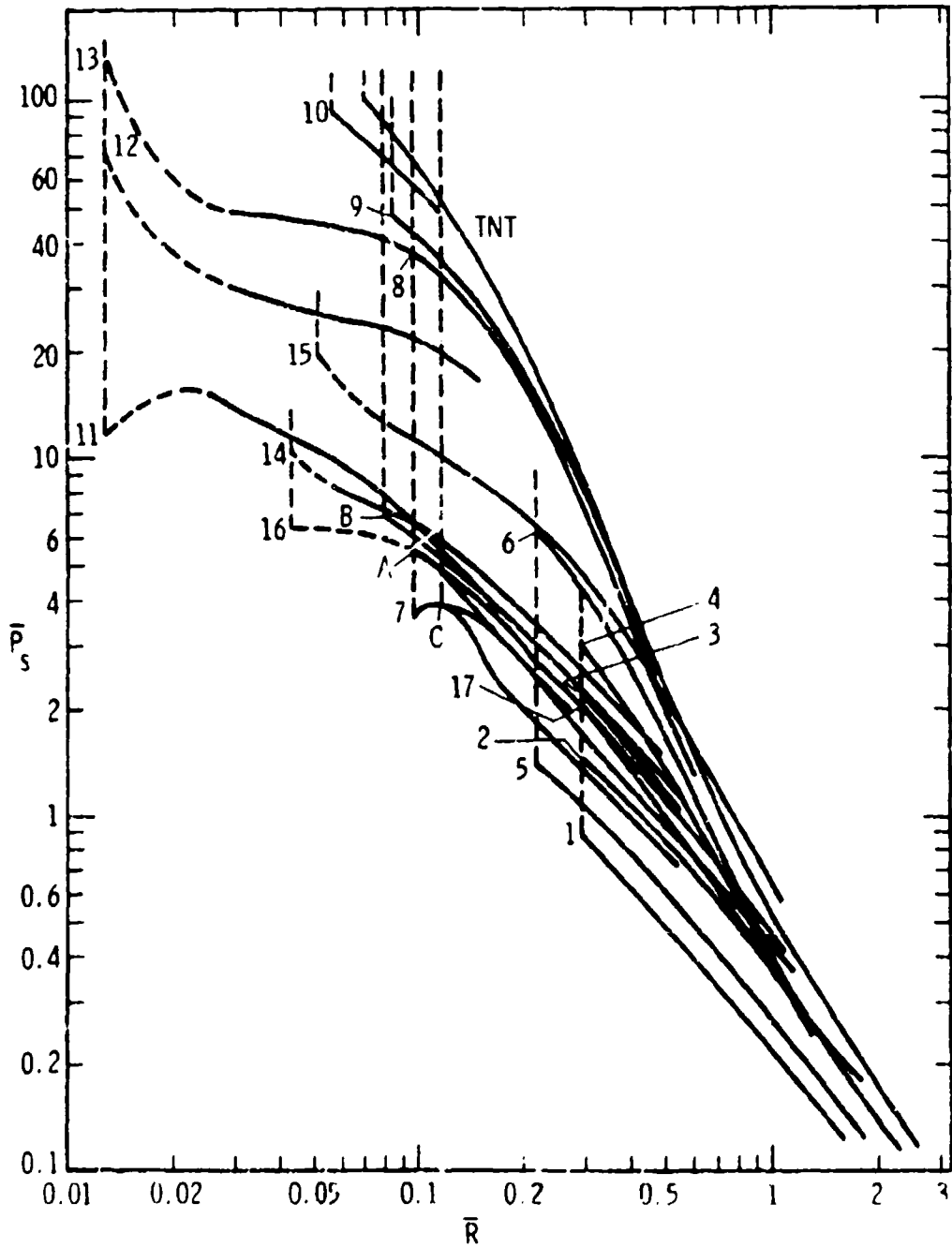
Figure 2A-1. $\bar{P}_s$ vs $\bar{R}$

The starting distance $\overline{R}_o$ corresponds to the surface of the vessel before it bursts, where $(r/r_o) = 1$.

$$\overline{R} = \frac{r}{\left[\dfrac{\left(\dfrac{p_1}{p_a} - 1\right) V_i}{\gamma_1 - 1}\right]^{1/3}} = \frac{r}{\left[\dfrac{\left(\dfrac{p_1}{p_a} - 1\right)\dfrac{4\pi r_o^3}{3}}{\gamma_1 - 1}\right]^{1/3}} =$$

(2A-4)

$$\frac{\dfrac{r}{r_o}}{\left[\dfrac{\left(\dfrac{p_1}{p_a} - 1\right)\dfrac{4\pi}{3}}{\gamma_1 - 1}\right]^{1/3}}$$

because $V_i = \dfrac{4\pi r_o^3}{3}$

(2A-5)

Then $\overline{R}_o = \dfrac{1}{\left[\dfrac{\left(\dfrac{p_1}{p_a} - 1\right)\dfrac{4\pi}{3}}{\gamma_1 - 1}\right]^{1/3}}$

(2A-6)

$\overline{P}_{so}$ is obtained by use of the shock tube equation:[6]

$$\frac{p_1}{p_a} = \frac{p_s}{p_a}\left[1 - \frac{(\gamma_a - 1)(a_a/a_1)(p_s/p_a - 1)}{\sqrt{2\gamma_a}\sqrt{2\gamma_a + (\gamma_a + 1)(p_s/p_a - 1)}}\right]^{\frac{-2\gamma_1}{\gamma_1 - 1}}$$

(2A-7)

where $\dfrac{a_a}{a_1} = \sqrt{\dfrac{\gamma_a}{\gamma_1}\dfrac{T_a}{T_i}}$, and $\gamma_a = 1.4$. For a given $\dfrac{p_1}{p_a}$, $\dfrac{T_1}{T_a}$, and γ_1, this equation must be solved iteratively for $\dfrac{p_s}{p_a}$. Then $P_{so} = \dfrac{p_s}{p_a} - 1$.

The $\dfrac{P_1}{P_a}$ versus $\dfrac{T_1}{T_a}$ versus $\overline{P}_{S_0}$ graphs (Figures 2-20 and 2-21 in the text) were obtained from this equation.

2A-4 Impulse Calculation

Specific impulse is calculated as $I = \int^{+} (p - p_a)\, dt$, where + denotes the positive phase of the pressure wave. See Figure 2A-2.

The $\overline{I}$ versus $\overline{R}$ data were plotted for several sets of initial conditions (Figure 2A-3). For $\overline{R}$ less than about 0.5, the behavior is not clear, and a maximum $\overline{I}$ was chosen for the $\overline{I}$ versus $\overline{R}$ relationship in Figure 2-23 of the text. For $\overline{R}$ greater than about 0.5, all of the curves lie within about 25% of the high explosive (pentolite) curve. The pentolite curve[7] was therefore chosen as the best $\overline{I}$ versus $\overline{R}$ curve in this region.

2A-5 Effect of Cylindrical Geometry

This analysis can be used for bursts for cylindrically shaped pressure vessels if the volume V_i is known. The cylinder is treated as an "equivalent sphere" with same energy as the given cylinder.

Besides the energy in the vessel, its orientation with respect to the target is important. Qualitative relationships between $\overline{P}_s$ and $\overline{I}$ and the angle between the location of the target and the longitudinal axis of the vessel can be observed from the high explosive data in Reference 8. However, this angular orientation is usually unknown, and the "worse case" must be assumed. Then, the peak overpressure will be greater than that calculated for a spherical vessel for all $\overline{R}$. The specific impulse would also be greater in the near field.

2A-6 Effect of Reflecting Surface (Burst at Ground Level)

In this analysis, it was assumed that the vessel burst occurs far away from any reflecting surface. To apply this to a burst occurring on the ground, assume that twice as much energy is released, implying that the volume of the vessel is doubled. The reason for this is illustrated in Figure 2A-4. In (a), all of the energy is released above the reflecting ground surface. In (b) one-half of the energy is released above the reflecting ground surface, and one-half of the energy is released below. For a point P located above the ground surface to experience the same blast wave, the energy in vessel B must be twice the energy in vessel A. For the same pressure and ratio of specific heats of the gas, the volume of vessel B must be twice the vessel A. The situation in (b) is chosen because the analysis requires a spherically symmetric flow field.
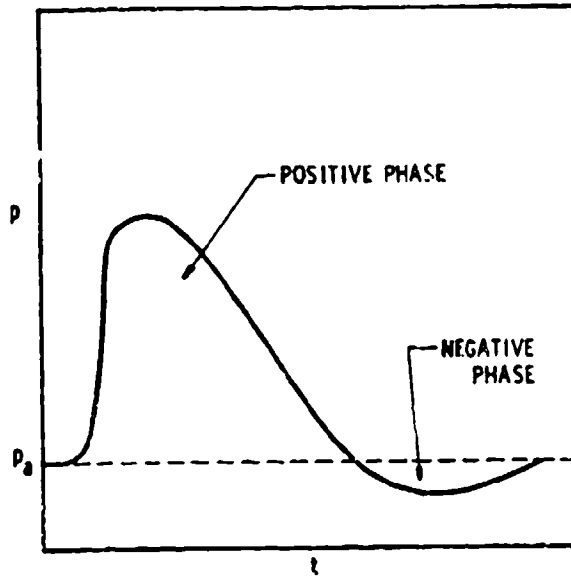
Figure 2A-2.   p vs t

In addition to the effect upon the effective energy released, the presence of the ground surface must be accounted for in another way. Data in Reference 8 indicate that the peak overpressure should also be doubled near the source of the burst, and this factor should be decreased to unity in the far field.   Those tests were conducted with high explosives, and, thus, only allow a qualitative description for pressure bursts, but it can be concluded that the overpressure would be greater for a sphere burst on the ground than would be expected from initial source energy considerations alone.   The specific impulse would also be higher, at least in the near field.

Figure 2A-3. $\bar{I}$ vs $\bar{R}$

• P
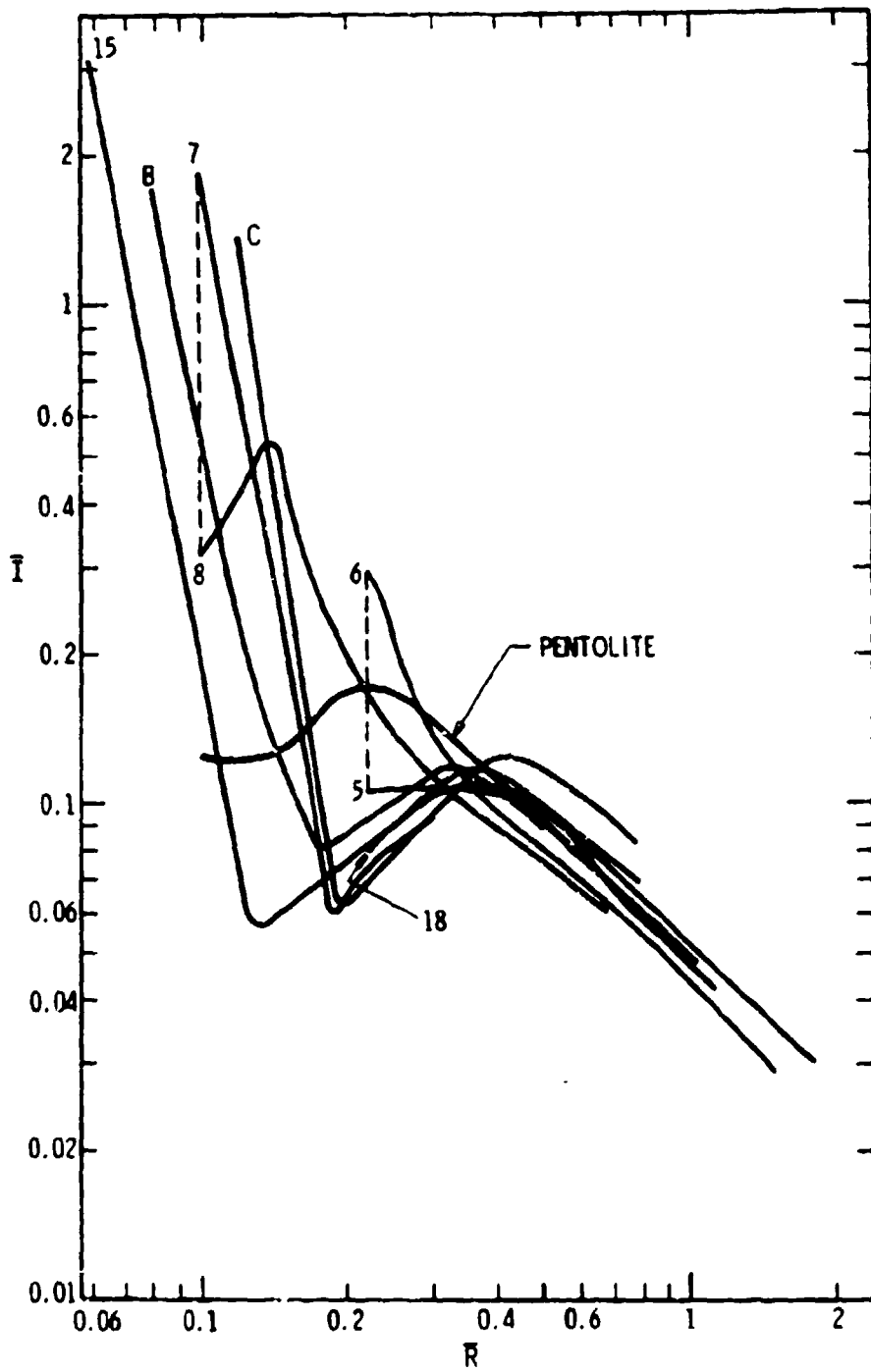
—VESSEL
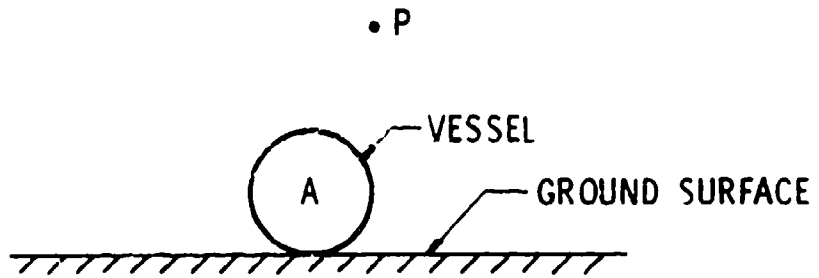
A   —GROUND SURFACE

(a)   Spherical vessel setting on ground surface

• P

—VESSEL

B   —GROUND SURFACE
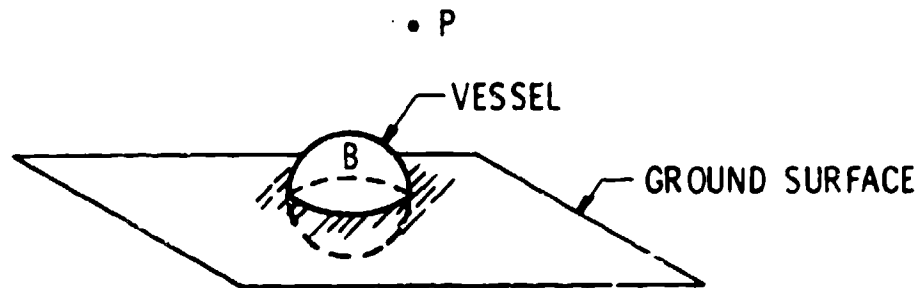
(b)   Spherical vessel bisected by ground plane

Figure 2A-4.   Assumed Spherical Geometry

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SYMBOLS

a	speed of sound
D	diameter of cylinder
E	energy in pressure vessel
I	specific impulse
$\overline{I}$	nondimensional specific impulse
L	length of cylinder
p	pressure
$\overline{P}_s$	nondimensional overpressure
$\overline{P}_{so}$	starting nondimensional overpressure
r	distance from center of vessel
R	radius of sphere
$\overline{R}$	nondimensional distance
r_o	radius of spherical vessel
t	time
T	temperature
V_i	volume of vessel before burst
γ	ratio of specific heats
θ	decay constant of pressure-time curve

SUBSCRIPTS

a	ambient conditions
s	behind shock wave
i	inside vessel before burst

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CHAPTER III

EFFECTS OF PRESSURE WAVES

3-1   Damage Estimates to Structures

Previous sections have shown how to predict the peak free field side-on overpressure P_s and side-on impulse i_s at various locations around an accidental explosion. In this section, we show how to relate these two loading parameters to structural damage to buildings and vehicles in the vicinity. Before this discussion proceeds, the reader must decide what constitutes damage. For example, is breakage of glass and some damage to ceilings an acceptable or unacceptable level of damage? Or, can you accept minor structural damage with partitions distorted and joinery wrenched from fittings? On the other hand, might the target structure be dangerous to inhabit with the roof partially or totally collapsed, at least partial damage to one or more external walls, and some failed load-bearing structural members? Or, can one tolerate the building being 50% to 75% completely demolished? There is no one answer to what level of damage is acceptable. The engineer must decide for himself. If buildings are or can be inhabitated by many people, the levels of damage should perhaps be low, while greater damage to individual dwellings could be tolerated.

Because different modes of response (or types of damage) must be considered, various solutions must be considered. The first solution deals with glass breakage. It yields a procedure for predicting the threshold of breakage of glass of various thickness and spans. The second solution is a curve fit to bomb damage data compiled by the British at the end of World War II. Although this curve fit was developed for a standard dwelling, it is also used for factories, main offices, and/or main engineering shops without introducing significant error. Three different empirical pressure versus impulse diagrams will be presented--the first is for minor structural damage involving wrenched joints and partitions, the second is for major structural damage with load bearing members at least partially destroyed, and the third is for 50% to 75% of the building demolished. These results yield general guidelines when accurate structural details are unknown. The third solution is for overturning a bus, truck, mobile home, missile on the launch pad, or other marginally stable target subject to toppling. The fourth and fifth solutions are for the initiation of yielding (the start of permanent deformation) in either beam or plate structural components. The beam elements can have

various support conditions. Plate elements can be either simply-supported* or clamped. These generalized solutions can be applied whenever the response of a structure looks critical and structural details are known in sufficient detail to override the second empirical solution based upon bombs damaging British residences. These generalized beam and plate solutions can be applied to many types of structures: cranes, frames, powerline towers, and components of houses and buildings. Each of the solutions will now be presented.

3-1.1   Breakage of Glass

The threshold applied pressure P_r for breaking glass can be determined from Equation (3-1).

$$\frac{P_r X^2}{\sigma_y h^2} = \frac{1.0 + 3.08 \left(\frac{X}{Y}\right)^2 + \frac{X}{Y}^4}{8.68 \left[0.79 + 0.11 \left(\frac{X}{Y}\right)^2 + 0.79 \left(\frac{X}{Y}\right)^4 \right]^{1/2}}$$

$$(3-1)$$

where

σ_y = yield stress of glass [use Equation (3-2)]

h = thickness of glass

X = short half span

Y = long half span

P_r = threshold applied maximum reflected pressure

(The equation is valid for any self-consistent set of dimensions). Equation (1-1) works for either sheet or plate glass. The yield stress σ_y for glass, however, is not a simple material property, as in steel or other metals. The strength of glass is related to flaws which are both statistical in nature and a function of thickness. Although a complete theory of the kinematics of flaw behavior is not possible, the effective yield point for glass can be approximated by Equation (3-2).

----

*Simple support boundary conditions imply restriction of displacements at the boundaries, but no restraint on rotations.

$$[\, c_y \ \text{Pa} \,]\,[\, h(m) \,] \;=\; 1.00 \times 10^{+6} \; \frac{N}{m} \qquad (3\text{-}2)$$

The parameter P_r in Equation (3-1) is the peak applied load, and not the side-on free field overpressure P_s. For weak shocks with $P_s < 10$ kPa that strike a wall head-on, P_r equals $2.0\,P_s$. For all shocks with flow parallel to a wall, P_r equals P_s. In general, the ratio P_r/P_s is a complex function of both shock strength P_s and the angle of incidence α. Figure 3-1 can be used to estimate P_r from P_s and α under ambient sea level atmospheric conditions. An α of $90°$ in Figure 3-1 means that the flow is parallel to the wall. All pressures in Figure 3-1 and this analysis are overpressures and not absolute pressures.

To illustrate the use of this solution, assume that a building has glass windows with panes that are 1.0 by 1.5 x 0.01 meters (3.28 by 4.92 by 0.0328 ft). Equation (3-2) indicates that the yield stress c_y equals 10^{+8} Pa (1.43×10^4 psi). Because the aspect ratio $\dfrac{X}{Y}$ equals 0.6666, Equation (3-1) gives a scaled applied load $\left(\dfrac{P_r X^2}{c_y h^2} \right)$ of 0.296. Substituting for c_y, X, and h in the scaled applied load yields an applied pressure P_r of 2960 Pa (0.424 psi). Because this is a weak applied load, glass will begin to break in walls facing an accident whenever P_s exceeds $\dfrac{P_r}{2}$ or 1480 Pa (0.212 psi). If the building has no glass in the walls facing the accident, but has glass in side walls, breakage will begin whenever P_s exceeds P_r or at 2960 Pa (0.424 psi).

The derivations of Equation (3-1) and (3-2) are presented in Appendix 3A. Equation (3-1) is a special case of a plate equation from subsequent sections: a brittle, simply-supported plate in the quasi-static loading realm. Experimental test data from static tests in the literature are also presented in Appendix 3A to demonstrate the validity of this solution. Figure 3-1 comes from curve fits to high-pressure data described in Reference 1.

3-1.2   Empirical Blast Damage Curves for Buildings

Figure 3-2 shows three different isodamage lines plotted as curves of side-on, free-field impulse versus side-on maximum overpressure. The basis for these curves is British data from enemy bombing in World War II plus records of explosions dating from 1871. Although this relationship was developed for the average British dwelling
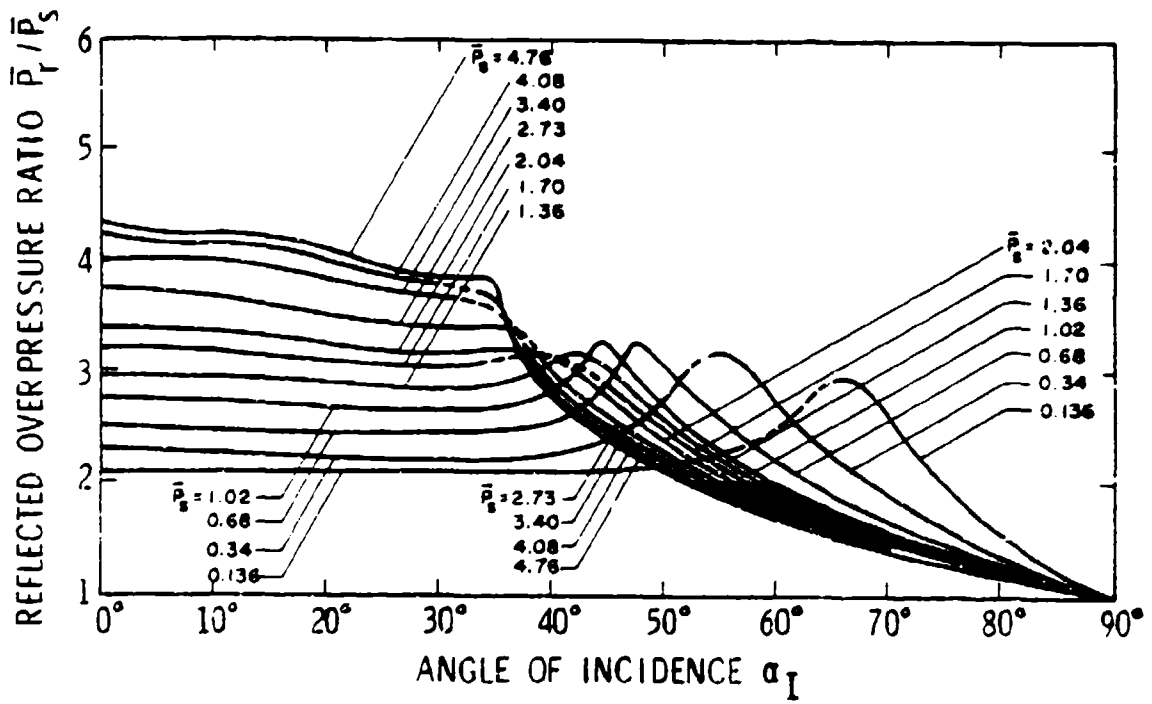
Figure 3-1. Reflected Overpressure Ratio as Function
of Angle of Incidence for Various Side-on
Overpressures
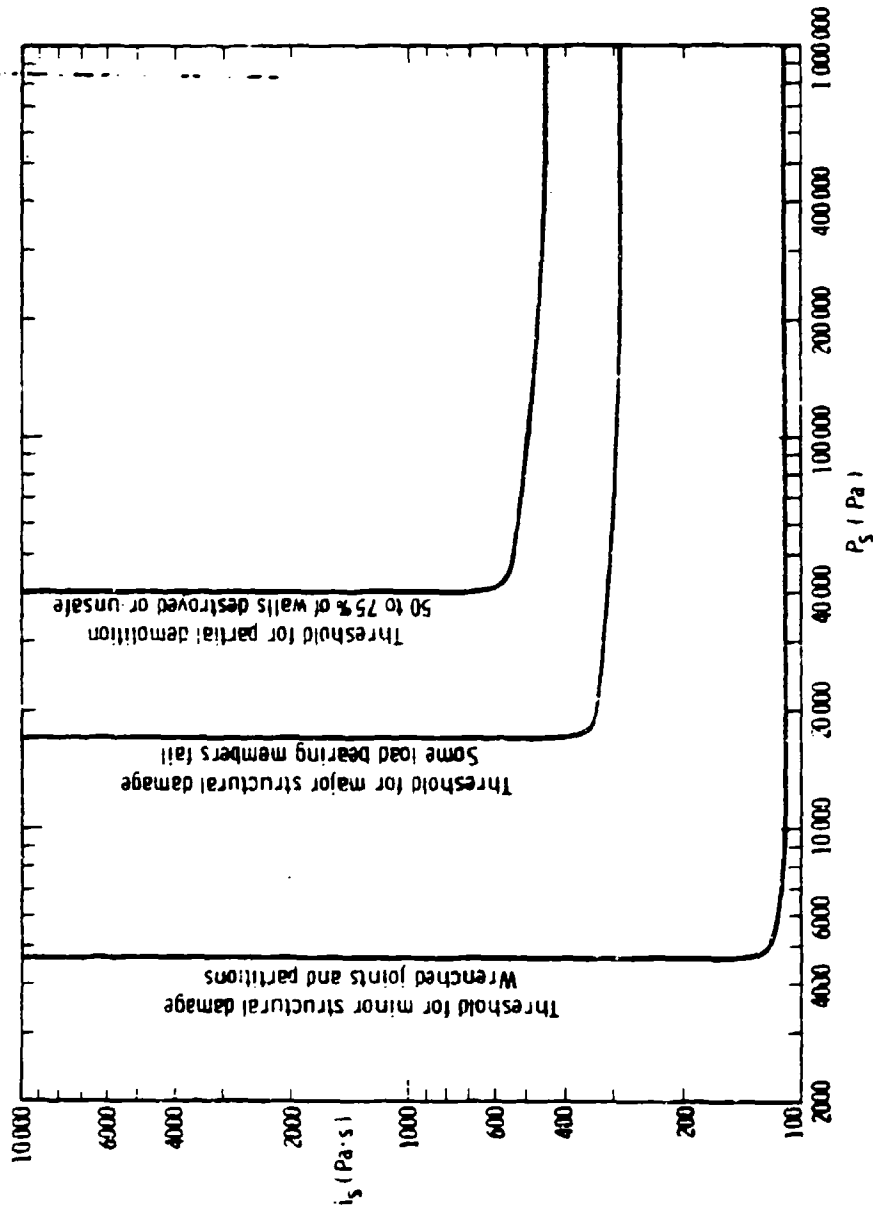
Figure 3-2. Pressure vs Impulse Diagram for Building Damage

house, it also works well for factories, main offices, and main engineering workshops. Reference 2 presents this relationship as a quantity-distance equation (charge weight versus standoff equation); however, we have modified the results so they can be presented as a pressure versus impulse diagram (a P-i diagram). Notice that as the level of damage increases, the pressures and impulses required to create the increased damage also increase. For pressures and impulses less than those shown in Figure 3-2, the specified magnitude of damage should not be obtained. The three levels of damage shown in Figure 3-2 are for minor structural damage, major structural damage, and partial demolition. By minor structural damage, we mean that glass has been broken, joints are wrenched, and partitions are out of some fittings. Major structural damage implies that the roof is partially or totally damaged, at least one external wall is partially damaged, and some load-bearing partitions or members have been destroyed. The term "partial demolition" implies that 50% to 75% of external brickwork or walls have been destroyed or rendered unsafe.

The British present an additional threshold for breakage of glass which we do not show in Figure 3-2. Most modern windows have larger spans and are often thinner than the standard window sizes associated with houses built in the 20's and 30's. The preceding analysis should be used if glass breakage constitutes serious damage. In addition, Jarrett presents a fifth contour for complete demolition. We do not present this contour because it is too extreme; a building suffering from partial demolition is uninhabitable and would have to be leveled.

Naturally, contours as presented in Figure 3-2 are approximations. These approximations suffice for large variations in structural types because the loads are also approximations. If a hardened structure or atypical building exists, damage can be better estimated by subdivision into its component plate and beam type elements. After a building has been subdivided into components, equations presented in subsequent sections can be applied to determine loads for initiating fracture in brittle structures and permanent deformation in ductile structures. These subsequent analysis procedures are more difficult to use than the graphical relationships shown in Figure 3-2; however, if they are properly applied, they can supplant Figure 3-2.

To illustrate the use of Figure 3-2, consider several illustrative examples. For example, suppose the free field blast conditions were P_s equal to 10 kPa (1.45 psi), i_s equal to 200 Pa·s (0.0290 psi/sec), then minor structural damage should be expected, but not major structural damage. On the other hand, if P_s equaled 50 kPa (7.25 psi) and i_s equaled 100 Pa·s (0.0415 psi/sec), partial demolition should be expected.

3-7

```
      SUBROUTINE PARUQP(PBAR,UBAR,QBAR,PBARR,PBR,UB,QB,PBR)
      DIMENSION PBR(5),UB(5),QB(5),PBR(5)
      REAL  PBAR,UBAR,QBAR,PBARR
      IF(PBAR.LE.PBR(5)) GO TO 20
      UBAR=QBAR=PBARR=0.0
      GO TO 11
20    DO 10 I=1,5
      IF (PBAR.EQ.PBR(I)) GO TO 9
      K=I+1
      PBXO=ABS(PBR(K)-PBR(I))
      PRX=ABS(PBAR-PBR(I))
      IF (PRX.GT.PBXO) GO TO 10
      UBAR=(UB(K)-UB(I))/(PBR(K)-PBR(I))*(PBAR-PBR(I))+UB(I)
      QBAR=(QB(K)-QB(I))/(PBR(K)-PBR(I))*(PBAR-PBR(I))+QB(I)
      PBARR=(PBR(K)-PBR(I))/(PBB(K)-PBR(I))*(PBAR-PBR(I))+PBR(I)
      GO TO 11
9     UBAR=UB(I)
      QBAR=QB(I)
      PBARR=PBR(I)
      GO TO 11
10    CONTINUE
11    RETURN
      END
```

Figure 3D-2. (Concl'd)
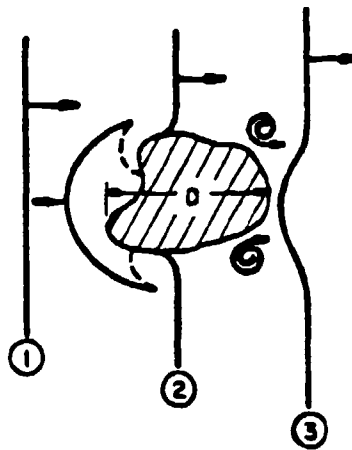
Figure 3D-3. Interaction of Blast Wave with
Irregular Object

To determine the momentum imparted to the body from the blast wave, it
is necessary to consider both the diffracted phase of loading and the drag
phase of loading.

Side-on overpressure is often expressed as a function of time by the
modified Friedlander equation: [8]

$$p(t) = P_s \left(1 - \frac{t}{T}\right) e^{-bt/T} \qquad (3D-1)$$

where

P$_s$ is peak side-on overpressure

T is the duration of the positive phase of the blast wave

b is a dimensionless time constant.

Integrating this equation gives specific impulse

$$I_s = \frac{P_s T}{b} \left[1 - \frac{(1 - e^{-b})}{b}\right] \qquad (3D-2)$$

Diffracted specific impulse I_r can be approximated by

$$I_r \cong \frac{P_r}{2} \Delta t \qquad (3D-3)$$

where

P_r is peak reflected pressure

Δt is length of time for the blast load to reach P_r after initial interaction with the blast wave

or

$$I_r \cong \frac{P_r}{2} \frac{d}{U} \qquad (3D-4)$$

where

d is effective diameter of human

U is shock front velocity

Shock front velocity can be expressed as

$$\left(\frac{U}{a_o}\right)^2 = 1 + \frac{6}{7} \frac{P_s}{P_o} \qquad (3D-5)$$

where

a_o is the speed of sound

P_s is peak side-on overpressure

p_o is ambient atmospheric pressure

For shocks of intermediate to weak strengths ($P_s/p_o \le 3.5$):[8]

$$\frac{P_r}{P_s} = 2\left(\frac{P_s}{P_o}\right) + \frac{3}{4}\left(\frac{P_s}{P_c}\right)^2 \qquad (3D-6)$$

Thus, from Equations (3D-4), (3D-5), and (3D-6),

$$I_r = \frac{\left[\left(\dfrac{P_s}{P_0}\right) + \dfrac{3}{8}\left(\dfrac{P_s}{P_0}\right)^2 \left(\dfrac{P_s d}{a_0}\right)\right]}{\sqrt{1 + \dfrac{6}{7}\left(\dfrac{P_s}{P_0}\right)}}$$ (3D-7)

The time history of drag pressure, slightly modified from Glasstone,[3] is

$$q(t) = Q\left(1 - \frac{t}{T}\right)^2 e^{-bt/T}$$ (3D-8)

where

Q is peak drag pressure.

Integrating Equation (3D-8) with respect to time over the time interval from 0 to T, drag specific impulse I_q becomes:

$$I_q = \left(\frac{QT}{b}\right)\left[1 - \frac{2}{b} + \frac{2}{b^2}(1 - e^{-b})\right]$$ (3D-9)

From Baker,[8] peak drag pressure (for $P_s/P_0 \leq 3.5$) can be determined by

$$Q = \frac{5}{2} C_D \frac{P_s^2}{(7 P_0 + P_s)}$$ (3D-10)

where

C_D is the drag coefficient for the human body.

Solving Equation (3D-2) for T and inserting Equation (3D-10) into Equation (3D-9):

$$I_q = \frac{5}{2} \frac{\left(\dfrac{P_s}{P_0}\right)}{\left[7 + \left(\dfrac{P_s}{P_0}\right)\right]} C_D I_s \left[\left(-\frac{2}{b}\right) + \left(\frac{b}{e^{-b} + b - 1}\right)\right]$$ (3D-11)

3D-11

Specific impulse is the integral of pressure with respect to time, while impulse is the integral of force with respect to time, pressure being force per unit area. Total momentum imparted to the body is equivalent to total impulse i_T:

$$i_T = m V \tag{3D-12}$$

where

m is the mass of the body

V is velocity

or

$$m V = (I_r + I_q) (5.5 \, d^2) \tag{3D-13}$$

where

$(5.5 \, d^2)$ is the assumed cross-sectional area of the body.

Substituting Equations (3D-11) and (3D-17) into (3D-13) and rearranging terms produces

$$\frac{a_o \, m V}{5.5 \, d^3 p_o} = \frac{\left[\left(\frac{P_s}{P_o}\right) + \left(\frac{3}{8}\right)\left(\frac{P_s}{P_o}\right)^2 \right]\left(\frac{P_s}{P_o}\right)}{\sqrt{1 + \frac{6}{7}\left(\frac{P_s}{P_o}\right)}} + \frac{(2.5)\left(\frac{P_s}{P_o}\right)}{\left[7 + \frac{P_s}{P_o}\right]}$$

$$\left[\left(-\frac{2}{b}\right) + \frac{b}{e^{-b} + b - 1} \right] \frac{a_o \, C_D \, I_s}{p_o \, d} \tag{3D-14}$$

which is a nondimensional equation. If one assumes that the density of man is the same as the density of water ρ_w and that the shape of man can be approximated by a cylinder with a length-to-diameter ratio of 5.5, then mass becomes

$$m = \rho w \frac{\pi d^2}{4} (5.5 \, d) \tag{3D-15}$$

or

$$d = \left(\frac{4m}{5.5 \, \pi \rho_w} \right)^{1/3} \tag{3D-16}$$

Substituting Equation (3D-16) into (3D-14) and rearranging terms, one can obtain

$$\frac{\rho_w a_o V}{4 p_o} = \frac{\left[\left(\frac{P_s}{P_o} \right) + \left(\frac{3}{8} \right) \left(\frac{P_s}{P_o} \right)^2 \right] \left(\frac{P_s}{P_o} \right)}{-\sqrt{1 + \left(\frac{6}{7} \right) \left(\frac{P_s}{P_o} \right)}} + \frac{(2.5) \left(\frac{P_s}{P_o} \right)}{\left[7 + \left(\frac{P_s}{P_o} \right) \right]}$$

$$\left[\left(-\frac{2}{b} \right) + \frac{b}{e^{-b} + b - 1} \right] \frac{a_o C_D I_s}{P_o} \left(\frac{5.5 \, \pi}{4} \right)^{1/3} \frac{\rho_w}{m^{1/3}} \tag{3D-17}$$

Thus,

$$\left(\frac{\rho_w a_o V}{P_o} \right) = f \left(\frac{P_s}{P_o}, \frac{C_D a_o I_s \rho_w^{1/3}}{P_o m^{1/3}} \right) \tag{3D-18}$$

Equation (3D-18) demonstrates a nondimensional functional dependence. Dimensionally, for constant values of ρ_w, a_o, and p_o, Equation (3D-18) becomes

$$V = f \left(P_s, \frac{I_s}{m^{1/3}} \right) \tag{3D-19}$$

Thus, after calculating the pressure and impulse combinations required to translate an individual of a certain mass at a specific potentially hazardous velocity, it is beneficial to plot the calculations on a graph of P_s versus $(I_s/m^{1/3})$. By doing this, pressure-impulse combinations needed to propel different body masses at the predetermined velocity can be acquired directly from the graph, assuming that the density and length-to-diameter ratios of the body are the same. Hence, eight graphs (2 damage conditions X 4 altitudes), instead of the previously mentioned 32 graphs (2 damage conditions X 4 masses X 4 altitudes), are required to identify

the pressure-impulse combinations which will produce the human transla-
tion velocities specified in Tables 3D-1 and 3D-2 for any mass human body
within the limits of the aforementioned assumptions. The results are plotted
in Figures 3-12 through 3-19.

It is a very simple matter to use the graphs to determine if there
exists a potential threat due to whole body translation and subsequent decel-
erative impact on a hard surface. An example will demonstrate the proced-
ure.

Suppose a propellant blast occurs at sea level (p_o = 101 kPa). The
closest people to the blast are several adult males with an approximate mass
of 70 kg (154 lb_m). Using methods established in Chapters I and II for cal-
culating pressure and impulse, it is determined that these humans are ex-
posed to an incident overpressure of 1600 Pa (0.232 psi) and a specific im-
pulse of 20 kPa·s (2.90 psi-sec). Scaled impulse ($I_s/m^{1/3}$) is then 4850
Pa·s/kg$^{1/3}$. Examining Figures 3-12 and 3-16 indicates that the point
(1600 Pa, 4850 Pa·s/kg$^{1/3}$) lies below the threshold curves for skull frac-
ture and for whole body impact, respectively. Since the point is below the
curves, no skull fracture or death is expected from whole body displacement.
It should be kept in mind that the curves cannot be extended for impulses
lower than those shown on the graph, and thus the graphs are somewhat
limited since they do not appear to be asymptotic.

3D-14

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CHARACTERISTICS OF FRAGMENTS

4-1 General

The fragments generated during accidental explosions of the types covered in this workbook can come from several sources. They can be pieces of the exploding vessels themselves, or pieces of wreckage from an impact which also results in an explosion, or nearby objects (appurtenances) accelerated by the blast waves from the explosion. The methods of prediction given in this chapter allow one first to estimate initial fragment velocities for various types of accident and geometry of vessel or explosion source. Next, predictions can be made of fragment ranges and impact conditions using initial velocities as inputs. Finally, fragment mass distributions can be predicted in a statistical sense for several classes of accidental explosion.

The various graphs and equations used to generate predictions of fragment characteristics are the result of exercise of a number of computer programs, and fits to experimental data. A number of appendices are included in the chapter to describe the computer programs, statistical analyses, and other supporting information.

4-2 Methods for Estimating Fragment Initial Velocities

4-2.1 Spherical Gas Vessels

The following is the deterministic technique for predicting initial fragment velocities for fragments emanating from containment vessels of spherical geometry. This technique requires that you know the external radius of the spherical confinement vessel, the thickness of the wall of the spherical confinement vessel, the density of the confinement vessel material, and the internal gas pressure at burst. The present figures allow this technique to be used for gases whose properties are similar to air and helium.

The first step in the procedure is to calculate a mass ratio consisting of the mass of a volume of gas equal to the internal volume of the sphere at standard temperature and pressure, divided by the mass of the confinement vessel. The equation for calculating this mass ratio is given in each of the examples in terms of the radius of the spherical confinement vessel, the thickness of the vessel walls, and the density of the gas and vessel material, respectively.

The second step in this procedure is to calculate a pressure ratio which is the pressure of the internal gas at the time the confinement vessel bursts divided by atmospheric pressure. Having obtained the mass ratio and the pressure ratio, a value for initial velocity ratio $\bar{v}$ can be obtained from Figures 4-1 through 4-8, which constitutes Step 3 in the procedure. The figure used to look up the value of $\bar{v}$ depends upon whether air or helium is considered and the radius of the confinement vessel. Since figures are not generated for all possible vessel radii, it is necessary to consult the figure with a radius value that is nearest to the radius of the confinement vessel considered. Since plots are not given in the figures for all possible mass ratios, it is also necessary to read values for $\bar{v}$ from the plots for mass ratios having values most nearly above and below the mass ratio considered. The appropriate value for $\bar{v}$ can then be obtained by the method of linear interpolation as in Step 4 of the examples. Once the velocity ratio value has been obtained for the specific case considered, it can be multiplied by the appropriate speed of sound at ambient conditions for the gas considered to obtain the initial fragment velocity.

Examples 1 through 3 illustrate how this procedure may be used to obtain initial fragment velocities from bursting spheres. Fragment velocities from bursting cylinders are discussed in the next section with examples. Example 1 is the calculation for a case in which some experimental data have been obtained to verify the results, as is Example 2. Discussion of experimental results which verify the code used to generate Figures 4-1 through 4-8 is given in Appendix 4A. Example 3 is taken from a proposed case where a Centaur pressure tank is overpressurized with helium.

The procedure illustrated here for estimating initial fragment velocities from bursting pressurized confinement vessels was made possible by the generation of Figures 4-1 through 4-8 from the computer code SPHER. This code and the theory behind it are discussed in the appendices. A similar code used to generate Figures 4-9 through 4-16 for cylindrical confinement vessels was generated from a code CYLIN. This code is also discussed in the appendices.

Example 1, For Spheres

Assume: A spherical containment vessel of glass

R = 2.54 cm (1 in.) internal radius of sphere

t = 1 mm (3.94×10^{-2} in.) glass wall thickness

Figure 4-1. Fragment Velocities for Contained Air
in a Sphere of Radius 0.0762 m

Figure 4-2. Fragment Velocities for Contained Air
in a Sphere of Radius 0.254 m

Figure 4-3. Fragment Velocities for Contained Air
in a Sphere of Radius 0.762 m

$\bar{V}$

10.0

6.0

4.0

2.0

$M_{os}/M_t = 5.18 \times 10^{-1}$

1.73×10^{-1} 5.18×10^{-2} 1.73×10^{-2} 5.18×10^{-3}

1.0

0.6

0.4

2   4   6 10^2 2   4   6 10^3 2   4   6   8

$\bar{P}$

Figure 4-4.   Fragment Velocities for Contained Air
in a Sphere of Radius 2.54 m

Figure 4-5. Fragment Velocities for Contained H₂
in a Sphere of Radius 0.0762 m

Figure 4-6. Fragment Velocities for Contained H₂
in a Sphere of Radius 0.254 m
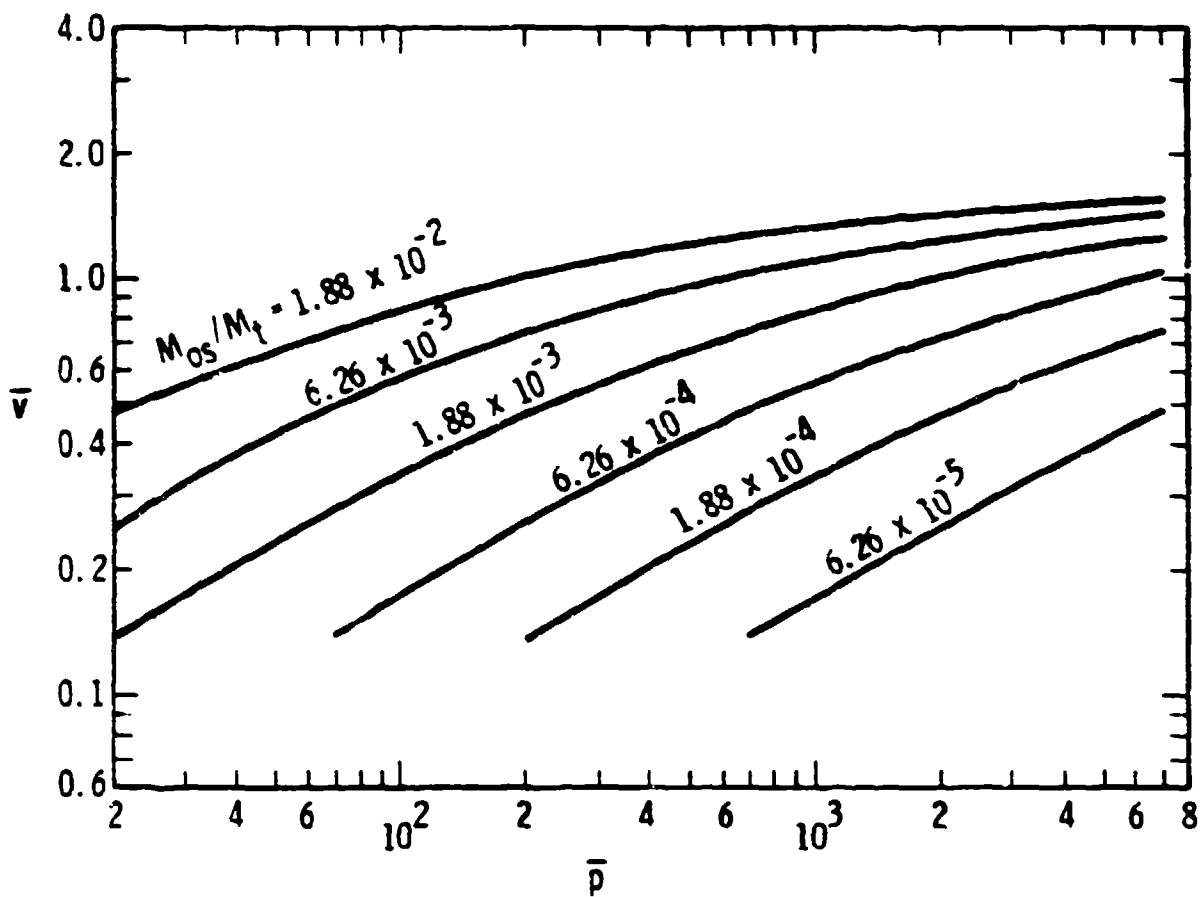
Figure 4-7. Fragment Velocities for Contained He
in a Sphere of Radius 0.762 m
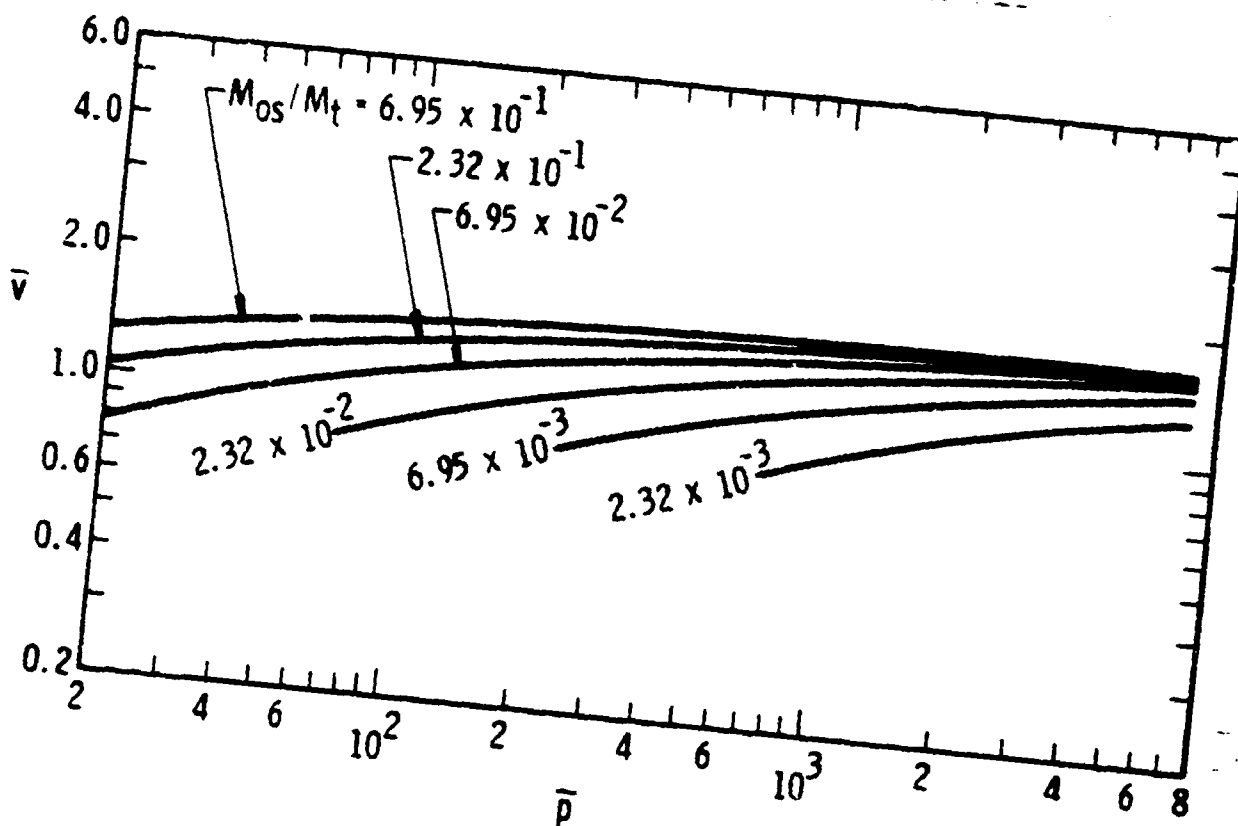
Figure 4-8. Fragment Velocities for Contained He in a Sphere of Radius 2.54 m

Burst from internal air pressure

P_0 = 2.25 x 10^6 Pa (326 psi)

Step 1. Calculate mass ratio M_{os}/M_t from equation

$$\frac{M_{os}}{M_t} = \frac{R^3 \, \rho_{air}}{[R^3 - (R-t)^3] \, \rho_{glass}}$$

From assumptions R = 2.54 cm

t = 0.1 cm

From density tables ρ_{air} = 1.293 x 10^{-3} g/cm^3, at standard temperature and pressure.

ρ_{glass} = 2.60 g/cm^3

Therefore,

$$\frac{M_{os}}{M_t} = \frac{(1.293 \times 10^{-3}) (2.54)^3}{[(2.54)^3 - (2.54 - 0.1)^3] (2.6)} = 4.38 \times 10^{-3}$$

Step 2. Calculate pressure ratio $\bar{p}$ from equation

$$\bar{p} = \frac{P_0}{1.01 \times 10^5}$$

From assumption P_0 = 2.25 x 10^6 Pa

Therefore,

$$\bar{p} = \frac{2.25 \times 10^6}{1.01 \times 10^5} = 22.21$$

Step 3. From Figure 4-2, for a vessel of radius closest to the vessel considered containing air, find $\bar{V}$ for the M_{os}/M_t ratio

most nearly above and below the value of Step 1 for the $\bar{p}$ of Step 2. This is:

at $\bar{p}$ = 22.2

M_1 = (M_{os}/M_t) below = 1.40×10^{-3} , $\bar{V}_1$ = 0.140

M_2 = (M_{os}/M_t) Step 1 = 4.38×10^{-3} , $\bar{V}_2$ = ?

M_3 = (M_{os}/M_t) above = 4.67×10^{-3} , $\bar{V}_3$ = 0.266

Step 4. Find $\bar{V}_2$ by linear interpolation from the equation

$$\bar{V}_2 = (\bar{V}_3 - \bar{V}_1) \left(\frac{M_2 - M}{M_2 - M_p} \right) + \bar{V}_1 =$$

$$\bar{V}_2 = (0.266 - 0.140) \left(\frac{4.38 - 1.40}{4.67 - 1.40} \right) + 0.140 = 0.255$$

Step 5. Multiply $\bar{V}_2$ by the a_{os} value given in Figure 4-2 to obtain the initial fragment velocity

$$V_i = \bar{V}_2 \cdot a_{os} = (0.255)(3.31 \times 10^2 \text{ m/s}) = 84.4 \text{ m/s}$$

The initial fragment velocity is 84.4 m/s (277 ft/sec).

Note: This example was run using code SPHER, the code used to generate Figure 4-2, for the specific data assumed. The results gave a V_i = 80.2 m/s (263 ft/sec) compared to our result of 84.4 m/s (277 ft/sec) obtained from the figure. This gives some indication of the interpolation error and error in reading numbers from the figure which can be expected.

This particular example was taken from the data of D. W. Boyer, et al., [1] who performed experiments in which glass spheres of various dimensions were burst under internal gas pressure. For this particular sphere dimension and gas pressure, the experimental data showed fragments had an average initial fragment velocity of 75.6 m/s (248 ft/s). Our value obtained from the tables is about 10% higher than this.

A comparison of other data from the tests by Boyer with fragment velocities obtained from code SPHER or the tables generated from code SPHER is given in Appendix 4A.

Example 2. For Spheres

Assume: A spherical containment vessel of glass

$R = 2.54$ cm (1 in.) internal radius of sphere

$t = 1$ mm (3.94×10^{-2} in.) glass wall thickness

Burst from internal helium (He) pressure

$P_o = 2.25 \times 10^6$ Pa (326 psi)

Step 1. Calculate mass ratio M_{os}/M_t from equation

$$\frac{M_{os}}{M_t} = \frac{R^3 \, \rho_{He}}{\left[R^3 - (R - t)^3 \right] \rho_{glass}}$$

From assumptions: $R = 2.54$ cm

$t = 0.1$ cm

From density tables: $\rho_{He} = 0.1785 \times 10^{-3}$ gm/cm^3 at STP

$\rho_{glass} = 2.60$ gm/cm^3

Therefore,

$$\frac{M_{os}}{M_t} = \frac{(0.1785 \times 10^{-3})(2.54)^3}{\left[(2.54)^3 - (2.54 - 0.1)^3 \right](2.6)} = 6.05 \times 10^{-4}$$

Step 2. $\bar{p} = 22.2$ (same as in Example 1)

Step 3. From Figure 4-5, for a vessel of radius closest to the vessel considered containing He, find $\bar{V}$ for the M_{os}/M_t ratio most nearly above and below the value of Step 1 for the $\bar{p}$ of Step 2.

at $\bar{p}$ = 22.2

M_1 = (M_{os}/M_t) below = 1.88×10^{-4} , $\bar{V}_1$ = 0.036

M_2 = (M_{os}/M_t) Step 1 = 6.05×10^{-4} , $\bar{V}_2$ = ?

M_3 = (M_{os}/M_t) above = 6.26×10^{-4} , $\bar{V}_3$ = 0.068

<u>Step 4.</u> Find $\bar{V}_2$ by linear interpolation from the equation

$$\bar{V}_2 = (\bar{V}_3 - \bar{V}_1)\left(\frac{M_2 - M_1}{M_3 - M_1}\right) + \bar{V}_1$$

$$\bar{V}_2 = (0.068 - 0.036)\left(\frac{6.05 - 1.88}{6.26 - 1.88}\right) + 0.036$$

$$= 0.066$$

<u>Step 5.</u> Multiply V_2 by the a_{os} value in Figure 4-5 to obtain the initial fragment velocity

$$V_i = \bar{V}_2 \cdot a_{os} = (0.066)(9.63 \times 10^2 \text{ m/s}) = 64.0 \text{ m/s}$$

The initial fragment velocity is 64 m/s (210 ft/sec)

Example 3, For Spheres

Assume: A Centaur pressurant tank

V = 0.121 m^3 (7361 in^3) volume of tank

t = 0.46 cm (0.181 in.) titanium wall thickness

Burst from internal He pressure

P_o = 2.07×10^7 Pa (3000 psi)

<u>Step 1.</u> Calculate mass ratio M_{os}/M_t from equation

$$\frac{M_{os}}{M_t} = \frac{R^3 c_{He}}{[R^3 - (R - t)^3] c_{titanium}}$$

from assumptions

$$V = \frac{4}{3}\pi R^3 = 0.121 \ m^3$$

Therefore

$$R = \left[\frac{(3)(0.121)}{4\pi}\right]^{1/3} m$$

$$R = 0.307 \ m = 30.7 \ cm$$

$$t = 0.46 \ cm$$

From density tables

$$c_{He} = 0.1785 \times 10^{-3} \ gm/cm^3 \qquad \text{at STP}$$

$$c_{Ti} = 4.5 \ gm/cm^3$$

Therefore,

$$\frac{M_{os}}{M_t} = \frac{(30.7)^3 (0.1785 \times 10^{-3})}{[(30.7)^3 - (30.7 - 0.46)^3](4.5)} = 8.96 \times 10^{-4}$$

Step 2. Calculate pressure ratio $\bar{p}$ from equation

$$p = \frac{P_o}{1.01 \times 10^5}$$

from assumption

$$P_o = 2.07 \times 10^7 \ Pa$$

Therefore,

$$\bar{p} = \frac{2.07 \times 10^7}{1.01 \times 10^5} = 205$$

Step 3. From Figure 4-6, for a vessel of radius closest to the vessel considered containing He, find $\bar{V}$ for the M_{os}/M_t ratio most nearly above and below the value of Step 1 for the $\bar{p}$ value of Step 2. This is:

at $\bar{p}$ = 205

$M_1 = (M_{os}/M_t)$ below $= 6.95 \times 10^{-4}$, $\bar{V}_1 = 0.30$

$M_2 = (M_{os}/M_t)$ Step 1 $= 8.96 \times 10^{-4}$, $\bar{V}_2 = ?$

$M_3 = (M_{os}/M_t)$ above $= 2.32 \times 10^{-3}$, $\bar{V}_3 = 0.49$

Step 4. Find $\bar{V}_2$ by linear interpolation from equation

$$\bar{V}_2 = (\bar{V}_3 - \bar{V}_1)\left(\frac{m_2 - m_1}{m_3 - m_1}\right) + \bar{V}_1$$

$$V_2 = (0.49 - 0.30)\left(\frac{8.96 - 6.95}{23.2 - 6.95}\right) + 0.30$$

$$= 0.32 \text{ m/s}$$

Step 5. Multiply V_2 by the a_{os} value given in Figure 4-6 to obtain the initial fragment velocity.

$$V_i = \bar{V}_2 \cdot a_{os} = (0.32)(963 \text{ m/s}) = 311 \text{ m/s}$$

The initial fragment velocity is 311 m/s (1022 ft/s).

4-2.2   Cylindrical Gas Vessels

The following deterministic procedure may be used to estimate initial fragment velocities emanating from containment vessels of cylindrical configuration. Figures 4-9 through 4-16 may be used to estimate initial fragment velocities for a broad spectrum of burst pressures and confinement vessel dimensions. Figures 4-9 through 4-12
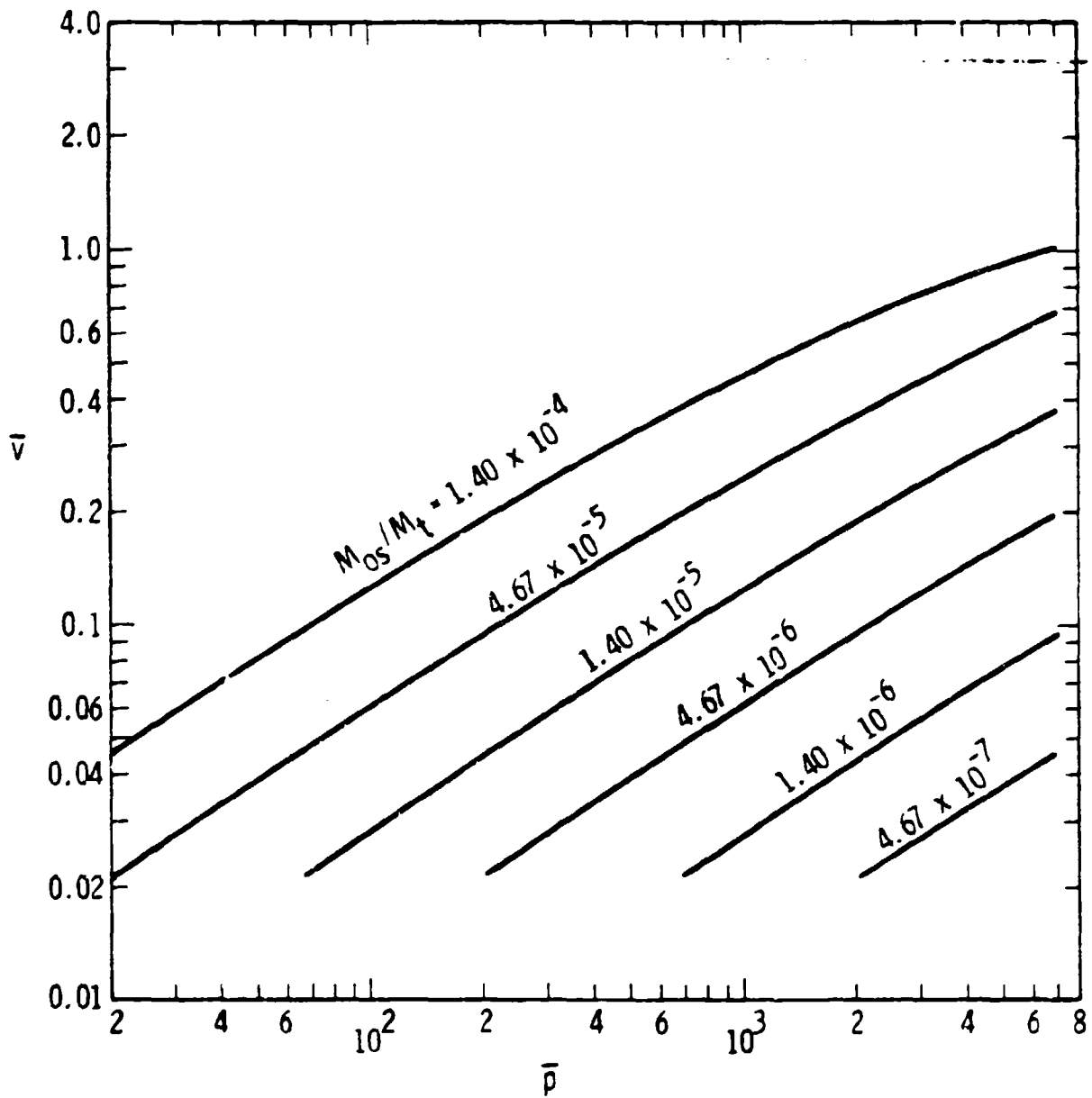
Figure 4-9. Fragment Velocities for Contained Air
in a Cylinder of Radius 0.0762 m
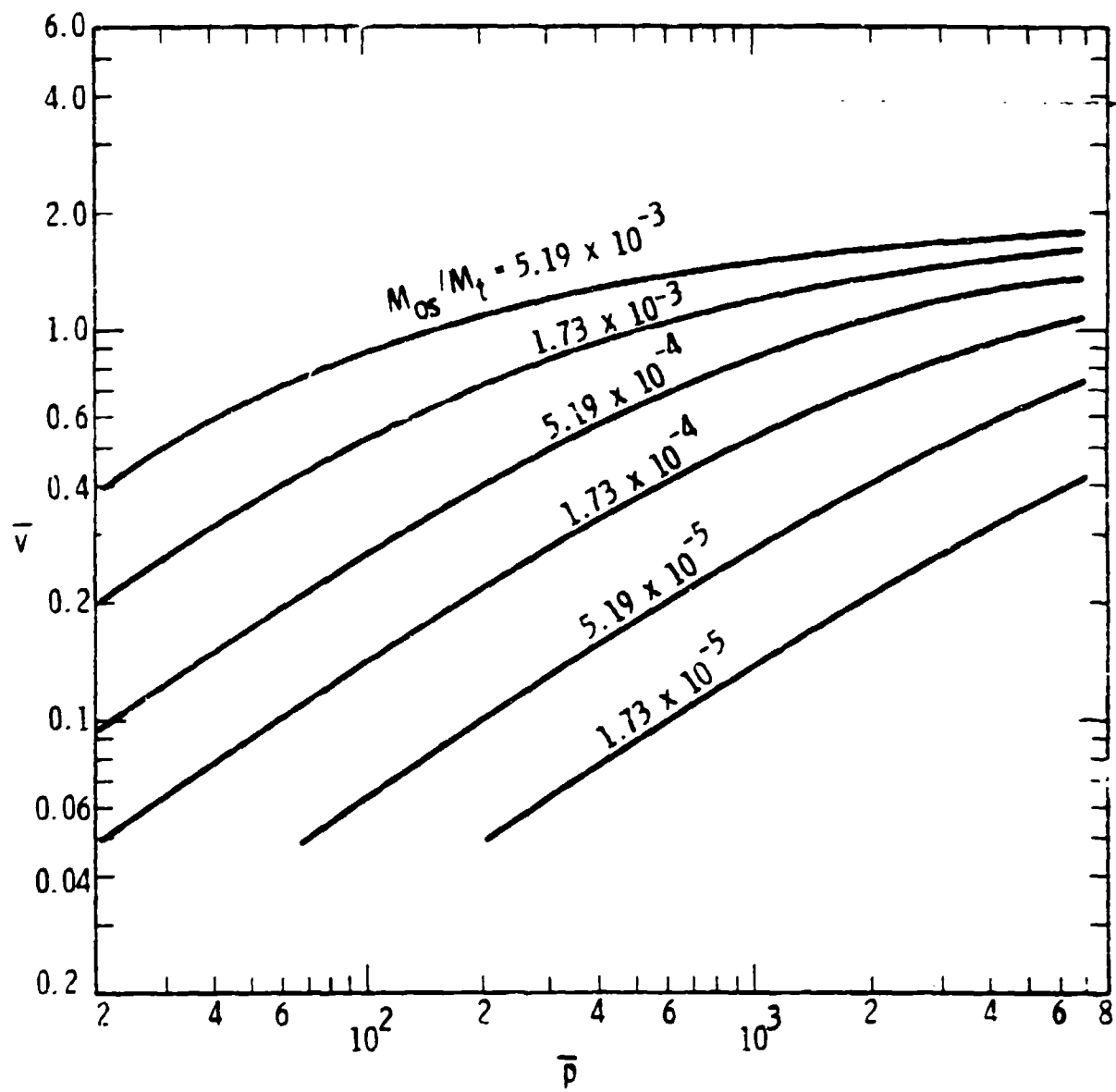
Figure 4-10. Fragment Velocities for Contained Air
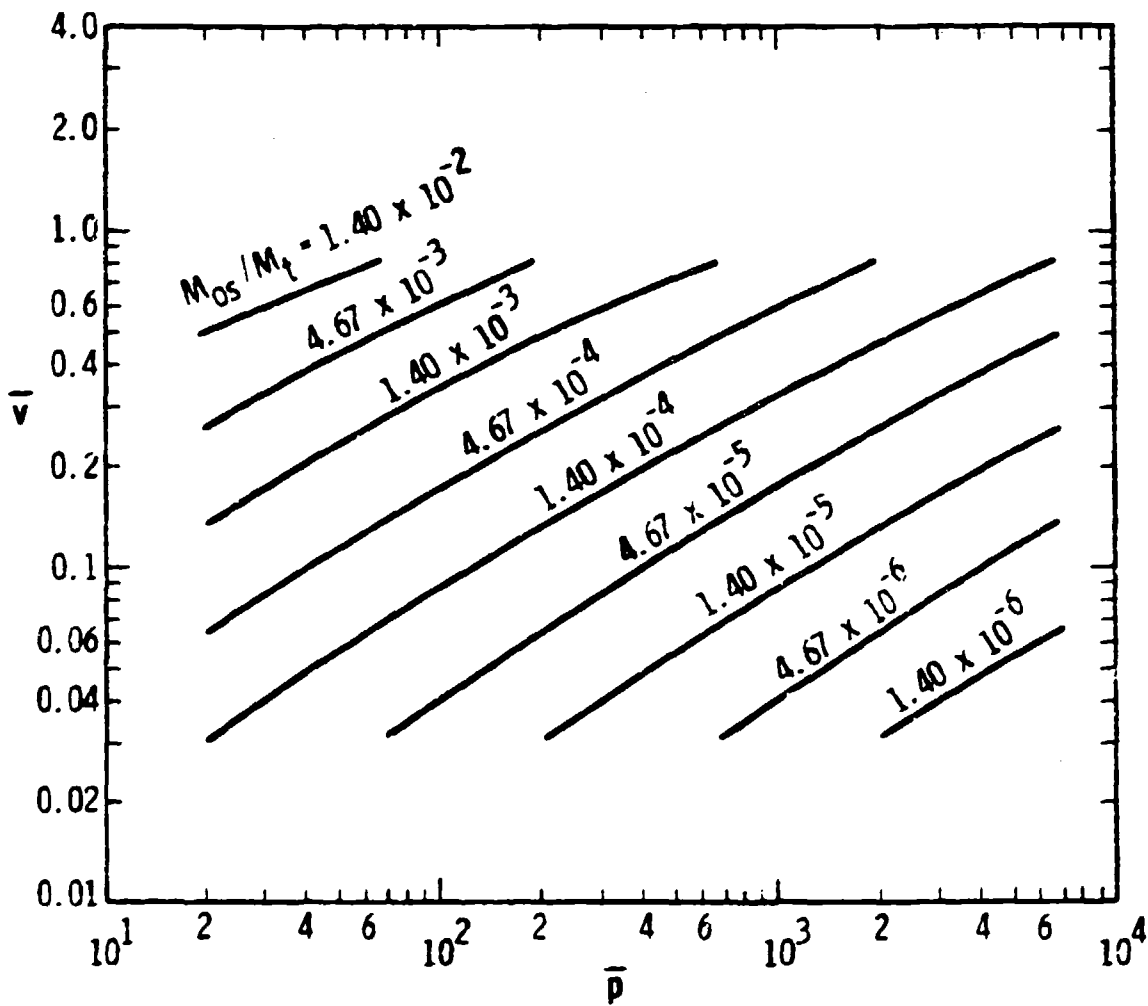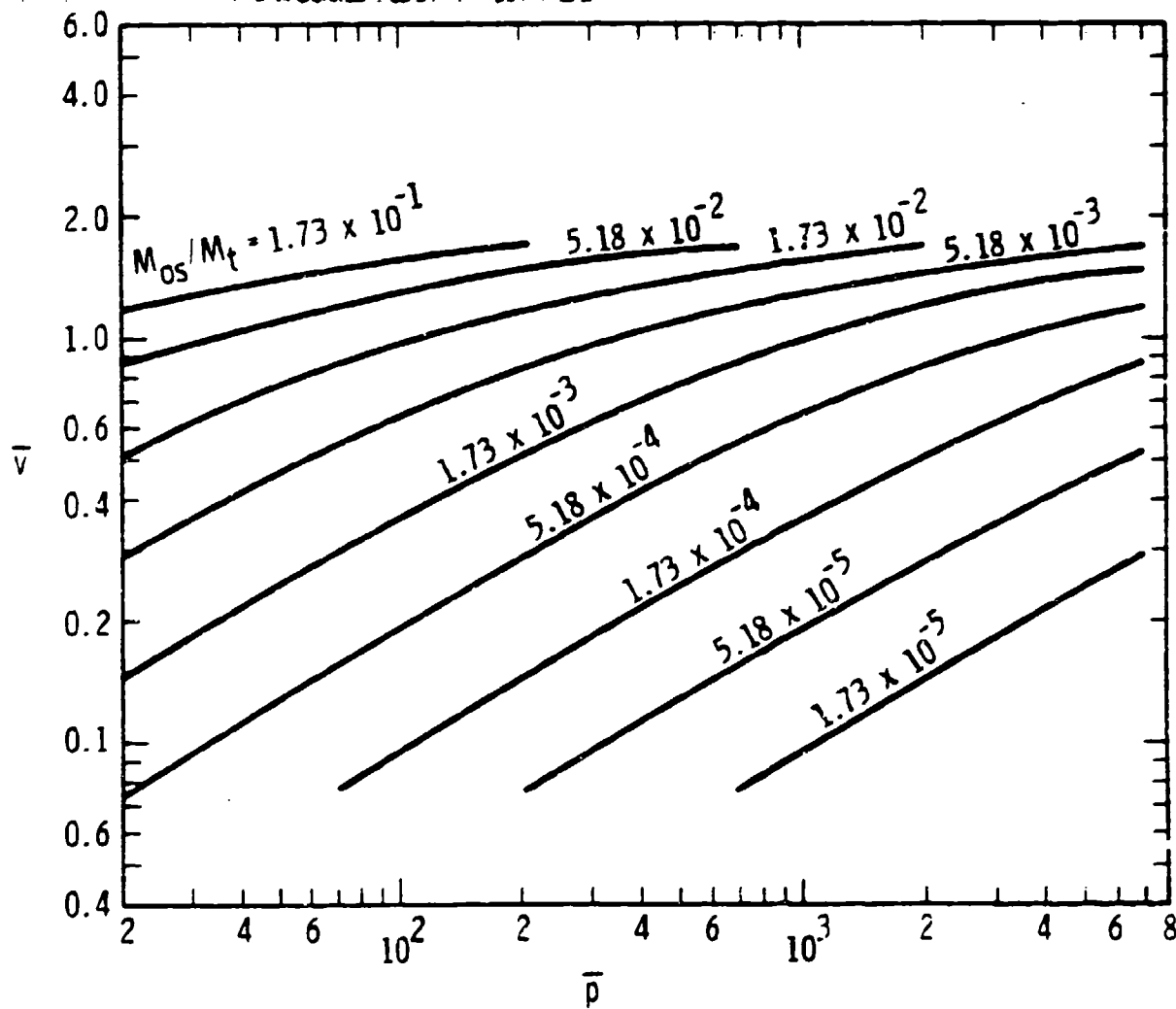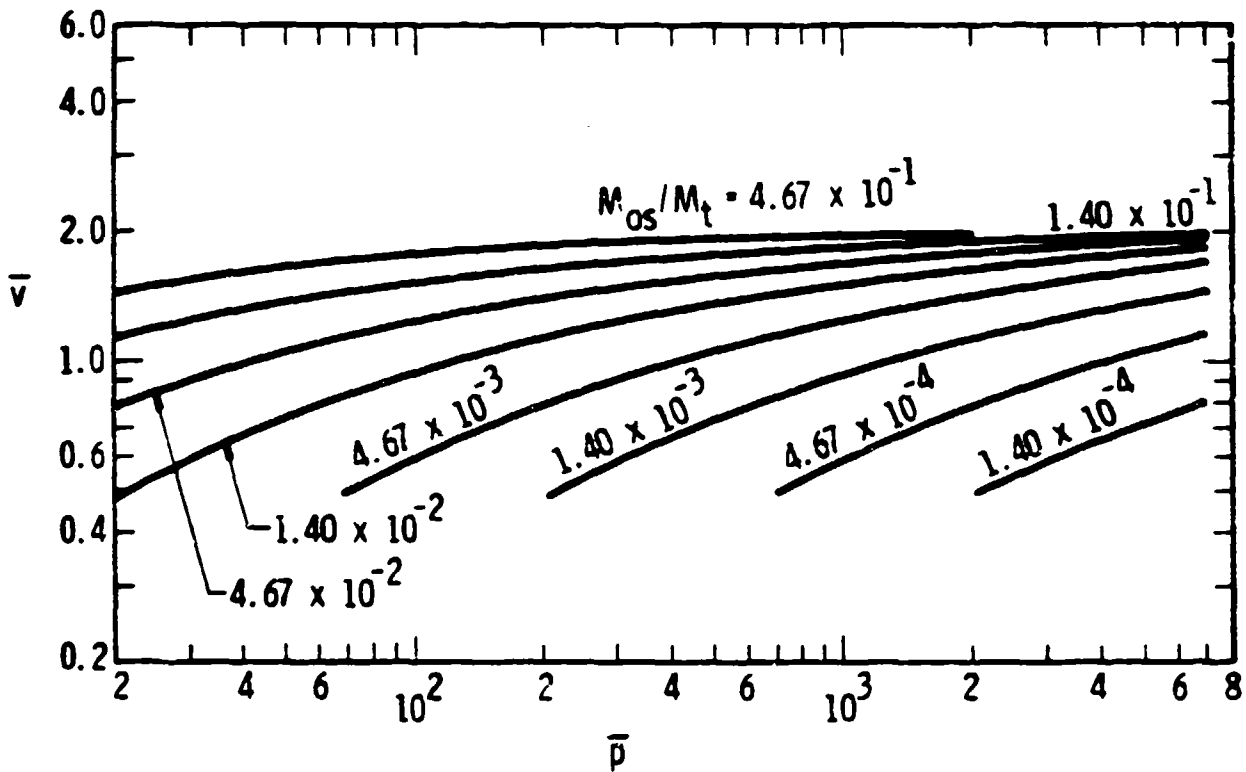in a Cylinder of Radius 0.254 m
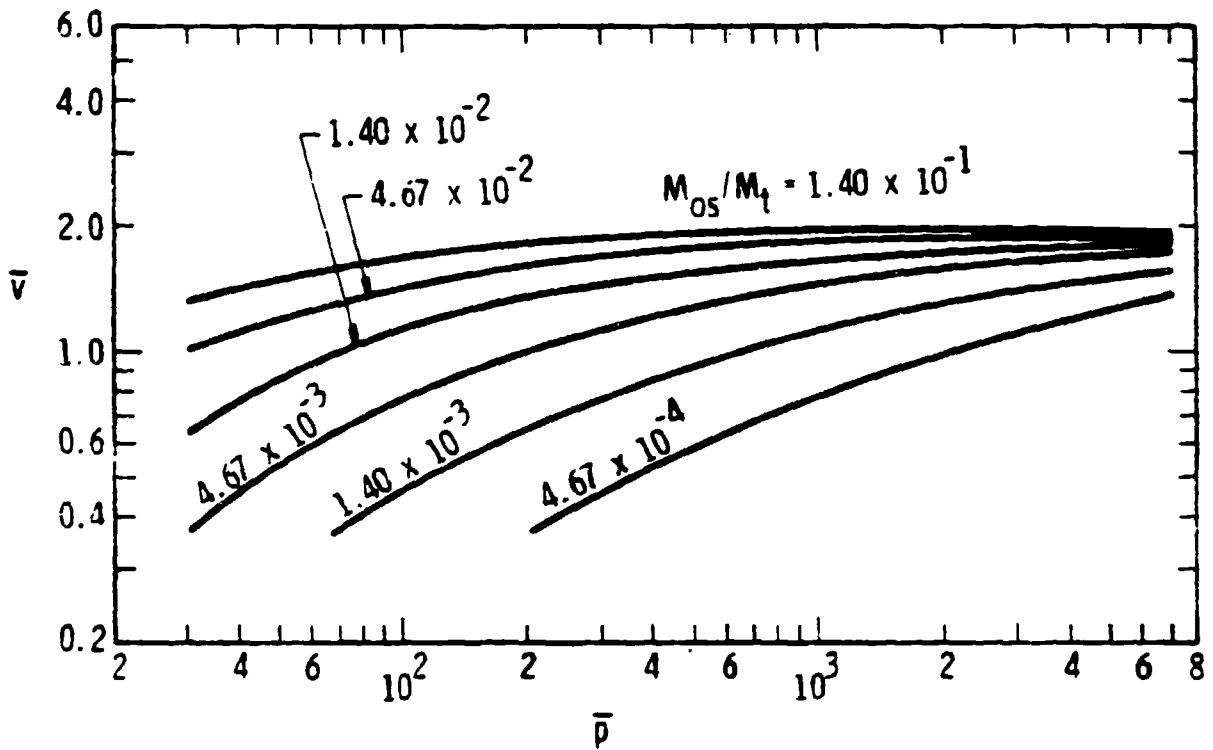
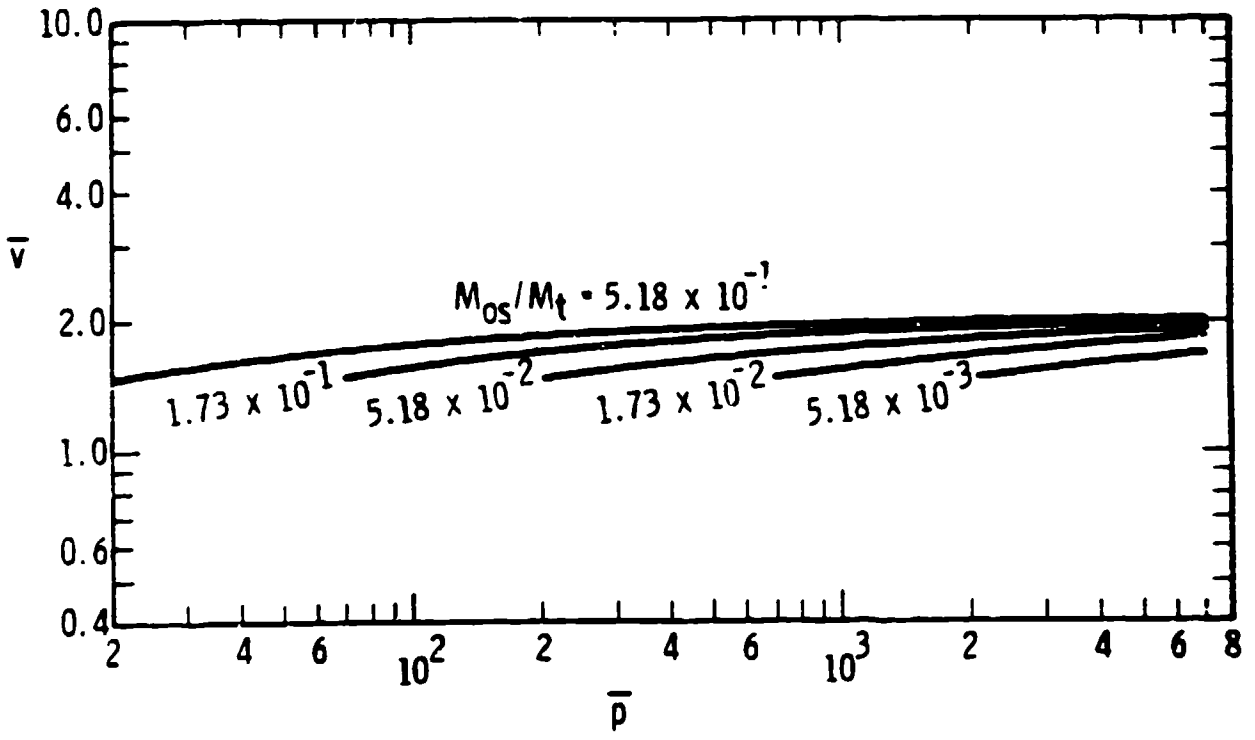Figure 4-11. Fragment Velocities for Contained Air
in a Cylinder of Radius 0.762 m
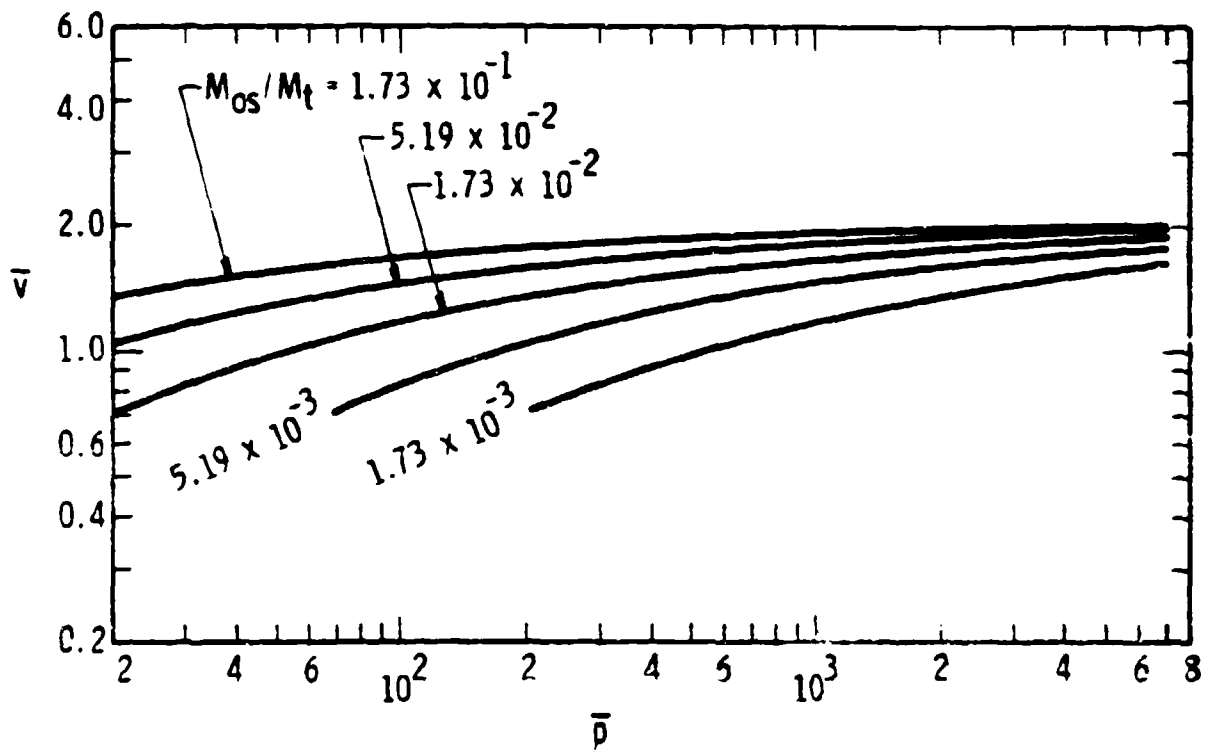
Figure 4-12. Fragment Velocities for Contained Air
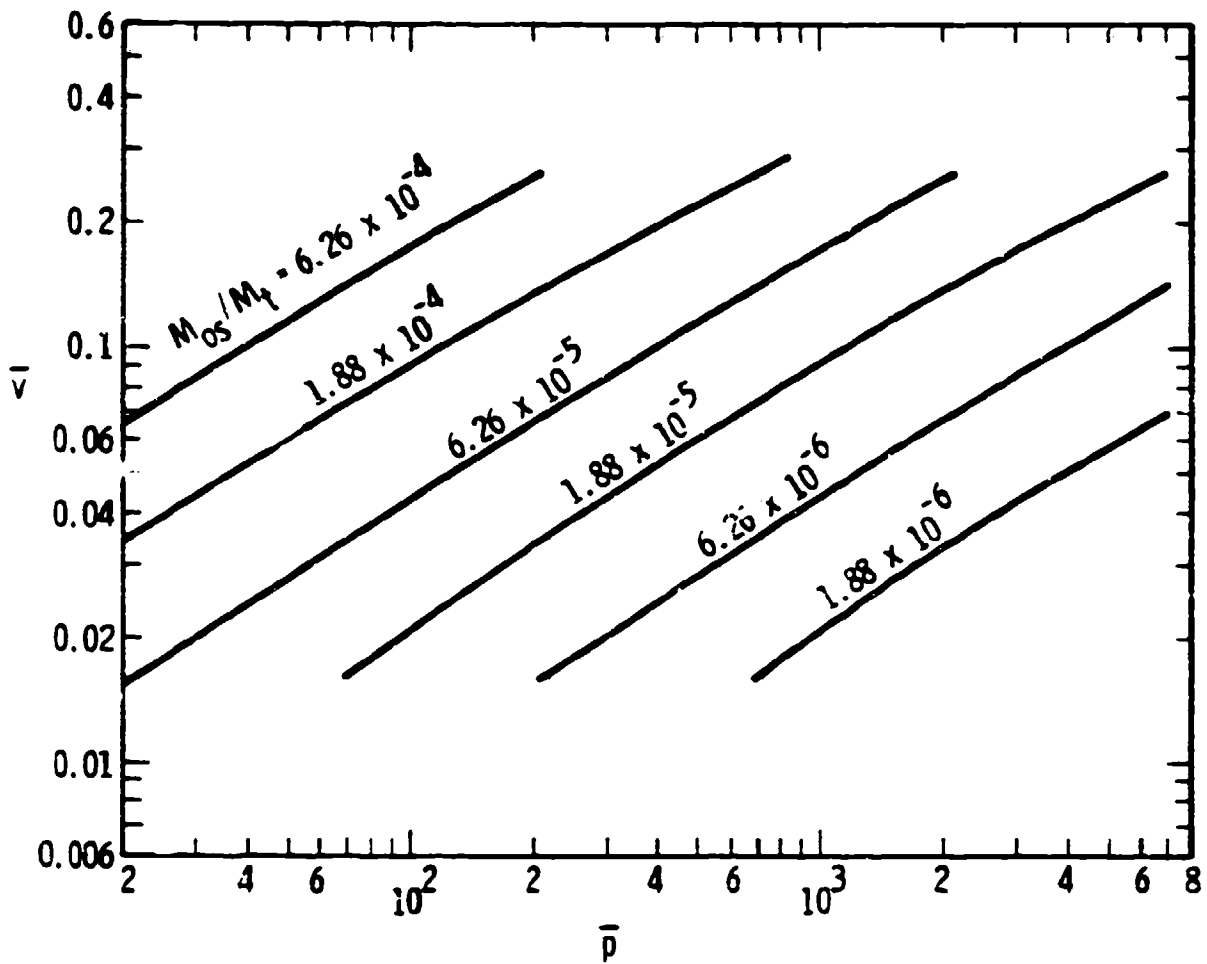in a Cylinder of Radius 2.54 m
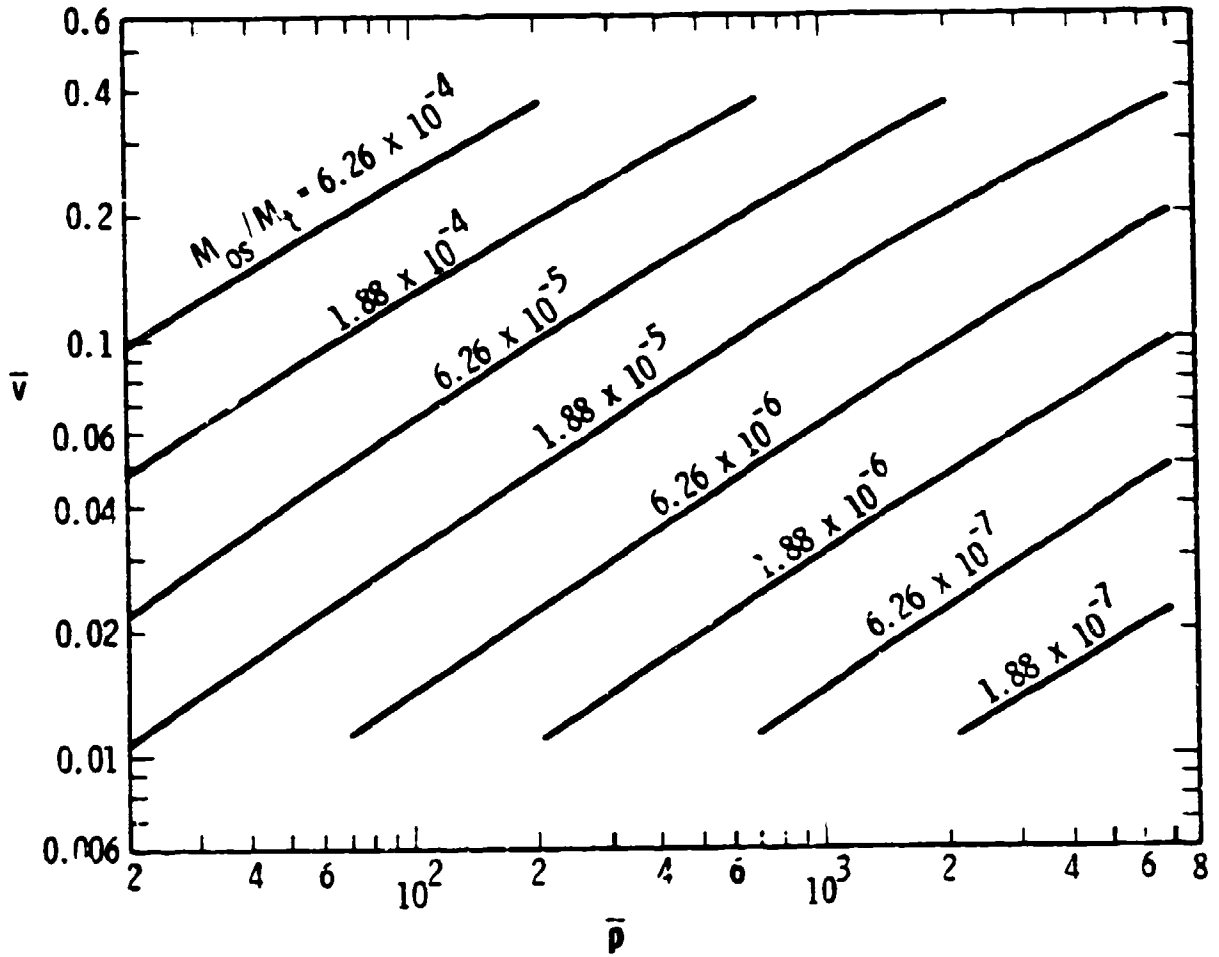
Figure 4-13. Fragment Velocities for Contained He
in a Cylinder of Radius 0.0762 m
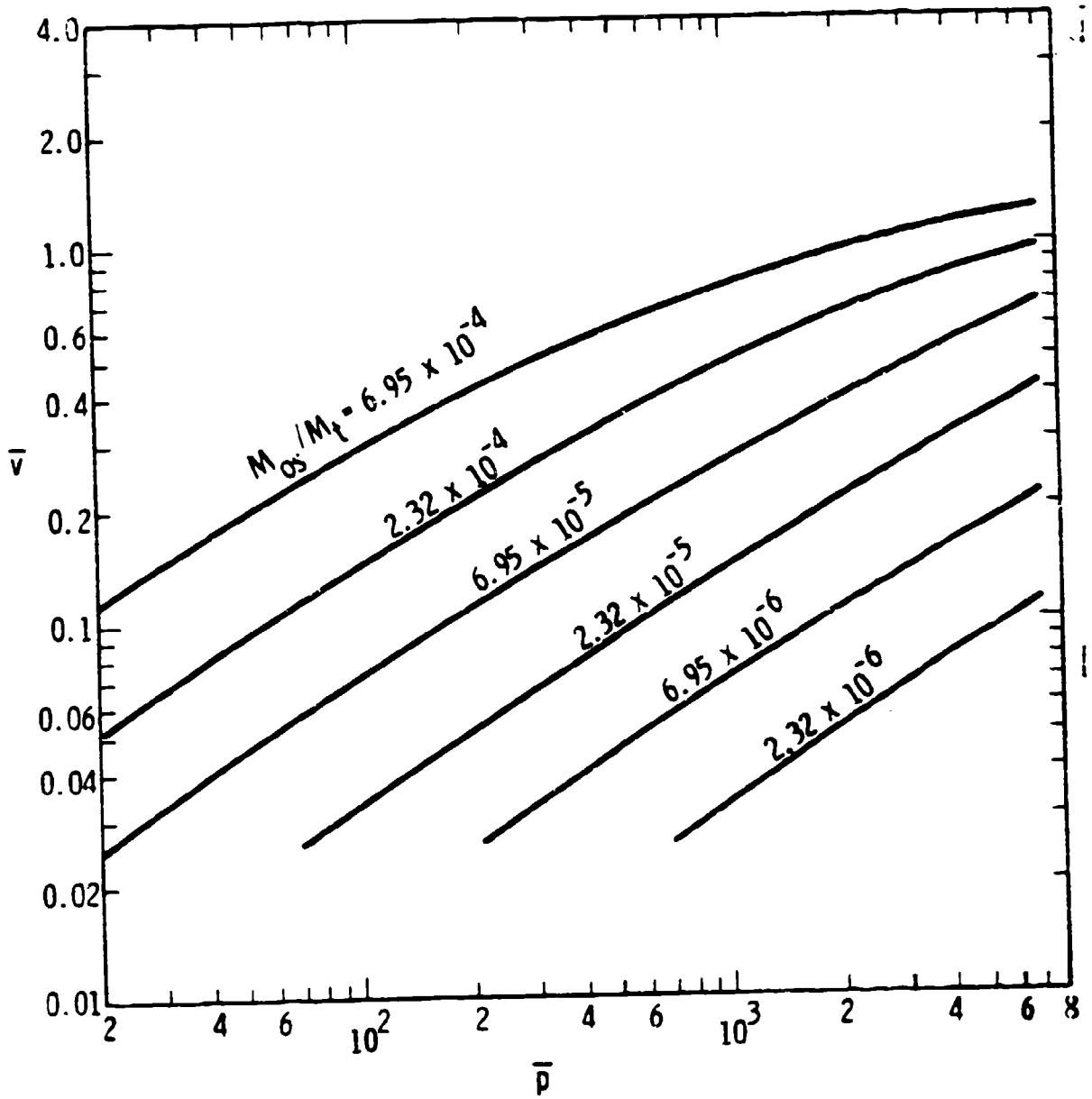
Figure 4-14. Fragment Velocities for Contained He
in a Cylinder of Radius 0.254 m
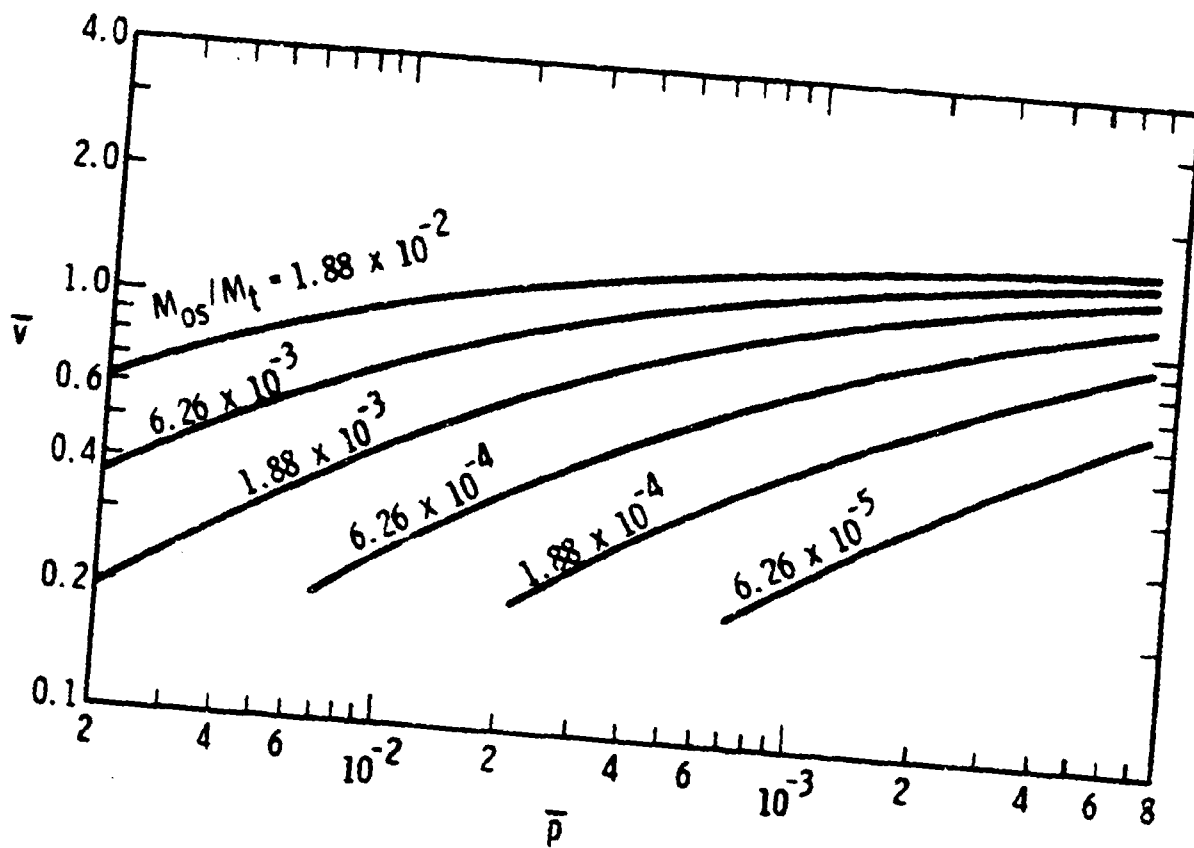
Figure 4-15. Fragment Velocities for Contained He
in a Cylinder of Radius 0.762 m
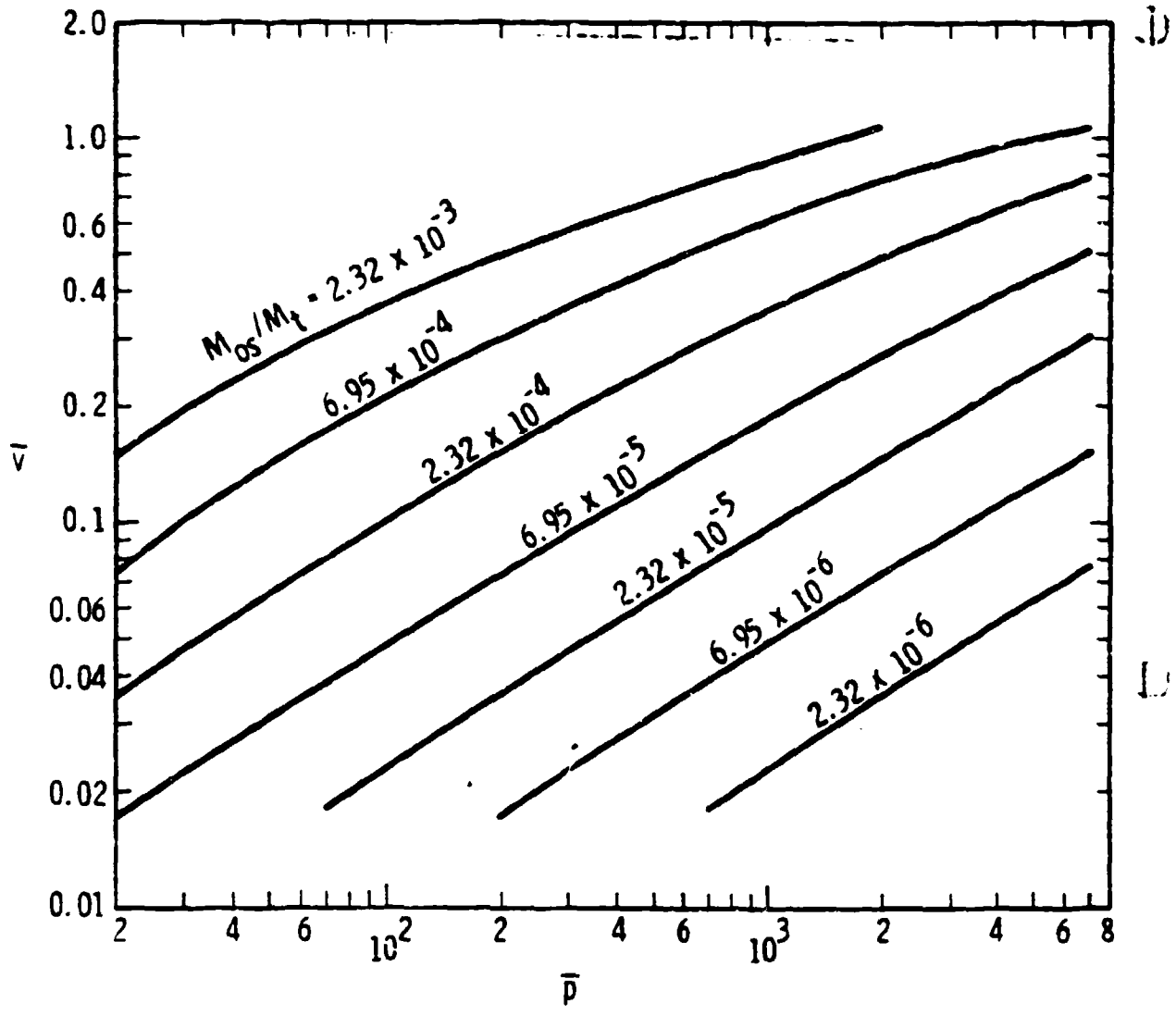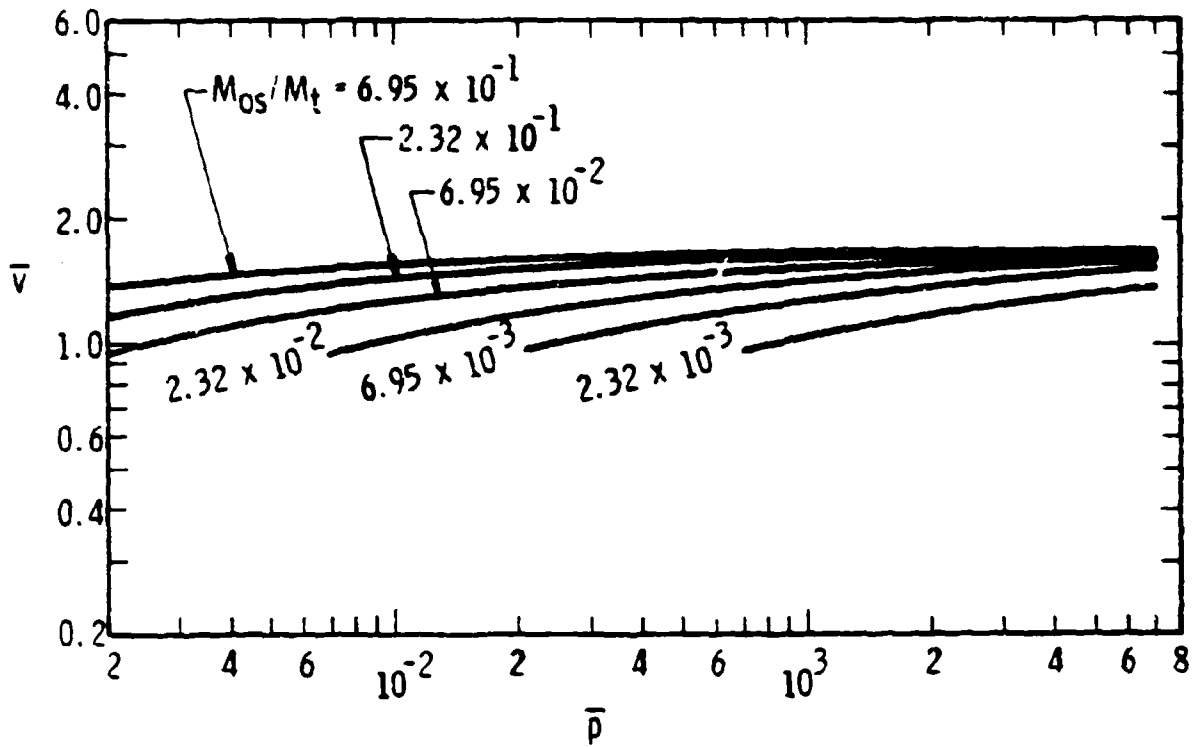
Figure 4-16. Fragment Velocities for Contained He in a Cylinder of Radius 2.54 m

may be used for estimating initial fragment velocities for a confined gas with properties similar to air. Figures 4-12 through 4-16 may be used for estimating initial fragment velocities for a confined gas whose properties are similar to helium. The code used to generate these figures (code CYLIN) is described in Appendix 4A. It should be pointed out that because of the two-dimensional nature of the analysis, the effects of the cylinder ends are not taken into account. The length of the cylinder thus does not affect results and is immaterial so long as the properties of the cylinder per unit length are known.

Example 1 below demonstrates how the initial velocity of fragments emanating from a bursting containment vessel may be obtained through the use of the figures. In this example, a steel cylinder approximately a foot in diameter and having wall thickness of approximately a quarter of an inch is assumed to burst at 10^4 psi from the pressure of confined air. It should be noted that all calculations are done using standard SI units. It should also be noted that the tank mass is nondimensionalized in the figures by the use of a ratio with the mass of the confined gas at standard temperature and pressure. Example 2 is a calculation for the initial fragment velocities emanating from a cylinder similar to that of Example 1, which bursts under pressurization from helium gas. The method for calculating fragment velocities shown in these examples for cylinders is the same as those for spheres with the exception of a different equation for calculating the mass ratio and the use of the different figures to obtain $\bar{v}$ as a function of $\bar{p}$ and the mass ratio.

Examples 1, For Cylinders

Assume:

A cylindrical confinement vessel

t = 0.5 cm (~0.25 in.) steel wall thickness

$2R$ = 0.30 m (~12.0 in.) diameter of tank

Bursts from internal air pressure

P_o = 7.00 x 10^7 Pa (~10^4 psi)

Step 1. Calculate mass ratio M_{os}/M_t from equation

$$\frac{M_{os}}{M_t} = \frac{R^2 \, \rho_{air}}{[R^2 - (R-t)^2] \, \rho_{steel}}$$

from assumptions

$$R = 0.15 \, m = 15 \, cm$$

$$t = 0.5 \, cm$$

from density tables

$$\rho_{air} = 1.293 \times 10^{-3} \, g/cm^3 \qquad \text{at STP}$$

$$\rho_{steel} = 7.8 \, gm/cm^3$$

Therefore,

$$\frac{M_{os}}{M_t} = \frac{(1.293 \times 10^{-3})(15)^2}{(7.8)(15^2 - 14.5^2)}$$

$$= 2.53 \times 10^{-3}$$

Step 2. Calculate pressure ratio $\bar{p}$ from equation

$$\bar{p} = \frac{P_o}{1.01 \times 10^5}$$

from assumptions

$$P_o = 7.0 \times 10^7 \, Pa$$

$$\bar{p} = \frac{7.0 \times 10^7}{1.01 \times 10^5} = 693$$

Step 3. From Figure 4-10 for a vessel of radius closest to the vessel considered, find V for M_{os}/M_t ratio most nearly above and below the value of Step 1 for the $\bar{p}$ of Step 2. This is:

$$\bar{p} = 693$$

$M_1 = (M_{os}/M_t) \text{ below} = 1.73 \times 10^{-3}$, $\overline{V}_1 = 1.05$

$M_2 = (M_{os}/M_t)_2 = 2.53 \times 10^{-3}$, $\overline{V}_2 = ?$

$M_3 = (M_{os}/M_t) \text{ above} = 5.19 \times 10^{-3}$, $\overline{V}_3 = 1.38$

<u>Step 4.</u> Find $\overline{V}_2$ by linear interpolation from equation

$$\overline{V}_2 = (\overline{V}_3 - \overline{V}_1) \left(\frac{M_2 - M_1}{M_3 - M_1} \right) + \overline{V}_1$$

$$\overline{V}_2 = (1.38 - 1.05) \left(\frac{2.53 - 1.73}{5.19 - 1.73} \right) + 1.05 = 1.13$$

<u>Step 5.</u> Multiply V_2 by the a_{os} value given in the figure to obtain the initial fragment velocity

$$V_i = \overline{V}_2 \cdot a_{os} = (1.13)(3.31 \times 10^2 \text{ m/s}) = 375 \text{ m/s}$$

The initial fragment velocity is 373 m/s (1220 ft/sec).

Example 2. For Cylinders

Assume same conditions as Example 1, but the vessel contains helium.

<u>Step 1.</u> Calculate mass ratio M_{os}/M_t from equation

$$\frac{M_{os}}{M_t} = \frac{R^2 \, \rho_{He}}{[R^2 - (R - t)^2] \, \rho_{steel}}$$

$$\rho_{helium} = 0.1785 \times 10^{-3} \text{ gm/cm}^3 \quad \text{at STP}$$

Other values as in Example 1.

$$\frac{M_{os}}{M_t} = \frac{(0.1785 \times 10^{-3})(15)^2}{(7.8)(15^2 - 14.5^2)} = 3.49 \times 10^{-4}$$

Step 2. Same as in Example 1, $\bar{p} = 693$.

Step 3. From Figure 4-14 for a tank of radius closest to the tank considered find $\bar{V}$ for M_{os}/M_t ratio most nearly above and below the value of Step 1 for the $\bar{p}$ of Step 2. This is

$$M_1 = (M_{os}/M_t) \text{ below} = 2.32 \times 10^{-4}, \quad \bar{V}_1 = 0.67$$

$$M_2 = (M_{os}/M_t) = 3.49 \times 10^{-4}, \quad \bar{V}_2 = ?$$

$$M_3 = (M_{os}/M_t) \text{ above} = 6.95 \times 10^{-4}, \quad \bar{V}_3 = 0.41$$

Step 4. Find $\bar{V}_2$ by linear interpolation from equation

$$\bar{V}_2 = (\bar{V}_3 - \bar{V}_1) \left(\frac{M_2 - M_1}{M_3 - M_1} \right) + \bar{V}_1$$

$$\bar{V}_2 = (0.67 - 0.41) \left(\frac{3.49 - 2.32}{6.95 - 2.32} \right) + 0.41 = 0.48$$

Step 5. Multiply V_2 by the a_{os} value given in the figure to obtain the initial fragment velocity

$$V_i = \bar{V}_2 a_{os} = (0.48)(963 \text{ m/s})$$

$$= 458 \text{ m/s}$$

The initial fragment velocity is 458 m/s (1500 ft/sec).

4-3   Estimate of Initial Velocities of Fragments from Spheres and Cylinders Bursting into Two Equal Halves

The method developed by Taylor and Price[2] for calculating velocities of fragments from bursting spherical reservoirs was modified to provide velocity calculations for fragments from both cylindrical and spherical gas vessels. The development of the necessary equations, the numerical iteration method used to simultaneously solve the resulting

differential equations, the computer program and results of the analysis are all explained in considerable depth for the interested reader in Appendix 4C. Only assumptions and conclusions necessary for determining fragment velocities are included here.

The assumptions relevant to the calculation of fragment velocity in this section follow. More complete listing of assumptions are contained in Appendix 4C, but only essential elements are contained here. The pertinent assumptions upon which conclusions which follow are based are:

(1)   The vessel with gas under pressure breaks into two equal halves along a plane perpendicular to the cylindrical axis, and the two container fragments are driven in opposite directions.

(2)   The thickness of the containment vessel is uniform.

(3)   The containment vessel has hemispherical end caps.

(4)   Vessels are made of Titanium or Titanium alloys (material used for containment vessels in flight-weight vehicles) and has a length-to-diameter (L/D) ratio of 10.0.

(5)   Contained gases are either air, carbon dioxide (CO_2) or hydrogen (H_2).

The summarized calculations are presented in nondimensionalized units in order to condense and simplify the determination of fragment velocity. The pertinent nondimensional (unitless) relations are defined as follows:

(1)   Nondimensional pressure

$\overline{P}$ = initial pressure/atmospheric pressure (or P/p_o) where the change in atmospheric pressure p_o with altitude is shown in Figure 4-17.

(2)   Nondimensional thickness

h/D = cylinder thickness/cylinder diameter

(3)   Nondimensional length

L/D = total length/cylinder diameter
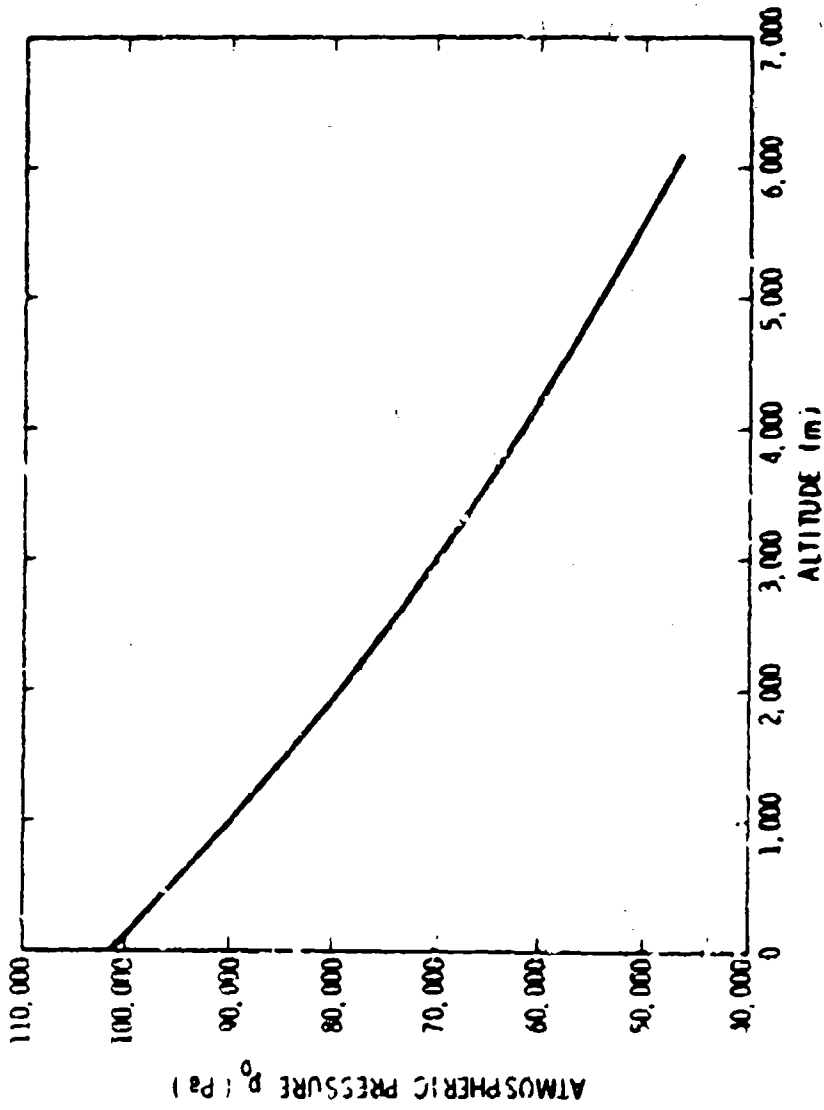
Figure 4-17. Atmospheric Pressure vs Altitude

(4)   Nondimensional velocity

$\overline{V}$ = final velocity/sound speed of gas (or V/a_o) where
V is the velocity of the fragment and a_o is sound speed.

The sound speeds a_o for the gases mentioned are:

Air - 344 m/s (13 550 in/sec)

CO_2 - 258 m/s (10 150 in/sec)

H_2 - 1270 m/s (50 000 in/sec)

Figures 4-18 through 4-20 contain plots of $\overline{V}$ versus $\overline{P}$ for air, carbon dioxide and hydrogen gases, respectively, the L/D ratios being held constant at 10.0 and as many as three curves, one for each h/D ratio (0.001, 0.01 and 0.1), being plotted on a single figure. Nondimensional velocity and pressure combinations for intermediate values of h/D can be approximated from these figures. Figure 4-21 contains a plot of $\overline{V}$ versus L/D. It should be noted that, for high nondimensional pressures ($\overline{P} \simeq 4080$), $\overline{V}$ is essentially independent for values of L/D from 1.0 (sphere) to 10.0.

The procedure for determining the velocity of fragments consisting of halves of spheres or cylinders made of Titanium or Titanium alloys and containing air, carbon dioxide or hydrogen gas under pressure, is as follows:

(1)   Determination atmospheric pressure p_o (see Figure 4-17).

(2)   Calculate nondimensional pressure $\overline{P}$:

$$\overline{P} = P/p_o$$

(3)   Calculate nondimensional thickness h/D.

(4)   Calculate nondimensional length L/D.
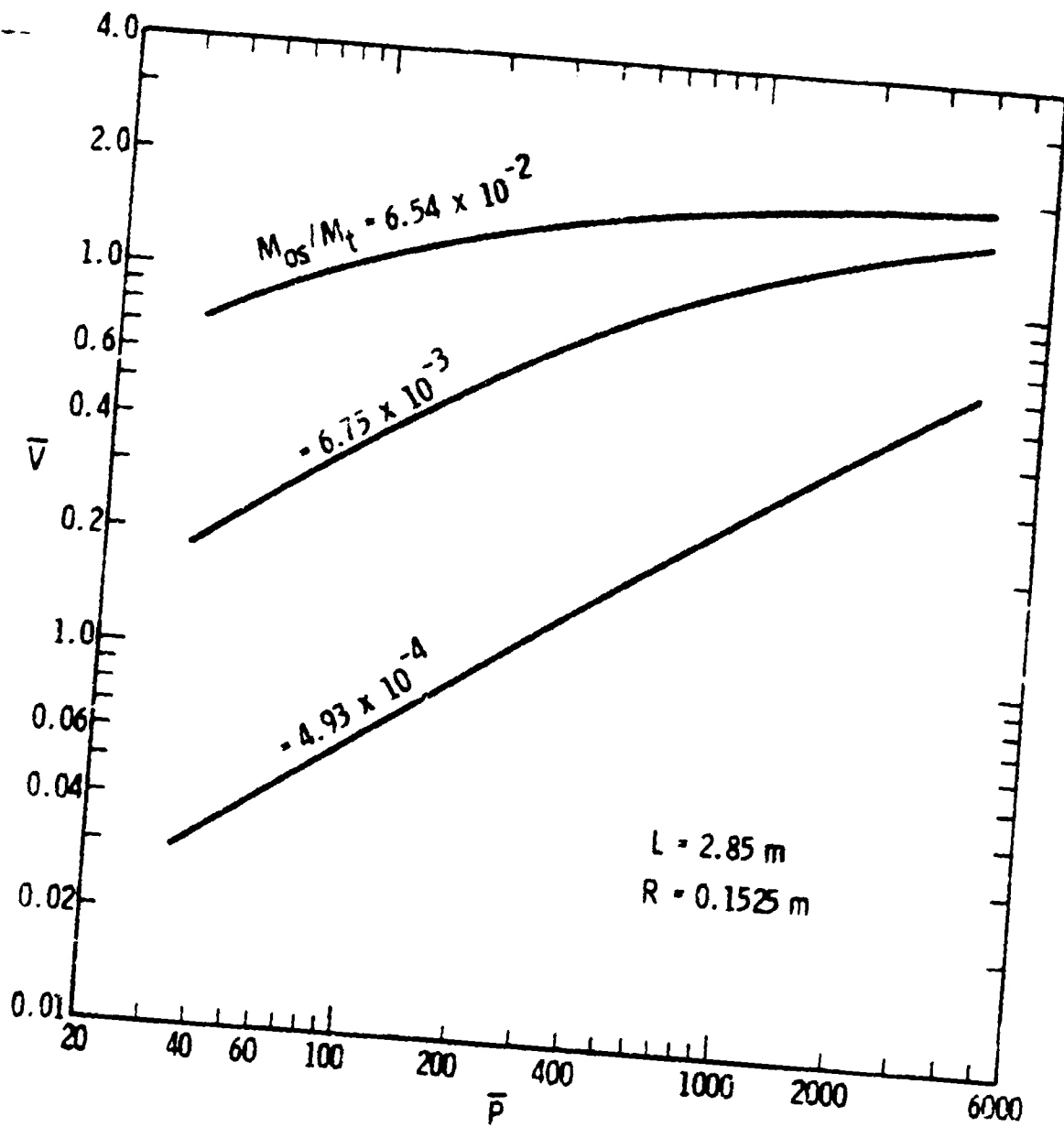
Figure 4-18. Nondimensional Velocity Vs Nondimensional Pressure for Vessels Containing Air
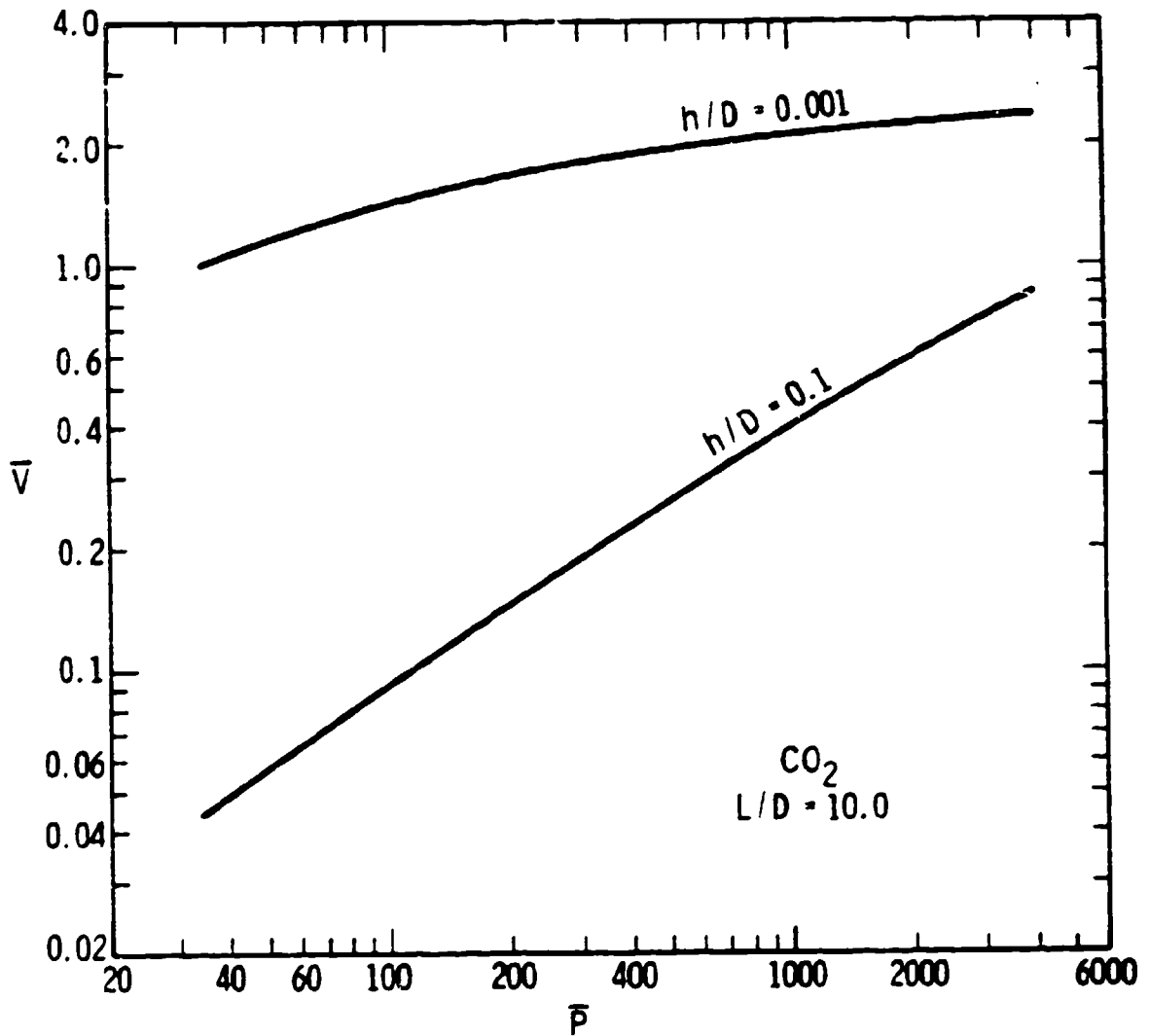
Figure 4-19. Nondimensional Velocity Vs Nondimensional
Pressure for Vessels Containing CO_2
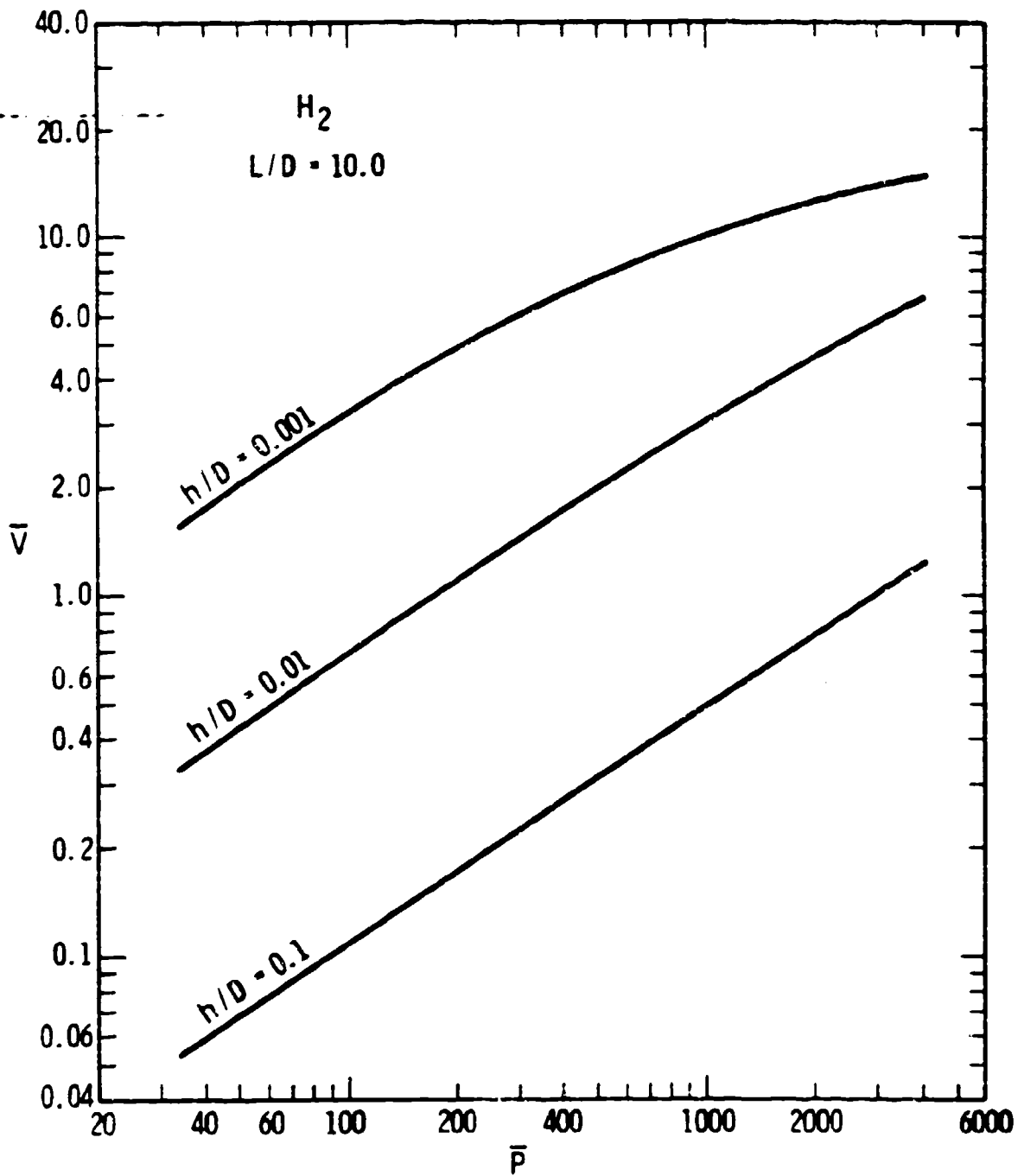
Figure 4-20. Nondimensional Velocity Vs Nondimensional
Pressure for Vessels Containing H_2
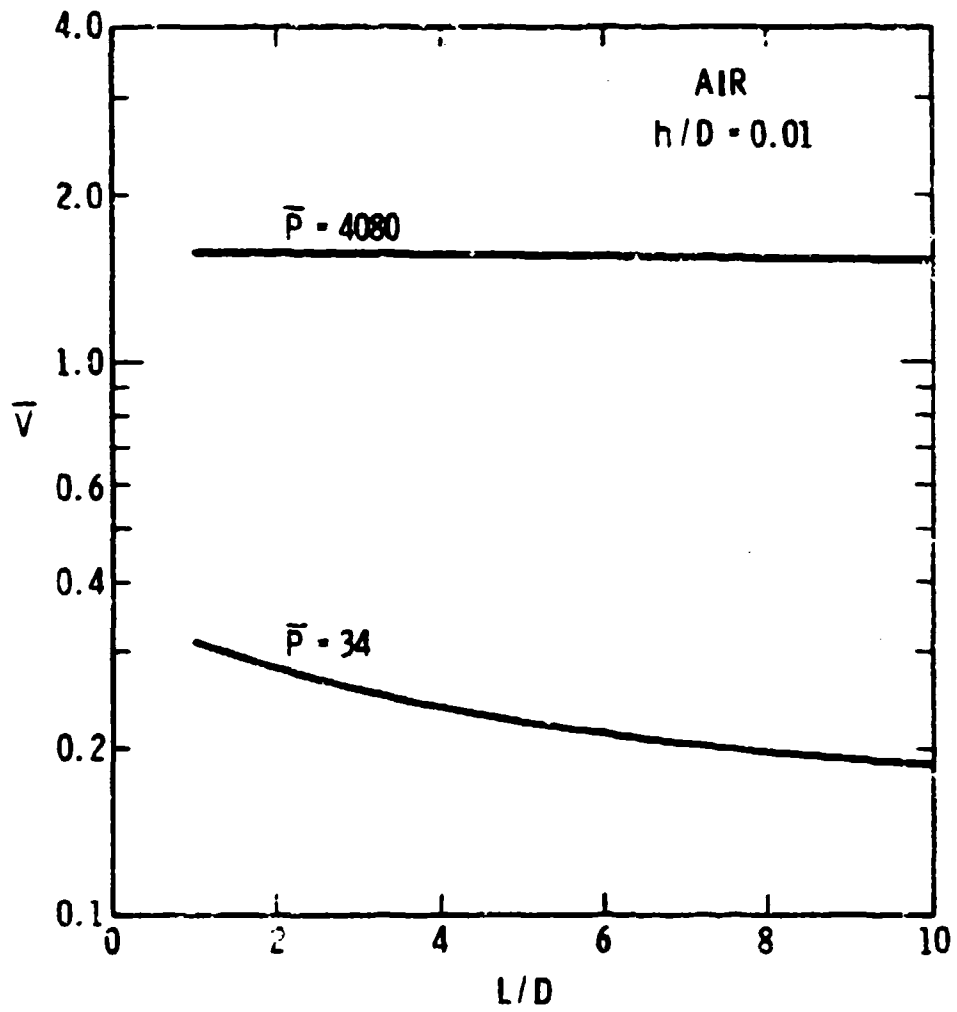
Figure 4-21. Nondimensional Velocity Vs Length-to-Diameter
(L/D) Ratio

(5)   For L/D equal to 10. 0, [*] choose the appropriate figure of Figures 4-13, 4-19 or 4-20 which relate to contained gases of air, carbon dioxide (CO_2) and hydrogen (H_2), respectively, and choose the curve with proper h/D value. Positions of curves for intermediate h/D values can be interpolated.

(6)   Knowing the gas, h/D and $\overline{P}$, find $\overline{V}$ from the figure and calculate velocity V (m/s):

$$V = \overline{V} a_o$$

where a_o 344 m/s (air)

258 m/s (CO_2)

1270 m/s (H_2)

Some examples will help clarify the procedure for calculating fragment velocity.

Example 1:

A pressure vessel made of a Titanium alloy is cylindrical in shape with hemispherical end caps. The vessel is 5 m (16. 4 ft) long and 0.5 m (1. 64 ft) outside diameter. Its thickness is uniform and is 0.5 cm (0. 197 in). Contained gas is air at a pressure of 1.0135×10^7 Pa (1. 47 x 10^3 psi). The vessel is located at sea level. If the vessel splits into two halves along a plane perpendicular to the cylindrical axis, what are the expected velocities of each of the two fragments?

Solution:

(1)   From Figure 4-17,

$$p_o = 1.0135 \times 10^5 \text{ Pa (14. 7 psi)}$$

(2)   Nondimensional pressure $\overline{P}$:

$$\overline{P} = \frac{P}{P_o} = \frac{1.0135 \times 10^7 \text{ Pa}}{1.0135 \times 10^5 \text{ Pa}} = 100$$

(3)   Nondimensional thickness L/D:

$$L/D = \frac{(0.5 \text{ cm})\left(.01\frac{\text{m}}{\text{cm}}\right)}{0.5 \text{ m}} = 0.01$$

(4)   Nondimensional length L/D:

$$L/D = \frac{5\text{m}}{0.5 \text{ m}} = 10.0$$

(5)   The center curve of Figure 4-18 is the appropriate curve for air, L/D of 10.0, and L/D of 0.01.

(6)   From Figure 4-18 and $\overline{P}$ of 100, one finds that

$$V \simeq 0.36$$

or

$$V = (0.36)(344 \text{ m/s}) \simeq 124 \text{ m/s } (407 \text{ ft/sec})$$

Example 2:

Same as Example 1, except let P be 3.45×10^6 Pa (48.5 psi) and length of the vessel be 1 m (3.28 ft).

Solution:

(1) $p_o = 1.0135 \times 10^6$ Pa (see Example 1)

(2) $\overline{P} = \dfrac{3.45 \times 10^5 \text{ Pa}}{1.0135 \times 10^5 \text{ Pa}} \simeq 34$

(3) $h/D = 0.01$ (see Example 1)

(4) $L/D = \dfrac{1\text{m}}{0.5 \text{ m}} = 2$

(5)   Since L/D is not 10.0, Figures 4-18, 4-19, and 4-20 cannot be used. Normally, the fragment velocity could not

be calculated from the information in this chapter. However, Figure 4-21 applies for contained air, h/D of 0.01 and $\overline{P}$ of 34, and can be used.

(6)   From Figure 4-21:

$V \simeq .28$

or

$V = (.28) (344 \text{ m/s}) \simeq 96 \text{ m/s} (315 \text{ ft/sec})$

Example 3:

Same as Example 1 except hydrogen is the contained gas.

Solution:

(1) $p_o = 1.0135 \times 10^5 \text{ Pa}$ (see Example 1)

(2) $P = 100$ (see Example 1)

(3) $h/D = 0.01$ (see Example 1)

(4) $L/D = 10.0$ (see Example 1)

(5)   The center curve of Figure 4-20 is the appropriate curve for hydrogen, L/D of 10.0, and h/D of 0.01.

(6)   From Figure 4-20 and $\overline{P}$ of 100 one finds that

$V \simeq (0.07)$

or

$V \simeq (0.07) (1270 \text{ m/s}) \simeq 89 \text{ m/s} (292 \text{ ft/sec})$

4-4   Determination of Appurtenance Velocity

The method used here to calculate appurtenance velocity is an extension of work performed by Baker, et al.[3] Appendix 4D contains the development of the basic equations as well as a listing of the computer program used to generate nondimensional velocity curves as a function of nondimensional pressure and nondimensional impulse. The interested reader is encouraged to examine the appendix for a better understanding

of the interaction of appurtenances with blast waves. In order to arrive
at values for appurtenance velocity, however, it is not necessary to refer
to the appendix since all of the curves and equations required to calculate
velocity are contained in this section. It is beneficial, however, to keep
in mind that the method used for calculating the velocity of an appurte-
nance assumes that the appurtenance behaves as a rigid body, that none
of the energy in the blast wave is absorbed in breaking the appurtenance
loose from its moorings or deforming it elastically or plastically, and
that gravity effects are ignored during the acceleration phase of the
motion.

The velocity of an appurtenance can be determined from a nondi-
mensional velocity which depends on nondimensional pressure and nondi-
mensional impulse. In functional format

$$\frac{M V a_o}{P_o A (KH + X)} = f \left(\frac{P_s}{P_o} , \frac{C_D I_s a_o}{P_s (KH + X)} \right) \quad (4-1)$$

nondimensional   nondimensional   nondimensional
velocity $\overline{V}$ pressure $\overline{P}_s$ impulse $\overline{I}_s$

where M   is the total mass of the appurtenance

       V   is the velocity of the appurtenance

       a_o is the velocity of sound in air

       P_o is atmospheric pressure

       A   is the mean presented area of the appurtenance

       K   is a nondimensional constant which is 4 for appurtenances
            on the ground and 2 for appurtenances in the air.

       H   is the minimum transverse distance of the mean presented
            area

       X   is the distance from the front of the object to the location
            of its largest cross-sectional area

       P_s is peak incident overpressure

C_D is the drag coefficient

and   ....

I_s is the peak incident specific impulse

The variables can be classified into three major categories:

(1)   static environmental variables (a_o, p_o)

(2)   blast wave variables (P_s, I_s)

(3)   appurtenance variables (M, V, A, K, H, X, C_D)

The static environmental variables, sound speed a_o and atmospheric pressure p_o vary with altitude or location above sea level. This altitude dependency is shown in Figures 4-22 and 4-23. The blast wave variables, peak incident overpressure P_s and specific impulse I_s at specific standoff distances (i.e., distance from center of the explosion to the center of the appurtenance) can be determined from Chapters I and II of this handbook. Appurtenance variables are all associated with the object which may be propelled after interaction with the blast wave. The method for determining the velocity V will be discussed later. The choice of total mass M depends on the volume and density of the object, and non-dimensional constant K depends on its position. Representative values for drag coefficient C_D can be acquired from Figure 4-24. The mean presented area A of the appurtenance depends on its shape. It is the largest projected area of the appurtenance facing the approaching blast wave. The transverse distance H is the minimum dimension of the largest cross-sectional area of the object facing the blast wave. The length X is the distance from the point of the appurtenance which first interacts with the blast wave to the plane containing the largest cross-sectional area facing the approaching blast wave. For objects which have a flat face facing the blast wave, which is also the location of the plane with the largest cross-sectional area, X equals zero (X = 0). Figure 4-25 helps explain the meaning of the various appurtenance variables.

Figure 4-26 is a graphical representation of Equation (1) for various values of nondimensional velocity. The procedure for calculating appurtenance velocity V follows. Care, however, should be taken when interpolating between curves and extending curves. Estimates made by extending the curves to lower nondimensional impulses are especially hazardous.
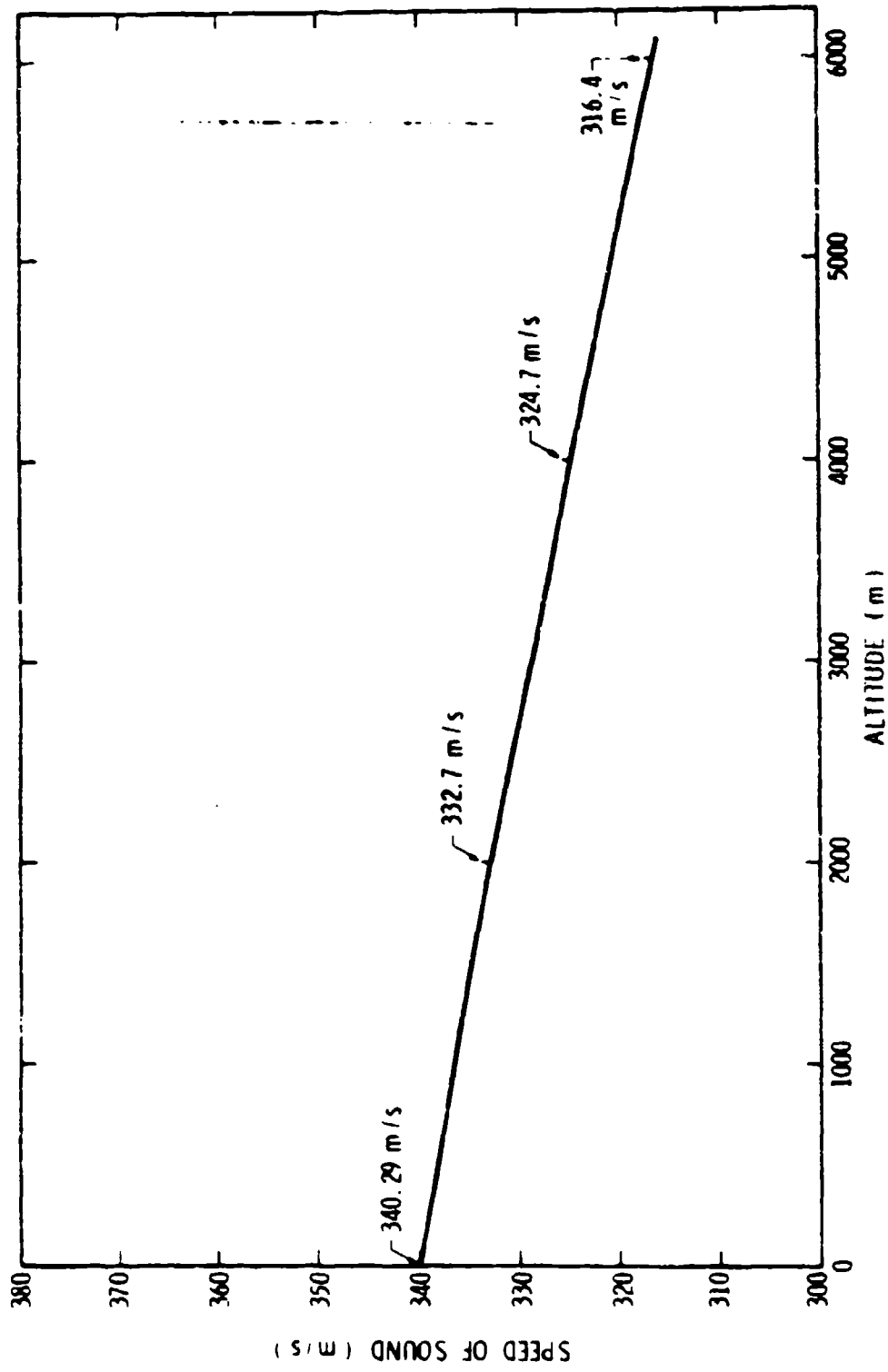
Figure 4-22. Speed of Sound Vs Altitude
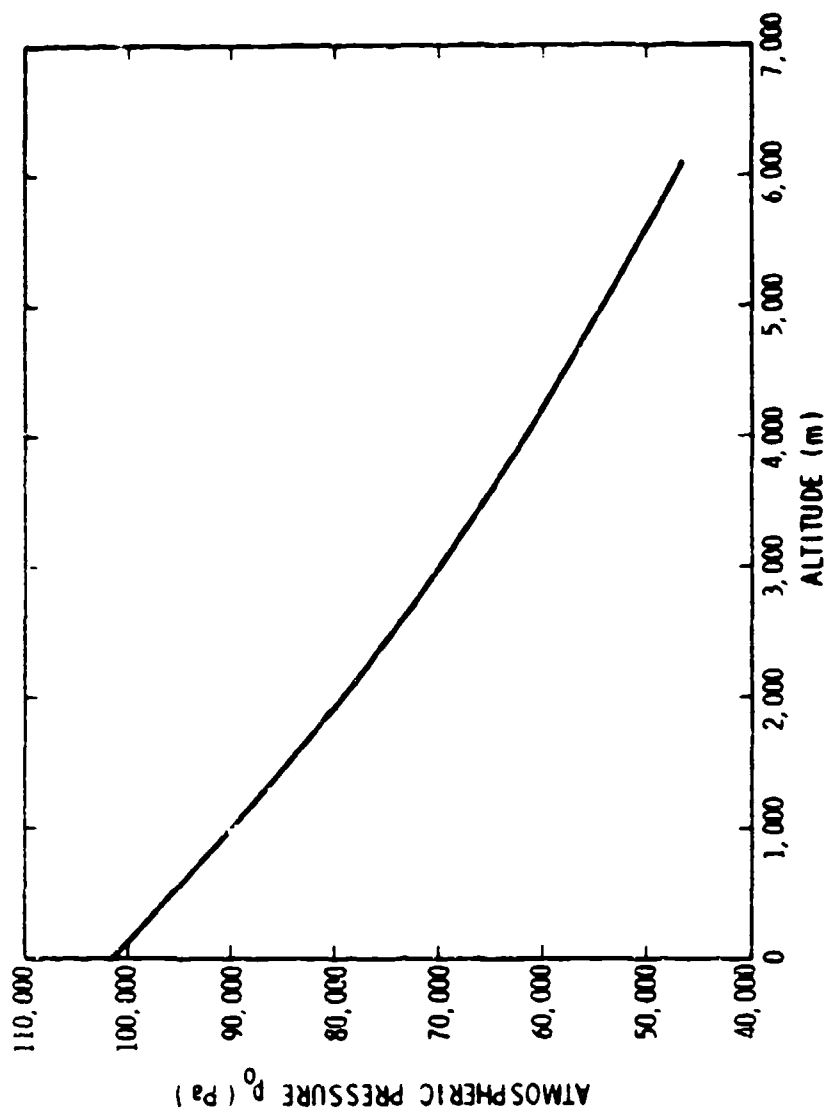
Figure 4-23. Atmospheric Pressure vs Altitude

ATMOSPHERIC PRESSURE P_0 (Pa)

ALTITUDE (m)

(psi = Pa X 1.450 X 10^{-4})

(ft = m X 3.281)
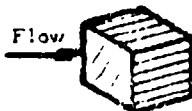
SHAPE	SKETCH	C_D
Right Circular Cylinder (long rod), side-on		1.20
Sphere		0.47
Rod, end-on		0.8?
Disc, face-on		1.17
Cube, face-on		1.0?
Cube, edge-on		0.80
Long Rectangular Member, face-on		2.05
Long Rectangular Member, edge-on		1.55
Narrow Strip, face-on		1.98

Figure 4-24. Drag Coefficients, C_D, of Various Shapes
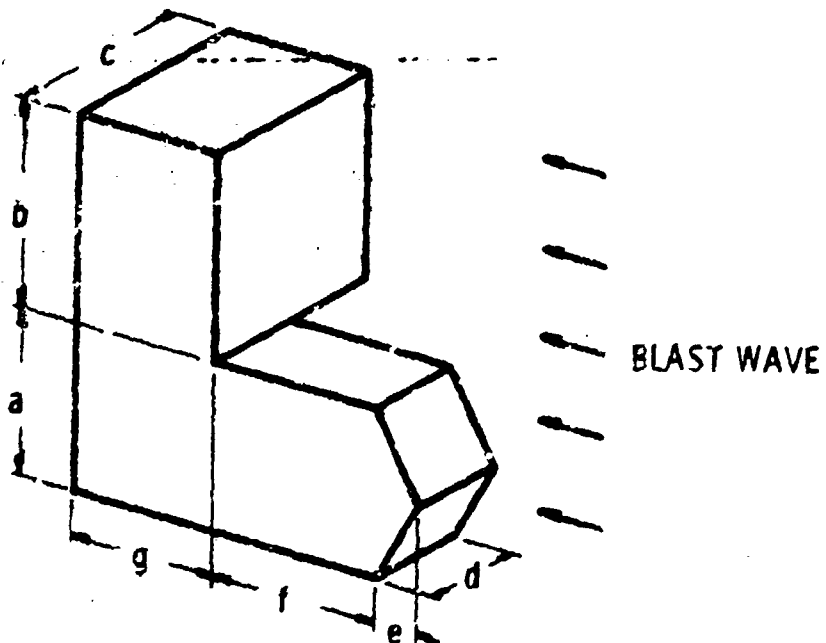
Isometric View of Appurtenance

$$A = bc + ad$$
$$H = d$$
$$X = e + f$$
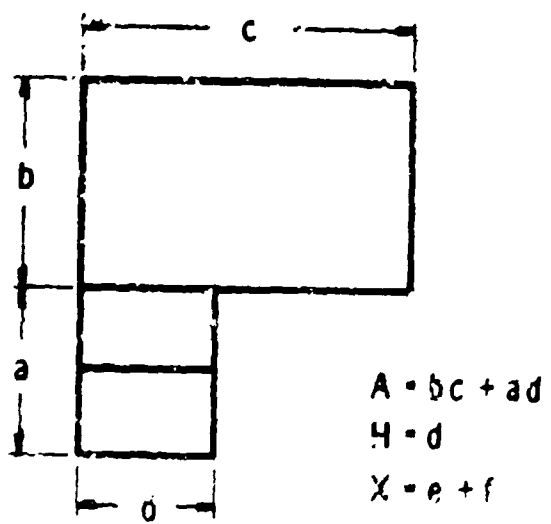
Front View of Appurtenance

Figure 4-25. Pictorial Explanation of Appurtenance
Variables
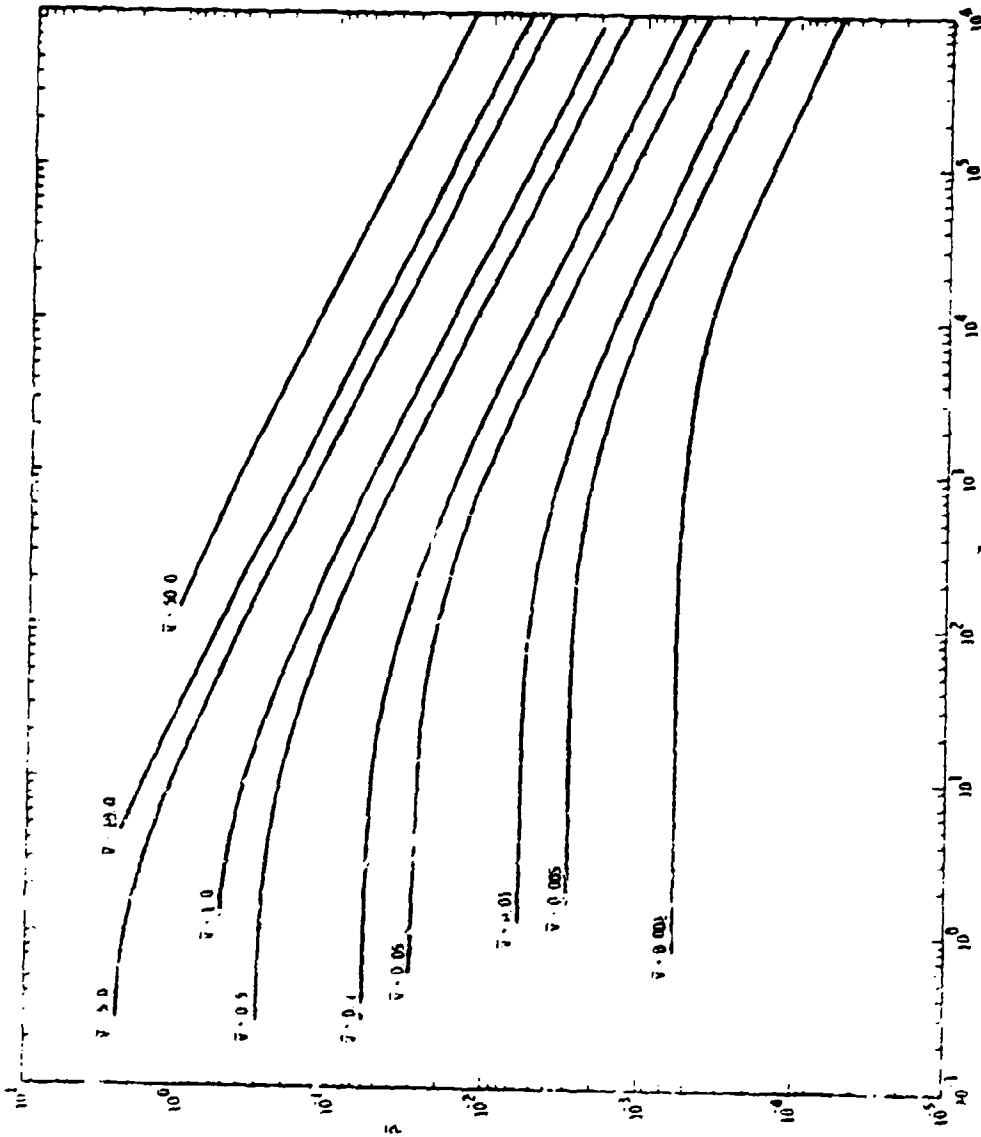
Figure 4-26. Nondimensional Appurtenance Velocity $\bar{V}$ as a Function of Nondimensional Pressure $\bar{P}$ and Nondimensional Impulse $\bar{I}$

(1)   Determine static environment variables, speed of sound
        a_o (m/s) and atmospheric pressure p_o (Pa), from Figures
        4-22 and 4-23, respectively.

(2)   Determine blast wave variables, peak incident overpres-
        sure P_s (Pa) and specific impulse I_s (Pa·s), from
        Chapters I and II.

(3)   Determine appurtenance variables:

        (a)   M - total mass in kilograms

        (b)   A - mean presented area in square meters

        (c)   K - dimensionless constant which equals 4 for
                      appurtenances on the ground and 2 for
                      appurtenances in the air

        (d)   H - minimum transverse distance of the mean
                      presented area in meters

        (e)   X - distance from the front of the appurtenance
                      to the location of its largest cross-sectional
                      area in meters

        (f) C_D - nondimensional drag coefficient of the
                      appurtenance (see Figure 4-24)

(4)   Calculate nondimensional pressure $\overline{P}$ where

$$\overline{P}_s = \frac{P_s}{P_o}$$

(5)   Calculate nondimensional impulse $\overline{I}_s$ where

$$\overline{I}_s = \frac{C_D I_s a_o}{P_s (KH + X)}$$

(6)   Find the location of the point $(\overline{I}_s, \overline{P}_s)$ on the graph in
        Figure 4-26 and estimate a value for nondimensional
        velocity $\overline{V}$ from the curves of constant nondimensional
        velocity.

(7)   Calculate appurtenance velocity V (in m/s) where

$$\overline{V} = \frac{M V a_o}{p_o A (KH + X)}$$

and thus

$$V = \frac{\overline{V} p_o A (KH + X)}{M a_o}$$

Some examples will clarify the procedure.

Example 1:

Assume that an explosion occurs at sea level. A cubical cement block with a side facing the blast front is located at such a distance from the source of the explosion that it is exposed to an incident peak overpressure P_s of 1.4×10^5 Pa (1.97 psi) and an incident specific impulse I_s of 1.9×10^4 Pa·s (0.267 psi/sec). The density of the cement block is 1.792×10^4 kg/m^3 (0.647 lb$_m$/in^3).

Solution:

(1)   Static environmental variables:

$a_o = 340$ m/s

$p_o = 1.0135 \times 10^5$ Pa

(2)   Blast wave variables:

$P_s = 1.0 \times 10^5$ Pa

$I_s = 1.9 \times 10^4$ Pa·s

(3)   Appurtenance variables:

(a)   M = density x volume

$= 1.792 \times 10^4$ kg/m^3 x (2.5 m)^3

$= 2.8 \times 10^5$ kg

(b) $A = (2.5 \text{ m})^2$

          $A = 6.25 \text{ m}^2$

(c)   Appurtenance is on the ground. Therefore,

          $K = 4$

(d) $H = 2.5 \text{ m}$

(e) $X = 0 \text{ m}$ since the portion of block facing the
          blast wave is flat.

(f)   Drag coefficient from Figure 4-24

          $C_D = 1.05$

(4) Nondimensional pressure

$$\overline{P}_s = \frac{P_s}{P_o} = \frac{1.0 \times 10^5 \text{ Pa}}{1.0135 \times 10^5 \text{ Pa}} = 0.99$$

(5) Nondimensional impulse

$$\overline{I}_s = \frac{C_D I_s a_o}{P_s (KH + X)} = \frac{(1.05)(1.9 \times 10^4)(340)}{(1.0 \times 10^5)[(4)(2.5) + (0)]} = 6.8$$

(6) From Figure 4-26, the point $(\overline{I}_s, \overline{P}_s)$ or (6.8, 0.99) is
located very close to the $\overline{V} = 5.0$ line

(7) Appurtenance velocity

$$V = \frac{\overline{V} P_o A (KH + X)}{M a_o}$$

$$V = \frac{(5)(1.0135 \times 10^5)(6.25)[(4)(2.5) + (0)]}{(2.8 \times 10^5)(340)} =$$

0.33 m/s (1.08 ft/sec)

Example 2:

Assume an upright cylindrical pole weighing 10.0 kg $(22$ lb$_m)$ with radius of 0.01 m (0.0323 ft) and length of 4 m (13.1 ft) is subjected to the same blast parameters as mentioned in Example 1. The blast is incident on the curved portion of the pole.

Solution:

(1) Static environmental variables:

$$a_o = 340 \text{ m/s}$$

$$p_o = 1.0135 \times 10^5 \text{ Pa}$$

(2) Blast wave variables:

$$P_s = 1.0 \times 10^5 \text{ Pa}$$

$$I_s = 1.9 \times 10^4 \text{ Pa} \cdot \text{s}$$

(3) Appurtenance variables:

    (a) $M = 10.0$ kg

    (b) $A = 2 \times$ radius $\times$ length

             $A = (2)(0.01)(4)$

             $A = 0.08 \text{ m}^2$

    (c) $K = 4$

    (d) $H = 2r = (2)(0.01) = 0.02$ m

    (e) $X = r = 0.01$ m

    (f) $C_D =$ (from Figure 4-24) $= 1.20$

(4) $\quad \overline{P}_s = \dfrac{P_s}{P_o} = \dfrac{1.0 \times 10^5}{1.0135 \times 10^5} \simeq 0.99$

$$(5) \quad \bar{I}_s = \frac{C_D I_s a_o}{p_s (KH + X)} = \frac{(1.20)(1.9 \times 10^4)(340)}{(1.0 \times 10^5)[(4)(0.02) + (0.01)]}$$

$$= 8.61$$

(6) Figure 4-26, the point $(\bar{I}_s, \bar{P}_s)$ or (8.61, 0.99) is located above the $\bar{V} = 50.0$ line at a location where one might expect $\bar{V} \simeq 200$.

(7) Appurtenance velocity

$$V = \frac{\bar{V} p_o A (KH + X)}{M a_o}$$

$$V \simeq \frac{(200)(1.0135 \times 10^5)(0.08)[(4)(0.02) + (0.01)]}{(10)(340)}$$

$$V \simeq 42.9 \text{ m/s (141 ft/sec)}$$

4-5   Methods for Computing Fragment Ranges and Impact Conditions

Two methods have been developed to estimate the range and terminal velocities of fragments. They depend on the fragment shapes. In the first method, the fragment is assumed to have a disc shape with a diameter at least five times greater than the thickness of the fragment. For these fragments lift effects are taken into consideration. A second method may be used where fragments are "chunky" shaped. These fragments may be represented by a sphere or cube where no single linear dimension can be said to be very much greater than any other. For these fragments lift forces are neglected and only drag forces are considered.

To estimate fragment ranges, the following techniques may be used based on Figures 4-27 through 4-30 which have been generated by computer codes. The codes (FRISB and TRAJE) and their underlying analysis are discussed in Appendix 4E. To determine fragment terminal velocities, data must be input to the codes themselves.
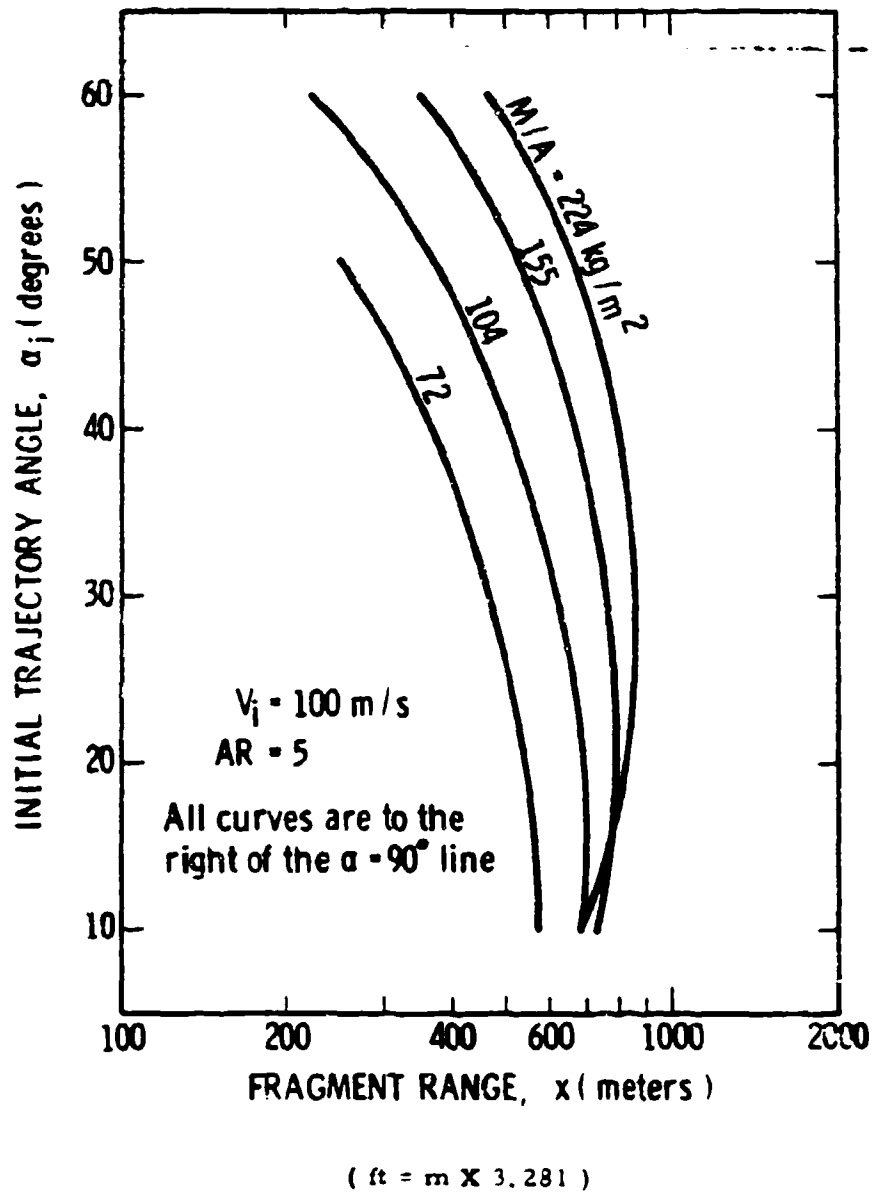
Figure 4-27. Disc Fragment Range for
$V_i = 100$ m/s , AR = 5
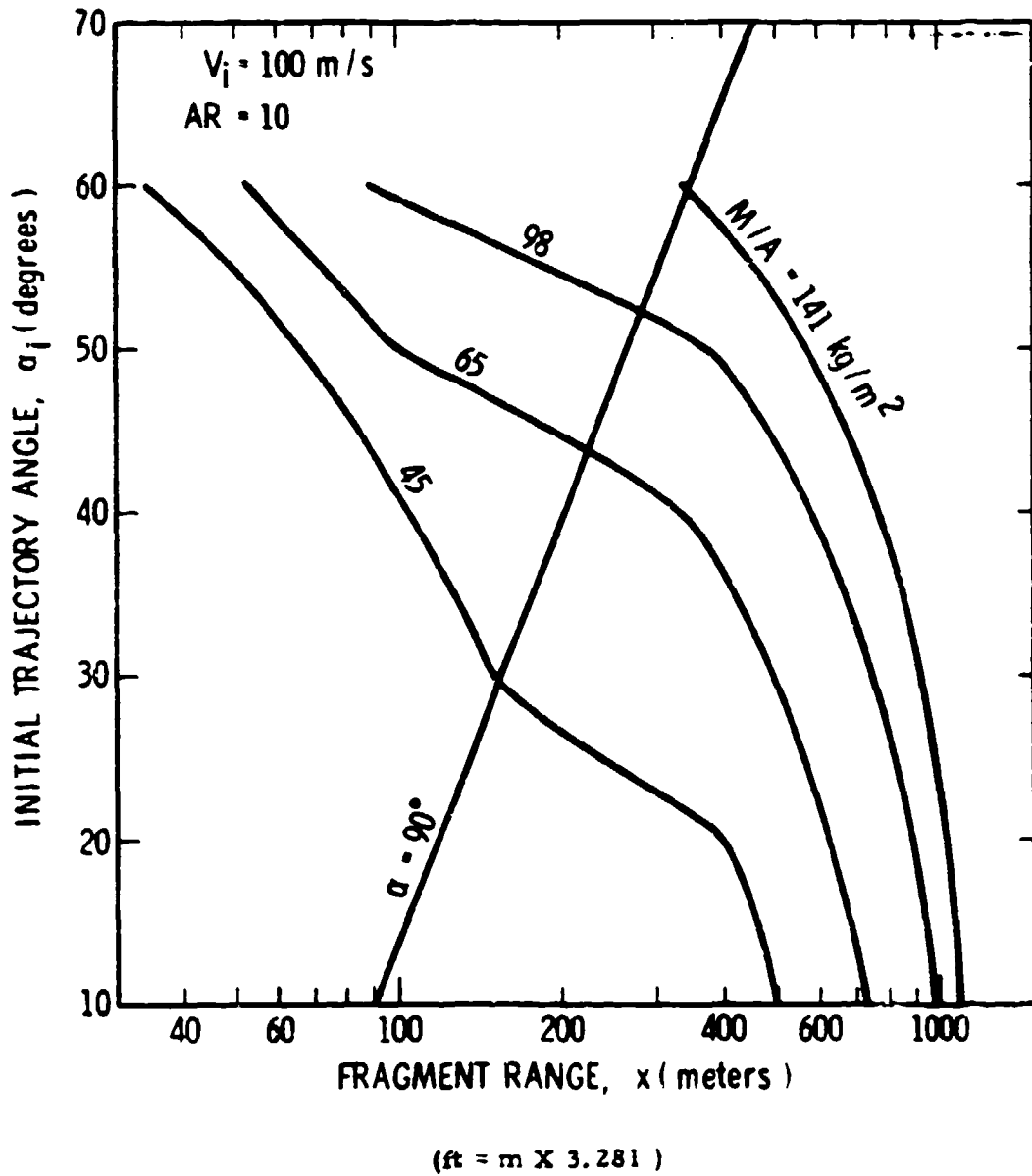
Figure 4-28. Disc Fragment Range for
$V_i = 100$ m/s, AR = 10

$V_i = 150 \text{ m/s}$
$AR = 5$

INITIAL TRAJECTORY ANGLE, σ_i (degrees)

$\alpha = 90°$

$M/A = 224 \text{ kg/m}^2$

155

104

72

FRAGMENT RANGE, x (meters)
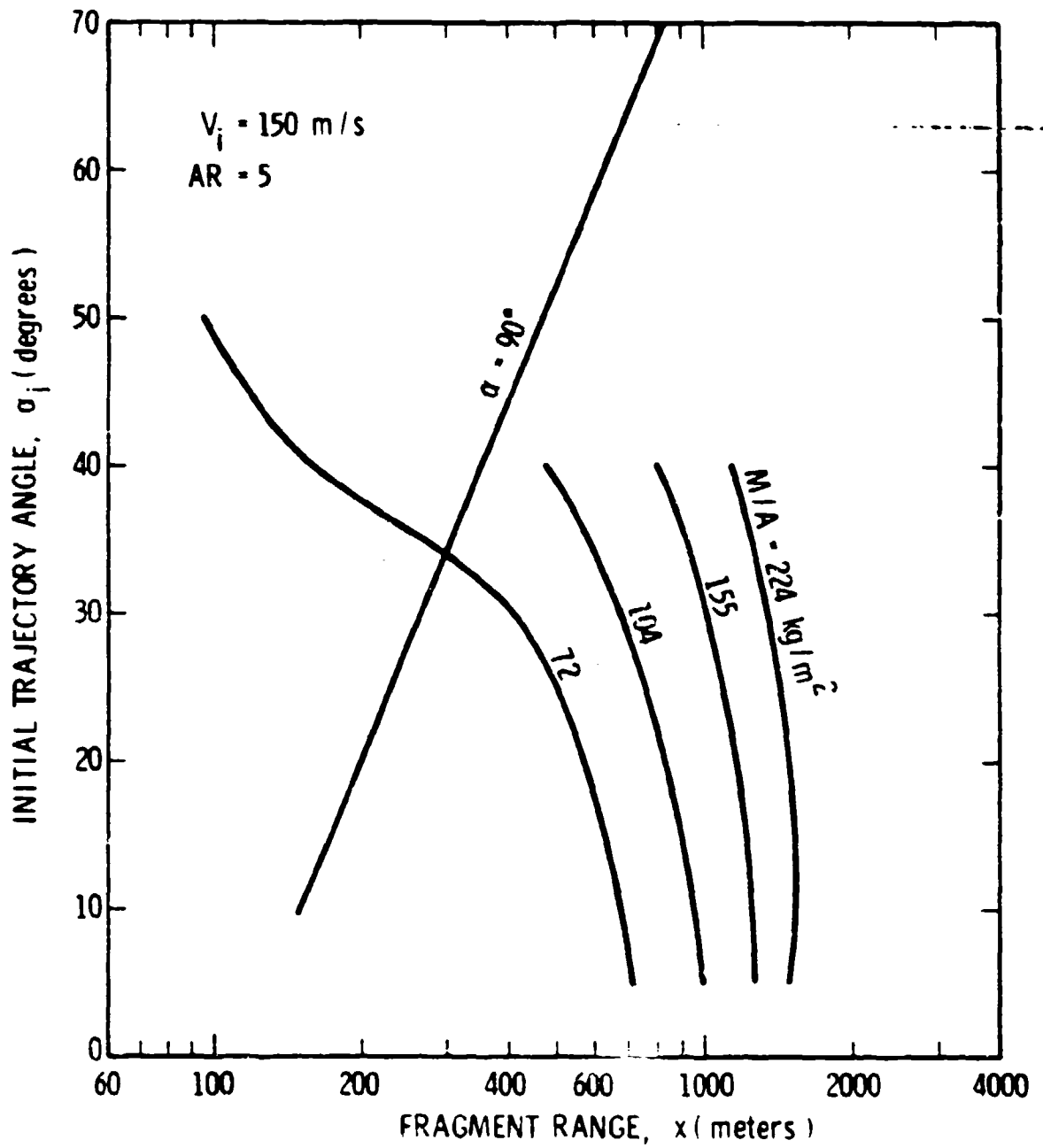
(ft = m X 3.281)

Figure 4-29. Disc Fragment Range for
$V_i = 150 \text{ m/s}$, AR = 5

Figure 4-30. Disc Fragment Range for
$V_i = 150$ m/s, AR = 10
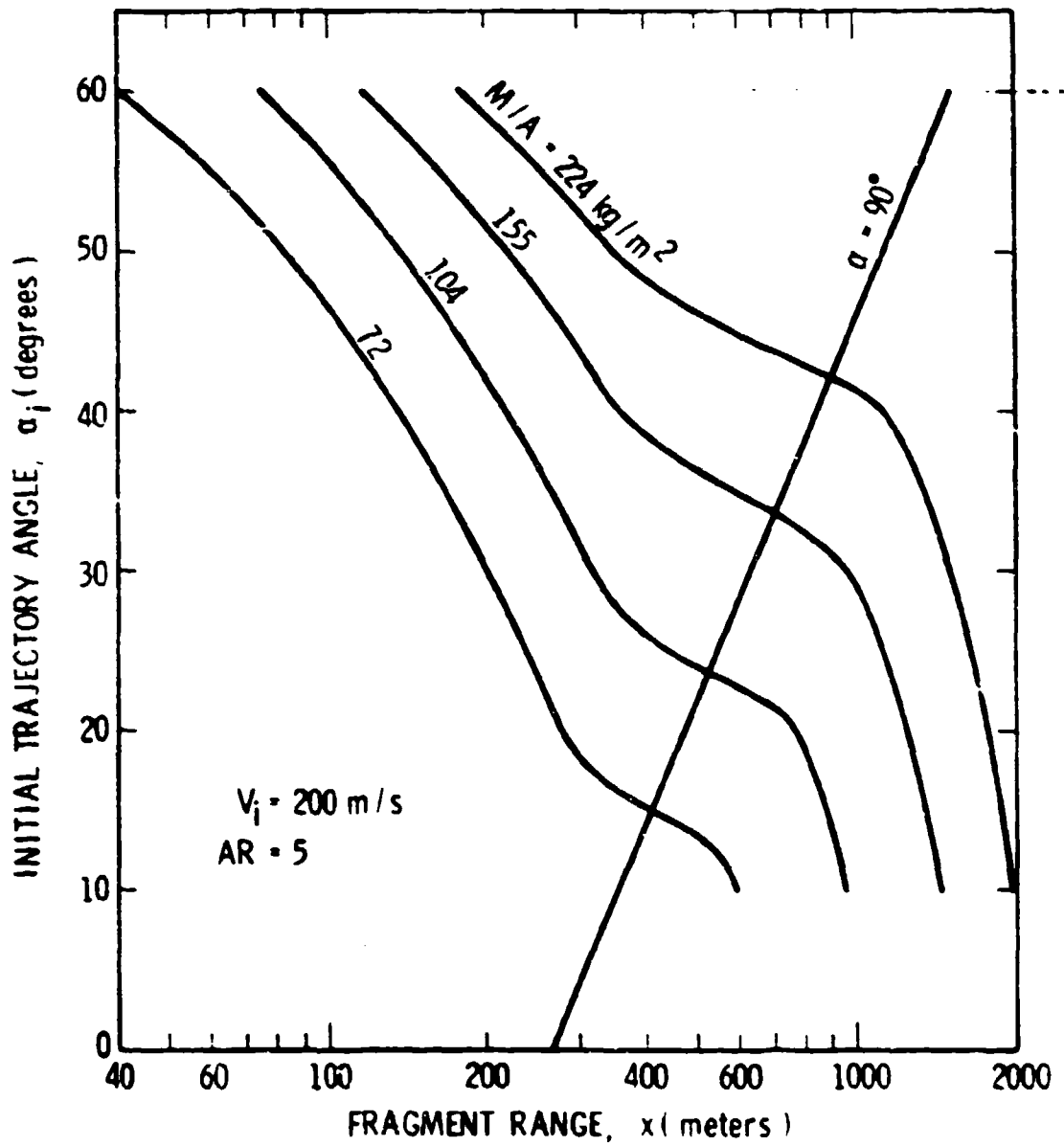
(ft = m X 3.281)

Figure 4-31. Disc Fragment Range for
$V_i = 200$ m/s, AR = 5
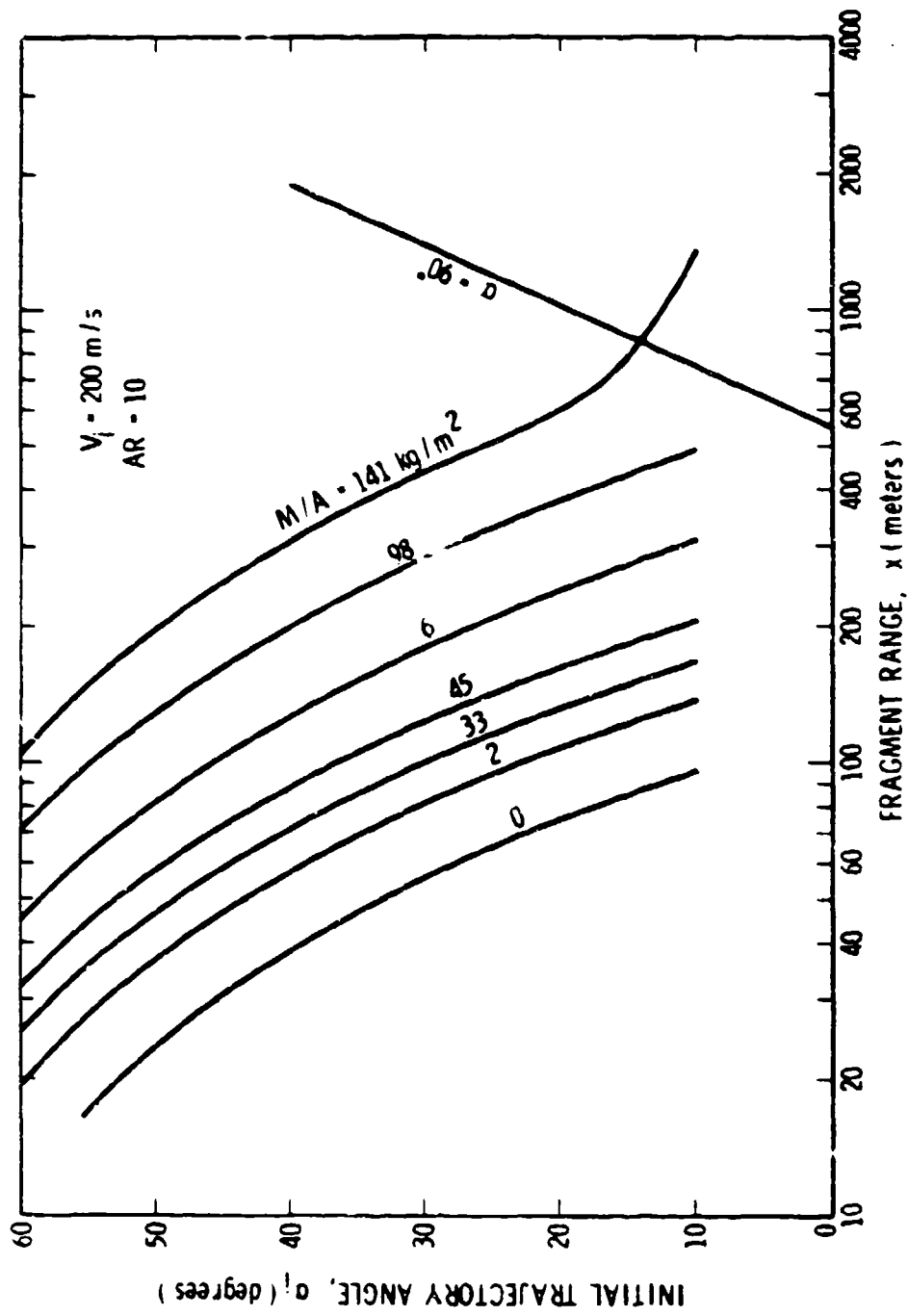
(ft = m X 3.281)

Figure 4-32. Disc Fragment Range for $V_i = 200$ m/s, AR = 10

$$(ft = m \times 3.281)$$

Chart labels:

INITIAL TRAJECTORY ANGLE, a_i (degrees)

FRAGMENT RANGE, x (meters)

$V_i = 200$ m/s
AR = 10

$M/A = 141$ kg/m^2

98

6

45

33

2

0

$D = 90.$
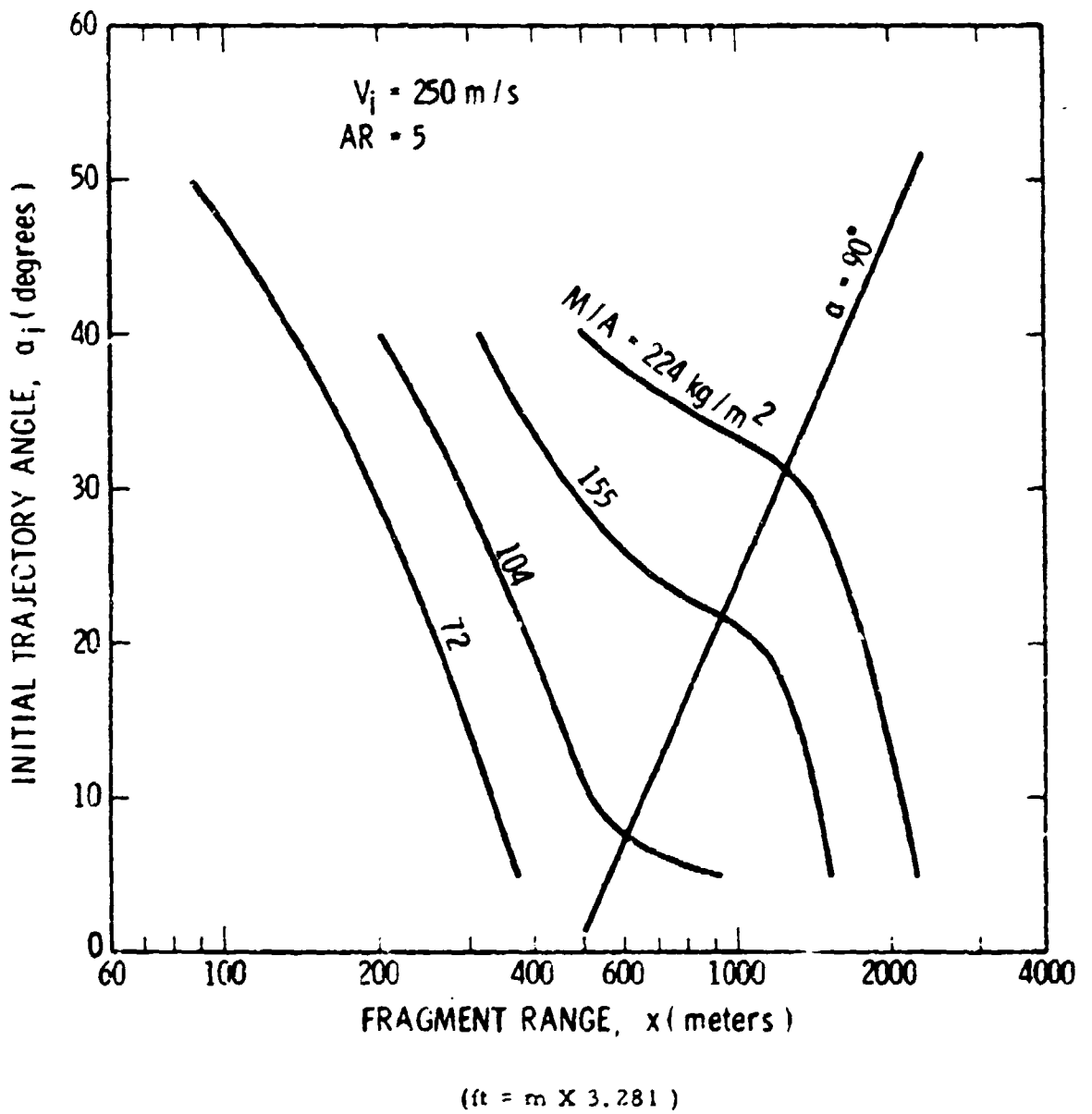
Figure 4-33. Disc Fragment Range for
$V_i = 250$ m/s, AR = 5
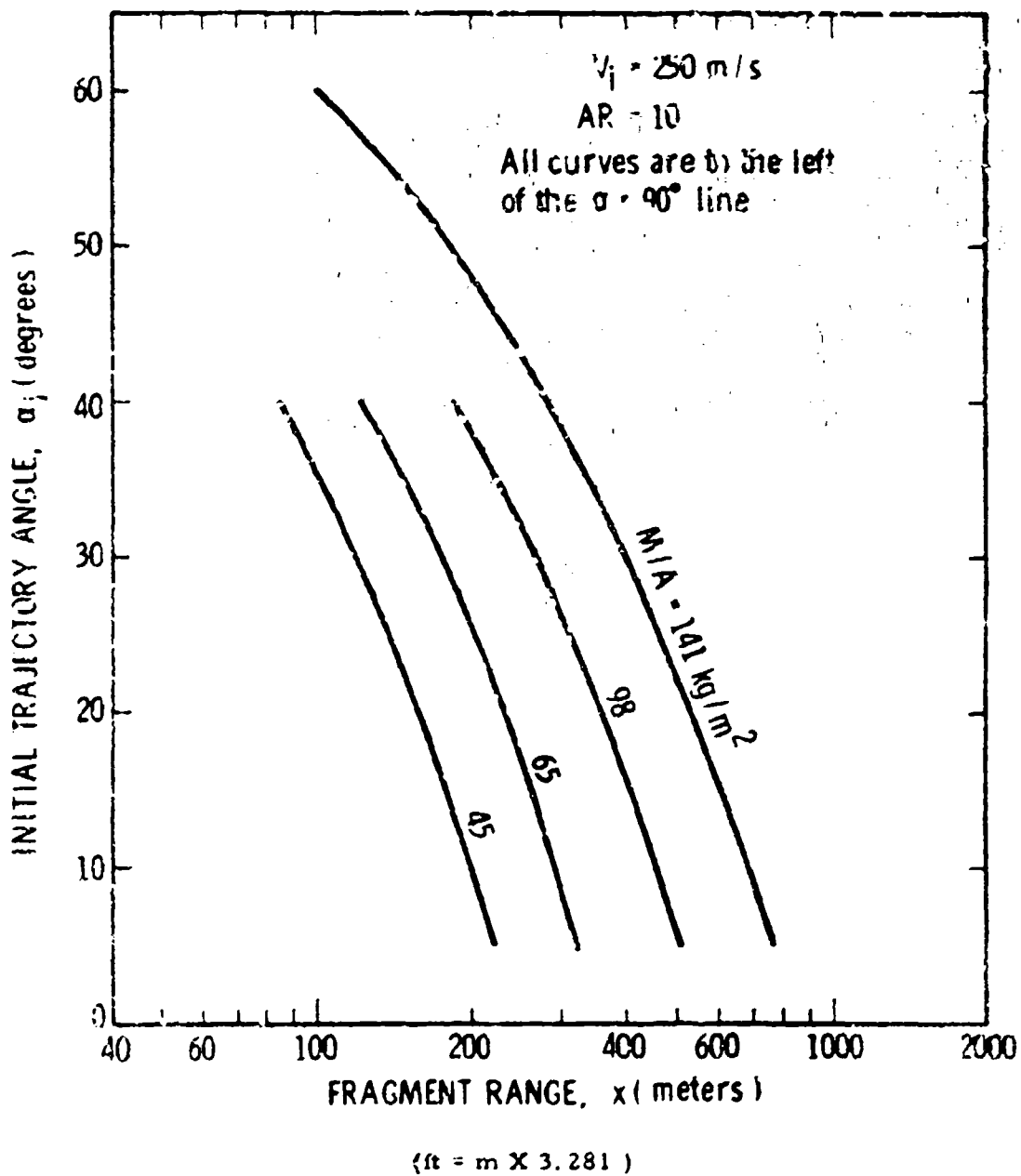
Figure 4-34. Disc Fragment Range for
V_i = 250 m/s, AR = 10
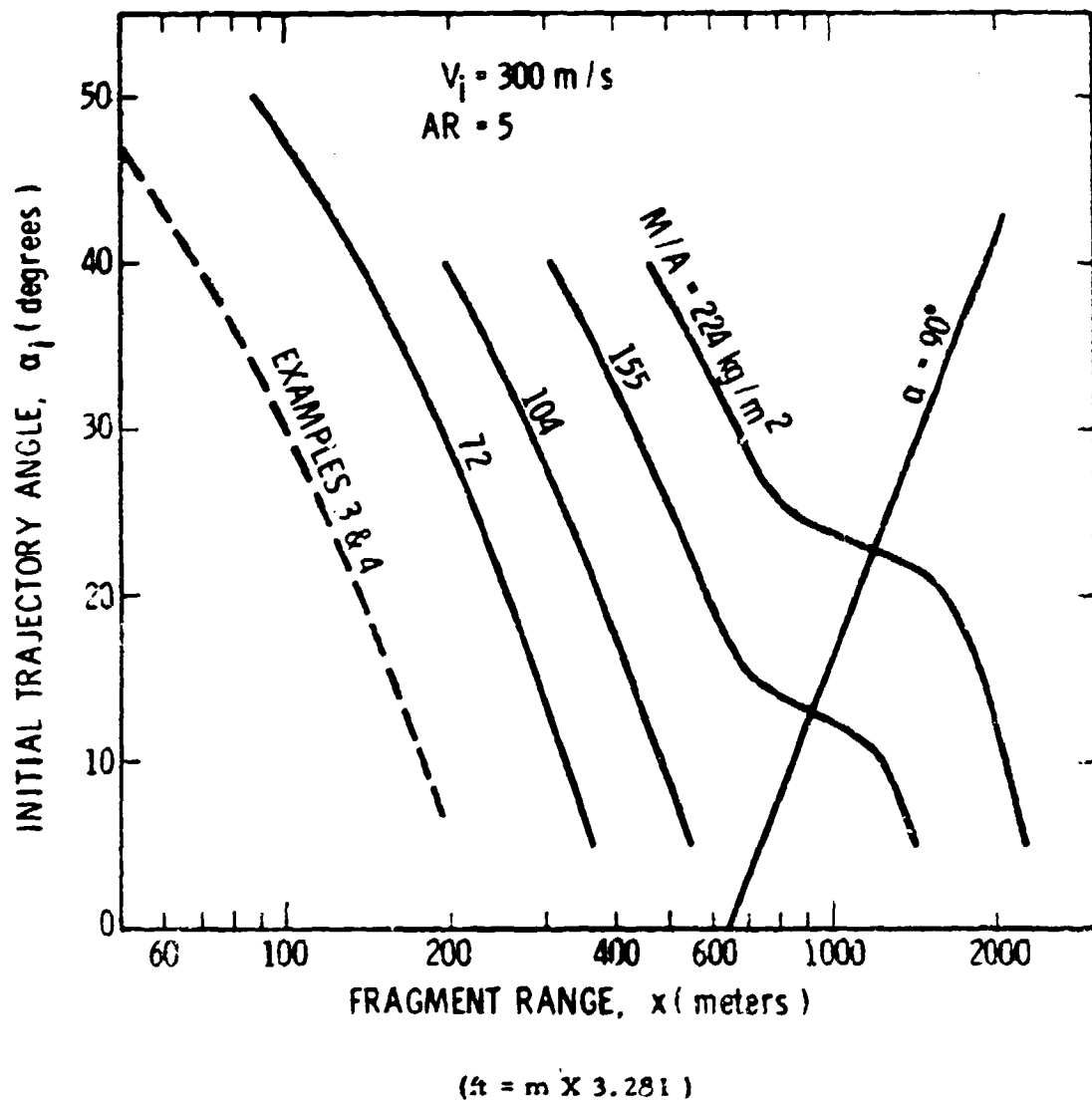
Figure 4-35. Disc Fragment Range for $V_i = 300$ m/s, AR = 5
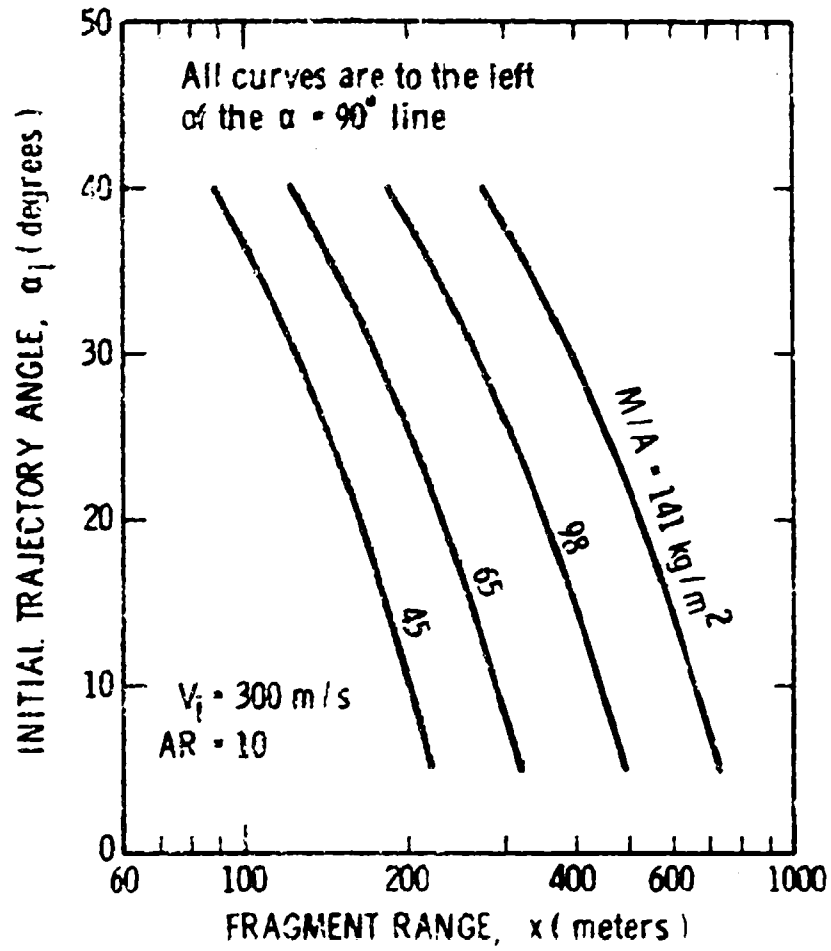
($ft = m \times 3.281$)

Figure 4-36. Disc Fragment Range for
$V_i = 300$ m/s, AR = 10

4-5.1 Lifting Fragments

Where fragments from bursting vessels are determined to be disc shaped, the fragment could conceivably fly or lift in much the same manner as a Frisbee. If this occurs the fragment may go further than one without lift. A computer program (FRISB) was written to determine the trajectory of a flying disc generated by an explosion. Details of the FRISB code are shown in Appendix 4E.

Several independent variables govern the flight of a disc fragment. To determine the effects of these variables on the fragment trajectory, a number of sample cases were analyzed by the FRISB code. A list of the input variables for the sample cases is presented in Table 4-1. Plots of maximum range versus initial trajectory angle are shown for those values of the independent variables in Figures 4-27 through 4-36. These graphs may be used to predict the maximum range of fragments having similar properties.

The following information must be known about the fragment to calculate its range using the figures:

1. initial fragment velocity - V_i (m/s)

2. mass of the fragment - M (kg)

3. diameter of the fragment - d (m)

4. thickness of the fragment - t (m)

5. planform or top surface area of fragment - A (m^2)

6. initial trajectory angle of the fragment - σ_i (rad)

The procedure for determining fragment range is:

Step 1.   calculate the aspect ratio, AR = d/t, for the fragment

Step 2.   calculate the mass to area ratio M/A for the fragment

Step 3.   locate the graph for the assumed value of V_0 and select the curve for the calculated value of the mass to area ratio, M/A

Step 4.   locate the point on the curve for the initial trajectory, angle, σ_i read the corresponding maximum range.

TABLE 4-1. PROGRAM FRISB TEST CASES

These cases were run for the
following initial velocities:

V_i = 100 m/s

V_i = 150 m/s

V_i = 200 m/s

V_i = 250 m/s

V_i = 300 m/s

Lift and Drag Coefficients

C_L = .32 C_D = .85

Fragment Aspect Ratio AR	Fragment Area $A - m^2$	Fragment Mass $M - kg$	Fragment Initial Trajectory Angle $\alpha_i - deg.$
5	0.0139	1	10
	0.0139	1	20
	0.0139	1	30
	0.0139	1	40
	0.0139	1	50
	0.0139	1	60
10	0.022	1	10
	0.022	i	20
	0.022	1	30
	0.022	1	40
	0.022	1	50
	0.022	1	60
5	0.0289	3	10
	0.0289	3	20
	0.0289	3	30
	0.0289	3	40
	0.0289	3	50
	0.0289	3	60

TABLE 4-1. (cont'd)

Fragment Aspect Ratio AR	Fragment Area $A - m^2$	Fragment Mass $M - kg$	Fragment Initial Trajectory Angle $a_i - deg.$
10	0.0461	3	10
	0.0461	3	20
	0.0461	3	30
	0.0461	3	40
	0.0461	3	50
	0.0461	3	60
5	0.0645	10	10
	0.0645	10	20
	0.0645	10	30
	0.0645	10	40
	0.0645	10	50
	0.0645	10	60
10	0.102	10	10
	0.102	10	20
	0.102	10	30
	0.102	10	40
	0.102	10	50
	0.102	10	60
5	0.134	30	10
	0.134	30	20
	0.134	30	30
	0.134	30	40
	0.134	30	50
	0.134	30	60

TABLE 4-1. (cont'd)

Fragment Aspect Ratio AR	Fragment Area $A - m^2$	Fragment Mass $M - kg$	Fragment Initial Trajectory Angle $\alpha_i - deg.$
10	0.213	30	10
	0.213	30	20
	0.213	30	30
	0.213	30	40
	0.213	30	50
	0.213	30	60

Since there are an infinite number of possible combinations of the independent variables, the graphs presented must be limited to particular values. However, most of the curves are parallel for varying values of the independent variables M/A, AR and V, allowing estimations to be made for fragments that are not represented by the curves presented. The procedure for this extrapolation is explained in Examples 3 and 4.

Example 1:

Determine the maximum range of a disc shape fragment assuming the following properties: $V_i = 100$ m/s (328 ft/sec), Mass = 1 kg (2.2 lb_m), Area = 0.0139 m^2 (0.150 ft^2), d = 0.25 m (0.820 ft), t = 0.05 m (0.164 ft), and the initial trajectory of the fragment at t = 0 was $\alpha_i = 30^o$.

Step 1.   First determine the value of the aspect ratio for the fragment AR = d/t = 0.25/0.05 = 5.

Step 2.   Determine the value of the mass to area ratio for the fragment M/A = 1/0.0139 = 72.

Step 3.   From Figure 4-27, which is the figure for $V_i = 100$ m/s and AR = 5 (which are given), it can be seen that the maximum range of the fragment is 465 meters (1530 ft).

Example 2:

Determine the maximum range of a disc shaped fragment assuming
the following properties: V_i = 300 m/s (984 ft/sec), Mass = 1 kg
(2.2 lb_m), Area = 0.0139 m^2 (0.150 ft^2), d = 0.25 m (0.820 ft), t =
0.05 m (0.169 ft), and γ_i = 30°.

Step 1. Same as Example 1.

Step 2. Same as Example 1.

Step 3. From Figure 4-35 for V_i = 300 m/s and
AR = 5, the maximum range is 188 meters (617 ft).
But this particular point lies to the left of the straight
line marked, γ_i = 90°. This line indicates that all
events to the left of this line resulted in the fragment
attaining a completely vertical flight. At this point it
was assumed that all lift and stability were lost and the
fragment fell straight to the ground. All events to the
right of the line indicate a "normal" flight. The γ_i =
90° line is present only where the initial velocities
and/or trajectory angles were sufficient to cause a
vertical trajectory.

Example 3:

Determine the maximum range of a disc-shape fragment assuming
the following properties: V_i = 230 m/s (755 ft/sec), Mass = 18.6 kg
(40.9 lb_m), A = 0.155 m^2 (1.67 ft^2), d = 0.444 m (1.46 ft), t =
0.0444 m (0.146 ft), and γ_i = 30°.

Step 1. Calculate the aspect ratio for the fragment from the
assumed data. AR = 0.444/0.0444 = 10.

Step 2. Calculate the mass to area ratio for the fragment from
the assumed data. M/A = 18.6/0.155 = 120.

Step 3. Since no graph exists for V_i = 230 m/s we must inter-
polate using the graphs for V_i = 200 and V_i = 250 m/s,
AR = 10.

A curve for M/A = 120 also does not exist so an interpolation pro-
cedure must also be used here. The curve for both graphs and all values
of MA are essentially parallel so it will only be necessary to determine
one point at the correct M/A and V_0 to construct the curve for all values
of γ_0. At γ_i = 30° for M/A = 98 and 141 for both V_i = 200 and

V_i = 250 (Figure 4-32 and 4-34) read the values of range.

V_i = 200 m/s V_i = 250 m/s

$\gamma_i = 30^\circ$ $\gamma_i = 30^\circ$

M/A = 98 Range = 283 m   M/A = 98 Range = 265 m

M/A = 141 Range = 440 m   M/A = 141 Range = 400 m

Step 4.   For each velocity find the range for M/A = 120 by
           interpolating between M/A = 98 and M/A = 141. For
           V_i = 200 m/s:

Range Difference 440 - 283 = 157 m

M/A Difference 141 - 98 = 43 kg/m^2

or $\frac{157}{43}$ = 3.65 m/(kg/m^2)

The difference between value of nearest curve and
required value of M/A is:

141 - 120 = 21 kg/m^2

The amount of change in the range for this increment is:

21 kg/m^2 (3.65) m /(kg/m^2) = 77 m

The range at M/A = 120 will therefore be

440 m - 77 = 363 m

Similarity for V_i = 250 m/s

440 - 265 = 135

141 - 98 = 43

135/43 = 3.13 m (kg/m^2)

(21) (3.13) = 66 m

440 - 66 = 334 m

With these values of range curves for M/A = 120 can be constructed by drawing the curves parallel to the curve for other values of M/A and through these values of range at $\cdot_i$ = 30°.

Step 5. With these values of range for M/A = 120, interpolate for the correct velocity of V_i = 230 m/s.

Difference in range for V_i = 200 m/s and V_i = 250 m/s is 363 - 334 m = 29 m

The velocity difference is 250 - 200 = 50 m/s.

The change in range per 1 m/sec change in velocity is

$$\frac{29 \text{ m}}{50 \text{ m/sec}} = .58 \text{ m/(m/s)}$$

The change in range from 200 to 230 m/s is: (30) (.58) = 17 m

Since the range is decreasing with increasing velocity, the range for M/A = 120, V_i = 230 m/s will be: 363 - 17 = 346 m (1140 ft).

A curve can be constructed to give the values of range at other values of $\neg_0$ using the procedure described in Step 4.

Example 4:

Determine the maximum range of a disc-shape fragment assuming the following properties: V_i = 448 m/s (1470 ft/sec), M = 0.0495 kg (0.109 lb_m), A = 0.00129 m^2 (0.0139 ft^2), d = 0.40 m (1.31 ft), t = 0.00919 m (0.030 ft) and $\neg_i$ = 15°.

Step 1. Calculate the aspect ratio for the fragment from the assumed data. AR = 0.040/0.00919 = 4.4.

Step 2. Calculate the mass to area ratio for the fragment from the assumed data. M/A = 38.4.

Step 3. Since no graph exists for a V_i = 448 m/s and an AR = 4.4 we must choose Figure 4-35 for V_i = 300 m/s, AR = 5 to obtain an approximation for range. There is no curve in Figure 4-35 for which M/A = 38 but the curves are parallel and evenly spaced. Between M/A = 72 and M/A = 104 at $\neg_i$ = 40° there is a difference in

range of 60 meters or $\dfrac{60}{104 - 72} = 188 \dfrac{m}{kg/m^2}$.

From $M/A = 104$ to $M/A = 155$ at $\alpha_i = 40°$, there is

a difference in range of 110 meters or $\dfrac{110}{155 - 104} =$

$2.10 \dfrac{m}{kg/m^2}$. This is an average of about $2 - \dfrac{m}{kg/m^2}$.

It is required to construct a curve for $M/A = 38 \text{ kg/m}^2$.
The nearest curve to this value is $M/A = 72$ for a dif-
ference of $72 - 38 = 34 \text{ kg/m}^2$. The value of the range
for $M/A = 38$ at $40°$ should be about 70 meters. Con-
struct a curve through this point and parallel to the
other curves. The range for $\alpha_i = 15°$ is then read as
155 meters (509 ft).

This particular case was checked by substitution of the assumed
data into the FRISB code (described in Appendix 4E). The maximum
range predicted by the code was 142 meters which is about 8% lower than
the curve approximation.

Several cases where the initial conditions did not match a particular
graph were checked in this manner to determine the accuracy of the
approximation. The error ranged from 5% to 80%. The greatest errors
occurred when trying to predict the range for values of (M/A) ~ 20.
These checks indicate that although the predictions from interpolation are
crude, they provide a means of obtaining a rough order of magnitude for
the fragment range, when gross extrapolations are required.

The FRISB code may also be used to predict the trajectory of a
fragment that generates no lift as does the TRAJE code. A value of $C_L =$
0 is input into FRISB for this computation. The code can also be used
to predict the trajectory of a fragment that is long and thin and spins like
a helicopter rotor blade. The input involved for the use of this feature is
presented in Appendix 4E along with a discussion of the analysis procedure.

4-5.2   Drag Fragments

Some fragments are shaped such that no one linear dimension is
significantly greater than any other. The maximum range for such frag-
ments (i. e., chunky fragments, fragments which can be approximated by
a cube or sphere) can be obtained using the technique to be described.

Required input data are the initial velocity, V_i, of the fragment, a
characteristic area A of the fragment (which can be generated as shown

below), the mass of the fragment, and an initial trajectory angle or spectrum of initial trajectory angles, v_i. Typical steps in the procedure for calculating the maximum range from Figures 4-37 through 4-45 are the following:

Step 1.   Find the characteristic area of the fragment:

(a)   from the equation

$$A = V^{2/3}$$

where V is the fragment volume. V may be obtained from the mass of the fragment, M, and its density, ρ, from the equation

$$V = M/\rho$$

(b)   from the projected area of the fragment if it has three-dimensional symmetry or can be nearly approximated by a solid of three-dimensional symmetry (i. e., a sphere or a cube).

Step 2.   Calculate the mass area ratio for the fragment, M/A.

Step 3.   Consult Figures 4-37 through 4-45 to find the figure for a V_i and A value most nearly equal that of the fragment considered. Linear interpolation can be used where necessary (see example problems).

Step 4.   Read the maximum range from the figure for the M/A of Step 2 and the initial trajectory angles considered.

For a more precise range calculation the computer code, TRAJE, used to generate these figures may be used along with the input data for the fragment.

Example 1, For Drag Fragments

Assume: A nearly spherical shaped fragment that can be approximated by a sphere of radius $R = 584$ mm (0.192 ft) having an initial velocity of 200 m/s (656 ft/sec) and made out of steel. Find the maximum range expected for any initial trajectory angle.

Step 1.   The characteristic area of the fragment is, by method (a)
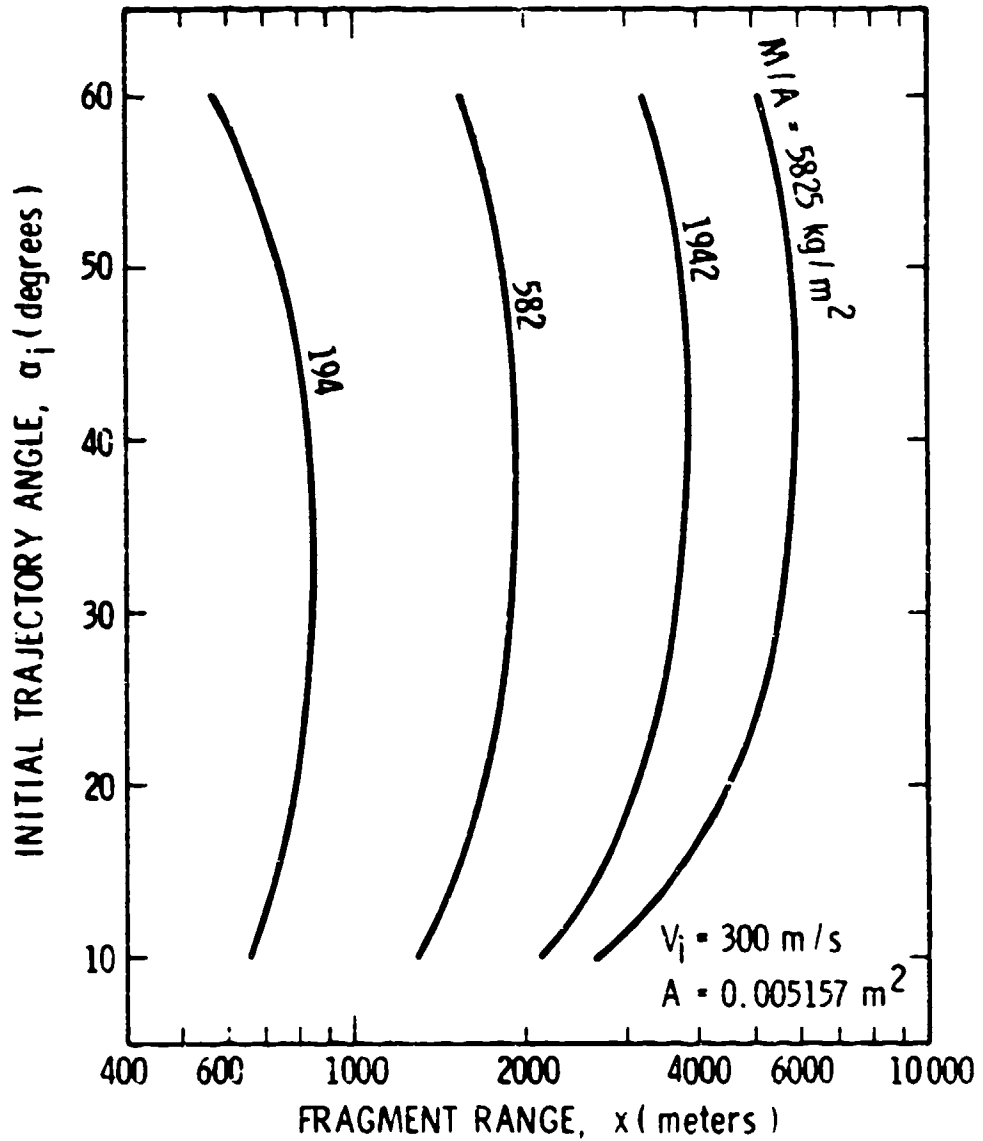
Figure 4-37. Fragment Range for Drag Fragments,
V_i = 300 m/s, A = 0.005157 m²
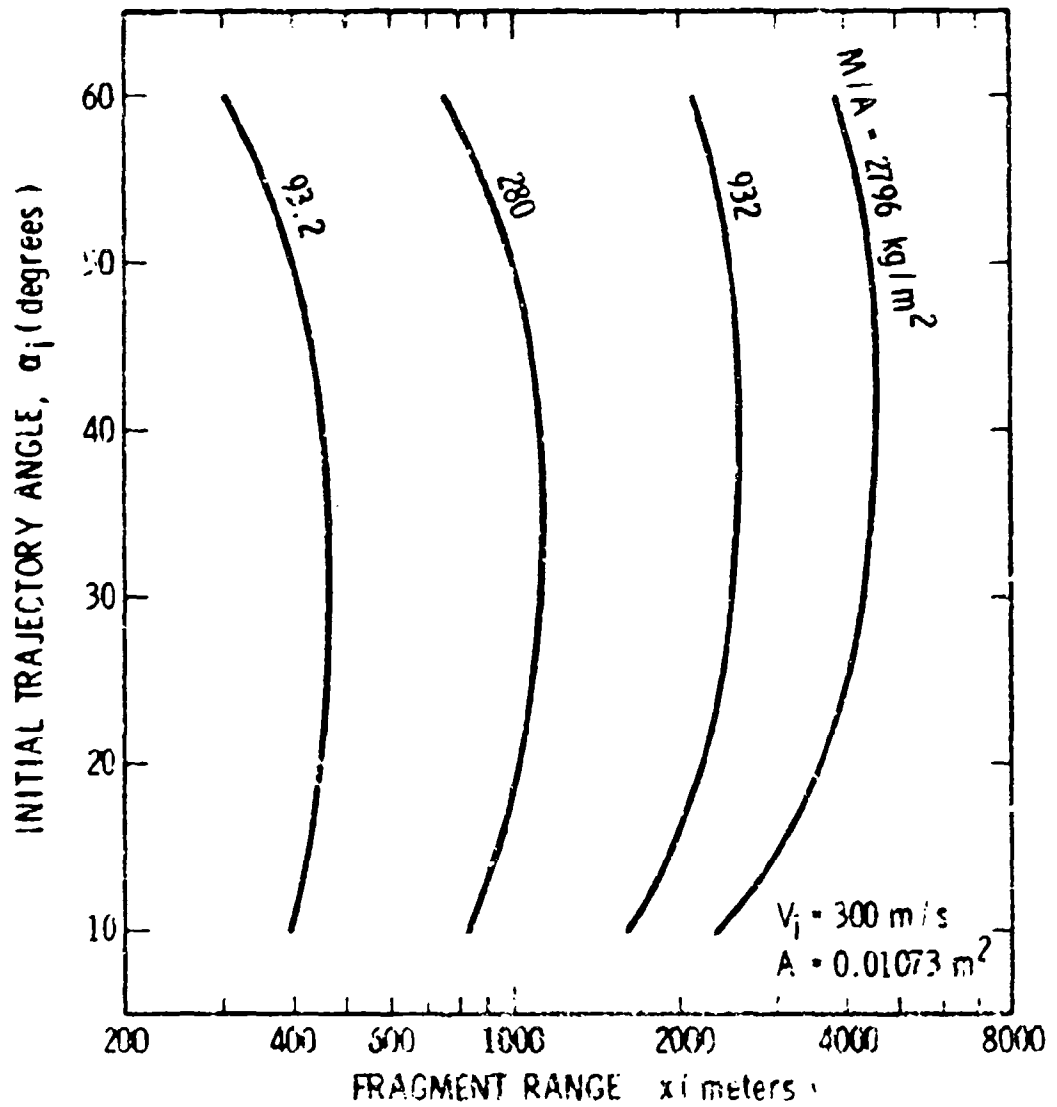
INITIAL TRAJECTORY ANGLE, α_i (degrees)

FRAGMENT RANGE x_i meters

$M/A = 2796 \text{ kg/m}^2$

932

280

93.2

$V_i = 300 \text{ m/s}$
$A = 0.01073 \text{ m}^2$

$(\text{ft} = \text{m} \times 3.281)$

Figure 4-58   Fragment Range for Drag Fragments,
$V_i = 300$ 0.01073 m^2

4-77
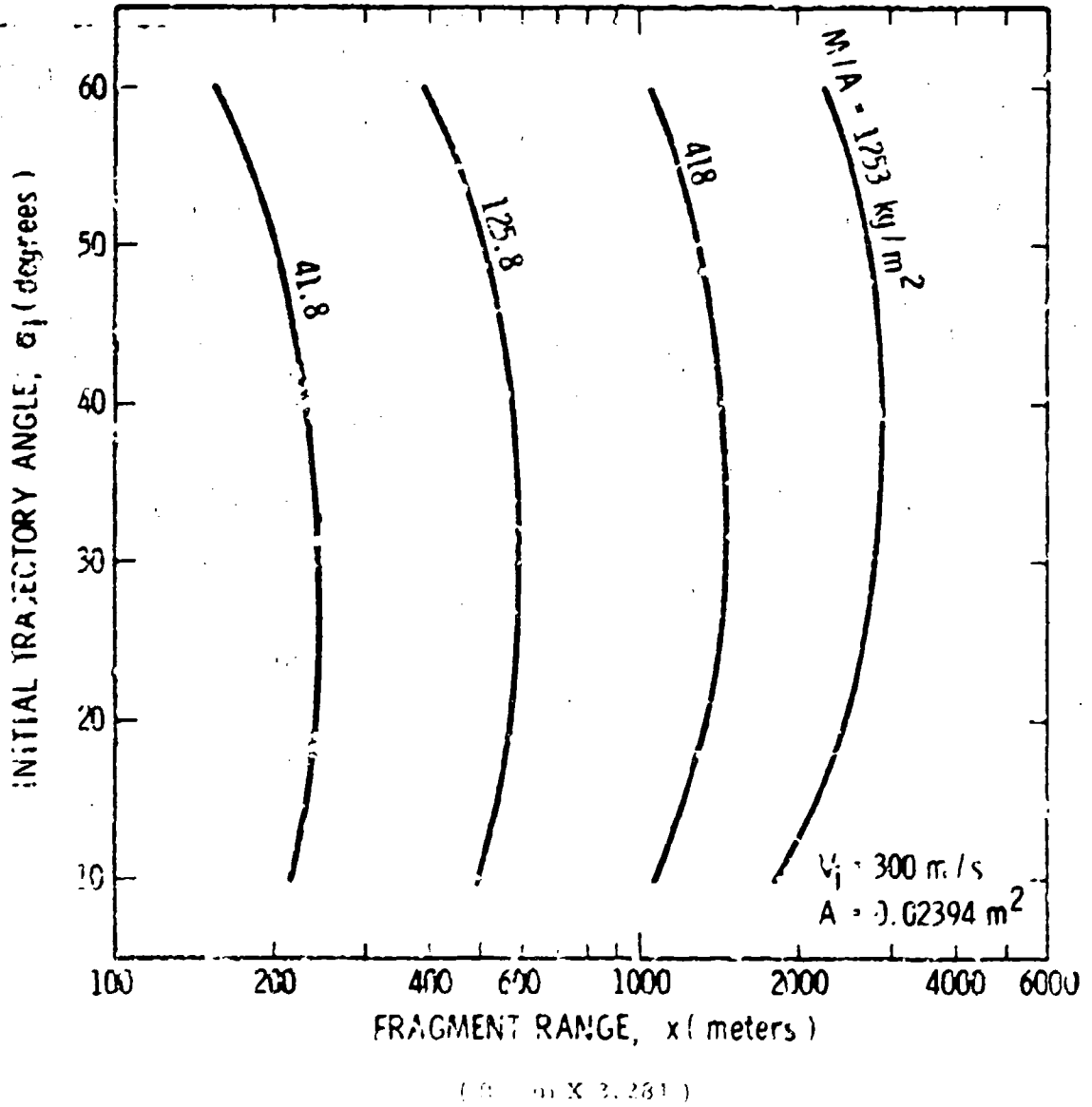
Figure 4-39. Fragment Range for Drag Fragments.
$V_i = 300$ m/s, $A = 0.02394$ m^2
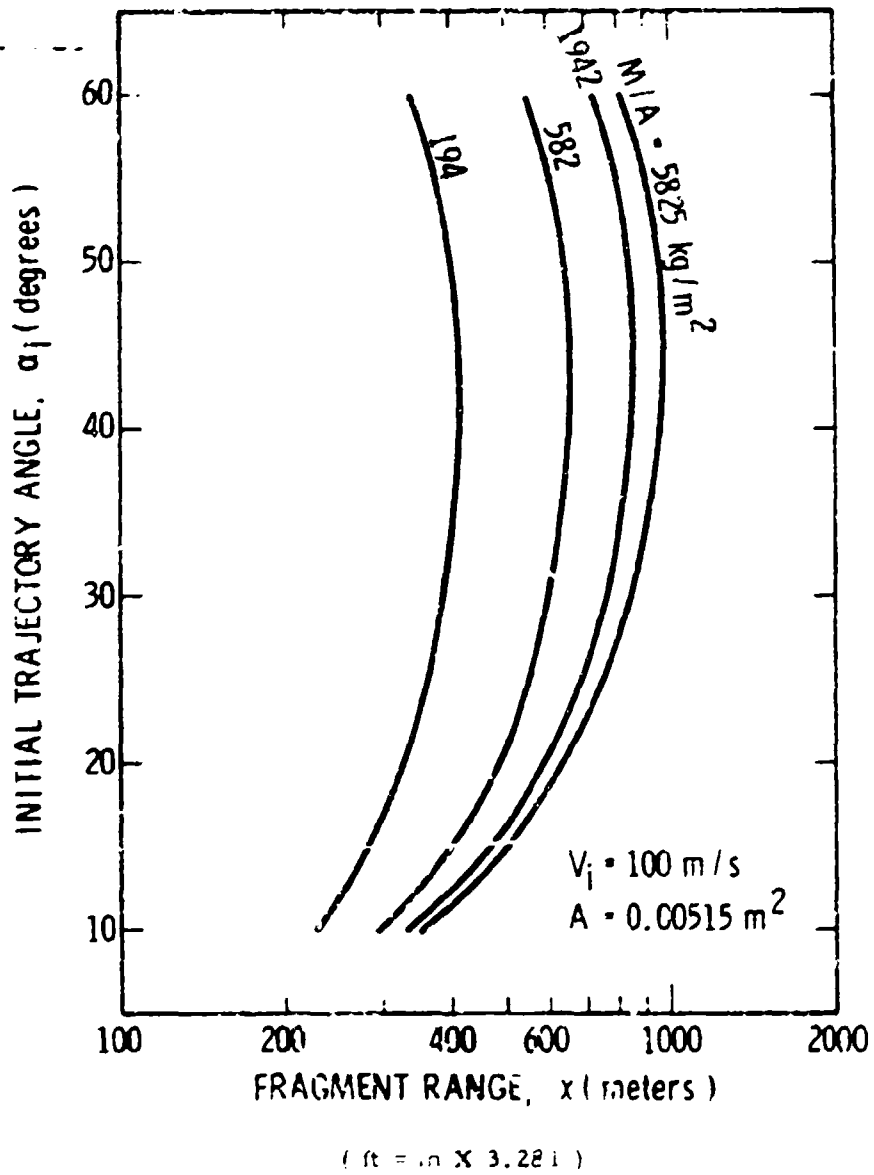
Figure 4-40. Fragment Range for Drag Fragments.
$V_i = 100$ m/s, $A = 0.00515$ m.²
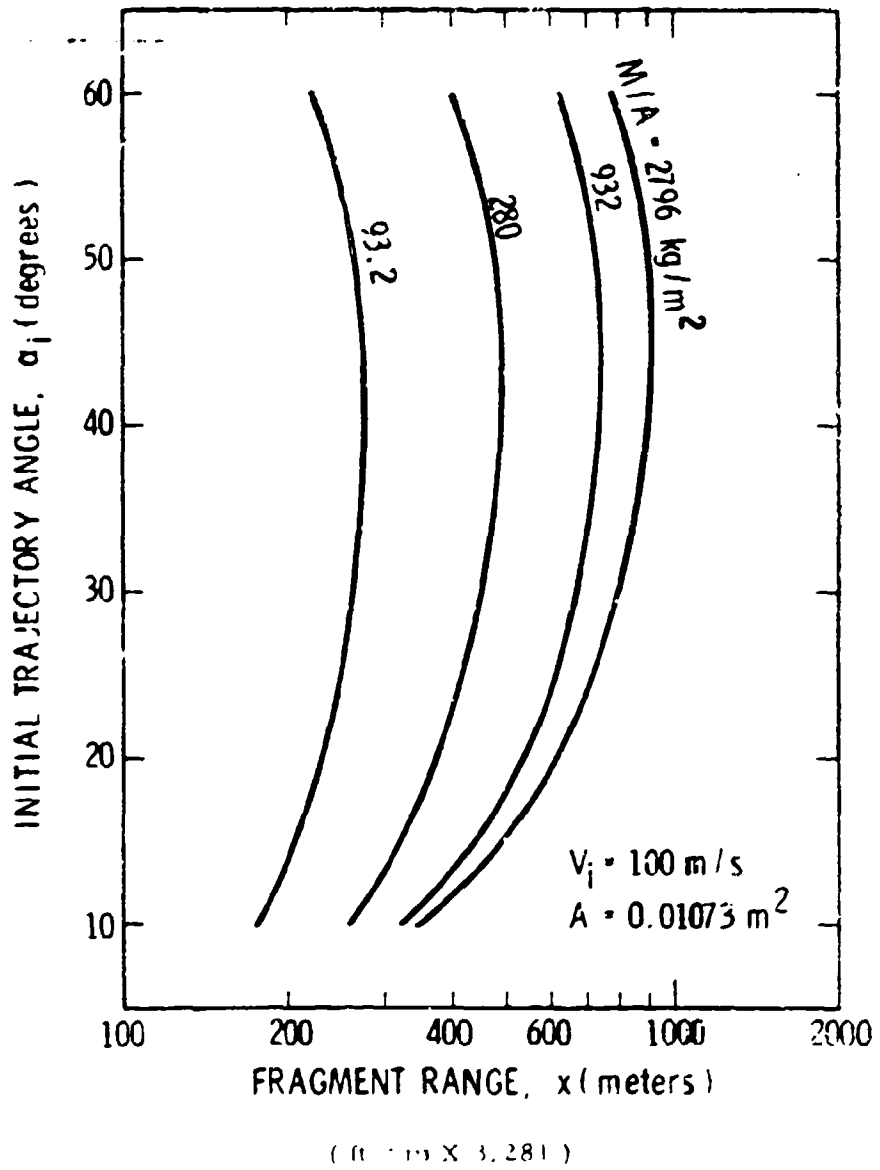
Figure 4-41. Fragment Range for Drag Fragments.
$V_i = 100$ m/s, $A = 0.01073$ m^2
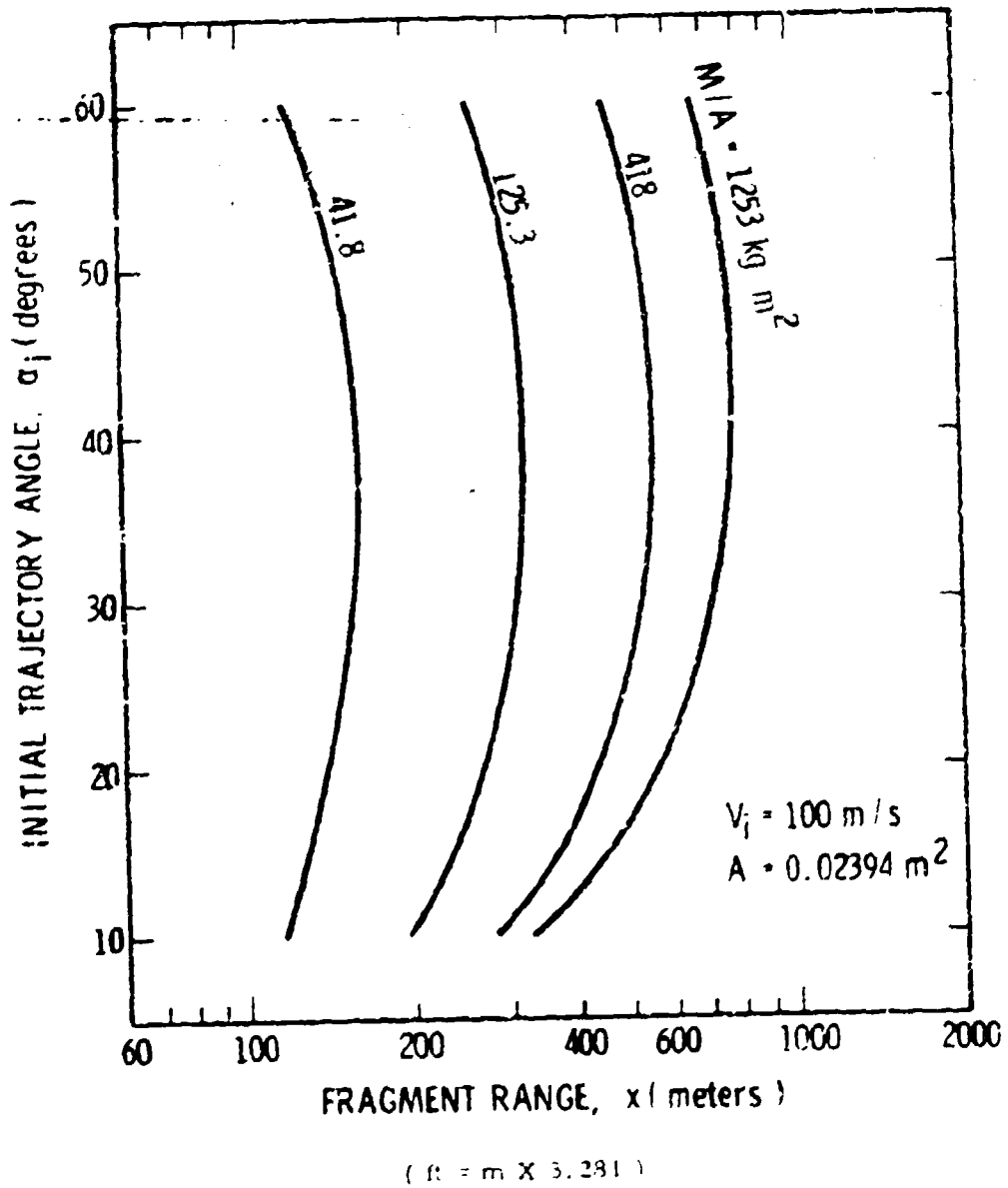
Figure 4-42. Fragment Range for Drag Fragments.
$V_i = 100$ m/s, $A = 0.02394$ m²
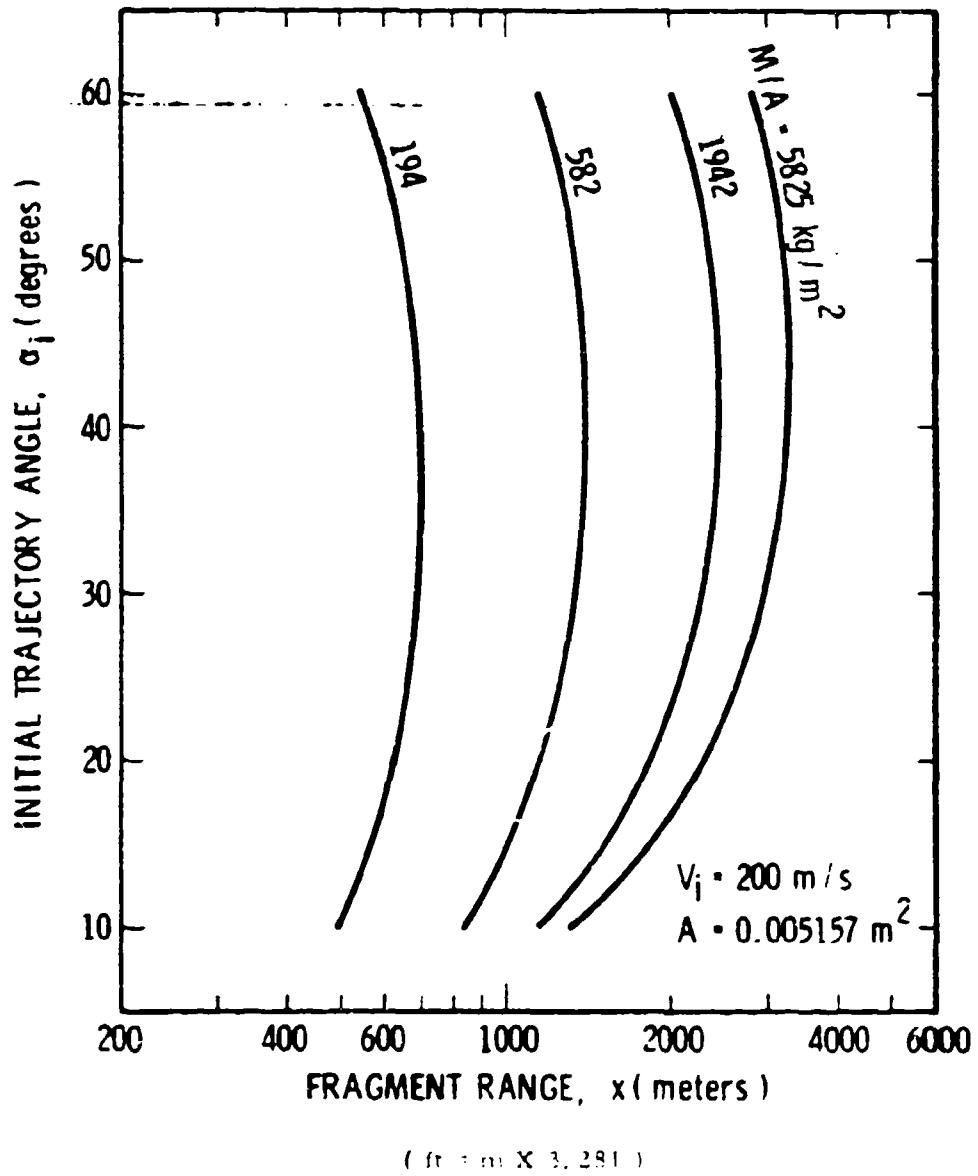
Figure 4-43. Fragment Range for Drag Fragments.
$V_i = 200$ m/s, $A = 0.005157$ m^2
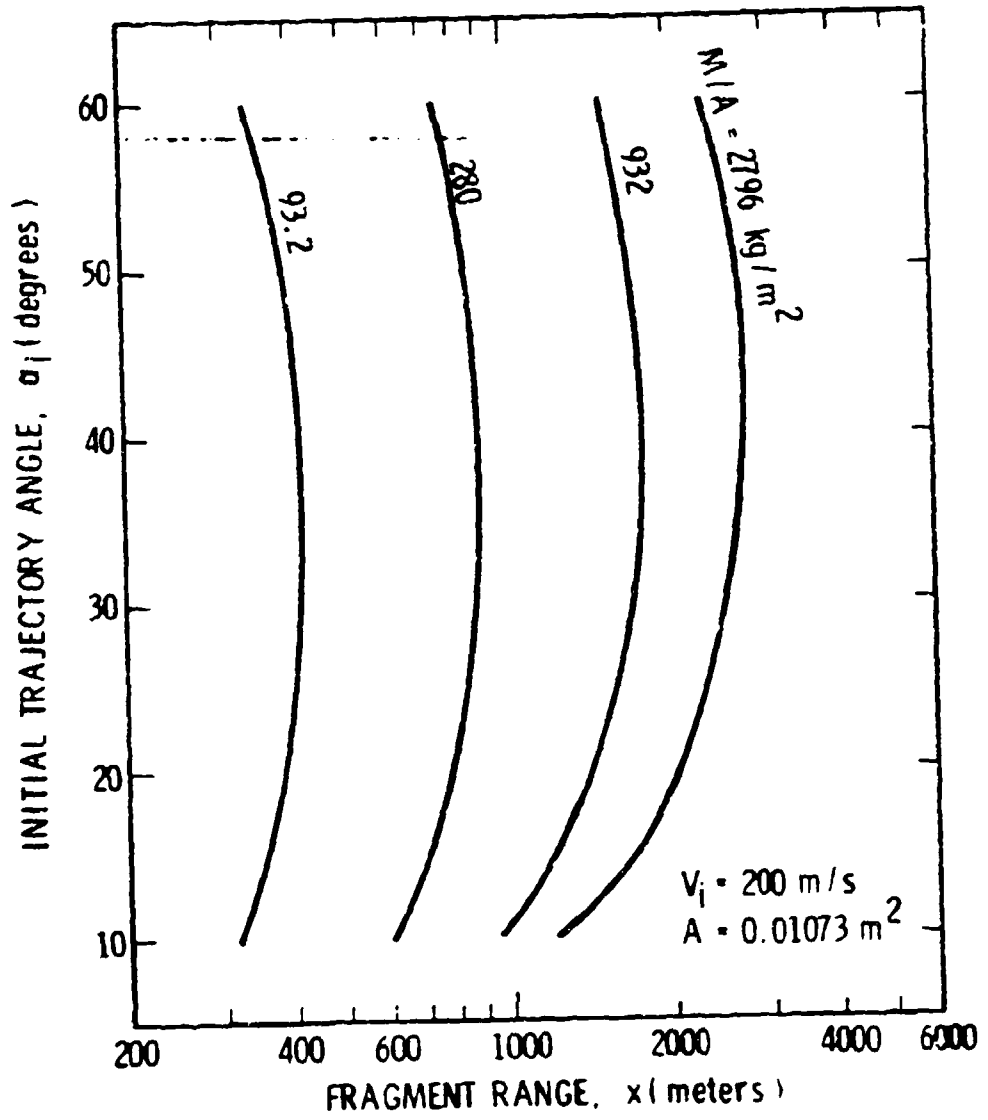
Figure 4-44. Fragment Range for Drag Fragments.
V_i = 200 m/s, A = 0.01073 m^2
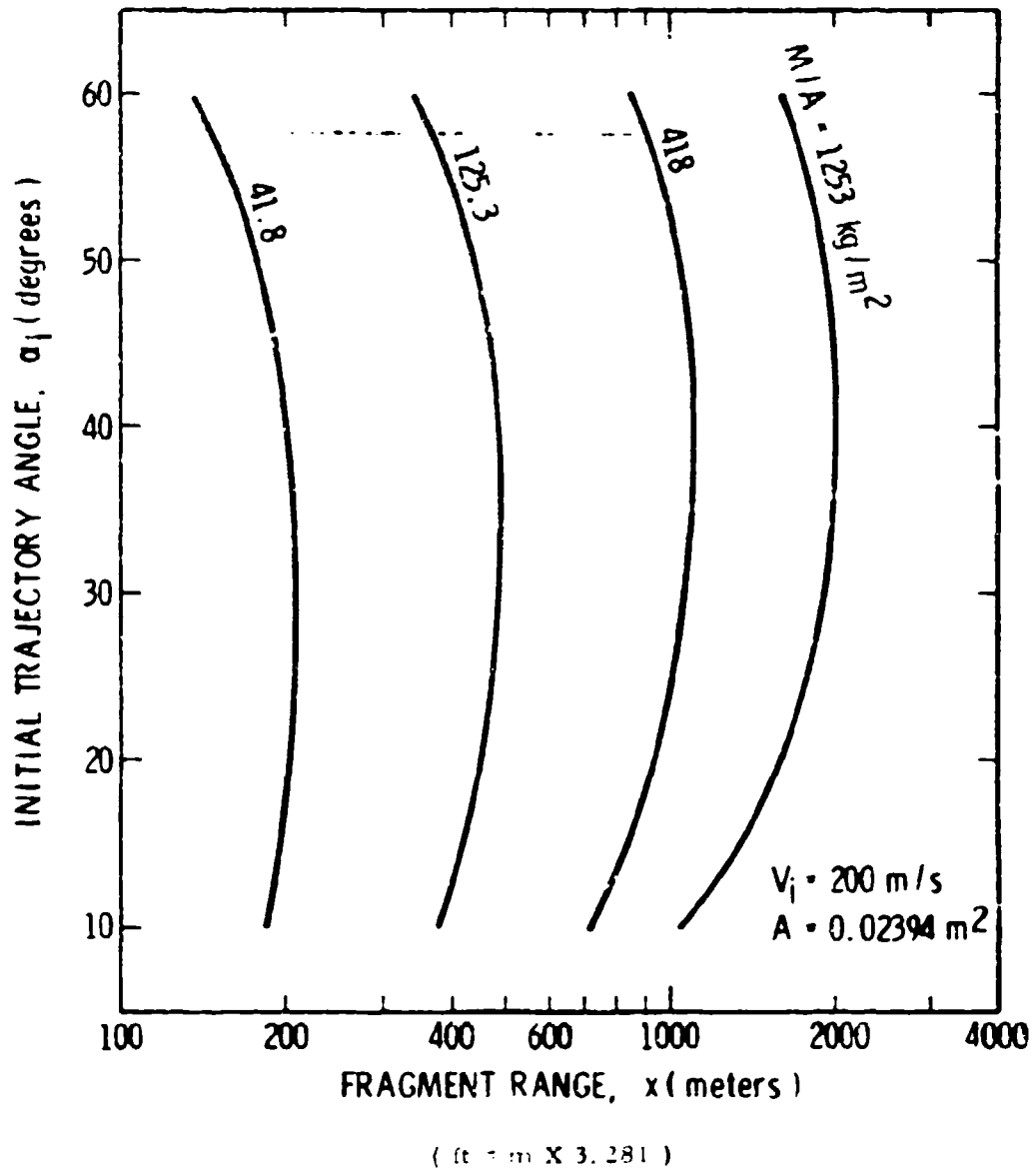
Figure 4-45. Fragment Range for Drag Fragments.
V_i = 200 m/s, A = 0.02394 m²

$$A_1 = [(4/3) \pi R^3]^{2/3} = 2.60 \, R^2 = 0.00887 \, m^2$$

by method (b)

$$A_2 = \pi R^2 = \pi [4/3 \pi R^3]$$

Step 2.   Calculate the mass area ratio for the fragment where

$$M = \rho V = (4/3) \pi R^3$$

For a sphere

$$\rho_{steel} = 7.8 \, g/cm^3$$

therefore

$$M = (7.8)(4/3)(\pi)(5.84)^3 = 6.51 \, kg$$

using A_2 from Step 1,

$$M/A_2 = 6.51/0.0107 = 608 \, kg/m^2$$

Step 3.   The given V_i of 200 m/s and $A_2 = 0.0107 \, m^2$ corresponds to values for Figure 4-41. From this figure it can be seen that the maximum range for a fragment having an M/A of 932 kg/m^2 is $x_3 = 1800 \, m$ and for an M/A of 280 kg/m^2 is $x_1 = 900 \, m$.

Step 4.   By linear interpolation for our M/A of 608 kg/m^2

$$m_1 = M/A = 280 \, kg/m^2 \qquad x_1 = 900 \, m$$

$$m_2 = M/A = 608 \, kg/m^2 \qquad x_2 = ?$$

$$m_3 = M/A = 932 \qquad x_3 = 1800 \, m$$

$$x_2 = (x_3 - x_1) \frac{(m_2 - m_1)}{(m_3 - m_1)} + x_1$$

$$x_2 = (1808 - 900) \frac{(608 - 280)}{(932 - 280)} + 900$$

$$= 1352 \text{ m } (4,430 \text{ ft})$$

Example 2. For Drag Fragments

Assume: A chunky aluminum fragment of a mass of approximately 1.20 kg (2.64 lb_m) and an initial velocity of 250 m/s (820 ft/sec). Find the maximum range expected for any initial trajectory angle.

Step 1.   The characteristic area of the fragment is, by method (a)

$$A = (M/\rho)^{2/3}$$

from density tables

$$\rho_{Al} = 2.7 \text{ g/cm}^3$$

therefore

$$A = (1200/2.7)^{2/3} = 58.3 \text{ cm}^2 = 5.83 \times 10^{-3} \text{ m}^2$$

Step 2.   M is given as M = 1.2 kg taking A from Step 1, thus

$$M/A = \frac{1.2}{5.83 \times 10^{-3}} = 206 \text{ kg/m}^2$$

Step 3.   A conservative value for the range will be obtained by using data from Figures 4-40 and 4-43 for a fragment of characteristic area 5.16 x 10^{-3} m^2 which is slightly less than the area of the fragment considered, calculated in Step 1.

From Figure 4-40, for a fragment having V_i = 200 m/s we may obtain a maximum range for M/A = 206 kg/m² by linear interpolation from the maximum ranges, x, for M/A ratios most nearly greater and less than M/A = 206 kg/m²:

4-80

$$m_1 = M/A = 194 \text{ kg/m}^2 \qquad x_1 = 700 \text{ m}$$

$$m_2 = M/A = 206 \text{ kg/m}^2 \qquad x_2 = ?$$

$$m_3 = M/A = 582 \text{ kg/m}^2 \qquad x_3 = 1400 \text{ m}$$

$$x_2 = (x_3 - x_1) \frac{(m_2 - m_1)}{(m_3 - m_1)} + x_1 = (1400 - 700) \frac{(206 - 194)}{(582 - 154)} -$$

$$700$$

$$x_i = 720 \text{ m}$$

From Figure 4-40, for a fragment having a $V_i = 300$ m/s we may obtain a maximum range for $M/A = 206$ kg/m^2 by linear interpolation as in the previous paragraph.

$$m_1' = M/A = 194 \text{ kg/m}^2 \qquad X_1' = 350 \text{ m}$$

$$m_2' = M/A = 206 \text{ kg/m}^2 \qquad X_2' = ?$$

$$m_3' = M/A = 582 \text{ kg/m}^2 \qquad X_3' = 1920 \text{ m}$$

$$X_2' = (1920 - 850) \frac{(206 - 194)}{(582 - 194)} + 850 = 880 \text{ m}$$

Step 4.   Interpolating for a $V_i = 250$ m/s between the values found for $V_i = 200$ m/s and 300 m/s

$$X_2' = (X_2' - X_2) \frac{(250 - 200)}{(300 - 200)} + X_2$$

$$= (880 - 700) \; 1/2 + 700$$

$$= 790 \text{ m}$$

A conservative value for range for this fragment is 790 m (2590 ft).

Example 3, For Drag Fragments

Assume: A titanium alloy fragment with a mass of 3.12 kg (6.84 lbm) initial velocity of 125 m/s (410 ft/sec). Find its maximum range for any initial trajectory angle.

Step 1. $A = (M/\rho Ti)^{2/3}$

since

$\rho_T = 4.46 \ g/cm^3$

$A = \dfrac{3.12 \times 10^3}{4.46}^{2/3} = 79 \ cm^2 = 7.0 \times 10^{-3} m^2$

Step 2. $M/A = \dfrac{3.12}{7.9 \times 10^{-3}} = 395 \ kg/m^2$

Step 3. For a conservative value for range use Figures 4-37 and 4-40 for an A 5.15×10^{-3} which is less than the area of the fragment considered, from Figure 4-37.

for $V_i = 100 \ m/s$ $A = 5.15 \times 10^{-3} m^2$ $M/A =$

$194 \ kg/m^2$ $X_i = 420 \ m$

for $V_i = 100 \ m/s$ $A = 5.15 \times 10^{-3} m^2$ $M/A =$

$582 \ kg/m^2$ $X_3 = 660 \ m$

therefore, interpolating as in the previous examples for an $M/A = 395 \ kg/m^2$

for $V_i = 100 \ m/s$ $A = 5.15 \times 10^{-3} m^2$ $M/A =$

$395 \ kg/m^2$ $X_2 = 544 \ m$

From Figure 4-40, similarly

for V_i = 200 m/s   A = 5.15 × $10^{-3} m^2$ M/A =

395 kg/m^2 X_2' = 1062 m

interpolating for a V_i of 125 m/s

V_i = 125 m/s   A = 5.15 × $10^{-3} m^2$ M/A =

395 kg/m^2 X_2'' = 673 m

Thus a conservative value for the range would be 673 m (2210 ft).

4-5.3   For Cylindrical Propellant Tanks

Data from initial velocity measurements of fragments from Project PYRO experiments (Reference 3) were used to derive an estimate of the fragment initial velocity distribution. For medium percent yields (5 to 15%), Figures 4-46 and 4-47 present the fragment initial velocity distributions for LO_2/LH_2, and $LO_2/RP-1$ respectively, confined in a cylindrical missile (CBM). For medium percent yields (5 to 15%) Figures 4-48 and 4-49 show the fragment initial velocity distributions for LO_2/LH_2 and $LO_2/RP-1$ respectively confined by the ground surface (CBGS). In the CBGS tests, the missiles were allowed to fall back to the pad. In the CBM tests, the bulkheads between the LO_2 and LH_2 were ruptured, allowing the liquids to mix inside the missile.

Figures 4-46 through 4-49 can be used to estimate the percentage of fragments which will have an initial velocity, V_i, equal to or less than a particular V_i.

For example, if we wished to estimate the percentage of fragments which would have an initial velocity equal to or less than 1,000 m/s (3280 ft/sec) for a LO_2/LH_2 CBM case, we would refer to Figure 4-46 and on the initial velocity axis (abcissa) at 1,000 m/s go upward to the intersection with the line. Then, at the intersection point read the percentage value from the ordinate, which is 95.5%. Conversely, if we wanted to know what initial velocity 90% of the fragments would not exceed, we would enter the chart on the 90% line, go over the intersection with the curve and read downward to the initial velocity axis the value 680 m/s (2230 ft/sec).

Figure 4-50 is a plot of fragment initial velocity versus yield (%) for LO_2/LH_2 CBM tests listed on page 86 of Reference 3. A 95th percentile has been included based on the same standard deviation as the
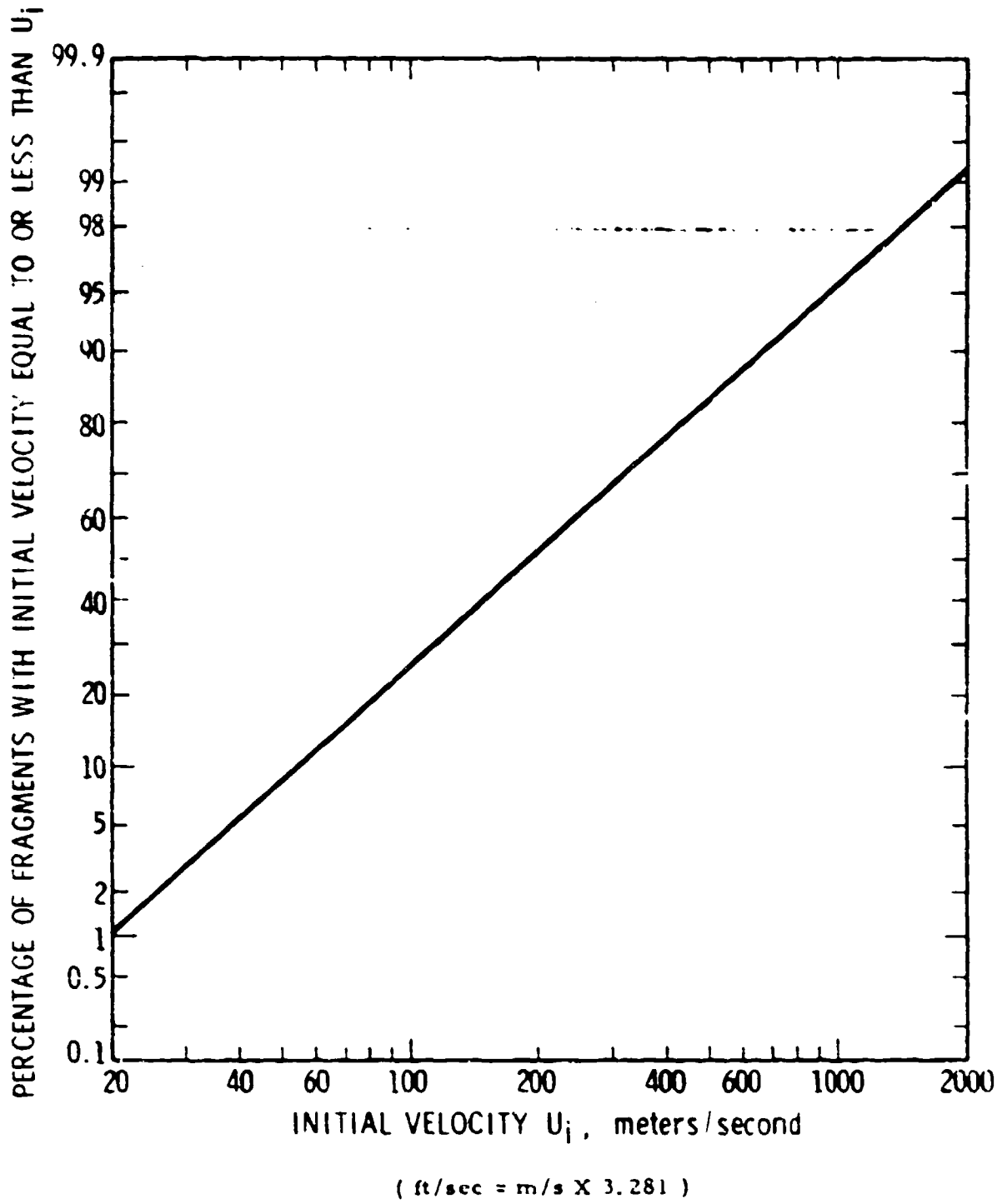
Figure 4-46. Initial Velocity Distribution, CBM, LO_2/LH_2
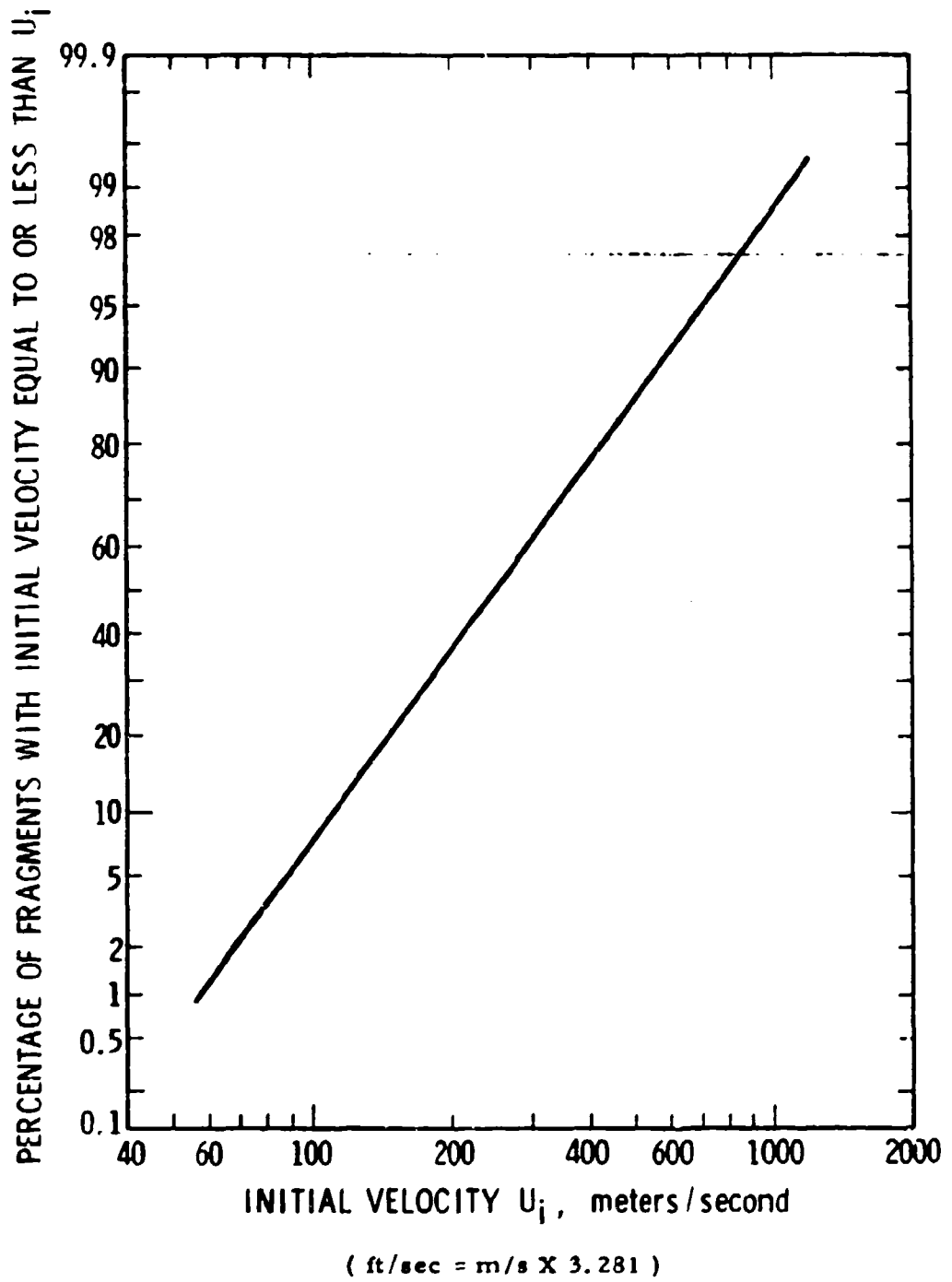
(ft/sec = m/s X 3.281)

Figure 4-47. Initial Velocity Distribution,
CBM, LO_2/(RP-1)
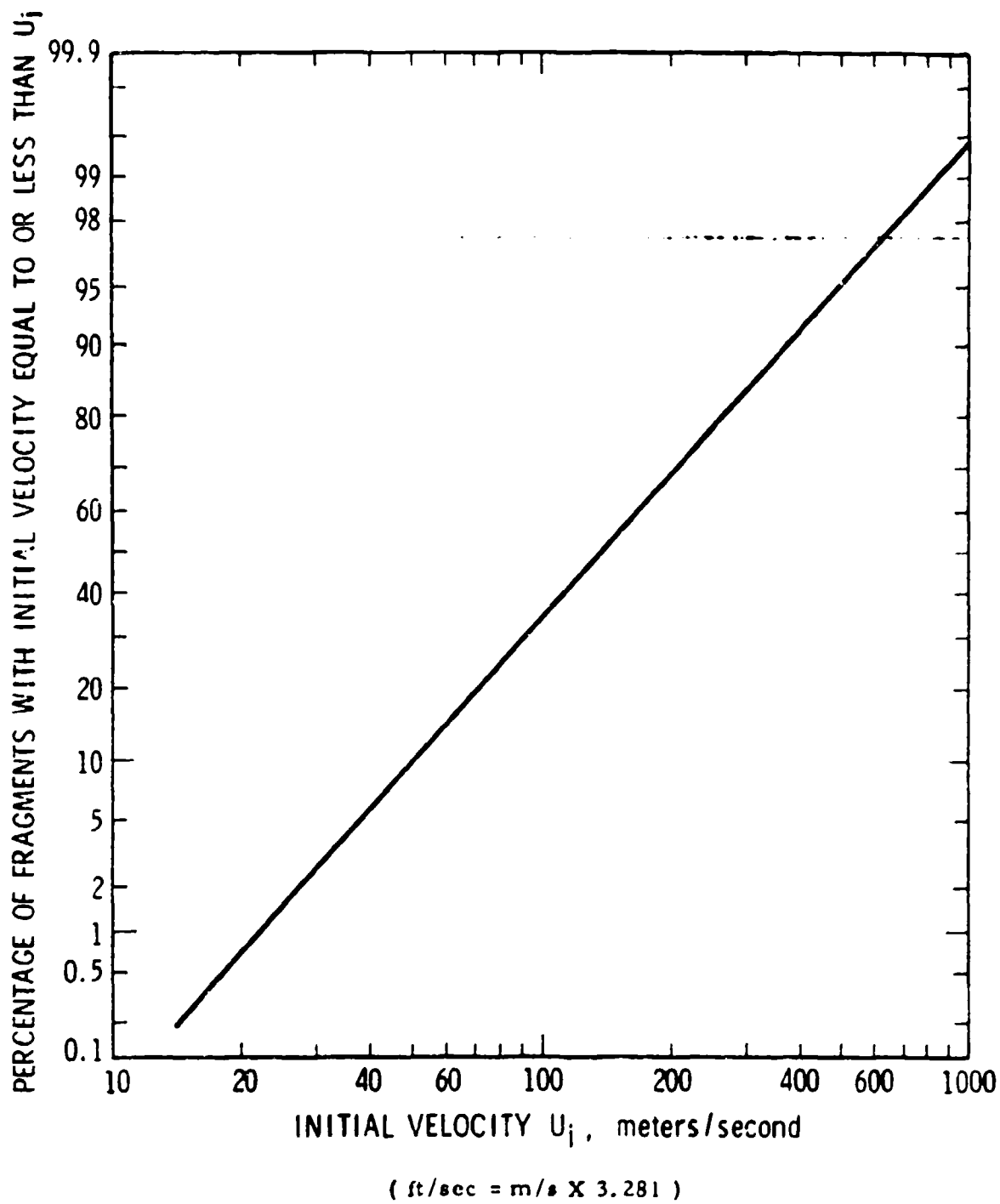
Figure 4-48. Initial Velocity Distribution,
CBGS, LO_2/LH_2

(ft/sec = m/s X 3.281)
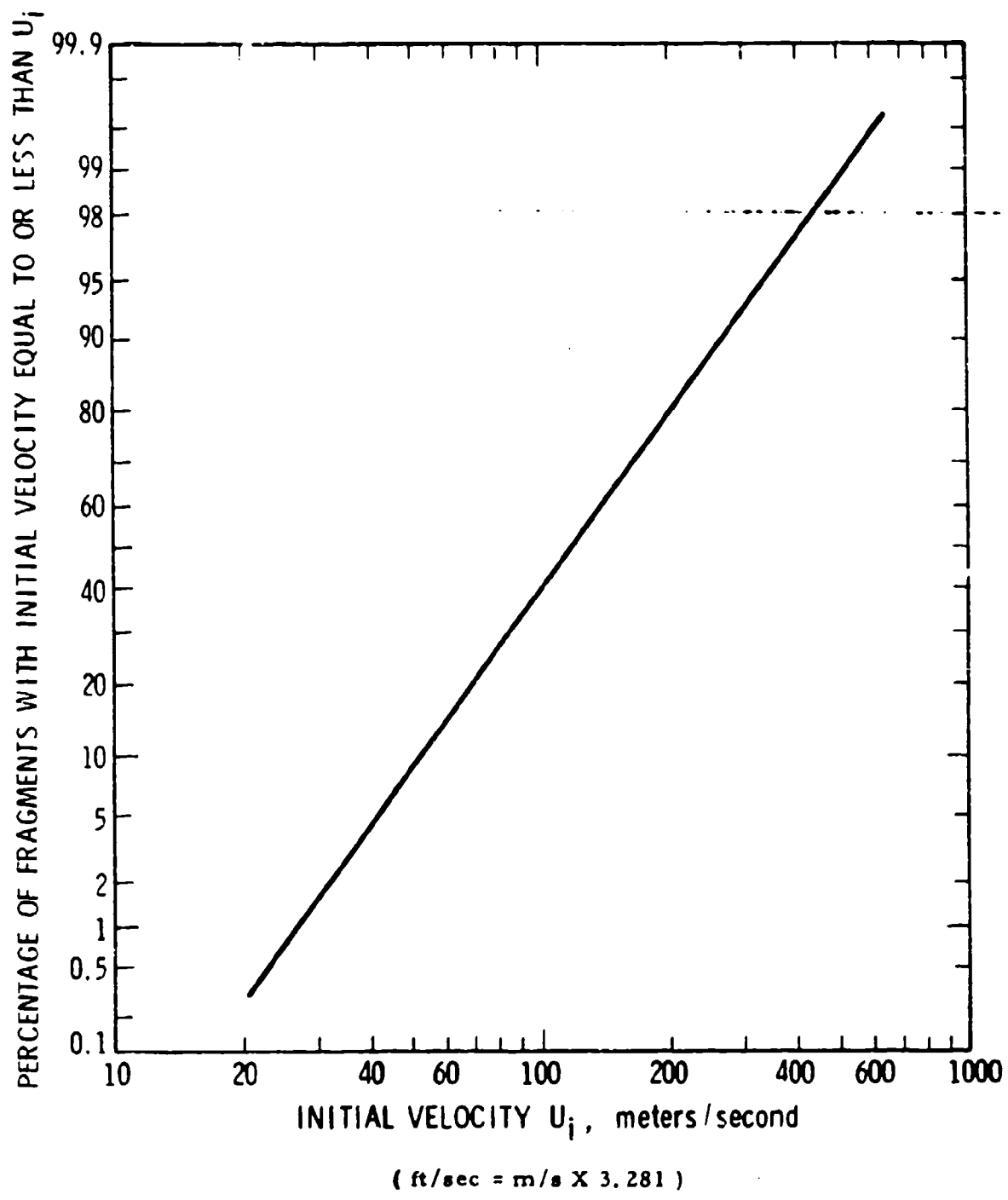
(ft/sec = m/s X 3.281)

Figure 4-49. Initial Velocity Distribution,
CBGS, LO_2/(RP-1)

4-87
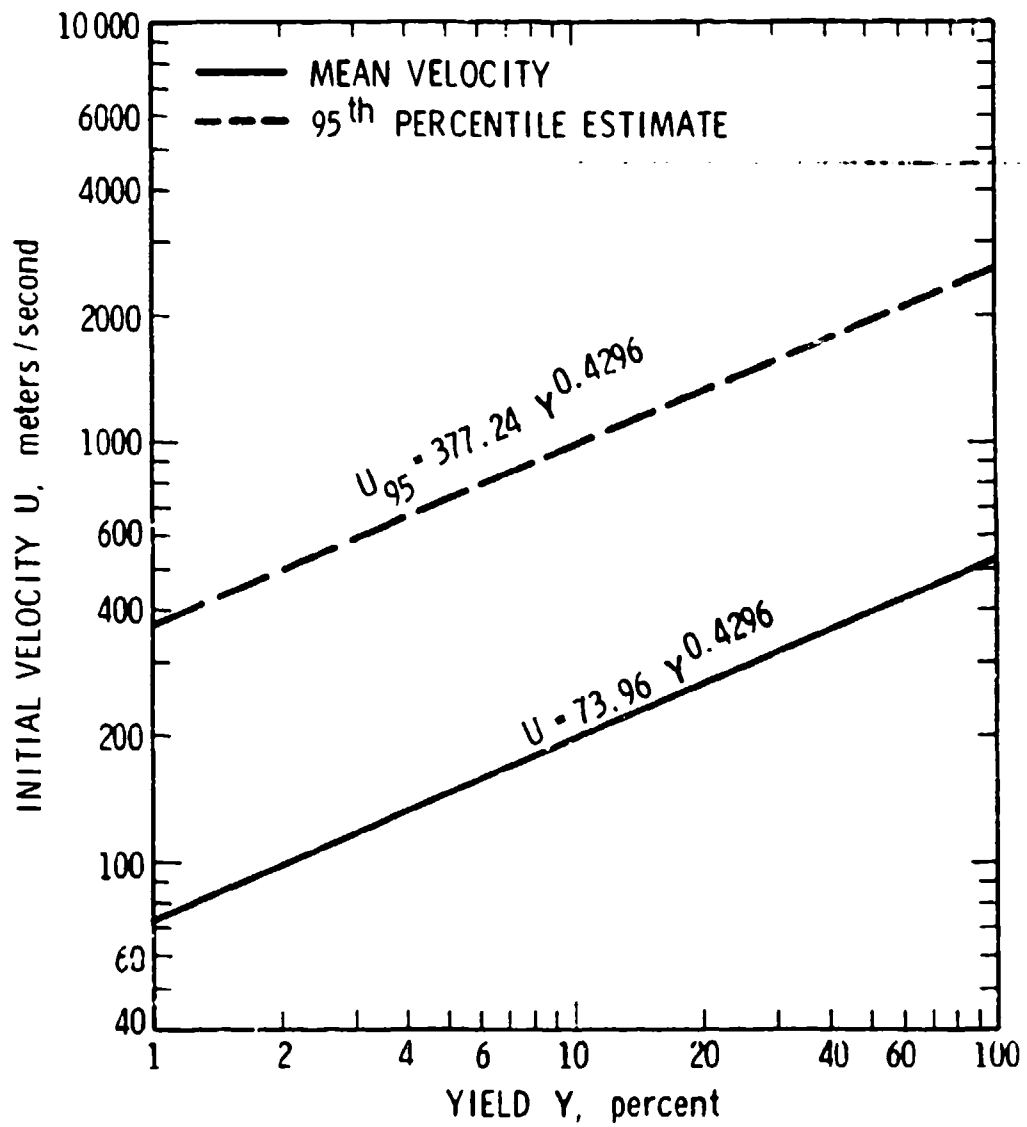
Figure 4-50. Initial Velocity Vs Yield,
CBM, LO_2/LH_2

distribution shown in Figure 4-46. From Figure 4-50, for a yield of
50%, we would expect that 95% of the fragments would have an initial
velocity of 1900 m/s (6230 ft/sec) or less.

Details on the derivation of Figure 4-46 through 4-50 are given
in Appendix 4A, Sections 4A-1 and 4A-2.

4-6   Fragment Mass Distribution

4-6.1   Propellant Explosions

From the data in Reference 3, the fragment mass (weight) follow-
ed log normal distributions. That is, the logarithms of the fragment
masses followed a normal or Gaussian distribution.

Figure 4-51 and 4-52 present the fragment mass (W_i) distribution
for two events taken from Reference 3. These were termed Events 1 and
2, and were Saturn IV confined-by-missile (CBM) explosions. Event 1
had a percent yield of 5%, and Event 2 a yield of 1.1%.

Figure 4-53 is an average of the distribution of Events 3, 4, and
5 from Reference 3. These events were spill tests using three tanks on
120 radials with $LO_2/LH_2/RP-1$, and mixing on the ground (CBGS). The
rationale for averaging the distribution of these events is given in
Appendix 4F.

These charts can be used in the same manner as Figures 4-46
through 4-50 are used for fragment initial velocity.

4-6.2   Gas Vessel Bursts

In experiments by Pittman, (Reference 4), five tanks (two cylin-
ders and three spheres) were ruptured by increasing pressurization
until rupture. The tanks were made of the same material (Ti 6 Al 4V
alloy) with an ultimate stress (σ_u) of 1.05 GPa (150,000 psi). Pertinent
data and calculated parameters for four of the tanks are given in Table
4-2, where $\overline{W}$ is the geometric mean fragment mass, $W(T)$ is the tank
weight, P is the burst pressure, and E_o is the energy of detonation of 1
gram of TNT or 4190 J. It is interesting to note that the ratio $[W/W(T)]$
doubles while the ratio (P/σ_u) changes by an order of magnitude. As
shown in Appendix 4F, the fragment mass follows a log normal distribu-
tion. That is, the logarithims of the fragment masses follow a normal
or Gaussian distribution.
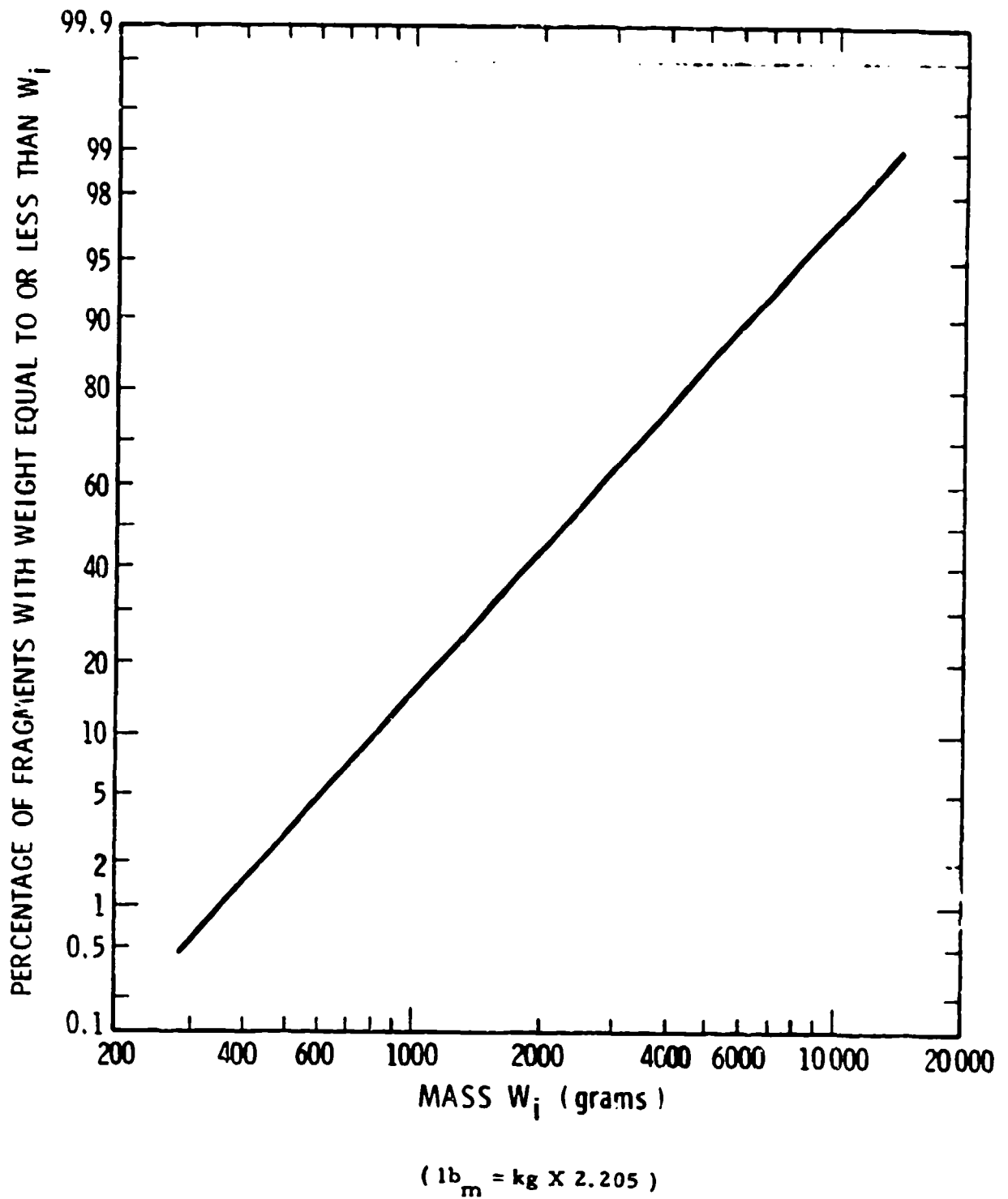
Figure 4-51. Fragment Mass Distribution from S IV CBM.
LO$_2$/LH$_2$, 5% Yield
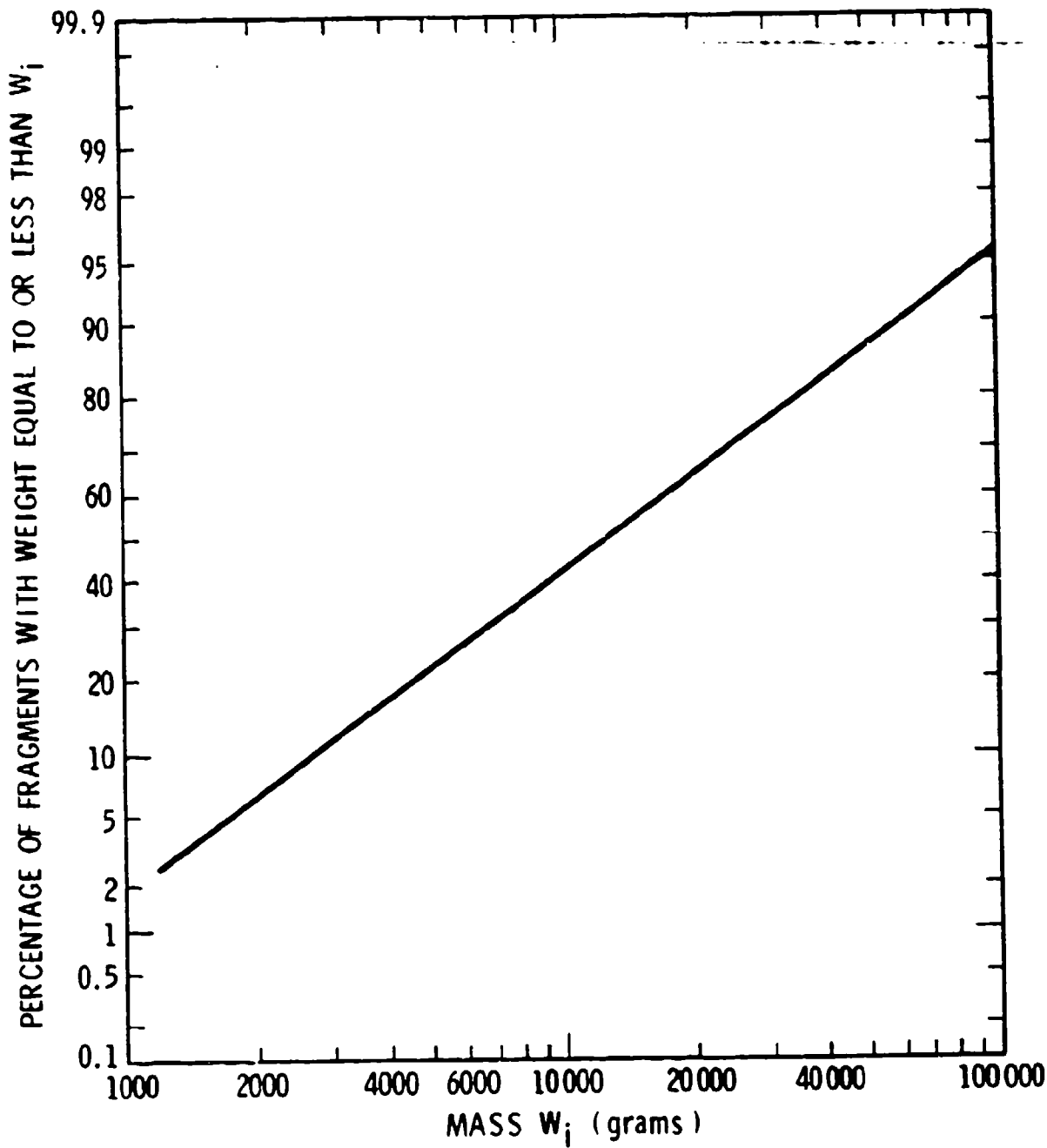
($1b_m$ = kg X 2.205)

Figure 4-52. Fragment Mass Distribution from S IV CBM,
LO_2/LH_2, 1.1% Yield
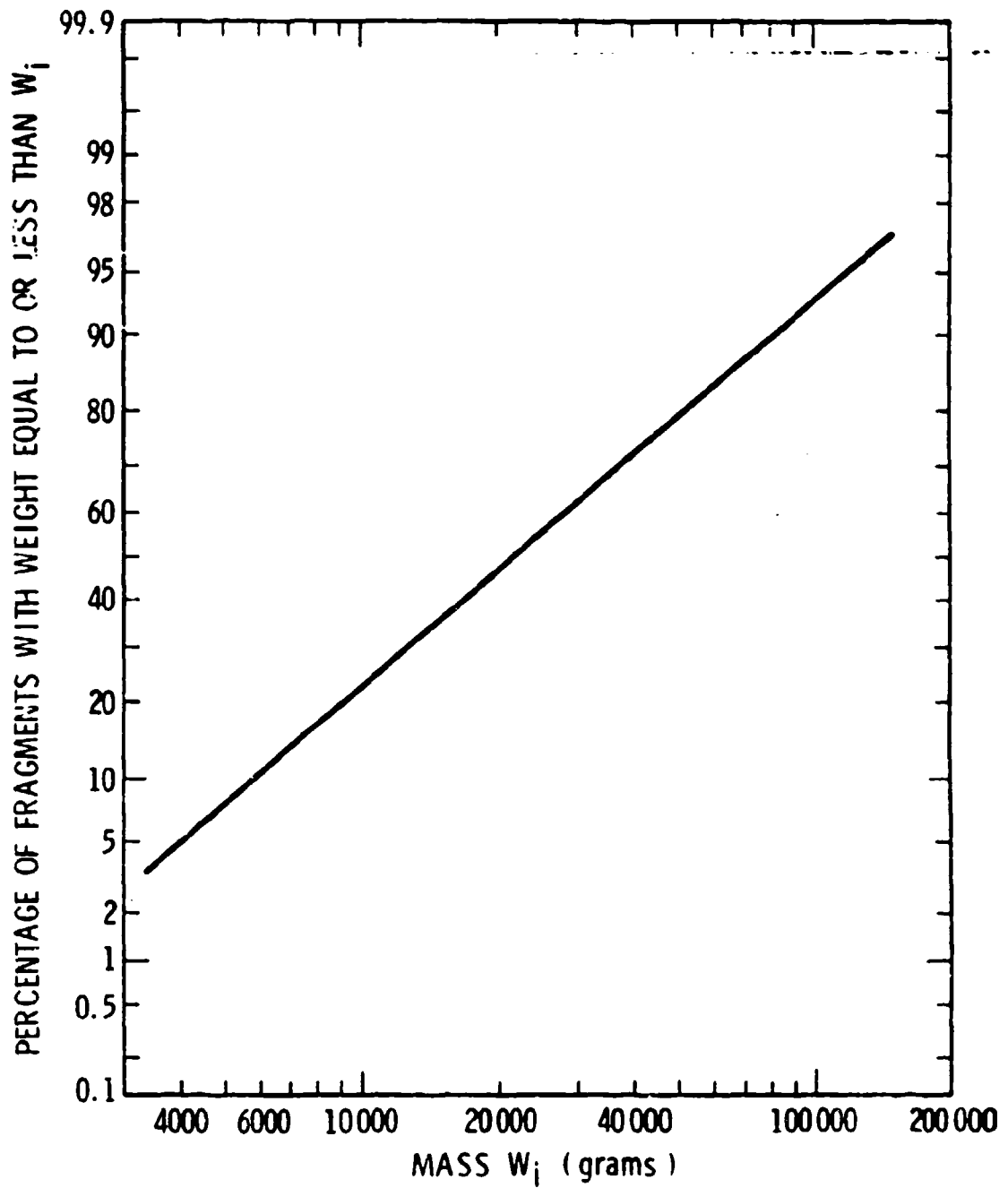
Figure 4-53. Average of Events 3, 4 and 5, Fragment Mass Distribution, CBGS
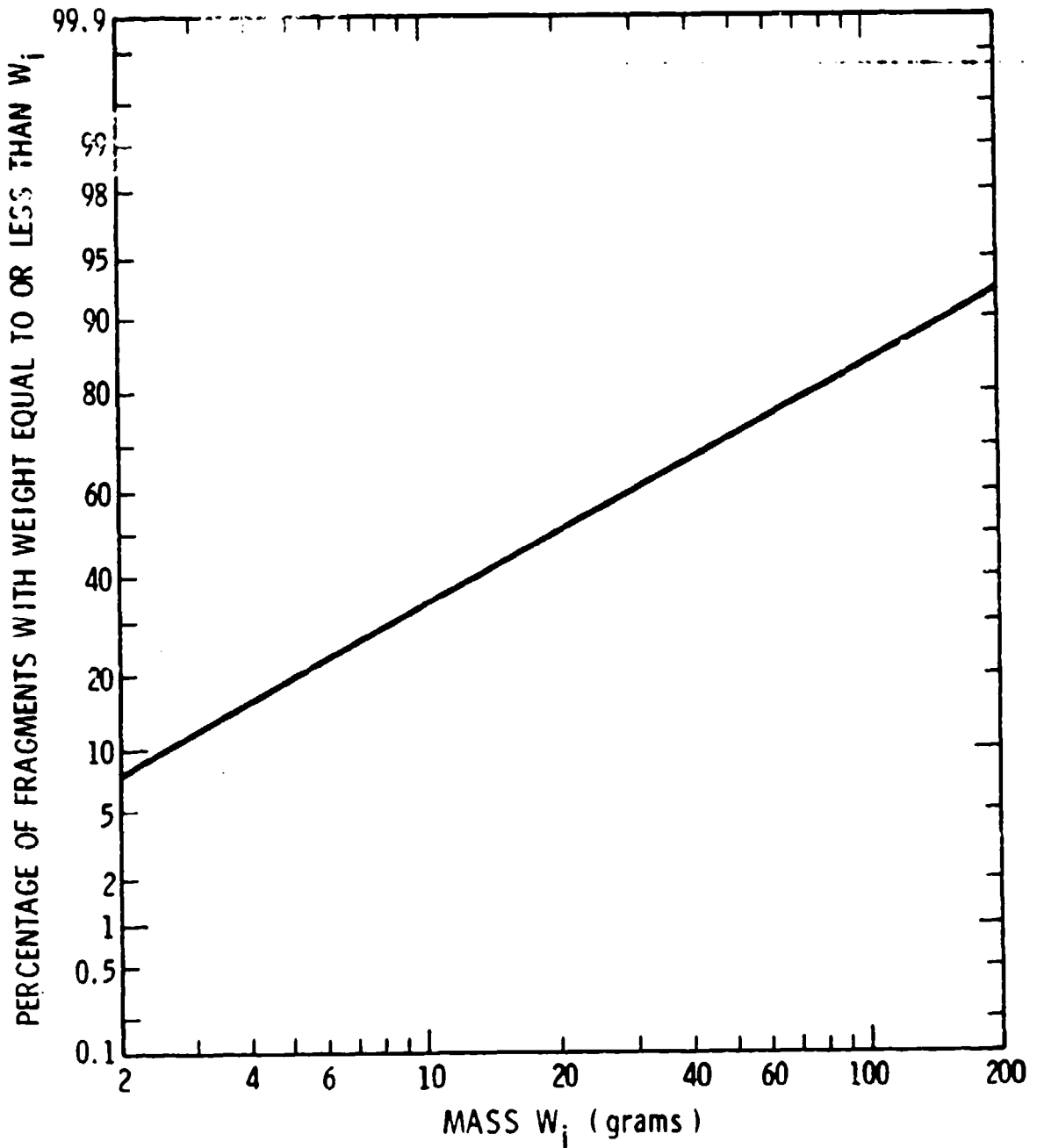
Figure 4-54. Fragment Mass Distribution for Small
Cylinders, $V = 0.05 \, m^3$, $P \approx 4.2 \, MPa$

$(\, lb_m = kg \times 2.205 \,)$

TABLE 4-2. PARAMETERS OF BURSTING TANKS

Tank #	Burst Pressure (P) MPa	Volume m³	Mean Frag. Mass ($\overline{W}$) g	$\dfrac{\overline{W}}{W(T)}$	$\dfrac{P}{\sim u}$	$\dfrac{PV}{Eo}$
A	4.309	0.038	19.5	0.00505	0.0042	3?
B	4.137	0.048	20.6	0.00444	0.0040	47
D	55.160	0.170	713	0.00917	0.0533	2,238
E	56.050	0.170	795	0.00964	0.0542	2,274

Tests for significant differences in means were made for Tanks A and B and for Tanks D and E. As shown in Appendix 4F no significant difference was found, so the fragment mass distribution of Tanks A and B and of Tanks D and E were averaged. These average distributions are shown in Figures 4-54 and 4-55. These figures can be used for fragment mass estimation in the same manner as Figures 4-46 through 4-50 are used for fragment initial velocity estimation.

Figure 4-56 is a plot of normalized yield (PV/E_o) versus mean fragment mass ($\overline{W}$) for the four tanks. Two of the four points are clustered at each end of the range shown in Figure 4-56. Thus, the response in the middle of the range is still unknown. That is, the relationship of $\overline{W}$ to PV/E_o may not be linear on a log-log-scale. Data points in the mid-ranges are needed to confirm or deny the linear relationship.

With the risks described above, one can estimate mean fragment mass for any decided ratio of PV/E_o up to 3 kg. One could then estimate the 90th percentile of the distribution (that value of fragment mass which would equal or exceed the mass of 90% of the fragments) by using the estimate of the standard deviation (S) from the average of Tanks D and E (1.695). An example follows:

For a burst pressure (P) of 10^8 Pa (1,400 psi) and a tank volume of 0.80 m³ (2.83 ft³)

$$PV = (.080)(10^8) = 8 \times 10^6$$
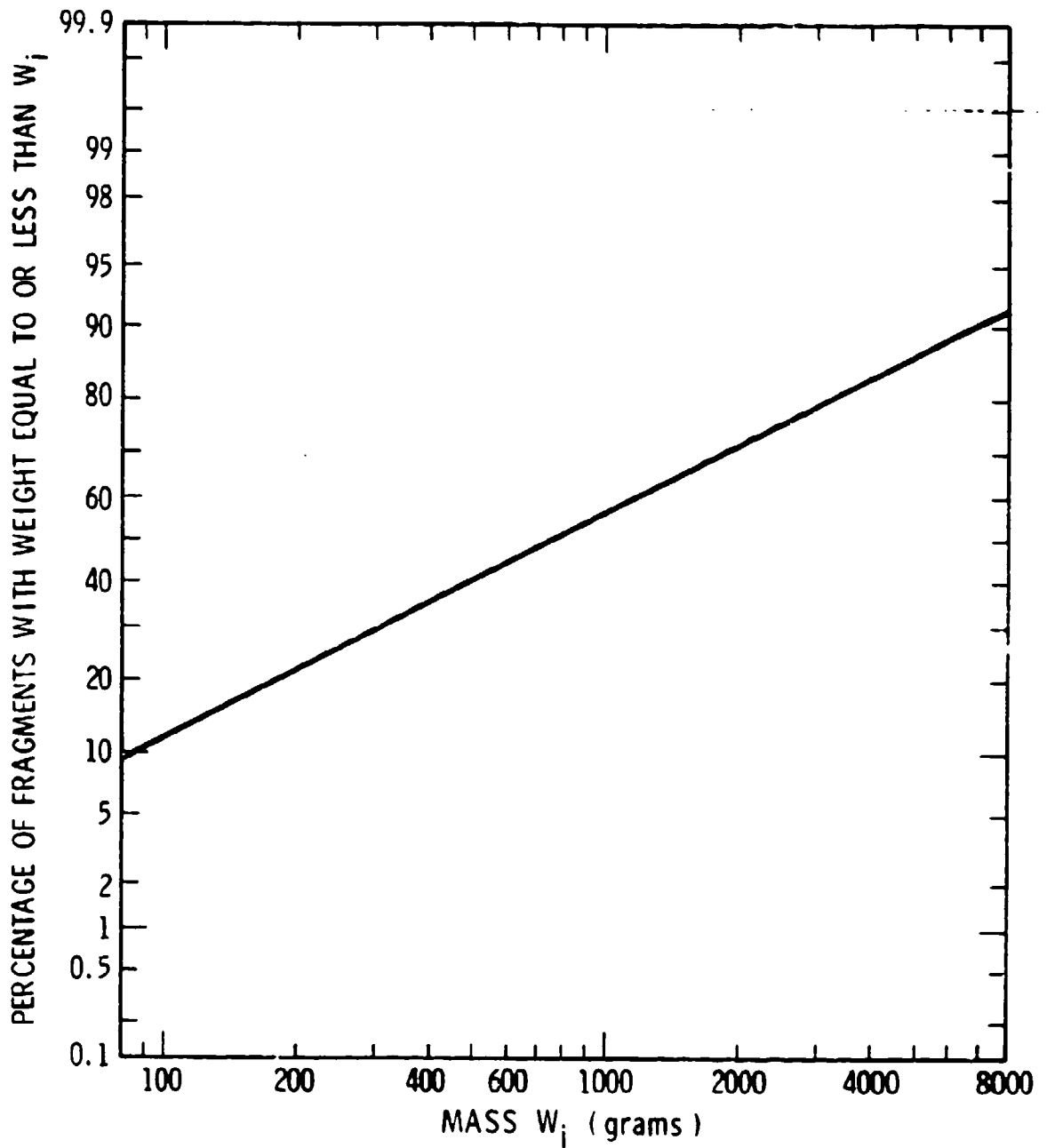
Figure 4-55. Fragment Mass Distribution for Titanium Alloy
Spheres, V = 0.170 m³, P = 55 MPa

The x-axis is labeled "MASS W_i (grams)" with values 100, 200, 400, 600, 1000, 2000, 4000, 8000.

The y-axis is labeled "PERCENTAGE OF FRAGMENTS WITH WEIGHT EQUAL TO OR LESS THAN W_i" with values 0.1, 0.5, 1, 2, 5, 10, 20, 40, 60, 80, 90, 95, 98, 99, 99.9.

($1b_m$ = kg X 2.205)

$$\frac{PV}{E_o} = \frac{8,000,000}{4190} = 1900$$

Entering the chart (Figure 4-56) on the abscissa of 1900, reading up to the intersection of the line and over the ordinate, a value of 560 g is obtained for mean fragment mass. Any Percentile (P_p) value of fragment mass can then be estimated by the formula:

$$P_p = \exp. (\ln \overline{W} + K s),$$

where $\overline{W}$ is the mean mass, s is the estimate for the standard deviation, and k is a value from the normal distribution table. Typical values are shown in Table 4-3.

For the 90th percentile,

$$P_{90} = \exp \lceil \ln 560 + 1.28 \cdot 1.695 \rceil$$

$$= \exp (8.4976) = 4.903 \text{ kg } (10.79 \text{ lb}_m)$$

Thus, one would expect that 90% of the fragments would have a mass equal to or less than 4.903 kg (10.79 lb$_m$).

TABLE 4-3. VALUES OF k OF PERCENTILES
OF THE NORMAL DISTRIBUTION

Percentile	99	95	90	80	70
k	2.33	1.65	1.28	0.84	0.53

4-7   Probability of Fragment Arrival Versus Range

4-7.1   Propellant Explosions

From Reference 3, Figure 4-57 is a representation of fragment distance versus percent yield, with a 95 percent confidence interval. The derivation of this figure is explained in Appendix 4F.
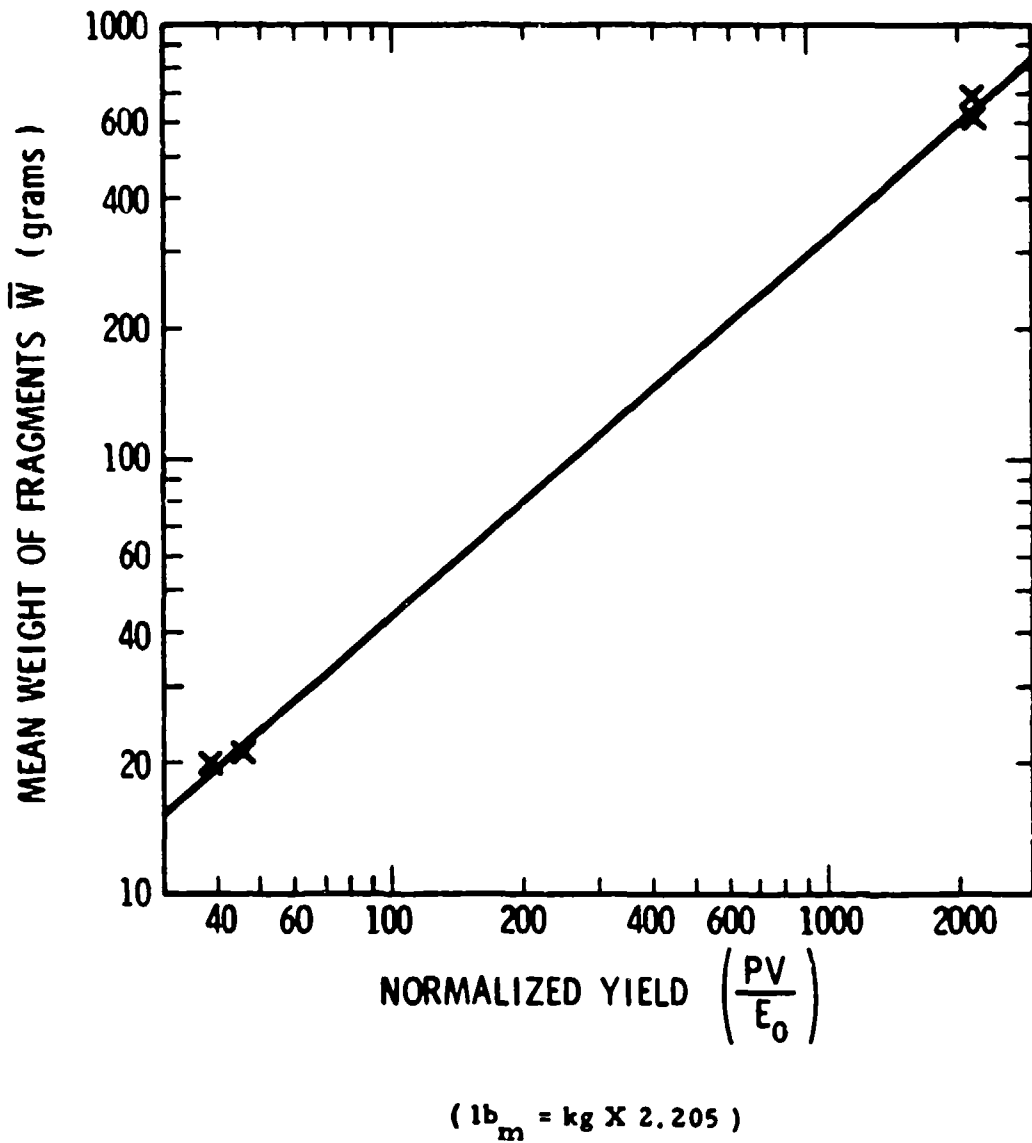
Figure 4-56. Normalized Yield Vs Mean Fragment Mass
for Bursting Tanks

MEAN WEIGHT OF FRAGMENTS $\overline{W}$ (grams)

NORMALIZED YIELD $\left(\dfrac{PV}{E_0}\right)$

$(1b_m = kg \times 2.205)$
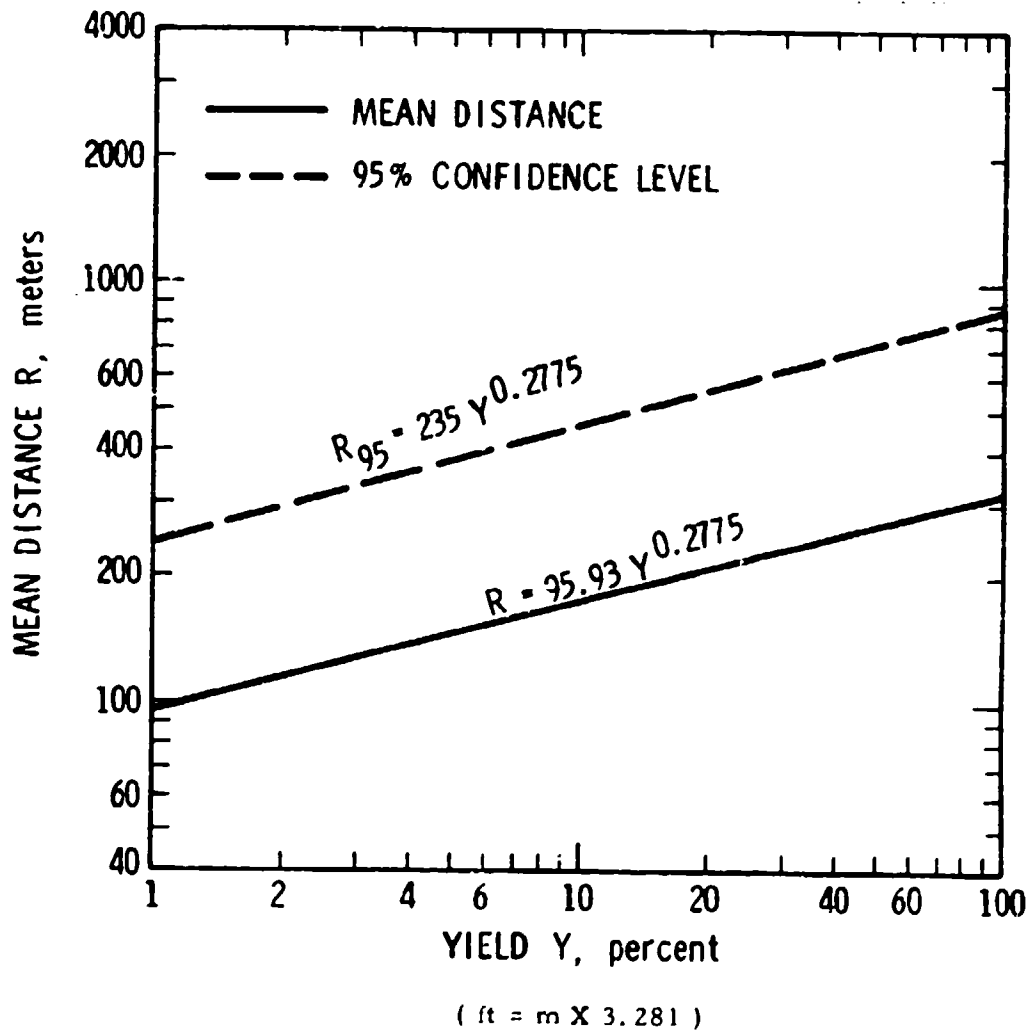
Figure 4-57. Fragment Range Vs Yield, Propellant
Explosions

Figure 4-57 can be used to estimate the mean distance of a fragment range for any given yield (percent). Also, one can obtain a 95% confidence level on maximum distance. For example, given a yield of 20%, one would expect that 95% or more of the fragments would fall within 560 meters of the explosion center.

4-7.2   Gas Vessel Bursts

In the experiment by Pittman (Reference 4), the fragments from the bursting tanks were partially contained in a circular area with a 20 foot radius with 8 ft high walls on the perimeter. Thus, the data on the fragment range was severely biased.

However, by exercising the computer programs (Appendix 4E) for fragment range as a function of fragment mass, drag, and flight angle, a distribution of fragment ranges was obtained for each of four tanks. These distributions were well fitted to members of the normal of Gaussian family.

Then, "t" tests for significant difference in mean ranges for Tanks A and B and for Tanks D and E were made. In the statistical sense, there were no significant differences in means between Tanks A and B, and between Tanks D and E.

Figures 4-58 and 4-59 present these simulated fragment range distributions for Tanks A and B and for Tanks D and E respectively. These charts can be used to estimate fragment range for similar gas vessels.

Complete details on the derivation of the simulated fragment range, goodness of fit tests, and "t" tests are given in Appendix 4F.
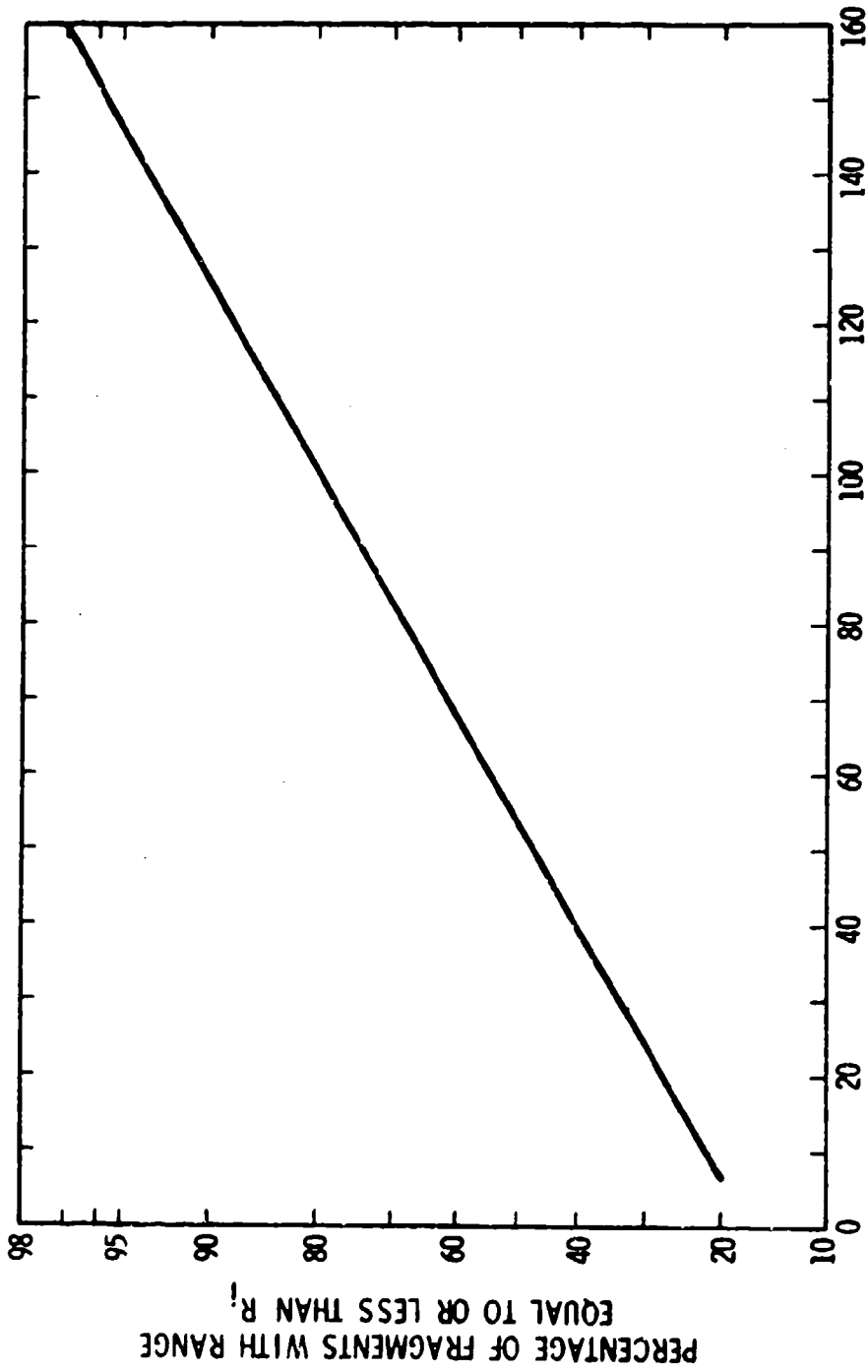
Figure 4-58. Fragment Range Distribution for Small
Cylinders, V = 0.05 m, P = 4.2 MPa

RANGE R, meters

(ft - m X 3.281)

PERCENTAGE OF FRAGMENTS WITH RANGE
EQUAL TO OR LESS THAN R_i

RANGE R, meters

(m m X 3.281)

PERCENTAGE OF FRAGMENTS WITH RANGE EQUAL TO OR LESS THAN R_i
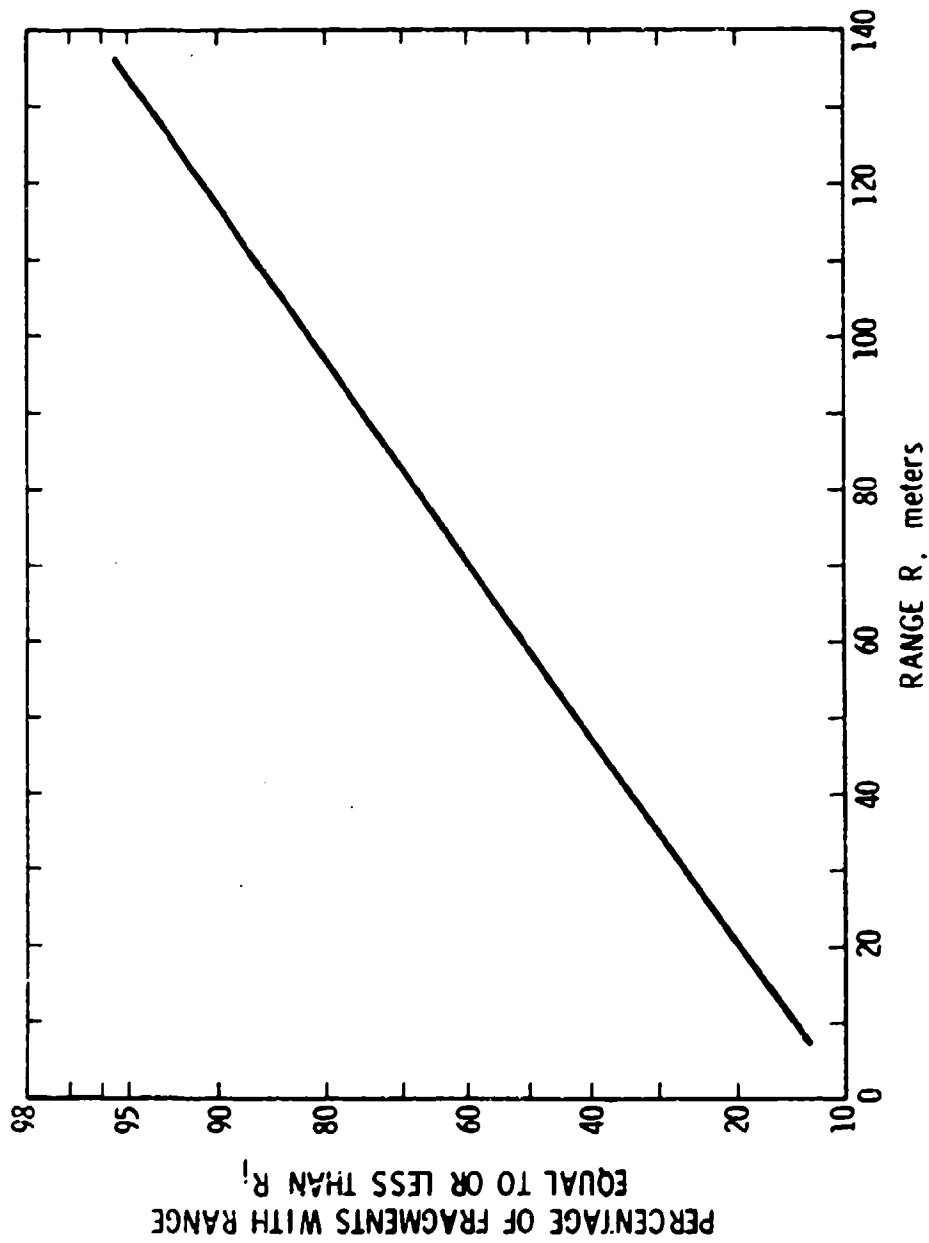
Figure 4-59. Fragment Range Distribution for Spheres.
V = 0.170 m^3, P = 55 MPa

LIST OF REFERENCES

1. Boyer, D. W., H. L. Brode, I. I. Glass, and J. G. Hall, Blast From a Pressurized Sphere, UTIA Report No. 48, Institute of Aerophysics, University of Toronto, 1958.

2. Taylor, D. B. and C. F. Price, "Velocities of Fragment From Bursting Gas Reservoirs," ASME Transactions, Journal of Engineering for Industry, November 1971.

3. Baker, W. E., V. B. Parr, R. L. Bessey, and P. A. Cox, "Assembly and Analysis of Fragmentation Data for Liquid Propellant Vessels," NASA Report CR-134538, January 1974.

4. Pittman, J. F., "Blast and Fragment Hazards From Bursting High Pressure Tanks", Naval Ordnance Laboratory Report NOLTR 72-102, May 1972.

APPENDIX IV. A

METHODS FOR ESTIMATING FRAGMENT
INITIAL VELOCITIES

Figure 4A-1 shows the conceptual models used in analyzing bursting confinement vessels to obtain estimates of initial fragment velocities. The spherical confinement vessel case has been discussed in References 1 and 2. For this case the sphere is conceived of as fragmenting into n fragments of circular projection, and the fragments travel in a radial direction without tumbling. The energy of the confined gas is partitioned between the kinetic energy of the fragment, the energy of the gas escaping between the cracks between the fragments as they are formed, and the energy of the expansion of the internal gas. The equations of motion for the fragments are developed in Reference 2, and a computer code SPHER has been developed for the solution of these nonlinear differential equations describing the fragment motion. Solution of the differential equations is accomplished by use of Runge-Kutta integration techniques. Program SPHER appears at the end of this appendix with a description of the input-output variables.

Figure 4A-1 also shows the conceptualization of a cylinder fragmenting into n fragments. For this case, the fragments are considered to be strips which move radially from the center of the cylinder. Motion of the cylinder ends is not considered. Figure 4A-2 shows the geometric parameters of the cylinder used in the analysis. A cylinder of length L and radius R is assumed to burst into n strip fragments of width d and thickness th. A cross-section of each strip is a segment of the cross-section of the cylinder having a segment height of h and segment diameter d. In the following analysis, the projected area of each fragment is obtained from the surface area and the initial subtended angle of the fragment at the center of the cylinder, with the result being Equation (4A-11). The area of a crack about any fragment at any time is obtained by assuming the cracks only form lengthwise along the cylinder, and by obtaining an equation for the width of these cracks in terms of the initial radius of the cylinder and the radial distance r, the fragment has traveled at any time, t. The equation for fragment area is given in Equation (4A-14). One of the differential equations of motion derived on the basis of an adiabatic gas expansion and radial motion of the fragments is the same for this analysis as it was for the sphere, as are the general equations used for nondimensionalization; see Equation (4A-15). A second differential equation, Equation (4A-35), is obtained from the perfect gas law assumption, an equation for the mass flow of gas through the cracks formed between the fragments [Equation (4A-19)], and cylinder geometry considerations. Values for the nondimensional constants are also obtained through these considerations and are given in Equations (4A-36) and (4A-37).

a. n - Fragment sphere

Fragment of circular
section traveling
radially

b. 2 - Fragment cylinder

c. n - Fragmenting cylinder
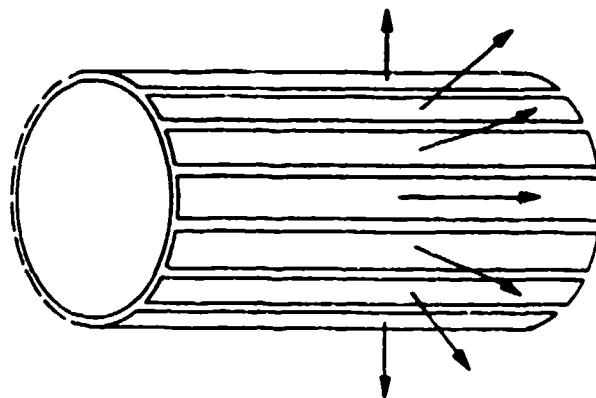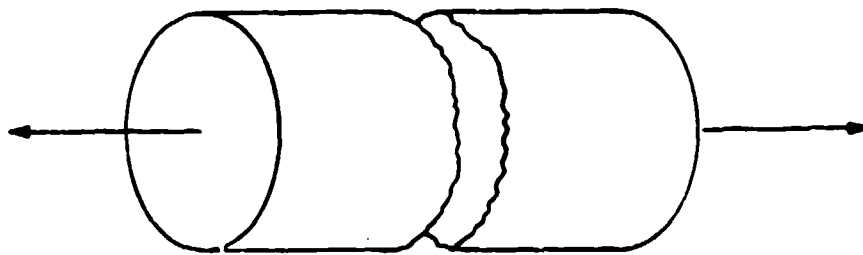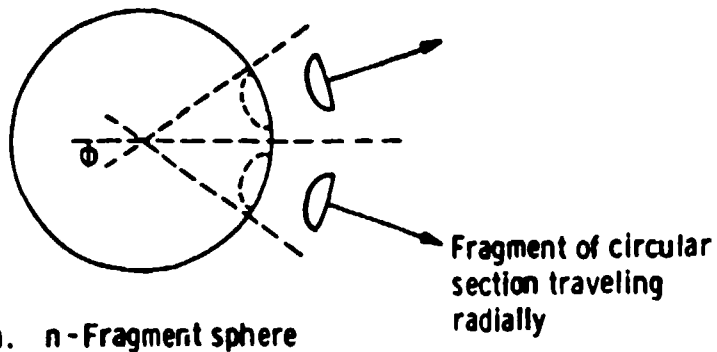
Figure 4A-1. Conceptual Models of Bursting
Confinement Vessels
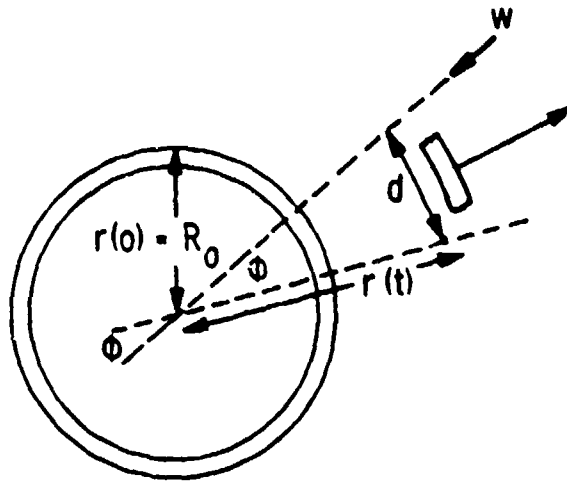
a. Cylinder cross section
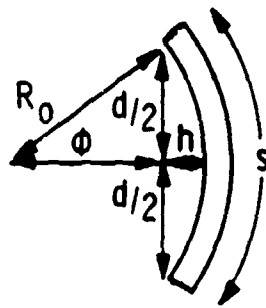
b. Strip fragment cross section

Figure 4A-2. Geometric Parameters for a
Fragmenting Cylinder

This analysis does not take into account the stored energy (strain energy) in the walls of the container immediately prior to burst. The strain energy for the spherical containment vessel case can be shown to be given approximately by:

$$SE = 2 \pi R^2 h (1 - K) \frac{\sigma_y^2}{E} \qquad (4A-1)$$

where

σ_y = the stress in the container wall

SE = the strain energy stored in the vessel

R = the sphere radius before burst

h = the sphere wall thickness

ν = Poisson's ratio for the material

E = the bulk modulus for the material

This equation may be written:

$$SE = \pi R^4 P^2 \frac{(1 - \nu)}{(2 Eh)} \qquad (4A-2)$$

where P is the pressure of the confined gas, by substitution of the approximate relation,

$$2 h \sigma_y = R P \qquad (4A-3)$$

The stored energy in the confined gas is

$$GE = \frac{4 \pi P R^3}{3 (K - 1)} \qquad (4A-4)$$

Thus, the ratio, e, of the strain to stored energy is

$$e = \frac{3 R P (1 - \gamma) (K - 1)}{8 h E} \qquad (4A-5)$$

For a steel container pressurized with air having $R/h \leq 100$,

4A-4

$$e = 5.25 \times 10^{-6} \, P \, (kg/cm^2)$$

$$\approx 3.70 \times 10^{-7} \, P \, (psi)$$

$$\approx 5.37 \times 10^{-11} \, P \, (Pa)$$

Thus, even for this very high radius-to-thickness ratio, pressure would have to exceed 10^5 psi to produce significant strain energy (3%) relative to the total energy available. We therefore conclude that, as a rule, strain energy can be neglected. This is emphatically not true when the vessel rupture process is similar to that of a high explosive bomb casing burst, where considerable expansion of the case occurs before rupture (up to 1.8 radii).

A computer code for the simultaneous solution of nonlinear differential equations [Equations (4A-15) and (4A-35)] (CYLIN) has been developed. This code, similar to code SPHER, uses the Runge-Kutta integration technique for the solution of the differential equations. The code, along with definitions for its input and output parameters, is given at the end of the appendix. Figures 4A-3 and 4A-4 show comparative results from the two computer codes. Figure 4A-4 shows the maximum fragment velocities predicted for spheres and cylinders of equivalent volume as a function of the number of fragments assumed. For all cases, the value for maximum fragment velocity becomes a constant when more than about 10 to 30 fragments are assumed. In general, for equal volumes and radii, the sphere fragment velocities are less than the cylinder fragment velocities. This may be because of the assumption that no energy is used in accelerating the ends of the cylinders. Thus, more energy is available for the fragments formed from the cylindrical wall. Figure 4A-3 gives comparative results for maximum fragment velocities for the two geometric cases versus mass ratio for gases of various specific heat ratios. Again, the predicted cylindrical velocities are higher than that of the spherical velocities.

Some empirical verification of the results from program SPHER is given in Appendix IV.B. Very little data are available, however, to verify this analysis. Although there are data available for fragment velocities from cylindrical confinement vessels, most of these data are from bursting artillery shells. The processes involved in the fragmentation of these shells are so dynamic that the shell may expand up to twice its diameter before cracks are formed between the fragments. Our analysis would not be applicable to this kind of event. Our analysis assumes a relatively brittle confinement vessel which does not expand significantly prior to the time that cracks are formed between the fragments. This would be the case for confinement vessels which are slowly pressurized, as opposed to the highly dynamic situation existing when a high explosive is detonated internal to the confinement vessel.
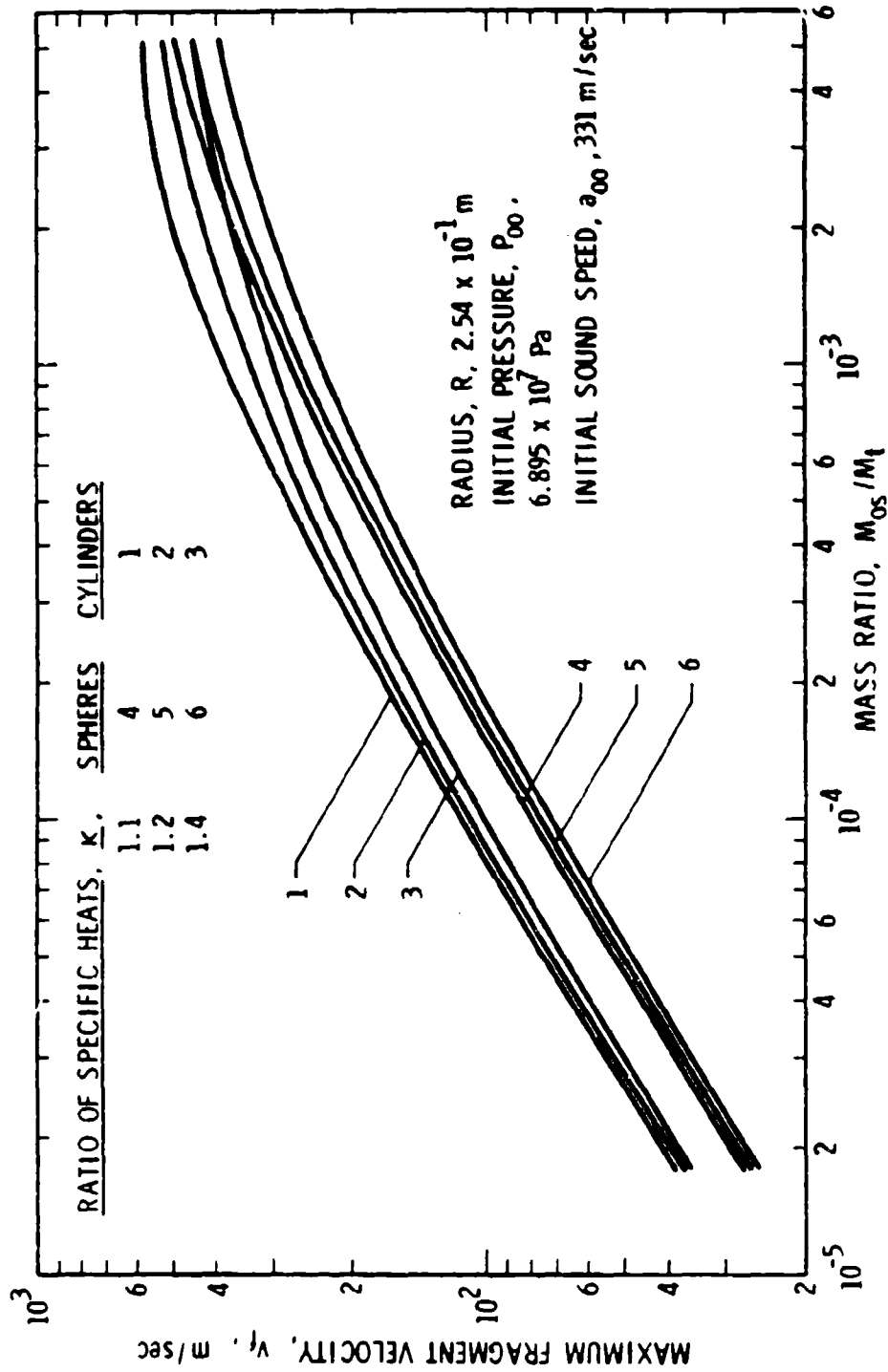
Figure 4A-3. Maximum Fragment Velocity as a Function of
Mass Ratio for Spheres and Cylinders of
Equivalent Volume
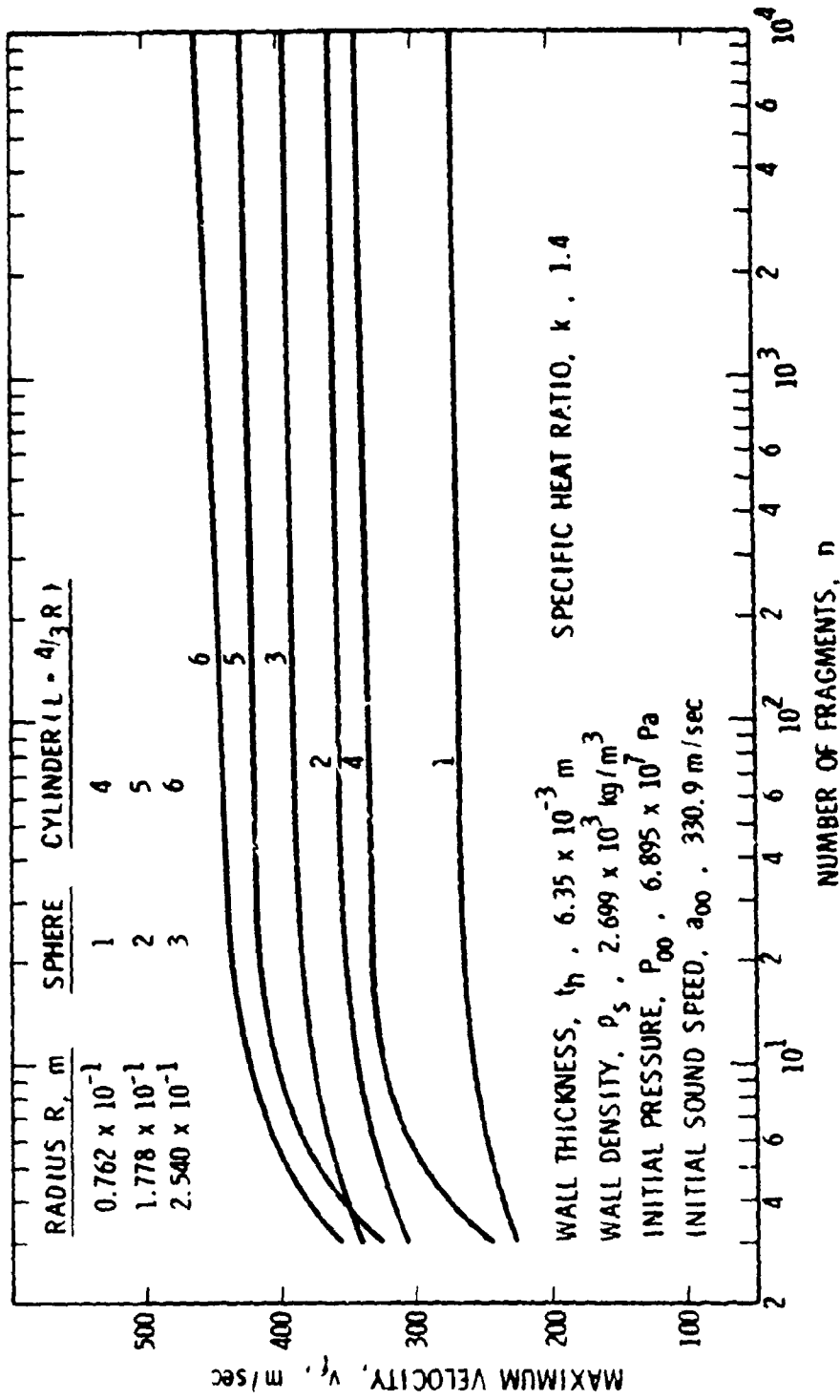
Figure 4A-4. Maximum Fragment Velocity as a Function of
Number of Fragments for Equivalent Volume
Cylinders and Spheres

Analysis for a Cylindrical Shell Fragmenting Into Strip Fragments

Variable List:

A   -   term in Equation (4A-16)

A_f -   fragment area

a_{oo} -   sound speed in confined gas, $\tau = 0$

a_* -   critical sound speed in mass flow equation

B   -   term in Equation (4A-16)

C   -   term in Equation (4A-16)

D   -   term in Equation (4A-16)

d   -   width of fragment segment

F   -   fragment projected area

g   -   nondimensionalized displacement of a fragment

h   -   segment height (see Figure 4A-2)

k   -   mass flow rate coefficient

L   -   cylinder length

M   -   mass of contained gas at any instant, τ

M_f -   fragment mass

M_t -   cylindrical shell mass

n   -   number of fragments

P   -   crack perimeter about a fragment

P_* -   nondimensionalized pressure

P_o -   pressure of confined gas at any instant, τ

P_{oo} - initial pressure of confined gas

R - initial cylinder radius

r - fragment displacement at any instant, τ

s - segment length

T_o - temperature of confined gas at any instant, τ

t_h - shell thickness

V_o - volume of confined gas at any instant, τ

V_s - volume of shell material

w - crack width

x - nondimensionalizing constant for displacement

α - nondimensional constant

β - nondimensional constant

Θ - nondimensionalizing constant for time

θ - angle subtended at the center of the cylinder by a fragment $\tau = 0$

κ - ratio of specific heats for confined gas

ρ_o - confined gas density at any instant, τ

ρ_* - critical density of gas in mass flow equation

ρ_s - density of shell material

τ - time

ξ - nondimensionalized time

Prime denotes derivatives with respect to ξ .

From considerations of the cylinder geometry (see Figure 4A-2):

$$M_t = \rho_s V_s = \pi \rho_s L \left[(R + t_h)^2 - R^2 \right] \tag{4A-6}$$

$$A_f = \frac{2 \pi R L}{n} \tag{4A-7}$$

$$F = L \cdot d = L \cdot 2 \left[R^2 - (R - h)^2 \right]^{1/2} \tag{4A-8}$$

From Figure 4A-2:

$$A_f = L \cdot S, \quad S = \frac{\theta}{2 \pi} \cdot 2 \pi R = \theta R, \quad \theta = \cos^{-1} \left(\frac{R - h}{R} \right)$$

Therefore,

$$A_f = L \cdot R \cdot \cos^{-1} \left(\frac{R - h}{R} \right) \tag{4A-9}$$

From Equations (4A-6) and (4A-9),

$$h = R \left(1 - \cos \frac{2 \pi}{n} \right) \tag{4A-10}$$

From Equations (4A-10) and (4A-8),

$$F = 2 L \cdot R \left[1 - \left(\cos \frac{2 \pi}{n} \right)^2 \right]^{1/2} \tag{4A-11}$$

The crack area at any time τ for fragment i is

$$(Pw)_i = 2 L \cdot w \tag{4A-12}$$

From Figure 4A-2, it may be seen that

$$w = \theta \left[r(\tau) - R \right] = \frac{2 \pi}{n} \left[r(\tau) - R \right] \tag{4A-13}$$

From Equations (4A-12) and (4A-13),

$$(Pw)_i = \frac{4 \pi L}{n} \cdot \left[r(\tau) - R \right] = \frac{4 \pi L \cdot R}{n} \left(\frac{r(\tau)}{R} - 1 \right) \tag{4A-14}$$

4A-10

From Reference 2, Equations (4A-19), (4A-20), and (4A-21),

$$
g'' = n P_* \left[1 - \frac{(g')^2}{(P_*)^{\kappa - 1/\kappa}} \right]^{\kappa / \kappa - 1}
$$

$$
X = \frac{M_t a_{oo}^2}{F P_{oo}} \left(\frac{2}{\kappa - 1} \right)^{1/2}
\tag{4A-15}
$$

$$
\theta = \frac{M_t a_{oo}}{F P_{oo}} \left(\frac{2}{\kappa - 1} \right)^{1/2}
$$

From differentiation of the ideal gas equation,

$$
\frac{d P_o(\tau)/d\tau}{P_o(\tau)} = \frac{1}{\rho_o(\tau) V_o(\tau)} \frac{d M(\tau)}{d\tau} + \frac{1}{T_o(\tau)} \frac{d T_c(\tau)}{d\tau}
$$

$$
- \frac{1}{V_o(\tau)} \frac{d V_o(\tau)}{d\tau}
\tag{4A-16}
$$

$$
A = B + C - D
$$

Using the variable changes $P_o(\tau) = P_{oo} \cdot P_*(\xi)$ t $\tau = \theta \xi$, term A becomes

$$
A = \frac{1}{\theta} \frac{P_*'(\xi)}{P_*(\xi)}
\tag{4A-17}
$$

and using these variable changes with the ideal gas law, term C becomes

$$
C = \frac{1}{\theta} \frac{\kappa - 1}{\kappa} \frac{P_*'}{P_*}
\tag{4A-18}
$$

The confined gas mass flow rate through the cracks is [from Equation (4A-12), Reference 2]

$$
\frac{d M(\tau)}{d} = - k \rho_* a_* P w
\tag{4A-19}
$$

The total crack area is

$$Pw = \Sigma (Pw)_i = n(Pw)_i$$

and from Equations (4A-14) and (4A-19)

$$= - k \rho_* a_* 4\pi L \cdot R \left(\frac{r(\tau)}{R} - 1 \right) \tag{4A-20}$$

But from the cylindrical geometry

$$V_o(\tau) = \pi r^2(\tau) \cdot L \tag{4A-21}$$

Thus, from Equations (4A-16), (4A-20) and (4A-21), term B becomes

$$B = \frac{1}{\rho_o(\tau) V_o(\tau)} \frac{dM(\tau)}{d\tau}$$

$$= \frac{1}{\rho_o(\tau) \cdot \pi r^2(\tau) \cdot L} \cdot \left[- k \rho_* a_* 4\pi L \cdot R \left(\frac{r(\tau)}{R} - 1 \right) \right]$$

$$= - \frac{4 k \rho_* a_* R}{\rho_o(\tau)} \left[\frac{1}{R r(\tau)} - \frac{1}{r^2(\tau)} \right] \tag{4A-22}$$

From standard one-dimensional flow relationships

$$\rho_* = \rho_o(\tau) \left(\frac{2}{\kappa + 1} \right)^{1/\kappa - 1} \tag{4A-23}$$

$$a_* = a_o(\tau) \left(\frac{2}{\kappa + 1} \right)^{1/2}$$

Assuming an adiabatic gas expansion

$$a_o(\tau) = a_{oo} P_*^{\kappa - 1/2\kappa}$$

and nondimensionalizing displacement and time

$$r(\tau) = X g(\xi) \qquad \tau = \theta \xi \tag{4A-24}$$

4A-12

we obtain from Equations (4A-22), (4A-23) and (4A-24)

$$B = -4k \left(\frac{2}{\kappa+1} \right)^{1/\kappa-1} \left(\frac{2}{\kappa+1} \right)^{1/2} a_{oo} P_*^{\kappa-1/2\kappa}$$

$$R \left[\frac{1}{R X g(\xi)} - \frac{1}{X^2 g(\xi)^2} \right] \tag{4A-25}$$

$$= \frac{-4k a_{oo} P_*^{\kappa-1/2\kappa} R \left(\frac{2}{\kappa+1} \right)^{\kappa+1/2(\kappa-1)}}{X^2 g^2(\xi)} \left[\frac{X g(\xi)}{R} - 1 \right] \tag{4A-26}$$

From Equation (4A-16)

$$D = \frac{1}{V_o(\tau)} \frac{d V_o(\tau)}{d\tau} \tag{4A-27}$$

Differentiating Equation (4A-21) gives

$$\frac{d V_o(\tau)}{d\tau} = \frac{d \pi r^2(\tau) \cdot L}{d\tau} = \pi L \cdot 2 r(\tau) \cdot \frac{d r(\tau)}{d\tau} \tag{4A-28}$$

Thus,

$$D = \frac{1}{V_o(\tau)} \frac{d V_o(\tau)}{d\tau} = \frac{2}{r(\tau)} \frac{d r(\tau)}{d\tau} \tag{4A-29}$$

Changing the variable with Equation (4A-24), term D becomes

$$D = \frac{2}{X g(\xi)} \frac{X}{\theta} g'(\xi) = \frac{2}{\theta} \frac{g'(\xi)}{g(\xi)} \tag{4A-30}$$

From Equations (4A-16), (4A-17), (4A-18), (4A-26), and (4A-30).

$$\frac{1}{\theta} \frac{P_*'}{P_*} = \frac{4 k a_{oo} P_*^{\kappa-1/2\kappa} R \left(\frac{2}{\kappa+1} \right)^{\kappa+1/2(\kappa-1)}}{X^2 g^2} \left(\frac{Y}{R} \cdot g - 1 \right)$$

(continued)

$$\mp \frac{1}{\theta} \left(\frac{\kappa - 1}{\kappa} \right) \frac{P'_*}{P_*} - \frac{2}{\theta} \frac{g'}{g} \tag{4A-31}$$

$$\frac{P'_*}{\theta \kappa P_*} = \frac{4 k a_{oo} P_*^{\kappa - 1/2\kappa} R \left(\frac{2}{\kappa + 1} \right)^{\kappa + 1/2(\kappa - 1)}}{X^2 g^2} \left(\frac{X}{R} g - 1 \right)$$

$$- \frac{2}{\theta} \frac{g'}{g} \tag{4A-32}$$

Multiplying through Eq. (4A-32) by $\theta \kappa g^2$

$$\frac{P'_*}{P_*} g^2 = - \frac{4 k \kappa \theta a_{oo} g \left(\frac{2}{\kappa + 1} \right)^{\kappa + 1/2(\kappa - 1)}}{X} P_*^{\kappa - 1/2\kappa}$$

$$+ \frac{\theta 4 k \kappa a_{oo} R \left(\frac{2}{\kappa + 1} \right)^{\kappa + 1/2(\kappa - 1)}}{X^2} P_*^{\kappa - 1/2\kappa} - 2 \kappa g g' \tag{4A-33}$$

From Equation (4A-15),

$$\frac{\theta}{X} = \frac{1}{a_{oo}} \left(\frac{2}{\kappa - 1} \right)^{-1/2}$$

$$\frac{\theta}{X^2} = \frac{F^2 P_{oo}^2}{M_t^2 a_{oo}^4} \left(\frac{2}{\kappa - 1} \right)^{-2} \cdot \frac{M_t a_{oo}}{F P_{oo}} \left(\frac{2}{\kappa - 1} \right)^{1/2}$$

$$= \frac{F P_{oo}}{M_t a_{oo}^3} \left(\frac{2}{\kappa - 1} \right)^{-3/2} \tag{4A-34}$$

Assume constants α and β such that Equation (4A-33) becomes

$$\frac{P'_*}{P_*} g^2 = [- \alpha g + \alpha \beta] P_*^{\kappa - 1/2\kappa} - 2 \kappa g g' \tag{4A-35}$$

4A-14

Then from Equations (4A-33), (4A-34), and (4A-35),

$$\alpha = 4 k \kappa a_{oo} \left(\frac{2}{\kappa+1} \right)^{\kappa+1/2(\kappa-1)} \cdot \frac{1}{a_{oo}} \left(\frac{2}{\kappa-1} \right)^{-1/2} \qquad (4A-36)$$

$$= 4 k \kappa \left(\frac{2}{\kappa+1} \right)^{\kappa+1/2(\kappa-1)} \left(\frac{2}{\kappa-1} \right)^{-1/2} \qquad (4A-37)$$

$$\beta = 4 k \kappa a_{oo} R \left(\frac{2}{\kappa+1} \right)^{\kappa+1/2(\kappa-1)} \cdot \frac{F P_{oo}}{M_t a_{oo}^3} \left(\frac{2}{\kappa-1} \right)^{-3/2}$$

$$\cdot \frac{1}{4 k \kappa \left(\frac{2}{\kappa+1} \right)^{\kappa+1/2(\kappa-1)} \left(\frac{2}{\kappa-1} \right)^{-1/2}}$$

$$\beta = R \left(\frac{2}{\kappa-1} \right)^{-1} \frac{F P_{oo}}{M_t a_{oo}^2} \qquad (4A-38)$$

Differential Equations (4A-15) and (4A-35) are solved simultaneously by code CYLIN using the Runge-Kutta integration technique for initial conditions

$$g(0) = \frac{R}{X}. \quad P_*(0) = 1.0 \text{ and } g'(0) = 0$$

Since M_t and F are both proportional to L, M_t/F is independent of the cylinder length. Thus, length L drops out of the equations for β, X, and θ; i.e., the cylinder length does not enter into the solution for Equations (4A-15) and (4A-35).

Computer Codes CYLIN and SPHER

The following computer codes were used to solve the simultaneous nonlinear differential equations for motion of fragments emanating from bursting confinement vessels of cylindrical and spherical configuration. These codes were used to generate the data for the method of deterministic fragment initial velocity calculations given in the text of the workbook.

PROGRAM VARIABLE DEFINITIONS FOR CODES
SPHER AND CYLIN

Program Variable	Definition	Units SI	English
CAPI	Ratio of specific heats of gas	--	--
AO	Sound speed	m/s	in/sec
PO	Initial pressure	Pa	psi
RR	Cylinder radius	m	in.
CL	Cylinder length	m	in.
EL	End length	m	in.
CT	Cylinder thickness	m	in.
ET	End thickness	m	in.
DEN	Density	kg/m^3	lb_f/in^{3*}
VO	Volume	m^3	in^3
TM	Total mass of confinement vessel	kg	lb_f^{**}
FN	Number of fragments (always two)	--	--
FK	Gas discharge coefficient	--	--
AH	Time interval of iteration	--	--
XMAX	Maximum time of iteration	--	--
PERI	Perimeter (calculated)	m	in.
FF	Area of cross section to which force is applied (calculated)	m^2	in^2
XX	Characteristic dimension (calculated)	m	in.

---

[*] lb_f indicates English weight measurement of pounds of force. Sea level gravitation is assumed.

Program Variable	Definition	Units SI	English
THETA	Characteristic time (calculated)	s	s
A1	Dimensionless mass parameter	--	--
B1	Dimensionless geometry parameter	--	--
NEND	Branching constant. If zero, program stops. If > 1, program continues.	--	--
G1	distance to initial velocity	m	in.
G2	initial fragment velocity	m/s	ft/sec
G3	initial fragment acceleration	m/s^2	in/sec^2
G4	final explosive product mixture pressure	Pa	psi
T1	time to initial velocity	s	s
PI	the constant, π	none	none
CAP2	the quantity $(1 - \kappa)/\kappa$	none	none
CAP3	the quantity $-1/\kappa$	none	none
CAP4	the quantity $(3\kappa - 1)/2\kappa$	none	none
CØ	normalized initial fragment displacement from center of sphere	none	none
X	normalized time	none	none
Y(2)	normalized velocity	none	none
Y(3)	normalized pressure	none	none
Y(1)	normalized fragment displacement	none	none
NA	number of differential equations to be solved	none	none
F(1), F(2), F(3)	differential equations solved		
TT	normalized time	none	none
PS	normalized pressure	none	none

```
C
C

      PROGRAM SPHER   (INPUT,OUTPUT,TAPE1 =OUTPUT,TAPE2 =INPUT)
      DIMENSION F(3),Y(3),W1(3),W2(3),PS(200),TT(200)
  310 FORMAT (3E10.5)
  312 FORMAT(4E10.3)
  314 FORMAT (2E10.3)
  315 FORMAT (3/,20H GAS CHARACTERISTICS,/,7H KAPPA=,E10.3,
     115H    SOUND SPEED=,E13.5,7H IN/SEC,/,10H PRESSURE  ,E10.3,4H PSI,
     12/,24H VESSEL CHARACTERISTICS,/,8H RADIUS=,E10.3,5H INS,,
     18H    MASS=,E10.3,16H LBS,-SEC,SO,/IN,/,18H NO, OF FRAGMENTS=,
     1E10.3,2/)
  319 FORMAT (3/,13H FINAL VALUES,/,6H TIME=,E10.3,4H SEC,/,
     110H DISTANCE=,E10.3,4H INS,/,10H VELOCITY=,E10.3,7H FT/SEC,/,
     114H ACCELERATION=,E10.3,10H IN/SQ-SEC,/,10H PRESSURE=,E10.3,
     14H PSI)
  320 FORMAT (52H CHARACTERISTICS OF MOTION OF FRAGMENTS (NORMALIZED)
     1,2/,10H    T-NORM,4X,1HG,10X,2HG',7X,3HG'',/)
  321 FORMAT ( /,22H PRESSURE (NORMALIZED),/,4X,7H T-NORM,6X,
     16HP-NORM,/)
  322 FORMAT (14H INITIAL CONDITIONS,/,6H X(0)=,E10.4,7H  G(0)=,E10.4,
     18H  G'(0)=,E10.4,9H  P-NORM=,E10.4,2/)
  502 FORMAT (/,8HTOO MUCH)
  600 FORMAT (I2)
 3001 FORMAT (E10.3)
  500 JJ=0
      READ (2,310) CAP1,AO,PO
      READ (2,312) FN,RR,TM,FK
      READ (2,314) AH,XMAX
      READ (2,600) NEND
      GO TO 551
  550 PO=PO/10,
      AH=1.0E-5
  551 CONTINUE
      WRITE (1,315) CAP1,AO,PO,RR,TM,FN
      PI= 3.1415926535
      FF=4,*PI*(RR**2 )*((1,/FN)-(1,/FN**2))
      XX=TM*(AO**2,0)*(2,0/(CAP1-1))/(FF*PO)
      THETA=TM*AO*((2,0/(CAP1-1,0))**0,5)/(FF*PO)
      CAP2=(1,00-CAP1)/CAP1
      CAP3=-1,0/CAP2
      CAP4=(3,0*CAP1-(1,0))/(2,0*CAP1)
      A1=3,*FK*CAP1*((2,/(CAP1+1,))**((CAP1+1,)/(2,*(CAP1-1,))))*
     1((2,0/(CAP1-1,))**-0,5)
      B1=((RR)**2)*((2,/(CAP1-1,))**-2)*((FF*PO)**2)/
     1((TM**2)*(AO**4))
      CO=RR/XX
      X=0,0
      Y(1)=CO
      Y(2)=0,0
      Y(3)=1,0
      YT=0,0
      YTT=0,0
      WRITE (1,322) X,Y(1),Y(2),Y(3)
      NA=3
      F(1)=Y(2)
      F(2)=FN*Y(3)*((1,00-(Y(2)**2,0)*(Y(3)**CAP2))**CAP3)
      F(3)=((Y(1)**-3)*(Y(3)**CAP4)*(A1*B1-A1*(Y(1)**2)))-
     13,*CAP4*(Y(2)*Y(3)/Y(1))
```

```
      F2=F(2)
   30 S=RKLDEQ (NA,Y,F,X,AH,0)
   50 F(1)=Y(2)
      F(2)=F11*Y(3)*((1.00-(Y(2)**2.0)*(Y(3)**CAP2))**CAP3)
      F(3)=((Y(1)**-3)*(Y(3)**CAP4)*(A1+B1-A1*(Y(1)**2)))-
     13.*CAP1*(Y(2)*Y(3)/Y(1))
      IF (S-1.) 40,30,40
   40 CONTINUE
      F2T=(F2-F(2))/F2
      F2T=ABS(F2T)
      IF (F2T-.10) 700,700,701
  700 AH=3.0*AH
  701 CONTINUE
      JJ=JJ+1
      IF(JJ-200) 504,503,503
  504 CONTINUE
      TT(JJ)=X
      PS(JJ)=Y(3)
      YTT=(Y(2)-YT)/Y(2)
      YT=Y(2)
      IF(YTT-.001) 10,10,41
   41 CONTINUE
      GO TO 30
   10 CONTINUE
      T1=THETA*X
      G1=XX*Y(1)-XX*CO
      G2=XX/THETA*(Y(2))
      G2=G2/12.0
      G3=(XX/(THETA)**2.0)*F(2)
      G4=PO*Y(3)
      WRITE (1,319) T1,G1,G2,G3,G4
      IF (PO-10000.) 552,552,550
  552 IF (NEND-1) 501,500,500
  503 CONTINUE
      WRITE  (1,502)
  501 STOP
      END
```

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OF POOR QUALITY

```
      PROGRAM CYLIN   (INPUT,OUTPUT,TAPE1 =OUTPUT,TAPE2 =INPUT)
      DIMENSION F(3),Y(3),W1(3),W2(3),PS(200),TT(200)
  310 FORMAT (3E10.5)
  312 FORMAT (4E10.3)
  314 FORMAT (2E10.3)
  315 FORMAT (3/,20H GAS CHARACTERISTICS,/,7H KAPPA=,E10.3,
     115H   SOUND SPEED=,E13.5,7H IN/SEC,/,10H PRESSURE ,E10.3,4H PSI,
     12/,23H VESSEL CHARACTERISTICS,/,8H RADIUS=,E10.3,5H INS.,
     18H   MASS=,E10.3,16H LBS.-SEC.SQ./IN,/,18H NO. OF FRAGMENTS=,
     1E10.3,2/)
  319 FORMAT (3/,13H FINAL VALUES,/,6H TIME=,E10.3,4H SEC,/,
     110H DISTANCE=,E10.3,4H INS,/,10H VELOCITY=,E10.3,7H FT/SEC,/,
     114H ACCELERATION=,E10.3,10H IN/SQ-SEC,/,10H PRESSURE=,E10.3,
     14H PSI)
  320 FORMAT (52H CHARACTERISTICS OF MOTION OF FRAGMENTS (NORMALIZED)
     1,2/,10H    T-NORM,4X,1HG,10X,2HG',7X,3HG'',/)
  321 FORMAT ( /,22H PRESSURE (NORMALIZED),/,4X,7H T-NORM,6X,
     16HP-NORM,/)
  322 FORMAT (19H INITIAL CONDITIONS,/,6H X(0)=,E10.4,7H  G(0)=,E10.4,
     18H  G'(0)=,E10.4,9H  P-NORM=,E10.4,2/)
  324 FORMAT (/,12H CYL LENGTH=,E10.3)
  502 FORMAT (/,8HTOO MUCH)
  600 FORMAT (I2)
 3001 FORMAT (E10.3)
  500 JJ=0
      READ (2,310) CAP1,AO,PO
      READ (2,312) FN,RR,TM,FK
      READ(2,3001) GNL
      READ (2,314) AM,XMAX
      READ (2,600) NEND
      GO TO 551
  550 PO=PO/10.
      AM=1.0E-5
  551 CONTINUE
      WRITE (1,324) GNL
      WRITE (1,315) CAP1,AO,PO,RR,TM,FN
      PI= 3.1415926535
      FF=2.*GNL*RR*((1.-((COS(2.*PI/FN))**2 ))**0.5)
      XX=TM*(AO**2.0)*(2.0/(CAP1-1))/(FF*PO)
      THETA=TM*AO*((2.0/(CAP1-1.0))**0.5)/(FF*PO)
      CAP2=(1.00-CAP1)/CAP1
      CAP3=-1.0/CAP2
      CAP4=(3.0*CAP1-(1.0))/(2.0*CAP1)
      A1=4.00*FK*CAP1*((2.0/(CAP1+1.0))**((CAP1+1.0)/(2.0*(CAP1-1.0))))
     1*((2.0/(CAP1-1.))**-0.5)
      B1=RR*((2./(CAP1-1.))**-1.)*(FF*PO)/(TM*(AO**2.))
      CO=RR/XX
      X=0.0
      Y(1)=CO
      Y(2)=0.0
      Y(3)=1.0
      YT=0.0
      YT1=0.0
      WRITE (1,322) X,Y(1),Y(2),Y(3)
      NA=3
      F(1)=Y(2)
      F(2)=FN*Y(3)*((1.00-(Y(2)**2  )*(Y(3)**CAP2))**CAP3)
```

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```
      TERM2=2.*CAP1*(Y(2)*Y(3)/Y(1))
      F(3)=((-Y(1)**-2 )*(Y(3)**CAP4)*(A1*B1=A1*(Y(1))))*TERM2
      F2=F(2)
   30 S=RKLDEQ (NA,Y,F,X,AM,0)
   50 F(1)=Y(2)
      F(2)=FN*Y(3)*((1.00=(Y(2)**2 )*(Y(3)**CAP2))+A*CAP3)
      TERM2=2.*CAP1*(Y(2)*Y(3)/Y(1))
      F(3)=((Y(1)**-2 )*(Y(3)**CAP4)*(A1*B1=A1*(Y(1))))*TERM2
      IF (S-1.) 40,30,40
   40 CONTINUE
      F2T=(F2-F(2))/F2
      F2T=ABS(F2T)
      IF (F2T-.10) 700,700,701
  700 AM=1.5*AM
  701 CONTINUE
      JJ=JJ+1
      IF(JJ-200) 504,503,503
  504 CONTINUE
      TT(JJ)=X
      PS(JJ)=Y(3)
      YTT=(Y(2)-YT)/Y(2)
      YT=Y(2)
      IF(YTT-.001) 10,10,41
   41 CONTINUE
      GO TO 30
   10 CONTINUE
      T1=THETA*X
      G1=XX*Y(1)=XX*CO
      G2=XX/THETA*(Y(2))
      G2=G2/12.0
      G3=(XX/(THETA)**2.0)*F(2)
      G4=PO*Y(3)
      WRITE (1,314) T1,G1,G2,G3,G4
      IF (PO-10000.) 552,552,550
  552 IF (NEND-1) 501,500,500
  503 CONTINUE
      WRITE  (1,503)
  501 STOP
      END
```

```
      FUNCTION RKLDEQ(N,Y,F,X,H,NT)
C 02 UCSD RKLDEQ RUNGE-KUTTA-GILL LINEAR DIFFERENTIAL EQUATION SOLVER    P=63
C    02 UCSD RKLDEQ
C    MODIFIED MAY 1963 (Q REMOVED FROM CALLING SEQUENCE)
C    TEST OF ALGOL ALGORITHM
      DIMENSION Y(10),F(10),Q(10)                                       RKLD0
C    REAL X,H--INTEGER N,NT--COMMENT--BEGIN INTEGER I,J,L-REAL A
      NT=NT+1                                                           RKLD:
      GO TO (1,2,3,4),NT                                                RKLD:
C    GO TO S(NT)
1     DO 11 J=1,N
11    Q(J)=0.                                                           RKLD0
      A=.5                                                              RKLD:
      X=X+H/2.                                                          RKLD0
      GO TO 5                                                           RKLDL
2     A=.2928932188                                                     RKLD6
      GO TO 5                                                           RKLD7
3     A=1.707106781                                                     RKLD0
      X=X+H/2.                                                          RKLD:
      GO TO 5                                                           RKLD:
4     DO 41 I=1,N                                                       RKLD:
41    Y(I)=Y(I)+H*F(I)/6.-Q(I)/3.                                       RKLD5
      NT=0                                                              RKLD7
      RKLDEQ=2.                                                         RKLD.
      GO TO 6                                                           RKLD:
5     DO 51 L=1,N                                                       RKLD.
      Y(L)=Y(L)+A*(H*F(L)-Q(L))                                         RKLD.
51    Q(L)=2.*A*H*F(L)+(1.-3.*A)*Q(L)                                   RKLD.
      RKLDEQ=1.                                                         RKLD:
6     CONTINUE                                                          RKLD:
      RETURN                                                            RKLD:
      END                                                               RKLD:
```

4A-22

LIST OF REFERENCES

1. Baker, W. E., V. B. Parr, R. L. Bessey, and P. A. Cox, "Assembly and Analysis of Fragmentation Data for Liquid Propellant Vessels," NASA CR-134538, NASA Lewis Research Center, January 1974.

2. Bessey, R. L., "Fragment Velocities from Exploding Liquid Propellant Tanks," Shock and Vibration Bulletin, No. 44, August 1974, pp. 133-139.

APPENDIX IV. B

COMPARISON OF EXPERIMENTAL RESULTS
WITH CODE PREDICTIONS

Some experimental data for initial fragment velocities from bursting containment vessels are available to check the predictions of fragment velocities from code SPHER. For example, D. W. Boyer, et al. (Reference 1) have measured fragment velocities from bursting glass spheres of various dimensions where the contained gas was air or helium (HE). The text of the workbook, "Example 1 for Spheres," shows how the initial fragment velocity for one of these cases could be obtained from the tables. Table 4B-1 lists the data from the Boyer report and compares it with values obtained from Tables 4-1 through 4-8 of the workbook text, using the method demonstrated in the examples shown in the text. The data are also compared to values obtained by runs of code SPHER for the specific burst pressure and sphere geometries used in the experimental runs.

Results are within about 10% of one another for any of the methods used.

Table 4B-2 lists data for fragments from bursting titanium alloy spheres pumped up with nitrogen. The experimental data are from a report by Pittman (Reference 2). Pittman measured the velocities of fragments emanating from the spheres with breakwire and strobe photographic techniques. Code SPHER and the tables predict the velocities from the small diameter sphere within 10%. Velocities predicted for the larger diameter spheres are low by 15% where breakwire techniques were used to measure the fragment velocities. They agree well with the measured data where strobe photography was used to measure the fragment velocities.

TABLE 4B-1. INITIAL FRAGMENT VELOCITIES, V_i, FROM BURSTING GLASS SPHERES

$(\rho = 2.6 \text{ cm}^3)$

Sphere Characteristics		Pressurizing Gas		Initial Fragment Velocities		
Radius cm	Wall Thickness cm	Type	Pressure Pa	V_i (Boyer)* m/s	V_i (Code) m/s	V_i (Tables) m/s
1.27	0.100	Air	2.25×10^6	51.8	51.5	57.6
2.54	0.100	"	" "	75.6	80.2	84.4
6.35	0.1...	"	1.38×10^6	69.8	78.0	75.6
1.27	0.100	He	2.25×10^6	44.2	38.4	43.6
2.54	0.100	"	" "	79.4	61.6	64.0

*V_i values were obtained from Reference 1 by averaging measured values for similar cases from Table 1 of Reference 1 for the 1.27 and 2.54 cm radius spheres and by measurements from Figure 13 of Reference 1 for the 6.35 cm radius sphere.

TABLE 4B-2. INITIAL FRAGMENT VELOCITIES, V_i, FROM BURSTING TITANIUM ALLOY SPHERES

$(\rho = 4.46 \text{ cm}^3)$

Sphere Characteristics		Pressurizing Gas		Initial Fragment Velocities		
Radius cm	Wall Thickness cm	Type	Pressure Pa	V_i (Pittman)* m/s	V_i (Code) m/s	V_i (Tables) m/s
11.7	0.274	N	5.51×10^7	366 ± 15	352	338
34.3	0.919	"	" "	342 ± 30[1]	339	322
34.3	0.919	"	" "	426 ± 27[2]	339	322
34.3	0.919	"	" "	448 ± 30[2]	339	322

*Values taken from Reference 2.

[1] This value was based on velocity measurements using a strobe photographic technique.

[2] These values were based on velocity measurements using breakwire measurement techniques.

LIST OF REFERENCES

1.   Boyer, D. W., H. L. Brode, I. I. Glass, and J. G. Hall, "Blast
     from a Pressurized Sphere," UTIA Report No. 48, Institute of
     Aerophysics, University of Toronto, January 1958.

2.   Pittman, J. F., "Blast and Fragment Hazards from Bursting High
     Pressure Tanks," Naval Ordnance Laboratory Report NOLTR 72-
     102, 17 May 1972.

APPENDIX IV.C

ESTIMATE OF INITIAL VELOCITIES OF FRAGMENTS FROM SPHERES AND CYLINDERS BURSTING INTO TWO EQUAL HALVES

The method developed by Taylor and Price[1] for calculating velocities of fragments from bursting spherical gas reservoirs was modified to provide velocity calculations for fragments from both cylindrical and spherical gas vessels. These modifications were primarily geometrical in nature and will be discussed in more detail in subsequent pages. To compute the velocity of fragments from bursting spheres or cylinders which contain gas under pressure, the following assumptions were made:

(1) The vessel with gas under pressure breaks into two equal halves along a plane perpendicular to the cylindrical axis, and the two container fragments are driven in opposite directions.

(2) Gas within the vessel obeys ideal gas laws.

(3) Originally contained gas escapes from the vessel through the opening between the fragments into a surrounding vacuum. The escaping gas travels perpendicular to the direction of motion of the fragments with local sonic velocity.

(4) Energy necessary to break the vessel walls is negligible compared to the total energy of the system.

(5) Drag and lift forces are ignored since the distance the fragment travels before it attains its maximum velocity and the time it takes to attain its maximum velocity are too short for drag and lift forces to have a significant effect.

A schematic depicting the essential characteristics of the Taylor and Price solution for bursting spheres is shown in Figure 4C-1. Before accelerating into an exterior vacuum, the sphere has internal volume V_{oo} and contains a perfect gas of adiabatic exponent (ratio of specific heats) K and gas constant R with initial pressure P_{oo} and temperature T_{oo} (Figure 4C-1a). At a time $\tau = 0$, rupture occurs along a perimeter π, and the two fragments are propelled in opposite directions due to forces applied against the area F which is perpendicular to the axis of motion of the fragments (Figure 4C-1b). The mass of the two frag-

(a)

CONTAINER MASS, M_t

$M_t = M_1 + M_2$

P_{00}, V_{00}, T_{00}

(b)

PLANE OF RUPTURE

x_2 x_1

FRAGMENT MASS, M_2

FRAGMENT MASS, M_1

AXIS OF MOTION

P_0, V_0, T_0

AREA F

PERIMETER Π

(c)

M_2

P_2 P_0

P_0, V_0, T_0

P_0 P_1

M_1

NEGLIGIBLE MASS OF ACCELERATING GAS

ESCAPE VELOCITY GAS $a^\bullet$
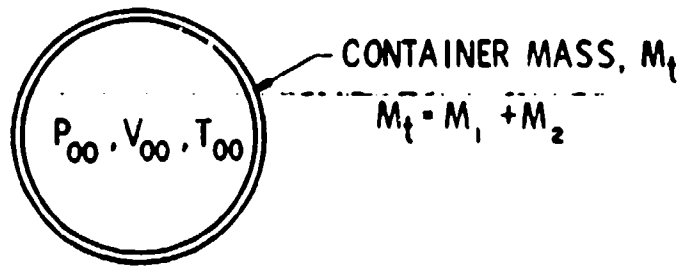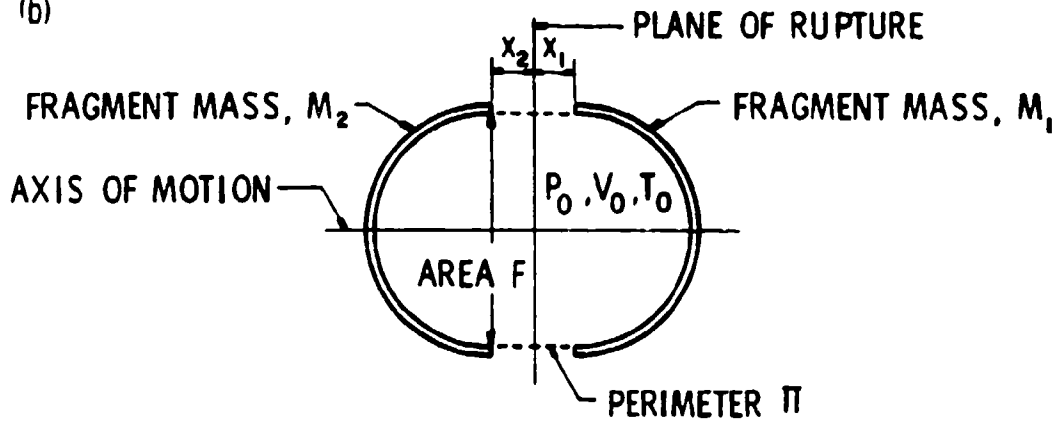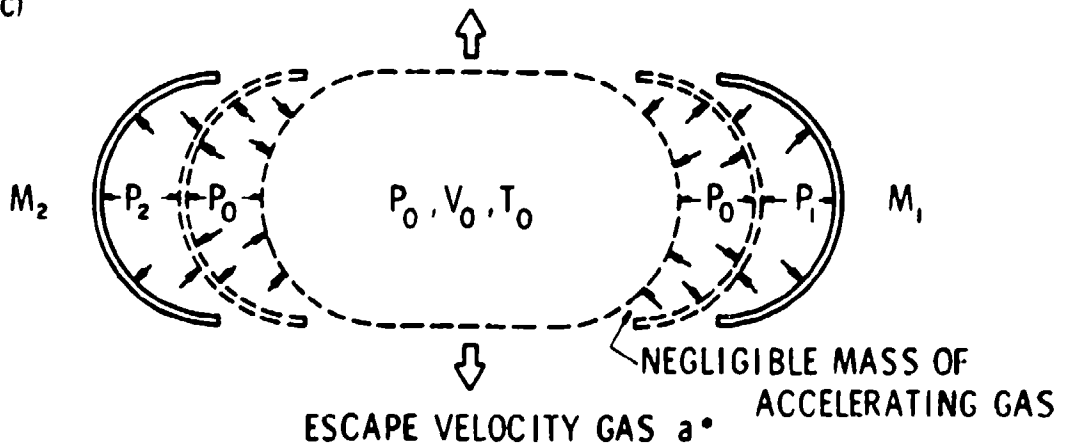
Figure 4C-1. Parameters for Sphere Bursting into Two Halves

ments, M_1 and M_2, is considered large relative to the mass of the remaining gas at elevated pressure (Figure 4C-1c).

As mentioned earlier, the Taylor and Price solution for calculating velocities of halves of bursting spheres was modified to predict velocities of halves of bursting cylinders. Figure 4C-2 contains the geometric parameters associated with cylindrical vessels. The generalized fragment velocity solution and subsequent computer program allow for computation of the velocity of half of the cylinder. The vessel is assumed to break into two equal halves along a plane perpendicular to its cylindrical axis. The cylinder can have spherical segment end caps or can have flat faces. The vessel has cylindrical radius r, cylindrical thickness C_t, end cap thickness E_t, cylindrical length C_ℓ, and end cap length E_ℓ beyond the cylindrical portion. When $C_t = C_\ell = 0$ and $E_\ell = r$, the containment vessel becomes a sphere, and the solution corresponds to that formulated by Taylor and Price. That is, a cylinder with hemispherical end caps with length-to-diameter (L/D) ratio of 1.0 is a sphere.

The Taylor and Price[1] solution, generalized to allow for cylindrical as well as spherical vessels, follows. The equations of motion and initial conditions of the two fragments are

$$M_1 \frac{d^2 x_1}{d\tau^2} = FP_1(\tau), \text{ with } x_1(0) = 0, \frac{dx_1(0)}{d\tau} = 0 \qquad (4C-1)$$

$$M_2 \frac{d^2 x_2}{d\tau^2} = FP_2(\tau), \text{ with } x_2(0) = 0, \frac{dx_2(0)}{d\tau} = 0 \qquad (4C-2)$$

where subscripts refer to each fragment and x_1 and x_2 are displacement distances and are taken along the axis of motion. To allow for cylindrical containment vessels, the cross sectional area F over which the force is applied becomes

$$F = \pi (r - C_t)^2 \qquad (4C-3)$$

The equation of state for the unaccelerated gas remaining within the confinement of the container fragments is

$$P_0(\tau) \ V_0(\tau) = C(\tau) RT_0(\tau) \qquad (4C-4)$$
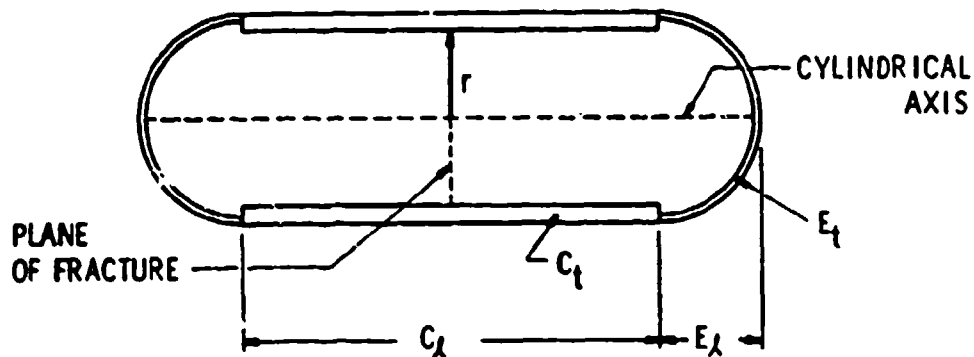
Figure 4C-2. Geometry of Cylindrical Vessels

where subscript 0 denotes reservoir conditions immediately after failure, R is the gas constant, P is pressure, V is volume, T is temperature and $C(\tau)$ is the mass of gas confined at high pressure as a function of time. The rate of change of the confined mass is

$$\frac{d\,C(\tau)}{d\,\tau} \;=\; -k\,\Pi\,x\,\rho_{*}\,a_{*} \tag{4C-5}$$

where

$$x \;=\; x_1 + x_2 \tag{4C-6}$$

and k is the coefficient of discharge of the area between the fragments and ρ_{*} is the gas density at critical gas velocity a_{*}. The expression for perimeter Π is the same as for spheres,

$$\Pi \;=\; 2\pi r \tag{4C-7}$$

Gas density ρ_{*} and a_{*} are standard expressions

$$a_* = p_0(\tau)\left(\frac{2}{K+1}\right)^{1/(k-1)}$$

$$a_* = a_0(\tau)\left(\frac{2}{K+1}\right)^{1/2}$$

where K is the adiabatic exponent (ratio of specific heats) for an ideal gas. The volume is assumed to be variable and can be described by

$$V_0(\tau) = V_{00} + FX \tag{4C-9}$$

Nearly all of the gas is assumed to be accelerated with the fragments, with gas immediately adjacent to the fragments being accelerated to the velocity of the fragments. From simple-one-dimensional flow relationships,

$$P_1(\tau) = P_0(\tau)\left\{1 - \frac{K-1}{2[a_0(\tau)]^2}\left(\frac{dx_1(\tau)}{d\tau}\right)^2\right\}^{K/(K-1)}$$

$$P_2(\tau) = P_0(\tau)\left\{1 - \frac{K-1}{2[a_0(\tau)]^2}\left(\frac{dx_2(\cdot)}{d\tau}\right)^2\right\}^{K/(K-1)}$$

To generalize the solution, one can use the following nondimensional forms of the variables:

Dimension: $x(\tau) = Xg(\tau)$ $x_1(\tau) = Xg_1(\theta)$, $x_2 = Xg_2(\theta)$

Time: $\tau = \theta \gamma$

Pressure: $P_0(\tau) = P_{00} P_*(\theta)$

From appropriate solutions and initial conditions:

$$\frac{dx_1(\tau)}{d\tau} = \frac{X}{\theta} g_1', \qquad \frac{dx_2(\tau)}{d\tau} = \frac{X}{\theta} g_2'$$

$$\frac{d^2 x_1(\tau)}{d\tau^2} = \frac{X}{\theta^2} g_1'', \qquad \frac{d^2 x_2(\tau)}{d\tau^2} = \frac{X}{\theta^2} g_2''$$

$$\frac{dP_o(\tau)}{d\tau} = \frac{P_{oo}}{\theta} P_*' \tag{4C-12}$$

$$x_1(0) = x_2(0) = \frac{dx_1(0)}{d\tau} = \frac{dx_2(0)}{d\tau} = g_o(0) = g_2(0) = g_1'(0) = g_2'(0) = 0$$

$$P_*(0) = 1$$

where primes denote differentiation with respect to τ. The pair of characteristic values for dimension X and time θ chosen by Taylor and Price are:

$$X = \frac{M_t a_{oo}^2}{F P_{oo}} \left(\frac{2}{K-1} \right) \tag{4C-13}$$

$$\theta = \frac{M_t a_{oo}}{F P_{oo}} \left(\frac{2}{K-1} \right)^{1/2}$$

The final derived equations contain two dimensionless groups which define the nature of the solutions, these are

$$\gamma = \frac{P_{oo} V_{oo}}{M_t a_{oo}^2} \tag{4C-14}$$

$$\beta = k \left(\frac{2}{K+1} \right)^{\frac{K+1}{2(K-1)}} \left(\frac{2}{K-1} \right)^{1/2} \frac{\beta V_{oo}}{F^2}$$

Differences between the Taylor and Price solution for spheres and our solution for cylinders, with spherical caps being a special case of cylinders, occur in the determination of area F given by Equation (4C-3) and perimeter Π given in Equation (4C-7) where r is cylindrical radius (except for the special case of a sphere where r is spherical radius) instead of spherical radius. A difference also exists in the calculation of initial volume of the gas which, for the cylindrical case with spherical segment endcaps with one base, becomes

$$V_{oo} = \pi \left[(r - C_t)^2 C_\ell + (E_\ell - E_t) \left[(r - E_t)^2 + 1/3 (E_\ell - E_t)^2 \right] \right]$$

$$(4C-15)$$

for the adiabatic case,

$$\frac{P_o(\tau)}{P_{oo}} = \left[\frac{\rho_o(\tau)}{\rho_{oo}} \right]^K = \left[\frac{T_o(\tau)}{T_{oo}} \right]^{\frac{K}{K-1}} = \left[\frac{a_o(\tau)}{a_{oo}} \right]^{\frac{2K}{K-1}}$$

$$(4C-16)$$

Substitution of Equations (4C-10), (4C-12) through (4C-14), and (4C-16) into Equations (4C-1) and (4C-2) gives

$$\frac{M_1}{M_t} g_1'' = P_* \left[1 - \frac{g_1'^2}{(P_*)^{\frac{K-1}{K}}} \right]^{\frac{K}{K-1}}$$

$$(4C-17)$$

$$\frac{M_2}{M_t} g_2'' = P_* \left[1 - \frac{g_2'^2}{(P_*)^{\frac{K-1}{K}}} \right]^{\frac{K}{K-1}}$$

Differentiation of Equation (4C-4) and substitution of Equations (4C-5) through (4C-9) and (4C-11) and (4C-12) yields

$$\left(\frac{K-1}{2} \right) \sigma + g \frac{P_*'}{P_*} = - \frac{\rho K}{\sigma} g (P_*)^{\frac{K-1}{2K}} - K g' \quad (4C-18)$$

4C-7

Since fragment masses are equal ($M_1 = M_2 = M_t/2$), the equations for the motion of the two fragments become identical, with identical initial conditions and identical solutions so that $g_1 = g_2 = g/2$. Equations in Equation (4C-17) then reduce to

$$g'' = 4 P_* \left[1 - \frac{g'^2}{4 (P_*)^{\frac{K-1}{K}}} \right]^{\frac{K}{K-1}}$$

(4C-19)

Rearranging terms in Equation (4C-18) produces

$$P_*' = \frac{-\frac{\beta K}{\alpha} g P_*^{\frac{3K-1}{2K}} - K g' P_*}{\left(\frac{K-1}{2}\right) \alpha + g}$$

(4C-20)

For initial conditions, $g(0) = 0$, $g'(0) = 0$, and $P_*(0) = 1$, nondimensional values of distance, velocity, acceleration and pressure as a function of time can be calculated by solving Equations (4C-19) and (4C-20) simultaneously using Runge Kutta method of numerical iteration. Dimensional values can then be calculated from

$$\tau = \theta \zeta, \qquad x_1(\tau) = \frac{X g(\tau)}{2}, \qquad x_1'(\tau) = \frac{X}{2\theta} g'(\tau),$$

(4C-21)

$$x_1''(\tau) = \frac{X}{2\zeta^2} g''(\tau), \qquad P_0(\tau) = P_{00} P_*(\tau)$$

The computer program entitled /Frag 2/ was written in Fortran IV and exercised on a teletype tymshare terminal. The computer program is user-oriented and accepts either SI or English units and outputs either SI or English units. Rigorous English measure input is not used for length and mass measurements. Instead, inches are used instead of feet for length measurements and pounds-force (weight measure) are used instead of slugs for mass measurements in both input and output stages of the program since these units are commonly used in these types of measurements. The ratio of specific heats (K), speed of sound (a_{00}), initial pressure (P_{00}), external radius of the cylinder of sphere, and the discharge coefficient, chosen as 1.0 in all cases examined, are input parameters. The user has a choice of inputting cylinder length, end length, cylinder thickness, end thickness, and wall density; or volume, mass of the reservoir and cylinder thickness (see Figure 4C-2). The

program also requires that a step size and limit be added to allow for the iteration process to begin and end. Nondimensional times are inputted for this purpose. The user has a choice of displaying nondimensional distance, velocity, acceleration and pressure as a function of nondimensional time and/or displaying dimensional distance, velocity, acceleration and pressure as a function of dimensional time. In all cases, final dimensional times, distance, velocity, acceleration and pressure are printed.

An explanation of the Runge-Kutta subroutine is contained in Table 4C-1. This is a standard computer library function which has nine arguments. After the Runge-Kutta subroutine explanation, one can find a list of the program variables, a listing of the program, and sample input and output in Table 4C-2.

TABLE 4C-1. RUNGE-KUTTA COMPUTER LIBRARY FUNCTION

FILE NAME: F16

SUBROUTINE   RUNGE
NAME:

PURPOSE: This subroutine employs the Fourth Order Runge-Kutta Method to solve N simultaneous first-order ordinary differential equations by calculating successive values of Y according to the formula:

$$Y_{i+1} = Y_i + \frac{h}{6} (K_1 + 2K_2 + 2K_3 + K_4)$$

where $K_1 = f(X_i, Y_i)$

$$K_2 = f(x_i + \frac{h}{2}, y_i + \frac{hK_1}{2})$$

$$K_3 = f(x_i + \frac{h}{2}, y_i + \frac{hK_2}{2})$$

$$K_4 = f(x_i + h, y_i + hK3)$$

METHOD:

The subroutine is called by the calling program five times in order to approximate successive Y(I)'s; the first time to initialize, the second time to calculate $K_1(I)$, the third time to calcualte $K_2(I)$, the fourth time to calculate $K_3(I)$ and the fifth time to calculate $K_4(I)$. In addition, each time the subroutine is called, it calculates a new Y(I) and a new X(I) which are returned to the calling program where the functions (first-order differential equations) are evaluated with the new X(I) and Y(I). These values of the function are then returned to the subroutine where they are used as $K_1(I)$, $K_2(I)$, $K_3(I)$, or $K_4(I)$ and approximately accumulated to obtain $Y_{i+1}(I)$ in the 5 calls to the subroutine.

ARGUMENTS:

The subroutine RUNGE uses nine arguements: N, Y, F, X, H, M, SAVEY, PHI, K.

1. The first argument, N, represents the number of simultaneous first-order ordinary differential equations to be solved.

2. The second argument, Y, is the array name which the calling program uses to transmit the initial Y(I) values for each differential equation. Upon completion of the 5 calls to RUNGE, Y(I) will contain the new approximated values for the $Y_{i+1}(I)$'s.

3. The third argument, F, is the array which contains the current values of the differential equations calculated by the main program, i.e., F(J) contains the value of the Jth first-order differential equation.

4. The fourth argument, X, represents the independent variable which should be initialized in the main program before calling RUNGE. RUNGE increments X by the stepsize H.

5. The fifth argument, H, represents the step size for X.

6. The sixth argument, M, indicates which of the five passes of the subroutine is to be executed. The main program must initialize this argument as 1. RUNGE then successively increments the variable by 1 up to 5.

7. The seventh argument, SAVEY, is used within RUNGE and must be dimensioned in the calling program to be of size N.

8. The eighth argument, PHI, is also used internally by RUNGE, but must be dimensioned in the calling program to be of size N.

9. The ninth argument, K, is manipulated within RUNGE. K should be tested right after the call to RUNGE, in the calling program.

   When K = 1, control should transfer to a set of code in the calling program which calculates new values for the first-order differential equations, F(I), with the current values of X and Y(I). Then RUNGE should be called again.

   When K = 2, the approximation for Y(I) is completed. Values for the $Y_{i+1}(I)$'s are stored in Y(I) at this time, and normal flow of the calling program should resume.

LIMITATIONS
AND
COMMENTS:

1. The calling program must dimension SAVEY and PHI.

2. The calling program must set M = 1 before calling RUNGE.

3. The calling program must set up the N first-order differential equation values in an array F to be passed through to RUNGE when the subroutine returns with K = 1.

4. The calling program must set up separate arrays if all X and Y values for the set of differential equations are to be saved, perhaps for plotting purposes.

TABLE 4C-2. COMPUTER PROGRAM ENTITLED/FRAG/ IN FORTRAN IV

Function: This program computes the velocity of a fragment from a bursting sphere or cylinder, with or without spherical segment end caps with one base, which contains gas under pressure. It is assumed that the vessel breaks into two equal halves along a plane perpendicular to the cylindrical axis. Distance, acceleration and residual pressure as a function of time are also computed.

Input-Output Considerations: The program accepts input in either SI or English units and can print output in SI or English units making any conversions needed internally. The program considers SI units of mass in kilograms, length in meters and time in seconds. The program considers English units of mass in pounds of force (weight measure used for convenience), length in inches and time in seconds. Input data are:

     (A)   Gas characteristics:

          (CAP1) Adiabatic exponent (ratio of specific heats) for gas in the containment vessel.

          (AO) Speed of sound in gas of vessel.

          (PO) Initial pressure of gas in vessel.

     (B)   Vessel characteristics:

          (RR) Cylinder radius

          choice of

          (ZN) = 1:   (A) Cylinder length

                    (B) Length of end cap

                    (C) Cylinder thickness

                    (D) Thickness of end cap

                    (E) Wall density

TABLE 4C-2. (cont'd)

(ZN) = 2:   (A) Volume of containment vessel

           (B) Mass of reservoir

           (C) Cylinder thickness

(C)   Dynamic variables:

(FN) Number of fragments (always 2.)

(FK) Discharge coefficient (chosen to be 1.)

(AH) Nondimensional time increment for calculations

(XMAX) Maximum r ndimensional time calculation.

(D)   Input/Output format:

(ZN2)	Input units 1. = SI 2. = English
(ZN3)	Output units 1. = SI 2. = English
(FN1)	Display nondimensional dynamic variance 1. = Yes 2. = No
(FN2)	Display dimensional dynamic variance 1. = Yes 2. = No
(FN3)	Make range calculation always 2. (NO)

Variables: The definition and units of variables in this program follow.

Program Variable	Variable	Definition	Units SI	English
FN2	--	if = 1., program displays normal time, distance, velocity, accelerations and pressure	--	--
FN3	--	(always 2.)	--	--
CL	C_ℓ	cylinder length	m	in
EL	E_ℓ	end length	m	in
CT	C_t	cylinder thickness	m	in
ET	E_t	end thickness	m	in
DEN	--	density	kg/m^3	$lb\text{-}f/in^{3}$[*]
VOO	--	outside volume of vessel	m^3	in^3
VO	V_{oo}	internal volume of vessel	m^3	in^3
VOW	--	wall volume	m^3	in^3
TM	M_Z	total mass of reservoir	kg	$lb\text{-}f$[*]
PO1	--	unit conversion step for PO	--	--
RR1	--	unit conversion step for RR	--	--
CL1	--	unit conversion step for CL	--	--
EL1	--	unit conversion step for EL	--	--
CT1	--	unit conversion step for CT	--	--

---

[*] lb-f indicates English weight measurement of pounds of force. Sea level gravitation is assumed.

Program Variable	Variable	Definition	Units SI	English
ET1	--	unit conversion step for ET	--	--
DEN1	--	unit conversion step for DEN	--	--
TM1	--	unit conversion step for TM	--	--
CAP1	K	ratio of specific heats of gas	--	--
A_o	a_{oo}	sound speed	m/s	in/sec
P_o	P_{oo}	initial pressure	Pa	psi
RR	r	cylinder radius	m	in
ZN1	--	if = 1., input is C_ℓ, E_ℓ, C_t, E_t, density of vessel (A, B, C, D, E in program)	--	--
		if = 2., input is V_{oo}, $M_,$, C_t (A, B, C in program)	--	--
ZN2	--	specifies input units 1. implies SI 2. implies English	--	--
ZN3	--	specifies output units 1. implies SI 2. implies English	--	--
FN	--	number of fragments (always 2)	--	--
FK	--	gas discharge coefficient		
AJ1	--	dimensionless time interval of iteration	--	--
SMAX	--	maximum dimensionless time of iteration	--	--

Program Variable	Variable	Definition	Units SI	Units English
FN1	--	if = 1., program displays θ, g, g', g'', P_*	--	--
VO1	--	unit conversion step for VO	--	--
PERI	Π	perimeter (calculated)	m	in
FF	F	area of cross-section to which force is applied (calculated)	m^2	in^2
XX	X	characteristic dimension (calculated)	m^2	in^2
THETA	θ	characteristic time (calculated)	s	sec
CAP2	--	quantity $K/(K-1)$	--	--
CAP3	--	quantity $(3K-1)/2K$	--	--
CAP 4	--	quantity $(K+1)/2(K-1)$	--	--
A1	α	dimensionless parameter	--	--
B1	β	dimensionless geometry parameter	--	--
X	--	normalized time	--	--
Y(1)	--	normalized initial fragment displacement	--	--
Y(2)	--	normalized velocity	--	--
Y(3)	--	normalized pressure	--	--
F(1), F(2), F(3)	--	differential equations solved (see Equations 4C-19 and 4C-20)	--	--

TABLE 4C-2. (concl'd)

Program Variable	Variable	Definition	Units SI	Units English
TT	--	normalized time (output)	--	--
G	g	normalized distance (output)	--	--
GG	g'	normalized velocity (output)	--	--
GGG	g″	normalized acceleration (output)	--	--
PS	P_*	normalized pressure (output)	--	--
T1	--	time (output)	s	sec
GL, FG1	--	distance (output)	m	in
G2, FG2	--	velocity (output)	m/s	in/sec
G3, FG3	--	acceleration (output)	m/s^2	in/sec^2
G4, FG4	--	pressure (output)	Pa	psi

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XTRAN
VER.  JUL 13

*QED
*APPEND/FRAG2/
*/
DIMENSION F(3),Y(3),W1(3),W2(3),PS(50),TT(50),G(50),GG(50),GGG(50)
3001 FORMAT (E10.3)
309 FORMAT (2/,45H READ IN KAPPA, SOUND SPEED, INITIAL PRESSURE)
310 FORMAT (3E10.5)
311 FORMAT (2/,19H IF PARAMETERS ARE:,/,62H CYL. LENGTH, END LENGTH,
CYL. THICK., END THICK., WALL DENS.,,/,
8H ENTER 1,2/,40H VOLUME, MASS OF RESERVOIR, CYL. THICK.,,/,
8H ENTER 2)
312 FORMAT (5E10.4)
313 FORMAT (2/,35H READ IN TIME INTERVAL, MAXIMUM TIME)
314 FORMAT (2E10.3)
316 FORMAT (2/,45H DISPLAY NONDIMENSIONAL DYNAMIC VAR.? YES=1 NO=2)
317 FORMAT (2/,45H DISPLAY DIMENSIONAL DYNAMIC VAR.? YES=1 NO=2)
318 FORMAT (2/,35H MAKE RANGE CALCULATION? YES=1 NO=2)
320 FORMAT (52H CHARACTERISTICS OF MOTION OF FRAGMENTS (NORMALIZED)
,2/,3X,6HT-NORM,6X,1HG,9X,2HG',8X,2HG",6X,6HP-NORM,/)
322 FORMAT (2/,19H INITIAL CONDITIONS,/,6H X(0)=,E10.4,7H  G(0)=,E10.4,
8H  G'(0)=,E10.4,9H  P-NORM=,E10.4,2/)
895 FORMAT (2/,29H ENGLISH INPUT/ENGLISH OUTPUT,2/,4X,5H ITEM,6X,
14H ENGLISH UNITS,2/,6H KAPPA,9X,E10.4,/,12H SOUND SPEED,3X,E10.4,
7H IN/SEC,/,9H PRESSURE,6X,E10.4,4H PSI,/,7H RADIUS,8X,F10.4,
3X IN,/,7H VOLUME,8X,E10.4,6H CU IN,/,15H RESERVOIR MASS,E10.4,
4X LBF,/,12H CYL. THICK.,3X,E10.4,3H IN,/,13H NO. OF FRAGS,2X,E10.4)
896 FORMAT (2/,24H ENGLISH INPUT/SI OUTPUT,2/,4X,5H ITEM,6X,14H
ENGLISH UNITS,10X,9H SI UNITS,2/,6H KAPPA,9X,E10.4,14X,E10.4,/,
12H SOUND SPEED,3X,E10.4,7H IN/SEC,7X,E10.4,6H M/SEC,/,9H PRESSURE,
6X,E10.4,4H PSI,10X,E10.4,8H PASCALS,/,7H RADIUS,8X,E10.4,3H IN,11X,
E10.4,7H METERS,/,7H VOLUME,8X,E10.4,6H CU IN,8X,E10.4,10H CU METERS,
/,15H RESERVOIR MASS,E10.4,4H LBF,10X,E10.4,3H KG,/,12H CYL. THICK.,
3X,E10.4,3H IN,11X,E10.4,7H METERS,/,13H NO. OF FRAGS,2X,E10.4,
14X,E10.4)
897 FORMAT (2/, __   ____ 'ENGLISH OUTPUT,2/,4X,5H ITEM,6X,9H
SI UNITS,15X,1_          TS,2/,6H KAPPA,9X,E10.4,14X,E10.4,/,12H
SOUND SPEF          . SEC,8X,E10.4,7H IN/SEC,/,9H PRESSURE,6X,E10.4
,8H P/ C/          _,4H PSI,/,7H RADIUS,8X,E10.4,7H METERS,7X,
E10.4,            . VOLUME,8X,E10.4,10H CU METERS,4X,E10.4,6H CU IN,/,
15H RE          _ASS,E10.4,3H KG,11X,E10.4,4H LBF,/,12H CYL. THICK.,
3X,E10.   . METERS,7X,E10.4,3H IN,/,13H NO. OF FRAGS,2X,E10.4,
14X,E10.4)
898 FORMAT (2/,19H SI INPUT/SI OUTPUT,2/,4X,5H ITEM,6X,9H SI
UNITS,2/,6H KAPPA,9X,E10.4,/,12H SOUND SPEED,3X,E10.4,6H M/SEC,/,
9H PRESSURE,6X,E10.4,8H PASCALS,/,7H RADIUS,8X,E10.4,7H METERS,/,
7H VOLUME,8X,E10.4,10H CU METERS,/,11H TOTAL MASS,4X,F10.4,3H KG,
/,12H CYL. THICK.,3X,E10.4,7H METERS,/,13H NO. OF FRAGS,2X,E10.4)
900 FORMAT (2/,24H READ IN CYLINDER RADIUS)
901 FORMAT (E10.5)
902 FORMAT (2/,15H READ IN VALUES)
903 FORMAT (5E10.5)
904 FORMAT (2/,46H READ IN NO. OF FRAGMENTS(2.) DISCHARGE COEF.)
```

```
905 FORMAT (2/,28H INPUT UNITS? SI=1 ENGLISH=2)
906 FORMAT (2/,29H OUTPUT UNITS? SI=1 ENGLISH=2)
907 FORMAT (2/,19H SI INPUT/SI OUTPUT,2/,4X,5H ITEM,6X,
9H SI UNITS,2/,6H KAPPA,9X,E10.4,/,12H SOUND SPEED,3X,E10.4,6H M/SEC,
/,9H PRESSURE,6X,E10.4,8H PASCALS,/,
7H RADIUS,8X,E10.4,7H METERS,/,12H CYL. LENGTH,3X,E10.4,7H METERS,/,
11H END LENGTH,4X,E10.4,7H METERS,/,12H CYL. THICK.,3X,E10.4,
7H METERS,/,11H END THICK.,4X,E10.4,7H METERS,/,13H WALL DENSITY,
2X,E10.4,8H KG/CU M,/,15H RESERVOIR MASS,
E10.4,3H KG,/,13H NO. OF FRAGS,2X,E10.4)
908 FORMAT (2/,24H SI INPUT/ENGLISH OUTPUT,2/,4X,5H ITEM,6X,9H SI
UNITS,15X,14H ENGLISH UNITS,2/,6H KAPPA,9X,E10.4,14X,E10.4,/,
12H SOUND SPEED,3X,E10.4,6H M/SEC,8X,E10.4,7H IN/SEC,/,9H PRESSURE,
6X,E10.4,8H PASCALS,6X,E10.4,4H PSI,/,7H RADIUS,8X,E10.4,7H METERS,
7X,E10.4,3H IN,/,12H CYL. LENGTH,3X,E10.4,7H METERS,7X,E10.4,
3H IN,/,11H END LENGTH,4X,E10.4,7h METERS,7X,E10.4,3H IN,/,12H CYL.
THICK.,3X,E10.4,7H METERS,7X,E10.4,3H IN,/,12H END THICK.,3X,
E10.4,7H METERS,7X,E10.4,3H IN)
9081 FORMAT (13H WALL DENSITY,2X,E10.4,8H KG/CU M,6X,E10.4,
10H LBF/CU IN,/,
15H RESERVOIR MASS,E10.4,3H KG,11X,E10.4,4H LBF,/,13H NO. OF FRAGS,
2X,E10.4,14X,E10.4)
909 FORMAT (2/,24H ENGLISH INPUT/SI OUTPUT,2/,4X,5H ITEM,6X,14H
ENGLISH UNITS,10X,9H SI UNITS,2/,6H KAPPA,9X,E10.4,14X,E10.4,/,
12H SOUND SPEED,3X,E10.4,7H IN/SEC,7X,E10.4,6H M/SEC,/,9H PRESSURE,
6X,E10.4,4H PSI,10X,E10.4,8H PASCALS,/,7H RADIUS,8X,E10.4,3H IN,
11X,E10.4,7H METERS,/,12H CYL. LENGTH,3X,E10.4,3H IN,11X,E10.4,
7H METERS,/,11H END LENGTH,4X,E10.4,3H IN,11X,E10.4,7H METERS,/,
12H CYL. THICK.,3X,E10.4,3H IN,11X,E10.4,7H METERS,/,12H END THICK.,
3X,E10.4,3H IN,11X,E10.4,7H METERS)
9091 FORMAT (13H WALL DENSITY,2X,E10.4,10H LBF/CU IN,4X,
E10.4,8H KG/CU M,/,
15H RESERVOIR MASS,E10.4,4H LBF,10X,E10.4,3H KG,/,13H NO. OF FRAGS,
2X,E10.4,14X,E10.4)
910 FORMAT (2/,29H ENGLISH INPUT/ENGLISH OUTPUT,2/,4X,5H ITEM,6X,
14H ENGLISH UNITS,2/,6H KAPPA,9X,E10.4,/,12H SOUND SPEED,3X,E10.4,
7H IN/SEC,/,9H PRESSURE,6X,E10.4,4H PSI,/,7H RADIUS,8X,E10.4,
3H IN,/,12H CYL. LENGTH,3X,E10.4,3H IN,/,11H END LENGTH,4X,E10.4,
3H IN,/,12H CYL. THICK.,3X,E10.4,3H IN,/,12H END THICK.,3X,E10.4,
3H IN,/,13H WALL DENSITY,2X,E10.4,10H LBF/CU IN,/,
15H RESERVOIR MASS,E10.4,4H LBF,/,13H NO. OF FRAGS,
2X,E10.4)
911 FORMAT (2/,50H CHARACTERISTICS OF MOTION OF FRAGMENTS (SI UNITS),
2/,2X,5H TIME,5X,6H DIST.,5X,5H VEL.,4X,7H ACCEL.,2X,9H PRESSURE,/)
912 FORMAT (2/,55H CHARACTERISTICS OF MOTION OF FRAGMENTS
(ENGLISH UNITS),
2/,2X,5H TIME,5X,6H DIST.,5X,5H VEL.,4X,7H ACCEL.,2X,9H PRESSURE,/)
913 FORMAT (3/,13H FINAL VALUES,/,6H TIME=,E10.4,4H SEC,/,10H
DISTANCE=,E10.4,7H METERS,/,10H VELOCITY=,E10.4,6H M/SEC,/,14H
ACCELERATION=,E10.4,9H M/SQ-SEC,/,10H PRESSURE=,E10.4,8H PASCALS)
914 FORMAT (3/,13H FINAL VALUES,/,6H TIME=,E10.4,4H SEC,/,10H
DISTANCE=,E10.4,3H IN,/,10H VELOCITY=,E10.4,7H IN/SEC,/,14H
ACCELERATION=,E10.4,10H IN/SQ-SEC,/,10H PRESSURE=,E10.4,4H PSI)
```

```
JJ=0
WRITE (1,309)
READ (0,310) CAPI,A0,P0
WRITE (1,900)
READ (0,901) RR
WRITE (1,311)
READ (0,3001) ZN1
WRITE (1,902)
READ (0,903) A,B,C,D,E
WRITE (1,905)
READ (0,3001) ZN2
WRITE (1,906)
READ (0,3001) ZN3
WRITE (1,904)
READ (0,314) FN,FK
WRITE (1,313)
READ (0,314) AH,XMAX
WRITE (1,316)
READ (0,3001) FN1
WRITE (1,317)
READ (0,3001) FN2
WRITE (1,318)
READ (0,3001) FN3
IF (ZN1-1.0) 100,100,101
100 CL=A
EL=B
CT=C
ET=D
DEN=E
PI=3.1415926535
V00=PI*(RR*RR*CL+EL*RR*RR+EL*EL*EL/3.0)
V0=PI*((RR-CT)**2.0*CL+(EL-ET)*((RR-ET)**2.0+(EL-ET)**2.0/3.0))
V0V=V00-V0
TM=DEN*V0V
IF (ZN2.EQ.1.0.AND.ZN3.EQ.1.0) G0 T0 102
IF (ZN2.EQ.1.0.AND.ZN3.EQ.2.0) G0 T0 103
IF (ZN2.EQ.2.0.AND.ZN3.EQ.1.0) G0 T0 104
IF (ZN2.EQ.2.0.AND.ZN3.EQ.2.0) G0 T0 105
102 WRITE (1,907) CAPI,A0,P0,RR,CL,EL,CT,ET,DEN,TM,FN
G0 T0 106
103 A01=A0/0.0254
P01=P0*0.0254*0.0254/4.448222
RRI=RR/0.0254
CLI=CL/0.0254
ELI=EL/0.0254
CTI=CT/0.0254
ETI=ET/0.0254
DEN1=(DEN/14.5939)*(9.80665/0.3048)*(0.0254**3.0)
TM1=TM/14.5939*(9.80665/0.3048)
WRITE (1,908) CAPI,CAPI,A0,A01,P0,P01,RR,RRI,CL,CLI,EL,ELI,CT,CTI,
ET,ETI
WRITE (1,9081) DEN,DEN1,TM,TM1,FN,FN
```

```
A0=A01
P0=P01
RR=RR1
CL=CL1
EL=EL1
CT=CT1
ET=ET1
DEN=DEN1/386.0886
TM=TM1/386.0886
V0=V0/0.0254**3.0
GO TO 106
104 A01=A0*0.0254
P01=P0*4.448222/0.0254/0.0254
RR1=RR*0.0254
CL1=CL*0.0254
EL1=EL*0.0254
CT1=CT*0.0254
ET1=ET*0.0254
DEN1=DEN*(0.3048/9.80665)*14.5939/(0.0254**3.0)
TM1=TM*(0.3048/9.80665)*14.5939
WRITE (1,909) CAP1,CAP1,A0,A01,P0,P01,RR,RR1,CL,CL1,EL,EL1,CT,CT1,
ET,ET1
WRITE (1,9091) DEN,DEN1,TM,TM1,FN,FN
A0=A01
P0=P21
RR=RR1
CL=CL1
EL=EL1
CT=CT1
ET=ET1
DEN=DEN1
TM=TM1
V0=V0*0.0254**3.0
GO TO 106
105 WRITE (1,910) CAP1,A0,P0,RR,CL,EL,CT,ET,DEN,TM,FN
DEN=DEN/386.0886
TM=TM/386.0886
GO TO 106
101 V0=A
TM=B
CT=C
PI=3.141592635
IF(ZN2.EQ.1.0.AND.ZN3.EQ.1.0) GO TO 95
IF(ZN2.EQ.1.0.AND.ZN3.EQ.2.0) GO TO 94
IF(ZN2.EQ.2.0.AND.ZN3.EQ.1.0) GO TO 93
IF(ZN2.EQ.2.0.AND.ZN3.EQ.2.0) GO TO 92
95 WRITE(1,898) CAP1,A0,P0,RR,V0,TM,CT,FN
GO TO 106
```

```
94 A01=A0/0.0254
P01=P0*0.0254*0.0254/4.448222
RR1=RR/0.0254
V01=V0/(0.0254)**3.0
TM1=(TM/14.5939)*(9.80665/0.3048)
CT1=CT/0.0254
WRITE(1,897) CAP1,CAP1,A0,A01,P0,P01,RR,RR1,V0,V01,TM,TM1,CT,CT1,
FN,FN
A0=A01
P0=P01
RR=RR1
V0=V01
TM=TM1/386.0886
CT=CT1
GO TO 106
93 A01=A0*0.0254
P01=P0*4.448222/0.0254/0.0254
RR1=RR*0.0254
V01=V0*(0.0254)**3.0
TM1=TM*(0.3048/9.80665)*14.5939
CT1=CT*0.0254
WRITE(1,896) CAP1,CAP1,A0,A01,P0,P01,RR,RR1,V0,V01,TM,TM1,CT,CT1,
FN,FN
A0=A01
P0=P01
RR=RR1
V0=V01
TM=TM1
CT=CT1
GO TO 106
92 WRITE(1,895) CAP1,A0,P0,RR,V0,TM,CT,FN
TM=TM/386.0886
106 CONTINUE
PERI=2.0*PI*RR
FF=PI*(RR-CT)**2.0
XX=TM*A0*A0*(2.0/(CAP1-1.0))/(FF*P0)
THETA=TM*A0*((2.0/(CAP1-1.0))**0.5)/(FF*P0)
CAP2=CAP1/(CAP1-1.0)
CAP3=(3.0*CAP1-1.0)/(2.0*CAP1)
CAP4=(CAP1+1.0)/(2.0*(CAP1-1.0))
A1=P0*V0/(TM*A0*A0)
B1=FK*(2.0/(CAP1+1.0);)**CAP4*((2.0/(CAP1-1.0))**0.5)*PERI*V0/(FF*FF)
X=0.0
Y(1)=0.0
Y(2)=0.0
Y(3)=1.0
WRITE (1,322) X,Y(1),Y(2),Y(3)
NA=3
```

```
F(1)=Y(2)
F(2)=4.0*Y(3)*(1.0-Y(2)*Y(2)/(4.0*Y(3)**(1.0/CAP2)))**CAP2
F(3)=(-B1*CAP1/A1*Y(1)*Y(3)**CAP3-CAP1*Y(2)*Y(3))/((CAP1-1.0)/2.0*A1*
Y(1))
IF (FN1-1.0) 200,200,30
200 WRITE (1,320)
30 CALL RUNGE (NA,X,Y,F,AH,KA,V1,V2)
IF (KA-1) 40,50,40
50 F(1)=Y(2)
F(2)=4.0*Y(3)*(1.0-Y(2)*Y(2)/(4.0*Y(3)**(1.0/CAP2)))**CAP2
F(3)=(-B1*CAP1/A1*Y(1)*Y(3)**CAP3-CAP1*Y(2)*Y(3))/((CAP1-1.0)/2.0*A1*
Y(1))
G0 T0 30
40 IF (FN1-1.0) 45,45,201
45 WRITE (1,312) X,Y(1),Y(2),F(2),Y(3)
201 CONTINUE
JJ=JJ+1
TT(JJ)=X
G(JJ)=Y(1)
GG(JJ)=Y(2)
GGG(JJ)=F(2)
PS(JJ)=Y(3)
IF (X-XMAX) 41,10,10
41 CONTINUE
G0 T0 30
10 CONTINUE
IF (FN2-1.0) 130,130,131
130 IF(ZN3-1.0) 108,108,109
108 WRITE(1,911)
G0 T0 110
109 WRITE(1,912)
110 D0 107 I=1,JJ
T1=THETA*TT(I)
G1=(XX*G(I))/2.0
G2=(XX/(2.0*THETA))*GG(I)
G3=XX/(2.0*THETA*THETA)*GGG(I)
G4=P0*PS(I)
107 WRITE(1,312) T1,G1,G2,G3,G4
131 FT1=THETA*X
FG1=(XX*Y(1))/2.0
FG2=(XX/(2.0*THETA))*Y(2)
FG3=XX/(2.0*THETA*THETA)*F(2)
FG4=P0*Y(3)
IF(ZN3-1.0) 111,111,112
111 WRITE(1,913) FT1,FG1,FG2,FG3,FG4
G0 T0 113
112 WRITE(1,914) FT1,FG1,FG2,FG3,FG4
113 CONTINUE
IF (FN3-1.0) 204,204,205
204 CONTINUE
205 CONTINUE
END
*
```

TABLE 4C-2. (cont'd)

```
READ IN KAPPA, SOUND SPEED, INITIAL PRESSURE
1.67,6880.,500.


READ IN CYLINDER RADIUS
6.0


IF PARAMETERS ARE:
CYL. LENGTH, END LENGTH, CYL. THICK., END THICK., WALL DENS.,
ENTER 1

VOLUME, MASS OF RESERVOIR, CYL. THICK.,
ENTER 2
1


READ IN VALUES
0.0,6.0,0.012,0.012,0.1622


INPUT UNITS? SI=1 ENGLISH=2
2


OUTPUT UNITS? SI=1 ENGLISH=2
1


READ IN NO. OF FRAGMENTS(2.), DISCHARGE COEF.
2.,1.


READ IN TIME INTERVAL, MAXIMUM TIME
0.1,1.7


DISPLAY NONDIMENSIONAL DYNAMIC VAR.? YES=1 NO=2
1


DISPLAY DIMENSIONAL DYNAMIC VAR.? YES=1 NO=2
1


MAKE RANGE CALCULATION? YES=1 NO=2
2
```

```
READ IN KAPPA, SOUND SPEED, INITIAL PRESSURE
1.67,6880.,500.


READ IN CYLINDER RADIUS
6.0


IF PARAMETERS ARE:
CYL. LENGTH, END LENGTH, CYL. THICK., END THICK., WALL DENS.,
ENTER 1

VOLUME, MASS OF RESERVOIR, CYL. THICK.,
ENTER 2
1


READ IN VALUES
0.0,6.0,0.012,0.012,0.1622


INPUT UNITS? SI=1 ENGLISH=2
2


OUTPUT UNITS? SI=1 ENGLISH=2
1


READ IN NO. OF FRAGMENTS(2.), DISCHARGE COEF.
2.,1.


READ IN TIME INTERVAL, MAXIMUM TIME
0.1,1.7


DISPLAY NONDIMENSIONAL DYNAMIC VAR.? YES=1 NO=2
1


DISPLAY DIMENSIONAL DYNAMIC VAR.? YES=1 NO=2
1


MAKE RANGE CALCULATION? YES=1 NO=2
2
```

ENGLISH INPUT/SI OUTPUT

ITEM	ENGLISH UNITS		SI UNITS	
KAPPA	.1670E+01		.1670E+01	
SOUND SPEED	.6880E+04	IN/SEC	.1748E+03	M/SEC
PRESSURE	.5000E+03	PSI	.3447E+07	PASCALS
RADIUS	.6000E+01	IN	.1524E+00	METERS
CYL. LENGTH	.0000E+01	IN	.0000E+01	METERS
END LENGTH	.6000E+01	IN	.1524E+00	METERS
CYL. THICK.	.1200E-01	IN	.3048E-03	METERS
END THICK.,	.1200E-01	IN	.3048E-03	METERS
WALL DENSITY	.1622E+00	LBF/CU IN	.4490E+04	KG/CU M
RESERVOIR MASS	.8788E+00	LBF	.3986E+00	KG
NO. OF FRAGS	.2000E+01		.2000E+01	

INITIAL CONDITIONS
X(O)= .0000E+01   G(O)= .0000E+01   G'(O)= .0000E+01   P-NORM= .1000E+01

CHARACTERISTICS OF MOTION OF FRAGMENTS (NORMALIZED)

T-NORM	G	G'	G"	P-NORM
.1000E+00	.1960E-01	.3845E+00	.3550E+01	.9765E+00
.2000E+00	.7434E-01	.6943E+00	.2619E+01	.9138E+00
.3000E+00	.1554E+00	.9116E+00	.1761E+01	.8293E+00
.4000E+00	.2543E+00	.1055E+01	.1151E+01	.7388E+00
.5000E+00	.3648E+00	.1149E+01	.7525E+00	.6516E+00
.6000E+00	.4831E+00	.1211E+01	.4952E+00	.5720E+00
.7000E+00	.6063E+00	.1251E+01	.3277E+00	.5015E+00
.8000E+00	.7329E+00	.1278E+01	.2171E+00	.4398E+00
.9000E+00	.8617E+00	.1296E+01	.1431E+00	.3864E+00
.1000E+01	.9919E+00	.1308E+01	.9316E-01	.3402E+00
.1100E+01	.1123E+01	.1315E+01	.5936E-01	.3003E+00
.1200E+01	.1255E+01	.1320E+01	.3658E-01	.2658E+00
.1300E+01	.1387E+01	.1323E+01	.2143E-01	.2359E+00
.1400E+01	.1519E+01	.1324E+01	.1163E-01	.2099E+00
.1500E+01	.1652E+01	.1325E+01	.5591E-02	.1873E+00
.1600E+01	.1784E+01	.1326E+01	.2174E-02	.1675E+00
.1700E+01	.1917E+01	.1326E+01	.5397E-03	.1502E+00
.1800E+01	.2050E+01	.1326E+01	.2697E-04	.1350E+00

TABLE 4C-2. (concl'd)

CHARACTERISTICS OF MOTION OF FRAGMENTS (SI UNITS)

TIME	DIST.	VEL.	ACCEL.	PRESSURE
.4804E-04	.1421E-02	.5804E+02	.1115E+07	.3367E+07
.9607E-04	.5391E-02	.1048E+03	.8230E+06	.3150E+07
.1441E-03	.1127E-01	.1376E+03	.5533E+06	.2859E+07
.1921E-03	.1844E-01	.1593E+03	.3618E+06	.2547E+07
.2402E-03	.2646E-01	.1735E+03	.2365E+06	.2246E+07
.2882E-03	.3503E-01	.1828E+03	.1556E+06	.1972E+07
.3363E-03	.4397E-01	.1889E+03	.1030E+06	.1729E+07
.3843E-03	.5315E-01	.1930E+03	.6821E+05	.1516E+07
.4323E-03	.6249E-01	.1956E+03	.4497E+05	.1332E+07
.4804E-03	.7193E-01	.1974E+03	.2928E+05	.1173E+07
.5284E-03	.8144E-01	.1985E+03	.1866E+05	.1035E+07
.5764E-03	.9100E-01	.1993E+03	.1150E+05	.9163E+06
.6245E-03	.1006E+00	.1997E+03	.6735E+04	.8132E+06
.6725E-03	.1102E+00	.1999E+03	.3655E+04	.7236E+06
.7205E-03	.1198E+00	.2001E+03	.1757E+04	.6456E+06
.7686E-03	.1294E+00	.2001E+03	.6831E+03	.5775E+06
.8166E-03	.1390E+00	.2001E+03	.1696E+03	.5179E+06
.8647E-03	.1486E+00	.2001E+03	.8476E+01	.4655E+06

```
.    VALUES
TIME= .8647E-03 SEC
DISTANCE= .1486E+00 METERS
VELOCITY= .2001E+03 M/SEC
ACCELERATION= .8476E+01 M/SQ-SEC
PRESSURE= .4655E+06 PASCALS
*STOP*
(SMAINS)205+1
+
-
```

The matrix of different initial conditions run on the computer is given in Table 4C-3. For these calculations, the containment vessel was chosen to be made of a titanium alloy since these alloys are often used for flight-weight containment vessels. Gases chosen were air, xenon (Xe), hydrogen (H_2), and carbon dioxide (CO_2). Table 4C-4 contains nondimensionalized input parameters and nondimensionalized final velocities. It should be noted that these nondimensional quantities are not the same as the dimensionless parameters generated in the program to calculate velocity. Rather, the nondimensional parameters in Table 4C-4 take the following form:

(1)   Nondimensional pressure $\overline{P}$ = initial pressure/atmospheric pressure

(2)   Nondimensional thickness h/D = cylinder thickness/cylinder diameter

(3)   Nondimensional length L/D = total length/cylinder diameter

(4)   Nondimensional velocity $\overline{V}$ = final velocity/sound speed of gas.

For all of the cases run, the following conditions hold:

(1)   All vessels were assumed to be made of titanium or a titanium alloy.

(2)   The thickness of the containment vessel is uniform.

(3)   All containment vessels have hemispherical endcaps.

Figures 4C-3 through 4C-5 contain plots of $\overline{V}$ versus $\overline{P}$ for h/d ratios of 0.001, 0.01 and 0.1, respectively, the L/D ratio being held constant at 10.0 and as many as three curves, one for each of the gases (CO_2, air, H_2), being plotted on each figure. Figures 4-18 through 4-20 contain plots of $\overline{V}$ versus P for air, carbon dioxide and hydrogen gases, respectively, the L/D ratio being held constant at 10.0 and as many as three curves, one for each h/D ratio (0.001, 0.01, and 0.1) being plotted on a single figure. Figure 4-21 contains a plot of $\overline{V}$ versus L/D ratio for air and a h/D ratio of 0.01. Two curves are plotted on this figure, one for each of two different initial gas pressures.

From the curves in the figures mentioned above, one can make a few conclusions.

TABLE 4C-3

INITIAL CONDITIONS

Containment Vessel Characteristics

R = 6.0 in
ρ_s = 0.1622 lbf/in^3
N = 2.
k = 1.0

Sonic Velocities

Air - 13550 in/sec = 344.17 m/s
Xe - 6880 in/sec = 174.752 m/s
H_2 - 50000 in/sec = 1270 m/s
CO_2 - 10150 in/sec = 257.81 m/s

Run No.	L/D	Gas	Y	a_{00} (in/sec)	P_{00} (psi)	CL (in)	EL (in)	h/D	CT (in)	ET (in)
1	1.0	Air	1.4	13550	500	0.0	6.0	0.001	0.012	0.012
2					60000			↓	↓	↓
3					500			0.01	0.12	0.12
4					60000			↓	↓	↓
5					500			0.1	1.2	1.2
6		↓	↓	↓	60000			↓	↓	↓
7		Xe	1.67	6880	500			0.001	0.012	0.012
8					60000			↓	↓	↓
9					500			0.01	0.12	0.12
10					60000			↓	↓	↓
11					500			0.1	1.2	1.2
12	↓	↓	↓	↓	60000	↓	↓	↓	↓	↓
13	2.5	Air	1.4	13550	500	18.0	6.0	0.01	0.12	0.12
14	↓	↓			60000	↓	↓	↓	↓	
15	5.0	Air	1.4	13550	500	48.0	6.0	0.01	0.12	0.12
16	↓	↓	↓	↓	60000	↓	↓	↓	↓	
17	7.5	Air	1.4	13550	500	78.0	6.0	0.01	0.12	0.12
18	↓	↓	↓	↓	60000	↓	↓	↓	↓	
19	10.0	Air	1.4	13550	500	108.0	6.0	0.001	0.012	0.012
20					2000					
21					8000					
22					25000					
23					60000			↓	↓	↓
24					500			0.01	0.12	0.12
25					2000					
26					8000					
27					25000					
28	↓	↓	↓	↓	60000	↓	↓	↓	↓	↓

Run No.	L/D	Gas	γ	a_{oo} (in/sec)	P_{oo} (psi)	CL (in)	EL (in)	h/D	CT (in)	FT (in)
29	10.0	Air	1.4	13550	500	108.0	6.0	0.1	1.2	1.2
30					2000					
31					8000					
32					25000					
33					60000					
34		H_2	1.4	50000	500			0.001	0.012	0.012
35					2000					
36					8000					
37					25000					
38					60000					
39					500			0.01	0.12	0.12
40					2000					
41					8000					
42					25000					
43					60000					
44					500			0.01	1.2	1.2
45					2000					
46					8000					
47					25000					
48					60000					
49		CO_2	1.225	10150	500			0.001	0.012	0.012
50					2000					
51					8000					
52					25000					
53					60000					
54					500			0.1	1.2	1.2
55					2000					
56					8000					
57					25000					
58					60000					

TABLE 4C-4. NONDIMENSIONAL INPUT PARAMETERS
AND NONDIMENSIONAL VELOCITY

Run No.	L/D	Gas	γ	Nondim. Pressure $(P_{00}/1\,Atm.)$	h/D	Nondim. Velocity (V/a_{00})	Velocity (m/sec)
1	1.0	Air	1.4	34.01	0.001	0.9519	327.6
2				4081.63		1.9066	656.2
3				34.01	0.01	0.3094	106.5
4				4081.63		1.5841	542.2
5				34.01	0.1	0.0527	18.3
6				4081.63		0.8406	263.3
7		Xe	1.67	34.01	0.001	1.1451	200.1
8				4081.63		1.6337	285.5
9				34.01	0.01	0.5734	109.2
10				4081.63		1.4918	260.7
11				34.01	0.1	0.1194	20.86
12				4081.63		1.0787	188.5
13	2.5	Air	1.4	34.01	0.01	0.2679	92.20
14				4081.63		1.5908	547.5
15	5.0	Air	1.4	34.01	0.01	0.2253	77.54
16				4081.63		1.5611	537.3
17	7.5	Air	1.4	34.01	0.01	0.2014	69.30
18				4081.63		1.5344	528.1
19	10.0	Air	1.4	34.01	0.001	0.7284	250.7
20				136.05		1.2128	417.4
21				544.22		1.5870	546.2
22				1700.68		1.7881	615.4
23				4081.63		1.9005	654.1
24				34.01	0.01	0.1851	63.72
25				136.05		0.4373	150.5
26				544.22		0.8792	302.6
27				1700.68		1.2703	437.2
28				4081.63		1.5129	520.7
29				34.01	0.1	0.0292	10.05
30				136.05		0.0731	25.16
31				544.22		0.1812	62.37
32				1700.68		0.3713	127.8
33				4081.63		0.6102	210.0

Run No.	L/D	Gas	γ	Nondim. Pressure (P_{00}/1 Atm.)	h/D	Nondim. Velocity (V/a_{00})	Velocity (m/sec)
34	10.0	H_2	1.4	34.01	0.001	0.1561	198.2
35				136.05		0.3739	474.8
36				544.22		0.7847	996.6
37				1700.68		1.1850	1505.
38				4081.63		1.4457	1836.
39				34.01	0.01	0.0333	42.35
40				136.05		0.0833	105.8
41				544.22		0.2054	260.8
42				1700.68		0.4159	528.2
43				4081.63		0.6712	852.4
44				34.01	0.1	0.0052	6.550
45				136.05		0.0130	16.46
46				544.22		0.0325	41.30
47				1700.68		0.0691	87.74
48				4081.63		0.1228	156.0
49		CO_2	1.225	34.01	0.001	1.0081	259.9
50				136.05		1.5550	400.9
51				544.22		1.9600	505.3
52				1700.68		2.1958	566.1
53				4081.63		2.3339	601.7
54				34.01	0.1	0.0440	11.35
55				136.05		0.1100	28.37
56				544.22		0.2711	69.90
57				1700.68		0.5446	140.4
58				4081.63		0.8627	222.4
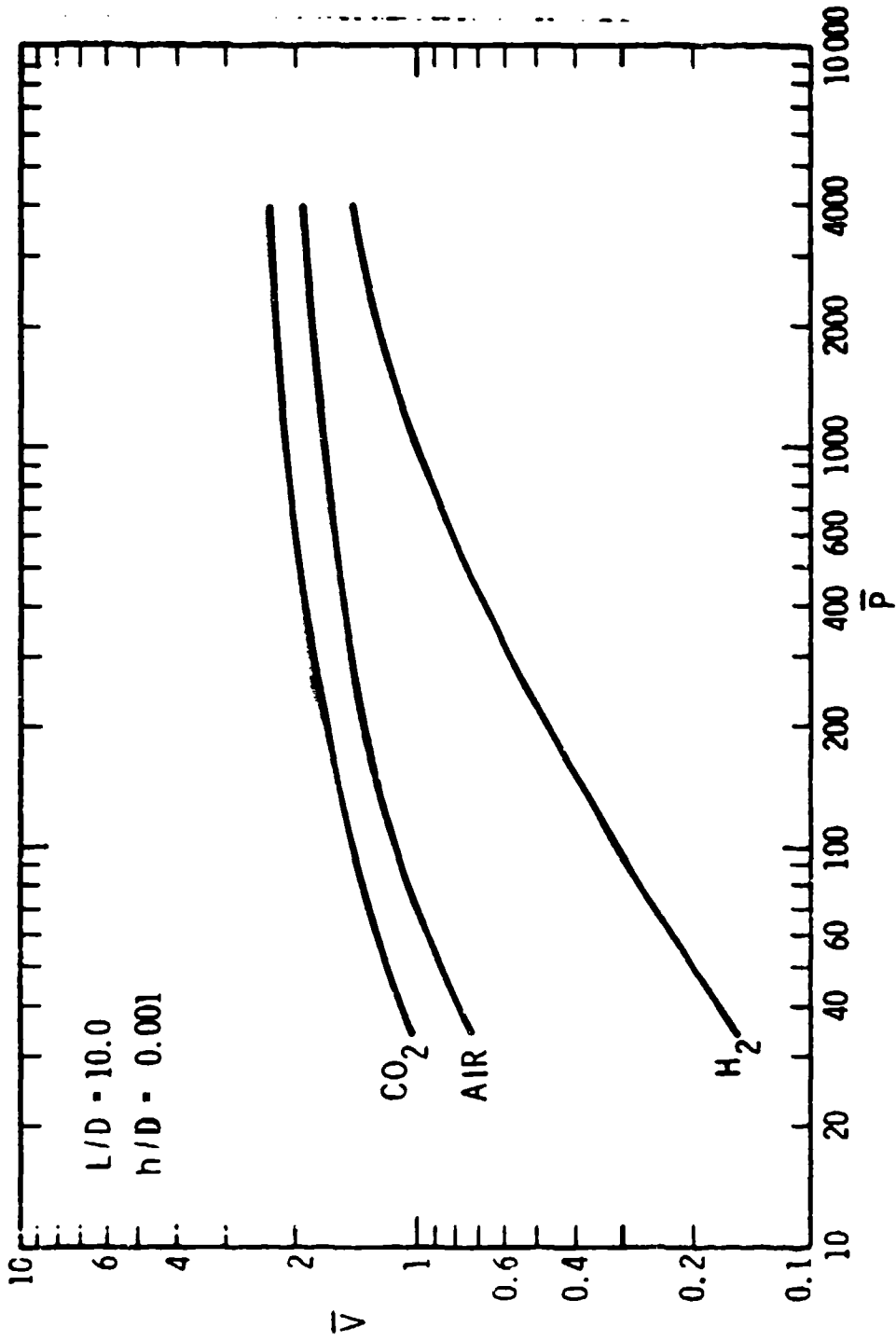
Figure 4C-3. Nondimensional Velocity Vs Nondimensional
Pressure for Several Gases
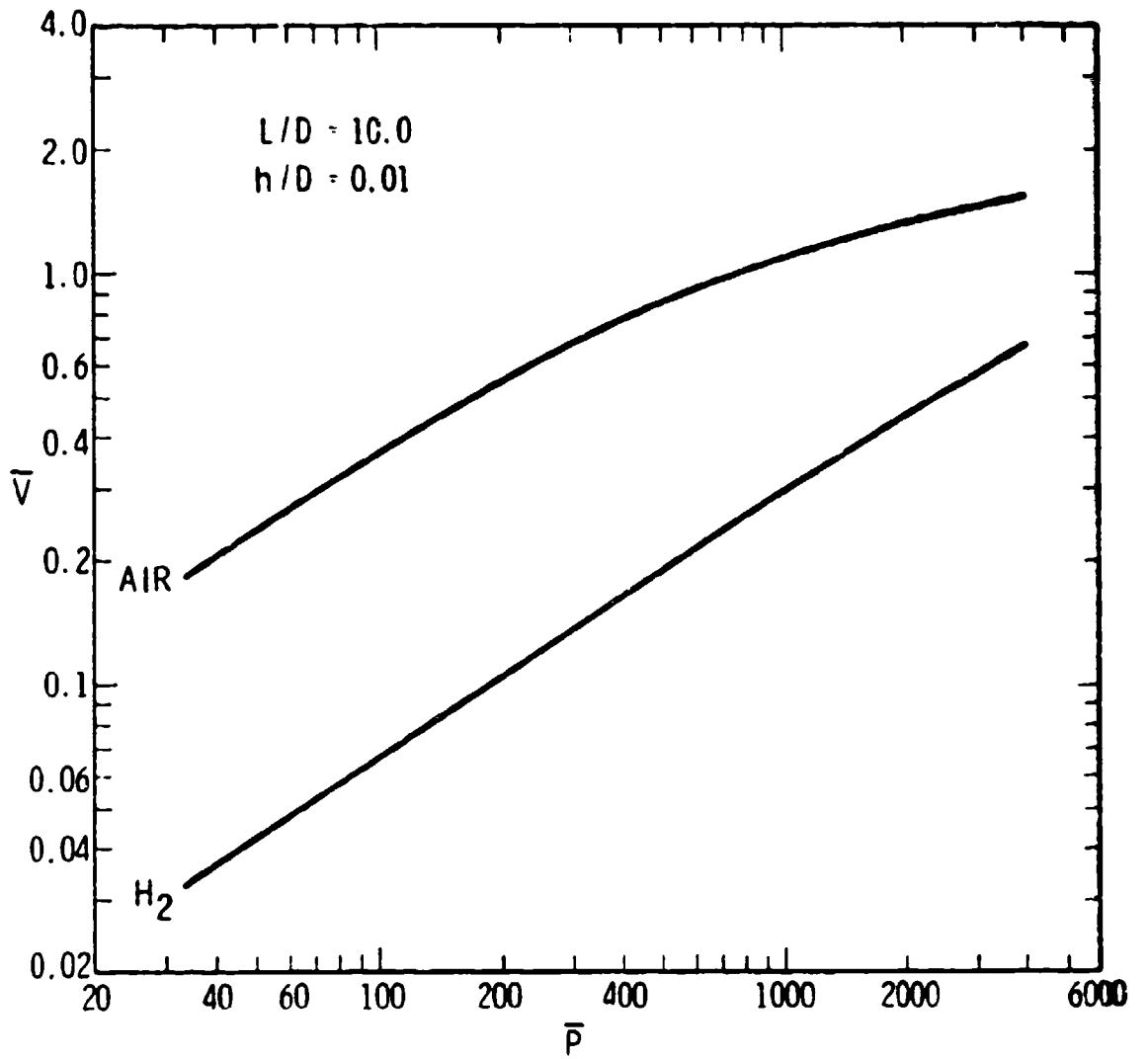
Figure 4C-4. Nondimensional Velocity Vs Nondimensional
Pressure, h/D = 0.01
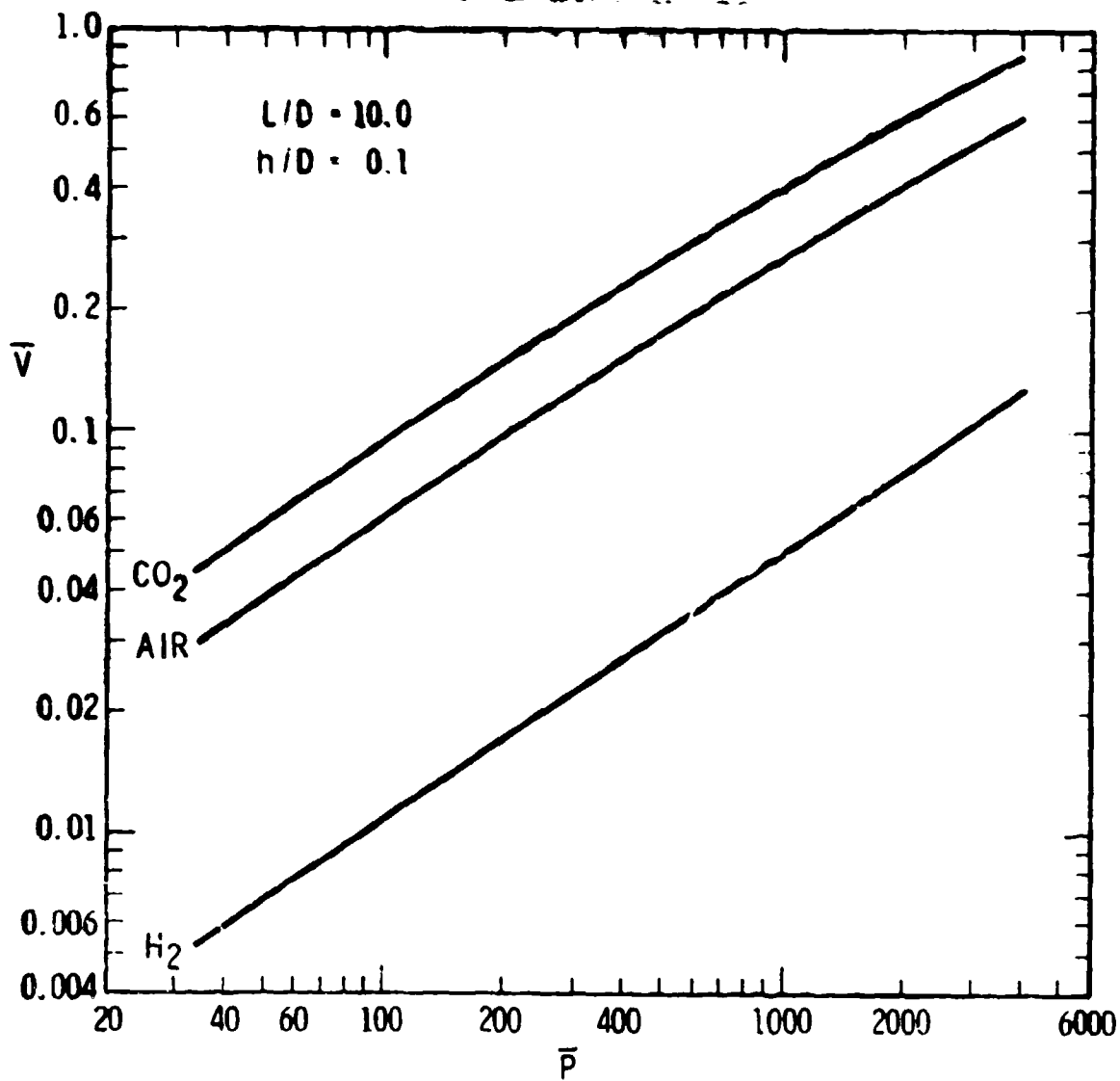
Figure 4C-5. Nondimensional Velocity Vs Nondimensional
Pressure, h/D = 0.1

Conclusions

(1) In all cases, fragment velocity increases as initial pressure increases, but at a decreasing rate.

(2) Fragment velocities from vessels containing the heavier gases (and the lower sonic velocities) are higher than that for the lighter gases (and the higher sonic velocities) for the same initial pressure, L/D ratio and h/D ratio. The rate of change in velocity with increasing pressure, however, is greater for the lighter gases, and all the curves plotted appear to approach an asymptotic limit for a fixed h/D ratio (Figures 4C-3 through 4C-5).

(3) Fragment velocities for thin-walled vessels (low h/D ratios) are higher than those for thick-walled vessels (high h/D ratios), for the same initial pressure, L/D ratio and gas. The rate of change in velocity with increasing pressure, however, is greater for the thick-walled vessels, and all the curves plotted appear to approach an asymptotic limit for a fixed gas (Figures 4-18 through 4-20).

(4) For a fixed initial pressure, fragment velocities decrease with increasing L/D ratios. For higher initial pressures, however, the rate of decrease in the fragment velocity with increasing L/D ratios decreases (Figure 4-21).

LIST OF REFERENCES

1. Taylor, D. B., and C. F. Price, "Velocity of Fragments from Burst Gas Reservoirs," *ASME Transactions, Journal of Engineering for Industry*, November 1971.

ESTIMATION OF VELOCITIES ATTAINED BY
APPURTENANCES SUBJECTED TO
BLAST LOADING

The situation discussed here involves the interaction of appurtenances (nearby objects) with the blast wave from propellant or pressure vessel explosions. These objects can be parts of the launch tower, storage tanks, vehicles, and objects in or attached to the upper stages of the launch vehicle itself, or they can be tools, benches, chairs, and machinery in a shop area. The types of appurtenances depend upon the location of the explosion, and, for this reason, results in this appendix are presented in such a manner that velocities of essentially any conceivable appurtenance in the blast field can be calculated.

To be able to predict velocities to which appurtenances are accelerated by explosions, one must consider the interaction of blast waves with solid objects. Figure 4D-1[1] shows schematically, in three stages, the interaction of a blast wave with an irregular object. As the wave strikes the object, a portion is reflected from the front face, and the remainder diffracts around the object. In the diffraction process, the incident wave front closes in behind the object, greatly weakened locally, and a pair of trailing vortices is formed. Rarefaction waves sweep across the front face, attenuating the initial reflected blast pressure. After passage of the front, the body is immersed in a time-varying flow field. Maximum pressure on the front face during this "drag" phase of loading is the stagnation pressure.

To predict the effect of a blast wave on an appurtenance, it is necessary to examine the net transverse pressure on the object as a function of time. This loading, somewhat idealized, is shown in Figure 4D-2. After time of arrival t_a, the net transverse pressure rises linearly from zero to a maximum peak reflected pressure P_r in time $(T_1 - t_a)$. For an object with a flat face nearest the approaching blast wave, this time interval is zero. Pressure then falls linearly to drag pressure in time $(T_2 - T_1)$ and decays more slowly to zero in time $(T_3 - T_2)$.

Once the time history of net transverse pressure loading is known, the prediction of appurtenance velocity can be made. The basic assumptions are that the appurtenance behaves as a rigid body, that none of the energy in the blast wave is absorbed in breaking the appurtenance loose from its moorings or deforming it elastically or plastically, and that gravity effects can be ignored during this acceleration phase of the motion. The equation of motion of the object is then
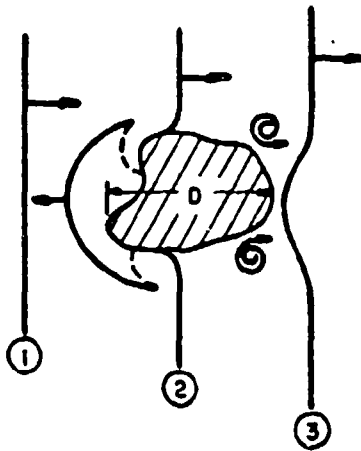
Figure 4D-1. Interaction of Blast Wave with
Irregular Object

$$f(t) = C_D q(t) = C_D \cdot \frac{1}{2} \rho u^2$$
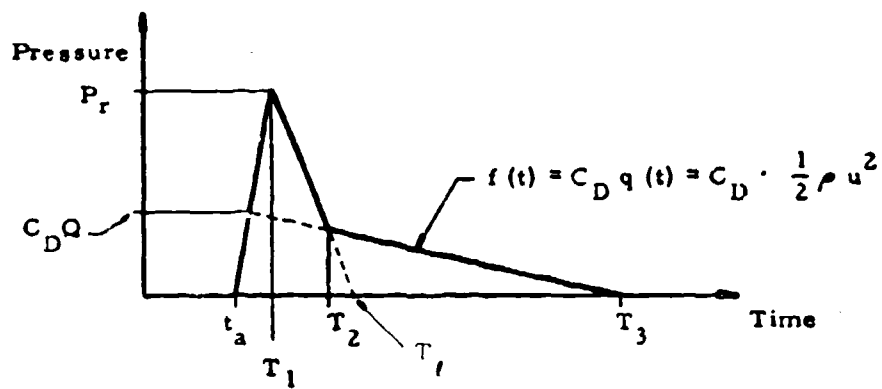
Figure 4D-2. Time History of Net Transverse Pressure on
Object During Passage of a Blast Wave

$$A\,p(t) = M\ddot{x} \qquad\qquad\qquad\qquad\qquad\qquad (4D-1)$$

where

A = area of the object presented to the blast front

$p(t)$ = net transverse pressure according to Figure 4D-2

M = total mass of the object

x = displace of the object (dots denote derivatives
with res to time)

The object is assumed to be at rest initially, so that

$$x(0) = 0 \;,\; \dot{x}(0) = 0 \qquad\qquad\qquad\qquad (4D-2)$$

Equation (4D-1) can be integrated directly. With use of the initial conditions, Equation (4D-2), this operation yields, for appurtenance velocity,

$$\dot{x}(T_3) = \frac{A}{M} \int_0^{(T_3 - t_a)} p(t)\,dt = \frac{A}{M}\,I_d \qquad (4D-3)$$

where

I_d = total drag and diffraction impulse

The integration in Equation (4D-3) can be performed explicitly if the pressure time history is described by suitable mathematical functions, or performed graphically or numerically if $p(t)$ cannot be easily written in function form. In either case, Equation (4D-3) yields the desired result--a predicted velocity for an object. The integral in Equation (4D-3) is merely the area under the curve in Figure 4D-2.

The time history of drag pressure is the modified exponential with maximum given by

$$C_D Q = C_D \cdot \frac{1}{2}\,\rho_s u_s^2 \qquad\qquad\qquad\qquad (4D-4)$$

where

$$C_D = \text{steady-state drag coefficient for the object}$$

$$Q = \text{peak dynamic overpressure}$$

$$\rho_s = \text{peak density}$$

$$u_s = \text{peak particle velocity}$$

The characteristics of the diffraction phase of the loading can be determined easily if the peak side-on overpressure P_s or the shock velocity u is known, together with the shape and some characteristic dimensions of the object. The peak amplitude of the drag phase $C_D Q$ can also be determined explicitly from P_s or u_s. The time history of the ensuing drag loading $C_D q(t)$, however, is quite difficult to predict accurately for propellant blasts or blasts from gas vessel explosions.

Side-on overpressure is often expressed as a function of time by the modified Friedlander equation. (2)

$$p(t) = P\left(\frac{1-t}{T}\right) e^{-bt/T} \tag{4D-5}$$

where

$$T = \text{duration of the positive phase of the blast wave}$$

Integrating this equation gives the impulse

$$I = \int_0^T p(t) \, dt = \frac{PT}{b}\left[1 - \frac{(1 - e^{-b})}{b}\right] \tag{4D-6}$$

The dimensionless parameter b is called the time constant, is a function of shock strength, and is reported in Chapter 6 of Reference 2. It is plotted graphically in Figure 4D-3 for a range of shock strengths, P, where

$$\bar{P} = \frac{P}{P_0} \tag{4D-7}$$

and p_0 is ambient air pressure. Ambient air pressure p_0 varies with altitude as shown in Figure 3-9. The peak reflected overpressure P_r and peak dynamic pressure Q are unique functions of P for a given ambient pressure p_0. For shocks of intermediate to weak strengths, $\bar{P} \leq 3.5$, these functions are [2]
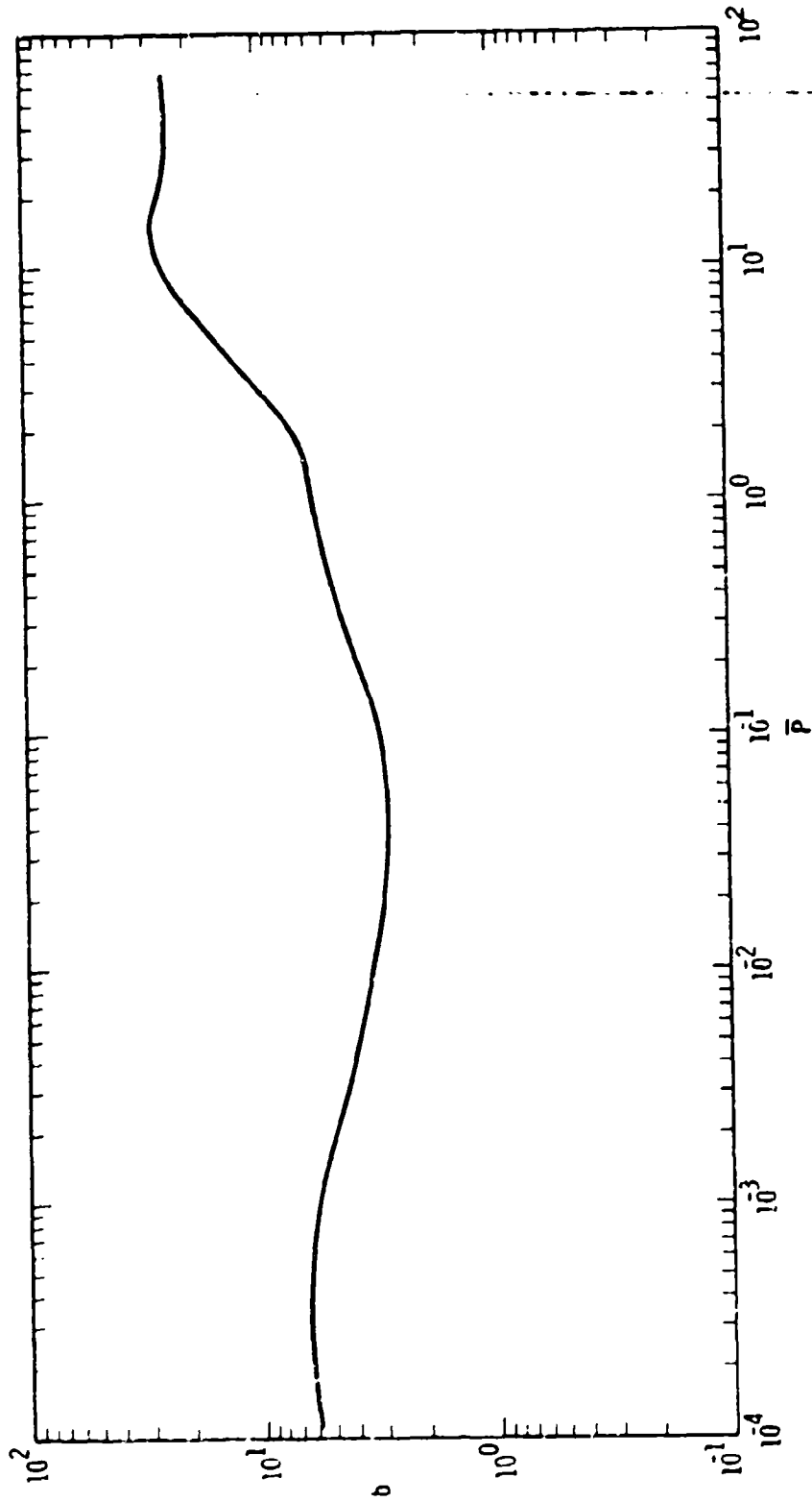
Figure 4D-3. Dimensionless Time Constant Vs
Nondimensional Overpressure

$$\overline{P}_r = 2\overline{P} + \frac{3\overline{P}^2}{4} \qquad (4D-8)$$

and

$$\overline{Q} = \left(\frac{5}{2}\right) \frac{\overline{P}^2}{7 + \overline{P}} \qquad (4D-9)$$

where

$$\overline{P}_r = \frac{P_r}{P_o} \quad, \quad \overline{Q} = \frac{Q}{P_o} \qquad (4D-10)$$

For the time history of drag pressure, a good fit to experimental data for TNT is a slightly modified form of that employed by Glasstone,[3]

$$q(t) = Q \left(\frac{1 - t}{T}\right)^2 e^{-bt/T} \qquad (4D-11)$$

In order to estimate values for the time intervals shown in Figure 4D-2, it is necessary to obtain the shock front velocity U. This is a unique function of the shock strength $\overline{P}$ and, for $\overline{P} \leq 3.5$, is given by[2]

$$\overline{U}^2 = 1 + \frac{6\overline{P}}{7} \qquad (4D-12)$$

for

$$U = \overline{U} a_o \qquad (4D-13)$$

where

$\quad a_o$ - speed of sound in air

The manner in which a_o varies with altitude is shown in Figure 3D-2. For shock strengths $\overline{P}$ greater than 3.5, $\overline{P}_r$, $\overline{Q}$ and $\overline{U}$ for Equations (4D-8), (4D-9), and (4D-12), respectively, can be approximated from tables in Chapter 6 of Reference 2. Methods for estimating $(T_1 - t_a)$ and $(T_2 - T_1)$ are given by Norris, et al.[4] and depend on the shock front velocity given above and the geometry of the appurtenance. The first time interval can be acquired from

$$(T_1 - t_a) = \frac{x}{U} \tag{4D-14}$$

where X is the distance from the front of the object to the plane facing the approaching blast wave which has the largest cross-sectional area. The latter time interval can be determined from

$$(T_2 - T_1) = \frac{4h}{U} \tag{4D-15}$$

for appurtenances on the ground and

$$(T_2 - T_1) = \frac{2h}{U} \tag{4D-16}$$

for appurtenances in the air, where H is the minimum transverse dimension of the largest mean presented area. Time interval $(T_3 - t_a)$ is equivalent to T and can be acquired by rearranging Equation (4D-6) giving

$$T = \frac{I b}{P \left[1 - \frac{(1 - e^{-b})}{b} \right]} \tag{4D-17}$$

The integral in Equation (4D-3) is just the area under the curve in Figure 4D-2. Using the law of similar triangles, time interval $(T_\ell - T_2)$ (see Figure 4D-2) can be obtained from

$$\frac{(T_\ell - T_2)}{(T_\ell - T_1)} = \frac{C_D q(T_2)}{P_r} \tag{4D-18}$$

Solving Equation (4D-18) for T_ℓ,

$$T_\ell = \frac{T_2 - \frac{C_D q(T_2)}{P_r} T_1}{1 - \frac{C_D q(T_2)}{P_r}} \tag{4D-19}$$

The total area under the curve in Figure 4D-2 is then

$$I_d = Area_{Total} = Area_{\Delta t_a P_r T_\ell} \left[C_D \int_{T_2}^{T_\ell} q(t) \, dt \right]$$

$$- Area_{\Delta T_2 [C_D q(T_2)] T_\ell} \tag{4D-20}$$

where $\Delta t_a P_r T_1$ represents the triangle with vertices t_a, P_r and T_ℓ, and $\Delta T_2 [C_D q(T_2)] T_1$ represents the triangle with vertices T_2, $C_D q(T_2)$, and T_1. The integral in Equation (4D-20) can be solved by substituting Equation (4D-11) for $q(t)$. Making similar substitutions and solving the integral, Equation (4D-20) becomes

$$I_d = \frac{P_r (T_\ell - t_a)}{2}$$

$$+ \frac{C_D Q T}{b} \left[e^{-(b/T)t} \left[\frac{2t}{T} - \frac{2t}{bT} - \left(\frac{t}{T}\right)^2 + \frac{2}{b} - \frac{2}{b^2} - 1 \right] \right]_{T_2}^{T_\ell}$$

$$- \frac{C_D Q}{2} \left[1 - \left(\frac{T_2}{T}\right)^2 \right] e^{-b T_2/T} (T_\ell - T_2) \tag{4D-21}$$

After substituting appropriate values for the variables and evaluating the middle portion of Equation (4D-21) over the time interval T_2 to T_ℓ, total drag and diffraction impulse I_d can be determined. Substituting total impulse I_d, the mean presented area A and total mass M of the object into Equation (4D-3), the maximum velocity of the appurtenance can be found.

Surely, this is a needlessly long procedure to follow every time an estimate of appurtenance velocity is required. In order to simplify the velocity calculation, Equation (4D-3) can be put into nondimensional form. This was done by substituting known environmental variables into Equations (4D-3) and (4D-21) and rearranging terms. After performing all of the substitutions, a tremendously long equation evolves, which reduces to the simple functional format

$$\frac{M V a_o}{p_o A (KH + X)} = f \left(\frac{P_s}{p_o}, \frac{C_D I_s a_o}{P_s (KH + X)} \right) \tag{4D-22}$$

where

4D-8

M = mass of object

V = velocity of object

a_o = velocity of sound in air

p_o = atmospheric pressure

A = mean presented area of object

K = constant (4 if appurtenance is on the ground and 2 if appurtenance is in air)

H = minimum transverse dimension at location of largest presented area of object

X = distance from the front of object to location of largest cross-sectional area

P_s = peak incident overpressure

C_D = drag coefficient

I_s = peak incident specific impulse

The manner in which p_o and a_o vary with altitude is shown in Figures 3-0 and 3D-2, respectively. Representative values for drag coefficient C_D can be found in Figure 4D-4. Equation (4D-22) states that nondimensional appurtenance velocity is a function of nondimensional pressure and nondimensional impulse. A computer program was written to determine combinations of nondimensional pressures and impulses required to produce various nondimensional velocities. A graphical representation of the nondimensional pressure $\overline{P}_s$ and nondimensional impulse $\overline{I}_s$ combinations producing various values of nondimensional velocity $\overline{V}$ is shown in Figure 4D-5. Objects of various sizes and shapes, as shown in the key for symbols, were used as input into the program to test the nondimensional scaling law. As expected, all calculated points were near the appropriate nondimensional velocity curves. Thus, Figure 4D-5 can be used to calculate the velocity of any type of appurtenance. Care should be taken when interpolating between curves and extending curves. Estimates made by extending the curves to lower nondimensional impulses are especially hazardous. An example for calculating appurtenance velocity follows.
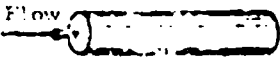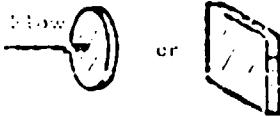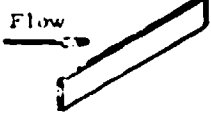
SHAPE	SKETCH	C_D
Right Circular Cylinder (long rod), side-on	Flow	1.20
Sphere		0.47
Rod, end-on	Flow	0.82
Disc, face-on	Flow or	1.17
Cube, face-on	Flow	1.05
Cube, edge-on	Flow	0.80
Long Rectangular Member, face-on	Flow	2.05
Long Rectangular Member, edge-on	Flow	1.55
Narrow Strip, face-on	Flow	1.98

Figure 4D-4. Drag Coefficients, C_D, for Various Shapes

Figure 4D-5. Nondimensional Appurtenance Velocity $\bar{V}$ as a
Function of Nondimensional Pressure $\bar{P}_s$ and
Nondimensional Impulse $\bar{I}_s$

Example

Suppose a square cement block is subjected to an explosion. At the block it was determined that

$$P_s = 1.0 \times 10^5 \text{ Pa } (14.5 \text{ psi})$$

$$I_s = 1.9 \times 10^4 \text{ Pa·s } (2.756 \text{ psi-sec})$$

The explosion occurs at sea level. Therefore,

$$P_o = 1.0135 \times 10^5 \text{ Pa}$$

$$a_o = 340 \text{ m/s } (1115 \text{ ft/sec})$$

The block has characteristics [see Equation (4D-22)]

$$X = 0 \text{ m}$$

$$H = 2.5 \text{ m } (8.2 \text{ ft})$$

$$C_D = 1.05$$

$$A = 25 \text{ m}^2 (269 \text{ ft}^2)$$

$$M = 2.8 \times 10^5 \text{ kg } (6.17 \times 10^5 \text{ lb}_m)$$

Since the appurtenance is on the ground,

$$K = 4$$

Nondimensional pressure $\bar{P}$ is then

$$\frac{P_s}{P_o} = \frac{1.0 \times 10^5 \text{ Pa}}{1.0135 \times 10^5 \text{ Pa}}$$

$$\bar{P}_s = 0.99$$

Nondimensional impulse $\bar{I}_s$ is

$$\bar{I}_s = \frac{C_D I_s a_o}{P_s (KH + X)} = \frac{(1.05)(1.9 \times 10^4)(340)}{(1.0 \times 10^5)[(4)(2.5) + (0)]}$$

4D-12

$$\bar{I}_s = 6.8$$

Locating the point (P_s, I_s) on Figure 4D-5, one can find that it lies very near the 5.0 nondimensional velocity $\bar{V}$ curve. Choosing $\bar{V}$ equal to 5.0, appurtenance velocity can be calculated as follows:

$$\frac{M V a_o}{p_o A (KH + X)} = 5.0$$

$$V = \frac{(5.0) p_o A (KH + X)}{M a_o}$$

$$V = \frac{(5.0)(1.0 \times 10^5 \text{ Pa})(25 \text{ m}^2)[(4)(2.5 \text{ m}) + (0)]}{(2.8 \times 10^5 \text{ kg})(340 \text{ m/s})}$$

$$V = 1.33 \text{ m/s} \ (4.36 \text{ ft/sec})$$

The listing of variables and list of the computer program follow.

COMPUTER PROGRAM ENTITLED /NDAPVE/
IN FORTRAN IV

Function:

This program computes nondimensional appurtenance velocities for various nondimensional pressures and nondimensional impulses. Input data are:

(A)   Nondimensional values for calculations

(PB, BB)   Ordered pairs of nondimensional peak incident overpressure $\bar{P}$ and dimensionless time constant $\bar{b}$.

(PBB, UB, QB, PRB)   Ordered quadraplets of non-dimensional values of incident overpressure $\bar{P}$, shock front velocity $\bar{U}$, dynamic pressure $\bar{Q}$, and reflected pressure $\bar{P}_r$.

		(NDV)	Nondimensional velocity values.
(B)		Blast wave characteristics	
		[P(I)]	Peak incident overpressure
		[PI(I)]	Specific impulse
(C)		Ambient conditions	
		[PO(I)]	Atmospheric pressure p_o
		[AO(I)]	Speed of sound a_o
(D)		Appurtenance characteristics	
		(X)	Distance X from front of object to location of largest cross-sectional area.
		(H)	Minimum transverse distance H of the mean presented area of the appurtenance.
		(CD)	Drag coefficient C_D
		(A)	Mean presented area A
		(TM)	Mass M of appurtenance

Variables:

The definition and units of the variables in this program are given in the following table.

TABLE 4D-1. DEFINITION OF PROGRAM VARIABLES FOR APPURTENANCE PROGRAM

Program Variable	Variable	Definition	Units
PB	$\bar{P}$	nondimensional pressure for calculating b	---
BB	b	dimensionless time constant b	---
PBB	$\bar{P}$	nondimensional peak incident pressure for calculating $\bar{u}$, $\bar{Q}$, $\bar{P}_r$	---
UB	$\bar{u}$	nondimensional shock front velocity	---
QB	$\bar{Q}$	nondimensional peak dynamic pressure	---
PBR	$\bar{P}_r$	nondimensional peak reflected pressure	---
NDV	$\bar{V}$	nondimensional velocity for internal calculations	---
P(I)	P_s	peak incident overpressure values	Pa
PI(I)	I_s	incident specific impulse values	Pa·s
PO(I)	p_o	atmospheric pressure values	Pa
AO(I)	a_o	speed of sound values	m/s
X	X	distance from front of object to location of largest mean presented area	m
H	H	minimum transverse distance of mean presented area of appurtenance	m
CD	C_D	drag coefficient	---
A	A	mean presented area	m^2
TM	M	mass of appurtenance	kg
G	--	number of p_o, a_o input combinations	---
V	--	number of P(I) input values	---
R	--	number of PI(I) input values	---
S	--	number of NDV(I) input values	---
PBAR	$\bar{P}$	nondimensional peak incident pressure for a particular iteration	---
T	T, T_3	total duration of blast wave	s
PBARR	$\bar{P}_r$	nondimensional peak reflected pressure for a particular iteration	---

Program Variable	Variable	Definition	Units
QBAR	$\bar{Q}$	nondimensional dynamic pressure for a particular iteration	...
UBAR	$\bar{U}$	nondimensional shock front velocity for a particular iteration	...
PR	P_r	peak reflected pressure	Pa
Q	Q	peak dynamic pressure	Pa
U	U	shock front velocity	m/s
T_1	T_1	time corresponding to occurrence of peak reflected pressure	s
T_2	T_2	time corresponding to second interaction of diffracted and drag phase of loading curves	s
Q2	$q(T_2)$	dynamic pressure at time T_2	Pa
CDQ	--	intermediate calculation for T_1	--
TD	T_t	time at which diffracted phase of loading is over	s
APR	--	intermediate calculation for I_D	Pa·s
ACDQ	--	intermediate calculation for I_D	Pa·s
P3	--	intermediate calculation for I_D	...
EXP13	--	intermediate calculation for I_D	Pa·s
TETI13	--	intermediate calculation for I_D	...
X513	--	intermediate calculation for I_D	Pa·s
EXPT13	--	intermediate calculation for I_D	...
DINAT	I_D	calculation for integral I_D	Pa·s
VEL(k)	V	calculated appurtenance velocity	m/s
NUDV(k)	$\bar{V}$	calculated nondimensional velocity $\bar{V}$	...
FIND	--	1 means calculated $\bar{V}$ is far from input $\bar{V}$ 2 means calculated $\bar{V}$ is near input $\bar{V}$	...

Program Variable	Variable	Definition	Units
NNNDV(M,J,L)	$\bar{V}$	final calculated $\bar{V}$	...
XXVV(M,J,L)	V	final calculated V	m/s
PP(M,J,L)	P	peak incident pressure for a particular final calculated V and input values	Pa
PPI(M,J,L)	I	specific impulse for particular final calculated and input values	Pa·s
POO(M,J,L)	P_0	atmospheric pressure	Pa
AOO(M,J,L)	a_0	speed of sound	m/s
Y(M,J,L)	$\bar{P}$	nondimensional pressure for particular calculated $\bar{V}$ and input parameters	...
XX(M,J,L)	$\bar{I}$	nondimensional impulse for particular calculated $\bar{V}$ and input parameters	...
PBARXO	..	subroutine variable used to calculate b	...
PBARX	..	subroutine variable used to calculate b	...
PIXO	..	subroutine variable used to calculate $\bar{U}$, $\bar{Q}$, $\bar{P}_r$	...
PIX	.	subroutine variable used to calculate $\bar{U}$, $\bar{Q}$, $\bar{P}_r$	...

Indicators of limits of calculations:

NNNDV = XXVV = -1.0 indicates $P_a < ...$

NNNDV = XXVV = -2.0 indicates $T_2 > T$ (or T_3)

NNNDV = +3.0 indicates input $\bar{V}$ is greater than maximum calculated $\bar{V}$

NNNDV = +4.0 indicates input $\bar{V}$ is less than minimum calculated $\bar{V}$

```
      PROGRAM NDAPVE(INPUT,OUTPUT)
C
C
C     THIS PROGRAM DETERMINES THE COMBINATIONS OF NONDIMENSIONAL
C     QUANTITIES WHICH WILL PRODUCE A SPECIFIED NONDIMENSIONAL VALUE
C     NDV (NONDIMENSIONAL VELOCITY) FOR VARIOUS APPURTENANCES.
C     NDAPVE OR N-D-AP-VE IS A CODE NAME DESIGNATING--NONDIMENSIONAL
C     APPURTENANCE VELOCITY.
C
C
      DIMENSION PH(30),BB(30),PHH(5),UH(5),GB(5),PBH(5),PO(4),AO(4),
     1P(50),PI(50),PP(20,4,50),PPT(20,4,50),POO(20,4,50),ACD(20,4,50),
     2XX(20,4,50),Y(20,4,50),XT3(50),XXT3(20,4,50)
      INTEGER G,R,S,V,FIND
      REAL IGRAL,NDV(20),NNDV(50),TNDV(20,4,50)
C
C     READ IN CURVES FOR PBAR VS. H AND
C     PBAR VS. UBAR,GBAR,PBBAR
C     PO = ATMOSPHERIC PRESSURE
C     AO = SPEED OF SOUND
C     G,  1 = OBJECT IN AIR
C         2 = OBJECT ON GROUND
C     P = PRESSURE
C     PI = IMPULSE
C     X = DIST. FROM FRONT OF OBJECT TO LOCATION OF LARGEST MEAN
C         PRESENTED AREA
C     H = MINIMUM TRANSVERSE (TO SHOCK WAVE DIRECTION) DISTANCE AT
C         LOCATION OF LARGEST MEAN PRESENTED AREA
C     CD = DRAG COEFFICIENT
C     A = MEAN PRESENTED AREA
C     TM = OBJECT MASS
C     XT3 = VELOCITY OF APPURTENANCE
C     NDV = CONSTANT VALUE FOR TM*AO*XT3/((PO*A)(G*H+X))
C
      READ 900,(PH(I),BB(I),I=1,21)
      READ 901,(PHH(I),UH(I),GB(I),PBH(I),I=1,5)
      READ 120,G
      READ 100,(PO(I),AO(I),I=1,4)
      READ 120,V
      READ 130,(P(I),I=1,V)
      READ 120,R
      READ 130,(PI(I),I=1,R)
      READ 120,S
      READ 901,(NDV(I),I=1,S)
  300 READ 110,X,H,CD,A,TM
      IF(X.EQ.0.0) GO TO 301
      DO 11 M=1,S
      DO 11 J=1,4
      DO 11 L=1,4
      DO 10 K=1,V
      FIND=1
   12 PBAR=P(K)/PO(J)
      CALL PARAMH(H,PBAR,PA,BH)
      IF(H.EQ.0.0) GO TO 30
      T=PI(L)*H/((CD*A)*(1.0-((1.0-EXP(-H))/B)))
      IF(PBAR.GT.1.5) GO TO 305
      PDBAR=2.0*PBAR+7.0*PBAR**2.0/4.0
```

```
        CBAR=5.0/2.0*PBAR**2.0/(7.0+PBAR)
        UBAR=SQRT(1.0+6.0*PBAR/7.0)
        GO TO 307
305 CALL PARUGP(PBAR,UBAR,QBAR,PBARR,PBB,UB,QB,PBR)
    IF(UBAR.EG.0.0) GO TO 30
307 PR=PBARR*PO(J)
    Q=QBAR*PO(J)
    U=UBAR*AO(J)
    T1=X/U
    IF(G.EQ.1) GO TO 308
    T2=4.0*H/U+T1
    GO TO 309
308 T2=2.0*H/U+T1
309 CONTINUE
    IF(T2.GT.T) GO TO 32
    GT2=U*(1.0-T2/T)**2.0*EXP(-B*T2/T)
    CDQ=CD*GT2/PR
    TL=(T2-CDQ*T1)/(1.0-CDQ)
    APR=PR*TL/2.0
    ACDQ=CD*GT2*(TL-T2)/2.0
    B1=(2.0/H)-(2.0/H**2.0)-1.0
    EXPT3=CD*Q*T*EXP(-B)/B
    TIMET3=1.0-2.0/H
    EXPT2=CD*Q*T*EXP(-B*T2/T)/B
    TIMET2=(2.0*T2/T)-(2.0*T2/(H*T))-(T2/T)**2.0
    IGRAL=(EXPT3*(TIMET3+B1))-(EXPT2*(TIMET2+B1))
    XT3(K)=4/TW*(APR+IGRAL-ACDQ)
    NNDV(K)=TW*AO(J)*XT3(K)/((PO(J)*4)-(G*H*X))
    IF(ABS((NDV(K)-NNDV(K))/NNDV(M)).LE.0.005) GO TO 16
    IF(NDV(M).LT.NNDV(1)) GO TO 17
    IF(K.EQ.1) GO TO 10
    IF(FIND.EQ.2) GO TO 13
    IF(NDV(M).GT.NNDV(K)) GO TO 10
    FIND=2
14  P(K+1)=P(K)
    P(K)=P(K-1)+(P(K+1)-P(K-1))/2.0
    GO TO 12
13  IF(NNDV(K).GT.NDV(M)) GO TO 14
    P(K-1)=P(K)
    P(K)=P(K-1)+(P(K+1)-P(K-1))/2.0
    GO TO 12
10  CONTINUE
    K=V
    NNDV(K)=-3.0
    GO TO 16
17  NNDV(K)=-4.0
    GO TO 16
30  NNDV(K)=XT3(K)=-1.0
    GO TO 16
32  NNDV(K)=XT3(K)=-2.0
16  NNNDV(M,J,L)=NNDV(K)
    XXT3(M,J,L)=XT3(K)
    PP(M,J,L)=P(K)
    PPI(M,J,L)=PI(L)
    POO(M,J,L)=PO(J)
    AOO(M,J,L)=AO(J)
    Y(M,J,L)=P(K)/PO(J)
```

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```
      XX(M,J,L)=CD*PI(L)*AO(J)/((P(K))*(G*H*X))
   11 CONTINUE

      PRINT OUT RESULTS
        PPI=IMPULSE
         PP=PRESSURE
        XXT3=VELOCITY OF APPURTENANCE
      NNNDV=XXT3=-1.0 INDICATES PP .GT. 67.9
      NNNDV=XXT3=-2.0 INDICATES T2 .GT.T
      NNNDV=-3.0 INDICATES NDV(M) .GT. NNDV(V)
      NNNDV=-4.0 INDICATES NDV(M) .LT. NNDV(1)
           Y=NONDIMENSIONAL PRESSURE
          XX=NONDIMENSIONAL IMPULSE

      IF(G.EQ.2) GO TO 400
      PRINT 499,X,M,CD,A,TM
      GO TO 401
  400 PRINT 500,X,M,CD,A,TM
  401 PRINT 501
      DO 20 M=1,5
      DO 20 J=1,4
      DO 20 L=1,9
   20 PRINT 502,PCC(M,J,L),AOO(M,J,L),PPI(M,J,L),PP(M,J,L),XXT3(M,J,L),
     1NDV(M),NNNDV(M,J,L),XX(M,J,L),Y(M,J,L)
      GO TO 300
  301 CONTINUE
  100 FORMAT(2F15.5)
  110 FORMAT(5F15.5)
  120 FORMAT(I2)
  130 FORMAT(8F10.2)
  499 FORMAT(1H1,5H X = ,E12.5,/,6H  M = ,E12.5,/,6H CD = ,E12.5,/,
     16H  A = ,E12.5,/,6H TM = ,E12.5,//,20H APPURTENANCE IN AIR)
  500 FORMAT(1H1,5H X = ,E12.5,/,6H  M = ,E12.5,/,6H CD = ,E12.5,/,
     16H  A = ,E12.5,/,6H TM = ,E12.5,//,23H APPURTENANCE ON GROUND)
  501 FORMAT(1H1,5X,3H PO,9X,3H AO,9X,4H PPI,9X,3H PP,8X,5H XXT3,7X,
     14H NDV,7X,6H NNNDV,7X,3H XX,9X,2H Y)
  502 FORMAT(1H ,9E12.5)
  900 FORMAT(8F12.9)
  901 FORMAT(1425.2)
      STOP
      END
```

```
      SUBROUTINE PARAMB(B,PBAR,PB,BB)
      DIMENSION PB(30),BB(30)
      REAL H,PBAR
      IF(PBAR.LE.PB(21)) GO TO 20
      B=0.0
      GO TO 11
   20 DO 10 I=1,21
      IF(PBAR.EQ.PB(I)) GO TO 9.
      K=I+1
      PBARXO=ABS(PB(K)-PB(I))
      PBARX=ABS(PBAR-PB(I))
      IF (PBARX.GT.PBARXO) GO TO 10
      B=(BB(K)-BB(I))/(PB(K)-PB(I))*(PBAR-PB(I))+BB(I)
      GO TO 11
    9 B=BB(I)
      GO TO 11
   10 CONTINUE
   11 RETURN
      END
```

3

```
      SUBROUTINE PARUOP(PRAH,UBAR,QBAR,PBARR,PBB,UB,QH,PBR)
      DIMENSION PBH(5),UB(5),QH(5),PBR(5)
      REAL PBAR,UBAR,QBAR,PRARR
      IF(PHAR.LE.PBB(5)) GO TO 20
      UBAR=QBAR=PBARH=0.0
      GO TO 11
   20 DO 10 I=1,5
      IF (PBAR.EQ.PHB(I)) GO TO 9
      K=J+1
      PBXO=ABS(PBR(K)-PBB(I))
      PBX=ABS(PBAH-PHB(I))
      IF (PBX.GT.PHXO) GO TO 10
      UBAH=(UH(K)-UB(I))/(PBH(K)-PBB(I))*(PHAR-PBB(I))+UB(I)
      QBAR=(QH(K)-UB(I))/(PBR(K)-PBB(I))*(PHAR-PHB(I))+QB(I)
      PBARH=(PBR(K)-PHR(I))/(PBB(K)-PBB(I))*(PHAR-PBB(I))+PBR(I)
      GO TO 11
    9 UBAR=UB(I)
      QBAR=QB(I)
      PBARH=PBR(I)
      GO TO 11
   10 CONTINUE
   11 RETURN
      END
```

C·5

LIST OF REFERENCES

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2. Baker, Wilfred E., Explosions in Air, University of Texas Press, Austin, Texas, May 1973.

3. Glasstone, Samuel, The Effects of Nuclear Weapons, U. S. Government Printing Office, Revised Edition, April 1962.

4. Norris, C. H., R. J. Hansen, M. J. Holley, J. M. Biggs, S. Namyet, and J. V. Minami, Structural Design for Dynamic Loads, McGraw-Hill Book Co., New York, 1959.

ANALYSES FOR FRAGMENT TRAJECTORIES

Analysis for Obtaining Fragment Range and Terminal
Velocities for Disc-Shaped Fragments

List of Variables

A	-	planform area - m^2
AP	-	projected area - m^2
AR	-	disc aspect ratio (diameter/thickness)
C	-	chord or width of rotor blade - m
C_D	-	drag coefficient
C_L	-	lift coefficient
D_p	-	profile drag - N
I	-	mass moment of inertia of rotor
L	-	lift - N
M	-	mass - kg
Q	-	torque - N-m
R	-	radius of rotor
T	-	thrust - N
V_c	-	rotor blade velocity along rotational axis
V_i	-	initial velocity of fragment
V_t	-	tip velocity of rotor
V_{in}	-	induced velocity from thrust
X	-	range - m

List of Variables (Cont.)

Y		altitude - m
$\dot{X}$		horizontal velocity
$\dot{Y}$		vertical velocity
$\ddot{X}$		horizontal acceleration
$\ddot{Y}$		vertical acceleration
a	-	airfoil curve slope
b	-	number of rotor blades
d	-	disc diameter
g	-	acceleration of gravity
r	-	disc radius
t	-	disc thickness
Δt	-	time increment
α	-	trajectory angle - rad
α_i	-	initial trajectory angle - rad
ρ	-	density of air - kg/m^3
θ	-	angle of attack of disc - rad
ω	-	angular velocity - rad/sec

The range of disc-shaped flying fragments from an explosion was determined from the fragment accelerations due to lift and drag forces. The forces acting on the particle are as follows:

4-6
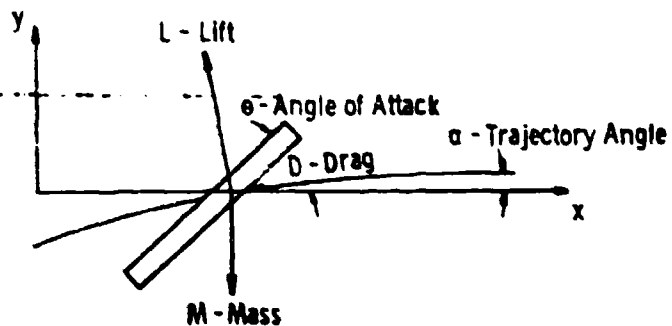
The acceleration in the Y direction is:

$$\ddot{Y} = -g - \frac{A C_D \rho (\dot{X}^2 + \dot{Y}^2)}{2M} \sin \alpha + \frac{A C_L \rho (\dot{X}^2 + \dot{Y}^2)}{M} \cos \alpha \qquad (4E\text{-}1)$$

and for the X direction

$$\ddot{X} = -\frac{A C_D \rho (\dot{X}^2 + \dot{Y}^2)}{2M} \cos \alpha - \frac{A C_L \rho (\dot{X}^2 + \dot{Y}^2)}{M} \sin \alpha \qquad (4E\text{-}2)$$

where

A = area of fragment

C_D = drag coefficient

C_L = lift coefficient

At $t = 0$

$$\dot{X} = V_i \cos \alpha_i \qquad (4E\text{-}3)$$

$$\dot{Y} = V_i \sin \alpha_i \qquad (4E\text{-}4)$$

where

V_i = initial velocity

α_i = initial trajectory angle

It is assumed that the fragment is spinning about its Y axis. This motion gives the required stability for flight and allows the fragment to maintain a constant angle with respect to the relative wind.

4E-3

A complete program (FRISB) was written to determine the particle trajectory from these equations. The second order differential equations were solved simultaneously using a fourth order Runge-Kutta method. These solutions gave the velocities, which were then numerically integrated to yield the distances.

The lift coefficient based on the planform area was determined from

$$C_L = 1.82 \tan(\theta) \quad \text{(see Reference 1)} \tag{4E-5}$$

which is valid for a "thin" circular wing. It was assumed that the particle retained a constant angle of attack throughout the flight, which resulted in a constant lift coefficient. The maximum lift coefficient would be for approximately a 10° angle of attack. Larger angles would result in stall or total loss of lift. Using $\theta = 10°$ in Equation (4E-5), $C_L = 0.32$.

The drag coefficient was chosen from Hoerner[2] for a fragment with a rectangular cross section
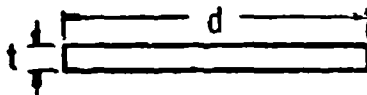
For a "thin" disc or $d/t \geq 3$, the drag coefficient based on the projected area is constant at 0.85.

As can be seen by examining Equations (4E-1) through (4E-4), the trajectory of a fragment is governed by a number of dependent and independent variables. The dependent variables are displacements X and Y; the independent variable list includes a_i, V_i, M, A, and AP. To construct a useful system of graphs, a spectrum of values for the independent variables was input to FRISB, which gave the flight trajectories.

The input data were selected by assuming a disc aspect ratio

$$AR = \frac{d}{t} \tag{4E-6}$$

and values of fragment mass and density. The mass is expressed as

$$M = \pi r^2 t \rho = \frac{2 \pi r^3 \rho}{AR} \tag{4E-7}$$

4E-4

and

$$r = \left(\frac{MAR}{2\pi\rho} \right)^{1/3} \tag{4E-8}$$

Now the planform or lift area is given as

$$A = \pi \left(\frac{MAR}{2\pi\rho} \right)^{2/3} \tag{4E-9}$$

The projected or drag area is

$$AP = dt \tag{4E-10}$$

where d is calculated from Equation (4E-8), and t is determined from Equation (4E-6) for a given value of AR. The independent variables used in various computer runs are shown in Table 4-1 of the text. The results of these runs are plotted in Figures 4-27 through 4-36 of the text. The graph shows the maximum range of the fragment versus the initial trajectory angle. For a given velocity and aspect ratio, a family of curves is shown for various values of M/A. For several cases the lift force would act to pull the fragment up into a completely vertical flight. When this occurred, it was assumed that the fragment became unstable and fell straight to the ground. This phenomenon generally occurred for relatively high initial velocities and/or trajectory angles. A line has been drawn on Figures 4-28 through 4-35 to depict this occurrence. All points to the right of the line represent a "normal" flight, and those to the left are for the fragments that attained a vertical flight.

The value 300 m/s (938 ft/s) was used as a maximum initial velocity for the test cases. This velocity is very close to Mach 1 for STP conditions, and velocities above this would result in the need for a more complex aerodynamic analysis. The FRISB code would most likely predict larger ranges than would actually occur at higher velocities due to the increased drag at supersonic speeds. Therefore, for the purpose of estimation, the results from FRISB could be used for higher velocities.

Some fragments may not be disc or spherical shaped, but long and thin as a helicopter blade. The disc analysis is not valid for such a fragment because of the differing mechanisms of flight. The disc depends upon the forward motion to generate lift, where a whirling blade would generate most of its lift from the thrust due to the whirling motion, much the same as a helicopter rotor blade. Due to the possible need for such an analysis, the FRISB code was adapted with a subprogram to compute the trajectory of a fragment that flies, such as a helicopter rotor blade. The fragment geometry is as follows:
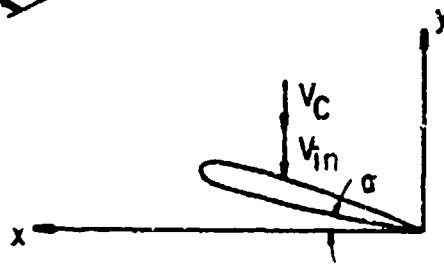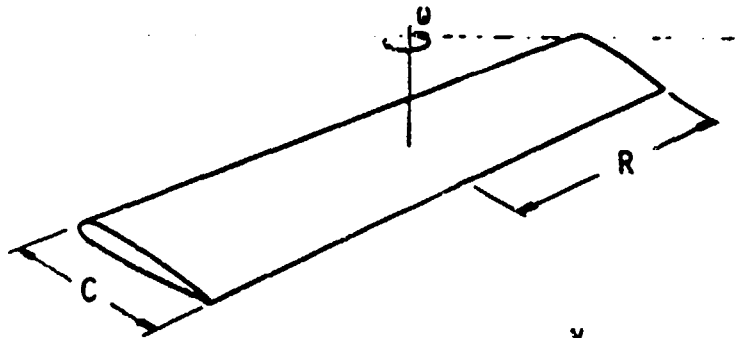
V_C = velocity at which blade moves along vertical axis
V_{in} = velocity induced by thrust of blade
α = pitch or trajectory angle
V_t = tip speed = $R\omega$

The induced velocity is obtained from (see Reference 3):

$$V_{in} = V_t \left[-\left(\frac{abc}{16\pi R} + \frac{V_c}{2V_t} \right) + \sqrt{\left(\frac{abc}{16\pi R} + \frac{V_c}{2V_t} \right)^2 + \frac{abc\alpha}{8\pi R} - \frac{abc V_c}{8\pi R V_t}} \right] \quad (4E-11)$$

The thrust is determined by

$$T = \frac{1}{2} C_L V_t^2 \rho \frac{bcR}{g} \quad (4E-12)$$

The acceleration in the y direction due to the thrust is

$$\ddot{Y} = \left[\left\{ \left(\frac{Tg}{M} \right) \cos\alpha - g \right\}^2 + \left\{ \left(\frac{Tg}{M} \right) \sin\alpha \right\}^2 \right]^{1/2} \quad (4E-13)$$

The change in vertical velocity is

4E-

$$\Delta V_c = \ddot{Y} \Delta t \qquad\qquad\qquad (4E\text{-}14)$$

The torque produced by the rotating blade is

$$Q = \left[\frac{T (V_c + V_{in})}{V_t} + D_p \right] R \qquad\qquad (4E\text{-}15)$$

where D_p is the profile drag, which is given by:

$$D_p = \frac{1}{2} \rho C_D \frac{V_t^2 C k}{g} \qquad\qquad (4E\text{-}16)$$

The change in angular rotation is

$$-\Delta \omega = \frac{Q \Delta t}{I} \qquad\qquad\qquad (4E\text{-}17)$$

where I is the mass moment of inertia of the blade.

A fragment flying in this fashion would eventually lose its angular velocity due to drag, and thus lose its lift. This procedure differs from that for a disc in that it assumes that the lift force comes from the rotation of the fragment and not the fragment forward motion. The drag due to the forward motion of the fragment blade is considered when the computation is returned from the subroutine to the main program.

Input Data

1st data card	NN - number of test runs included in data check
2nd data card	N - number of differential equations to be solved by Runge-Kutta = 2
	X - initial time - 0.0
	H - time increment (0.1 sec is usually sufficient)
	*AP - projected area and drag area - m^2
	OPER - 1 for disc - 2 for rotor blade

---

*If rotor subprogram is used, this is read in as anything because it will not be used.

3rd data card

RO - density of air - kg/m^3

A - lift area (planform) - m^2

CL - lift coefficient

CD - drag coefficient

AMASS - fragment mass - kg

ALPHAO - initial trajectory angle - rad

VO - initial fragment velocity - m/s

G - acceleration of gravity - m/s^2

4th data card
(only if using
rotor analysis)

EMEGA - angular velocity - rad/s

R - radius of blade - m

ASLF - lift curve slope of rotor airfoil - 2π

C - chord or width of rotor

B - number of rotor blades - 2

EMI - mass moment of inertia - $N-s^2-m$

4E-N

```
      PROGRAM FRISB  (INPUT,OUTPUT,TAPE5 =OUTPUT)
. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .

      THIS PROGRAM SOLVES THE SECOND ORDER DIFFERENTIAL EQUATIONS THAT
   GOVERN THE TRAJECTORY OF AN EXPLOSION FRAGMENT. THE SECOND ORDER
   EQUATIONS ARE WRITTEN AS FIRST ORDER AND SOLVED BY RUNGE KUTTA
   TECHNIQUES. THE SOLUTIONS ARE THEN INTEGRATED TO OBTAIN THE FRAGMENT
   TRAJECTORY.

      THE INPUT VARIABLES ARE; X-INITIAL TIME, N-NUMBER OF EQUATIONS,
   RO-AIR DENSITY,A-FRAGMENT PLANFORM AREA,CL-LIFT COEFFICIENT,CD-DRAG
   COEFFICIENT,AMASS-PARTICLE MASS,ALPHAO-INITAL TRAJECTORY ANGLE,
   VO-INITIAL VELOCITY,THETA-ANGLE OF ATTACK,H-TIME INCREMENT, AP-PROJEC
   AREA, OPER-SIGNALS USE OF ROTOR SUBROUTINE, OPER=1-DISC,OPER=2-ROTOR


. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .
      DIMENSION Y(2),F(2),AA(2),BB(2),DSUMY(1000),DSUMX(1000),DXDOT(2)
      INTEGER OPER
      READ 25,NN
      DO 999 K=1,NN
      READ 99,N,X,H,AP,OPER
      READ 100,RO,A,CL,CD,AMASS,ALPHAO,VO,G
      IF(OPER.NE.2)GO TO 314
      READ 1000,EMEGA,H,ASLP,C,B,EMI
314   CONTINUE
      PRINT 106
      PRINT 112,CL,CD
      PRINT 116
      PRINT 113, AMASS
      PRINT 116
      PRINT 263,A
      PRINT 116
      PRINT 114, ALPHAO
      PRINT 116
      PRINT 115,VO
      PRINT 116
      PRINT 111, H
      PRINT 116
      PRINT 110
      PRINT 116
1     CONTINUE
      LL=0
      I=0
      VC = 0.
      ALPHA=ALPHAO
      NT=0
      SUMY=0.0
      SUMX=0.0
      ICNT = 0
      Y(1)=0.0
      Y(2)=0.0
24    CONTINUE
      ICNT = ICNT + 1
      YDOT=Y(1) + VO*SIN(ALPHAO)
      IF(OPER.EQ.2)YDOT = YDOT + VC*COS(ALPHA)
      XDOT=Y(2) + VO*COS(ALPHAO)
```

4E-9

```
      IF(OPER.EQ.2)XDOT=XDOT-VC*SIN(ALPHA)
      DXDOT(1) = XDOT
      DALPHA = ATAN(YDOT/XDOT)
      ALPHA = DALPHA
      IF(ALPHA.GT.1.5) GO TO 997
      IF(ALPHA.LT.-1.4) GO TO 997
      IF(OPER.NE.2) GO TO 320
      CALL ROTOR(FMEGA,R,CL,CD,ALPHAO,ASLP,C,B,EMI,RO,VC,DVC,H,G,AMASS,A
     1LPHA)
  320 CONTINUE
      AA(1) = Y(1)
      BB(1) = Y(2)
      BETA = .5*RO*AP*CD/AMASS
      GAM = .5*RO*A*CL/AMASS
      IF(OPER.EQ.2)GAM = 0.0
   22 CONTINUE
      YSPXS = Y(1)**2 + Y(2)**2 + 2*Y(1)*VO*SIN(ALPHAO) + 2*Y(2)*VO*COS(
     SALPHAO) + VO**2
      F(1) = -G - BETA*(YSPXS)*SIN(ALPHA) + GAM*(YSPXS)*COS(ALPHA)
      F(2) = -BETA*(YSPXS)*COS(ALPHA) -GAM*(YSPXS)*SIN(ALPHA)
      S = RKLDEG(H,Y,F,X,H,NT)
      SS = S-1.0
      IF(SS.EQ.0.0)GO TO 22
      AA(2) = Y(1)
      BB(2) = Y(2)
      YDOT=Y(1) + VO*SIN(ALPHAO)
      IF(OPER.EQ.2)YDOT = YDOT + VC*COS(ALPHA)
      XDOT=Y(2) + VO*COS(ALPHAO)
      IF(OPER.EQ.2)XDOT=XDOT-VC*SIN(ALPHA)
      DXDOT(2) = XDOT
      IF(X.GE.0.5) GO TO 13
   13 CONTINUE
      DISY = (AA(1) + (AA(2)- AA(1))/2.)*H  +VO*SIN(ALPHAO)*H
      DISX = (BB(1) + (BB(2)- BB(1))/2.)*H  + VO*COS(ALPHAO)*H
      IF(OPER.EQ.2)DISY = DISY + DVC*H
      SUMY = SUMY + DISY
      SUMX = SUMX + DISX
      LLELL +1
      LL=0
    6 CONTINUE
      I=I+1
      DSUMY(I) = SUMY
      DSUMX(I) = SUMX
      PRINT 101,X,SUMY,SUMX,YDOT,XDOT,ALPHA
  101 FORMAT(2X,F10.5,10X,F10.3,10X,F10.3,10X,F10.3,10X,F10.3,10X,F10.3)
    7 CONTINUE
      IF(SUMX.LT.0.) GO TO 997
      IF(SUMY.GT.0.0)GO TO 24
  997 CONTINUE
      IN = ALOG10(SUMX)
      MM=(SUMX/(10**IN)) + 1
      YMAX = MM*10**IN
      CALL EXTVAL(DSUMY,ICNT,YMAX,DMIN)
      PRINT 3001
 3001 FORMAT(1H1)
      CALL PLOT1(2,2)
      CALL PLOT2(XMAX,0.,YMAX,0.)
      CALL PLOT3(1HX,DSUMX,DSUMY,I)
```

```
      CALL PLOT=(0,0,1H )
  999 CONTINUE
   25 FORMAT(I10)
  100 FORMAT(8F10.6)
  106 FORMAT(1H1)
  110 FORMAT(7X,=TIME=,12X,=Y DISPLACEMENT=,6X,=X DISPLACEMENT=,4X,=Y VE
     =LOCITY=,11X,=X VELOCITY=,12X,=ALPHA=)
  111 FORMAT(10X,=TIME INCREMENT = =,F5.2,=SEC=)
  112 FORMAT(10X,=LIFT COEFFICIENT = =,F10.5,10X,=DRAG COEFFICIENT = =,F
     =10.5)
  113 FORMAT(10X,=INITIAL MASS = =,F10.6,=KG=)
  114 FORMAT(10X,=INITIAL TRAJECTORY ANGLE ==,F10.3,=RADIANS=)
  115 FORMAT(10X,=INITIAL VELOCITY = =,F10.3,=M/SEC=)
  116 FORMAT(1H0)
  263 FORMAT(10X,=FRAGMENT AREA = =,F10.4,=SQ. METERS=)
 1000 FORMAT(6F10.5)
   99 FORMAT(I10,3F10.6,I10)
      STOP
      END
```

```fortran
      SUBROUTINE PLOT1(NVS,NHS)
      COMMON/GRAPH2/POINT(41,101),CH
C
C********* INPUT *********
C
C     NVS = NO. OF VERTICAL GRID LINES (MUST EQ. 11,6,3, OR 2)
C     NHS = NO. OF HORIZONTAL GRID LINES (MUST EQ. 5,3, OR 2)
C
C     THIS IS A FORTRAN PROGRAM WHICH BUILDS A PLOT GRID FOR A PRINTER-PLOT
C     THE FOLLOWING PROGRAMS HAVE TO BE USED IN CONJUNCTION WITH THIS PROGRAM
C           A SUBROUTINE PLOT2
C           B SUBROUTINE PLOT3
C           C SUBROUTINE PLOT4
C
C
C     *************************
C
      BL = 1H
      VC = 1HI
      HC = 1H-
      C = 1H+
C     BLANK OUT THE PLOT AREA
      DO 1 I=1,41
      DO 1 J=1,101
    1 POINT(I,J) = BL
C     DETERMINE TYPE OF GRID TO BE USED
      JS = 100/(NVS - 1)
      IS = 40/(NHS - 1)
C     BUILD THE HORIZONTAL GRID LINES
      DO 2 I=1,41,IS
      DO 2 J=1,101
    2 POINT(I,J)=HC
C     BUILD THE VERTICAL GRID LINES, AND PUT CHARACTER AT INTERSECTING
C     POINTS
      DO 3 J=1,101,JS
      DO 3 I=1,41
      IF(POINT(I,J) .EQ. HC) GO TO 4
      POINT(I,J) = VC
      GO TO 3
    4 POINT(I,J) = C
    3 CONTINUE
C     PUT CHARACTER AT EACH TENTH SPOT OF THE PERIMETER OF THE GRID
      DO 5 J=1,101,10
      DO 5 I=1,41,40
    5 POINT(I,J) = C
      DO 6 I=1,91,10
      DO 6 J=1,101,100
    6 POINT(I,J) = C
      RETURN
      END
```

4E-12

```fortran
      FUNCTION RKLDFQ(N,Y,F,X,H,NT)
C  D2 UCSD RKLDEQ RUNGE-KUTTA-GILL LINEAR DIFFERENTIAL EQUATION SOLVER
C      D2 UCSD RKLDEQ
C      MODIF.ED MAY 1963 (Q REMOVED FROM CALLING SEQUENCE).
C      TEST OF ALGOL ALGORITHM
      DIMENSION Y(10),F(10),Q(10)
C      REAL X,H--INTEGER N,NT--COMMENT--BEGIN INTEGER I,J,L-REAL A
      NT=NT+1
      GO TO (1,2,3,4),NT
C      GO TO S(NT)
1     DO 11 J=1,N
11    Q(J)=0.
      A=.5
      X=X+H/2.
      GO TO 5
2     A=.2928932188J
      GO TO.5
3     A=1.7071067812
      X=X+H/2.
      GO TO 5
4     DO 41 I=1,N
41    Y(I)=Y(I)+H*F(I)/6.-Q(I)/3.
      NT=0
      RKLDEQ=2.
      GO TO 6
5     DO 51 L=1,N
      Y(L)=Y(L)+A*(H*F(L)-Q(L))
51    Q(L)=2.*A*H*F(L)+(1.-3.*A)*Q(L)
      RKLDEQ=1.
6     CONTINUE
      RETURN
      END
```

```
      SUBROUTINE ROTOR(EMEGA,R,CL,CD,ALPHA0,ASLP,C,B,EMI,RO,VC,DVC,H,G,A
     1MASS,ALPHA)
      ZZ = VC
      VT = EMEGA*R
      VA = VT/2.
      DD = ASLP*B*C/(3.1417*R)
      VI = VT*(-DD/16. - VC/(2.*VT) + ((DD/16. + VC/(2*VT))**2.+(DD*ALPH
     1AD)/8. - (DD*VC)/(8.*VT))**.5)
      T = .5*CL*(VA**2)*RO*9*C*R/G
      ACC = (((T*G/AMASS)*COS(ALPHA)-G)**2 + ((T*G/AMASS)*SIN(ALPHA))**2
     1)**.5
      DP = .5*RO*CD*(VI**2)*.0032/G
      Q  = (T*((VC + VI)/VA) + DP )*R
      DMEGA = Q*H/EMI
      EMEGA = EMEGA - DMEGA
      VC = ACC*H
      DVC = VC - ZZ
      PRINT191,EMEGA,VC,T,Q
191   FORMAT(5X,*EMEGA =*,F10.2,5X,*VC=*,F10.4,5X,*T=*,F10.4,5X,*Q=*,F10
     /.4)
      RET
      END
```

```
      SUBROUTINE PLOT2(XMAX,XMIN,YMAX,YMIN)
      COMMON/GRAPH1/X(100),Y(100),XF,XL,YF,YL,NPTS
C
C ******** INPUT ********
C
C      XMAX = XL = THE MAX, SCALE VALUE FOR THE X-AXIS
C      XMIN = XF = THE MIN, SCALE VALUE FOR THE X-AXIS
C      YMAX = YL = THE MAX, SCALE VALUE FOR THE Y-AXIS
C      YMIN = YF = THE MIN, SCALE VALUE FOR THE Y-AXIS
C
C  THIS IS A FORTRAN PROGRAM WHICH SETS THE PLOT SCALE
C
C *******************
C
      XL = XMAX
      XF = XMIN
      YL = YMAX
      YF = YMIN
      RETURN
      END
```

```fortran
      SUBROUTINE PLOT3(CHAR,XARAY,YARAY,N)
      DIMENSION XARAY(200),YARAY(200)
      COMMON/GRAPH1/X(100),Y(100),XF,XL,YF,YL,NPTS
      COMMON/GRAPH2/POINT(41,101),CH
C
C ********* INPUT *********
C
C     CHAR  = PLOT CHARACTER TO BE USED
C     XARAY = VALUES OF X TO PLOT
C     YARAY = VALUES OF Y TO PLOT
C     N     = NO. OF POINTS (OR DIMENSION OF XARAR, AND YARAY)TO PLOT
C             IF .GT. 100 THE ARRAY WILL BE SCALED TO .LE. 100
C
C     THIS IS A FORTRAN PROGRAM WHICH SCALES ARRAYS TO BE PLOTTED.
C
C ***********************
C
      J = 0
      CH = CHAR
      ISTEP = N/100 + 1
      DO 1 I=1,N,ISTEP
      J=J+1
      X(J) = XARAY(I)
    1 Y(J) = YARAY(I)
      NPTS = J
      CALL PLOT
      RETURN
      END
```

```
SUBROUTINE PLOT
COMMON/GRAPH1/X(100),Y(100),XF,XL,YF,YL,N
COMMON/GRAPH2/POINT(41,101),CH
COMMON/GRAPH3/S(11),T(5)
C1=1H
C2=1HI
C3=1H-
C4=1H+
C5=1H*
KOLD = 102
LOLD = 42
IF(XL .EQ. XF)RETURN
IF(YL .EQ. YF)RETURN
A = 100./(XL - XF)
B = 40./(YL - YF)
DX = (XL - XF)/10.0
DY = (YL - YF)/4.0
S(1) = XF
T(1) = YF
DO 6 I=1,10
6 S(I+1) = S(I) + DX
DO 61 I=1,4
61 T(I+1) = T(I) + DY
DO 10 I=1,N
K = (X(I) - XF)*A + 1.5
L = 40.0 - (Y(I) - YF)*B + 1.5
IF(K .GT. 101)GO TO 10
IF(L .LT. 0)GO TO 10
IF(L .GT. 41)GO TO 10
IF(K .EQ. KOLD)GO TO 11
GO TO 12
11 IF(L .EQ. LOLD) GO TO 10
12 KOLD = K
LOLD = L
IF(POINT(L,K).NE.C1.AND.POINT(L,K).NE.C2.AND.POINT(L,K).NE.
$   C3.AND.POINT(L,K).NE.C4)GO TO 9
POINT(L,K) = CH
GO TO 10
9 CONTINUE
POINT(L,K)=C5
10 CONTINUE
RETURN
END
```

```
      SUBROUTINE PLOTM(NCY,NCX,LABEL)
      COMMON/GRAPH1/X(100),Y(100),XF,XL,YF,YL,N
      COMMON/GRAPH2/POINT(41,101),CM
      COMMON/GRAPH3/S(11),T(S)
      DIMENSION LABEL(26)
C
C ******** INPUT ********
C
C     NCY = SWITCH INDICATING Y-AXIS CAPTION
C         = 0, NO CAPTION
C         = 1, UP TO 12 BCD CHARACTERS IN TITLE
C     NCX = SWITCH INDICATING X-AXIS CAPTION
C         = 0, NO CAPTION
C         = 1, UP TO 72 BCD CHARACTERS TO BE PRINTED AS A HEADING
C             ABOVE THE PLOT, AND UP TO 72 BCD CHARACTERS TO BE PRINTED
C             ON A LINE BELOW THE PLOT
C
C     THIS IS A FORTRAN PROGRAM WHICH PRINTS THE PLOTS, CAPTIONS AND SCALES
C     OF THE DESIRED GRAPHS
C
C ****************************
C
      IF(NCX .EQ. 0) GO TO 1
      PRINT 101,(LABEL(IX),IX=3,14)
  101 FORMAT(1H1,/,29X,4H*** ,12A6,1X,3H***,//)
    1 DO 40 I=1,15
      IF(MOD(I,10) .EQ. 1) GO TO 45
      PRINT 110,(POINT(I,J),J=1,101)
  110 FORMAT(20X,101A1)
      GO TO 40
   45 INDX = 6 - (I+11)/10
      PRINT 180,T(INDX),(POINT(I,J),J=1,101)
  180 FORMAT(3X,E15.3,2X,101A1)
   40 CONTINUE
      IF(NCY .EQ. 0)GO TO 2
      PRINT 120,(LABEL(IY),IY=1,2),(POINT(16,J),J=1,101)
  120 FORMAT(8X,2A6,101A1)
      GO TO 3
    2 PRINT 110,(POINT(16,J),J=1,101)
    3 DO 50 I=17,41
      IF(MOD(I,10) .EQ. 1) GO TO 55
      PRINT 110,(POINT(I,J),J=1,101)
      GO TO 50
   55 INDX = 6 - (I + 11)/10
      PRINT 180,T(INDX),(POINT(I,J),J=1,101)
   50 CONTINUE
      PRINT 130,(S(I),I=1,11,2)
  130 FORMAT(1H0,6X,E15.3,5(6X,E15.3))
      IF(NCX .EQ. 0) GO TO 4
    4 RETURN
      END
```

```
      SUBROUTINE EXTVAL(X,N,XMAX,XMIN)
      DIMENSION X(1)
C
C     FIND MAXIMUM AND MINIMUM VALUES IN THE ARRAY X WHICH HAS N ENTRIES
      XMAX=X(1)
      XMIN=X(1)
      DO 200 I=2,N
      IF (XMAX.GT.X(I)) GO TO 100
      XMAX=X(I)
  100 IF (XMIN.LT.X(I)) GO TO 200
      XMIN=X(I)
  200 CONTINUE
      NN=ALOG10(XMAX)
      M=(XMAX/(10**NN)) + 1
      XMAX = M*10**NN
      RETURN
      END
```

Computer Code TRAJE for Obtaining the Range and Terminal Velocities of Drag Fragments

The following computer code, TRAJE, was used to generate figures for fragment range versus initial trajectory angle for fragments which experience no lift forces. It can be used to determine the terminal velocity of fragments at their maximum range. The program is based on a perturbation technique described in Reference 4. The following table lists the program variables used in TRAJE that were not previously defined in FRISB.

Program Variable	Definition	Unit
FM	input fragment mass	kg
AF	input fragment characteristic area	m^2
CD	input fragment drag coefficient	--
NCD	input branch constant (for NCD $\geq$ 1 the velocity dependent drag coefficient is introduced)	--
DT	input time increment	s
TM	input maximum time limit	s
V∅	initial fragment velocity	m/s
AL∅	initial trajectory angle	rad
BBT	drag constant	N/kg
TT	test time	s
XQ	fragment horizontal displacement	m
Y	fragment vertical displacement	m
VX	fragment instantaneous horizontal velocity	m/s
VY	fragment instantaneous vertical velocity	m/s
ALP	instantaneous trajectory angle	rad
V	total fragment velocity	m/s

```
      PROGRAM TRAJE   (INPUT,OUTPUT,TAPE1 =OUTPUT,TAPE2 =INPUT)
      COMMON /VAR/ BET,    AF,FM
    1 FORMAT (E12.5)
    2 FORMAT (2E12.5)
    3 FORMAT (/,7H ALPHA=,E11.4,9H RAD, VO=,E11.4,7H M/SEC)
    5 FORMAT (/,6H MASS=,E11.4,11H KG,   AREA=,E11.4,5H SQ,M)
    7 FORMAT (/,4H CD=,E11.4)
    8 FORMAT (/,17H TEST TIME VALUES,E11.4)
   10 FORMAT (2/,62H    TIME       X-DISH      Y-DISH      X-VEL      Y-VEL
     1    ANG )
   11 FORMAT (40H    (SECS)     (METER)    (METER)    (M/SEC)    (M/SEC)
     1 (RAD) )
   12 FORMAT (/,4E11.4)
   13 FORMAT (/,4E11.4)
   16 FORMAT (I2)
      DO 105 K=1,10
      READ (2,2) FM,AF
      WRITE (1,5) FM,AF
      READ (2,1) CD
      WRITE (1,7) CD
      READ (2,16) NCD
      READ (2,2) OT,TM
      VO=0.0
      DO 500 II=1,3
      ALO=0.0
      VO= VO+100.
      DO 501 IJ=1,4
      ALO= ALO+ 0.1745
  111 WRITE (1,3) ALO,VO
      BET= (CD*AF*1.2050)/(2.*FM)
      TT=(AF*0.0.M1)**0.5
      WRITE (1,8) TT
      SET INITIAL VALUES
      X=0.0
      V=0.0
      VX=VO*COS(ALO)
      VY=VO*SIN(ALO)
      DX=0.0
      DVX=0.0
      DY=0.0
      DVX=0.0
      DVY=0.0
      DO 100 I=1,800
      IF (I-1) 120,120,121
  120 ALP=ALO
      GO TO 122
  121 ALP=DA
  122 CONTINUE
      X=X+DX
      Y=Y+DY
      IF (Y-10.) 503,502,502
  503 CONTINUE
      PRINT OUT VALUES
      IF (I-1.) 101,101,106
  101 T=0.0
      WRITE (1,10)
      WRITE (1,11)
```

```
      WRITE (1,13) T,X,Y,VX,VY,ALP
      GO TO 103
108   WRITE (1,13) T,X,Y,VX,VY,ALP
500   CONTINUE
      IF (I) 501,106,106
106   CONTINUE
      CALC. NEW INPUT PARAMETERS
103   TO TONT
      IF (T-TM) 104,104,105
104   VI=((VX**2)+(VY**2))**0.5
      IF (NCD-1) 300,301,301
301   IF (VI-150.) 302,302,303
302   CD=1,2N
      GO TO 300
303   IF(VI-275.) 305,305,305
304   CD=(.00175*(VI-150.))+1.2N
      GO TO 300
305   IF (VI-115.) 306,306,307
306   CD=(.00012*(VI-275.))+.75
      GO TO 300
307   IF(VI-475.) 308,308,308
308   CD=(.0181*(VI-335.))+2.30
      GO TO 300
309   IF(VI-675.) 310,310,311
310   CD=(.001*(VI-475.))+2.85
      GO TO 300
311   CD=(.00865*(VI-675.))+1.05
300   CONTINUE
      RETD=(CD*A*P/26501/(P,*FM)
      CALC, CHGS. FOR NEW T
      CALL DEL (DT,ALP,VI,DX,DY,VX,VY,DA)
100   CONTINUE
501   CONTINUE
500   CONTINUE
103   CONTINUE
      END
```

```fortran
      SUBROUTINE DEL (DT,ALP,VI,DX,DY,VX,VY,DA)
      REAL LNF
      COMMON/VAR/BET,   AF,FM
150   FORMAT (8E12.5)
      G=9.81
      EK=BET*VI
      U=EK*DT
      DETERMINE VALUE OF LOG FUNC.
      IF (U-.0001) 201,201,202
201   LNF=1-(0.5*(U**2))+((1.0/3.0)*(U**3))-(0.25*(U**4))
      S=(1.+U)
      GO TO 203
202   S=(1.+U)
      LNF= ALOG(S)
      CALC. DX AND DVX IN MOVING COORD.
203   X0=LNF/BET
      XD0=VI/S
      GS=G*SIN(ALP)
      GC=G*COS(ALP)
      XP=0.5*GS*(DT**2)*(1.+(U/3))/S
      XPD=GS*DT*(1.+U+((1./3.)*(U**2)))/(S**2)
      DX=X0+XP
      DVX=XD0+XPD
      CALC. DY AND DVY IN MOVING COORD.
      YPD= -((GC*0.5/EK)*(S-(1./S)))
      TS=(S**2)/2.
      SMT2=(TS-LNF-0.5)
      YP=-((0.5*GC/(EK**2))*SMT2)
      DY=YP
      DVY=YPD
      CALC. DX DY DVX DVY IN FIXED COORD.
      DX=(DX*COS(ALP))-(DY*SIN(ALP))
      DY=(DX*SIN(ALP))+(DY*COS(ALP))
      VX=(DVX*COS(ALP))-(DVY*SIN(ALP))
      VY=(DVX*SIN(ALP))+(DVY*COS(ALP))
      DA=ATAN( VY/ VX)
      V=((VX**2)+(VY**2))**0.5
      RETURN
      END
```

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1. Milne-Thompson, L. M., Theoretical Aerodynamics, MacMillan, London, 1966, 4th Edition, p. 230.

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3. Stepniewski, W. Z., "Basic Aerodynamics and Performance of the Helicopter," Helicopter Aerodynamics and Dynamics--AGARD Lecture Series No. 63, AGARD-LS-63, April 1973.

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APPENDIX IV. F

STATISTICAL FITTING TO FRAGMENT DATA

4F-1   Derivation of Figures 4-46 through 4-49

From the initial fragment velocity data on grouped tests by propellant and configuration given on page 102 of Reference 1, the following estimated means and standard deviations for the log-normal (to the base e) distributions are shown in Table 4F-1.

TABLE 4F-1.   LOG NORMAL DISTRIBUTIONS OF FRAGMENT
INITIAL VELOCITY (TO THE BASE e) BY PROPELLANT
TYPE AND CONFIGURATION

	CBM LO_2/LH_2	CBM $LO_2/RP-1$	CBCS LO_2/LH_2	CBCS $LO_2/RP-1$
Estimated Mean	5.2759[*]	5.5249	4.9410	4.7739
Estimated Std. Dev.	0.9875	5.5249	0.7715	0.6387

These distributions are plotted on Figures 4-46 through 4-49, respectively.   The goodness of fit statistics (W) are given in Reference 1.

4F-2   Derivation of Figure 4-50

The data from page 86 of Reference 1 for fragment initial velocity measurements were used to determine the regression line (least squares fit) shown of initial velocity, U, in Figure 4-50.   The 95th percentile (U_{95}) estimate was constructed by taking the estimate for the standard deviation (σ) from the CBM LO_2/LH_2 group in Section 4F-1 above, establishing a point 1.65σ above the point U = 73.96, Y = 1% by the formula:

$$U_{95} = \exp \left[\ln\ 73.96 + (1.65)(0.9875) \right]$$

$$= 377.24 \text{ meters } (1237.7 \text{ ft})$$

---

[*]To determine the geometric mean in meters/second, raise e to the power shown.

A line was then extended from the point $U = 377.24$, $Y = 1$, parallel to the regression line for U on Y ($U = 73.96 \, Y^{0.4296}$).

The values for nine tests from Reference 1 are presented in Table 4F-2.

TABLE 4F-2. MEAN AND MAXIMUM FRAGMENT INITIAL
VELOCITY FOR LO_2/LH_2 CBM

Test No.	Yield (%)	Mean Velocity m/s	Maximum Velocity Measured
053	4	110.3	240
091	29	457.2	1100
118	20	215.4	340
199	8	201.2	455
200	17	268.2	504
210	7	198.1	462
212	27	240.8	383
213	35	301.8	459
265	10	210.3	441

Figure 4F-1 shows the regression line, the estimated 95-h percentile line, and the mean and maximum observed velocity point...

4F-3 Rationale for Averaging Fragment Mass Distribution for Events 3, 4, and 5

The estimated means and standard deviations (log-normal to the base e) for the fragment mass for the five events from Reference 1 are shown in Table 4F-3.

The estimated means and standard deviations of events 3, 4, and 5 were fairly close to each other, and the events were of the same type. Therefore, it seemed reasonable to apply a "t" test (see Reference 8) for significant difference in means. This test was applied to events 3 and 4 since the difference in estimated means was the greatest for any pair of estimated means from events 3, 4, and 5.
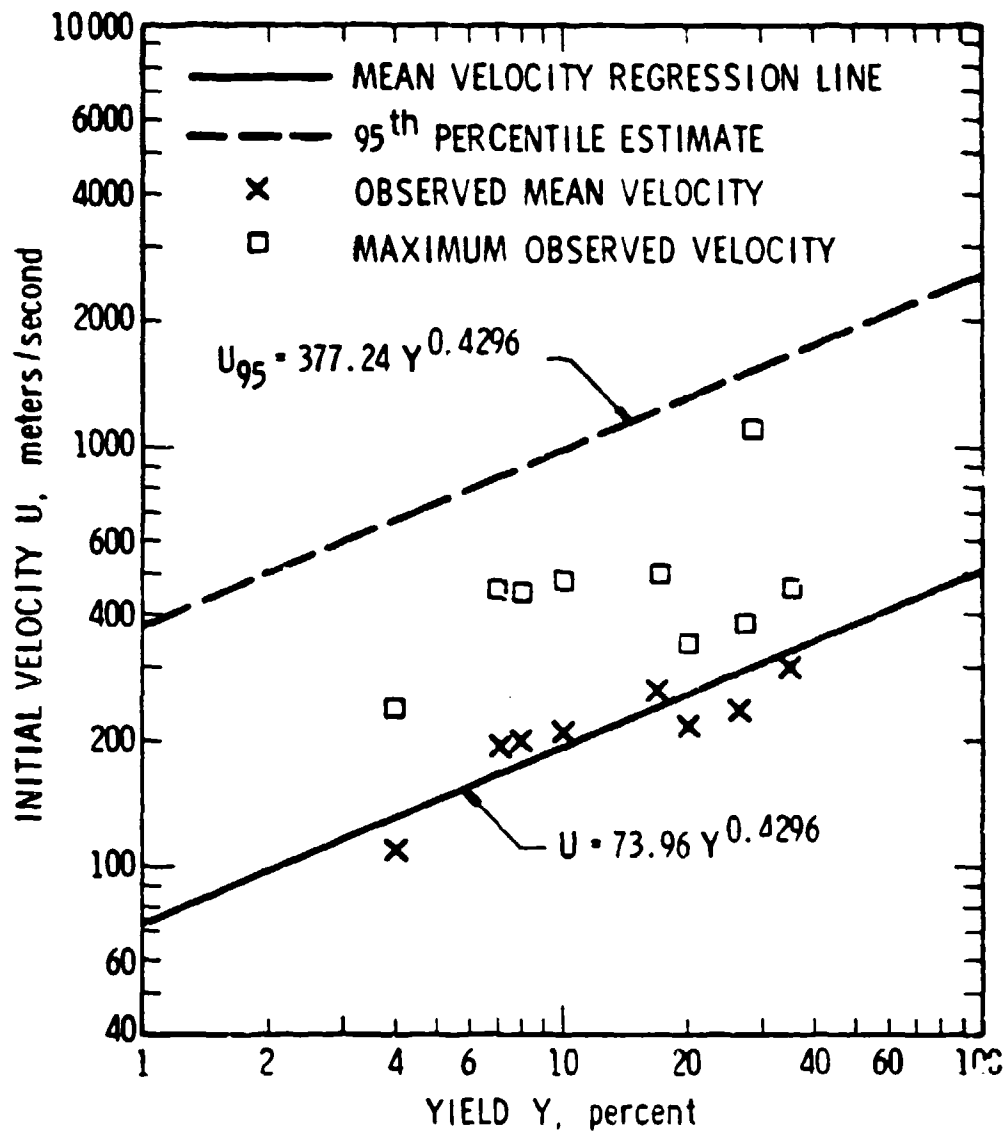
Figure 4F-1. Initial Velocity Vs Yield.
CBM. LO_2/LH_2

(ft/sec = m/s X 3. 281)

TABLE 4F-3. ESTIMATED MEAN AND STANDARD DEVIATION FOR FRAGMENT MASS DISTRIBUTION (LOG NORMAL TO BASE e) FOR FIVE EVENTS

| Event No. | Fragment Mass Distribution | | Percent Yield |
	Mean	Standard Dev.	
1	7.7226*	0.8020	5.0
2	9.3940	1.1142	1.1
3	9.7761	1.1787	23.0
4	10.1488	1.0367	24.4
5	10.0522	0.8838	62.6

The "t" test is applied using the following steps:

(1)   The pooled estimate for the standard deviation (Sp) is calculated by:

$$Sp = \sqrt{(S_1^2 + S_2^2)/2}$$

(2)   The "t" statistic is calculated by

$$t = (\overline{W}_1 - \overline{W}_2)/(Sp)(\sqrt{2}/n),$$

where n is the number of points to estimate $\overline{W}_1$ and $\overline{W}_2$ in our case n = 9.

(3)   The "t" statistic is then compared to a value in the t distribution table, $t_{\alpha; 2(n-1)}$, where α is the probability of type 1 error or risk of accepting the hypothesis that there is no significant difference in means where there is, and $2(n-1)$ is a parameter in the t distribution (degree of freedom) used to find the tabled value.

(4)   If the calculated value of t (from step 2) is between $\pm t_{\alpha; 2(n-1)}$ (the table value), we accept the hypothesis

---

*To determine geometric mean weight, raise e to power shown in table.

that there is no significant difference in the means. If not, we reject the hypothesis, and conclude there is a significant difference in the means.

Choosing an α of 0.20, the table value of t for 16 degrees of freedom is ± 1.337.

The formula for calculating "t" can be further simplified to:

$$t = \frac{\sqrt{n}\,(\overline{W}_1 - \overline{W}_2)}{S_1^{\,2} + S_2^{\,2}} \qquad (4F-1)$$

Using the above formula, the calculated value of t is:

$$t = \frac{3\,(10.1488 - 9.7761)}{1.0367^2 + 1.1787^2} = 0.712$$

Since the calculated value of t of 0.712 lies between the table value ± 1.337, we accept the hypothesis that there is no significant difference in means and can use a single distribution for the fragment mass distribution for events 3, 4, and 5. Averaging the means of events 3, 4, and 5 yielded an average value of 9.9924, and for the standard deviation an average value of 1.0331. These values were used to construct Figure 4-53.

4F-4   Fragment Mass Distributions For Gas Vessel Bursts

The fragment mass data from each of the tanks were sorted in ascending order; the values for the mass for the 10th to the 90th percentiles in 10% steps were identified. Table 4F-4 is a listing of these values.

Figures 4F-2 through 4F-5 are plots of the percentile points on log normal probability paper for tanks A, B, D and E, respectively.

Table 4F-5 is a listing of the estimated means and standard deviations for the log normal (to the base e) distributions.

A "W" statistic (see Reference 9) for goodness of fit was calculated for each of the distributions. The approximate probability of obtaining the calculated test statistic, given that the chosen distribution is correct, was then determined. The results are shown in Table 4F-6.

TABLE 4F-4. PERCENTILES FOR PLOTTING FRAGMENT MASSES OF TANKS A, B, D, AND E

Percent	Tank A	Mass (g) Tank B	Tank D	Tank E
10	2.2	1.1	85	61
20	3.7	4.6	199	199
30	5.2	6.6	454	454
40	11.0	24.0	624	738
50	15.0	31.0	1731	1277
60	42.0	38.0	2015	1617
70	53.0	63.0	2156	1873
80	96.0	92.0	2270	2270
90	145.0	125.0	2639	3036

TABLE 4F-5. LISTING OF ESTIMATED MEANS AND STANDARD DEVIATIONS FOR LOG-NORMAL DISTRIBUTION (TO THE BASE e) FOR GAS VESSELS

Tank No.	Estimated Mean	Estimated Standard Deviation
A	2.9730	1.4821
B	3.0327	1.6829
D	6.5698	1.8080
E	6.6782	1.5815
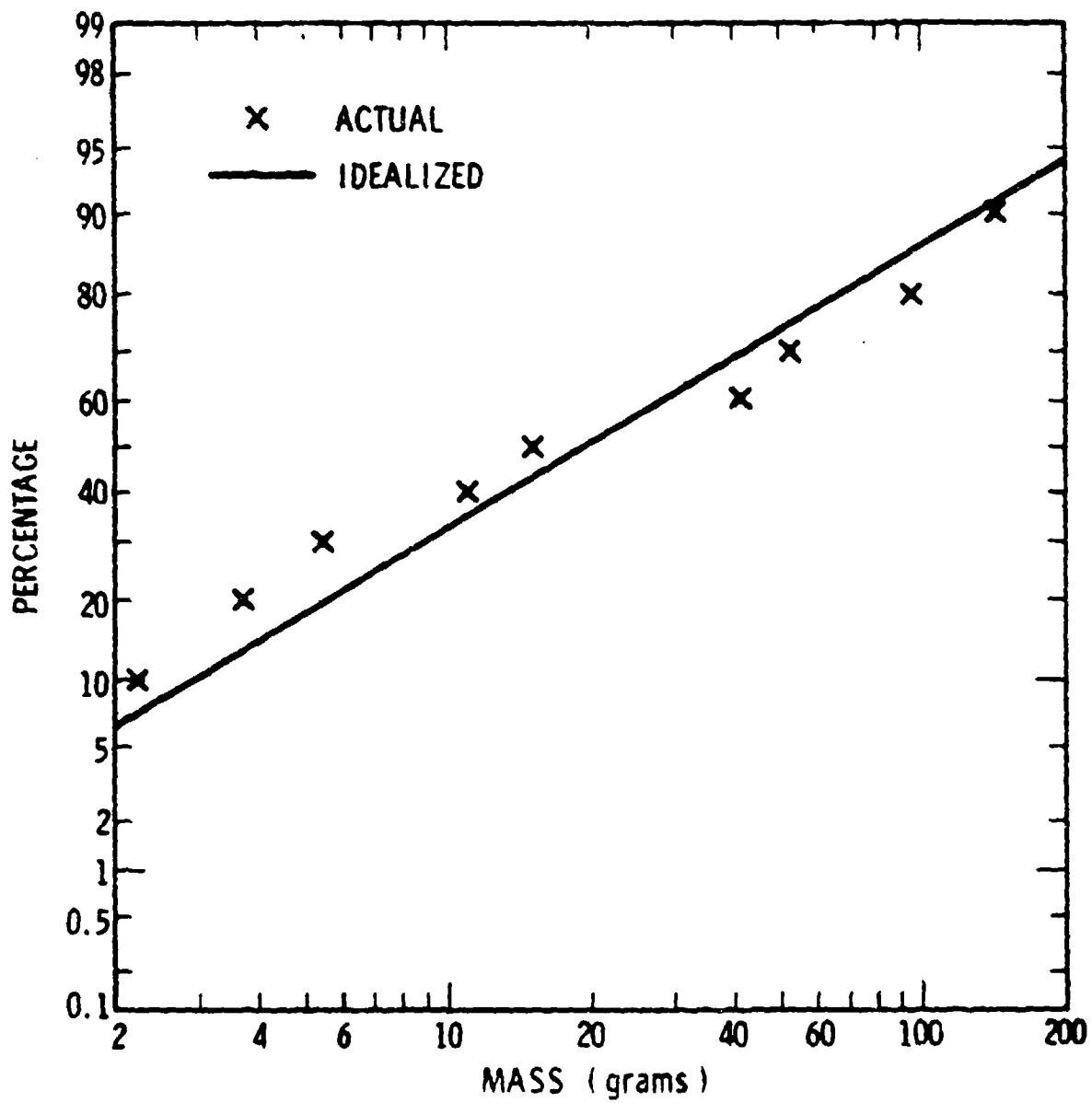
Figure 4F-2. Fragment Mass Distribution, Tank A
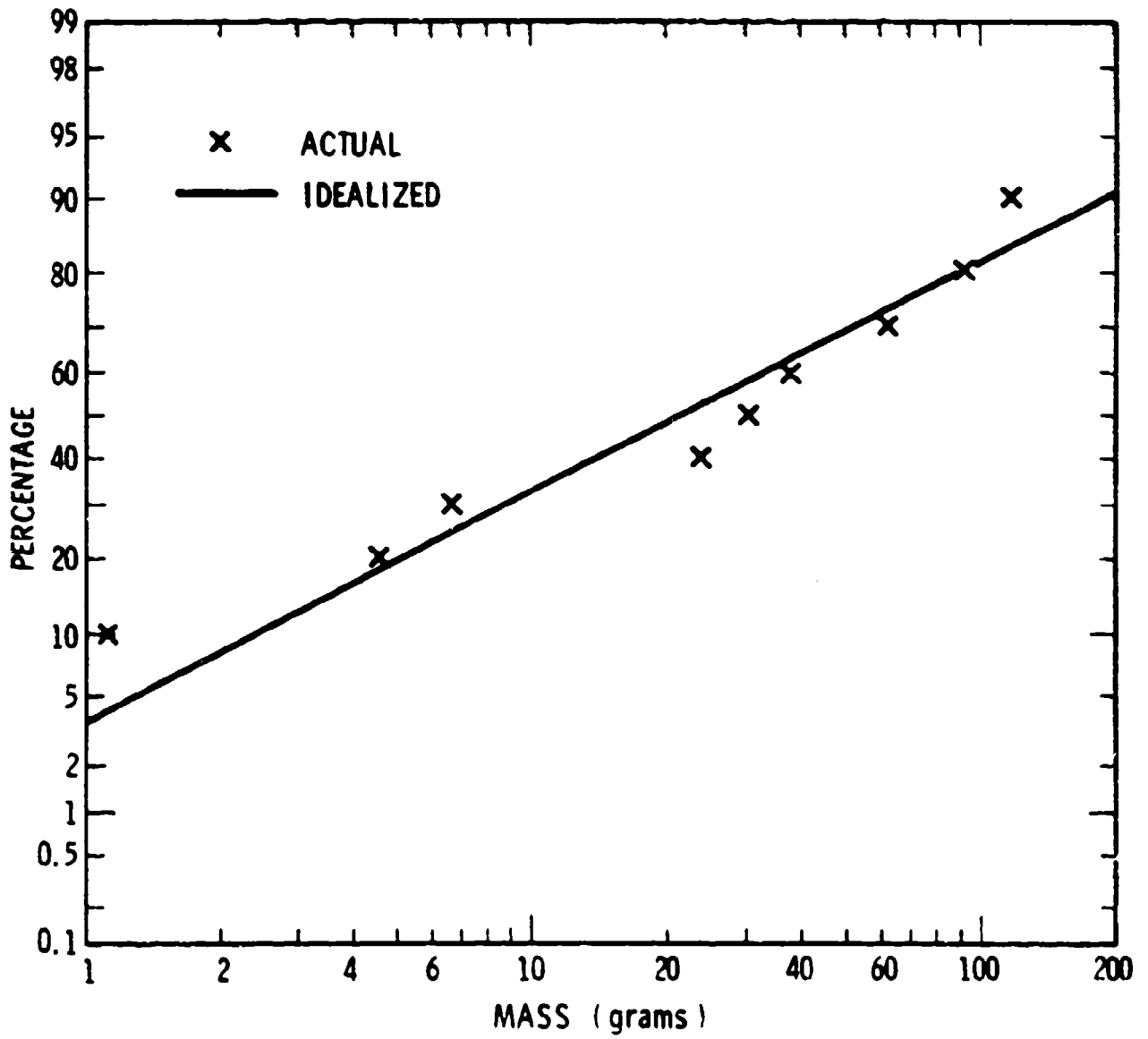
($1b_m$ = kg X 2.205)

Figure 4F-3. Fragment Mass Distribution, Tank B
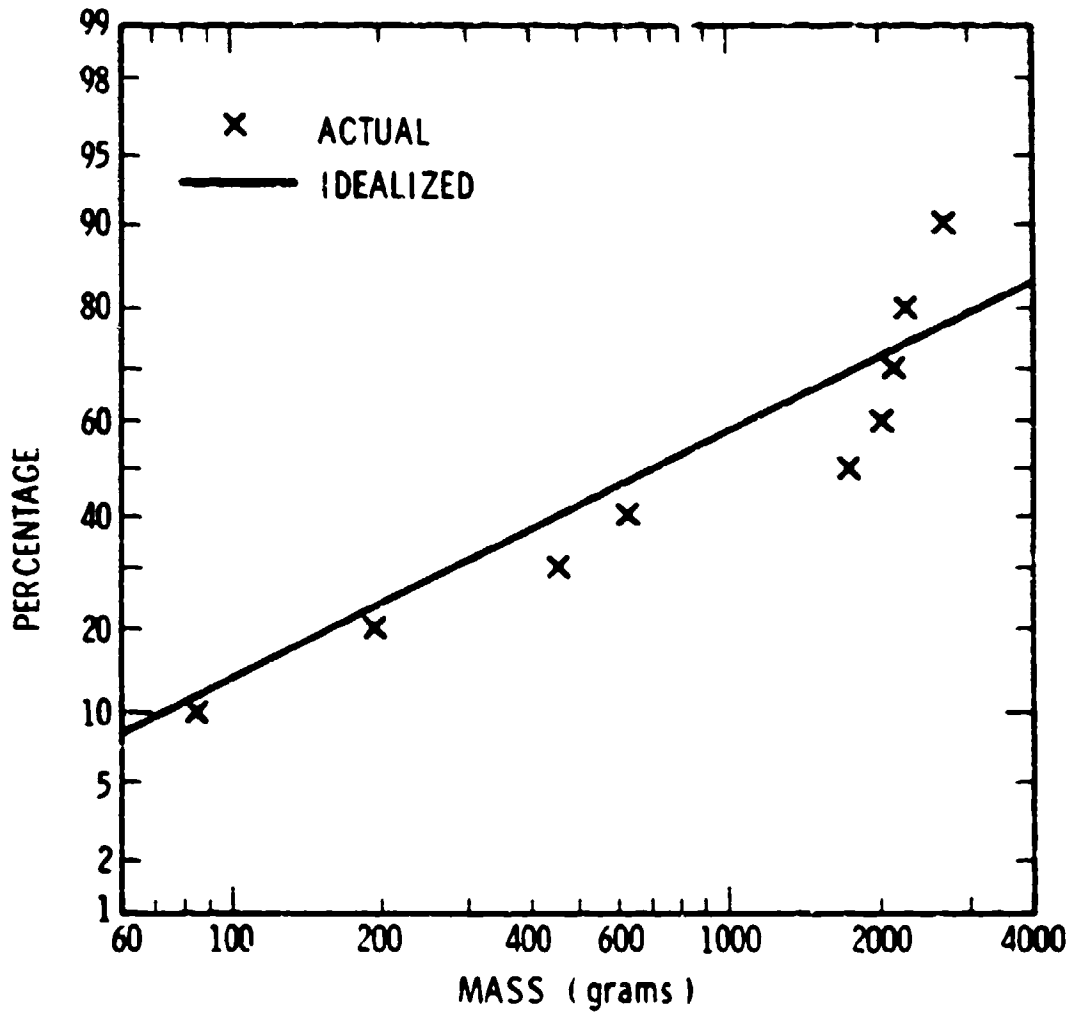
$(1b_m = kg \times 2.205)$

(1b$_m$ = kg X 2.205)

Figure 4F-4. Fragment Mass Distribution, Tank D
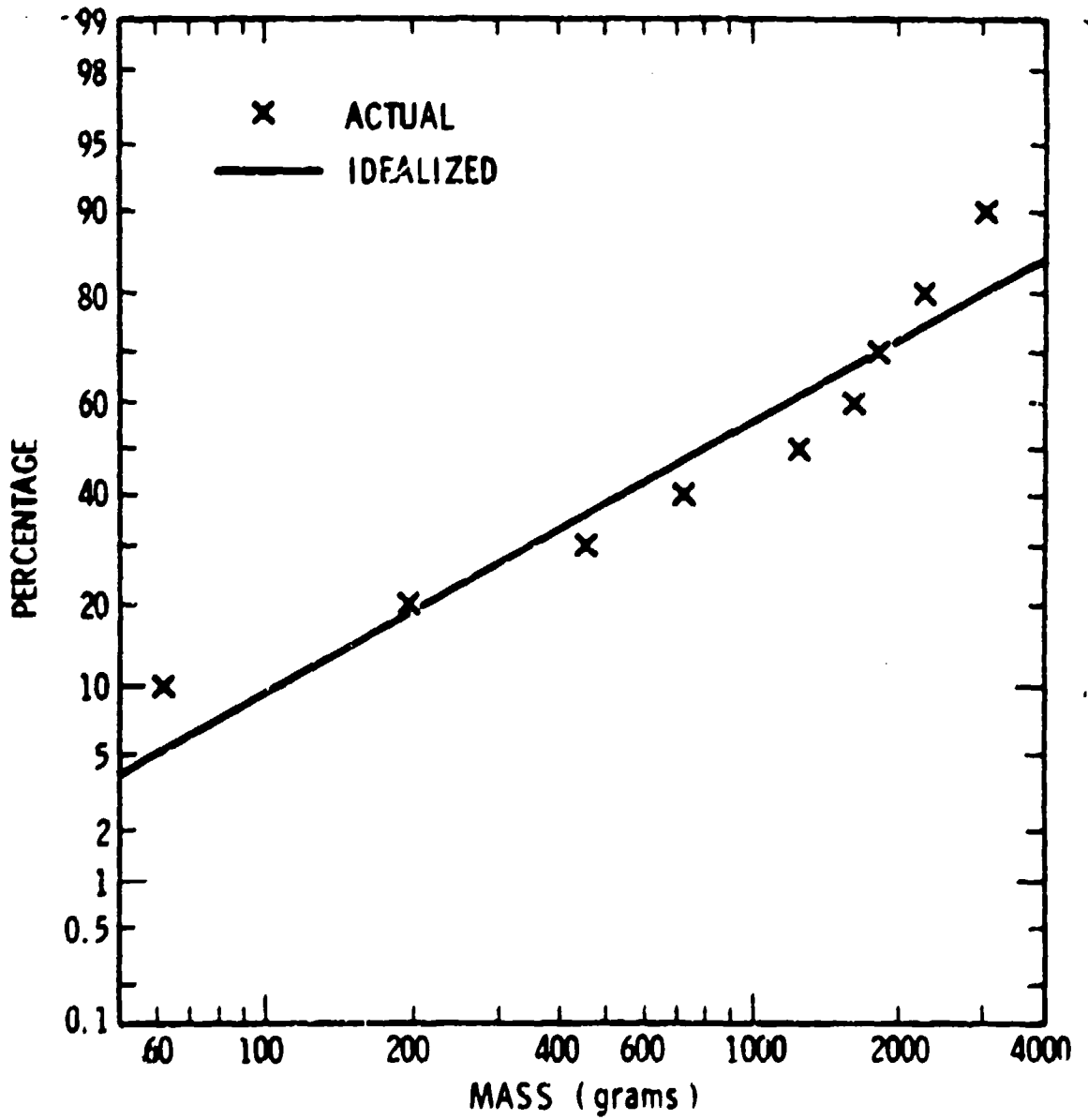
Figure 4I-5. Fragment Mass Distribution, Tank E

TABLE 4F-6. SUMMARY OF "W" TEST ON NORMALITY FOR FRAGMENT MASS DISTRIBUTION FOR TANKS A, B, D, AND E

Tank No.	"W"	Probability
A	.948	.65
B	.929	.45
D	.651	.08
E	.956	.74

As it is customary to consider values exceeding 2 to 10% as adequate grounds for not rejecting the hypothesis that the data belong to the chosen distribution, the fits for tanks A, B, and E are more than adequate, and for D somewhat questionable.

Except for Tank D, the other values compare favorably with those obtained for the log-normal fragment distribution for Events 1, 2, 3, 4 and 5 for the propellants (Reference 1).

4F-5   Rationale For Averaging Fragment Mass Distributions For Tanks A and B and Tanks D and E

A "t" test for significant difference in means was made for each of the pairs of tanks, with the following results:

For tanks A and B, the calculated value of "t" was 0.314 versus the table value of ± 1.337.

For tanks D and E, the calculated value of "t" was .1354 versus the table value of ± 1.337.

Thus, no significant difference in means for either pair was found, and a single distribution for each pair was derived by averaging the respective pair of means and standard deviations. Table 4F-7 presents the results, and the distributions are charted in Figures 4-54 and 4-55.

TABLE 4F-7. ESTIMATED MEAN, AND STANDARD DEVIATION
(TO THE BASE e) FOR TANKS A AND B, AND D AND E

Tanks	Estimated Mean	Estimated Standard Dev.
A and B	2.9984	1.583
D and E	6.6240	1.695

4F-6   Derivation of Figure 4-57, Fragment Distance Versus Percent
Yield For Propellant Explosions

Table 4F-8 is taken from Reference 1, with some minor correc-
tions. For each of the five events, a 95% upper confidence limit was put
on the estimated mean (M) and a 90% upper confidence limit was estab-
lished for the estimated standard deviation (S), using methods outlined in
Reference 8.

The confidence limit on the mean was calculated using the follow-
ing formula:

$$CL = M + \frac{S}{\sqrt{n}} \, t_{(n; 95)}$$

n is the number of fragments and $t_{(n;95)}$ is the value of the t distribu-
tion with n degrees of freedom at the 95th percentile.

The confidence interval for the standard deviation was calculated
using the following formula:

$$CL = \left[\frac{\sum X_i^2 - (\sum X_i)^2/n}{\chi^2_{(n-1); 90}} \right]^{-1/2}$$

where X_i is the distance of the ith fragment, n is the number of frag-
ments, and $\chi^2_{(n-1); 90}$ is the value of a chi square distribution with
n - 1 degrees of freedom at the 90th percentile.

Then, using the new upper confidence level values of M and S,
the R_{95} in which 95% of the fragments should fall was calculated as
follows:

TABLE 4F-8. CONFIDENCE LIMITS ON MEAN, STANDARD DEVIATION, AND DISTANCE CONTAINING 95% OF FRAGMENTS

Event No.	Sample Size	Yield %	Yield TNT	Distance (R)(m) Normal Distribution M	S	S.E.	95% CL M	90% CL S	95% CL Dist	Max Dist
1	342	5	1.55×10^{2}	136.3	59.13	3.20	141.4	62.33	244	313
2	38	1.1	1.08×10^{3}	102.7	61.87	10.05	132.0	73.15	255	335
3	105	23	4.03×10^{2}	253.0	169.77	16.56	280.4	186.23	590	671
4	86	24.4	4.28×10^{2}	225.6	104.24	11.23	244.1	115.82	477	504
5	31	62.6	1.027×10^{2}	300.5	174.96	31.44	353.9	211.23	712	695

$$R_{95} = M + S t_{(n\,;\,95)}$$

The interval from the mean (M) to R_{95} is indicated for each event on Figure 4F-6 by a bar.

A line was then drawn parallel to the regression line, and just touching the longest bar. Thus, the distances read from this line could be expected to encompass at least 95% of the fragments resulting from a given yield.

4F-7   Derivation of Simulated Fragment Range Distribution for Gas Vessel Bursts

For each tank, the fragments were divided into classes by fragment area. The computer program FRISB was then exercised taking into account fragment shape (from drag) for initial angles of 15, 30, 45, 60, and 75° to determine a range for each angle for each class of fragment. Table 4F-9 presents the results of the range simulation.

In the table the fragments have been divided into groups or classes with the average planform area $\overline{AL}$ and the average mass $\overline{M}$ of each class listed. The area data were obtained by measurement from the photographs of Reference 2. Mass data were given in the reference for each fragment, $\overline{AD}$ is the average drag area for each class of fragment; this area is calculated on the basis of the thickness of the fragments and a characteristic width dimension equal to the square root of the fragment, planform area. The maximum range of the classes of fragments for various values of initial trajectory angle ($n = 5 n°$, $n = 3$ 15) was calculated using code FRISB assuming the average characteristics for the fragments in each class, and that the initial velocity was the maximum initial velocity for the fragments measured for each tank.

The fragment ranges were ordered, and the percentiles were determined and are shown in Table 4F-10. Then the percentiles were plotted on normal probability paper and are shown in Figures 4F-7 through 4F-10. The estimates for the mean and standard deviation for each distribution were then calculated and are shown in Table 4F-11.

A "W" goodness of fit statistic was calculated for each distribution and the probability of obtaining the calculated test statistic value, given that the chosen distribution is correct was then determined. The results are shown in Table 4F-12.
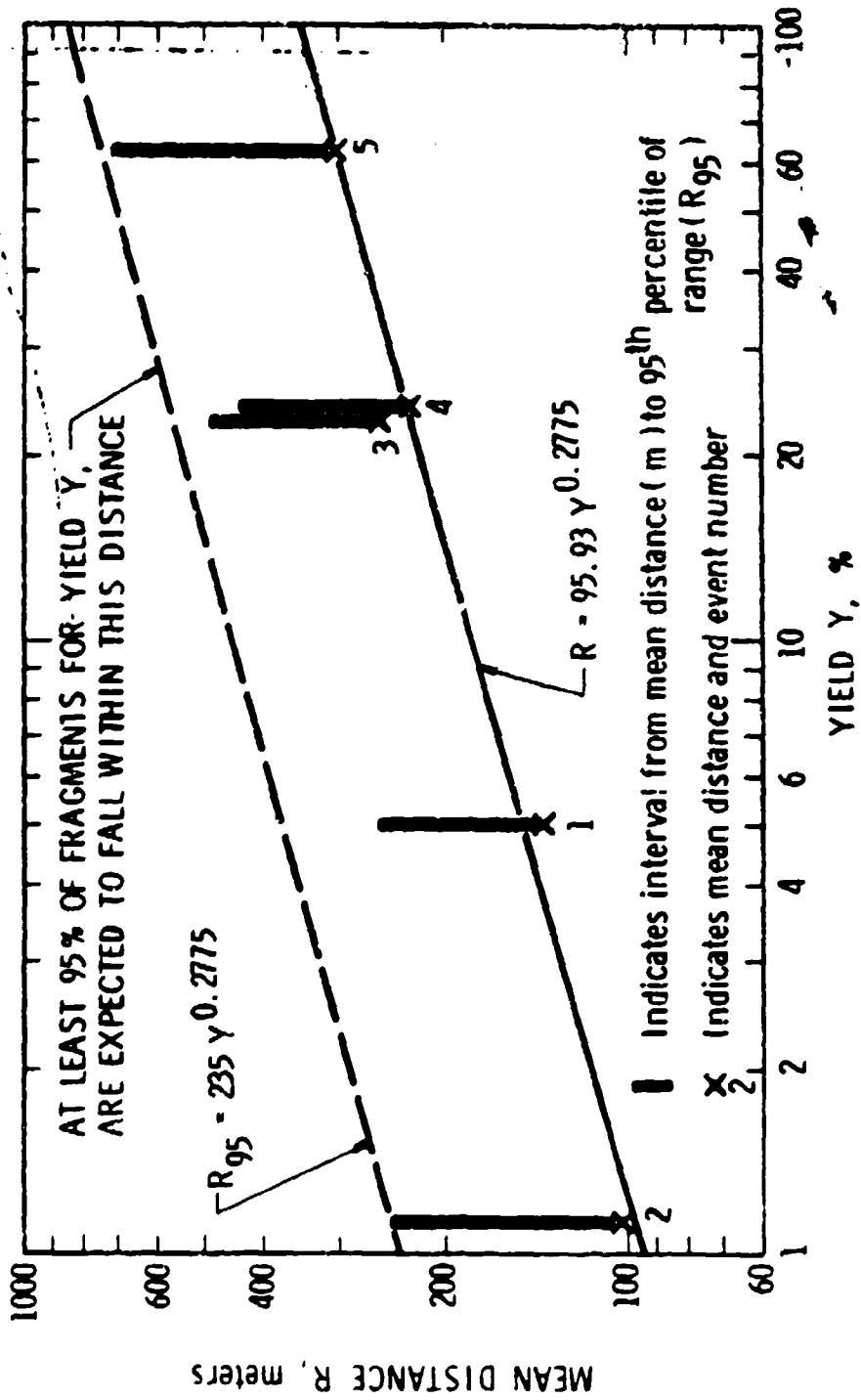
Figure 4F-6. Mean Distance Vs Yield with Estimated Range
Containing 95% of the Fragments (R₉₅)

The following text appears within the figure:

AT LEAST 95% OF FRAGMENTS FOR YIELD "Y", ARE EXPECTED TO FALL WITHIN THIS DISTANCE

$R_{95} = 235 \, Y^{0.2775}$

$R = 95.93 \, Y^{0.2775}$

YIELD Y, %

$(ft = m \times 3.281)$

MEAN DISTANCE R, meters

| Indicates interval from mean distance (m) to 95th percentile of range (R_{95})

X₂ Indicates mean distance and event number

TABLE 4F-9. COMPUTER SIMULATED FRAGMENT RANGE FOR GAS VESSEL BURSTS

4F-16

TABLE 4F-10. PERCENTILES FOR SIMULATED RANGES FOR GAS VESSEL BURSTS

Percentile	Tank A	Tank B	Tank D	Tank E
10	0.566	0.532	6.4	6.9
20	0.806	0.747	11.9	20.8
30	2.330	1.98	23.5	25.4
40	2.947	2.95	28.7	45.4
50	5.107	4.33	43.8	56.0
60	6.473	6.38	63.8	77.4
70	8.679	7.39	66.5	96.3
80	11.120	10.25	108.4	114.6
90	12.969	11.00	131.6	143.3

TABLE 4F-11. ESTIMATES FOR MEAN AND STANDARD DEVIATION FOR SIMULATED RANGE DISTRIBUTIONS

Tank No.	Estimate for Mean (M)	Estimate for Standard Deviation (S)
A	5.67	6.72
B	5.06	3.92
D	53.05	44.05
E	65.1	46.20
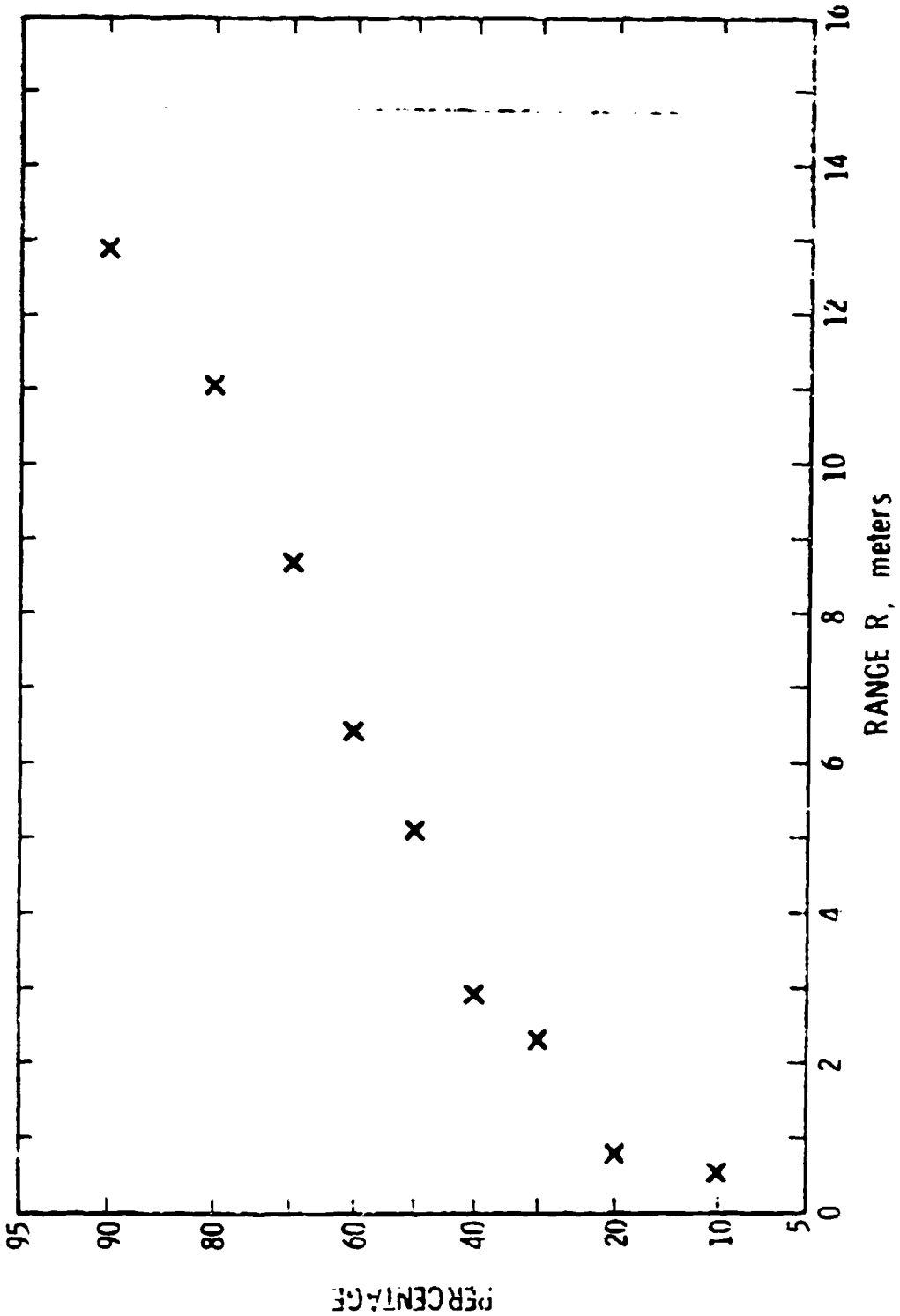
Figure 4F-7. Simulated Range Distribution for Tank A

RANGE R, meters

$(R = D \times 1.281)$
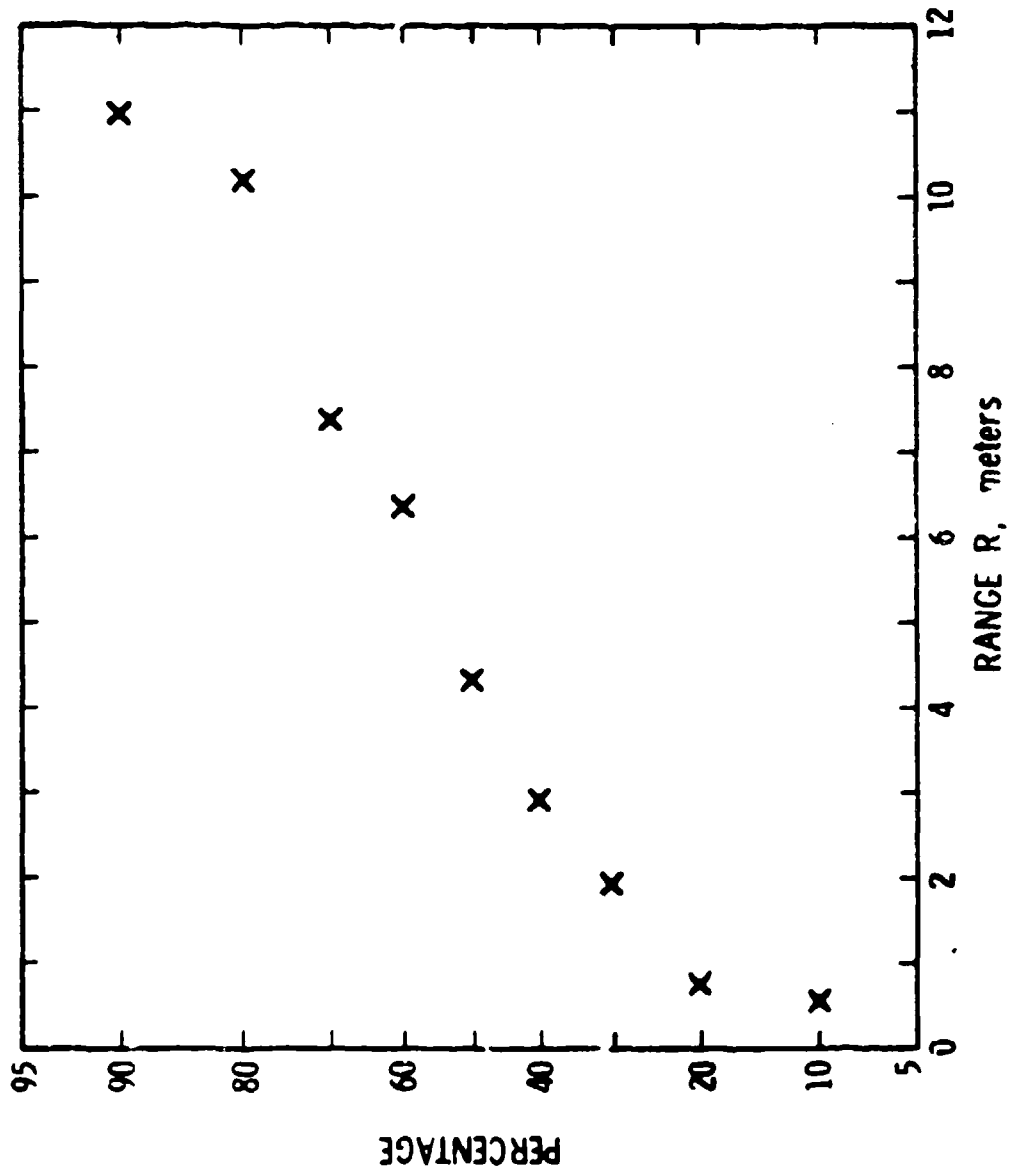
Figure 4F-8. Simulated Range for Tank B
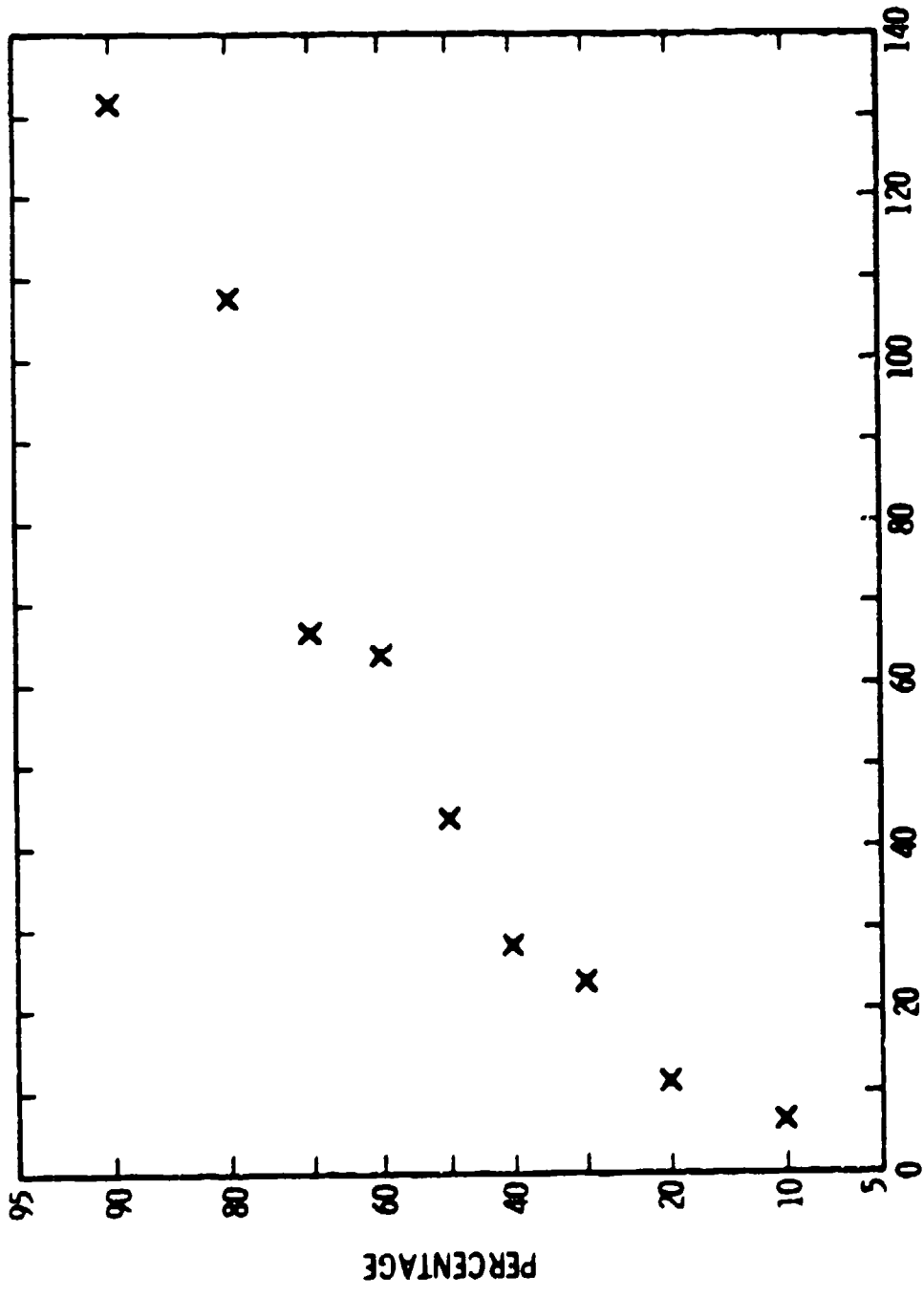
Figure 4F-9. Simulated Range for Tank D

RANGE R, meters
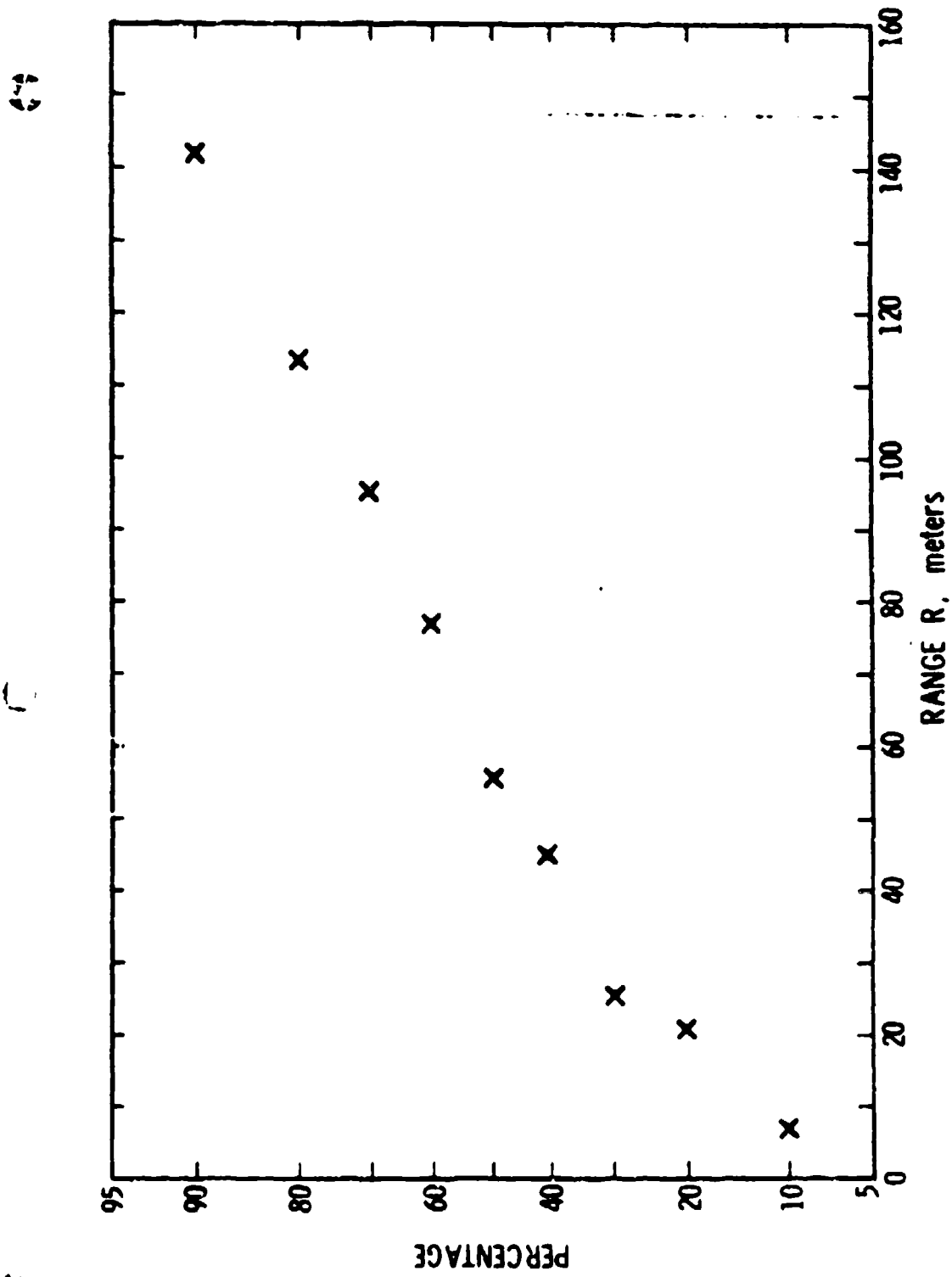
(ft = m X 3.281)

Figure 4F-10. Simulated Range for Tank E

TABLE 4F-12. SUMMARY OF "W" TEST ON NORMALITY FOR
SIMULATED FRAGMENT RANGE DISTRIBUTION FOR
GAS VESSEL BURSTS

Tank No.	"W"	Probability
A	.929	.46
B	.921	.37
D	.933	.47
E	.956	.74

As shown from the probability column of Table 4F-12, the normal
distributions are fairly good fits to the data.

4F-8   Rationale For Combining Simulated Range Distribution For Tanks
        A and B and for Tanks D and E

A "t" test for significant differences in means was made for each
of the pairs of tanks, with the following results.

For tanks A and B, the calculated value of "t" was 0.235 and for
tanks D and E was 0.558 versus the table value of ± 1.337. Thus, no
significant difference in means for either pair was found, and a single
distribution for the simulated range for each pair was derived by
averaging the respective pair of means and standard deviations. Table
4F-13 presents the results, and the distributions are charted in Figures
4-58 and 4-59.

TABLE 4F-13. ESTIMATED MEAN AND STANDARD
DEVIATION FOR SIMULATED RANGE DISTRIBUTION FOR
TANKS A AND B, AND TANKS D AND E

Tanks	Estimated Mean	Estimated Standard Deviation
A and B	5.4	5.5
D and E	59.2	45.1

LIST OF REFERENCES

1. Baker, W. E., V. B. Parr, R. L. Bessey, and P. A. Cox, "Assembly and Analysis of Fragmentation Data for Liquid Propellant Vessels," NASA CR-134538, NASA Lewis Research Center, January 1974.

2. Pittman, J. F., "Blast and Fragment Hazards From Bursting High Pressure Tanks," NOLTR 72-102, May 1972.

3. Chelson, Paul O., "Reliability Computation Using Fault Tree Analysis," JPL-TR-32-1542, NASA CR 124740, December 1, 1971.

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UNCLAS

EFFECTS OF FRAGMENTS

5-1   Damage Estimates to Structures and Facilities

5-1.1   General

One can see from Chapter IV that there are wide variations in characteristics of fragments generated during accidental explosions of the types covered in this handbook. Large sections of pressure vessels, and appurtenances accelerated by the explosions, can be quite massive (over 500 kg or 1000 lb_m), while some fragments thrown to large distances are quite light (less than 1 g or 0.002 lb_m). Impact velocities can range from a few meters per second to several hundred meters per second. Also, in Chapter IV, methods are given for estimating the probability that fragments of given mass and impact velocity will strike a structure located a specified distance from an accident. An important characteristic of fragments from these accidents is that they are of low velocity, and large average mass, compared to fragments from munitions which are intended to cause damage by penetration or perforation.

Conventional structures which can be damaged by fragments include frame or masonry residences, light to heavy industrial buildings, office building , public buildings, mobile homes, cars, and others too numerous to name. Damage can be superficial, such as denting of metal panels or breakage of panes of glass. But, massive fragments can cause more extensive damage such as perforation of wooden roofs, severe crushing of mobile homes or cars, etc. Most of the fragments will be nonpenetrating and will cause damage by imparting impulsive loads during impact. Methods similar to those used to establish threshold damage levels under blast loadings can also be used to establish thresholds for impact damage by fragments, i.e., lower limits for superficial damage. The methods will be somewhat simpler because the impacts will almost certainly be of short enough duration to be purely impulsive for almost any "target" structure or structural component. Impact conditions with large fragments which can be certain to cause significant structural damage can probably also be established by equating kinetic energy in the fragment to energy absorption capability for typical roof panels, roof supporting beams, etc.

Launch facilities for liquid-propellant rockets present some special "targets" to fragments from accidental explosions which can be especially susceptible to perforation damage. These are thin-walled tanks for storage or transport of energetic propellant liquids such as

LH_2, RP-1, or LO_2. Fragment impact conditions which would cause perforation of such tanks can be estimated from ballistic perforation formulas for munitions fragments and from hailstone impact data. These formulas will be presented and discussed.

5.1-2   Impact of Fragments on Thin Metal Targets

The following methods can be used for fragment impact on metal sheets or plates. The details of the formulation of these methods are presented in Appendix 5A.

The V_{50} limit velocity is defined as the velocity at which a projectile will have a 50% chance of penetrating a given target. Knowing the properties of the projectile (fragment) and the target, V_{50} can be obtained from Figure 5-1.

In this figure, a is the radius of the fragment (assuming a spherical shape), h is the thickness of the target, ρ_p is the density of the fragment (or projectile), ρ_t is the density of the target material, and σ_t is the yield stress of the target material.

The solid line in Figure 5-1 gives the relationship between limit velocity and target thickness. As the graph shows, there is uncertainty in this relation. For hard fragments which are less likely to deform, a lower nondimensional limit velocity (more conservative) should be chosen. For softer fragments, a higher limit velocity can be used. At this time, it is not known whether this relationship holds for values of $\frac{h}{a}$ greater than about 2.2.

This method is good for the impact of a fragment with its velocity normal to the target surface. For oblique impacts, the normal component of the velocity should be used. According to one report, [1] for oblique impacts, the penetration velocity is minimum at an angle of $30°$ from the normal direction. The difference between the penetration velocities at $0°$ and at $30°$ may be as great as 20%. Therefore, if oblique impact is expected, the penetration velocity obtained by use of Figure 5-1 should be multiplied by 0.8.

For fragment velocities less than V_{50}, the permanent deflection δ at the impact point on the target can be determined. Figure 5-2 is a graph of nondimensional deflection versus nondimensional velocity.

For given fragment properties, a given target, and a given normal component of fragment velocity, δ can be obtained. Of course, for very low fragment velocities, there is no permanent deflection.

5-2
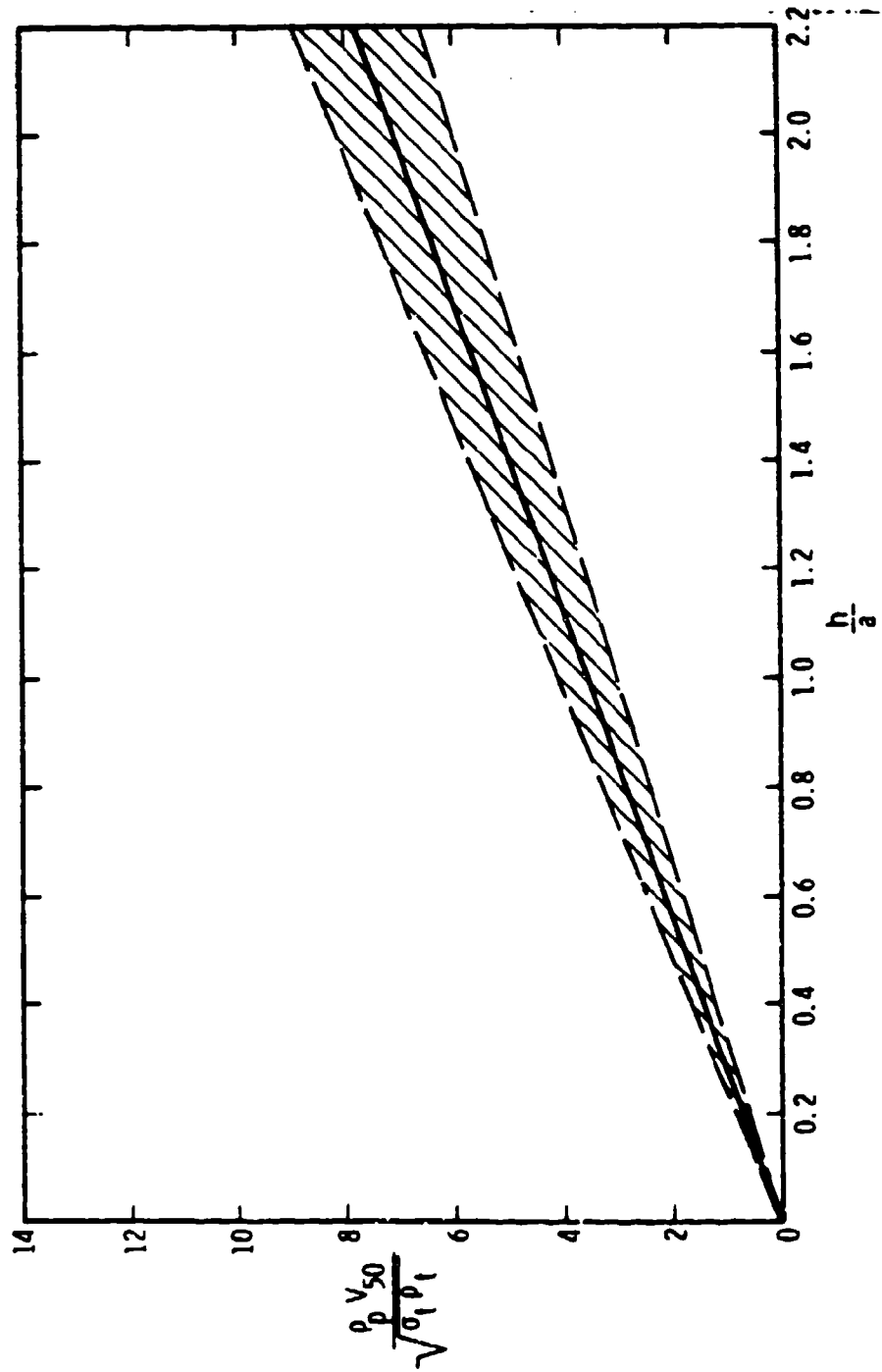
Figure 5-1. Nondimensional Limit Velocity Vs Nondimensional Thickness
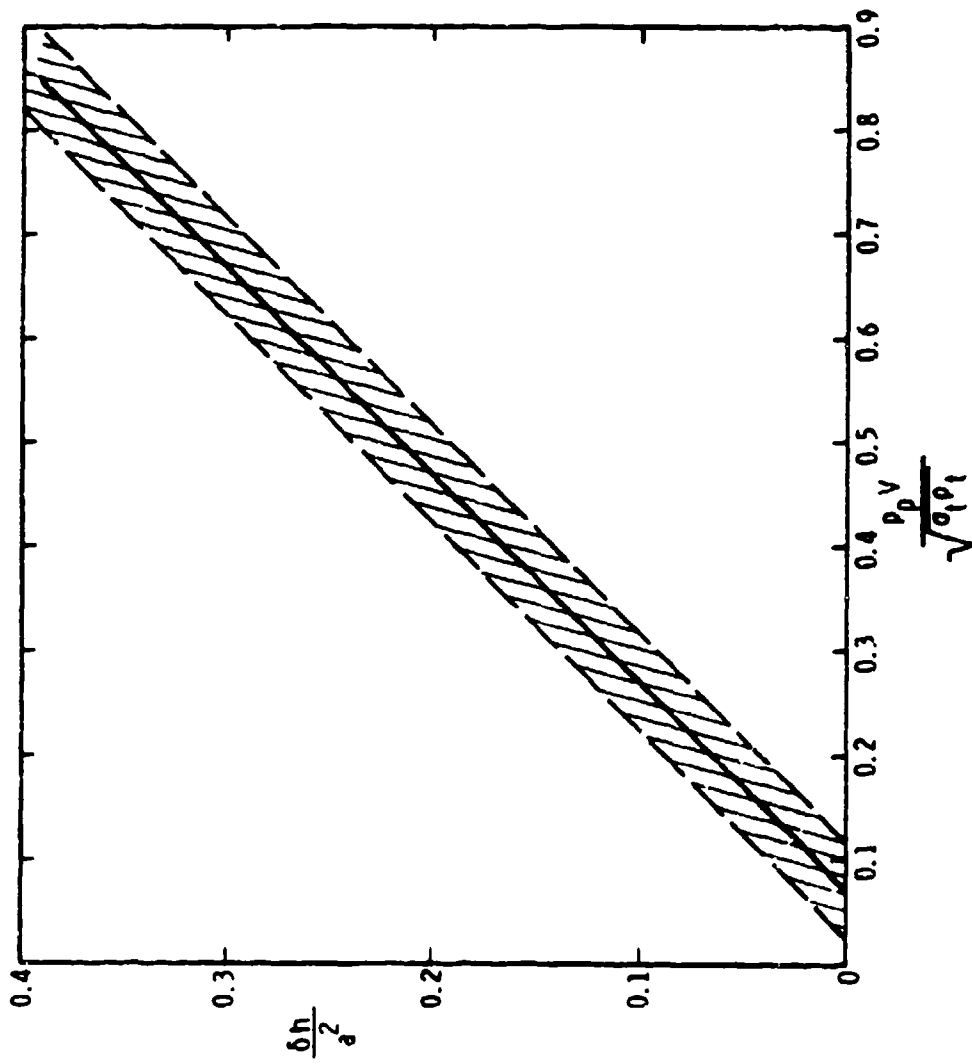
Figure 5-2. Nondimensional Deflection Vs
Nondimensional Velocity

This method was developed for impacts not very close to the edge of a sheet or plate. For fragment impact near the edge of an unsupported or simply-supported sheet or plate, the deflection may be twice the deflection that would be otherwise expected.

This analysis has been formulated for spherical fragments. To apply this to fragments of other shapes, let $a = \left(\dfrac{m}{\rho_p \frac{4\pi}{3}} \right)^{1/3}$, where m is the mass of the fragment. More research must be done to determine other effects of fragment shape.

Table 5-1 is a list of the important properties (density and yield stress) of a few selected fragment and target materials.

TABLE 5-1. MATERIAL PROPERTIES
(References 2, 3)

| | density ρ | | yield stress σ | |
	$\dfrac{kg}{m^3}$	$\dfrac{lb_m}{ft^3}$	P_a	psi
Steel	7850	489		
1015			$3.46 - 4.49 \times 10^8$	50,000 - 65,000
1018			3.66×10^8	53,000
1020 (large grained)			4.42×10^8	64,000
1020 (sheet)			3.11×10^8	45,000
Aluminum Alloys (sheet)	2770	173		
2024-O			8.85×10^7	12,800
2024-T3			3.66×10^8	53,000
2024-T4			3.66×10^8	53,000
Titanium Alloy	4520	282		
6Aℓ4V			1.11×10^9	160,000

Example 1:

Given fragment radius $a = 0.020$ m (0.066 ft) and density $\rho_p = 7000$ kg/m^3 (440 lb$_m$/ft^3), target density $\rho_t = 7000$ kg/m^3 (440 lb$_m$/ft^3) and yield stress $\sigma_t = 4.40 \times 10^8$ Pa (6.38 x 10^4 psi) and fragment velocity $V = 200$ m/s (660 ft/sec), find the minimum target thickness h to prevent penetration. Solution: Nondimensional velocity is computed, and h/a is read from Figure 5-1:

$$\frac{\rho_p V_{50}}{\sqrt{\sigma_t \rho_t}} = \frac{(7000 \text{ kg/m}^3)(200 \text{ m/s})}{[(4.40 \times 10^8 \text{ N/m}^2)(7000 \text{ kg/m}^3)]^{1/2}} = 0.798$$

Then from Figure 5-1, $h/a = 0.202$. For the given a, $h = 0.0040$ m (0.013 ft).

Example 2:

Given fragment radius $a = 0.010$ m (0.033 ft) and density $\rho_p = 7000$ kg/m^3 (440 lb$_m$/ft^3), target density $\rho_t = 7000$ kg/m^3 (440 lb$_m$/ft^3), yield stress $\sigma_t = 4.40 \times 10^8$ Pa (6.38 x 10^4 psi) and thickness $h = 0.0010$ m (0.0033 ft), find V_{50}. Solution: h/a is computed, and the nondimensional velocity is read from Figure 5-1:

$$h/a = \frac{0.0010 \text{ m}}{0.010 \text{ m}} = 0.10$$

Then from Figure 5-1, $\dfrac{\rho_p V_{50}}{\sqrt{\sigma_t \rho_t}} = 0.43$. For the given

properties, $V_{50} = 110$ m/s (360 ft/s).

Example 3:

Given the same fragment and target properties as in Example 2, and a fragment velocity less than the limit velocity $V = 52.0$ m/s (171 ft/s), find the deflection at the impact point on the target.

$$\frac{\sqrt{\rho_p} V}{\sqrt{\sigma_t \rho_t}} = \frac{(700 \text{ kg/m}^3)(52.0 \text{ m/s})}{[(4.40 \times 10^8 \text{ N/m}^2)(7000 \text{ kg/m}^3)]^{1/2}} = 0.207$$

From Figure 5-2, $\frac{\delta h}{a^2} = 0.068$. Then for example, $\delta = 0.0068$ m (0.022 ft).

5-1.3   Impact of Fragments on Roofing Materials

Nearly any impact of a fragment upon the roof of a building will cause at least some superficial damage. Damage which only affects the appearance but which does not interfere with the performance of the roofing will not be discussed here. Serious damage includes cracking and complete penetration.

Because of the many kinds of roofing and the scarcity of data of fragment impact upon roofing materials, the following discussion will be kept as general as possible, presenting only the lower limits of damage for groupings of roofing materials, with the understanding that these are not known very accurately.

The analysis for the impact upon metal targets leads one to believe that the important projectile property is momentum. Until more information is obtained, it must be assumed that momentum is also important in impact upon roofing materials. (The following discussion is based upon data in Reference 4 in which synthetic hailstones were projected at roofing materials targets. The velocities in the tests correspond to the terminal fall velocities of hailstones of the particular sizes used).

The roofing materials can be separated into three classes: asphalt shingles, built-up roofs (alternate layers of bitumen and reinforcing membranes, often topped with pebbles or crushed stone), and miscellaneous materials (asbestos cement shingles, slate, cedar shingles, clay tile, and sheet metal). Lower limits of fragment momentum for serious damage to common roofing materials are given in Table 5-2.

For oblique impact, the component of the velocity normal to the surface of the roof should be used in the calculation of momentum.

Aged shingles may sustain serious damage at a lower fragment momentum than that which is given in the table. Also, the tests were conducted at room temperature. The limiting momentum would be greater for shingles at a higher temperature, and less for shingles at a lower temperature.

TABLE 5-2. FRAGMENT IMPACT DAMAGE FOR ROOFING MATERIALS (Reference 4)

Roofing Material	Minimum Fragment Momentum For Serious Damage (mv)		Comments
	$kg\ m/s$	$lb_m\ ft/sec$	
Shingles	0.710	5.13	crack shingle
	6.12	44.1	damage deck
Built-up roof	<0.710	< 5.13	crack tar flood coat
	2.00	14.5	crack surface of conventional built-up roof without top layer of stones
	>4.43	>31.9	with a 14 kg/m^2 top layer of slag, there was no damage up to 4.43 kg m/s, which was the maximum momentum of the test
Miscellaneous			
0.003 m (1/8") asbestos	0.710	5.13	
0.006 m (1/4") asbestos cement shingles	1.27	9.16	
0.006 m (1/4") green slate	1.27	9.16	
0.006 m (1/4") grey slate	0.710	5.13	
0.013 m (1/2") cedar shingles	0.710	5.13	
0.019 m (3/4") red clay tile	1.27	9.16	
Standing seam terne metal	4.43	31.9	plywood deck cracked

<u>Example 4:</u>

A fragment with a mass of 0.25 kg (0.55 lb_m) and a velocity of 20.0 m/s (65.6 ft/s) strikes a roof of asphalt shingles in a direction normal to the surface of the roof. What kind of damage can be expected? Solution: Calculate the momentum of the fragment, and compare it to the values in Table 5-2. Momentum = mv = (9.25 kg) (20.0 m/s) = 5.0 kg m/s. According to Table 5-2, this momentum will crack the shingle, but it will not damage the deck.

5-2   Damage Estimates to People from Secondary Fragments

5-2.1   Penetrating Fragments

Fragments can be divided into two categories, penetrating and nonpenetrating. Due to a limited amount of available data, penetrating fragments will refer to fragments weighing up to 0.015 kg (0.033 lb_m) and area-to-mass ratio A/M up to 0.09 m^2/kg where A is the cross-sectional area of a fragment along its trajectory and M is the mass of the fragment. Nonpenetrating fragments will refer to fragments weighing 4.54 kg (10 lb_m) or more. Only a summary of the methods for determining fragment damage to people will be presented here. The development of these methods is given in Appendix 5B for the convenience of the interested reader.

To determine whether a fragment can cause severe body penetration damage, it is necessary to determine its striking velocity V in (m/s) and A/M ratio: these parameters can, in general, be determined from other portions of this handbook with the exception of parameters from glass window fragments which follow. The ballistic limit velocity V_{50} (in m/s), which is the velocity at which half of the missiles incident on the body are expected to perforate the skin with enough residual velocity to cause severe damage is[5, 6]

$$V_{50} = 1247.1 \left(\frac{A}{M} \right) + 22.03 \text{ m/s} \tag{5-1}$$

for

$$A/M \leq 0.09 \text{ m}^2/\text{kg}, \quad M \leq 0.015 \text{ kg}$$

where

A is the cross-sectional area of the fragment along its trajectory in m^2

M is the mass of the fragment in kg

V_{50} is the ballistic limit velocity in m/s

If $V \geq V_{50}$, then one can expect some serious wounds from body penetration.

To determine if a glass fragment from a window pane broken by the blast wave can cause severe body penetration damage, it is necessary to calculate an effective peak overpressure P_e

where

$$P_e = \overline{P}_s \, p_o \tag{5-2}$$

for windows oriented side-on or back-on to the approaching blast wave where p_o is atmospheric pressure in Pa, see Figure 5-3.

or

$$P_e = \overline{P}_r \, p_o \tag{5-3}$$

for windows oriented face-on to the approaching blast wave.

for

$$\overline{P}_s \leq 3.5^{(7)},$$

$$\overline{P}_r = 2\overline{P}_s + \frac{(\gamma + 1)\overline{P}_s^2}{(\gamma - 1)\overline{P}_s + 2} \tag{5-4}$$

where

$$\gamma \simeq 1.4$$

For $\overline{P}_s \sim 3.5$, $\overline{P}_r$ can be acquired directly from Figure 5-4. The ratio A/M should be chosen as the smaller of

$$\frac{A}{M} = \frac{1}{t_g} \tag{5-5}$$

or
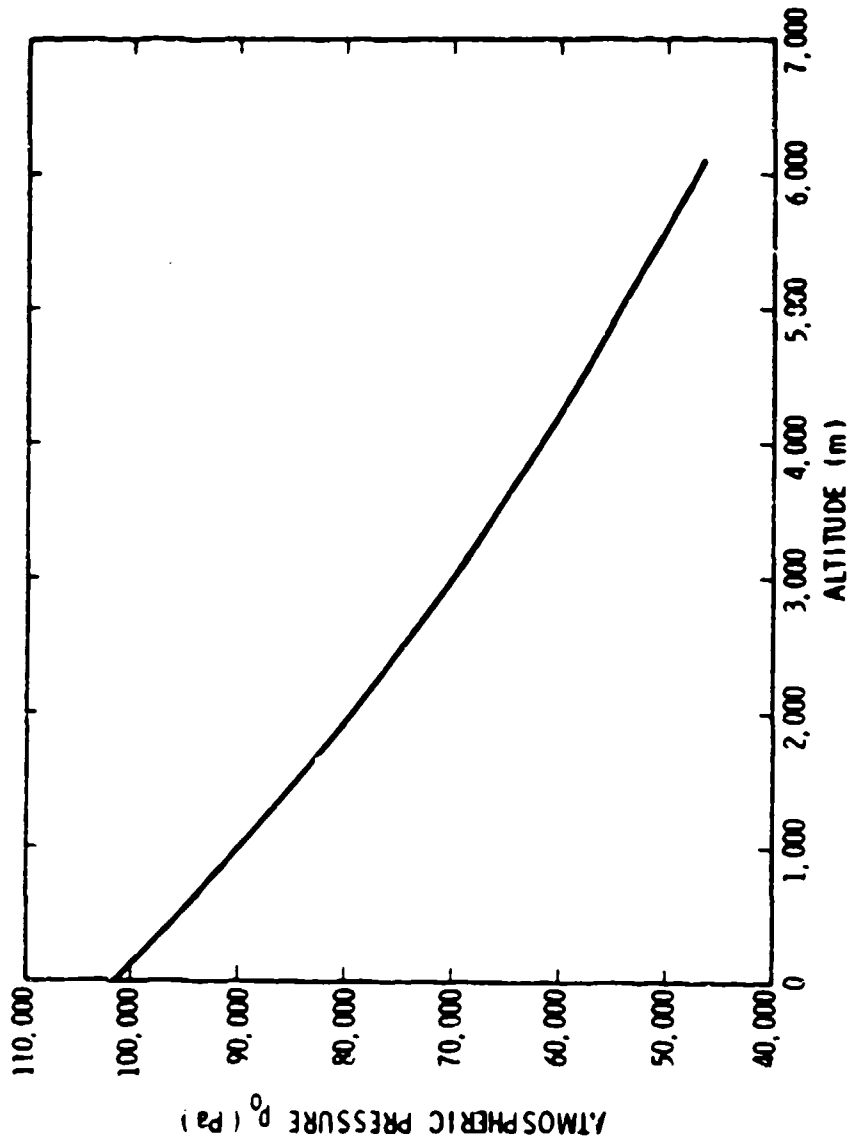
Figure 5-3. Atmospheric Pressure Vs Altitude Above
Sea Level
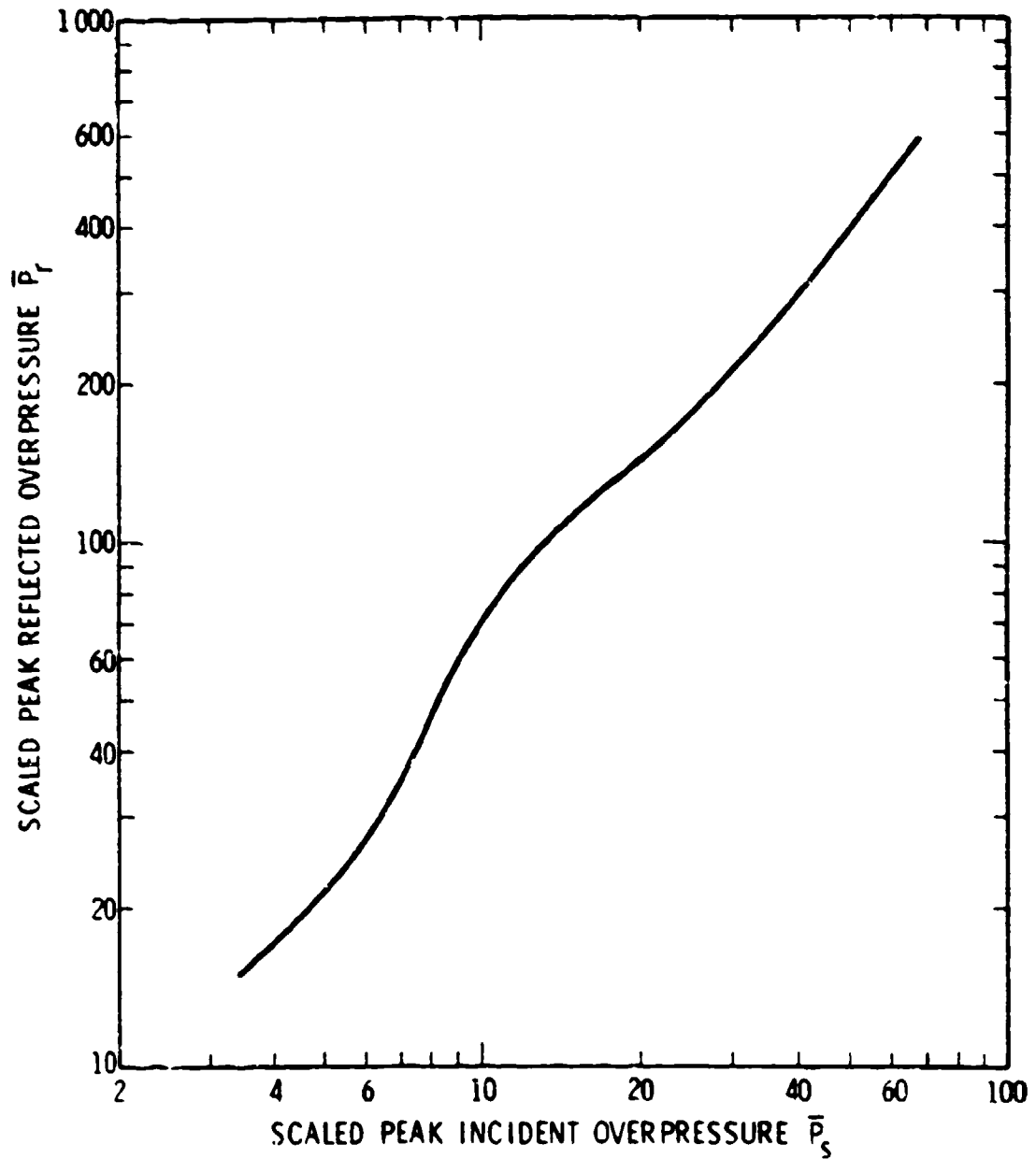
Figure 5-4. Scaled Reflected Overpressure Vs Scaled
Side-on Overpressure

$$\frac{A}{M} = \frac{1}{\rho \sqrt{A'}}$$ (5-6)

where

t is the thickness of the window pane in meters

ρ is the density of the glass which is approximately 2471 kg/m^3 (from Reference 8)

A'_2 is the geometric mean frontal area of the glass fragment in m^2 expressed by

$$A' = 6.4516 \times 10^{-4} \left[2.4 - \sqrt{12.5 + (5.8566 \times 10^{-5} \, P_e)^2} \right]$$ (5-7)

for P_e in the range 0 Pa to 96.5 kPa. (From References 8 and 9).

Striking velocity v (in m/s) is

$$V = \left[(0.2539) + (1.896 \times 10^{-4}) (t - 7.62 \times 10^{-4})^{-0.928} \right]$$ (5-8)

$$\times \ 3.3443 \, P_c^{0.547}$$

for P_e in range 690 Pa to 689 KPa and $t \geq 7.62 \times 10^{-4}$ m.

If $V \geq V_{50}$, then one can expect some serious wounds from body penetration.

5-2.2 Nonpenetrating Fragments

Criteria for body damage from nonpenetrating objects are contained in Table 5-3. It should be noted that damage is dependent on fragment mass and velocity only. The table also only contains one fragment mass value. One can logically assume that larger masses propelled at the same velocities shown in the table will produce more damage than the 4.54 kg (10 lb) mass presented in the table.

TABLE 5-3. TENTATIVE CRITERIA FOR INDIRECT BLAST EFFECTS FROM NONPENETRATING FRAGMENTS
(References 10, 11, 12)

Mass	Event	Extent of Damage	Impact Velocity
4.54 kg (0.1b$_m$)	Cerebral Concussion	Mostly "safe"	3.05 m/s (10 ft/sec)
		Threshold	1.57 m/s (15 ft/sec)
	Skull Fracture	Mostly "safe"	3.05 m/s (10 ft/sec)
		Threshold	4.57 m/s (15 ft/sec)
		Near 100%	7.01 m/s (2_ ft/sec)

5-2.3 Example Calculations for Determining Damage Estimates to People from Secondary Fragments

Example 1:

Environmental Conditions:

P_s = 3.3 x 10^4 Pa (0.53 psi)

I_b = 1.16 x 10^3 Pa·s (0.0163 psi/sec)

P_0 = 1.0135 x 10^5 Pa (14.2 psi)

Penetrating fragments - Mass M = 0.015 kg (0.033 lb$_m$)

Velocity V = 131 ft/sec

Cross sectional area A along trajectory of fragment = 0.0016 m^2 (0.0172 ft^2)

Windows in a nearby building are 3.175 m (0.125 in) thick and are faced on to the approaching blast wave.

Nonpenetrating fragment - Mass M = 4.00 kg (8.8 lb$_m$)

Velocity V = 20 m/s (76 ft/sec)

5-14

$$\overline{P}_r = \quad .$$

From Equation (5-3)

$$P_e = \overline{P}_r P_0 = (0.864)(101,350) = 87,567 \text{ Pa}$$

(b) $\quad \left(\dfrac{A}{M}\right)_1 = \dfrac{1}{t\,\rho} =$

$$\frac{1}{(3.175 \times 10^{-3}\text{m})(2.471 \times 10^3 \text{ kg/m}^3)} =$$

$$0.1275 \text{ m}^2/\text{kg}$$

$$\left(\frac{A}{M}\right)_1 = \frac{1}{\rho \sqrt{A'}}$$

From Equation (5-7):

$$A' = (6.4516 \times 10^{-4})$$

$$X e^{2.4} = \left\{ 12.5 + \left[(5.8566 \times 10^{-5}) (8.7567 \times 10^{4}) \right]^2 \right\}^{1/2}$$

$$A' = 0.1402 \text{ m}^2$$

Therefore,

$$\left(\frac{A}{M}\right)_2 = \frac{1}{(2471) \sqrt{0.1402}} = 0.00108 \text{ m}^2/\text{kg}$$

The smaller value for A/M ($0.00108 \text{ m}^2/\text{kg}$) is the better choice.

(c) V_{50} for A/M = $0.00108 \text{ m}^2/\text{kg}$ can be calculated from Equation (5-1):

$$V_{50} = (1247.1) (0.00108) + 22.03$$

$$V_{50} = 23.4 \text{ m/s } (76.8 \text{ ft/sec})$$

(d)   From Equation (5-8), the striking velocity V is

$$V = (10.2539) + (1.896 \times 10^{-4}) (3.175 \times 10^{-3} -$$

$$7.62 \times 10^{-4})^{-0.928} \quad (0.3443) (8.7567 \times$$

$$10^{4})^{0.547}$$

$$V = 53.0 \text{ m/s } (174 \text{ ft/sec})$$

(e)   Since V > V50, one can expect some severe body penetration damage.

(3)   Nonpenetrating fragments:

The mass (4. 00 kg) and velocity (2 m/s) of the nonpene-
trating fragment are less than the mass and velocity re-
quired for the mostly "safe" damage condition shown in
Table 5-3.   Thus, one would not expect deaths to result
from nonpenetrating fragments.

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APPENDIX V.A

EFFECTS OF FRAGMENTS ON STRUCTURES

The structures that are considered here are metal plates and sheets. There does not appear to be any effect of the curvature of the target; therefore, it is reasonable to use data for flat targets and apply them to any general shape that may be of interest.

The methods described in Section 5-1 are based upon an examination of data of fragment and hailstone impact upon metal sheets and plates.[1-3] In these studies, synthetic hailstones (ice spheres) were fired at target sheets of aluminum alloys, and various shapes of fragments were fired at steel targets. A model analysis was performed, using the methods described in Reference 4. The parameters of interest are listed in Table 5A-1.

TABLE 5A-1. LIST OF PARAMETERS

a	radius of fragment (assuming spherical shape)
h	thickness of target
V	velocity of fragment
δ	permanent deflection of target at point of impact
c_r	density of fragment (projectile)
ρ_t	density of target
σ_t	yield stress of target material

This analysis is concerned with plastic deformation, which makes the parameter σ_t more important than the modulus of elasticity of the target material. Also, the fragment is assumed to be a rigid body, which makes the strength of the fragment an unnecessary parameter. The model analysis and a study of the data resulted in the nondimensional terms (Table 5A-2).

TABLE 5A-2. NONDIMENSIONAL TERMS

$$\left(\frac{\rho_p V}{\sqrt{\sigma_t \sigma_t}} \right)$$ dimensionless projectile velocity

$$\left(\frac{\delta h}{a^2} \right)$$ dimensionless target deflection

$$\left(\frac{h}{a} \right)$$ dimensionless target thickness

When $\left(\dfrac{\delta h}{a^2} \right)$ is plotted versus $\left(\dfrac{\rho_p V}{\sqrt{\sigma_t \rho_t}} \right)$, the data follow a straight line with some scatter in the data points (see Figure 5-2 in text). The line intersects the horizontal axis at a positive value of velocity. This is expected because there is a finite fragment velocity below which no permanent target deflection occurs.

Letting the velocity in the dimensionless projectile velocity term be the limit velocity, the locus of $\left(\dfrac{\rho_p V_{50}}{\sqrt{\sigma_t \sigma_t}} \right)$ versus $\dfrac{h}{a}$ is linear with the data points lying within about 15% of the values on the line (see Figure 5-1 in the text). The hailstone impact data fall in the region above the line (higher limit velocity), and the steel fragment data fall on and below the line (lower limit velocity). This indicates a possible effect of fragment strength. For this reason it may be desirable to be more conservative with steel fragments, choosing a lower limit velocity, and less conservative with aluminum fragments, choosing a higher limit velocity.

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APPENDIX V.B

DAMAGE ESTIMATES TO PEOPLE FROM
SECONDARY FRAGMENTS

5B-1   Penetrating Fragments

Undoubtedly a great deal of research has been conducted to produce classified wound ballistics equations for the military. Although thorough unclassified equations of this type do not exist, some publicly available body penetration data have been accumulated in recent times and some relatively simple analyses have been performed. Methods for predicting body damage from fragments using fragment parameters available in this document are presented in this appendix. More reliable damage criteria will undoubtedly be produced as the state-of-the-art improves.

Sperrazza and Kokinakis[1,2] concerned themselves with a ballistic limit velocity V_{50} for animal targets. The V_{50} velocity is the striking velocity at which one expects half the impacting missiles to perforate an object. They found that this velocity depended on the area to mass ratio, that is

$$V_{50} \propto \frac{A}{M} \tag{5B-1}$$

where A is cross-sectional area of the projectile along the trajectory, and M is the mass of the projectile. They fired steel cubes, spheres and cylinders of various masses up to 0.015 kg (0.033 lb$_m$) into 3 mm (0.118 in.) thick isolated skin (human and goat) to establish a ballistic limit. One of their assumptions was that, if the projectile penetrates the skin, its residual velocity would be sufficient enough to cause severe damage. This cautious assumption is appropriate for establishing a certain margin of safety in the calculation. Their conclusions were that, in the range of their data for steel cubes, spheres and cylinders, V_{50} depended linearly on projectile A/M ratio. Specifically,

$$V_{50} = 1247.1 \frac{kg}{m \cdot s} \left(\frac{A}{M} \right) + 22.03 \, m/s \tag{5B-2}$$

where A/M is in m^2/kg, and V_{50} is in m/s.

---

*Equation (5B-2) has been adjusted for SI units.

Kokinakis[2] later fired plastic sabots end-on into 20% gelatin that was 1 cm thick. The sabots were fired end-on since this represents the worst case, and 20% gelatin was used because this ballistically simulates isolated human skin. The linear relation of V_{50} versus A/M formulated by Sperrazza and Kokinakis[1] is plotted in Figure 5B-1. The average values for these experiments are located on this graph. Circles on the figure represent the initial experiments using steel cubes, spheres and cylinders weighing up to 0.015 kg (0.033 lb$_m$), and each average value represents as many as 30 data points. The line drawn on the graph is a least squares fit to these average values. Upward pointed triangles represent the average values for the subsequent experiments with end-on plastic sabots. These average values also lie near the line drawn for the prior study, thus adding a degree of confidence in the analysis.

Unfortunately, other authors have not presented their penetration data in the same form as Sperrazza and Kokinakis. Glasstone[3] expressed the probability of glass fragments penetrating the abdominal cavity in terms of the mass of the glass fragments. To compare Glasstone's conclusions with that of Sperrazza and Kokinakis, it is necessary to make a few assumptions. The first assumption is that the glass fragment velocity for 50% probability of penetration of the abdominal cavity is biologically equivalent to the ballistic limit velocity V_{50} for penetrating isolated human skin. This assumption is true provided that, after the glass fragment penetrates the skin, it does not encounter too much resistance before it perforates the abdominal cavity. Glasstone only specifies the mass of the glass required for penetration and does not give its cross-sectional area, thickness or density. For the purpose of comparing the conclusions of Glasstone with those of Sperrazza and Kokinakis, it was assumed that glass fragments are propelled edge-on, which is probably the worst case, and that they are square with thicknesses of 3.175 mm (1/8 in.) to 6.35 mm (1/4 in.). It was also assumed that the glass fragments have an average density of 2471 kg/m^3.[4] With these assumptions, it is not difficult to calculate A/M. If the glass fragment has a thickness t, and edge length y, then for volume

$$V = y^2 t \tag{5B-3}$$

where

V = volume of the fragment

y = edge length

t = thickness

Thus, the mass m of the fragment is
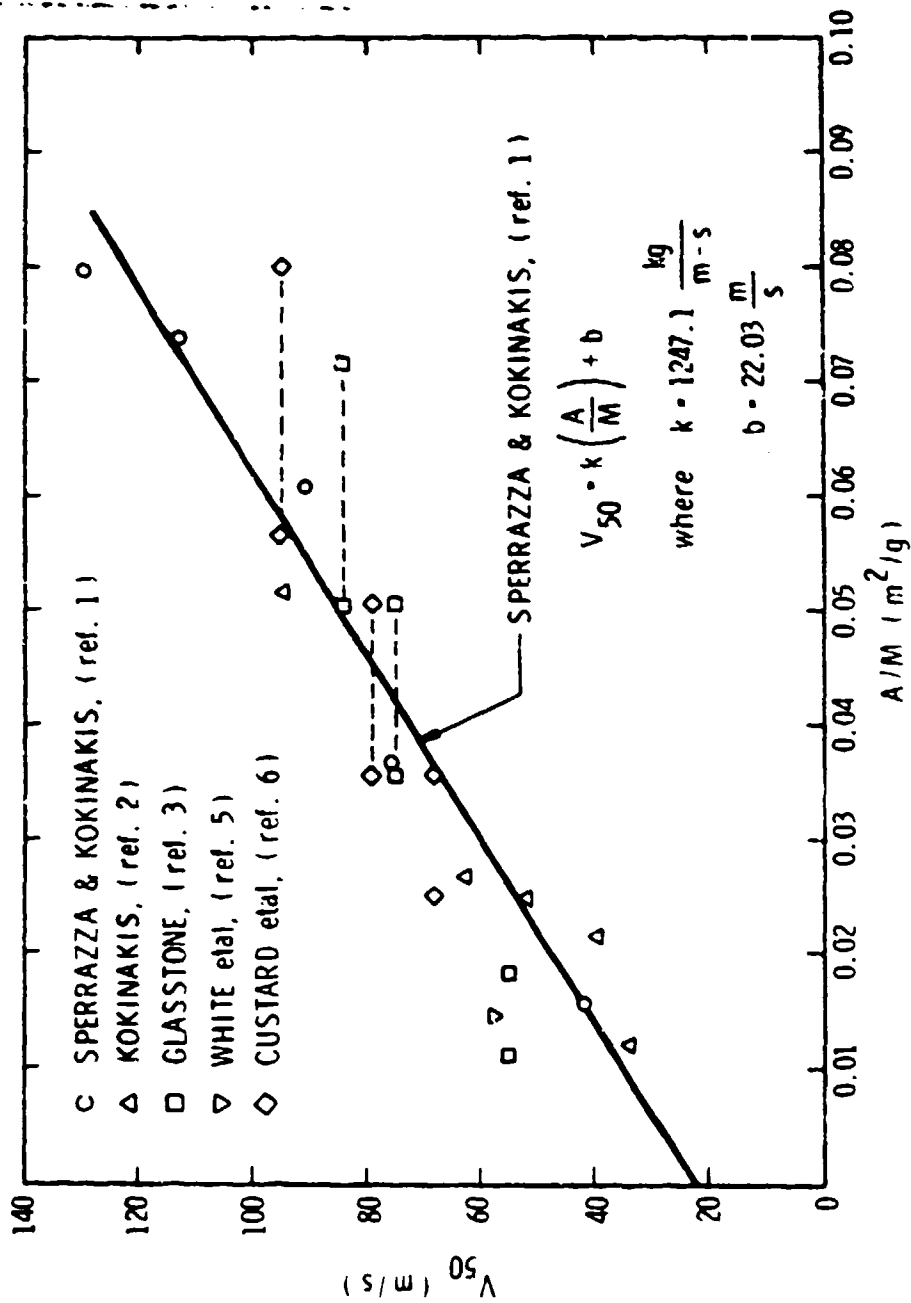
Figure 5B-1. Ballistic Limit (V_{50}) Vs Fragment Area/Mass for Isolated Human and Goat Skin

$$m = \rho y^2 t \qquad\qquad (5B\text{-}4)$$

where ρ is the density of the glass. Rearranging Equation (5B-4) gives the edge length,

$$y = \sqrt{\frac{M}{\rho t}} \qquad\qquad (5B\text{-}5)$$

The area-to-mass ratio A/M, assuming edge-on impact, is

$$\frac{A}{M} = \frac{ty}{M} \qquad\qquad (5B\text{-}6)$$

or from Equations (5B-4), (5B-5) and (5B-6),

$$\frac{A}{M} = \sqrt{\frac{t}{\rho M}} \qquad\qquad (5B\text{-}7)$$

Glasstone's criteria for 50% probability of glass fragments penetrating the abdominal cavity are shown in Table 5B-1. This table also contains the estimates for A/M for glass thicknesses of 3.175 mm (1/8 in.) and 6.35 mm (1/4 in.). The velocity values and calculated values for A/M which fall in the range of values used by Sperrazza and Kokinakis are plotted as squares in Figure 5B-1. The dashed lines indicate a range of A/M values for thickness values from 2.175 mm (1/8 in.) to 6.35 mm (1/4 in.). Even with the crude assumptions mentioned above, the calculated points fall very near the line drawn on Figure 5B-1.

White[5] also related skin penetration velocity to the masses impacting fragments. He concluded that slight skin laceration occurred when spherical bullets with mass 0.0087 kg (0.0191 lb$_m$) were propelled into the body at 57.9 m/s (190 ft/sec). Assuming that the density ρ of steel is 7925 kg/m^3, the A/M ratio can be calculated from

$$\frac{A}{M} = \frac{\pi r^2}{M} \qquad\qquad (5B\text{-}8)$$

where r is the radius of the spherical penetrator or

$$\frac{A}{M} = \frac{\pi}{M} \left(\frac{3M}{4\pi\rho}\right)^{2/3} \qquad\qquad (5B\text{-}9)$$

TABLE 5B-1. 50 PERCENT PROBABILITY OF GLASS FRAGMENTS PENETRATING ABDOMINAL CAVITY[3]*

Mass of Glass Fragment kg	Impact Velocity m/s	Impact Velocity (ft/sec)	A/M [3.175 mm (1/8 in.) thick] m²/kg	A/M [6.35 mm (1/4 in.) thick] m²/kg
0.0001	125	(410)	0.1136	0.1603
0.0005	84	(275)	0.0507	0.0717
0.001	75	(245)	0.0358	0.0507
0.01	55	(180)	0.0113	0.0160

*Table 5B-1 has been adjusted for SI units.

Using Equation (5B-9) and the mass and density mentioned above, A/M becomes 0.0148 m²/kg. The velocity value given above (57.9 m/s) and the calculated value for A/M are plotted on Figure 5B-1 as a downward pointed triangle. This point appears to be a little higher than expected, especially since only slight skin laceration is expected at these velocities instead of 50% penetration.

Custard, et al.,[6] like Glasstone, specify velocity as a function of mass only for 50% penetration. Making the assumptions that the thickness of the glass can vary from 3.175 mm (1/8 in.) to 6.35 mm (1/4 in.), that the fragments travel edge-on and are square, and that the density of glass is 2471 kg/m³, A/M was calculated from Equation (5B-7). The results are plotted on Figure 5B-1 as diamonds and agree fairly well with the conclusions of Sperrazza and Kokinakis. Thus, for values of A/M up to 0.06 m²/kg and values of M up to 0.015 kg (0.033 ibₘ), the functional relationship expressed in Equation (5B-2) and drawn as a solid line in Figure 5B-1 is an adequate representation of 50% probability of skin penetration by a projectile that can result in serious wounds.

Estimates of velocities, presented areas and masses [up to 0.015 kg (0.033 lbₘ)] of fragments from a propellant or gas explosion can be acquired from other portions of this document and compared with Figure 5B-1 to determine if penetration is likely. No estimate, however, of the velocity, mass and area of window glass fragments has been made elsewhere in this report. Since wounding from flying glass is a major concern, a method for determining these parameters will be included here. Fletcher, Richmond and Jones[4,7] conducted blast experiments to obtain information on glass fragments from breaking window panes. From their statistical analysis of the data, they were able to establish functional relationships among several variables. To be able to be used in conjunction with the work of Sperrazza

and Kokinakis,[1,2] it is necessary to obtain the velocity and area to mass ratio of the glass fragments (from the work of Fletcher, et al.[4,7]) After converting their equations to SI units, the geometric mean frontal area A' of fragments becomes:

$$A' = 6.4516 \times 10^{-4} \, e^{\left[2.4 - \sqrt{12.5 + (0.8500 \times 10^{-5} \, P_e)^2} \right]}$$

(5B-10)

for P_e in range 0 to 96.5 kPa, where P_e is effective peak overpressure in Pascals.

The effective peak overpressure P_e is equivalent to incident peak overpressure P_s for windows oriented side-on or back-on to the approaching blast wave and reflected peak overpressure P_r for windows oriented face-on to the approaching blast wave. This handbook contains methods for determining P_s. For $P_s \leq 3.5$ ($\bar{P}_s = P_s/p_0$ where p_0 is atmospheric pressure), $P_r = P_r/p_0$ can be determined from

$$\bar{P}_r = 2\bar{P}_s + \frac{(\gamma + 1)\bar{P}_s^2}{(\gamma - 1)\bar{P}_s + 2}$$

(5B-11)

where $\gamma = 1.4$.

Atmospheric pressure p_0 can be acquired from Figure 5-3 at sea level and various altitudes above sea level. For $P_s > 3.5$, P_r can be acquired from Figure 5-4. Effective peak pressure P_e is the

$$P_e = \bar{P}_s \, p_0$$

(5B-12)

for windows oriented side-on or back-on to the approaching blast wave, or

$$P_e = \bar{P}_r \, p_0$$

(5B-13)

for windows oriented face-on to the approaching blast wave.

If one assumes that all fragments are equal, then mass M can be determined from

$$M = \rho \, \ell^3$$

(5B-14)

where ρ is the density of the glass fragments
the glass is known.

If all glass fragments travel flat side forward, then

$$A = A' \tag{5B-15}$$

If all glass fragments travel edge forward, then

$$A = t / \bar{A}' \tag{5B-16}$$

Thus, for these two cases, the ratio A/M is

$$\frac{A}{M} = \frac{1}{t \varrho} \tag{5B-17}$$

or

$$\frac{A}{M} = \frac{1}{\varrho / A'} \tag{5B-18}$$

Whichever gives the lower value for A/M should be chosen for safety reasons. The geometric mean velocity can be acquired from Fletcher, et al.[4.7] After converting their equations to SI units,

$$\left[(0.2539) + (1.896 \times 10^{-4})(t - 7.62 \times 10^{-4}) \right]^{-0.028}$$

$$0.3443 \, P_e^{0.547} \tag{5B-19}$$

for P_e in the range 690 Pa to 689 kPa and $t \geq 7.62 \times 10^{-4}$ m.

A summary of the methods for determining the combinations of parameters which may produce serious penetration damage from fragments less than 0.015 kg (0.033 lb$_m$) is given here for convenience. To determine whether a fragment can cause severe body penetration damage, it is necessary to determine its striking velocity V (in m/s) and A/M ratio where A is the cross-sectional area of the projectile along its trajectory (in m^2) and M is the mass of the projectile (in kg). These parameters can, in general, be determined from other portions of this handbook. The ballistic limit velocity V_{50} (in m/s) is then

$$V_{50} = 1247.1 \left[\frac{A}{M} \right] + 22.03 \text{ m/s} \tag{5B-20}$$

for $A/M \leq 0.09$ m^2/kg where A is the cross-sectional area of the fragment along its trajectory in m^2, M is the mass of the fragment in kg, and

V_{50} is the ballistic limit velocity in m/s. If $V \geq V_{50}$, then one can expect some serious wounds from body penetration.

To determine whether a glass fragment from a window pane broken by the blast wave can cause severe body penetration damage, it is necessary to calculate an effective peak overpressure P_e where

$$P_e = \bar{P}_s \, p_o \tag{5B-21}$$

for windows oriented side-on or back-on to the approaching blast wave (p_o is atmospheric pressure in Pa; see Figure 5B-2), or

$$P_e = \bar{P}_r \, p_o \tag{5B-22}$$

for windows oriented face-on to the approaching blast wave.

For $\bar{P}_e \leq 3.5$,

$$\bar{P}_r = 2\bar{P}_e + \frac{(\gamma + 1)\,\bar{P}_s^2}{(\gamma - 1)\,\bar{P}_e + 2\gamma} \tag{5B-23}$$

where $\gamma = 1.4$.

For $\bar{P}_e > 3.5$, $\bar{P}_r$ can be acquired directly from Figure 5B-5. The ratio A/M should be chosen as the smaller of

$$\frac{A}{M} = \frac{1}{t\rho} \tag{5B-24}$$

or

$$\frac{A}{M} = \frac{1}{\rho\,\sqrt{A'}} \tag{5B-25}$$

where t is the thickness of the window pane in meters, ρ is the density of the glass which is approximately 2471 kg/m^3,[4] and A' is the geometric mean total area of the glass fragment in m^2 expressed by

$$A' = 6.4716 \times 10^{-4} \, e^{\left[2.4 - \sqrt{12.5 + (5.8566 \times 10^{-5}\,P_e)}\right]^2} \tag{5B-26}$$

for P_e in the range 0 Pa to 96.5 kPa.

5B-8

Striking velocity V (in m/s) is

$$V = \left[(0.2539) + (1.896 \times 10^{-4})(t - 7.62 \times 10^{-4}) \right]^{-0.928}$$

$$\times \quad 0.3443 \, P_e^{0.547} \tag{5B-27}$$

for P_e in the range 690 Pa to 689 kPa, and $t \geq 7.62 \times 10^{-4}$ m. If $V \geq V_{50}$, then one can expect some serious wounds from body penetration.

5B-2   Nonpenetrating Fragments

Criteria for body damage from nonpenetrating fragments are rather limited. Table 5B-2 contains tentative damage criteria for indirect blast effects involving nonpenetrating objects. It should be noted that the table applies to a fragment of only one mass. One can logically assume that larger masses propelled at the same velocities shown in the table will produce more damage than the 5.54 kg (10 lb) mass presented in the table.

TABLE 5B-2.   TENTATIVE CRITERIA FOR INDIRECT BLAST
EFFECTS FROM NONPENETRATING FRAGMENTS[9-11]

Mass	Event	Extent of Damage	Impact Velocity
4.54 kg (10 lb)	Cerebral Concussion	Mostly "safe"	3.05 m/s (10 ft/sec)
		Threshold	4.57 m/s (15 ft/sec)
	Skull Fracture	Mostly "safe"	3.05 m/s (10 ft/sec)
		Threshold	4.57 m/s (15 ft/sec)
		Near 100%	7.01 m/s (23 ft/sec)

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RISK ASSESSMENT AND INTEGRATED EFFECTS

6-1 Risk Assessment

A systematic, effective approach is required to identify the type, magnitude, and probability of occurrence of undesired events in the operation of any given system. Certain well-known related techniques have been used in industry (chemical, aerospace, nuclear and defense) to accomplish this result. These systems analyses are alternately referred to as "Hazard Analysis," "Safety Analysis," "Risk Assessment" and "Reliability Analysis."

Three basic related systematic methods are employed, either singly or in combination, to accomplish these types of analyses. These methods are:

(1) Event Tree - Starts with an event that initiates a possible accident and develops the possible consequences of the event by considering the response o. engineered safety systems that would be called upon as a result of the initial event.

(2) Fault Tree - Provides a method for determining the probabilities needed for the event trees. Fault trees employ a logic almost the reverse of event trees in that they start with an undesired event and identify the ways it may have been caused.

(3) FMECA - The Failure Mode Effects and Criticality Analysis is a systematic procedure for identifying each failure mode of the system and for evaluating the consequences. The FMECA starts with the components of the system, works up through the subsystem to the system level, and identifies the effects of each failure mode on the system operation.

An example of a simple event tree is shown in Figure 6-1 and a simple fault tree in Figure 6-2 for a chemical spill in a storage transfer system. Given an outcome from the event tree, a spill magnitude is defined. For each spill magnitude, a hazard or risk assessment can be made. From the fault tree, the probabilities of failure are determined to assign to each branch of the event tree. Then, the probability (or expected frequency) of occurrence

EVENT

Pipe Break
Vessel Rupture
Transfer Overflow
Transfer Leak

SAFETY SYSTEM #1

SAFETY SYSTEM Backup #2

SAFETY SYSTEM Backup #3

MAGNITUDE

P1

P2 Fails

(1 - P2) Works

P3 Fails

(1 - P3) Works

P4 Fails

(1 - P4) Works

(P_A) Very Large Spill

(P_B) Large Spill

(P_C) Moderate Spill

(P_D) Small or No Spill
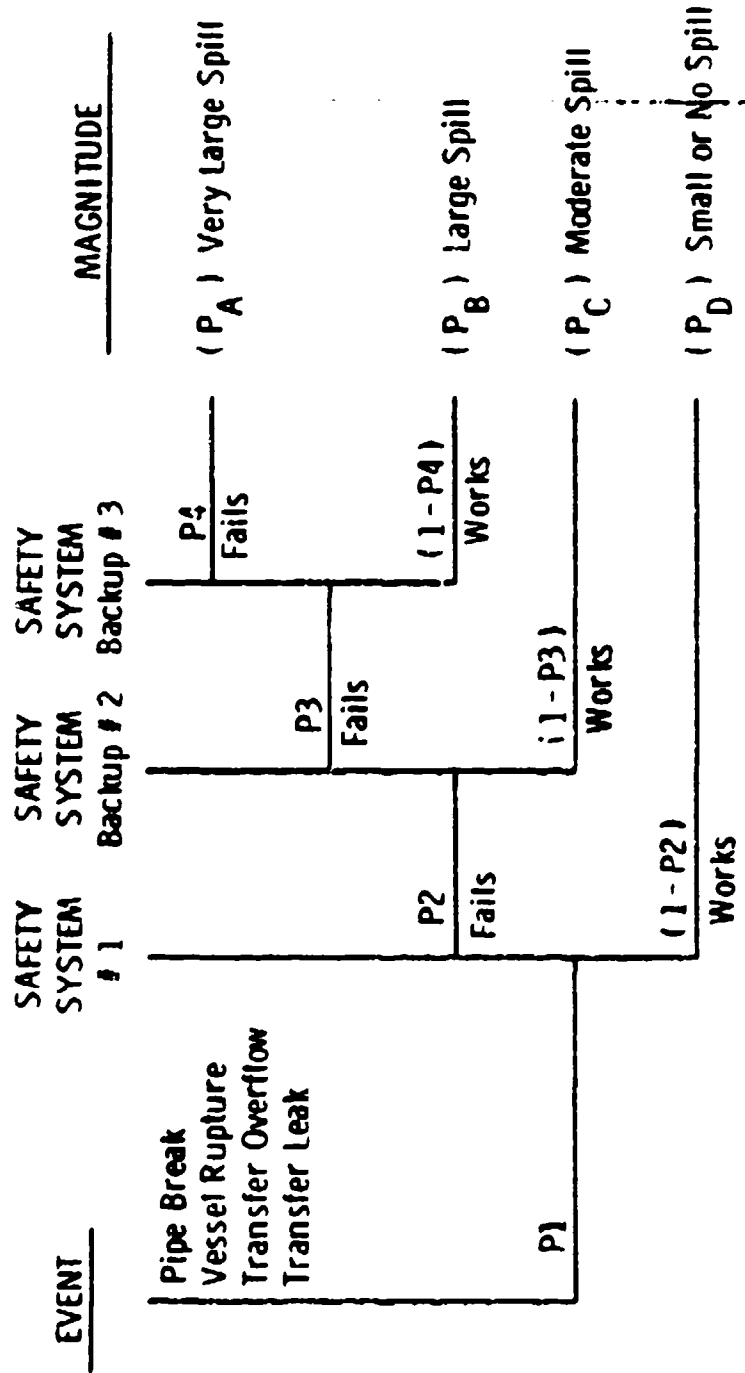
P - PROBABILITY OF FAILURE
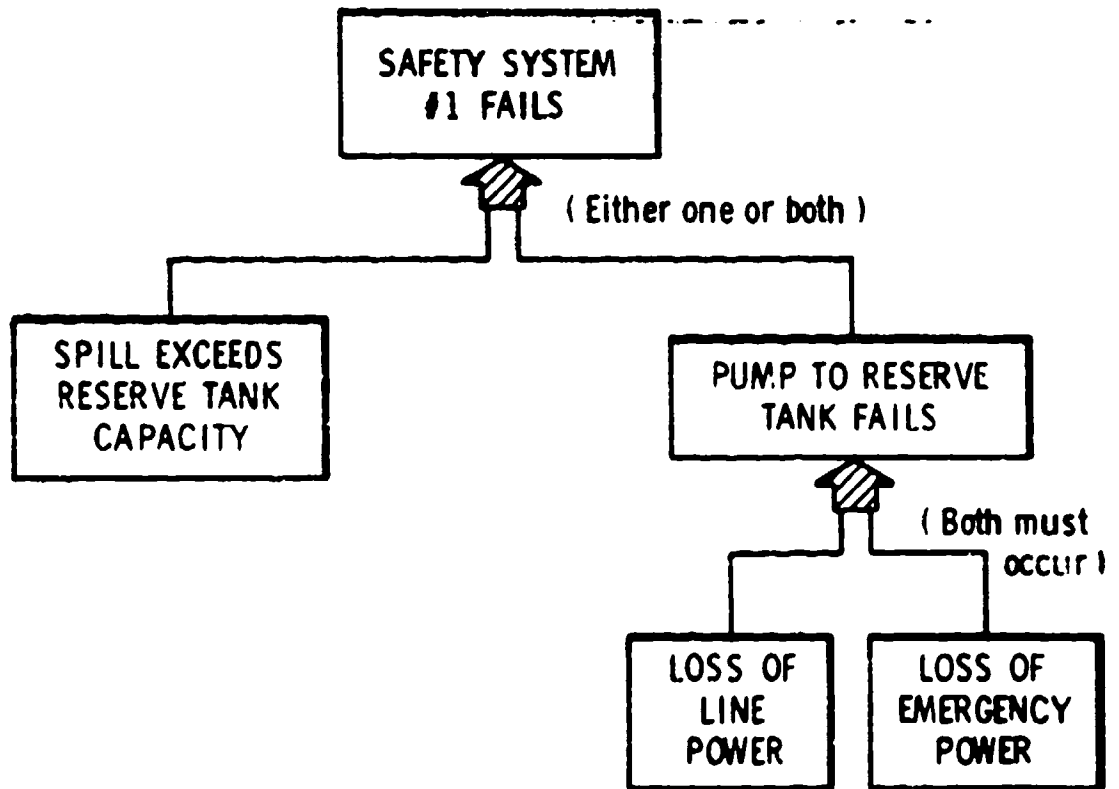
Figure 6-2. Typical Fault-Tree Diagram: Combining of
Failure Probabilities

is determined by the proper algebraic combination of the branch probabilities leading to the outcome.

Examples of these types of analyses can be found in references 1, 2, 3, 4, and 5.

For gas vessel or propellant systems, the figures and methods described in Chapters I through V can be used to assess the possible effects of any given undesired event based on the characteristics of fragments (mass initial velocity, and range) or blast phenomena.

The workbook does <u>not</u> give methods for estimating probabilities of catastrophic events occurring, nor does it employ the methods of risk assessment just discussed. It <u>does</u>, however, allow prediction of severity of certain classes of accidental explosion, as well as effects, under the assumption that an explosion does occur.

6-2 Prediction of Relative Blast and Fragment Effects

In Chapters II through IV, we give a number of examples of specific calculations for use of graphs, tables or simple equations each of which provides an estimate of some aspect of explosion hazards or their effects. But here we give a series of more complete examples. Each example represents a possible accident which can occur at aerospace launch or test facilities. Our assessment, as is true for all such estimates which can be made from this workbook, starts with the assumption that an accident has occurred and does not consider the probability of occurrence. Five different accident "scenarios" are presented, and estimates of blast and fragmentation effects are made for each scenario. The quantitites of propellant, volumes and types of compressed gases, masses of vehicle structure, etc., are often approximate, but they are realistic values. The problems are intended to illustrate the way in which the data in Chapters II through IV can be used to estimate relative blast and fragment characteristics, for some "typical" accidents.

6-2.1 Scenario #1. Fall-back of Space Shuttle during launch.

The scenario for this accident is a failure of thrust just after lift-off of the space shuttle. This multi-stage vehicle is a large, winged orbiter and landing vehicle similar in configuration to a large aircraft, which is boosted by the solid propellant rocket engines and a liquid-fueled engine. At lift-off, all three engines are firing and delivering thrust. The vehicle is assumed to rise at most a few meters, and then to fall back onto the launch pad with sufficient impact velocity to rupture the liquid rocket tankage. The propellants mix on the ground surface and reach an ignition source after some time delay.

6-4

Data for types and amounts of propellant in the Space Shuttle at lift-off, flow rates, and estimates of structural weight are given in Table 6-1. Because this accident occurs immediately after lift-off, all propellant weights are (conservatively) assumed to be the same as at lift-off. Assuming fall-back under gravity from a height of 10 meters (33 ft), the impact velocity is $U_i = 14.0$ m/s (45.9 ft/sec).

The propellants in the solid propellant boosters are assumed not to be explosive. This assumption seems well founded, based on the extensive testing of detonability of solid propellants in Project SOPHY. Furthermore, the quantities of liquid propellants listed for the first four subsystems in Table 6-1 are relatively small, and the type of accident postulated would be unlikely to rupture tanks containing these propellants. So, we assume for this example problem that only the external tank ruptures and spills its propellants in a CBGS type of accident. For estimating fragmentation effects, we also use only the structural mass of the damaged external tankage.

A number of other hazards are obviously associated with this type of accident, but some are not calculable from methods given in this workbook. In particular, the trajectories and impact effects of the propulsive solid propellant boosters, which are burning and thrusting when fall-back occurs, cannot be estimated. Presumably, the orbiter with its human payload can escape by igniting escape rockets in the event of fall-back. If we can estimate its flight location when explosion occurs, some predictions of blast effects can possibly be made. But, we have too little data in hand at present to make this estimate.

6-2.1.1   Yield

The yield is calculated by the methods in Chapter I. According to Table 1-2, Equation 1-2 and Figure 1-7 are used to determine a value for the yield, which is compared with a value obtained from Figure 1-1. The smaller value is used:

Equation 1-2: $Y_m = 10\% + \dfrac{4.43\%}{(m/s)} U_i$ $(0 < U_i < 24.4 \text{ m/s})$

$$= 10\% + \frac{4.43\% \ (14.0 \text{ m/s})}{(m/s)} = 72.0\%$$

In Figure 1-7, choose $t_{ignition}$ for maximum Y: $t_{ignition} = 0.6$ sec.

TABLE ?-?. ON-BOARD PROPELLANT WEIGHTS FOR PAGE SHUTTLE AT ...

Subsystem	Propellant Type	Quantity (kg)	Quantity (lbm)	Flow Rate (kg/s)	Flow Rate (lbm/s)	Structural Mass (kg)	Structural Mass (lbm)
Aux. Power Units (APU)	Hydrazine	281	618	0.04	0.09	--	--
Orbital Maneuvering (OMS)	MMH	4 240	9370	3.29	7.24	--	--
	N_2O_4	7 010	15,400	5.42	11.9	--	--
Reaction Control (RCS)	MMH	1 270	2790	0.523	1.15	--	--
	N_2O_4	2 030	4470	0.841	1.85	--	--
Power Reactant Storage System (fuel cells)	LH_2	83.6	184	0.000221	0.000486	--	--
	Max. mission	502	1100	--	--	--	--
	LO_2	710	1560	0.00176	0.00387	--	--
	30 day	4 260	9370	--	--	--	--
External Tank	LH_2	103 000	227,000	900	2000	178 000	392,000
	LO_2	608 000	1,340,000	5 450	12,000		
Experimental Control System	NH_3	46.4	102	--	--	--	--
Total Propellants	--	1 006 000	2,210,000	4 020	8800	...	...

Then

$$\frac{Y \cdot 100}{Y_m} = 62, \quad Y = \frac{62 \ Y_m}{100} = \left(\frac{\cdots}{100}\right)^{\cdots} = 44.6\%$$

From Figure 1-1 (using a total propellant and oxidizer mass of 711000 kg), y = 0.06. The multiplier is 370%. Y = (0.06)(370%) = 22.2%. Choose the lower value of Y which is 22.2%.

6-2.1.2   Overpressure and Specific Impulse

The overpressure and specific impulse are calculated by the methods in Chapter II. The effective mass is calculated from Equation 2-9: $W = W_T X \frac{Y}{100}$. Table 2-1 gives the procedure for finding the overpressure and specific impulse as functions of distance:

$$W = W_T X \frac{Y}{100} = (711000 \ kg) \ \frac{22.2\%}{100} = 153000 \ kg \quad (348,000 \ lb_m)$$

According to Table 2-1, the overpressure is read from Figure 2-16, and the specific impulse is read from Figure 2-17.

The following (Table 6-2) is a list of overpressures (P$_s$) and specific impulses (I$_s$) from Figures 2-16 and 2-17. The solid lines in these figures were used. The other terms in Table 6-2 will be explained later.

6-2.1.3   Effect of Blast Waves on Structures.

The methods described in Section 3-1 are used to determine the effects of blast waves on structures.

Glass Breakage

Equation 3-1 relates overpressure for glass breakage to the properties of the glass pane.

$$\left[\frac{P_r X^2}{\sigma_y h^2}\right] = \frac{1.0 + 3.08\left(\frac{X}{Y}\right)^2 + \left(\frac{X}{Y}\right)^4}{8.6\left[0.79 + 0.11\left(\frac{X}{Y}\right)^2 - 0.79\left(\frac{X}{Y}\right)^4\right]^{1/2}} \tag{3-1}$$

TABLE 6-2. OVERPRESSURES AND IMPULSES

$\dfrac{R}{W^{1/3}}$	R (m)	P_s (Pa)	$\bar{P}_s$	I_s (Pa·s)	$\dfrac{I_s}{W^{1/3}}$ (Pa·s/kg$^{1/3}$)	$\dfrac{I_s}{m^{1/2}}$ (Pa·s/kg$^{1/3}$)	$\dfrac{I_s}{P_o^{1/2}\,m^{1/3}}$ (Pa$^{1/2}$·s/kg$^{1/3}$)
0.6	32.4	1.400×10^6	13.8	2.09×10^4	386	1.22×10^4	38.4
1.0	54.1	5.60×10^5	5.53	1.29×10^4	238	7.54×10^3	23.7
2.0	108	1.52×10^5	1.50	7.03×10^3	130	4.11×10^3	12.9
4.0	216	4.71×10^4	0.465	3.82×10^3	70.6	2.23×10^3	7.02
10.0	541	1.31×10^4	0.129	1.71×10^3	31.6	1.00×10^3	3.14
20.0	1080	5.22×10^3	0.0515	9.24×10^2	17.1	5.40×10^2	1.70

(ft = m X 3.281)

(psi = Pa X 1.450 X 10^{-4})

(psi-sec = Pa·s X 1.450 X 10^{-4})

$P_r = 2P_s$ for a blast wave striking a window head-on.

$P_r = P_s$ for a blast wave traveling parallel to the surface of the glass.

It can be shown that P_r increases as $\frac{X}{Y}$ increases. For the lowest P_r to break any kind of glass that is likely to be found, choose $\frac{X}{Y} = 0.20$, and $X = 0.300$ m (0.98 ft). Then, $P_s = 2420$ Pa (0.351 psi) for glass breakage with the glass surface perpendicular to the direction of travel of the blast wave. $P_s = 4840$ Pa (0.702 psi) for glass breakage with the direction of propagation of the blast wave parallel to the surface of the window.

Looking at the data in Table 6-2, it can be seen that, for no glass breakage with windows facing the source of the blast wave, the distance must be much greater than 1080 m (3500 ft). (By extrapolating curve #1, the i_s vs P_s curve in the next Figure, Figure 6-3, it appears that the distance for an overpressure of 2420 Pa is near 2000 m (6000 ft).) With the glass surface parallel to the direction of travel of the blast wave, the distance for no glass breakage must be about 1100 m (3600 ft.).

Building Damage

The degree of building damage as a function of distance from the source of the blast wave can be observed in Figure 6-3. Figure 6-3 is a copy of Figure 3-2, with the (impulse, overpressure) points for selected distances R. The (i_s, P_s) paths for four of the scenarios to be discussed in this chapter are included in this figure. The paths cross the limit of damage lines. By finding the values of R at which they cross one knows the minimum distance at which a given degree of safety exists. One can interpolate between two adjacent values of R by assuming a logarithmic scale for R on Figure 6-3. Alternatively, one can determine the overpressure or impulse at the point of the intersection of the (i_s, P_s) path and the damage limit curve, and then go back to the figure in the text where the overpressure or impulse was obtained and find the corresponding distance. The resulting building damage for this scenario (#1) is presented in Table 6-3.

Overturning of Objects

One can use the methods of Section 3-1.3 to determine the minimum distance from this explosion at which a Saturn V rocket may be placed, for which it will not be overturned by the blast wave. Assume that the fueled Saturn V is standing vertically without restraints. Assume standard atmospheric temperature and pressure. Let $h = 110$ m (360 ft), $h_{cg} = 30$ m (100 ft), $b = 10.1$ m (33 ft), $H = 10.1$ m (33 ft), $h_{bl} = h/2 = 55$ m (180 ft), $m = 2.8 \times 10^6$
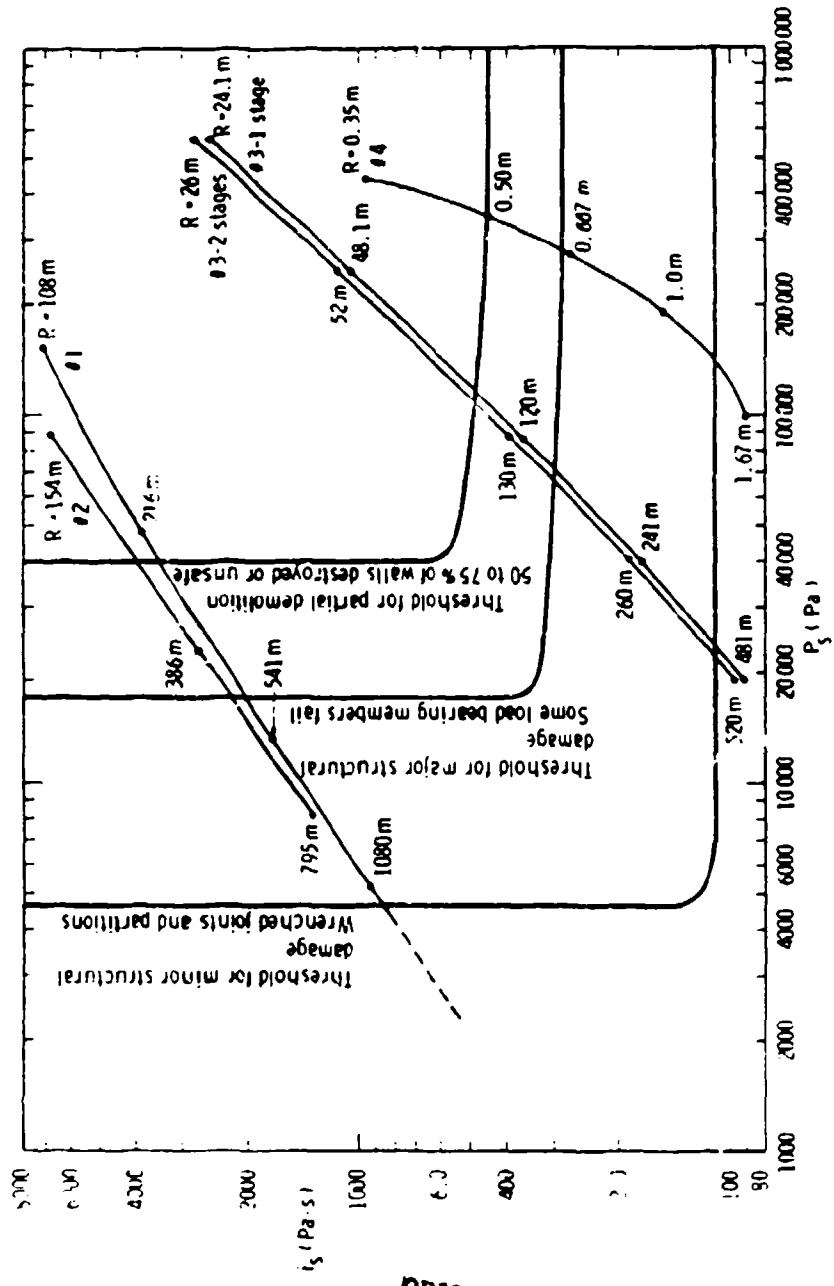
Figure 6-3. Pressure Vs Impulse Diagram for Building Damage with Blast Curves for Scenarios 1 Through 4

TABLE 6-3. BUILDING DAMAGE

Degree of Damage	Distance (m)	(ft)
threshold of minor structural damage	1200	3900
threshold of major structural damage (some load-bearing members fail)	470	1500
threshold of partial demolition	270	890

kg $(6.2 \times 10^6 \, lb_m)$, and $C_D = 1.2$.   Then, $A = 1100 \, m^2$ $(12000 \, ft^2)$,
$h/b = 10.9$, and $h_{cg}/h = 0.273$.   The procedure is to find the minimum impulse
i_o for overturning. Setting this equal to the applied impulse i_t allows one
to find the maximum distance for which the vehicle will overturn.   For all
larger distances, the vehicle will not overturn.

h/b is too large for Figure 3-4, so use Equation 3-4.

$$\frac{i_\theta A h_{b\ell}}{m g^{1/2} b^{3/2}} = \sqrt{\left[\frac{2}{3} + \frac{h^2}{6b^2} + \frac{2h^2}{b^2}\left(\frac{h_{cg}^2}{h^2}\right)\right]\left[\sqrt{\frac{1}{4} + \left(\frac{h^2}{b^2}\right)\left(\frac{h_{cg}^2}{h^2}\right)} - \left(\frac{h}{b}\right)\left(\frac{h_{cg}}{h}\right)\right]}$$

$= 1.25$.   Then $i_o = 5810 \, Pa \cdot s$. $(.8427 \, psi \cdot sec)$

Let $i_t = 5810 \, Pa \cdot s$.   Then $a \, i_t/p_o H = 1.77$ $(.000257 \, psi \cdot s)$.
This is the minimum nondimensional applied impulse for overturning which
is shown on Figure 6-4, a copy of Figure 3-3.   The points $(a \, C_D i_s/p_o H, \overline{P}_s)$
were plotted on Figure 6-4 for several values of R.   The place where this
curve (curve #1) crosses the line of minimum applied impulse for overturning
gives the value of R for the "threshold" of overturning.   For Scenario #1
this distance is 220 m (720 ft).   At distances greater than 220 m (720 ft,
a Saturn V will not be overturned by a blast wave from this explosion.

6-2.1.4   Effect of Blast Waves on Humans

The methods described in Section 3-2 are used to determine the effects
of blast waves on humans.

SCALED SIDE-ON OVERPRESSURE $\frac{p_s}{p_0}$

SCALED TOTAL IMPULSE $\frac{a_0 i_t}{p_0 H}$

$\frac{a_0 c_D i_s}{p_0 H}$ =

Minimum for overturning of Saturn $\overline{V}$

R = 216m #1

R = 52m #3-2 stages

130m

260m

520m

1080m

541m

100.0
70.0
40.0
20.0
10.0
4.0
1.0
0.100
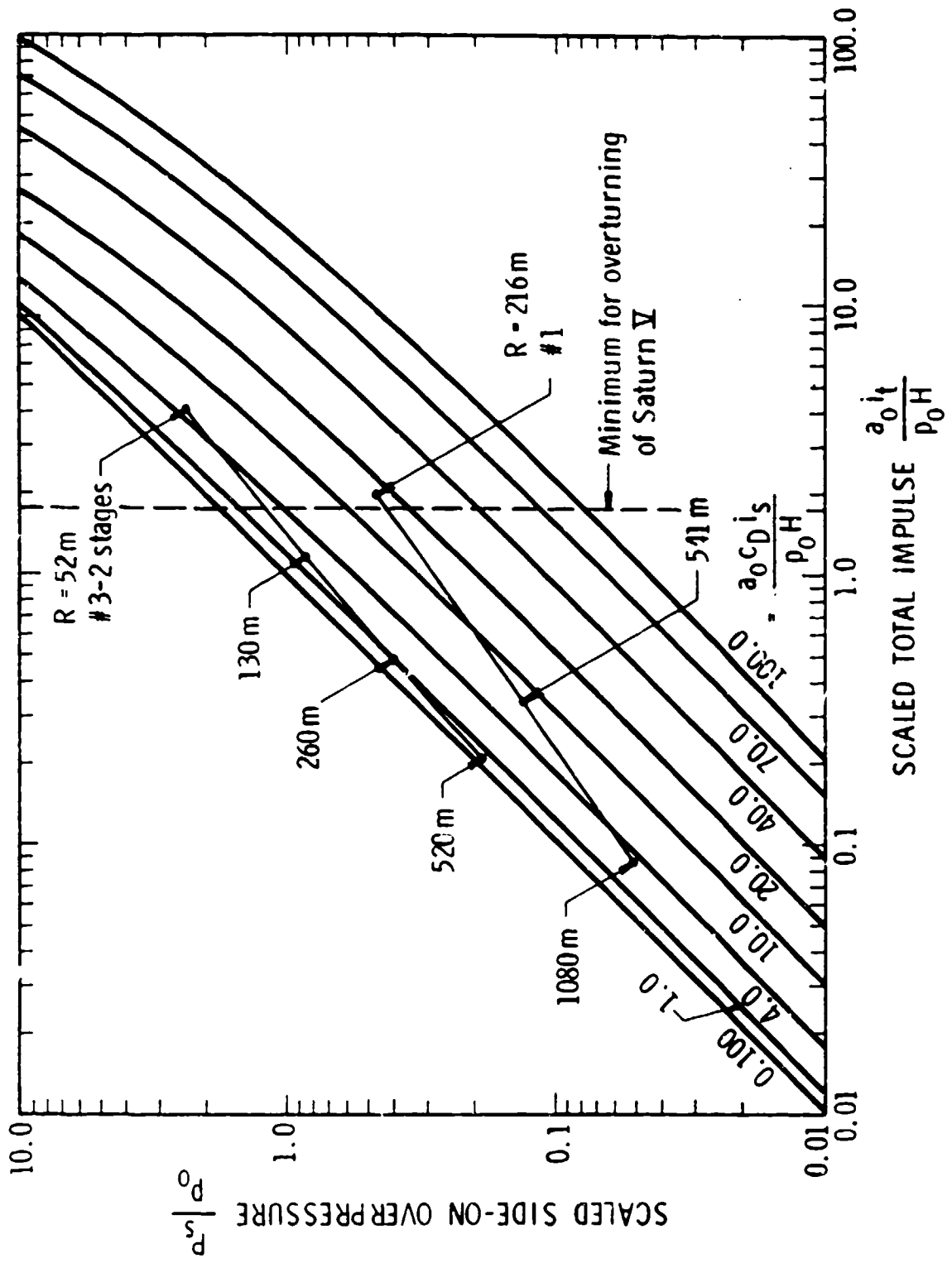
Lung Damage

Figure 3-10 in Section 3-2 is used to determine the extent of damage to the lungs of humans by blast waves. Figure 6-5 is a copy of Figure 3-10 with the $(\bar{P}_s, \frac{\bar{I}_s}{p_o^{1/2} m^{1/3}})$ points for selected values of R. $p_o = 1.013 \times 10^5$ Pa

(14.7 psi). The value of m is chosen as 5.00 kg (11 lb_m). The same procedure as the one that was used for building damage is also used here to determine the values of R for various degrees of lung damage. The results are presented in Table 6-4.

TABLE 6-4. LUNG DAMAGE

Degree of Damage	Distance (m)	(ft)
threshold of lung damage	170	560
99%	100	330
90%	100	330
50%	90	300
10%	70	230
1%	70	230

Ear Damage

Figure 3-11 is used to determine the extent of damage to the ears of humans by blast waves. Figure 6-6 is a copy of Figure 3-11 in Section 3-2 with the (P_s, I_s) points for selected values of R. Table 6-5 shows the results. Note that a value of R cannot be determined for TTS because the curve for Scenario #1 never reaches the TTS damage limit curve, and it is inadvisable to try to extrapolate this curve.
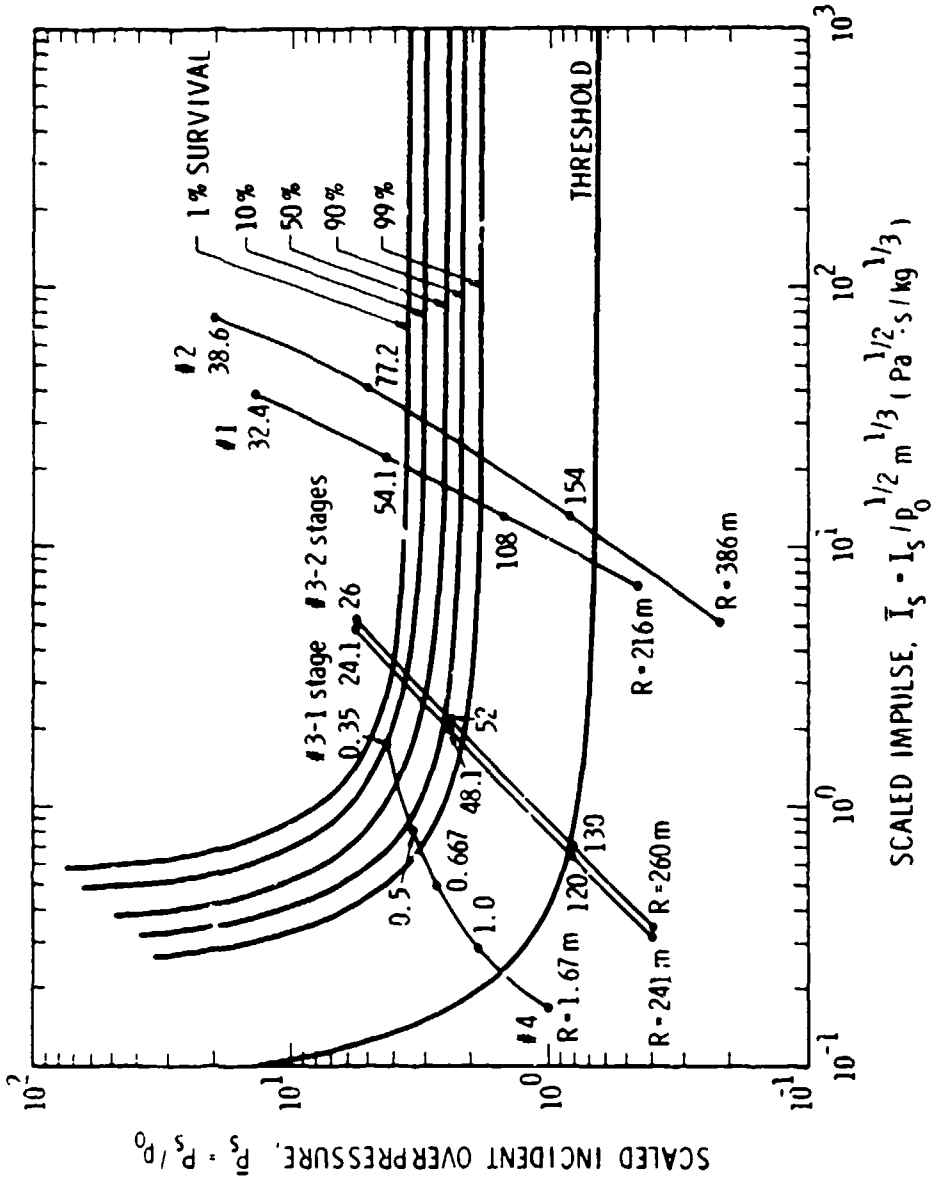
Figure 6-5. Survival Curves for Lung Damage with Curves for Scenarios 1 Through 4
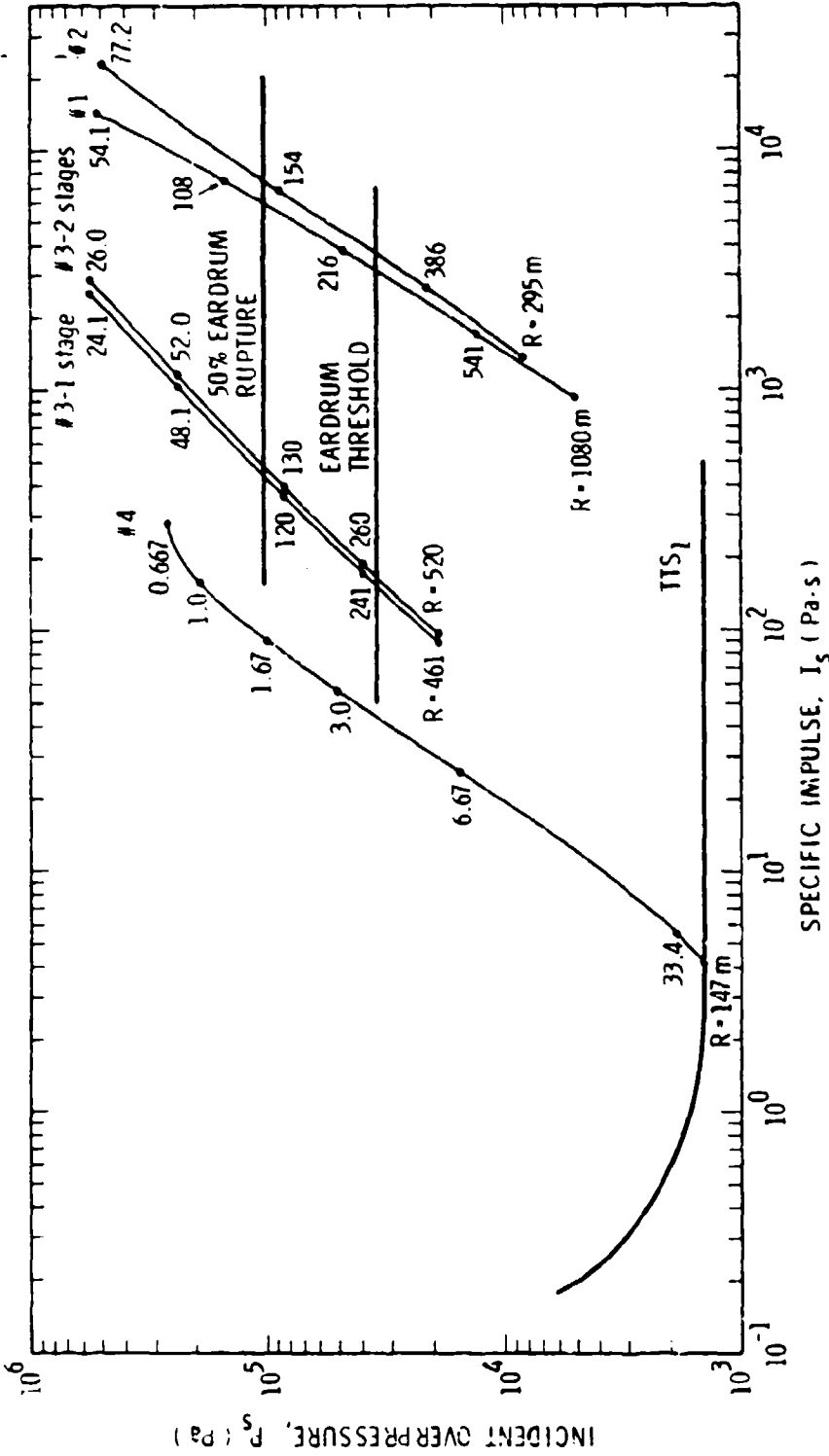
Figure 6-6. Human Ear Damage Curves for Blast Waves Arriving at Normal Angle of Incidence with Curves for Scenarios 1 Through 4

TABLE 6-5. EAR DAMAGE

Degree of Damage	Distance (m)	(ft)
temporary threshold shift (TTS) (90%-no loss)	over 2000	over 6000
threshold of eardrum rupture	270	890
50% eardrum rupture	130	430

Skull Fracture

Figure 3-12 is used to determine the chance of Skull Fracture due to bodily translation and impact caused by blast waves. Figure 6-7 is a copy of Figure 3-12 with the $(P_s, \frac{I_s}{m^{1/3}})$ points for selected values of R. The body mass, m, is chosen as 5.00 kg (11 lb_m). The results are presented in Table 6-6.

TABLE 6-6. SKULL FRACTURE

Chance of Skull Fracture	Distance (m)	(ft)
mostly safe	350	1100
threshold	310	1000
50%	270	890
near 100%	240	790

Body Translation and Impact

Figure 3-16 is used to determine the probability of mortality from whole-body translation and impact upon a hard surface caused by blast waves. Figure 6-8 is a copy of that figure with the $(P_s, \frac{I_s}{m^{1/3}})$ points for selected values of R. The body mass m is chosen as 5.00 kg. Table 6-7 shows the results. Note that no value of distance is given for "near 100% mortality" because it is inadvisable to extrapolate the curves in Figure 6-8.
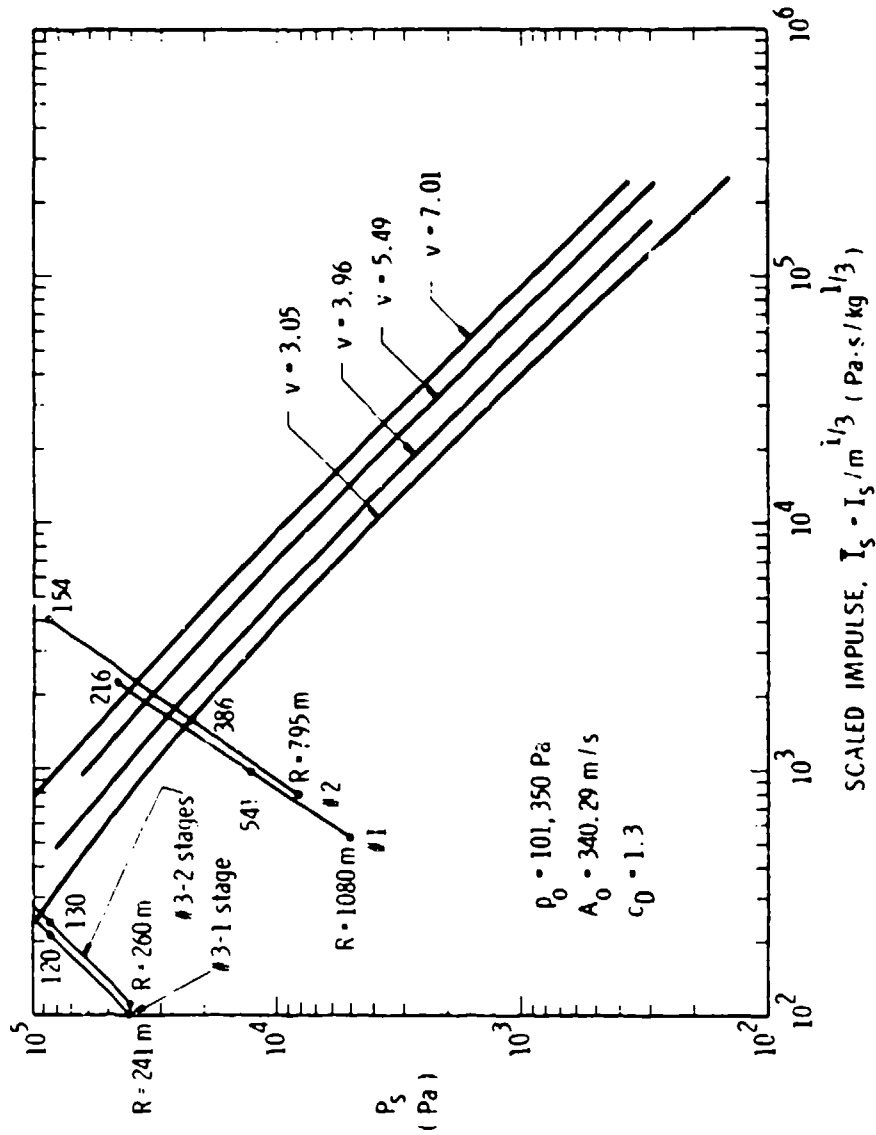
Figure 6-7. Skull Fracture, 0 m Altitude, with Curves for Scenarios 1, 2, and 3
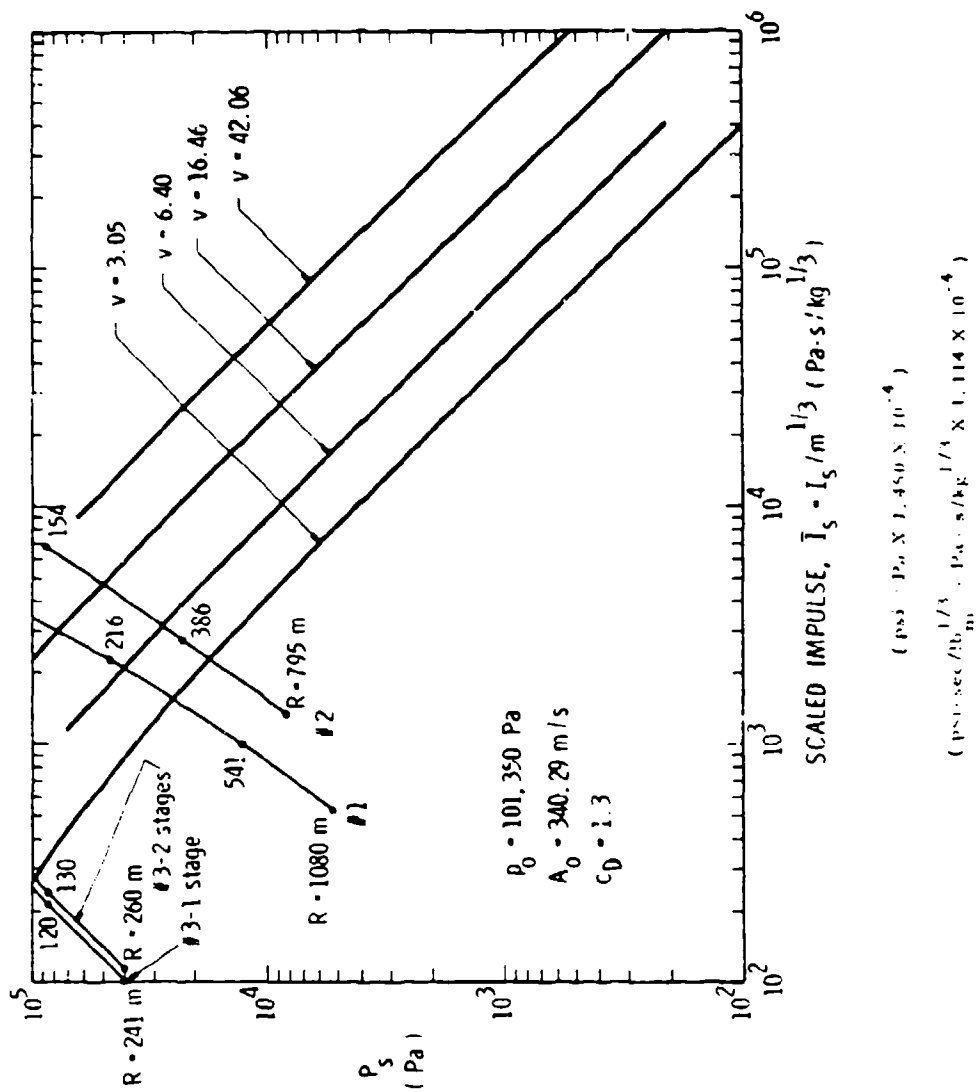
Figure 6-8. Lethality from Whole Body Translation, 0 m Altitude, with Curves for Scenarios 1, 2, and 3

TABLE 6-7. MORTALITY FROM BODY IMPACT

Degree of Mortality	Distance	
	(m)	(ft)
mostly safe	340	1100
threshold of lethality	240	790
50% mortality	160	520

6-2.1.5 Fragment Characteristics

The initial fragment velocity distribution is obtained from Figure 4-48. 95% of the fragments have an initial velocity less than or equal to 500 m/s (1600 ft/sec).

The fragment mass distribution is obtained from Figure 4-55. 95% of the fragments have a mass less than or equal to 120 kg (264 lb_m).

The fragment range is obtained from Figure 4-57. 95% of the fragments will strike the ground at a distance less than or equal to 580 m (1900 ft).

6-2.1.6 Appurtenances

As an example of an appurtenance, a cement block identical to that described in Example 1 of Section 4-4 will be used. Suppose that it is located at a distance of 108 m (350 ft) from the source of the blast wave, and one must know its velocity after being picked up by the blast wave.

At $R = 108$ m, $P_s = 1.52 \times 10^5$ Pa, $\overline{P}_s = 1.50$, and $I_s = 7.03 \times 10^3$ Pa·s. The nondimensional impulse is

$$\overline{I}_s = \frac{C_D I_s a_0}{P_s (KH + X)} = \frac{1.05(7.03 \times 10^3)(340)}{1.52 \times 10^5 \left[4(2.5) + 0\right]} = 1.65 .$$

Locating the $(\overline{P}_s , \overline{I}_s)$ point on Figure 4-26, one finds that $\overline{V} \cong 3.5$. Then,

$$V = \frac{\overline{V} P_0 A(KH + X)}{M a_0} = \frac{(3.5)(1.013 \times 10^5)(6.25)\left[4(.5) + 0\right]}{(2.8 \times 10^5)(340)}$$

$$= 0.24 \text{ m/s } (0.76 \text{ ft/sec}).$$

This cement block would be thrown at a very low velocity.

6-2.1.7   Effect of Fragments on Humans

The effect on humans of flying glass from windows broken by blast waves will be considered. In Example 1 of Section 5-2, the 50% penetration limit velocity V_{50} for typical glass was found to be 23.4 m/s (76.8 ft/sec). Equation 5-8 relates striking velocity V to overpressure P_e, which may be P_s or P_r, depending upon the orientation of the glass with the blast wave.

$$V = 0.2530 + (1.806 \times 10^{-4}) (t - 7.62 \times 10^{-4})^{-0.928} \qquad 0.3443 \, P_e^{0.547}$$

$$5-8$$

Setting $V = V_{50}$, one can solve for the minimum P_e for human injury from flying glass. Letting $t = 3.175 \times 10^{-3}$ m, $P_e = 1.96 \times 10^{4}$ Pa (2.84 psi).

For windows where the direction of propagation of the blast wave is parallel to the glass surface, $P_e = P_s$. Then $P_s = 1.96 \times 10^{4}$ Pa. From Figure 2-16, R = 380 m (1200 ft). At any distance less than 380 m, there is likelihood of human injury by flying glass from windows with surfaces parallel to the direction of propagation of the blast wave.

For windows where the direction of propagation of the blast wave is normal to the glass surface, $P_e = P_r$. Solving 5-4 for $\bar{P}_s$ and manipulating gives $P_s = 9.45 \times 10^{3}$ Pa (1.37 psi). From Figure 2-16, R = 640 m (2100 ft). Tables 6-8 and 6-9 summarize the damage and injury that can be expected.

6-2.2   Scenario #2.   Explosion of Space Shuttle Propellant Tanks in Early Stages of Flight

In this "scenario", the Space Shuttle has lifted off from the pad and started its ascent. A failure occurs in the tankage for the main liquid propellant rocket engine, causing the LH_2 and LO_2 to mix and ignite within the tanks (CBM). The explosion occurs at about 100 m (3280 ft) altitude, where ground reflections do not affect the blast wave properties. This altitude is not great enough, however, to affect blast wave characteristics other than by lack of ground reflection. The initial quantities of propellants at lift-off are given in Table 6-1. Assuming 30 seconds of propellant consumption, remaining weights are:

External Tank LH_2, 75 700 kg (167,000 lb$_m$)

LO$_2$, 444 000 kg (977,000 lb$_m$)

Solid Propellants - 885 000 kg (1,950,000 lb$_m$)

TABLE 6-8 SCENARIO 1: DAMAGE TO STRUCTURES

Damage to Structures	Distance (m)	(ft)
threshold of overturning Saturn V	220	720
threshold of partial demolition	270	870
threshold of major structural damage	470	1570
99% of fragments will strike the ground within this distance	580	1900
threshold of side-on glass breakage	1100	3600
threshold of minor structural damage	1200	3900
threshold of face-on glass breakage	2000	6900

TABLE 6-9 SCENARIO 1: HUMAN INJURY

Human Injury	Distance (m)	(ft)
1%-10% survival (lung damage)	70	230
50% survival (lung damage)	90	300
90-99% survival (lung damage)	100	330
50% eardrum rupture	130	430
50% mortality from body impact	160	520
threshold of lung damage	170	560
near 100% chance of skull fracture threshold of lethality from body impact	240	770

TABLE 6-9 SCENARIO 1: HUMAN INJURY (CONCLUDED)

Human Injury	Distance	
	(m)	(ft)
threshold of eardrum rupture, 50% chance of skull fracture	270	890
threshold of skull fracture	310	1000
mostly safe from body impact injury	340	1100
mostly safe from skull fracture	350	1100
threshold of injury from flying glass (side-on)	380	1200
threshold of injury from flying glass (face-on)	640	2100
temporary threshold shift (hearing)	over 2000	over 6000

In this type of accident, we can estimate explosive yield and blast effects, as well as initial velocities of fragments, making the same restrictive assumptions as for Scenario #1. But, fragment trajectories and impact conditions cannot be estimated, because all of the graphs in Chapter IV relating to these properties of fragments are based on explosions which occur on the ground surface. The methods for computing fragment trajectories are applicable, but the appropriate computer programs have not been exercised for initial conditions of significant altitudes above the ground. Because we cannot estimate impact conditions, we, of course, cannot use the methods of Chapter V for predicting damaging effects of fragments.

6-2.2.1   Yield

The yield is calculated by the methods in Chapter I. According to Table 1-2, values for the yield are obtained from Figures 1-1 and 1-6, and the lower value is used:

From Figure 1-1, for a fuel and oxidizer mass of 5.20×10^5 kg, $y = 0.06$. The multiplier is 370%. $Y = (0.06)(370\%) = 22.2\%$

In Figure 1-6, choose $t_{ignition}$ for maximum Y. Then $Y = 38\%$. Using the lower value, $Y = 22.2\%$.

The overpressure and impulse curves for propellant explosions were obtained from data of explosions occurring on the ground. An argument similar to that used in Section A-2-6 can be used here. The ground explosion can be approximated by the vessel in Figure A2-4b, where half of the energy is released above the ground. To apply the analysis to an explosion in free air, the energy (or yield) must be halved. Then $Y = 11.1\%$..

6-2.2.2   Overpressure and specific impulse

The overpressure and specific impulse are calculated by the methods in Chapter II. The effective mass is calculated from Equation 2-9: $W = W_m \times \frac{Y}{100}$. Table 2-1 gives the procedure for finding the overpressure and specific impulse as functions of distance:

$$W = W_T \times \frac{Y}{100} = (5.20 \times 10^5 \text{ kg}) \frac{11.1\%}{100\%} = 57\ 500 \text{ kg } (126,000 \text{ lb}_m)$$

According to Table 2-1, the overpressure is read from Figure 2-14, and the specific impulse is read from Figure 2-15.

The following (Table 6-10) is a list of overpressures (P_s) and specific impulses (I_s) from Figure 2-14 and 2-15. The solid lines in these figures were used.

TABLE 6-19. OVERPRESSURES AND IMPULSES

$\frac{R}{W^{1/3}}$ (m·s/kg$^{1/3}$)	P_s (Pa)	P_s	P_r (Pa)	$\frac{I_s}{W^{1/3}}$ (Pa·s/kg$^{1/3}$)	I_s (Pa·s)	I_r (Pa·s)	$\frac{I_s}{m^{1/3}}$ (Pa$^{1/3}$·s/kg$^{1/3}$)	$\frac{I_r}{P_o^{1/2}m^{1/3}}$ (Pa$^{1/2}$·s/kg$^{1/3}$)	$\overline{P}_r$
0.400	2.45×10^5	24.5	1.17×10^5	451	1.74×10^4	1.24×10^5	7.25×10^3	2.25×10^2	175
0.700	1.13×10^5	11.2	5.79×10^5	344	1.33×10^4	9.02×10^4	5.28×10^3	1.66×10^2	76
1.00	1.39×10^5	4.38	2.49×10^5	255	9.16×10^3	4.23×10^4	2.47×10^6	7.77×10^1	20
1.50	1.53×10^5	1.50	5.05×10^5	186	5.23×10^3	2.27×10^4	1.33×10^3	4.17×10^1	5.2
3.0	6.44×10^4	0.466	5.51×10^3	60.9	2.50×10^3	6.85×10^3	4.00×10^3	1.26×10^1	0.872
10.0	1.08×10^4	0.107	2.27×10^4	33.8	1.30×10^3	2.72×10^3	1.59×10^3	5.00	0.224
40.0	4.12×10^3	0.0906	2.15×10^3	12.2	1.04×10^2	1.95×10^2	2.49×10^2	2.48	0.0805

(ft = m X 3.281)

(Pa-sec = Pa·s X 1.450 X 10^{-4})

(psi = Pa X 1.450 X 10^{-4})

6-2.2.3   Effect of Blast Waves on Structures

The methods described in Section 3-1 are used to determine the effects of blast waves on structures.

Glass Breakage

In Scenario #1, it was found that the minimum overpressure to break a typical pane of glass facing the explosion is 2420 Pa. For a pane of glass parallel to the path of the blast wave the minimum overpressure required to break it is 4840 Pa. We are concerned with damage on the ground. The blast wave will be reflected by the ground. Therefore, the reflected overpressure is important here. Replace P_s by P_r and calculate the new P_s. From Equation 2-3, P_r = 2420 Pa (0.351 psi), P_s = 1280 Pa (0.186 psi). For P_r = 4840 Pa (0.702 psi), P_s = 2420 Pa (0.351 psi). As in this particular calculation, <u>P_r and I_r will be used in place of P_s and I_s throughout this scenario.</u> From Figure 2-14, one would expect to be able to obtain the distance at which these overpressures would be observed for Scenario #2. For P_s = 2420 Pa, or P_s = 1280 Pa a value of $R/W^{1/3}$ cannot be read from Figure 2-14, but it can be seen that the distance R must be over 1000 m (3000 ft). Therefore, glass breakage will occur on the ground below the explosion.

Building Damage

The (i_s, P_s) points for selected values of R for Scenario #2 are included in Figure 6-3. Using the same techniques as in Scenario #1, but using the reflected overpressures and impulses, Table 6-11 was assembled. (The reflected impulses are calculated by Equation 2-4). For this explosion at an altitude of 1000 m, there might be building damage on the ground (possibly minor structural damage).

TABLE 6-11. BUILDING DAMAGE

Degree of Damage	Distance	
	(m)	(ft)
threshold of minor structural damage	over 800	over 2600
threshold of major structural damage	450	1500
threshold of partial demolition	300	980

6-2.2.4   Effect of Blast Waves on Humans

The methods described in Section 3-2 are used to determine the effects of blast waves on humans.

Lung Damage

The $(\bar{P}_s, \dfrac{\bar{i}_s}{p_o^{1/2} m^{1/3}})$ points for selected values of R for Scenario #2 are included in Figure 6-5. Table 6-12 was obtained from this figure. There will be no lung damage to humans from this explosion.

TABLE 6-12.   LUNG DAMAGE

Chance of Survival	Distance	
	(m)	(ft)
threshold of lung damage	170	560
99%	100	330
90%	100	330
50%	90	300
10%	90	300
1%	90	300

Ear Damage

The (P_s, i_s) points for selected values of R for Scenario #2 are included in Figure 6-6. Table 6-13 was assembled using this figure. The data could not be extrapolated to find the distance for "Temporary Threshold Shift."

TABLE 6-13. EAR DAMAGE

Degree of Damage	Distance (m)	(ft)
threshold of eardrum rupture	340	1100
50% eardrum rupture	150	490

Skull Fracture

The $(P_s, \frac{I_s}{m^{1/3}})$ points for selected values of R for Scenario #2 are included in Figure 6-7. Table 6-14 is the result.

TABLE 6-14. SKULL FRACTURE

Chance of Skull Fracture	Distance (m)	(ft)
mostly safe	390	1300
threshold	360	1200
50%	340	1100
near 100%	320	1000

Body Translation and impact

The $(P_s, \frac{I_s}{m^{1/3}})$ points for selected values of R for Scenario #2 are included in Figure 6-8. In the result, Table 6-15, note that no value of R is given for "near 100% mortality" because extrapolation is not recommended.

TABLE 6-15.   MORTALITY FROM BODY IMPACT

Degree of Mortality	Distance (m)	(ft)
mostly safe	390	1300
threshold of lethality	370	1200
50% mortality	300	660

There would be injury to people on the ground due to the blast wave.

6-2.2.5   Fragment Characteristics

The initial fragment velocity distribution is obtained from Figure 4-50; 95% of the fragments have an initial velocity less than or equal to 1000 m/s (3300 ft/s).

The fragment mass distribution cannot be determined with the methods that are presently available. Figures 4-51 and 4-52 show the mass distribution for CBM explosions with yields of 5% and 1.1%. There is obviously a strong dependence of mass distribution upon yield, and it is not valid to attempt to extrapolate the information in these figures to a yield of 11.1%.

6-2.2.6   Effect of Fragments on Humans

The effect on humans of flying glass from windows broken by blast waves will be considered. In Scenario #1, it was shown that for injury from flying glass, $P_s = 9.45 \times 10^3$ Pa (1.37 psi) with the blast wave striking the pane of glass head-on, and $P_s = 1.96 \times 10^4$ Pa (2.84 psi) with the blast wave propagating in a direction parallel to the surface of the glass.

As for other types of damage in this Scenario, the reflected over-pressure must be used in place of P_r. Then, $P_r = 9.45 \times 10^3$ Pa for normal blast impact and $P_r = 1.96 \times 10^4$ Pa for blast impact parallel to the glass surface. The corresponding values of P_s are then 4.64×10^3 Pa (0.673 psi) and 9.45×10^3 Pa (1.37 psi). From Figure 2-14 of Chapter II, at a distance R less than 930 m (3100 ft), there is likelihood of human injury by flying glass from windows normal to the direction of travel of the blast wave. The corresponding distance for windows parallel to the direction of travel is 420 m (1400 ft).

There will be no injury by flying glass to humans on the ground.

6-2.3   Scenario #3. Fall Back of the Titan Centaur Vehicle During Launch

The scenario for this accident is nearly identical to the first, except that the launch vehicle is different. The Titan Centaur is a three-stage, liquid-fueled rocket vehicle with a mass fraction of 0.85. The first two stages are fueled with the hypergolic propellant combination N_2O_4 and Aerozine 50, and the third stage with LO_2 and LH_2 . The missile is assumed to rise a short distance when loss of thrust in the first stage allows it to fall back on the launch pad. The impact is assumed to be sufficiently violent that at least the first stage ruptures and spills its propellant on the launch pad. Impact velocity is 14.0 m/s (45.9 ft/s). Table 6-16 gives propellant masses and estimates of structural masses for each stage, based on the mass fraction of 0.85.

Several possible assumptions regarding severity of the fall-back accident can be made. We will make two such assumptions, and predict effects for both. These assumptions are:

(1) Only the first stage ruptures and explodes, and

(2) Both first and second stages rupture and explode

For the first assumption, the structure of the first stage is assumed to be the only source of fragments, while for the second assumption, the structures of both first and second stages are fragment sources.

TABLE 6-16.   PROPELLANTS AND STRUCTURES
AT LIFT-OFF OF TITAN CENTAUR ROCKET

Stage	Propellants	Propellant Masses (kg)	(lb_m)	Structure Masses (kg)	(lb_m)
Titan First	N_2O_4	75 900	167,000	20 600	45,300
	Aerozine 50	40 400	88,900	--	--
Titan Second	N_2O_4	19 500	42,900	5 360	11,800
	Aerozine 50	10 900	24,000	--	--
Centaur (Third)	LO_2	11 400	25,100	2 410	5300
	LH_2	2 270	4990	--	--

6-2.3.1   Yield

The yield is calculated by the methods in Chapter 1.   According to Table 1-2 values for the yield are obtained from Figure 1-1 and Table 1-1, and the lower value is used:

From Figure 1-1, for a fuel and oxidizer mass of 116 000 kg (255,000 lb_m) (only the first stage), or 146 000 kg (321,000 lb_m) (first and second stages), y = 0.06.   The multiplier is 240%.   Y = (0.06)(240%) = 14.4%. From Table 1-1, Y = 1.5%. Using the lower value,   Y = 1.5%.

6-2.3.2   Overpressure and Specific Impulse

The overpressure and specific impulse are calculated by the methods in Chapter II.   The effective mass is calculated from Equation 2-9. $W = W_T \times \frac{Y}{100}$.   Table 2-1 gives the procedure for finding the overpressure and specific impulse as functions of distance:

$$W_1 = W_{T_1} \times \frac{Y}{100} = (1.16 \times 10^5 \text{ kg}) \frac{1.5\%}{100\%} = 1740 \text{ kg } (3820 \text{ lb}_m)$$

(only the first stage)

$$W_{1+2} = (1.46 \times 10^5 \text{ kg}) \frac{1.5\%}{100\%} = 2190 \text{ kg } (4820 \text{ lb}_m)$$

(first and second stages)

According to Table 2-1, the overpressure is read from Figure 2-7, and specific impulse is read from Figure 2-8.

The following (Table 6-17) is a list of overpressures (P_s) and specific impulses (I_s) from Figures 2-7 and 2-8.   The solid lines in the figures were used.

6-2.3.3   Effect of Blast Waves on Structures

The methods described in Section 3-1 are used to determine the effects of blast waves on structures.

Glass Breakage

In Scenario #1, it was found that the minimum overpressure to break a typical pane of glass facing the explosion is 2420 Pa (.351 psi). For a pane of glass parallel to the path of the blast wave, the minimum overpressure required to break it is 4840 Pa (.702 psi).   From Figure 2-7 one would expect to be able to obtain the distance at which these overpressures would be observed for Scenario #3. For P_s = 2420 Pa or 4840 Pa, a value of

TABLE 6-12. OVERPRESSURES AND IMPULSES

(ft = m X 3.281)
(psi = Pa X 1.450 X 10⁻⁴)
(psi-sec = Pa-s X 1.450 X 10⁻⁴)

$R/W^{1/3}$ cannot be read from Figure 2-7, but it can be seen that $R/W^{1/3}$ must be over 60, corresponding to R greater than 720 m (2400 ft) for only one stage exploding and R greater than 780 m (2600 ft) for both the first and second stages exploding.

Building Damage

The (i_s, P_s), points for selected values of R for Scenario #3 are included in Figure 6-3. Using the same technique as in Scenario #1, Table 6-18 was assembled.

TABLE 6-18. BUILDING DAMAGE

	Distance			
	1st Stage		1st and 2nd Stages	
Degree of Damage	(m)	(ft)	(m)	(ft)
threshold of minor structural damage	380	1200	416	1400
threshold of major structural damage	140	460	160	520
threshold of partial demolition	95	310	100	330

Overturning of Objects - Two Stages Exploding

The $(\dfrac{a_o C_d i_s}{p_o H}, \bar{P}_s)$ points for selected values of R are included

in Figure 6-4. For R less than or equal to 95 m (310 ft), a Saturn V rocket can be expected to overturn as a result of this explosion.

6-2.3.4   Effect of Blast Waves on Humans

The methods described in Section 3-2 are used to determine the effects of blast waves on humans.

Lung Damage

The $(\bar{P}_s, \dfrac{i_s}{p_o^{1/2} m^{1/3}})$ points for selected values of R for Scenario

#3 are included in Figure 6-5. Table 6-19 was obtained from this figure.

TABLE 6-19.   LUNG DAMAGE

	Distance			
	1st Stage		1st and 2nd Stages	
Chance of Survival	(m)	(ft)	(m)	(ft)
threshold of lung damage	120	390	130	430
99%	53	170	55	180
90%	46	150	52	170
50%	39	130	45	150
10%	35	110	40	130
1%	32	100	36	120

Ear Damage

The (P_s, I_s) points for selected values of R for Scenario #3 are included in Figure 6-6.   Table 6-20 was assembled using this figure.   The data could not be extrapolated to find the distance for "Temporary Threshold Shift".

TABLE 6-20.   EAR DAMAGE

	Distance			
	1st Stage		1st and 2nd Stages	
Degree of Damage	(m)	(ft)	(m)	(ft)
threshold of eardrum rupture	260	850	280	920
50% eardrum rupture	110	360	120	390

Skull Fracture

The $(P_s, \frac{I_s}{m^{1/3}})$ points for selected values of R for Scenario #3 are included in Figure 6-7.   Table 6-21 is the result.   The curves in Figure 6-6 should <u>not</u> be extrapolated to find the damage limits beyond "mostly safe".

TABLE 6-21. SKULL FRACTURE

| Chance of Skull Fracture | Distances | | | |
| | 1st Stage | | 1st and 2nd Stages | |
	(m)	(ft)	(m)	(ft)
mostly safe	110	360	120	390

Body Translation and Impact

The $(P_s, \dfrac{I_s}{m^{1/3}})$ points for selected values of R for Scenario #3 are included in Figure 6-8. In the result, Table 6-22, note that a value of R is given only for "mostly safe" because extrapolation is not recommended.

TABLE 6-22. MORTALITY FROM BODY IMPACT

| Degree of Mortality | Distances | | | |
| | 1st Stage | | 1st and 2nd Stages | |
	(m)	(ft)	(m)	(ft)
mostly safe	110	360	120	390

6-2.3.5 Fragment Characteristics

The fragment mass and initial velocity distributions cannot be determined by the methods in Chapter IV because the figures there are not to be used for hypergolic propellants.

The fragment range is obtained from Figure 4-57. 95% of the fragments will strike the ground at a distance less than or equal to 270 m (890 ft).

6-2.3.6 Appurtenances

As an example of an appurtenance a cement block will be used as in Scenario 1. The stand-off distance is 52 m (170 ft), where P = 2.4 × 10³ Pa. P = 2.42, and I = 1149 Pa · s. Then I = 0.268. Locating the (P, I) point on Figure 4-26, one finds that V = 580. Then V = 0.33 m/s (1.1 ft/s). Thus, this cement block would be thrown at a low velocity.

6-2.3.7   Effect of Fragment on Humans

The effect on humans of flying glass from windows broken by blast waves will be considered. In Scenario #1, it was shown that for injury from flying glass, $P_s = 9.45 \times 10^3$ Pa with the blast wave striking the pane of glass head-on, and $P_s = 1.90 \times 10^4$ Pa with the blast wave propagating in a direction parallel to the surface of the glass. From Figure 2-7, at a distance $R/W^{1/3}$ less than 38.0, there is likelihood of human injury by flying glass from windows parallel to the direction of travel of the blast wave. The corresponding distance $R/W^{1/3}$ for windows normal to the direction of travel cannot be read from the graph. The maximum distances from the explosion for human injury from flying glass are shown in Table 6-23.

The damage and injury to be expected in Scenario #3 are summarized in Tables 6-24 and 6-25.

TABLE 6-23.   MINIMUM SAFE DISTANCE FOR INJURY
BY FLYING GLASS

	Distance			
Orientation of Glass to Direction of Travel of Blast Wave	1st Stage		1st and 2nd Stages	
	(m)	(ft)	(m)	(ft)
parallel	460	1500	490	1600

TABLE 6-24.   SCENARIO 3: DAMAGE TO STRUCTURES

	Distance			
	1st Stage		1st and 2nd Stages	
Damage to Structures	(m)	(ft)	(m)	(ft)
Saturn V overturning threshold of partial demolition	95	310	95	310
threshold major structural damage	140	460	160	520
95% of fragments will strike the ground within this distance	270	890	270	890
threshold minor structural damage	380	1200	416	1400
threshold of side on glass breakage	> 720	> 2400	> 780	> 2600

TABLE 6-25. SCENARIO 3: HUMAN INJURY

Human Injury	Distance 1st Stage (m)	(ft)	1st and 2nd Stages (m)	(ft)
1% survival (lung damage)	32	100	3?	12?)
10% survival (lung damage)	35	110	4?)	130
50% survival (lung damage)	39	130	4?	150
90% survival (lung damage)	46	150	52	170
99% survival (lung damage)	53	170	??	1?0
50% eardrum rupture, mostly safe from skull fracture and body impact	110	360	12?	3??
threshold of lung damage	120	390	130	430
threshold of eardrum rupture	260	850	280	920
threshold injury from flying glass (side-on)	460	1500	490	1600

6-2.4   Scenario #4. Pressure Burst of a Centaur Pressurant Tank
During Pneumatic Strength Testing in a Shop Area

One of the spherical pressurant tanks for the Centaur launch vehicle
is assumed to fail catastrophically while it is being proof tested in a shop
area. The vessel is spherical, made of Ti-6 Al4V alloy, has a volume of
0. 1206 m^3 (4.26 ft^3), and fails at the design pressure of 20.7 M Pa (3000 psi),
and at room temperature of 25 C (77 F). The vessel is being pressurized
with helium, with a ? of 1.67. The radius of the vessel is 0. 507 m (1. 66 ft),
and the wall thickness is 4.60 mm (0.0151 ft). The density of the titanium
alloy is 4. 5 Mg/m^3 (279 lb_m/ft^3), making the mass of the vessel 24. 3 kg
(53. 5 lb_m) .

6-2.4.1   Overpressure and Specific Impulse

Determine the starting point and locate it on Figure 2-18. Use the nearest curves to find the overpressure versus distance behavior. Use Figure 2-23 to determine the specific impulse versus distance behavior:

$$p_1 = 2.07 \times 10^7 \text{ Pa (g)} = 2.08 \times 10^7 \text{ Pa (absolute)}$$

$$p_a = 1.013 \times 10^5 \text{ Pa. Then } p_1/p_a = 205.3$$

$$T_1 = T_a = 208°K. \text{ Then } T_1/T_a = 1.00.$$

For $\gamma_1 = 1.667$, from Figure 2-21, $\bar{P}_{so} = 4.8$.

$$\bar{R}_o = \frac{1}{\left[\dfrac{\dfrac{4\pi}{3}\left(\dfrac{p_1}{p_a} - 1\right)}{\gamma_1 - 1}\right]^{1/3}} = \frac{1}{\left[\dfrac{\dfrac{4\pi}{3}\left(\dfrac{2.08 \times 10^7 \text{ Pa}}{1.013 \times 10^5 \text{ Pa}} - 1\right)}{1.667 - 1}\right]^{1/3}} = 0.0920$$

In Figure 2-18 the point $(\bar{R}_o, \bar{P}_{so})$ lies nearest the 4th curve from the bottom. This gives $\bar{P}_s$ versus $\bar{R}$.

$$\bar{R} = \frac{\dfrac{r}{r_o}}{\left[\dfrac{\dfrac{4\pi}{3}\left(\dfrac{p_1}{p_a} - 1\right)}{\gamma_1 - 1}\right]^{1/3}} \quad . \quad \text{Then } r = \bar{R}\, r_o \left[\dfrac{\dfrac{4\pi}{3}\left(\dfrac{p_1}{p_a} - 1\right)}{\gamma_1 - 1}\right]^{1/3}$$

$$= R(0.307 \text{ m})\left[\dfrac{\dfrac{4\pi}{3}\left(\dfrac{2.08 \times 10^7 \text{ Pa}}{1.013 \times 10^5 \text{ Pa}} - 1\right)}{1.667 - 1}\right] = \bar{R}(3.336) \text{ (r in m)}$$

$$\bar{P}_s = \frac{p_s - p_a}{p_a} \quad . \quad \text{Then } p_s - p_a = p_a \bar{P}_s = (1.013 \times 10^5 \text{ Pa}) \bar{P}_s \text{ (}p_s \text{ in Pa)}$$

$$E = \frac{p_1 - p_a}{v_1 - 1} \qquad V_i = \frac{(2.08 \times 10^7 \text{ Pa} - 1.013 \times 10^5 \text{ Pa})(0.1206 \text{ m}^3)}{1.667 - 1}$$

$$= 3.74 \times 10^6 \text{ J}$$

$$\bar{I} = \frac{I a_a}{p_a^{2/3} E^{1/3}} \qquad \text{Then} \quad I = \frac{\bar{I} p_a^{2/3} E^{1/3}}{a_a}$$

$$= \frac{\bar{I} (1.013 \times 10^5 \text{ Pa})^{2/3} (3.743 \times 10^6 \text{ J})^{1/3}}{331 \frac{m}{s}} = 1019 \, \bar{I}. \quad (I \text{ in } Pa \cdot s)$$

Overpressures and specific impulses versus distance are listed in Table 6-26 and graphed in Figures 6-9 and 6-10.

6-2.4.2   Effect of Blast Waves on Structures

The methods described in Section 3-1 are used to determine the effects of blast waves on structures.

Glass Breakage

In Scenario #1, it was found that the minimum overpressure to break a typical pane of glass facing the explosion is 2420 Pa. For a pane of glass parallel to the path of the blast wave, the minimum overpressure required to break it is 4840 Pa. From Figure 6-9 one can obtain the distance at which these overpressures would be observed for Scenario #4. For $P_s = 2420$ Pa, it can be seen that the distance R must be 28 m (92 ft). For $P_s = 4840$ Pa, the distance R is 16 m (52 ft).

Building Damage

The (i_s, P_s) points for selected values of R for Scenario #4 are included in Figure 6-3. Using the same techniques as in Scenario #1, Table 6-27 was assembled. It is unlikely that any building damage will result.

$\bar{R}$	r (ft)	$\bar{P}_s$	P_s (Pa)	$\bar{I}$	I (Pa·s)	$\dfrac{\bar{I}}{n^{1/3}}$ (Pa·s/kg$^{1/3}$)	$\dfrac{\bar{I}}{P_0^{1/2} m^{1/3}}$ (Pa$^{1/2}$·s/kg$^{1/3}$)
0.03	0.307	4.5	4.0×10^5	1.1	1100	640	2.1
0.10	0.33	4.0	4.0×10^5	2.7×10^{-1}	280	160	5.1×10^{-1}
0.30	0.65	2.7	2.7×10^5	1.5×10^{-1}	150	60	2.8×10^{-1}
0.35	1.0	1.9	1.9×10^5	9.2×10^{-2}	94	55	1.7×10^{-1}
0.50	1.5	1.0	1.0×10^5	5.4×10^{-2}	55	32	1.0×10^{-1}
0.90	3.0	0.49	6.0×10^4	2.6×10^{-2}	26	16	4.9×10^{-2}
2.0	6.7	0.16	1.2×10^4	5.4×10^{-3}	5.5	3.2	1.9×10^{-2}
10	33	0.019	1.9×10^3	4.1×10^{-3}	4.2		
44	120	0.014	1.4×10^2	4.7×10^{-4}	0.48	0.28	6.8×10^{-4}
100	330	1.4×10^{-3}	1.4×10^2	4.6×10^{-5}	0.047	0.027	8.6×10^{-5}
1000	3300	1.1×10^{-4}	1.1×10^1				

(ft = m X 3.281)
(psi = Pa X 1.450 X 10^{-4})
(psi-sec = Pa·s X 1.450 X 10^{-4})
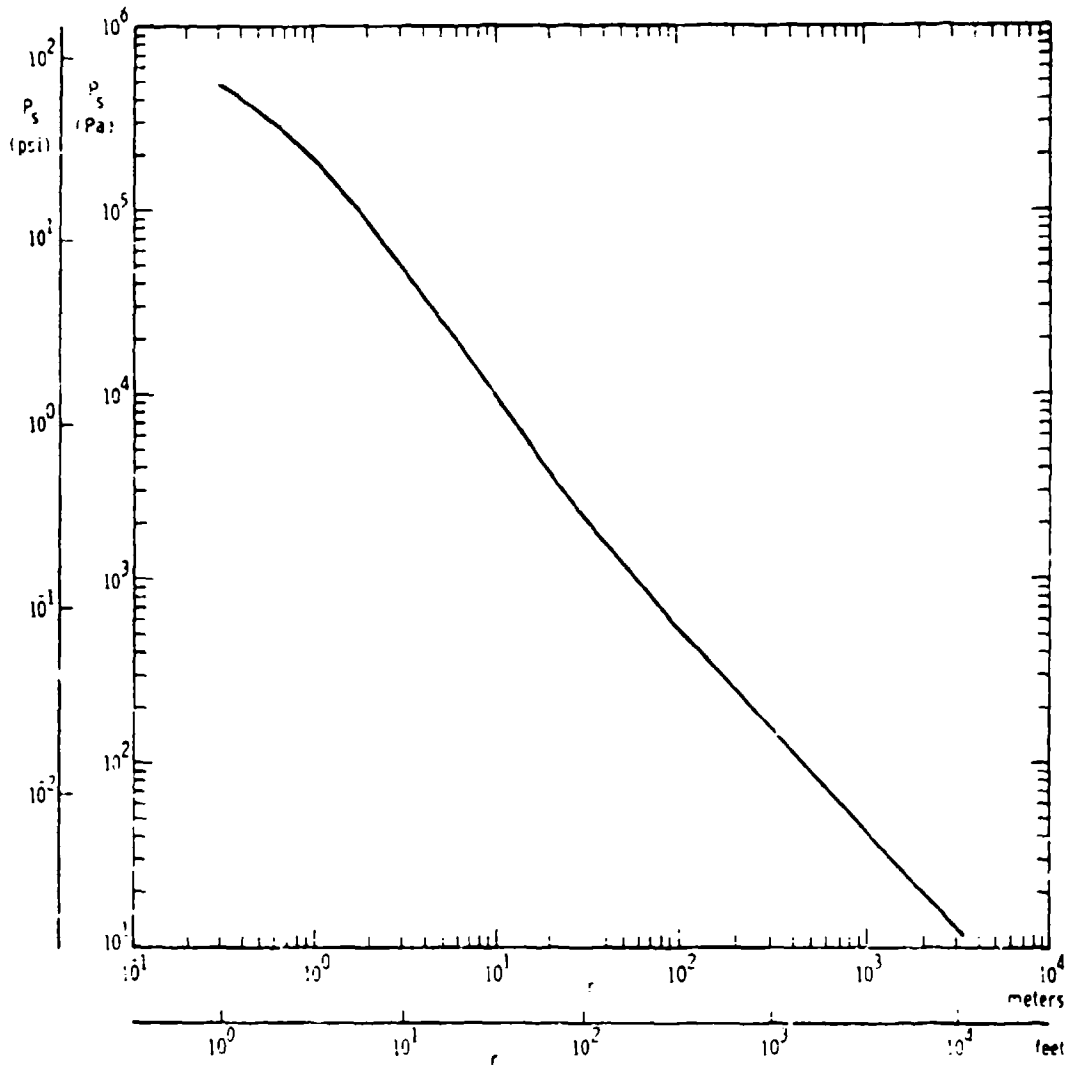
Figure 6-9. Overpressure Vs Distance for Pressurant
Tank Burst
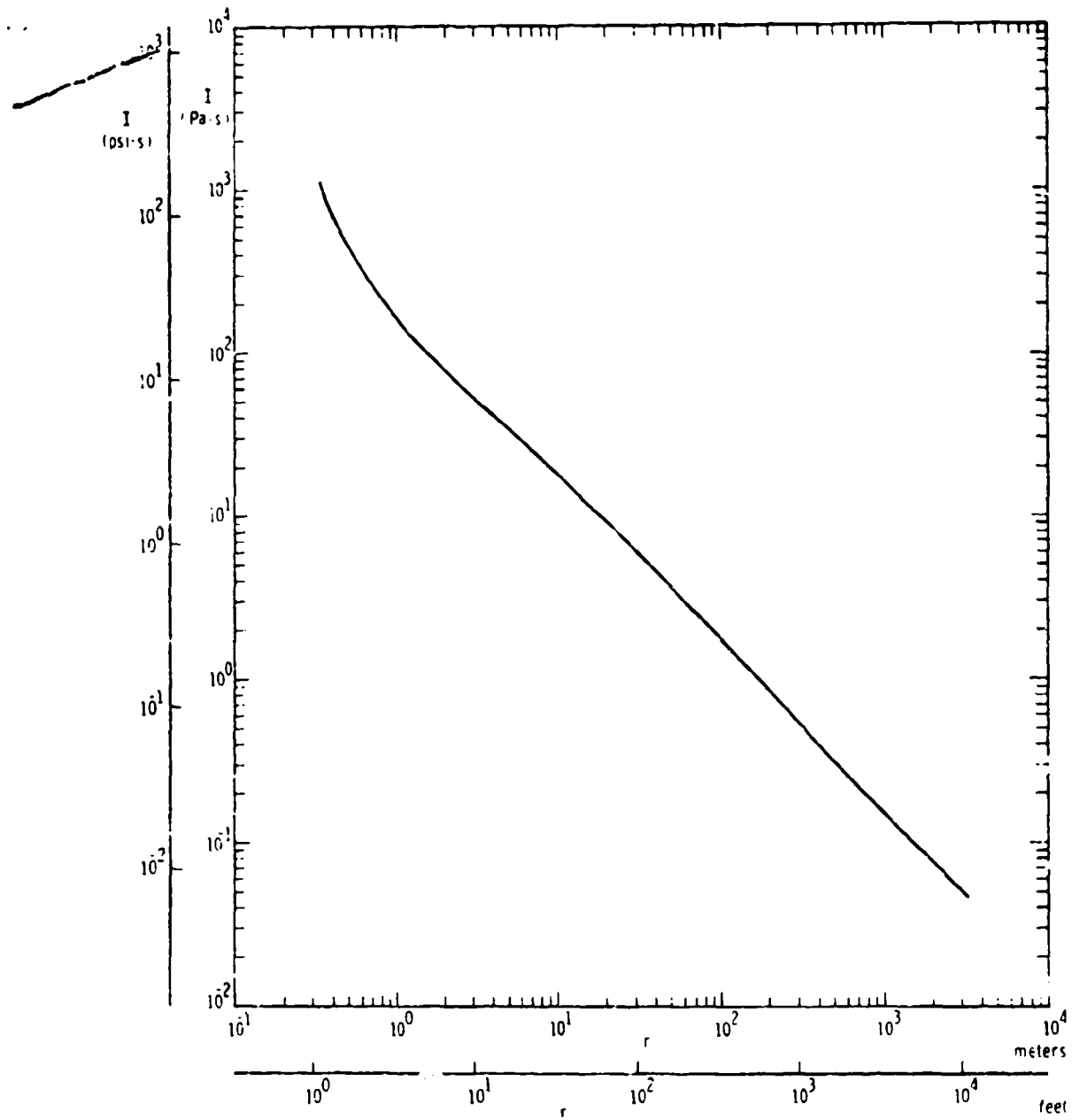
Figure 6-10.   Specific Impulse Vs Distance for Pressurant
Tank Burst

TABLE 6-27. BUILDING DAMAGE

Degree of Damage	Distance (m)	(ft)
threshold of minor structural damage	1.3	4.3
threshold of major structural damage	0.6	2
threshold of partial demolition	0.5	1.6

6-2.4.3   Effect of Blast Waves on Humans

The methods described in Section 3-2 are used to determine the effects of blast waves on humans.

Lung Damage

The $(P_s, \frac{I_s}{P_o^{1/2} m^{1/3}})$ points for selected values of R for Scenario #4 are included in Figure 6-5. Table 6-28 was obtained from this figure. The "1% survivability" limit cannot be determined, but it certainly lies within the gas vessel, and therefore is of no interest.

TABLE 6-28. LUNG DAMAGE

Chance of Survival	Distance (m)	(ft)
threshold of lung damage	1.2	3.9
99%	0.54	1.7
90%	0.48	1.6
50%	0.41	1.4
10%	0.35	1.1

Ear Damage

The (P_s, I_s) points for selected values of R for Scenario #4 are

included in Figure 6-6. Table 6-29 was assembled using this figure.
Although it is inadvisable to extrapolate the curves in Figure 6-6, one
can estimate values of R for "threshold of eardrum rupture" and "50%
eardrum rupture".

TABLE 6-29.   EAR DAMAGE

Degree of Damage	Distance (m)	(ft)
threshold of eardrum rupture	4(approx.)	13(approx.)
50% eardrum rupture	1.6(approx.)	5(approx.)
TTS	147	480

Skull Fracture

The $(P_s, \dfrac{I_s}{m^{1/3}})$ points for selected values of R for Scenario #4

could not be included in Figure 6-7. Because extrapolation is not recommended,
little information on safe stand-off distances (with respect to skull fracture)
can be obtained. It appears that distances greater than about 1 m (3ft) will
be safe for humans for this type of injury.

Body Translation and Impact

The $(P_s, \dfrac{I_s}{m^{1/3}})$ points for selected values of R for Scenario #4

could not be included in Figure 6-8. As above, it seems that a safe distance
for humans, considering whole body translation and impact, is about 1 m (3 ft).

6-2.4.4   Appurtenances

This vessel burst occurs in a laboratory. A reasonable object for an
appurtenance might be a hammer. This is grossly idealized as two vertical
cylinders, one on top of the other. The top cylinder, the head, has a radius
of 0.01905 m (0.75 in), a length of 0.1016 m (4.0 in), and a mass of 0.918 kg
(2.0 lb_m). The lower cylinder (the handle) has a radius of 0.01905 m (0.75 in),
a length of 0.254 m (10 in), and a mass of 0.679 kg (1.5 lb_m). The total
mass is 1.60 kg (3.537 lb_m), and the cross-sectional area facing the blast
wave A is 0.0135 m^2 (0.145 ft^2). C_D = 1.20. K = 4.

Then, $X = 0$, and $H = 0.01905$ m (0.06250 ft). Assume that the hammer is located 0.667 m (2.19 ft) from the center of the vessel. At this distance, $P_s = 2.74 \times 10^5$ Pa (39.7 psi), $\bar{P}_s = 2.7$, and $I_s = 275$ Pa · s (0.0399 psi · s)

For Figure 4-26, $\quad \bar{I}_s = \dfrac{C_D I_s A_o}{P_s(KH + X)}$

$$= \frac{(1.20)(275)(331)}{(2.74 \times 10^5)[4(0.01905) + 0]} = 5.23. \quad \text{From that graph,} \quad \bar{V} \approx 20.$$

Then $V = \dfrac{\bar{V} P_o A(KH + X)}{M a_o} = \dfrac{(20)(1.013 \times 10^5)(0.0135)[4(0.01905) + 0]}{(0.679)(331)} = 9$ m/s

(30 ft/s). A hammer can be thrown at a high enough velocity to be dangerous.

6-2.4.5 Effect of Fragments on Humans

The effect on humans of flying glass from windows broken by blast waves will be considered. In Scenario #1, it was shown that for injury from flying glass, $P_s = 9.45 \times 10^3$ Pa with the blast wave striking the pane of glass head-on, and $P_s = 1.96 \times 10^4$ Pa with the blast wave propagating in a direction parallel to the surface of the glass. From Figure 6-9, at a distance R less than 9.8 m (32 ft), there is likelihood of human injury by flying glass from windows normal to the direction of travel of the blast wave. The corresponding distance for windows parallel to the direction of travel is 5.9 m (19 ft).

A summary of damage and injury for Scenario #4 is given in Table 6-30.

6-2.4.6 Fragment Barrier

A metal sheet or plate can be used as a barrier to stop fragments from a bursting pressurant tank. It was found that the initial fragment velocity is 311 m/s. Assume that the barrier is close enough to the vessel that the fragment velocity does not decrease significantly before the fragment strikes the barrier.

For a barrier, assume a steel sheet or plate ($c_t = 7850$ kg/m^3, $\sigma = 3.11 \times 10^8$ N/m^2). The barrier may surround the vessel, but effects of curvature and oblique impact will be ignored.

TABLE 6-30.   SCENARIO 4:   DAMAGE TO STRUCTURES AND INJURY

Damage and Injury	Distance (m)	(ft)
10% survival (lung damage)	0.35	1.1
50% survival (lung damage)	0.41	1.4
90% survival (lung damage)	0.48	1.6
99% survival (lung damage)	0.54	1.7
mostly safe from skull fracture and mortality due to body impact	~1	~3
threshold of lung damage	1.2	3.9
50% eardrum rupture	~1.6	~5
threshold of eardrum rupture	~4	~13
threshold of injury from flying glass (face-on)	9.8	32
threshold of injury from flying glass (side-on)	5.9	19
threshold of side-on glass breakage	16	52
threshold face-on glass breakage	28	92
temporary threshold shift	147	480

The fragment mass is determined by choosing the 90th percentile of distribution of fragment mass (the mass which would equal or exceed the mass of 90% of the fragments). From Figure 4-55, the fragment mass is then 6.6 kg (15 lb$_m$). Assume that the fragment is a sphere of radius a.

$$a = \left(\frac{m}{c_p \frac{4\pi}{3}}\right)^{1/3} = \left(\frac{6.6 \text{ kg}}{4520 \frac{\text{kg}}{m^3} \frac{4\pi}{3}}\right)^{1/3} = 0.0704 \text{ m } (0.271 \text{ ft})$$

The nondimensional limit velocity is

$$\frac{c_p V_{50}}{\sqrt{\sigma_t c_t}} \quad \frac{(4520 \frac{\text{kg}}{m^3})(311 \frac{m}{s})}{\sqrt{(3.11 \times 10^8 \frac{N}{m^2})(7850 \frac{\text{kg}}{m^3})}} = 0.900$$

From Figure 5-1, h/a to stop the fragment is 0.23. Then h = 0.23, a = (0.23)(0.0704) = 0.016 m = 0.052 ft = 0.63 in.

A steel plate of 0.016 m (0.63 in) thickness would stop 50% of the fragments with the given initial velocity. Before such a barrier is used, the blast loading should also be determined.

6-2.5   Scenario #5.   Rotor Burst of an Aircraft Gas Turbine Running on a Test Stand

This problem is quite different from the previous four. It does not involve accidental explosions at all and is included to demonstrate the utility of some of the methods given in the workbook to safety problems other than the primary intended ones.

The problem is as follows: Predict the maximum range and terminal velocity for a fan blade fragment of a gas turbine engine assuming that the blade failure occurs at its connection to the rotor disk.

For Case I, assume the spinning blade leaves through the engine inlet with a deflection that tips it into the horizontal plane within an initial trajectory greater than 33°, with no loss of kinetic energy. Although the twist in blade may not contribute to the assumption of lift forces, assume that the blade is a spinning body or deformed into a boomerang-like shape. Identify the angle-of-attack and trajectory angle for maximum fragment range.

For Case II - The fan blade is deflected and deforms by curling into a cylinder or sphere-like shape upon leaving the inlet to the gas turbine with

a loss of 10% of the translational kinetic energy. In this case, predict the maximum possible range and terminal velocity using drag coefficients for a cylinder or sphere.

Fragment characteristics are as follows:

Geometrical shape (see Fig. 6-11)	
Rotational kinetic energy	= 17,400 J
Translational kinetic energy	= 260 J
Mass	= 0.5 kg
Fan blade tip speed	= 393 m/s
Fan speed	= 123.1 RPS
Fan jet velocity	= 255 m/s
Location of fan blade center of gravity (CG) from C_L of engine	= 0.342 m
Location of fan blade CG from failure	= 0.116 m

These types of jet engine rotor failures have occasionally occurred during takeoff and climb-out. Some have also occurred on static jet engine test stands. Documented evidence shows that trajectories have been as much as 57° forward, relative to the plane of failure for fan rotors. Containment barriers cannot be provided at the inlet of engines on static test stands without upsetting inlet performance data. Thus, it becomes important to identify hazards to people and risk of damage to facilities for such failures.

Case I was run under two sets of assumptions. Since FRISB was written for "disc" fragments, it was necessary to assume that the blade curled into a disc shape. The planform area of the blade fragment was set equal to the surface area of a representational disc. The planform thickness of the blade as viewed from the front was set equal to the thickness of a representational disc. The optimal lift coefficient for a circular wing (C_L = 0.32) was taken, assuming gyro stability for the circular disc and assuming a constant angle of attack. A drag coefficient of 0.85 was obtained from tables relating drag coefficient to the thickness-to-diameter ratio of a plate-shaped fragment.[6] The area over which pressure drag acted was taken as the thickness times the diameter of the representational disc. The initial velocity of the disc was assumed to be the initial translational velocity of the fragment. The rotational velocity of the fragment only contributes to the gyro stability of the disc. Results were obtained from the spectrum of initial trajectory angles from 30 to 70° in five-degree intervals. The results given in Table 6-31 are for the maximum range obtained.

As a check on the results obtained for Case I under the assumptions of the disc geometry, the trajectory characteristics of the fragment were determined under a different set of assumptions relating to lift. For these

"thrust ' assumptions, the blade was assumed to spin about an axis normal to its planform area, producing a thrust like a helicopter rotor blade, and thus lift. All other sources of lift were ignored. The fragment was approximated from drawings to have the shape of a NACA 4412 air foil. The rotational kinetic energy contributing to the thrust is assumed to dissipate as a result of pressure drag forces as a function of the average linear velocity of the blade in rotation. The rotation of the blade contributes only to lift. The initial velocity of the blade is the initial translational velocity as in the disc case. The drag resulting from the translational velocity of the blade acts to dissipate the translational kinetic energy.

For Case II in which no lift is considered, the fragment was assumed to deform into a cylindrical shape, and a pressure drag coefficient of 0.85 was used (which is approximately correct for cylindrical fragments traveling at Mach numbers less than $1/2$). Trajectory differential equations were solved both by the use of Runge-Kutta techniques and the time interval perturbation technique as of Zaker.[7] Results were the same. Predictably, for the no lift case the maximum range is less than for the case where lift is assumed. The terminal velocity is also slightly less. See Table 6-31.

TABLE 6-31

	α_i deg	R_m m	V_t m/s	β deg
Case I				
Disc	37.5	110	29.0	38
Thrust	40	97	27.9	24
Case II				
No lift	45	84	27.0	47

Table 6-31 and Figure 6-11 show the results of predictions obtained for both cases for the optimum initial trajectory angle α_i and under various assumptions to be described. The maximum range in meters R_m is given, as well as the terminal velocity V_t in meters per second, and the terminal ballistic angle of attack in degrees β. From the table it may be seen that the maximum range expected under any of these sets of assumptions is 112 meters (367 ft) and the terminal velocity is only slightly less than the initial translational velocity of 30 meters per second (98 ft/sec). To put the damage potential of this fragment in perspective, a spherical fragment having the same mass with this terminal velocity could penetrate a 0.6-mm-thick (.0236 in) steel plate or a 1.6-mm-thick (.0629 in) aluminum plate.
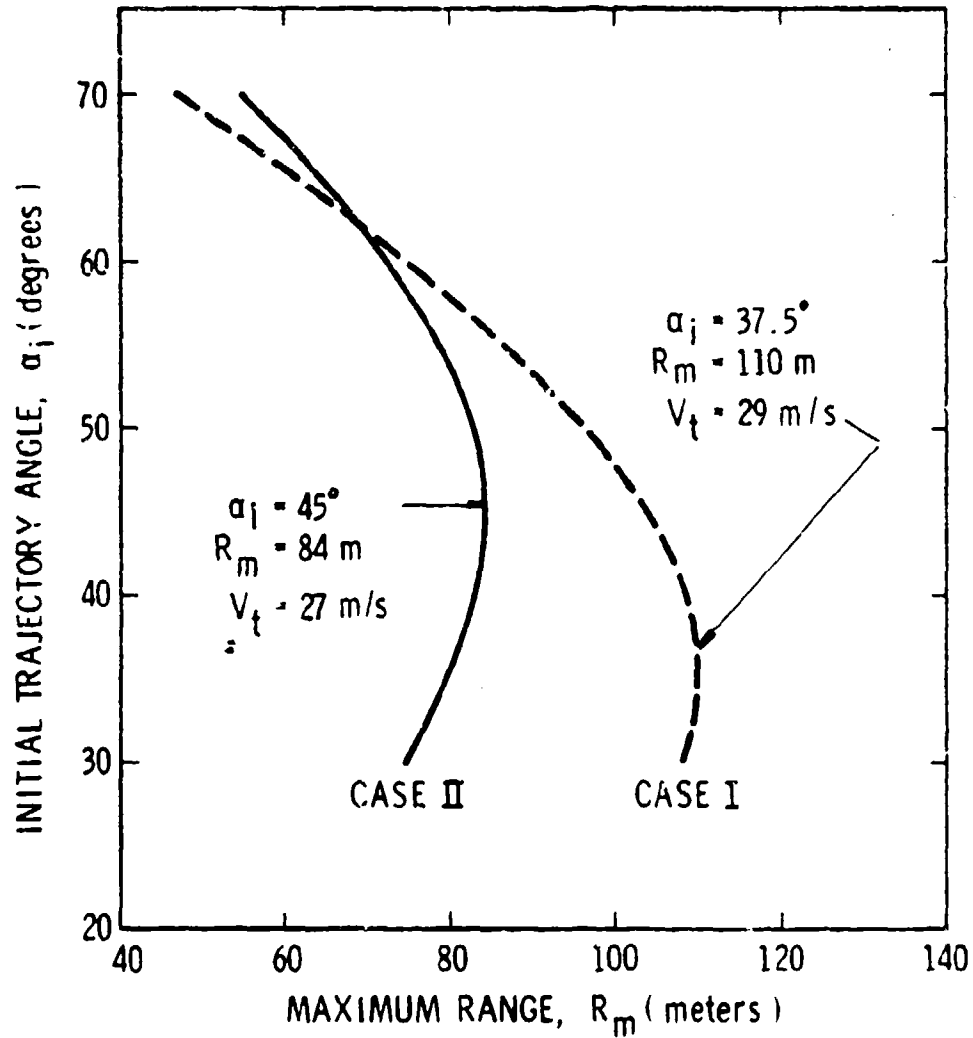
Figure 6-11. Maximum Range as a Function of Initial
Trajectory Angle, Cases I and II, Turbine
Rotorblade Example

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CHAPTER VII

DISCUSSION OF RESULTS

Chapters 1 through VI in this workbook give a number of simplified prediction methods which hopefully can be used by a typical safety engineer to estimate damaging effects for certain classes of accidental explosions in aerospace launch facilities and flight vehicles. All prediction methods employ relatively simple graphs or equations, and require at most the use of a desk calculator or slide rule to make estimates. Example calculations are given in each chapter to illustrate use of the graphs.

Generally, the first step in predicting the effects of an accident is to estimate the total explosive yield or energy. For accidents involving the liquid propellants commonly used in rocket vehicles, a number of curves are presented in Chapter I for prediction of explosive yields given the propellant mixture and type of postulated accident. These graphs are based primarily on scaled results from Project PYRO tests, with upper limits established by other related work. This chapter also contains scaled graphs for estimating explosive energy release for gas vessel bursts, given the vessel characteristics and size, type of gas, and initial conditions. These graphs are based primarily on computer code solutions rather than experimental data.

Once explosive yields or energies are estimated from Chapter I, they can be used as inputs to graphs in Chapter II to obtain predictions of blast wave characteristics over a range of distances from the explosive sources. The primary blast wave properties included in Chapter II are side-on peak overpressure P_s and side-on impulse I_s, although we include discussions of other properties such as reflected peak overpressure P_r and time histories of drag pressure q. Again, blast data for liquid propellants are based primarily on experiment, while data for bursting gas vessels are estimated from computer code solutions for such waves.

Chapter III is devoted to prediction of damaging effects of blast waves, and is designed to give such predictions once blast pressures and impulses are known. The chapter therefore contains a number of scaled P-I (pressure-impulse) curves which are associated with various levels of damage or injury to a variety of structures, structural elements, and people. From different graphs, one can estimate minor damage through complete collapse of residences, threshold for glass breakage, incipient damage to beams or plates, and incipient toppling or overturning of a vehicle. Probability of injury or mortality of people can be predicted

from other scaled graphs. These give estimates of threshold of ear damage, various probabilities of mortality as functions of size of an individual as well as blast wave properties, tertiary blast damage from individuals being tumbled by a blast wave, and probability of injury from flying glass from windows destroyed by blast waves. The prediction methods for blast damage to structures are based on bomb damage studies from World War II. and a variety of other analytic and experimental sources. Extensive work by Lovelace Foundation over a number of years is the primary basis for the estimates of injury and mortality to people.

Knowledge or estimate of some of the general characteristics of vessels involved in accidental explosions, and explosive yield estimates from Chapter I, will allow one to estimate characteristics of fragments generated by these xplosions. The first set of graphs allows estimation of fragment initial velocities. These, and fragment mass and shape distributions, allow use of other graphs to predict fragment terminal velocities and impact conditions. Finally, several curves give probability of fragment arrival versus range. Most of the predictions from this chapter are statistical functions because of the inherent statistical nature of fragmentation. The graphs for fragment initial velocities are based on exercise of computer program developed under this contract and a previous one, supported by limited experimental data. Graphs for mass and shape distributions of fragments are, on the other hand, based entirely on fits of statistical functions to experimental "missile maps".

Once fragment impact conditions are known, one should then be able to estimate effects of such impacts on structures, facilities and people. Chapter V provides data for making some such predictions. These include incipient damage to light structures or panels, and blunt object impact injury to people. Some data on thresholds of penetration of light panels are also given. This part of the workbook is, because of lack of sufficient experimental data or analyses, and in some instances the classified nature of fragment impact effects on humans, less complete than other chapters. Some of the graphs for impact damage are based on tests and analysis of what one might think to be an unrelated field. i.e., hail damage to aircraft and ground structures.

The sixth chapter includes a brief discussion of the more complete field of risk assessment, of which damage estimation is a part. We point out that a more complete analysis is needed if one is to estimate the probability of an accident occurring, which type of accident is more probable than another, etc. Most of Chapter VI is devoted to a series of illustrations of use of the methods of Chapters I through V in predicting both blast and fragmentation effects for five accident "scenarios". The five postulated accidents include several which could occur during launch or flight of multi-stage rocket vehicles, or during test of components in

a test bay or laboratory. Hopefully, study of these examples should lead the reader through the workbook methods for reasonably complete estimates of effects of certain accidents, as opposed to calculation of separate parts of the effects given in previous chapters.

Throughout the workbook, the "tolerances", or possible errors, involved in various calculations are indicated. These are included in various ways, such as error bands about groups of measured data, a range of probabilities of mortality or fragment impact, etc. A wide error band indicates either large inherent spread of data or considerable uncertainty in the method of estimation because it has not been validated by experiment. Factors of safety are not included as such, although use of upper bounds to loading parameters such as blast pressure and impulse or impact velocities of fragments will assure conservation.

CHAPTER VIII

CONCLUSIONS

Some conclusions can be drawn regarding the applications of this workbook, and limitations to its use. These are discussed in this brief chapter.

It is possible using methods given in the workbook to make reasonable estimates of blast wave characteristics over a wide range of distances from the source of the accident. These characteristics can then be used to predict damage to structures, for a number of types of structures and damage modes, and can also be used to predict various levels of injury to and probability of mortality of humans. Confidence in blast damage and injury prediction is good, given knowledge of the blast wave properties, because of extensive past testing and analysis. The blast damage prediction methods are cast in a format which allow their use for other types of explosions.

Prediction methods are given for estimating initial velocities, ranges, masses, and impact conditions for fragments generated by propellant explosions and gas vessel bursts. The methods for predicting initial velocities are reasonably well founded on theoretical analyses and experimental data, and apply over a wide range of simulated burst conditions. Methods for predicting fragment ranges and impact conditions have a good theoretical basis, and can be used for other predictions involving flight through the air of high-velocity objects. Such predictions can be made for objects launched over a very wide range of initial Mach numbers. Methods for predicting fragment mass and shape distributions are entirely based on statistical fits to quite limited data, and therefore involve considerable uncertainty, as well as being impossible to accurately extrapolate.

Some predictions can be made of fragment impact effects on structures and structural elements from graphs and equations given in the workbook. These effects are much less well-known than are blast effects, so only limited predictions are possible. Some effects of fragment impact on humans can also be predicted, but these predictions are limited by security restrictions on wounding potential of fragments. Throughout the workbook, limitations such as this are noted when they are known.

This workbook is hopefully presented in a manner which allows easy use by typical safety engineers. For readers who are interested in the detail behind the relatively simple equations or graphs used to make predictions, a number of detailed appendices are included in appropriate

chapters. We believe that the workbook is the first to provide safety engineers with relatively simple estimates of blast and fragment hazards for accidental explosions in liquid-propellant fueled flight vehicles.

As noted before, some parts of the workbook have wider potential application than explosive hazard prediction for liquid-fueled rockets. The sections on fragment trajectory prediction, or the associated computer programs, can be used to predict ranges and impact conditions for many types of fragments or objects thrown into the air. The sections on blast effects apply for blast loads from any source. The methods for estimating fragment impact damage, though limited, are independent of the sources of these fragments or impacting objects.

8-2

CHAPTER IX

RECOMMENDATIONS

This workbook will allow prediction of blast and fragmentation effects for a wide variety of explosive accidents which could occur at aerospace launch and test facilities. It is based on a rather exhaustive review of existing test and accident data; analyses of blast and shock wave physics and effects of such waves on objects and humans; and analyses of fragment velocities, trajectories, impact conditions, and effects of impacts. A number of supporting studies have been made in generating relatively simple application formulas or graphs - these are reported in appropriate appendices.

The bases for the prediction methods given in this workbook range from a firm foundation of extensive testing and analysis, through analyses supported by limited testing or accident reporting, to some predictions which are quite speculative because of little or no corroborating evidence. Predictions in the latter case could often be improved by additional research. Also, some of the methods which have been developed here have potentially wide application to problems in hazards prediction other than explosive effects for flight-weight aerospace vehicles. We therefore give in this short chapter a list of recommendations for areas in which we feel there is a need for additional testing, analysis, or correlation of prediction methods.

Some of these areas are:

(1)   Definition of fragmentation characteristics for bursting gas storage bottles. Existing data consist of only five tests for two bottle geometries, one material, and one gas. There are no reliable "missile maps" for such bursts. Curves for fragment range presented in the workbook are based on computer-generated predictions, which should be validated by test.

(2)   Definition of blast wave characteristics for burst of cylindrical gas storage vessels, either analytically or experimentally. Present methods are limited to essentially spherically symmetric cases.

The analysis in this workbook is based upon data generated by a computer program. It has been confirmed to some extent by experimental data, but more experiments are needed. More work must be done to determine specific

impulse versus distance for gas vessel bursts. Then, a good nomograph should be developed.

The effects of changing the vessel shape from spherical to cylindrical should be investigated, both theoretically and experimentally.

In this analysis of the blast wave, the energy required to burst a pressure vessel and accelerate the fragments was neglected. Analytical and experimental studies would allow this effect to be included in the calculation of the blast wave parameters.

(3)   This workbook deals with very particular types of fragments and targets. The analysis should be extended to include shapes of fragments other than spherical and targets other than metal sheets and plates.

Targets that might be studied include wood, concrete, brick and glass. Also, it may not be desirable to treat the side of a fuel tank as an unsupported metal sheet or plate. There is probably some effect of the liquid, and one is concerned with the possibility of a fragment igniting a fuel tank, in addition to only puncturing it.

Oblique impacts by fragments deserve more study, and the effects of the strength of fragments is presently unknown. A model-scale experimental program is recommended to fill this void.

(4)   We recommend extension of the present work to accidental explosions in thick-walled storage vessels typical of ground transport and storage vessels. The current work is directed toward explosions of flight-weight hardware. Blast and fragmentation characteristics can be drastically different for heavier vessels, and consequently, so can the effects on structures, facilities, vehicles and humans. Included in this work should be exercise of the SPHER and CYLIN codes for typical initial conditions for massive vessels.

(5)   The analyses used to develop scaled curves for fragment range and impact conditions, for both lifting and drag-type fragments, have potentially wider application than generation of some of the scaled curves of Chapter IV. We

2

recommend that those programs be used to develop more nomographs which include other parameters such as initial altitude of an explosion, flight velocity as a function of this altitude, and additional mass to area ratios typical of ground storage vessels. We also recommend that the programs be used for other types of accidents involving high-velocity missiles or fragments such as the pieces from a turbine rotor burst postulated in the fifth application problem in Chapter VI.

(6) The existing codes for predicting initial fragment velocities are limited to one space dimension and time (1-D codes). We recommend the development of a limited 2-D code for cylinder fragmentation, based on a combination of the assumptions inherent in the FRAG-2 and CYLIN codes used in this workbook. Such a code should more accurately predict initial fragment velocities for real vessels, but would certainly be more complex and more expensive to run than either of the existing codes.

(7) As a part of studies of accidental explosions of thick-walled vessels, we recommend a literature search for tests or accident cases, where data on projection of large parts of tanks could be compared with predictions from FRAG-2, which assumes that a tank separates into two pieces which are propelled by the exhausting fluids. Rail tank car accident reports, and burst tests of tank cars conducted at White Sands Missile Range, would perhaps be appropriate sources of such data.

(8) We recommend using the programs for prediction of fragment ballistics to generate tables for range and terminal impact conditions, such as was done in a limited sense for fragments from bursting gas spheres in Chapter IV. These predictions would supplement, or could conceivably supplant, missile map data for this class of explosion.

The specific recommendations listed before can be supplemented by a last general recommendation. This workbook contains, we believe, the most accurate assessments which can be made based on the current state of the art. In almost all areas covered, either ongoing or future studies may well alter the prediction methods, or the results of applying the prediction methods. The workbook is so organized that alterations or modifications can be made to individual chapters, without a complete revision of the entire book. It is strongly recommended that revisions be considered on some regular schedule, say at two-year intervals.

LIST OF SYMBOLS

A, B, C, D — terms in equations for bursting vessel motion

A — presented target area

— area of an object presented to the blast front

— planform or top surface area of fragment

— cross-sectional area of a fragment along its trajectory

— mean presented area of object

$\overline{AD}$ — average drag area

$\overline{AL}$ — average planform area

A_f — fragment area

A^1 — geometric mean frontal area of glass fragment

a — radius of a fragment

— airfoil curve slope

a_* — critical sound speed in mass flow equation

a_o — ambient sound velocity

a_{oo} — sound speed in confined gas, $\tau = 0$

b — vehicle track width or depth of target base

— number of rotor blades

C_D, C_d — drag coefficient

C_L — lift coefficient

C_l — cylinder length

C_t — cylinder thickness

$C(\tau)$ — mass of gas confined at high pressure as a function of time

LIST OF SYMBOLS (Cont'd)

D_p -   profile drag

d -   diameter of fragment

    -     width of fragment segment

E -   modulus of elasticity

    -     effective blast energy

    -     bulk modulus

E_l -   end cap length

E_t -   end cap thickness

e -   stored energy ratio

F -   fragment projected area

g -   nondimensionalized displacement of a fragment

    -     acceleration of gravity

H -   minimum transverse dimension at location of largest presented area of object

h -   thickness of a target, glass, or plate

    -     sphere wall thickness

    -     segment height

I -   mass moment of inertia of rotor

$\bar{I}$ -   nondimensional specific impulse

I_d -   total drag and diffraction impulse

I_s -   incident specific impulse

$\bar{I}_s$ -   nondimensional incident specific impulse

$\bar{i}$ -   initial trajectory angle of the fragment

i -   side-on impulse

I	-	threshold impulse
K	-	adiabatic exponent (ratio of specific heats)
	-	constant (4 if appurtenance is on the ground and 2 if appurtenance is in air)
	-	value from the normal distribution table
k	-	mass flow rate coefficient
L	-	cylinder length
L/D	-	length-to-diameter ratio
M	-	mass of fragment; of contained gas
$\overline{M}$	-	average mass
M_i	-	fragment mass
M_t	-	cylindrical shell mass
m	-	total mass of target; of fragment
n	-	number of fragments
P	-	pressure of confined gas
	-	crack perimeter about a fragment
$\overline{P}$	-	nondimensional pressure
P_e	-	peak overpressure
P_o	-	pressure of confined gas at any instant
P_{oo}	-	initial pressure of confined gas
P_r	-	threshold applied maximum reflected pressure
	-	reflected peak overpressure

P_r -   peak reflected pressure

P_s -   peak side-on overpressure

$P_{\ast}$ -   nondimensional pressure

p_o -   ambient air pressure

$p(t)$ -   net transverse pressure

Q -   peak dynamic pressure

     -     peak dynamic overpressure

R -   gas constant

     -     sphere radius before burst

     -     radius of rotor

     -     initial cylinder radius

r -   distance from center of a vessel

     -     cylinder radius

     -     disc radius

     -     fragment displacement at any instant

SE -   strain energy stored in vessel

s -   estimate for the standard deviation

s -   segment length

T -   duration of the positive phase of the blast wave

     -     temperature

T_o -   temperature of confined gas at any instant

T_{00}	-	temperature
t	-	thickness of fragment; disc; window pane
t_a	-	time of arrival
t_h	-	shell thickness
U	-	shock velocity
U_s	-	peak particle velocity
V	-	velocity of fragment
	-	volume
$\overline{V}$	-	nondimensional velocity
	-	initial velocity ratio
V_c	-	rotor blade velocity along rotational axis
V_i	-	volume of the vessel before it bursts
	-	initial fragment velocity
V_{in}	-	induced velocity from thrust
V_o	-	volume of confined gas at any instant
V_s	-	volume of shell material
V_t	-	tip velocity of rotor
V_{50}	-	ballistic limit velocity
W	-	effective mass of propellant
$\overline{W}$	-	mean mass
W_T	-	total mass of propellant and oxidizer
w	-	crack width

LIST OF SYMBOLS (Cont'd)

X   -   displacement of an object

     -      distance from the front of object to location of largest cross-sectional area

     -      the distance from the front of the object to the plane facing the approaching blast wave

$\dot{X}$ -   horizontal velocity

$\ddot{X}$ -   horizontal acceleration

x   -   short halfspan

     -      nondimensionalizing constant for displacement

Y   -   terminal blast yield

$\dot{Y}$ -   vertical velocity

$\ddot{Y}$ -   vertical acceleration

y   -   edge length

     -      long half span

α -   nondimensional constant

α_i -   initial trajectory angle

β -   nondimensional constant

δ -   permanent deflection of target at point of impact

Δt -   time increment

θ -   nondimensionalizing constant for time

ϕ -   angle of attack of disc

     -      angle subtended at the center of the cylinder by a fragment

LIST OF SYMBOLS (Cont'd)

κ — ratio of specific heats for confined gas

κ — ratio of specific heats for confined gas

ν — Poisson's ratio for the material

ξ — nondimensionalized time

ρ — density of glass, air

ρ_o — confined gas density at any instant

ρ_p — density of a fragment (or projectile)

ρ_r — density of fragment

ρ_s — density of shell material

— peak density in shock wave

ρ_t — density of target

ρ_* — critical density of gas in mass flow equation

σ_t — yield stress of target material

σ_y — yield stress of glass; plate

— stress in container wall

τ — time

ϕ_i — impulse shape factors

ϕ_p — pressure shape factors

ω — angular velocity

CONVERSION FACTORS

The following table provides multiplying factors for converting numbers and miscellaneous units to corresponding new numbers and SI units.

The first two digits of each numerical entry represent a power of 10. An asterisk follows each number which expresses an exact definition. For example, the entry "—02 2.54*" expresses the fact that 1 inch = 2.54×10^{-2} meter, exactly, by definition. Most of the definitions are extracted from National Bureau of Standards documents. Numbers not followed by an asterisk are only approximate representations of definitions, or are the results of physical measurements.

To convert from	to	multiply by
atmosphere	newton/meter^2	+05 1.013 25*
bar	newton/meter^2	+05 1.00*
British thermal unit (mean)	joule	+03 1.055 87
calorie (mean)	joule	+00 4.190 02
dyne	newton	—05 1.00*
erg	joule	—07 1.00*
Fahrenheit (temperature)	Celsius	$t_c = (5/9)(t_F - 32)$
foot	meter	—01 3.048*
inch	meter	—02 2.54*
lb$_f$ (pound force, avoirdupois)	newton	+00 4.448 221 651 260 5*
lb$_m$ (pound mass, avoirdupois)	kilogram	—01 4.535 923 7*
pascal	newton/meter^2	+00 1.00*
pound force (lb$_f$ avoirdupois)	newton	+00 4.448 221 615 260 5*
pound mass (lb$_m$ avoirdupois)	kilogram	—01 4.535 923 7*
poundal	newton	—01 1.382 549 543 76*
slug	kilogram	+01 1.459 390 29

To convert from	to	multiply by
foot/second^2	meter/second^2	-01 3.048*
inch/second^2	meter/second^2	-02 2.54*
gram/centimeter^3	kilogram/meter^3	$+03$ 1.00*
lb$_m$/inch^3	kilogram/meter^3	$+04$ 2.767 990 5
lb$_m$/foot^3	kilogram/meter^3	$+01$ 1.601 846 3
slug/foot^3	kilogram/meter^3	$+02$ 5.153 79
lb$_f$/foot^2	newton/meter^2	$+01$ 4.788 025 8
lb$_f$/inch^2(psi)	newton/meter^2	$+03$ 6.894 757 2
foot/second	meter/second	-01 3.048*
inch/second	meter/second	-02 2.54
foot^3	meter^3	-02 2.831 684 659 2
inch^3	meter^3	-05 1.638 706 4*

GLOSSARY OF TERMS

Air-embolic insult - air bubbles circulating in the blood which can contribute to the collapse of the heart.

Angle of attack - angle between fragment horizontal axis and the relative wind vector.

Applied impulse - actual impulsive loading applied to a "target".

Appurtenance - a piece of equipment or an object located near a source of an explosion, which can be accelerated by the blast wave from the explosion.

Blast yield - energy release in an explosion inferred from measurements of the characteristics of blast waves generated by the explosion.

Blunt trauma - injury caused by a nonpenetrating object.

Burst pressure - the pressure at which a gas storage vessel bursts or fails.

CBGS - Confined by Ground Surface. This abbreviation designates a liquid propellant explosion occurring on the ground after spill and mixing.

CBM - Confined by Missile. This abbreviation designates an explosion within the tankage of a liquid propellant vessel or rocket.

Critical threshold impulse - blast wave impulse which determines the impulse asymptote for an isodamage contour.

Drag coefficient - ratio or drag force to dynamic force exerted by wind pressure on a reference area.

Edema - abnormal accumulation of fluid in connective tissues causing local swelling.

Energy of detonation - the energy in an explosion which drives a blast wave.

Event tree - a method employed in risk assessment for systematic estimation of consequences of an accident.

Explosive yield - energy released in an explosion, often expressed as a percent or fraction of energy which would be released by the same mass of a standard high explosive such as TNT.

FMECA - abbreviation for Failure Mode Effects and Criticality Analysis. A systematic procedure for identifying failure modes of a system and for evaluating consequences of failures.

Fall-back - an accident in which a launch vehicle settles or falls back to earth in initial stages of launch.

Fault tree - a method employed in risk assessment for determining probabilities for event trees (see event tree).

Fibrotic foci - fine scars of the lungs.

Free-field impulse - see side-on impulse.

Free-field pressure - see side-on overpressure.

HVI - High Velocity Impact. This abbreviation designates a liquid propellant explosion occurring after a vehicle with unburned propellant impacts the earth at relatively high velocity.

Ignition time - time after beginning of an accident involving liquid propellants at which initiation of an explosion occurs.

Induced velocity - velocity along rotor axis, induced by thrust generated by the whirling blade.

Initial trajectory angle - angle of fragment's horizontal axis relative to the ground surface at the beginning of the flight.

Isodamage line - Loci of combinations of overpressure and impulse which produce the same level of blast damage to a given "target".

Lift coefficient - ratio of lift force to dynamic force exerted by wind pressure on a reference area.

Limit velocity (V_{50}) - impact velocity, for a fragment or missile striking a target, at which 50% perforations occur.

Major structural damage - damage to a residence involving partial or total collapse of roof, partial demolition of one or two external walls, or severe damage to load-bearing partitions requiring replacement.

Minor structural damage - damage to a residence involving window breakage and wall and support cracking.

Overpressure - pressure in a blast wave above atmospheric pressure.

Partial demolition - damage to a residence in which 50% to 75% of the external brick work is destroyed, or the building is rendered so unsafe that it must be demolished.

Planform area - the area viewed by looking down on the fragment - top surface area.

Plate aspect ratio - ratio of length to width for a rectangular plate.

Projected area - area of fragment viewed perpendicular to the top surface area.

Pulmonary hemorrhage - internal bleeding occurring in the lungs.

Reflected impulse - integral of reflected pressure-time history.

Relative wind vector - vector along which the fragment flies.

Side-on impulse - integral of time history of side-on overpressure.

Side-on overpressure - blast wave overpressure in an undisturbed blast wave.

Standoff distance - distance from center of an explosion.

Temporary threshold shift - the case where 90 percent of those exposed to a blast wave advancing at normal angle of incidence to the earth are not likely to suffer an excessive degree of hearing loss.

Terminal yield - blast yield from measurements made far enough from an explosion that the waves are similar to those generated by a specified mass of TNT.

Threshold bending impulse - blast wave impulse which produces an incipient bending failure.

Threshold membrane impulse - blast wave impulse which produces an incipient stretching failure.

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