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#### WORKBOOK FOR ESTIMATING EFFECTS OF ACCIDENTAL EXPLOSIONS IN PROPELLANT GROUND HANDLING AND TRANSPORT SYSTEMS

W.E. Baker, et al

Lewis Research Center San Antonio, Texas

Aug 78

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## NASA Contractor Report 3023

# Workbook for Estimating Effects of Accidental Explosions in Propellant Ground Handling and Transport Systems

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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. T. R. Jackson, for assistance in debugging and running the complex TUTTI computer program for calculating two-dimensional blast wave properties.
- Ms. Deborah J. Stowitts, for organizing and editing the report.

We also gratefully acknowledge the help of Dr. Del Lehto, Naval Surface Weapons Center, White Oak Laboratory, for providing the TUTTI code documentation, and consulting on its use.

The technical support and guidance of our project manager at the NASA Lewis Research Center, Mr. Paul M. Ordin, contributed materially to the success of this work. In particular, he provided excellent technical guidance throughout the contract, and also provided several excellent accident reports as input data for fragment characteristics in Chapter IV.



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#### SUMMARY

This workbook is a supplement to an earlier NASA publication, NASA CR-134906, which is intended to provide the designer and safety engineer with rapid methods for predicting damage and hazards from explosions of liquid propellant and compressed gas vessels used in ground storage, transport and handling. As in the earlier workbook, information is presented in the form of graphs and tables to allow easy calculation, using only desk or handheld calculators. When complex methods have been used to develop simple prediction aids, they are fully described in appendices.

Topics covered in various chapters are:

- (1) Estimates of explosive yield
- (2) Characteristics of pressure waves
- (3) Effects of Pressure waves
- (4) Characteristics of fragments
- (5) Effects of fragments and related topics

A short concluding chapter gives a general discussion and some recommendations for further work.

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WASA CR-134906. For the microfiche of NASA CR-134906, please refer to N76-19296.

#### INTRODUCTION

#### General Discussion

This workbook is a companion to an earlier NASA workbook [Baker, et al (1975)], NASA CR-134906, which was prepared to aid designers and safety engineers in predicting damage and hazards from accidental explosions involving liquid propellants and compressed gases in flight hardware. This book, in contrast, is devoted to blast and fragment hazards for the same classes of accidental explosion sources in propellant ground handling and transport systems. Prediction methods which were thoroughly covered in the earlier workbook and which apply without change will not be repeated here. Instead, explosion hazards peculiar to ground storage and transport systems, or ranges of input parameters specific to these systems, will be emphasized. For completeness, the reader should use the earlier workbook in conjunction with this one.

A microfiche supplement of the workbook is attached to the back cover for the convenience of the reader.

#### Nature of the Hazards

The general nature of the hazards from accidental explosions in propellant and industrial gases ground handling systems is similar in many respects to the hazards which occur in such explosions in flight vehicles. These accidents cause damage by air blast loading, fragment or appurtenance impact, radiation from fireballs, or fire from ignition of combustible materials following an explosion. Damage can occur to buildings and other facilities, vehicles, and flora and fauna--including humans. Depending on the severity, type and location of an explosion accident, the damage can range from minor to extensive.

The sequences of events or causes of accidental explosions in ground handling systems for liquid propellants and compressed gases can be quite similar to those which can occur in flight vehicles, or can differ markedly. Failure by material fatigue on overstress can occur in either case. But, many of the possible causes of flight vehicle explosions such as loss of thrust during launch, guidance system failure, or rupture of a bulkhead separating a fuel from an oxidizer, are inapplicable for ground handling systems. Conversely, transportation accidents followed by explosions are causes which are absent in flight vehicle accidents.

Ground handling systems usually have less serious weight constraints than do flight vehicles. This difference dictates some of the differences in the nature of the hazards. Ground sys-

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tems can employ relatively massive, ductile materials in pressure vessel and piping construction. On failure, such vessels generate relatively few fragments compared to similar failures in flight-weight vessels. A failure of a long cylindrical vessel near one end can often result in most of the vessel remaining intact, and "rocketing" as the internal compressed fluid is ejected from the rupture. This mode of failure has never been observed in flight-weight pressure vessels or tankage, which have less ductility and instead break into a relatively large number of fragments. Pressure vessels used in ground systems are often of much larger capacity than flight systems. The total stored energy in compressed gases or total chemical energy in stored fuels and oxidants can then be much greater than for many flight systems.

Unfortunately, many more accidental explosions have occurred involving fuels and compressed fluids in ground handling than in flight vehicles. There is a considerable body of accident report literature [see, for example, Strehlow & Baker (1975, 1976)] which highlight the probable types of accident. These are (not necessarily in order of probability):

- 1) Simple pressure vessel failure because of fatigue or flaw growth.
- Vessel failure induced by impact during a transportation accident.
- 3) Vessel failure by overpressure because of overheating. This often follows a derailment accident with railroad tank cars.
- 4) Vessel and pipeline failure by overpressure, corrosion or erosion.
- 5) Fuel leakage followed by a vapor cloud explosion.

Blast and some type of fragment or massive body impact usually result from the first four types of accident; the last type causes primarily a pressure wave and fireball; while the first four may or may not cause fireball or fire depending on the fluid and circumstances in the accident.

Assessment of the magnitudes and the effects of the blast and fragments for ground system explosions is the topic of this workbook.

#### Means for Assessment of Risk

The term "risk assessment" implies not only the estimation of effects of some potentially dangerous operation or situation,

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but also the estimation of the probability that the event will occur and cause some level of damage. We do not address here the overall problem of risk assessment, but instead cover only the prediction of the effects. Throughout, we assume that some postulated explosive accident can and has happened. This workbook therefore covers only the more deterministic aspects of explosions and their effects, but can serve as inputs to the probabilistic models used in complete risk assessment studies.

#### Scope and Significance of Material Presented

From the material presented in this workbook, one should be able to make predictions of blast and fragment characteristics and effects for a wide range of possible explosion accidents in ground systems. The body of the workbook gives the prediction methods in the form of graphs, equations, or tables. All detailed development and some computer programs are given in appendices. Given a number of accident scenarios, the material should allow prediction of:

- 1) Explosive energy yield or energy release.
- Characteristics of blast pressure waves generated by spherical and non-spherical explosions.
- Effects of pressure waves on certain classes of targets or for blast loading conditions not covered in Baker, et al (1975).
- 4) Characteristics of fragments generated by ground equipment explosions. This includes massive vessel parts which "rocket."
- 5) Effects of fragment impact not covered in Baker, et al (1975), including effects of fragment revetments on blast waves.

The scope of the material presented here is deliberately limited to avoid duplication with the previous workbook [Baker, et al (1975)]. As noted earlier, it should be used in conjunction with that reference. (Microfiche)

Significant advances presented here are:

- Prediction of blast wave characteristics for nonspherical sources.
- Some additional methods for rapid prediction of structural damage from blast waves and massive fragment impact.

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- Extensions of methods of predicting such fragment characteristics as initial velocity, maximum range, and impact conditions.
- Development of method for predicting trajectories and impact conditions for "rocketing" vessels.
- 5) Inclusion of predictions for effects of barricades on blast waves.

#### Intended Purpose and Limits of Use

The purpose of the workbook is to provide safety engineers with methods for rapid estimation of blast and fragment hazards from accidental explosions in ground support and transport equipment. 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 we 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 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.

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#### Applications to Areas Other Than Aerospace Propellant and High Pressure Gas Handling Facilities

This workbook can be as easily applied to many types of industrial explosive accidents as to those limited to aerospace propellants and high pressure gases. There have been many gas pressure vessel failures, road and rail tanker accidents with fuels such as LPG (liquified petroleum gas) followed by explosion and fire, and piping failures in chemical plants followed by vapor cloud explosions. For all such accidents, the methods presented here can be applied to estimation of blast and fragment hazards.

#### Additional Areas of Research

The methods given here are based on the best test data, analysis methods, and accident reports available to us. But, in many of these areas, the data base is quite sketchy and the governing physical processes are as yet poorly understood. We feel that additional work is needed in the following areas:

- A better understanding and better methods of prediction of conditions under which vapor cloud explosions will occur, and the blast wave properties for such explosions.
- A more thorough study of non-spherical accidental explosion effects.
- 3) Extension of the pressure-impulse (P-I) damage concept to typical blast waves for accidental explosions. In particular, the pronounced negative phase characteristics of such explosions should be considered.
- 4) Better definition of impact effects for large, massive fragments or objects.
- 5) Establishment of a more comprehensive and accurate system or method for reporting of explosion accidents. In particular, good industrial accident reporting could greatly increase the data base for comparison with these prediction methods or for judging explosion severity.

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Strehlow, R. A. and Baker, W. E. (1975), "The Characterization and Evaluation of Accidental Explosions," NASA CR-134779, Grant NSC 3008, June 1975.

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#### CHAPTER I

#### ESTIMATES OF EXPLOSIVE YIELD

#### 1-1 General

Methods for estimating explosive yields, i.e., total energies which can be released in an explosive accident, are discussed in some depth by Baker, et al (1975) for the common mixtures of fuels and oxidizers employed in liquid-fueled rockets. Methods are given in that reference for estimating explosive yields for a variety of classes of explosive accident and propellant mixtures. No new data or methods have been developed since, and one should simply use that reference to estimate explosive yields for liquid propellant mixtures.

Baker, et al, (1975) also give a formula for estimating explosive yields for bursts of compressed gas vessels. Considerable analytic and experimental work on this topic has been done recently, and we will use this work as a basis for improving estimation of blast yields for this source.

A significant number of explosive accidents have occurred after failure of pressure vessels containing flash-evaporating liquids under high pressure, either at ambient temperature or heated. Methods have been developed to estimate blast yields for such explosions and these will be presented here.

An important class of accidental explosions in ground systems is the unconfined vapor cloud explosion. A quantity of fuel is released to the atmosphere as a vapor or aerosol, the fuel mixes with the air, and the resulting fuel-air mixture is then ignited by some ignition source. An explosion may or may not result, depending on a number of variables. We will survey knowledge on this class of accidental explosion, and recommend some ways of obtaining rough estimates of blast yield.

#### 1-2 Compressed Gas Bursts

In Baker, et al (1975), the formula for total energy release originally proposed by Brode (1959) was used to predict explosive yield for compressed gas vessel bursts. This formula is

$$E = \left(\frac{p_1 - p_a}{\gamma_1 - 1}\right) V_1 \tag{1-1}$$

where E is blast yield (energy),  $p_1$  is initial absolute pressure in the vessel,  $p_a$  is outside atmosphere absolute pressure, and  $\gamma_1$  is the ratio of specific heats for the gas in the vessel. A number of other formulas have been proposed, and these are

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discussed in some detail and analyzed by Adamczyk and Strehlow (1977). They include an estimate based on isentropic expansion from initial burst pressure to atmospheric pressure [Baker (1973), Brinkley (1969)],

$$E = \frac{P_1 V_1}{\gamma_1 - 1} \left[ 1 - \left(\frac{P_a}{P_1}\right)^{\frac{\gamma_1 - 1}{\gamma_1}} \right]$$
(1-2)

and, as a lower limit, the energy released by constant pressure addition of energy to the explosion source region [Adamczyk and Strehlow (1977)],

$$E = P_a (V_f - V_1)$$
 (1-3)

where  $V_f$  is the final volume occupied by the gas which was originally in the vessel. These three equations are given in descending order of total blast energy, with eq. (1-3) representing the energy release for a process which is so slow that no blast wave is formed.

Adamczyk and Strehlow (1977) show that the blast yield must lie between eqs. (1-2) and (1-3). However, eq. (1-1) gives only slightly higher values than does (1-2), and is simpler. So, realizing that its use results in an overestimate of blast yield, we retain it for this workbook. The reader can use eq. (1-2), however, for a somewhat more accurate estimate which is <u>still</u> an overestimate, and hence is conservative.

The equations given here for blast yield are all based on the assumption that all of the energy which can drive a blast wave does so, depending only on the energy release rate. For real vessels, some energy must be absorbed by the vessel as it fractures, both in the fracturing process itself and in accelerating the vessel pieces or fragments to their maximum velocity. For failure of a compressed gas vessel, the energy absorbed in the fracture process is negligible because the vessel is already stressed to failure. But, the energy absorbed in accelerating vessel fragments can be significant. In experiments such as those of Esparza and Baker (1977a) and Boyer, et al (1958) with pressurized glass spheres and Pittman (1972), (1975) with metal pressure vessels, the fragments were observed with high speed cameras or other velocity measuring systems. In accidental vessel bursts, the velocities of fragments can be estimated by methods to be presented in Chapter IV. Knowing mean fragment velocity U and total mass M of the vessel, one can then compute the kinetic energy of the vessel fragments

$$E_k = M U^2/2$$
 (1-4)

To obtain an estimate of effective blast yield for gas vessel bursts, we then use either eq. (1-1) or (1-2) and subtract fragment kinetic energy, i.e.,

$$E_e = E - E_k \tag{1-5}$$

1-3 Flash-Evaporating Liquid Bursts

Many fluids are stored in vessels under sufficient pressure that they remain essentially liquid at the vapor pressure corresponding to the storage temperature for the particular liquid. Examples are the fuels propane or butane which are normally stored at "room" temperature, methane (LNG) and hydrogen (LH<sub>2</sub>) which must be stored at cryogenic temperatures, and refrigerants such as ammonia or the Freons which are also stored at room temperature. If a vessel containing such fluids fails, the resulting sudden pressure release can cause expansion of vapor in ullage space and partial flash evaporation of the liquid, and drive a blast wave into the surrounding air.

Because the properties of flash-evaporating fluids differ markedly from perfect gases, the methods for estimating blast yield for gas vessel bursts are inapplicable. Instead, one must know the complete thermodynamic properties of the fluid in the vessel as functions of state variables such as pressure, specific volume, temperature, and entropy.

For any expansion process from state 1 to state 2, the specific work done is defined (see any basic thermodynamics text) as

$$e = u_1 - u_2 = \int_1^2 p \, dv$$
 (1-6)

where u is internal energy, and v is specific volume. We assume that an isentropic expansion process occurs after vessel burst. This process is shown schematically in a p-v diagram in Fig. 1-1, and in a T-s (temperature-entropy) diagram in Fig. 1-2. The particular initial state 1 shown in these two figures lies in the superheated vapor region, and so does the final state 2 after isentropic expansion to ambient pressure p. The cross-hatched area in Fig. 1-1 is the integral of eq. (1-6), and therefore represents the specific energy e. Also shown in the two figures are the saturated liquid and saturated vapor lines, which bound the wet vapor region. Whenever the expansion process occurs near or in the wet vapor region, as is always true for flash-evaporating fluids, the functional relationship between pressure and specific volume is quite complex and the integral in eq. (1-6) cannot be obtained analytically. But fortunately, there are tables of thermodynamic properties available for many fluids, and the in-

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FIGURE 1-1. P-V DIAGRAM OF EXPANSION



FIGURE 1-2. T-S DIAGRAM OF EXPANSION

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ternal energy u or enthalpy h defined as

$$h = u + pv \tag{1-7}$$

are tabulated for the entire wet vapor region and the superheat region, as functions of pressure and specific volume, or temperature and entropy. When an initial or a final state falls within the wet vapor region, an important parameter is the quality of the vapor, defined as

$$x = \frac{v - v_{f}}{v_{q} - v_{f}} = \frac{s - s_{f}}{s_{q} - s_{f}} = \frac{u - u_{f}}{u_{q} - u_{f}} = \frac{h - h_{f}}{h_{q} - h_{f}}$$
(1-8)

where subscript f refers to fluid (saturated liquid) and subscript g refers to gas (saturated vapor). Also, within the wet vapor region, a given pressure uniquely defines a corresponding temperature, and vice versa.

In bursts of vessels containing flash-evaporating fluids, three combinations of state variables are possible at states 1 and 2. These are:

- Case 1) Superheated vapor at state 1 and at state 2 (as for the process shown in Figs. 1-1 and 1-2)
- Case 2) Superheated vapor at state 1 and wet vapor at state 2
- Case 3) Wet vapor (including both saturated liquid and saturated vapor) at state 1, and wet vapor at state 2.

The process of estimating e and total blast yield E is basically the same, but, depending on where state 1 lies, the procedure for entering the thermodynamic tables differs somewhat. The basic procedure is as follows:

- Step 1) Estimate the initial state variables, including  $p_1$ ,  $v_1$ ,  $s_1$ ,  $u_1$ , or  $h_1$
- Step 2) Assume isentropic expansion to atmospheric pressure  $p_a$ , i.e.,  $s_2 = s_1$ . Determine  $v_2$ ,  $u_2$ , or  $h_2$ .

Step 3) Calculate specific work e from eq. (1-6)

Step 4) Calculate total blast yield E by multiplying e by mass m of fluid initially present in the vessel.

In Step 4, we use the basic definition of specific volume to obtain 12

the mass m of fluid from the known vessel volume  $V_1$ ,

$$\mathbf{v}_1 = \mathbf{v}_1 / \mathbf{m} \tag{1-9}$$

and compute E from

$$E = m(u_2 - u_1)$$
 (1-10)

Let us describe the differences in the three cases enumerated above. In Cases 1 and 2, the initial state conditions must be obtained from superheat tables for the fluid, usually entering In Case with knowledge of the pressure and temperature together. 1, superheat tables are also used for  $p_2 = p_a$ ,  $s_2 = s_1$ , to obtain the final state conditions; while in Case 2, the saturated vapor tables must be used with the definition of final quality  $x_2$ , determined from final entropy s2, being the most important factor. In case 3, all values are found in the saturated vapor table, with initial quality x1 usually being determined from a real or fictitious initial specific volume. This case is probably the most common for flash-evaporating fluid vessel bursts. The fictitious initial specific volume for a vessel which is partially filled is obtained simply from eq. (1-9) by using m as the mass of liquid in the vessel of volume  $V_1$ .

Some tables of thermodynamic properties for fluids which can be used to estimate blast yields by the process just described are the ASHRAE Handbook of Fundamentals for refrigerants, Keenan, et al (1969) for steam, Din (1962) for a number of fluids including fuels such as propane and ethylene, and Goodwin (1974) and Goodwin, et al (1976) for methane and ethane. In many instances, these tables do not include internal energy u directly, but instead include h, p and v. One then has to use eq. (1-7) to calculate u. Also, most of tables are given in English units, so calculations are usually made in these units. SI units are shown, and a conversion table is provided.

Several example calculations of blast energy for Freon 12 refrigerant, using tables from the ASHRAE handbook, follow:

Isentropic expansion of Freon-12 liquid at  $p_1/p_1 = 20.3$ and room temperature  $\theta = 76^{\circ}F$ . Since no properties a for compressed (subcooled) liquid Freon-12 seem to be available, properties for state 1 will be assumed as those of a saturated liquid. Furthermore, since this is an estimate of the change in internal energy caused by the expansion of the pressurized refrigerant, interpolation of table values will be minimized.

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For  $p_1 = 290 \text{ psi} \approx 296 \text{ psia}$ 

specific volume  $v_1 = 0.01465 \text{ ft}^3/1b_m$ enthalpy  $h_1 = 48.065 \text{ Btu/lb}_m$ entropy  $s_1 = 0.091159 \text{ Btu/lb}_m^{\circ}F$ and internal energy  $u_1 = h_1 - p_1v_1$ ,

therefore  $u_1 = 47.27 \text{ Btu/lb}_m$ .

At state 2 after expansion (s  $_1$  = s  $_2)$  to p  $_2$  ~ 14.22 psia, the quality of vapor  $x_2$  is

$$x_2 = \frac{s_1 - s_f}{s_g - s_f} = 0.508$$

Therefore,

$$v_2 = v_f + x v_{fg} = 1.328 \text{ ft}^3/1b_m$$
  
 $h_2 = h_f + x h_{fg} = 39.759 \text{ Btu/1b}_m$ 

and

$$u_2 = h_2 - p_2 v_2 = 36.263 \text{ Btu/lb}_m$$

Thus,

$$e = u_1 - u_2 = 11.0 Btu/lb_m$$

Converting this to an energy per unit volume,

$$\frac{e}{v_1} = 247.6 \text{ Btu/ft}^3$$

For a vessel with initial volume  $V_1 = 31.24 \text{ in}^3$ , the estimated energy available due to an isentropic expansion was

$$E = \frac{e}{v_1} \quad v_1 = 247.6 \text{ Btu/ft}^3 \times 9336 \text{ in-lb}_f/\text{Btu } \times \frac{1}{1728} \text{ ft}^3/\text{in}^3 \times 31.24 \text{ in}^3$$

or

E = 11,200 Joules

If the fragment velocity is measured, then the kinetic energy of the fragments would be subtracted to obtain the energy available for driving a blast wave, using eq. (1-5).

For an isentropic expansion of Freon-12 vapor at  $p_1/p_a = 3.45$  and  $\theta_1 = 78^{\circ}F$ ,

and

 $u_1 = h_1 - p_1 v = 80.2 \text{ Btu/lb}_m$ 

At  $P_2 \sim 14.0$  psia

 $s_2 = s_1 > s_g$  (still in superheated region)  $v_2 = 2.83 \text{ ft}^3/1b_m$  $h_2 = 78.42 \text{ Btu/1b}_m$ 

and

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 $u_2 = 71.09 \text{ Btu/lb}_m$ 

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Therefore,

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$$e = 9.11 \text{ Btu/lb}_{m}$$

and

$$\frac{e}{v_1} = 3.337v_1$$

For a vessel with  $V_1 = 37.59 \text{ in}^3$ 

 $E = 3.337 \text{ BTU/ft}^3 \times 9336 \text{ in-lb}_f/\text{BTU} \times \frac{1}{1728} \text{ ft}^3/\text{in}^3 \times 37.59 \text{ in}^3$ 

$$E = 678 \text{ in-lb}_{f}$$

or

E = 76.5 Joules

1-4 Vapor Cloud Explosions

A number of very damaging explosions have occurred after release of fuels as gases or aerosols. Strehlow and Baker (1975) have listed some of the more significant accidental explosions of this nature. Probably the most damaging vapor cloud explosion to date occurred in a chemical plant at Flixborough [Tucker (1975), Parker, et al (1974)] in 1974, with 28 fatalities and well over \$100 million in damage including almost complete destruction of the plant. The fuel which was released in this explosion was the hydrocarbon cyclohexane, an ingredient used in the manufacture of nylon.

The history of vapor cloud explosions shows that almost any liquid or gaseous fuel can cause such explosions, given appropriate time for mixing with the air, appropriate ratios of fuel to air, and an ignition or explosion source. In Strehlow and Baker (1975), fuels noted as causing serious explosions were propane, ethylene, propylene, butane, liquid hydrocarbon residues, and hot cyclohexane. For some fuels, true <u>detonations</u> can occur, i.e., rapid chemical reactions progressing at rates greater than sound velocity in the fuel-air cloud. For the vast majority of accidental vapor cloud explosions, it is unlikely that detonations have or will occur because this most violent type of reaction requires fuel-air mixtures within the rather narrow detonable limits plus a strong ignition source, or a very large cloud in which a less violent burning or deflagration can build to a detonation.

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Ľ H H Ľ U - 11 Ľ K L Ľ H 11 Ш 11 H L 1 L Also, this transition usually requires some confinement. But detonating fuel-air mixtures are used as weapons [Robinson (1973)], and gaseous fuels mixed with oxygen are used as large blast sources for simulation of nuclear weapons blast [Choromokos (1972)].

Assessment of damage and correlation of the damage with blast yield has been attempted for some large vapor cloud explosions [Tucker (1974), Strehlow and Baker (1975)]. Generally, these estimates show that accidental vapor cloud explosions are almost invariably much less damaging than the planned vapor detonations mentioned above. Blast yields seem to have been, at most, 20% of values estimated on the basis of total heats of combustion of the fuels involved. This is probably so because not all (perhaps very little) of the fuel-air cloud has a mixture ratio lying within the detonable range, because no strong ignition sources capable of starting detonations were present, and because only a deflagration rather than a detonation occurred. This is of small comfort to the victims of vapor cloud explosions, but does indicate that the full potential for damage is probably never realized in an accident. In a way, this conclusion parallels the results of Project PYRO tests for explosions of liquid propellants, which are summarized by Baker, et al (1975). In those experiments, blast yields were seldom greater than a few percent of the maximum potential yield for large-scale experiments.

Because of the great variability in vapor cloud explosions and the uncertainties noted above, estimation of the blast yield of vapor cloud explosions can only be very approximate. We suggest the following procedure:

- 1) Assume a stoichiometric mixture of the fuel in air and calculate the total heat of combustion, E.
- 2) Multiply the heat of combustion by some blast effectiveness factor less than one to obtain estimated blast yield E. The effectiveness factor can be based on past accident data and should at present be considered as a very crude estimate. Accident data to date indicate that it should probably never be greater than 20%.

Fuels which are gaseous at normal ambient conditions, but have vapor densities\* greater than one, seem the most potentially dangerous candidates for vapor cloud explosions because they remain near the ground surface as they mix with air. Table 1-1 gives a partial listing of some such common fuels, together with detonable limits (when known), flammable limits expressed as volume percents in air, and values of E from Zabetakis (1965). This table also contains properties for the two most common fuels shipped or stored as cryogenics, hydrogen and methane.

\*Vapor density is defined as the ratio of the density of the vapor to that of air at standard temperature and pressure.

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Fuels which are gaseous but have low vapor densities (< 1) under normal ambient conditions seem potentially much less susceptible to vapor cloud explosions, because they rise rapidly as they mix with air. The two most common such fuels are methane (natural gas) with a vapor density of 0.55 and hydrogen, with a vapor density of 0.07. But both of these fuels are very energetic, and have wide flammability limits, so they cannot be completely excluded as potential sources for vapor cloud explosions.

By listing or mentioning only a limited number of fuels, we, of course, do not mean to exclude only liquid or gaseous fuel as a potential source for vapor cloud explosions. At present, we also cannot give good guidelines for estimating the effectiveness factor for converting maximum chemical energy release to blast yield.

	Molecular Wt, M	Vapor Density	Boiling Point, °F	Detonabil Lower, %	ity Limits Upper, 8	Flammabil Lower, §	ity Limits Upper, §	
Acetylene	26.04	16.0	gas	10	25	2.5	100	
Ethylene oxide	44.05	1.736	51	Q	24	3.0	100	
Ethylene	28.05	0.97	gas	7	21	2.7	36	
Propane	44.09	1.52	gas	a 1	1	2.1	9.5	
l,3-Butadiene	54.09	1.9	gas	ł	ł	2	12	
Monomethyl- amine	31.06	1.105	gas	!	ł	4.2	20.8	
Propylene	42.08	1.5	gas	1	1	2	11	
Vinyl chloride	62.50	2.2	7	!	8	3.6	33	
Butane	58.12	2.01	gas		ł	1.8	8.4	
Ethane	30.07	1.044	gas	8	ł	3.0	12.4	
l-Butene	56.10	1.995	gas	1	3	1.6	10	
Propadiene	40.06	1.38	gas	8	t t	2.6	;	
Hydrogen	2.016	0.07 1.11	gas at B.P (-400.3)	20	65	4.0	75	
Methane	16.043	0.55 1.52	gas at B.P (-115.8)	9	14	5.0	15	

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TABLE 1-1. SOME FUELS WITH HIGH POTENTIAL FOR VAPOR CLOUD EXPLOSIONS

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#### CHAPTER II

#### CHARACTERISTICS OF PRESSURE WAVES

#### 2-1 General

The characteristics of blast waves from liquid propellant explosions and spherical gas vessel bursts, and their similarities and differences compared to waves from condensed high explosives such as TNT, are discussed at some length by Baker, et al (1975). Much of the data presented in that reference can be used with no change to predict blast wave properties for explosions in ground systems. Here, we supplement that reference with discussions of later theoretical predictions and experimental results, and give some additional curves for prediction of blast properties based on the more recent work. The theory we will present includes some two-dimensional blast propagation effects for bursting pressure vessels, while the new test data include measurements of blast waves from bursting, frangible spheres containing high pressure gases and a flash-evaporating fluid.

#### 2-2 Two-Dimensional Blast Wave Characteristics

Gases are often stored in tanks under high pressure. When a pressure vessel bursts, a shock wave propagates away from it. To estimate the damage and injury from such an explosion, one must know the side-on overpressure  $P_s$  and the side-on specific impulse  $I_s$ .

In Baker et al (1975), a method is given for calculating sideon overpressure and specific impulse, P and I, from a pressure vessel burst. The flowfield is assumed to be spherical, and the effects of the container upon the blast wave are ignored. This treatment is reasonably good for lightweight vessels, e.g., spacecraft tanks. However, for heavy vessels, one must account more accurately for the effects of the vessel itself.

The following is a method for predicting P and I from a spherical pressure vessel burst of a type common in failure of ground-based vessels, with the vessel breaking in half and the two pieces being propelled in opposite directions. The situation is shown in Figure 2-1. The analysis is based on the computer program TUTTI and is discussed in Appendix A.

Briefly, to find the overpressure at a given distance from the center of the vessel, one calculates a "starting overpressure" and locates this pressure on a curve on a graph of dimensionless overpressure versus dimensionless distance,  $\overline{P}$  vs  $\overline{R}$ . The nearest  $\overline{P}$  vs  $\overline{R}$  curve is used to find P at the given distance. The specific impulse is calculated as in Baker, et al (1975).

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The "starting overpressure" is calculated as follows: The terms

$$\frac{P_1}{P_a}$$

and

$$\frac{\gamma_1 (MW)_a T_1}{\gamma_a (MW)_1 T_a}$$

are computed, where  $p_1$  is pressure,  $\gamma$  is the ratio of specific heats, (MW) is molecular weight, and T is absolute temperature. The subscript l refers to conditions inside the vessel before it bursts, and a refers to conditions in the surrounding atmosphere. The point

$$\left(\frac{\mathtt{p}_{1}}{\mathtt{p}_{a}},\frac{\mathtt{Y}_{1}(\mathtt{MW})_{a}\mathtt{T}_{1}}{\mathtt{Y}_{a}(\mathtt{MW})_{1}\mathtt{T}_{a}}\right)$$

is located on one of the graphs in Figures 2-2, 2-3, or 2-4, depending on  $\gamma_1$ .  $\overline{Ps}$  is read for the point. The "starting over-pressure" is  $\overline{P}_A = 0.21 \ \overline{Ps}_0$ . Figure 2-5 is a graph of  $\overline{P}$  vs  $\overline{R}$ , where

$$\overline{P}_{s} = \frac{P_{s}}{P_{a}}$$

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

[r is the distance along the plane of symmetry from the center of the tank, and the energy in the tank is given by eq. (1-1)]. On Figure 2-5, the intersection of the constant  $\overline{P}_{s}$  line (where  $\overline{P}_{s} = \overline{P}_{A}$ ) and Curve A is found. This is the starting point. The nearest curve or curves give the  $\overline{P}$  vs  $\overline{R}$  behavior. For the distance of interest, calculate  $\overline{R}$ .  $\overline{P}_{s}$  is then read from the appropriate curve.

 $\overline{I}$  is read from Figure 2-6 or 2-7, whichever is more convenient.

$$\overline{I} = \frac{I_s A_a}{P_a^{2/3} E^{1/3}}$$

where A<sub>a</sub> is the speed of sound in the surrounding atmosphere.

$$I_{s} = \overline{I} \frac{pa^{2/3}E^{1/3}}{A_{a}}$$

P and I are accurate to about  $\pm 15$ %. The curves should not be extrapolated.



FIGURE 2-1. BURST OF A SPHERICAL PRESSURE VESSEL

The computer analysis on which these curves are based does not extend far enough in time to allow prediction of negative phase characteristics or second shock characteristics.

Example: A spherical vessel containing air ( $\gamma_1 = 1.4$ ) at a pressure of 10<sup>8</sup>P (987.2 atm) and a temperature of 300°F bursts at sea level. The inner vessel radius is 0.19m. Find P<sub>s</sub> and I<sub>s</sub> at a distance r of 1.14m along the plane of symmetry from the center of the vessel.

Solution:

$$\frac{p_1}{p_a} = 987.2$$

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FIGURE 2-5.  $\overline{P}_{s}$  VS.  $\overline{R}$  FOR OVERPRESSURE CALCULATIONS. DISTANCE ALONG PLANE OF SYMMETRY

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FIGURE 2-6.  $\overline{I}$  VS  $\overline{R}$  FOR PENIOLITE AND GAS VESSEL BURSTS

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FIGURE 2-7.  $\bar{\rm I}$  VS  $\bar{\rm R}$  FOR GAS VESSEL BURSTS, SMALL  $\bar{\rm R}$ 

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$$\frac{\gamma_1 (MW)_a T_1}{\gamma_a (MW)_1 T_a} = 1$$

Locating this point on Figure 2-2,  $\overline{P}_{so} = 11$ .

$$\overline{P}_{A} = 0.21 \overline{P}_{so} = 0.21(11) = 2.3$$

Next, find the point on Figure 2-5 where Curve A crosses

$$\overline{P}_{s} = \overline{P}_{A} = 2.3.$$

This is near the third curve from the bottom of the page. This gives the  $\overline{P}_S$  vs  $\overline{R}$  behavior.

$$E = V_1 \frac{p_1 - p_a}{\gamma_1 - 1} = \frac{4\pi}{3} (0.19)^3 \frac{10^8 - 1.013 \times 10^5}{1.4 - 1} = 7.8 \times 10^6 \text{ J}$$
  
$$\overline{R} = \frac{r p_a}{E^{1/3}} = \frac{1.14m (1.013 \times 10^5 P_a)^{1/3}}{(7.18 \times 10^6)^{1/3}} = 0.27$$

For this value of  $\overline{R}$ ,  $\overline{P}_{s} = 1.8$ .  $P_{s} = \overline{P}_{s} P_{a} = (1.8)$  (1.013 X 10<sup>5</sup>Pa) =  $1.8 \times 10^{5} Pa$ 

From Figure 2-7,  $\overline{I}_{s} = 0.16$ . Then  $I_{s} = \overline{I} \frac{P_{a}^{2/3} E^{1/3}}{A_{a}} = \frac{0.16(1.013 \times 10^{5})^{2/3}(7.18 \times 10^{6})^{1/3}}{344 \text{ m/s}} = 1.9 \times 10^{3} \text{ Pa·s}$ 

Two recent experimental studies form the basis for some additional prediction curves for blast wave properties near bursting pressure spheres. Esparza and Baker, (1977a) and (1977b), report measurements of blasts from bursting frangible pressure spheres containing air and argon (1977a), and the refrigerant Freon 12 as both a compressed liquid and a compressed vapor (1977b).

These measurements, which include side-on pressure-time data over a range of scaled distances, show that compressed gas and vapor sphere explosions can generate waves which are distinctly different from the more familiar waves from condensed explosives.

A typical pressure-time trace is shown in Fig. 2-8. The distinctive characteristics are the pronounced negative phase compared to the first positive phase, and the strong second shock wave. By contrast, waves from condensed explosives show much smaller negative phases and seldom have a discernible second shock.

To report these blast wave properties, we must define more parameters than the usual ones. We have chosen the following ones (see Fig. 2-8).



FIGURE 2-8. TYPICAL BLAST PRESSURE HISTORY FOR FRANGIBLE GAS SPHERE BURST

$$P_{s1}$$
 first shock side-on overpressure  
 $I_s^{(+)}$  positive phase impulse for first shock  
 $T_s^{(+)}$  duration of positive impulse for first shock  
 $I_s^{(-)}$  negative phase impulse for first shock  
 $T_s^{(-)}$  duration of negative phase for first shock  
 $P_{s2}$  second shock side-on overpressure.  
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Prediction curves for scaled values of these parameters are given here. As in section 2-2, the scaling is given by:

$$\overline{P} = P/P_{a}$$

$$\overline{I} = I A_{a} P_{a}^{2/3}/E^{1/3}$$

$$\overline{T} = T A_{a} P_{a}^{1/3}/E^{1/3}$$

$$\overline{R} = R P_{a}^{1/3}/E^{1/3}$$
(2-1)

and blast yield E is defined by

$$E = E' - E_k$$
 (2-2)

where

$$E^{\prime} = \frac{V_{1}(p_{1}-p_{a})}{(\gamma_{1}-1)}$$
(2-3)

for perfect gases and

$$E' = \frac{V_1}{V_1} \quad (u_1 - u_2) \tag{2-4}$$

for wet vapors or gases near the thermodynamic "vapor dome."\*

Figures 2-9 through 2-16 are derived from Esparza and Baker (1977a) for compressed gases. Blast wave characteristics were found to be only weakly dependent on specific heat ratio  $\gamma_1$  for gas in the vessels and on initial pressure ratio  $(p_1/p_a)$ .

The latter parameter was varied over the range  $9.9 \leq (p_1/p_a) \leq 42.0$  in the tests. Because of the weak dependence on these two parameters, all data are combined for various initial pressure ratios and ratios of specific heat. The figures show the range of all test data within the cross-hatched areas, and a "best fit" solid curve through the data. We suggest that the best fit curve be used for estimation, but one can use the upper limit curves to indicate uncertainties in the data.

Figures 2-17 through 2-22 are curves for compressed vapor for Freon-12 refrigerant, similar to the previous figures for compressed gases, from Esparza and Baker (1977b). That reference

\*Chapter 1 gives methods for calculating the internal energy change  $(u_1 - u_2)$ .

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FIGURE 2-9. SCALED TIME OF ARRIVAL OF FIRST SHOCK WAVE FROM BURSTING GAS SPHERES

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FIGURE 2-10. SCALED SIDE-ON PEAK OVERPRESSURE FOR FIRST SHOCK FROM BURSTING GAS SPHERES

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FIGURE 2-11. SCALED DURATION OF FIRST POSITIVE PHASE OF BLAST WAVE FROM BURSTING GAS SPHERES

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FIGURE 2-12. SCALED SIDE-ON POSITIVE IMPULSE FROM BURSTING GAS SPHERES

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FIGURE 2-13. SCALED DURATION OF NEGATIVE PHASE OF BLAST WAVE FROM BURSTING GAS SPHERE

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FIGURE 2-14. SCALED SIDE-ON NEGATIVE IMPULSE FROM BURSTING GAS SPHERES

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FIGURE 2-15. SCALED TIME OF ARRIVAL OF SECOND SHOCK WAVE FROM BURSTING GAS SPHERES

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FIGURE 2-16. SCALED SIDE-ON PEAK OVERPRESSURE OF SECOND SHOCK FOR BURSTING GAS SPHERES

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FIGURE 2-17. SCALED SIDE-ON PEAK OVERPRESSURE FOR BURSTING FREON-12 VAPOR SPHERE AT ROOM TEMPERATURE

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FIGURE 2-18. SCALED DURATION OF POSITIVE PHASE OF BLAST WAVE FROM BURSTING FREON-12 VAPOR SPHERE

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FIGURE 2-19. SCALED DURATION OF NEGATIVE PHASE OF BLAST WAVE FROM BURSTING FREON-12 VAPOR SPHERE

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FIGURE 2-21. SCALED TIME OF ARRIVAL OF SECOND SHOCK WAVE FROM BURSTING FREON-12 VAPOR SPHERE

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FIGURE 2-22. SCALED SIDE-ON PEAK OVERPRESSURE OF SECOND SHOCK WAVE FROM BURSTING FREON-12 VAPOR SPHERE

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shows that blast waves from sudden release of compressed liquid Freon-12 were almost always so weak that they were essentially sound waves, and therefore had negligible damaging potential. No data were taken for the intermediate cases of wet vapor, which should have intermediate explosion properties between saturated liquid and saturated vapor.

Some data exist for blast waves generated by bursts of heated, ductile pressure vessels containing steam as a flash-evaporating fluid [Baker, et al (1978)] which show that such bursts can indeed be quite energetic blast sources. Strong vessels containing varying amounts of water which were heated to steam and burst at pressures of about 32 MPa generated strong blast waves, with specific source energies as great as 2.31 x 10° J/m° on a volume basis or 4.04 x 10° J/kg of fluid on a mass basis. The latter figure, when compared to the specific energy for TNT of 4.19 x 10° J/kg, gives a "TNT equivalent" of 0.097 kg TNT/kg H<sub>2</sub>O. But, the data are too sparse to generate prediction curves.

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### CHAPTER III

### EFFECTS OF PRESSURE WAVES

## 3-1 General

It should be clear from the discussions in earlier chapters that the pressure (blast) waves from accidental explosions in groun systems can differ significantly from "classical" blast waves from condensed explosives. But, the basic methods presented by Baker, et al (1975) for predicting effects of pressure waves are independent of the exact character of the explosion source, and are primarily related to blast wave properties such as peak side-on overpressure P<sub>s</sub> and positive impulse i<sub>s</sub>, or peak reflected overpressure P<sub>r</sub> and the corresponding reflected impulse i<sub>r</sub>.

Because of the correlation of the blast effects prediction methods in Baker, et al (1975) with blast wave properties, all of the graphs and equations in Chapter III of that reference are equally applicable for the ground burst accidents which are the topic of this workbook. Topics covered in Baker, et al (1975) are:

- 1) Thresholds for glass breakage.
- Empirical blast damage estimates for residential buildings.
- 3) Toppling or overturning of vehicles and other objects.
- 4) Damage thresholds for beam structural elements.
- 5) Damage predictions for brittle and ductile rectangular plate elements.
- 6) Damage thresholds for rectangular membranes.
- 7) Blast injury estimates for humans.

We will not duplicate any of those prediction methods here, but will instead give supplementary prediction curves based on further damage prediction analyses by our staff.

3-2 Additional Beam Response Predictions

Methods were given in Baker, et al (1975) for prediction of damage thresholds for beams with various boundary conditions. The techniques used to obtain that set of prediction curves were based on assumed rigid-plastic beam behavior, and energy balance methods. Other prediction curves can be obtained by assuming elastic-plastic beam behavior, or purely elastic behavior. The curves are given here, and the procedures used in developing them are given in 50

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### Appendix B.

Figure 3-1 is a nondimensionalized pressure-impulse (P-i) diagram for determining the maximum strain and deflection in beams loaded by a blast wave. The blast wave is characterized by its peak applied pressure P and impulse i. These pressures and impulses are either side-on or reflected ones dependent upon the orientation of the building relative to the enveloping wave. In this graphical solution, we assume that the loading is uniform over the entire span of length  $\ell$ . The beam has a loaded width b, a mass density  $\rho$ , a cross-sectional area A, a total depth H, an elastic modulus E, a yield point  $\sigma$ , a second moment of area I, and a plastic (not elastic) section modulus Z.

Different boundary conditions can be evaluated by inserting the appropriate nondimensional numbers, i.e., the appropriate  $\Psi$ coefficients from the table in Figure 3-1. Simply-supported, clamped-clamped, clamped-pinned, and cantilever beams are all included in this graphical solution. No strain energy is absorbed in extensional or shear behavior. This solution is entirely a bending one. Any self-consistent set of units can be used because this solution is nondimensional.

As an illustration of how Figure 3-1 may be applied, consider a 12H5 as a joist in a flat roof.\* The joist will have 4-ft centers and be a simply-supported beam with a 20-ft span. The weight of the concrete and insulation being supported by this joist is assumed to equal 30.2 lb/ft<sup>2</sup>. The joist is made of steel with a weight density of 0.283 lb/in<sup>3</sup>, an elastic modulus of 30 x 10<sup>6</sup> psi, and a yield stress of 33,000 psi. The AISC handbook gives a weight per length of 7.1 lb/ft, a maximum moment based on a 30,000-psi yield of 222 in-kips, and a depth of 12.0 inches. These properties indicate that the second moment of area equals Mh/2 $\sigma$ , or 44.4 in<sup>4</sup>, and that the elastic section modulus is 2I/h, or 7.4 in<sup>5</sup>. We will assume that the plastic section modulus Z equals the elastic section modulus in a beam with this shape. In a simply-supported beam, the  $\Psi$  number equals 10.0,  $\Psi_i$  equals 0.913, and  $\Psi_r$  equals 1.25.

Next the nondimensional quantities

$$\frac{Pbl^2}{\Psi_p \sigma_y z}$$

and

\*English units are used in this and some subsequent examples because all of the handbook properties of structural steel members are given in these units, and they are the common units used by structural designers.

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$$\frac{ib\sqrt{EI}}{\psi_i\sqrt{\rho A}\sigma_y Z}$$

must be computed for some given input pressure and impulse. Let us assume that these values are P = 1.42 psi and i = 0.0145 psi-sec. Substituting P = 1.42 psi, b = 48 in.,  $\ell$  = 240 in.,  $\Psi$  = 10.0,  $\sigma_{\rm v}$  = 33,000 psi, and Z = 7.4 in gives a scaled pressure of 1.61 for the quantity

$$\frac{Pbl^2}{\sqrt[p]{p'y}}.$$

Before the quantity

$$\frac{ib\sqrt{EI}}{\Psi_{i}\sqrt{\rho A}\sigma_{y} z}$$

can be determined, multiplying and dividing by  $\sqrt{g}$ , the square root of the acceleration of gravity, simplifies computations by forming the quantity

$$\frac{\text{ib }\sqrt{\text{EI }}\sqrt{\text{g}}}{\Psi \sqrt{\rho \text{gA }}\sigma_{\text{v}}\text{Z}}$$

The quantity (pgA) is the weight per unit length for both the beam and the roof that it supports. Because of the 2.0-ft centers, the quantity (pgA) equals  $\{(30.2 \times 4) + 7.1\}$  1/12, or 10,66 lb/in. Substituting i = 0.0145 psi-sec, b = 48 in., E = 30 x 10<sup>6</sup>, I = 44.4, g = 386 in/sec,  $\Psi_{1}$  = 0.913, pgA = 10.66,  $\sigma_{y}$  = 33,000 psi, and Z = 7.4 gives a scaled impulse of 0.685 for the quantity

$$\frac{\text{ib }\sqrt{\text{EI }}\sqrt{\text{g}}}{\Psi_{\text{i}}} \sqrt{\rho \text{g} \text{A}} \sigma_{\text{v}}^{\text{Z}}} \ .$$

Now Figure 3-1 can be entered to determine the scaled strain for this loading. The scaled strain

$$\frac{\text{IE} \ \varepsilon_{\text{max}}}{\Psi_{\varepsilon} \ \text{HZ}\sigma}$$

equals 0.33. The strain  $\varepsilon_{max}$  is found to equal 907  $\mu\varepsilon$  after substituting 44.4 for I, 30 x 10+6 for E, 33,000 for  $\sigma$ , 7.4 for Z, 12 for H, and 1.25 for  $\Psi$ . This strain is elastic and corresponds to a stress of about 27,200 psi.

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Figure 3-2 is a corresponding bending beam solution for elastic response only. The major added benefit derived from Figure 3-2 is that it can be used to estimate the shear forces at the supports. For a Bernoulli-Euler beam, a plastically responding beam has no shear force at the instant of maximum deformation, as

$$\frac{\mathrm{d}M}{\mathrm{d}x} = 0.$$

Obviously, a maximum shear is reached earlier in the response which is not handled by an energy solution. An energy solution only handles end states; it never yields a transient solution. For an elastic solution, a maximum shear force V is reached when the beam is in its maximum elastically deformed position. Provided the response is elastic, Figure 3-2 essentially yields the same solution as an elastically responding beam from the more generalized Figure 3-1 solution.

We will illustrate the use of Figure 3-2 with the same 12H5 roof joint exposed to the same 1.42 psi and 0.0145 psi-sec pressure-impulse blast loading as in the previous example. The elastic scaled pressure and impulse quantities which must be calculated are

$$\frac{PbH\ell^2}{\alpha_p EI}$$
 and  $\frac{ibH}{\alpha_i \sqrt{\rho EIA}}$ .

Once again multiply and divide the scaled impulse by  $g^{1/2}$  to form

which takes advantage of the weight per unit length quantity ( $\rho$ gA). Substituting as before, P = 1.42 psi, b = 48 in., H = 12 in., l = 240 in<sub>3</sub>,  $\alpha_p = 8.00$ , E = 30 x 10<sup>+6</sup> psi, and I = 44.4 in<sup>4</sup> gives 4.42 x 10<sup>-5</sup> for the scaled pressure quantity

$$\frac{PbH\ell^2}{\alpha_p EI}$$
 .

Substituting i = 0.0145 psi-sec, b = 48 in., H = 12 in., g = 386 in/sec,  $_4\alpha_i$  = 1.461, ( $\rho gA$ ) = 10.66 lb/in, E = 30 x 10<sup>+8</sup>, and I = 44.4 in gives 9.43 x 10<sup>-6</sup> for the scaled impulse quantity

$$\frac{ibHg^{1/2}}{\alpha_i \sqrt{\rho Ag EI}}$$

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STRESSES, SHEARS, AND DEFLECTIONS IN BLAST LOADED ELASTIC BEAMS FIGURE 3-2.

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The coefficients differ in Figures 3-1 and 3-2; however, the appropriate values are provided in tabular inserts. Entering Figure 3-2 for this specific combination of scaled pressure and scaled impulse gives a scaled stress

$$\left(\frac{\sigma_{\max}}{E} \times 10^{+3}\right)$$

of approximately 1.0 after extrapolating. After substituting for E, this calculation indicates that the maximum stress caused by the air blast wave is approximately 30,000 psi. This answer is identical, within the limits of graphical accuracy, to the 27,200 psi stress found using Figure 3-1. In addition, the shear force at the support caused by this dynamic load can also be determined. The equations in the upper left hand corner of Figure 3-2 permit the maximum elastic deformation  $w_0$  and the shear force at the supports to be determined after  $\sigma_{max}$  has been computed. The coefficients C, and C, also found in the table accompanying Figure 3-2, depend upon the boundary conditions. For a simplysupported beam, C = 8.0. Substituting C = 8.0,  $\sigma_{max}$  = 30,000 psi, I = 44.4 in<sup>4</sup>,  $l = ^240$  in., and H = 12 in. gives 3,700 lbs for the maximum elastic shear force caused by the blast load.

Whenever a member undergoes large deformations relative to its thickness, the principal mode of energy dissipation is extensional rather than bending. Figure 3-3 presents an elasticplastic, one-dimensional, extensional solution. An extensional solution assumes that the ends are constrained from moving together so that in-plane forces can be developed. The results presented in Figure 3-3 are very similar to the previously presented bending solution in that contours of constant scaled strain are presented on a plot of scaled applied impulse and pressure. All loads are assumed to be uniformly distributed over the member being loaded. After the strain has been determined, the maximum deformation, the slope at the boundaries, and the magnitude of the anchoring force can all be determined using Figure 3-3.

The symbols in Figure 3-3 are very similar to those used previously. The one new symbol is A, the cross-sectional area of the member. Other symbols include the applied reflected or side-on overpressure P, the applied reflected or side-on impulse i, the loaded width b, the total span  $\ell$ , the mass density  $\rho$ , the elastic modulus E, the yield point  $\sigma_y$ , the maximum strain  $\varepsilon_{max}$ , the maximum deformation  $w_{\rho}$ , and the maximum slope

 $\left(\frac{dy}{dx}\right)_{max}$ ,

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Any self-consistent set of units can be used, as all scaled quantities are nondimensional.

We will illustrate the use of Figure 3-3 by evaluating wall siding. Let us assume normally reflected pressure of 3.0 psi, and a normally reflected impulse of 30.0 psi-ms. Most siding is corrugated so one direction is much stiffer than its orthogonal counterpart. This observation means we can use a strip theory for estimating the response. If we have a steel siding with a yield point of 33,000 psi, a cross-sectional area per inch of width of 0.0625\_in /in, a weight per inch width and per inch length of 0.0236 lb/in , and a span of 156 in., then the scaled pressure can be presented in the format

$$\frac{\text{Ple}^{1/2}}{\sigma_{y}^{3/2}(\text{A/b})}$$

which equals

 $\frac{(3.00)(156)(30 \times 10^{+6})^{1/2}}{(33,000)^{3/2}(0.0625)}$ , or 6.84.

The scaled impulse should be multiplied and divided to  $g^{1/2}$  to form

$$\frac{\text{i}\text{E}^{1/2}\text{g}^{1/2}}{\left(\text{pg}_{\overline{b}}^{A}\right)^{1/2}\sigma_{y}\!\left(\frac{A}{b}\right)^{1/2}},$$

which equals

$$\frac{(0.030)(30 \times 10^{+6})^{1/2}(386)^{1/2}}{(0.0236)^{1/2}(33,000)(0.0625)^{1/2}}, \text{ or } 2.55.$$

Entering Figure 3-3 for these values of scaled pressure and impulse gives a scaled strain

$$\frac{\frac{\varepsilon_{\max}}{\sigma_{x}}}{\sigma_{y}}$$

 $\frac{\sigma_{\mathbf{Y}}}{\mathbf{E}}$ 

of approximately 4.0. Because

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is the yield strain, this calculation predicts a maximum strain of 4.0 times the yield strain. The maximum in-plane stress at the support will equal 33,000 psi because the member has yielded. This stress will act at an angle of

$$\sqrt{2}(4) \frac{33,000}{30 \times 10^{+6}}$$

or 0.0938 radians, according to the formula for the maximum slope in Figure 3-3. Because the in-plane stress and line of action are known, fasteners for attaching this wall could be selected and appropriately spaced.

## 3-3 Buckling of Axially-Loaded Members

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Figure 3-4 shows a scaled pressure-impulse diagram for buckling of an axially loaded elastic column. Different boundary conditions and whether or not side-sway can occur is accounted for in the  $\alpha_n$  and  $\alpha_i$  coefficients associated with pressure and impulse. The solid line in Figure 3-4 is the threshold separating unstable column response from stable. If the nondimensionalized loads imparted to a column establish a point which is to the left and/or below the threshold line, then the column should remain stable. On the other hand, should these nondimensionalized loads establish a point above and to the right of the threshold, large permanent, unstable deformation should be expected. In developing this solution, energy procedures were once again applied. The major new parameter is the mass (not weight) of the overlying floor M. We assume that the mass of the column is insignificant relative to the mass of the rigid floor above. The parameters  $\ell$ , E, I,  $\sigma$ , and H all pertain to the total span, modulus of elasticity, second moment of area, yield point, and total depth of the column itself. The parameter A is the loaded area of the roof or floor over the column. All influence of dead weight effects is ignored in this solution; they are assumed to be insignificant relative to the dynamic loads from the applied blast wave.

As an illustrative example, consider a W10 x 49 with a 150-in. span acting as a clamped-clamped column that might undergo sidesway. The second moment of area equals 93.0 in<sup>4</sup>, and the depth is 10.0 in. about the minor axis of this column. We will assume a 33,000 psi yield strength, a 288 by 240 in. loaded area over each column, and an 0.2285 lb/in<sup>2</sup> weight per unit area for the overlying roof. The side-on pressure applied to the roof is 1.42 psi, and the side-on impulse is 0.0145 psi-sec. From the table inserted into Figure 3-4, we learn that the  $\alpha_1$  coefficient equals 1.41, and the  $\alpha_2$  coefficient equals 9.87 for a clampedclamped column undergoing side-sway. Substituting these values into the scaled pressure parameter

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FIGURE 3-4. BUCKLING FOR DYNAMIC AXIAL LOADS

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$$\frac{PAl^2}{\alpha_p^{EI}}$$

gives

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$$\frac{(1.42)(288 \times 240)(150)^2}{(9.87)(30 \times 10^{+6})(93.0)},$$

or 0.0802. The scaled impulse parameter

$$\frac{iAH \sqrt{E}}{\alpha_{i} \sqrt{M\&I} \sigma_{y}}$$

gives

$$\frac{(0.0145)(288 \times 240)(10)(30 \times 10^{+6})^{1/2}}{1.41\sqrt{\frac{0.02285 \times 288 \times 240}{386}}(150)(93)},$$

or 1.56. Because this combination of loads plots below the scaled pressure asymptote of 1.0, the column should be stable.

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### REFERENCES, CHAPTER III

AISC Handbook, (1961) "Steel Construction," American Institute of Steel Construction, 5th Edition, New York, New York, 1961.

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Baker, W. E., Kulesz, J. J., Ricker, R. E., Bessey, R. L., Westine, P. S., Parr, V. B. and Oldham, G. A., (1975) "Workbook for Predicting Pressure Wave and Fragment Effects of Exploding Propellant Tanks and Gas Storage Vessels," NASA CR-134906, Contract NASA-19231 November 1975 (reprinted September 1977).

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### CHAPTER IV

### CHARACTERISTICS OF FRAGMENTS

### 4-1 General

In Baker, et al (1975), there was extensive coverage of such characteristics of fragments from flight-weight vehicles as initial velocities, size and mass distributions, fragment trajectories, and the distances or ranges the fragments travelled. The data and prediction methods given in that reference were based on accident reports and tests with liquid propellant explosions and lightweight gas vessel bursts, development and exercise of a variety of special-purpose computer programs, and statistical analysis of test and accident data.

Accidental explosions in ground systems tend to produce very different types of fragments or missiles than do similar explosions in flight-weight systems. The most striking difference lies in the number of fragments generated, with the number usually being much less for the ground systems than for flight systems. This difference is primarily a function of the differences in storage or pressure vessel materials and construction. Relatively thick-walled vessels, made of ductile steels, dominate in ground storage and transport systems. These vessels often split, or fragment into only two pieces, after failure. Accidental explosions which generate more than a dozen vessel fragments are quite uncommon. For storage or transport vessels containing flash-evaporating liquids such as propane (LPG), a common failure mode is an asymmetric burst of a long cylindrical vessel, with the major part remaining intact and "rocketing" as the fluid exhausts and flashes. Accident reports of such failures show that the vessel can travel great distances, and of course cause a major hazard where they impact.

In this chapter, we present the results of studies on the characteristics of fragments from ground vessel explosions, and highlight the differences from fragmentation of flight-weight vehicles. As before, a survey and statistical analysis of accident data is included; several new computer programs were developed and exercised; and prediction curves on methods generated for various characteristics of the relatively large and massive fragments generated in accidental explosions in ground systems are presented.

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### 4-2 Analytical Predictions of Fragment Velocity Distributions

### Estimates of Initial Velocities of Fragments from Bursting Spheres and Cylinders

### Equal Fragments

The method developed by Taylor and Price (1971) and modified by Baker, et al (1975) for calculating velocities of fragments from bursting spherical and cylindrical pressure vessels was used to provide velocities of various fragments which could be plotted in some form of prediction curve. The model analyses for reducing and analyzing the data and the results of these analyses are explained in Appendix C. The development of the necessary equations, the numerical iteration method used to simultaneously solve the differential equations and the computer programs can be found in Appendix IV A and Appendix IV C of Baker, et al (1975) (see microfiche). The only assumptions included here are those needed to determine fragment velocities.

The basic assumptions are:

- 1) The vessel with gas under pressure bursts into equal fragments. If there are only two fragments, and the vessel is cylindrical, the vessel bursts perpendicular to its axis of symmetry. If there are more than two fragments, and the vessel is cylindrical, strip fragments (end caps are ignored) are formed and expand radially about the axis of symmetry (see Figure 4-1).
- 2) The cylindrical containment vessel has hemispherical end caps. (These are ignored when the vessel bursts into multiple fragments.)
- 3) The thickness of the containment vessel is uniform.
- 4) Vessels have a length-to-diameter (L/D) ratio of 10.0 for cylinders or 1.0 for spheres.
- 5) Contained gases are either hydrogen (H<sub>2</sub>), air, argon (Ar), helium (He) or carbon dioxide (CO<sub>2</sub>).

Figure 4-2 contains plots of the velocity term versus the pressure term for two fragments, ten fragments and one hundred fragments from spherical or cylindrical vessels. Three separate regions have been bounded to account for scatter: (1) cylindrical vessels bursting into multiple fragments; (2) spherical vessels bursting in half or multiple fragments and (3) cylindrical vessels bursting into two fragments. Estimates of the initial velocities of cylinders and spheres can be extracted from the nondimensional terms read directly from the appropriate bounded regions on the graph. The two nondimensional

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### terms in Figure 4-2 are:

1) Nondimensional pressure term

$$= \frac{(P-P_a)V_o}{M_c \gamma R_m T_o} = \frac{(P-P_a)V_o}{M_c a_{gas}^2} =$$

Nondimensional velocity term

$$= \frac{u}{K\sqrt{\gamma R_{m}T_{o}}} = \frac{u}{Ka_{gas}} = \frac{(velocity)}{(constant) (sound speed of the gas)}$$

where K equals 1.0 for equal fragments.

The technique for predicting initial fragment velocities for spherical or cylindrical pressure vessels bursting into equal fragments requires knowledge of the internal pressure P, internal volume  $V_0$ , mass of the container  $M_C$ , ratio of specific heats  $\gamma$ , ideal gas constant adjusted for the gas  $R_m$ , and the temperature of the gas  $T_0$ , at burst. Table 4-1 contains the corresponding  $\gamma$ 's and  $R_m$ 's for the gases for which this analysis is appropriate.

In summary, in order to estimate the initial velocity of fragments from pressurized spheres and cylinders which burst into equal fragments, one should use the following procedures:

Step 1. Calculate the nondimensional pressure term  $\frac{(P-p_{o})V}{M_{c}\gamma R_{m}T_{o}}$ 

Step 2. Locate the corresponding value of the nondimensional velocity term  $\underbrace{u}_{K\sqrt{\gamma R_m T_o}}$  and solve for velocity u (Note: K = 1.0 for equal fragments)

Note: Axes of Figure 4-2 are nondimensional terms and merely require that one use a self-consistent set of units.

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Gas	Ratio of Specific Heats y	$\begin{pmatrix} \frac{\text{Ideal Gas}}{\frac{\text{m}^2}{\sec^2 \cdot \circ_K}} \end{pmatrix}$	$\left(\frac{\operatorname{in}^{2}}{\operatorname{sec}^{2} \cdot \circ_{\mathrm{R}}}\right)$
Hydrogen	1.4	4124	3.551X10 <sup>6</sup>
Air	1.4	287.0	2.471X10 <sup>5</sup>
Argon	1.67	208.1	1.792X10 <sup>5</sup>
Helium	1.67	2078	1.789X10 <sup>6</sup>
Carbon Dioxide	1.225	188.9	1.627x10 <sup>5</sup>

### TABLE 4-1. SUMMARY OF RATIOS OF SPECIFIC HEAT AND IDEAL GAS CONSTANTS FOR DIFFERENT GASES

### Example 1:

Determine the initial velocity of a fragment from a pressurized sphere containing hydrogen gas which bursts in half. The following properties may be assumed:

= 10 X 10<sup>6</sup> Pa(1464.7 psi) Р  $V_{o} = 0.03 m^3 (1830 in^3)$ M = 17.13Kg (37.76 lbs)  $T_{O} = 300 \,^{\circ} K$ From Table 4-1  $\gamma$  = 1.4

$$R_{\rm m} = 4124 \ \frac{{\rm m}^2}{{\rm sec}^2 \cdot {}^{\circ}{\rm K}} \ (3.551 \ {\rm X} \ 10^6 \ \frac{{\rm in}^2}{{\rm sec}^2 \cdot {}^{\circ}{\rm R}})$$

Step 1. Nondimensional pressure term =

...

$$\frac{(P-p_{o})V_{o}}{M_{c}\gamma R_{m}T_{o}} = \frac{(10 \times 10^{6}) (0.03)}{(17.13) (1.4) (4124) (300)} = 0.01011$$

Step 2. Since the sphere bursts in half, K = 1.0. From Figure 4-2 <u>u</u> = .071 and solving for u re-KVYRT mo sults in an initial velocity of 93.44 m/sec (306.6 ft/sec).

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Program SPHERE [See Chapter IV, Baker, et al (1975) (microfiche)] results show the initial velocity to be 94.92 m/sec (311.4 ft/sec).

Percent Error =  $\frac{94.92-93.44}{94.92}$  X 100 = 1.6%

### Example 2:

Determine the initial velocity of a fragment from a pressurized cylindrical vessel containing argon which bursts into 50 equal fragments. Assume the following properties:

$$P = 1.5 \times 10^{6} Pa(217.7 psi)$$
$$V_{o} = 0.03m^{3} (1830 in^{3})$$
$$M_{c} = 3.21Kg (7.07 lbs)$$
$$T_{o} = 700^{\circ}K$$

From Table 4-1  $\gamma$  = 1.67

$$R_{m} = 208.1 \frac{m^{2}}{\sec^{2} \cdot {}^{\circ}K} (1.792 \times 10^{5} \frac{in^{2}}{\sec^{2} \cdot {}^{\circ}R})$$

Step 1. Nondimensional pressure term =

$$\frac{(P-P_{O})V_{O}}{M_{C}\gamma R_{m}T_{O}} = \frac{(1.4\times10^{6})(0.03)}{(3.21)(1.67)(208.1)(700)} = 0.0538$$

Step 2. Since the cylinder bursts into 50 equal fragments, K = 1.0. From Figure 4-2, u = 0.3 and solving  $K\sqrt{\gamma R_m T_o}$ for u results in an initial velocity of 148 m/sec (485 ft/sec).

Program SPHERE results show the initial velocity to be 149.2 m/s (489.4 ft/sec).

Percent error =  $\frac{149.2-148}{149.2}$  X 100 = 0.80%

### Cylinders with Length-to-Diameter Ratio of 10.0 Bursting into two Unequal Fragments

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The Taylor and Price (1971) method modified by Baker, et al (1975) for calculating velocities of fragments from bursting spherical and cylindrical gas vessels has been expanded to provide initial velocities of unequal fragments from cylindrical vessels. The development of the necessary equations and the subsequent computer program UNQL are explained in depth in Appendix D. The assumptions essential to the velocity calculations follow:

- The vessel with gas under pressure breaks into two unequal fragments along a plane perpendicular to the cylindrical axis, and the two container fragments are driven in opposite directions (see Figure 4-3).
- The containment vessel is cylindrical and has hemispherical end caps.
- 3) The thickness of the containment vessel is uniform.
- 4) Vessels have a length-to-diameter (L/D) ratio of 10.0.
- 5) Contained gases are either hydrogen (H<sub>2</sub>), air, argon (Ar), helium (He) or carbon dioxide (CO<sub>2</sub>).

The technique for predicting initial fragment velocities for fragments from a cylinder (L/D = 10.0) which breaks into two <u>unequal</u> fragments perpendicular to its axis of symmetry is identical to that for equal fragments except for the value of the constant K. The value of K depends on the ratio of the fragment mass to the total mass of the cylinder as shown in Figure 4-4. To estimate the initial velocity of a fragment from a pressurized cylinder (L/D = 10.0) which bursts into <u>unequal</u> fragments, one should use the following procedures:

- Step 1. Calculate the nondimensional pressure term =  $\frac{(P-P_{O})V_{O}}{M_{C}\gamma R_{m}T_{O}}$
- Step 2. Locate the corresponding value of the nondimensional velocity term  $\underline{u}$  in the region bounded for  $K\sqrt{\gamma R_m T_o}$ n = 2 (cylindrical vessels).
- Step 3. Determine the value of K from Figure 4-4.
- Step 4. Solve for velocity u.

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FIGURE 4-3. ASSUMED BREAKUP INTO TWO UNEQUAL FRAGMENTS

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Note: Axes of Figure 4-2 are nondimensional terms and merely require that one use a self-consistent set of units.

### Example 1:

Determine the initial velocity of a fragment from a pressurized cylindrical vessel containing carbon dioxide which bursts into two unequal fragments. Assume the following properties:

 $P = 69 \times 10^{6} Pa (10,010 psi)$   $V_{o} = 30.0m^{3} (1.83 \times 10^{6} in^{3})$   $M_{c} = 1.92 \times 10^{5} kg (4.23 \times 10^{5} lbs)$   $T_{o} = 500^{\circ} K$ 

From Table 4-1,  $\gamma = 1.225$ 

$$R_{m} = 188.9 \frac{m^{2}}{\sec^{2} \cdot {}^{\circ}K} (1.627 \times 10^{5} \frac{in^{2}}{\sec^{2} \cdot {}^{\circ}R})$$

Fraction of the total mass for fragment under consideration = 0.75.

Step 1. Nondimensional pressure term =

$$\frac{(P-P_O)V_O}{M_C \gamma R_m T_O} = \frac{(68.9 \times 10^6) (30.0)}{(1.92 \times 10^5) (1.225) (188.9) (500)} = 0.093$$

Step 2. The corresponding value of  $\frac{u}{K\sqrt{\gamma R_m T_o}} = 0.13$ .

Step 3. From Figure 4-4, K = 0.61.

Program UNQL results (Appendix D) show the initial velocity to be 26.5 m/s (86.9 ft/sec).

Percent error =  $\frac{27-26.5}{26.5} \times 100 = 1.9$ %

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4-3 Analytic Predictions of Fragment Trajectories, Ranges and Impact Conditions

### Predicting Ranges of Free-Flying Fragments

The range of a flying fragment from a bursting container is dependent on the lift and drag forces acting on the fragment. Two types of fragment cases were studied in this analysis: (1) fragments whose geometry is such that both the lift and drag forces act on them during flight, i.e., disc-shaped fragments and long, thin fragments; and (2) fragments whose geometry is such that only the drag forces act and there is no lift. A method of predicting the distance traveled by a fragment was developed and computerized (Code FRISB) by Baker, et al (1975) and this section expands on their efforts.

A set of generalized curves (Figure 4-5) was developed for use in estimating the maximum fragment range. These curves were developed by performing a model analysis to generate dimensionless parameters which describe the general problem (Appendix E), next using the computer code FRISB to determine ranges for selected cases, and then plotting the results to form the curves. It should be noted that, in generating these curves, several initial trajectory angles were used in the analysis to obtain the maximum range for the respective fragments. For ease in understanding the use of these curves, the example which follows is presented. The procedure for determining fragment range is:

- Calculate the lift/drag ratio =  $\frac{C_L A_L}{C_D A_D}$  for the frag-ment. Step 1.
- Calculate the velocity term =  $\frac{\rho_0 C_D A_D V^2}{Mg}$  for the frag-Step 2. ment.
- Step 3. Select the curve on the graph for the appropriate lift/drag ratio; locate the velocity term on the horizontal axis; find the corresponding range term,  $\frac{\rho_{O}C_{D}A_{D}R}{M}$  and determine the range, R.

Note that, for lift to drag ratios  $\frac{C_L^A{}_L}{C_D^A{}_D}$  that are not on the

curve, a linear interpolation procedure can be used to determine the range from the curve. Interpolation in the steep areas of the curve can cause considerable error and it is recommended that, for these cases, the computer code FRISB be exercised.

FRISB example: Assume  $\rho_0$  = density of air = 1.293  $\frac{\text{kg}}{\text{m}^3}$ 

 $q = qravity constant = 9.807 m/s^2$ 

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### Example 1, for lifting fragments:

Determine the maximum range of a long rectangular fragment assuming the following properties:  $V_i = 100 \text{ m/s}$  (328 ft/ sec), Mass = 30.827 kg (67.96 lb<sub>m</sub>), Projected area = 0.03018m<sup>2</sup> (0.3249 ft<sup>2</sup>), Cylinder length = 1.58m (5.18 ft), Thickness of fragment = 0.0191m (0.0627 ft), Planform or lift area = 0.20623m<sup>2</sup> (2.2198 ft<sup>2</sup>), Drag coefficient = 2.05, lift coefficient = 0.3, and the initial trajectory of the fragment at t = 0 was  $\alpha_i = 20^\circ$ .

Step 1. Determine the lift/drag ratio for the fragment =

$$\frac{C_{\rm L}^{\rm A} L}{C_{\rm D}^{\rm A} L} = \frac{(0.3) (0.20623)}{(2.05) (0.03018)} = 1.0$$

Step 2. Determine the value of the velocity term =

$$\frac{\rho_0 C_D A_D V^2}{Mg} = \frac{(1.293) (2.05) (0.03018) (100)^2}{(30.827) (9.807)} = 2.65$$

Step 3. From Figure 4-5  $\frac{\rho_0 C_D A_D R}{M}$  = 1.65 and solving for R

results in a range of 635.8 meters (2086 ft).

Program FRISB results show the maximum range to be 633.43m (2078 ft).

Percent error =  $\frac{635.8 - 633.43}{633.43}$  X 100 = 0.37%

# Predicting Ranges of Rocketing Fragments

In an accident involving propellant (propane, butane, etc.) storage systems, large fragments (greater than one-fourth of the vessel), which travel long distances, are sometimes generated. These large fragments are typically sections of the tank which break free intact and initially contain some entrapped propellant. These large fragments exhibit a rocketing behavior (see Appendix E) which results from the changing of all or part of the liquid propellant into a gas when the external pressure is released during the fracturing of the vessel (flash evaporation). The gas escapes from the opening in the vessel in a manner similar to gas exiting a rocket motor and propels the somewhat stabilized fragment to great distances.

The physics of this process is explained in greater detail in Appendix F. This appendix also contains a computer program for predicting the range and impact velocity of the rocketing

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fragment. As explained in the model analysis in Appendix G, this phenomenon is not readily adaptable to consolidated prediction curves and requires some further development effort in this area. Therefore, for the present, in order to predict the distance traveled by "thrusting" fragments, one must either run the computer program in Appendix F or acquire the values from Table 4-2, (see Appendix G, p. 7) if the storage tanks and fragments being examined have characteristics similar to the vessels and fragments contained in the table. Table 4-2 was generated for comparison to some accident reports. Calculated values for fragment ranges were in good agreement with actual values, considering limitations in available information. In general, rocketing fragments from accidents of this type have low launch angles (5-10 degrees). To determine range, or impact velocity, of rocketing fragments (see Table 4-2 and/or Appendix F), one needs to know the pressure of the fluid at rupture, the volume of the container, the volume partially enclosed by the fragment, the volume of the liquid before rupture, the volume of the vapor before rupture, the exit area for the propellant contained in the fragment, the mass of the fragment, and the launch angle of the fragment.

4-4 Statistical Analysis of Fragments

### Statistical Analysis of Accidental Explosions

### Introduction

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Data were gathered on twenty-five events. A detailed description of these events, in terms of the explosive source and the containment vessel, is given in Table H-1 in Appendix H. Table H-2 in Appendix H gives available fragment information (mass, range, trajectory elevation and shape) for each event.

Due to the limited amount of data on most of the events, it was desirable to group the data from like events in order to yield an adequate base for meaningful statistical analysis. From Tables H-1 and H-2, the six groups of like events shown in Table 4-3 were obtained. Statistical analyses were performed on data from each of the groups to yield (as the data permitted) estimates of fragment range distribution, fragment mass distribution and fragment mean velocity as a function of the ratio of explosion energy to vessel weight. Other relationships were also investigated and the results are given in the following paragraphs.

### Fragment Range Distribution

As shown in Appendix H-2, the fragment range for each of the groups of events follows a log normal distribution. That is, the logarithms of the fragment ranges follow a normal or

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TABLE

BEST ESTI- MATE FOR LAUNCH AN-	2	Ś	Ś	5-10	510	5-10	5-10
PERCENT DIFFERENCE IN RANGE	36	18	-6.7	266	~ 588	-27	40 3
ACTUAL RANGE	314	398	165	123	123	123	123
CALCU- LATED RANGE	426	471	154	450	846	6	179
CALCULATED IMPACT VELOCITY (m/c)	194	189	76	159	154	72	ĩ
LAUNCH ANGLE (degrees)	5	ŝ	ŝ	Ś	10	ۍ	10
MASS OF FRAGMENT (kz)	3885	506 î	652	11	171	171	171
EXIT AREA (m <sup>2</sup> )	57.E	14.6	3.41	2.336	2.336	0.6567	0.6567
VOLUME OF VAFOR BE- FORE RUPTURE (m <sup>3</sup> )	4.916	10.56	10.56	0.3067	0.3067	0.3067	0.3067
VOLUME OF LIQUID BE- FORE RUPTURE (m <sup>3</sup> )	<b>33.</b> 10	27.29	27.29	1.586	1.586	1.586	1.586
VOLUME OF FRAGMENT ENCLOSURE (m <sup>3</sup> )	28.23	30.32	1.28	0.5513	0.5513	0.2002	0.2002
VOLUME OF CONTAINER (a <sup>3</sup> )	38.02	37.85	37.85	1.8927	1.8927	1.8927	1.8927
LNITIAL PRESSURE (P <sub>a</sub> )	701,197	1,034,214	1,034,214	1, 378, 951	1, 378, 951	1, 378, 951	1, 378, 951
SOURCE OF ACTUAL DATA	NTSB- HAR- 76-4 4/29/75	NTSB- HAR- 73-4 9/21/72	NTSB- HAR- 73-4 9/21/72	Propane Tank Explosion in San Antonio	Propane Tank Explosion in San Antonio	Propane Tank Explosion in San Antonio	Propane Tank Explosion in San Antonio
EXAMPLE NUMBER	I	8	m	4.8	4 <b>b</b>	4 C	P*

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	Number of Fragments	14	28	35	31	14	11
Vessel	Mass, kg	25,542 to 83,900	25,464	145,842	6,343 to 7,840	46.26 to 187.33	511.7
	Shape	RR Tank Car	RR Tank Car	Cylinder Pipe and Spheres	Semi Trailer (cylindrical)	Sphere	Cylinder
n Source	Energy Range, J	1.487X10 <sup>5</sup> to 5.95X10 <sup>5</sup>	3814 to 3921.3	5.198X10 <sup>11</sup>	549.6	2.438X10 <sup>9</sup> to 1.133X10 <sup>10</sup>	24.78
Explosic	Material	Propane, anhydrous ammonia	LPG	Air	LPG, Propylene	Argon	Propane
	Event	1,2,3,18	6,7,8,9,10, 13,14,15,19	17	20,24	21,22,23	25
	Event Group Number		7	m	4	ъ	9

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Gaussian distribution. Figure 4-6 presents the fragment range distributions for groups 1 and 2, and Figure 4-7 presents the fragment range distributions for groups 3, 4, 5 and 6.

Figures 4-6 and 4-7 can be used to estimate the percentage of fragments which will have a range,  $R_i$ , equal to or less than a particular range.

For example, if we wished to estimate the percentage of fragments which would have a range equal to or less than 600 m for an explosion involving a rail tank car filled with propane (group 1), we would refer to Figure 4-6, and on the range axis (abscissa) at 600 m go upward to the intersection of the group 1 line. Then, at the intersection point read the percentage value from the ordinate, which is 96%. Conversely, if we wanted to know what range 90% of the fragments would not exceed, we would enter the chart on the 90% line, go over to the intersection of the group 1 line and read downward to the range axis the value of 380 m.

### Fragment Mass Distribution

Pertinent fragment mass information was available on three event groups (2, 3 and 6). As shown in Appendix H-3, the fragment mass for each of the three groups follows a log normal distribution. Figure 4-8 presents the fragment mass distributions for groups 2 and 3, and Figure 4-9 presents the fragment mass distribution for group 6.

These charts can be used in the same manner as Figures 4-6 and 4-7 are used for fragment range.

# Mean Fragment Mass as a Function of Normalized Yield

In events 21, 22 and 23, spherical containers were pressurized until rupture. The spheres were constructed of steel with an approximate ultimate stress ( $\sigma_u$ ) of 834 MPa. The spheres were the same volume for all three events. The wall thickness of the spheres was the same within events, but was different across events.

Pertinent data and calculated parameters for each of the spheres are given in Table 4-4, where  $\overline{W}$  is the geometric mean fragment mass for each event, W(T) is the sphere weight for each event,  $\overline{P}$  is the average burst pressure for each event, and  $E_0$  is the energy of detonation of 1 gram of TNT or 4190J.

Figure 4-10 is a plot of the normalized yield  $(\overline{PV}/E_0)$  versus mean fragment mass  $(\overline{W})$  for the three events. One could estimate the mean (geometric) fragment mass for any decided ratio of  $\overline{PV}/E_0$  from 693 to 2347.

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The correlation coefficient, r, for the regression equation shown on Figure 4-10 was 0.9999, which indicates a high degree of correlation between  $\overline{PV}/E_{\Omega}$  and  $\overline{W}$ .

### Correlation Between Fragment Range and Fragment Mass Within Event Groups

Only three event groups (2, 3 and 6) contained sufficient fragment range and mass data for correlation analysis. Various curve fitting techniques were employed to determine if a predictable relationship existed between fragment range and mass as indicated by the data on the three events. Appendix H-4 contains a description of the techniques and the results.

Figure 4-11 depicts the relationship of the fragment range to fragment mass for Group 2. The correlation coefficient is 0.79.

Figure 4-12 shows the relationship of the fragment range to fragment mass for Group 6. The correlation coefficient is 0.68.

### Correlation of Fragment Range to the Ratio of Mean Fragment Weight to Vessel Weight for Cylindrical Tanks

Five events contained sufficient information for this type of analysis. Data for each of the events are contained in Appendix H-5. Figure 4-13 is a plot of the mean (arithmetic) fragment weight versus the ratio of mean fragment weight to the vessel weight for the events.

From Figure 4-13, one could estimate the mean fragment range for any decided ratio of mean fragment weight to vessel weight for the types of tanks in the events.

### Correlation of Fragment Velocity to the Ratio of Energy to Vessel Weight

Only in event group 5 were there reports of mean velocity for fragments. Figure 4-14 is a plot of the relationship between the mean fragment velocity and the ratio of the energy to vessel weight. The velocities were chosen as the maximum velocity reported within an event for events 21, 22 and 23 (see Table 4-4). The correlation coefficient for the regression equation is 0.93.

One could use Figure 4-14 to predict the average velocity for fragments from bursting steel spheres over a range of an energy to vessel weight ratio of  $4.5 \times 10^7$  to  $6.05 \times 10^7$ . However, the analytic predictions for fragment velocity presented earlier in this chapter are more useful because they cover a much wider range of bursting vessel conditions.

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# TABLE 4-4. PARAMETERS OF BURSTING SPHERES

(2) Eo	693.43			1541.6		2347.1	
Average(1) Fragment Weight, W, kg	23,14			55.69		89.75	
Energy, J	2.438X10 <sup>9</sup>			6.078X10 <sup>9</sup>		1.133X10 <sup>10</sup>	
Vessel Weight WT,(kg)	46.26	46.46	46.26	136.08	136.08	187.33	187.33
Volume, V (m <sup>3</sup> )	.0283	.0283	.0283	.0283	.0283	.0283	.0283
Burst Pressure,P, Pa	1.044X10 <sup>8</sup>	1.030X10 <sup>8</sup>	1,006X10 <sup>8</sup>	2.372X10 <sup>8</sup>	2.193X10 <sup>8</sup>	3.475X10 <sup>8</sup>	3.475X10 <sup>8</sup>
Fragment Average Velocity, (m/s)	96.9	98.6		107.59	83.52	65.84	71.63
Fragment Mass, Kg	22.49 23.77	22.36 23.90	23.18 23.18	69.18 66.90	48.99 42.41	117.03 70.03	122.92 64.41
Shot No.	I	8	Q	m	7	4	<u>ب</u>
vent	21			22		23	

(1) Geometric mean fragment mass (2)  $\vec{P}$  = Average burst pressure

P = Average burst pressure E<sub>0</sub> = Energy of detonation of 1 g TNT Į



FIGURE 4-10. NORMALIZED YIELD VERSUS MEAN FRAGMENT WEIGHT FOR BURSTING SPHERES

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FIGURE 4-14. MAXIMUM MEAN VELOCITY VERSUS RATIO OF ENERGY TO VESSEL WEIGHT FOR BURSTING SPHERES

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### LIST OF REFERENCES

- 1. Baker, W. E., Kulesz, J. J., Ricker, R. E., Bessey, R. L., Westine, P. S., Parr, V. B. and Oldham, G. A. (1975), "Workbook for Predicting Pressure Wave and Fragment Effects of Exploding Propellant Tanks and Gas Storage Vessels", NASA CR-134906, Contract NASA-19231, November 1975 (reprinted September 1977).
- Taylor, D. B. and Price, C. F. (1971), "Velocities of Fragments From Bursting Gas Reservoirs", <u>ASME Transactions</u>, <u>Journal of Engineering for Industry</u>, November 1971.

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### CHAPTER V

### EFFECTS OF FRAGMENTS AND RELATED TOPICS

### 5-1 General

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In Chapter V of Baker, et al (1975), some methods were given for prediction of effects of impact of typical fragments from accidental explosions involving flight-weight hardware. For the even more massive fragments typical of explosions in ground systems, the voluminous literature on terminal effects of military fragments and projectiles is of very little use. But, since the earlier workbook was prepared, some data and prediction methods have been developed related to impact effects of tornado-borne missiles. Generally, this class of missile lies within the range of masses and velocities shown in Chapter IV for fragments from explosions in ground systems. Wooden poles and planks, pipes, pieces of steel reinforcing bar, and more massive bodies such as compact cars and entire storage tanks have been picked up and hurled at damaging velocities by tornadoes. Much of this work is summarized in Peterson (1976), and has its impetus in tornadoproof design requirements for nuclear plants.

Similarly, new nuclear plants must now be designed to be proof against other accidents including crash of aircraft on the containment structures, and external vapor-cloud explosions. Some preliminary design methods have evolved for massive, nonpenetrating missile impacts to meet the aircraft crash design requirements. Typical of recent literature references to this problem are Drittler and Gruner (1976 a and b) Hammel (1976), and Degen, et al (1976). But in spite of these recent additions to the literature, we feel that impact effects of quite massive, but crushable, missiles are not well enough known to be reduced to design graphs in this workbook.

In Baker, et al (1975), methods were given to predict velocities of fragments and objects located near accidental explosions (appurtenances). In preparing this workbook, we were asked to consider modifying these procedures to account for the twodimensional character of some accident blast waves. Although we have generated some graphs for the prediction of two-dimensional blast wave properties in Chapter II, these are not extensive enough to allow modification of the previous procedures. We suggest that at present the reader simply use the procedures in the previous workbook.

In certain fixed ground installations having a high potential for accidental explosion, or limited real estate, barricades may be built in an attempt to attenuate blast waves and to reduce fragment hazards. The barricades may be earth berms, retaining

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walls backed by earth fill, or built-up walls of reinforced concrete, timber, or steel construction. Unless structures to be protected are located very close to the barricades, they are almost totally ineffective in attentuating blast waves. The waves simply diffract over the barricades and reform. Barricades are, however, quite effective in arresting fragments and may be worth constructing for that purpose alone. We will give some prediction graphs for blast attentuation for barricades of several forms located close to protected structures. No data or proven prediction methods exist for effects of barricades on non-ideal blast waves, so the predictions will be limited to attentuations for condensed high explosives.

## 5-2 Penetration Effects of Massive Missiles

Some prediction methods of penetrating effects of massive missiles can be added to the methods in Baker, et al (1975). The "targets" for these missiles are primarily reinforced concrete or steel plate panels or walls.

### Concrete Panels

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Concrete containment walls are very likely to be struck by fragments generated by an accidental explosion. Unfortunately, analytical prediction of penetration phenomena is in many ways more difficult for concrete than for homogeneous materials. This is due to the inhomogeneity of the panels and to the different construction techniques in use today--prestressing and posttensioning, for example. In addition, since concrete targets are so expensive to fabricate, the amount of extant test data is limited.

Figure 5-1 shows schematically three different mechanisms of missile impact damage. At low velocities, the missile strikes the panel and rebounds without causing any local damage. As the velocity increases, pieces of concrete are spalled (ejected) off of the front or impacted face of the target. This spalling forms a spall crater that extends over a substantially greater area than the cross-sectional area of the striking missile. As the velocity continues to increase, the missile will penetrate the target to depths beyond the depth of the spall crater, forming a cylindrical penetration hole with a diameter only slightly greater than the missile diameter. As the penetration depth increases, the missile will stick to the concrete target rather than rebounding. At this stage the impact meets the criterion of a "plastic" impact. However, even at lesser penetration depths the impact can be approximately treated as a plastic impact when determining the energy absorbed by the impacted target. Further increases in velocity produce cracking of the concrete on the back surface followed by scabbing (ejection) of concrete from this rear surface. The zone of scabbing will generally be much wider, but not as deep as the front face spall crater. One scabbing begins, the

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depth of penetration will increase rapidly. For low barrier thickness to missile diameter ratios (less than 5), the pieces of scabbed concrete can be large in size and have substantial velocities. As the missile velocity increases further, perforation of the target will occur as the penetration hole extends through to the scabbing crater. Still higher velocities will cause the missile to exit from the rear face of the target.



- (a) Missile penetration and spalling
- (b) Target spalling and scabbing
- (c) Missile perforation

Figure 5-1. Missile Impact Damage [Kennedy (1976)]

Upon plastic impact, portions of the total kinetic energy of the impacting missile are converted to strain energy associated with deformability of the missile, and energy losses associated with target penetration. The remainder of the energy is absorbed or inputted to the impact target. This absorbed energy results in overall target response that includes flexural deformation of the target barrier and deformation of its supporting structure.

Currently depth of penetration, perforation and scabbing thickness are being predicted using one of several empirical formulas. These equations are based on experiments conducted prior to 1946 for concrete slabs perforated by projectiles and bombs. The most commonly used formulas are the modified Petry, Army Corps of Engineers, modified NRDC, the Amman and Whitney, and the BRL. [These formulas and their limitations and limits of applicability are summarized by Kennedy (1976)]. All of these formulas were derived for a nondeformable projectile (often made from armor-piercing steel) impacting normal to the target face.

In 1946 the National Defense Research Committee proposed a theory of penetration for a short, nondeforming projectile pene-

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trating a massive concrete target which offered a good approximation of the experimental results. This theory of penetration enables one to not only calculate the total depth of penetration, but also to calculate the impact force-time history and penetration-depth time history. Based upon this theory of penetration, the National Defense Research Committee (NDRC) proposed that the penetration depth x be obtained from

$$G_{(x/d)} = KNd^{0.20}D (V_S/304.7)^{1.80}$$
 (5-1)

where

$$G_{(x/d)} = \begin{cases} (x/2d)^2, \text{ for } x/d \leq 2.0 \\ [(x/d) - 1], \text{ for } x/d \geq 2.0 \end{cases}$$
(5-2)

and

- K = Concrete penetrability factor (measures the resistance of concrete to penetration) (m<sup>2</sup>·<sup>8</sup>/kg).
- N = Projectile nose shape factor: 0.72 for flat nose shapes, 0.84 for blunt bodies, 1.0 for average bullet nose, and 1:14 for very sharp nose.
- d = Projectile diameter (m). The equations presented herein are based entirely on cylindrical projectiles. For arbitrary shaped fragments, d is the diameter of an equivalent cylindrical projectile with the same contact surface area as the actual missile.
- $D = M/d^3$  = caliber density of the projectile (kg/m<sup>3</sup>)
- $V_c$  = Missile striking velocity (m/s).
- x = Total penetration depth (m); the depth a missile will penetrate into an infinitely thick target. This neglects all rear face boundary effects and therefore applies only when target thickness is sufficient to prevent scabbing at the rear face.

The primary advantage of this formula is that, since it is based on a theory of penetration, it can be extrapolated beyond the range of available test data with greater confidence than is true with the other equations. Unfortunately, because of the reduction of interest in projectile penetration of concrete after 1946, the NRDC effort was aborted before the factor K was completely defined.

According to the NDRC report, K should lie between 2 and 5 (in English units), depending upon the concrete strength, to fit the available test data. Based upon both theoretical and experi-

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mental considerations, it was suggested in 1966 that the concrete penetrability factor K is proportional to the reciprocal of the ultimate concrete tensile strength, which in turn was taken to be proportional to the square root of the ultimate concrete compressive strength  $f_C$ . By fitting this relationship to the experimental data available for the larger missile diameters, the following relationship for K was obtained:

$$K = 1.134/(f_{c})^{1/2} (m^{2.8}/kg)$$
(5-3)

The combination of Equations 5-2 and 5-3 is defined herein as the modified NDRC formula for penetration.

For slab thickness to projectile diameter ratios greater than three, Equation 5-1 can be used in conjunction with Equations 5-4 and 5-5 for predicting perforation and scabbing thicknesses.

e/d = 1.32 + 1.24 (x/d), for  $(3 \le e/d \le 18)$  (5-4)

s/d = 2.12 + 1.36 (x/d), for  $(3 \le s/d \le 18)$  (5-5)

where

e = perforation thickness (m); the maximum thickness of concrete which will be completely penetrated by missile at a given velocity.

and

s = scabbing thickness (m); thickness of a target required to prevent scabbing of material from the backface for a missile with a given velocity.

However, for many impact problems, the slab thickness to projectile diameter is substantially less than three. Beth (1945) gives a curved-fit extrapolation of these equations for slab thickness to projectile diameter ratios less than three so that the equation would pass through the origin. Parabolic fits which both pass through the origin and have the same slope as Equations 5-4 and 5-5 at a slab thickness to projectile diameter ratio of three have been proposed [Kennedy (1976)]. This parabolic fit

$$\frac{e}{d} = 3.19 \left(\frac{x}{d}\right) - 0.718 \left(\frac{x}{d}\right)^2, \text{ for } x/d \le 1.35, \quad (5-6)$$
$$\frac{s}{d} = 7.91 \left(\frac{x}{d}\right) - 5.06 \left(\frac{x}{d}\right)^2 - \text{ for } x/d \le 0.65, \quad (5-7)$$

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whereas for larger x/d ratios, Equations 5-4 and 5-5 are to be used. These modifications, when used together with Equations 5-2 and 5-3, are known as the modified NDRC formulae for perforation and scabbing. Their primary advantage over the other formulae is that they can be extrapolated to slab thickness to projectile diameter ratios less than three without leading to unreasonable results.

All of the formulas for concrete penetration are based on a limited range of parameter variation. Unless otherwise noted, these formulas are valid only for the following ranges:

 $t/d \ge 3$   $d \le 0.4 \text{ m}$   $5.5 \times 10^3 \text{ kg/m}^3 \le D \le 2.20 \times 10^4 \text{ kg/m}^3$   $500 \text{ m/s} \le V \le 3000 \text{ m/s}$   $3 \le e/d \le 18$   $3 \le s/d \le 18$ (5-8)

For long rods impacting concrete panels, recent model and full-scale testing of simulated tornado-borne missiles also gives prediction methods for scabbing thresholds for reinforced concrete panels. Sources for the basic data are discussed, and the curves generated, by Baker, Hokanson, et al (1976).

Figure 5-2 gives scabbing thresholds for steel pipes impacting normally on lightly reinforced concrete panels, with rebar percentages <1%. In this figure, KE is impact kinetic energy, h is concrete panel thickness, d is pipe outside diameter, and tw is pipe wall thickness. Length-to-diameter ratios are variable, but all are greater than 5:1. Each curve gives the scabbing threshold for a particular wall thickness ratio.

Curves for scabbing caused by normal impact of solid rods, of material strong compared to the concrete, are given in Figure 5-3. The thresholds are quite different for slabs which are reinforced heavily enough for the rebar spacing to be significantly closer than the rod diameter (heavy reinforcing) and for spacing open enough that a rod can pass through without striking a rebar (light reinforcing). Rods were of  $\ell/d$  ratios ranging from 1.75-40. A number of long wooden missiles were also fired against reinforced concrete panels, but these missiles were invariably defeated by the panels, with negligible damage to the panels themselves.

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FIGURE 5-2. SCABBING THRESHOLD FOR MILD STEEL PIPES IMPACTING REINFORCED CONCRETE PANELS

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FIGURE 5-3. SCABBING THRESHOLDS FOR SOLID ROD MISSILES IMPACTING REINFORCED CONCRETE PANELS

#### Steel Panels

In Baker, et al (1975), prediction curves have already been given for perforation thresholds for thin metal impacted by chunky fragments of essentially nondeforming material. Long, deforming missiles, such as wood poles, can also perforate steel plate panels. Baker, Hokanson et al (1976) fit a penetration threshold curve for wooden missiles impacting large steel panels normally. This curve is reproduced here as Figure 5-4, and the empirically-fitted equation is given by

$$\frac{\rho_{\rm p} V_{\rm s}^2}{\sigma_{\rm t}} = 1.751 \left(\frac{h}{d}\right) \left(\frac{\ell}{d}\right)^{-1} + 144.2 \left(\frac{h}{d}\right)^2 \left(\frac{\ell}{d}\right)^{-1}$$
(5-9)

Here,  $\rho_p$  is density of projectile material,  $V_s$  is striking velocity, and  $\sigma_t$  is yield strength of the steel plate material. Figure 5-4 applies for the test length-to-diameter ratio,  $\ell/d = 31.1$ .

In using the empirically-fitted curves in Figures 5-2, 5-3 and 5-4, the reader is cautioned to avoid extrapolation. Equation 5-9 should also be limited to the ranges:

$$5 \le \ell/d \le 40$$
(5-10)
  
0.042 \le h/d \le 0.1

#### Example 1:

A flat-ended cylindrical steel rod, with a mass M of 8 kg and diameter d of 75 mm impacts a thick concrete wall with compressive strength  $f_{c} = 26$  MPa at a striking velocity  $V_{s} = 600$  m/s. What is the penetration depth x, perforation thickness e, and scabbing thickness s?

Step 1. Calculate K from Equation 5-3.

$$K = 1.134/(26 \times 10^6)^{1/2} = 2.224 \times 10^{-4} m^{2.8} kg$$

Step 2. Chose projectile nose shape factor N. This is 0.72 for the flat nose shape.

Step 3. Calculate caliber density D from its definition.

$$D = M/d^3 = 8/(0.075)^3 = 1.896 \times 10^4 \text{ kg/m}^3$$

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FIGURE 5-4. PREDICTION OF PENETRATION THRESHOLD FOR STEEL PANELS IMPACTED BY WOODEN PROJECTILES WITH  $\ell/d = 31.1$ 

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Step 4. Substitute in Equation (5-1) and calculate G.

 $G = 2.224 \times 10^{-4} \times 0.72 \times 0.075^{0.2} \times 1.896 \times 10^{4} \left(\frac{600}{304.7}\right)^{1.8}$ 

$$G = \underline{6.124}$$

Step 5. Use Equation (5-2) to calculate penetration x. Assume that (x/2d) > 2.0. Then, (x/d) = 1 + G = 1 + 6.124 = 7.124.

x = 7.124 d = 7.124 x 75 = 534 mm = 0.534 m

Step 6. Use Equation (5-4) to calculate e.

Step 7. Use Equation (5-5) to calculate s.

#### Example 2:

A steel rod of diameter d = 25 mm with a mass M = 10 kg impacts a heavily reinforced concrete wall which has a thickness h = 100 mm with an impact velocity v = 60 m/s. Will the wall scab?

Step 1. Calculate impact kinetic energy.

KE = 
$$(\frac{1}{2})$$
 MV<sup>2</sup> =  $\frac{1}{2}$  x 10 x 60<sup>2</sup> = 18kJ

Step 2. Calculate scaled kinetic energy.

$$\frac{\text{KE}}{\text{h}^3} = \frac{18 \times 10^3}{0.1^3} = 18 \text{ MPa}$$

and scaled target thickness

$$\frac{h}{d} = \frac{100}{25} = 4$$

Step 3. Enter Figure 5-3, and plot intercept from Step 2. This lies well <u>above</u> the threshold curve for heavy reinforcing, so scabbing <u>should</u> occur.

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Example 3:

A long steel pipe with d = 75 mm,  $t_w = 3.0 \text{ mm}$  impacts a 100 mm reinforced concrete panel at 20 m/s. It has a mass of 10 kg. Will it cause scabbing?

Step 1. Calculate impact kinetic energy.

$$KE = \frac{1}{2} \times 10 \times 20^2 = 2 \text{ kJ}$$

Step 2. Calculate scaled kinetic energy, and scaled target thickness, scaled wall thickness

$$\frac{\text{KE}}{\text{h}^3} = \frac{2 \times 10^3}{0.1^3} = 2 \text{ MPa}$$

$$\frac{h}{d} = \frac{75}{100} = 0.750$$

$$\frac{2t_{\rm w}}{d} = \frac{2 \times 3}{75} = 0.08$$

Step 3. Enter Figure 5-2. In this case, our intercept lies along the bottom line and somewhat to the left of the curves. We wish to compare to the middle curve, for which scaled wall thickness is 0.08. We cannot say unequivocally whether scabbing will or will not occur, because we are beyond the range of the fitted curves.

#### Example 4:

A wooden post is hurled against a steel curtain wall at 100 m/s. The post has a diameter d = 150 mm, a length l = 4.5 m, and a density  $\rho_p$  = 650 kg/m<sup>3</sup>. The steel curtain wall is 6 mm thick and has a yield strength  $\sigma_t$  = 240 MPa. Will the post penetrate?

Step 1. Calculate scaled quantities to enter Equation (5-9).

$$\frac{h}{d} = \frac{6}{150} = 0.04$$
$$\frac{\ell}{d} = \frac{4500}{150} = 30$$

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Step 2. Calculate scaled striking velocity from Equation(5-9) for incipient penetration.

$$\frac{\frac{\rho_{p} V_{s}^{2}}{\sigma_{t}}}{\frac{\rho_{p} V_{s}^{2}}{\sigma_{t}}} = \frac{1.751 \times 0.040}{30} + \frac{144.2 \times 0.04^{2}}{30}$$
$$\frac{\frac{\rho_{p} V_{s}^{2}}{\sigma_{t}}}{\frac{\rho_{p} V_{s}}{\sigma_{t}}} = \frac{1.00 \times 10^{-2}}{100}$$

Step 3. Calculate scaled striking velocity from input parameters, and compare to threshold value.

$$\frac{\rho_{\rm p} V_{\rm s}^2}{\sigma_{\rm t}} = \frac{650 \times 100^2}{240 \times 10^6} = \frac{2.71 \times 10^{-2}}{1000}$$

This value is more than double the threshold for penetration, so the wood post goes through the steel curtain wall like a knife through hot butter.

5-3 Effects of Barricades on Blast Waves

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Barricades are constructed either near potential explosion sources or near structures and facilities located in the vicinity of potential explosion sources. As noted earlier, they are intended as protective devices to arrest fragments or attenuate blast waves.

The two most common types of barricades are earthworks (mounds), and earthworks behind retaining walls (singlerevetted barricades). The definitions of these types of barricades, taken from Department of Defense explosive safety regulations, follow:

Mound. An elevation of earth having a crest at least 3 feet wide, with the earth at the natural slope on each side and with such elevation that any straight line drawn from the top of the side wall of a magazine or operating building or the top of a stack containing explosives to any part of a magazine, operating building or stack to be protected will pass through the mound. The toe of the mound shall be located as near the magazine, operating building, or stack as practicable.

Single-Revetted Barricade. A mound which has been modified by a retaining wall, preferably of concrete, of such slope and thickness as to hold firmly in place the 3-feet width of earth required for the top, with

the earth at the natural angle on one side. All other requirements of a mound shall be applicable to the single-revetted barricades.

Most of the useful data on attenuation of blast effects behind barricades appear in a single reference, Wenzel and Bessey (1969). Scaled tests for both mound and single-revetted barricades, with spherical Pentolite explosion sources generating the blast waves, were conducted for the explosion sources near the barricades (near field) and near the protected structure (far field). Specific configurations tested are shown in Figure 5-5. All explosive spheres were located at scaled height  $\overline{H} = 0.036$  above an armor plate reflecting surface to eliminate cratering effects, at the scaled distances  $\overline{R}$  shown in Figure 5-5. The barricade dimensions were scaled to represent full-size barricades with heights h of about 3 m and 6 m.

The principal conclusions reached by Wenzel and Bessey (1969) as a result of their tests were:

- Barricades do reduce the peak pressures and impulses immediately behind the barricades.
- Single-revetted barricades are more efficient in reducing peak pressures and impulses than mound barricades.
- 3) Values of peak pressure and impulse are greatly influenced by the gage height relative to the ground, the location of the barricade, and the barricade dimensions and configurations.
- 4) In the near field case for single-revetted barricade configurations, a significant reduction of pressure and impulse was observed out to scaled distances of R = 1. Beyond that distance, the peak pressures tend to approach those of the free field case very rapidly, and the impulses also tend to approach those of the free field case but not as rapidly as the peak pressures. The times of arrival in specific locations are greater than those of the free field case up to scaled distances of R = 1.6. At scaled distances greater than R = 1.6they approach rapidly those of the free field case.

Definitions for scaled distance are given in Chapter II.

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- 5) In the near field case, mound configuration, the peak pressures and impulses are not greatly reduced, and actually are increased over the free field case at a scaled gage height of  $\overline{H}_{g} = 0.02$  and a scaled distance of  $\overline{R} = 0.43$ . However, the pressure and impulse observed at the scaled gage height of  $\overline{H}_{g} = 0.05$  at  $\overline{R} = 0.32$  are both less than the free field values. There was a considerable decrease in pressure and impulse for the gage located at  $\overline{R} = 4.84$  and scaled height of  $\overline{H}_{g} = 0.016$ , respectively. The times of arrival were the same as those observed in the free field case for all scaled distances and scaled heights.
- 6) For the far field case, single-revetted barricade configuration, the peak pressures and impulses were significantly reduced immediately behind the barricade; however, their individual values varied as a function of gage height. The times of shock arrival were the same as those observed in the free field case for all stations measured.
- 7) For the far field case, mound configuration, the same observations as those made for the single-revetted case can be made here except that the effect of the barricades is considerably less than for the single-revetted configurations.

The blast attenuation caused by mound barricades, although measurable in the experiments cited above, is small enough to be essentially negligible, for the purposes of this workbook. Similarly, the attenuation for single-revetted barricades in the far-field case is so localized and directional that no general predictions can be made. But, for the single-revetted barricades in the near field, we can give scaled curves for blast wave properties which are attenuated from surface burst explosion waves without barricades. Figure 5-6 shows variation of scaled side-on overpressure  $\overline{P}_S$  with scaled distance  $\overline{R}$  for this configuration, for surface burst explosive charges without barricade and with single-revetted barricade. Similarly Figure 5-7 gives variation of scaled scaled scaled scaled side-on pressures  $\overline{I}_S$  versus  $\overline{R}$  for this situation.

These curves should only be used to predict blast attenuations over the ranges of scaled distances shown, i.e.,  $0.35 \le R \le$ 9.0. They should also be applied with caution for blast sources other than condensed explosives because there are no extant data for effects of barricades on the non-ideal blast waves from accidental explosions. Data scatter for the peak overpressure curves is about  $\pm 5\%$ , and for the impulse curves, about  $\pm 10\%$ .

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FIGURE 5-7. EFFECT OF NEAR-FIELD, SINGLE-REVETTED BARRICADE ON SIDE-ON IMPULSE

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## Example Problem

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A single-revetted barricade is located close to a propellant storage source with potential blast energy E = 1000MJ, calculated by methods given in Chapter I. If the source explodes, what are the incident blast wave parameters at a distance of 100 m? The site is located near sea level, with  $p_0 = 1.01 \times 10^5$  Pa and  $a_0 = 340$  m/s.

Step 1. Calculate scaled distance  $\overline{R}$ . It is defined as (see Chapter II).

$$\overline{R} = R p_0^{1/3} / E^{1/3}$$

$$\overline{R} = \frac{100 \times (1.01 \times 10^5)^{1/3}}{(10^9)^{1/3}} = \frac{4.66}{100}$$

Step 2. Enter Figures 5-6 and 5-7 to obtain scaled overpressure and impulse. From dashed curves,

$$\overline{P}_{s} = 0.070, \overline{I}_{s} = 0.0087$$

Step 3. "Unscale" to obtain blast parameters.

$$P_{s} = \overline{P}_{s} \times P_{o} = 0.070 \times 1.01 \times 10^{5} = \frac{7.07 \text{ kPa}}{2.07 \text{ kPa}}$$

$$I_{s} = \frac{\overline{I}_{s} \times P_{o}^{2/3} \times E^{1/3}}{a_{o}} = \frac{0.0087 \times (1.01 \times 10^{5})^{2/3} \times (10^{9})^{1/3}}{340}$$

$$I_s = 55.5 \text{ Pa} \cdot s$$

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#### CHAPTER VI

#### DISCUSSION AND RECOMMENDATIONS

We believe that this workbook should be a definite aid to designers and safety engineers in predicting damage and hazards from accidental explosions in ground handling systems. It should prove to be a useful adjunct to our earlier workbook for predicting explosion hazards in flight systems, NASA CR-134906. For the convenience of the reader, microfiche copies of the earlier work are attached to each copy of this report.

Parts of this work should have wider application than indicated by the title. The additional methods for rapid structural damage prediction can be used for any blast source, provided the peak overpressures and positive impulses can be predicted. The computer programs and methods for prediction of velocities and trajectories of lifting fragments and thrusting burst vessels can be effectively applied to transportation accidents with tank cars and tank trucks containing many types of pressurized fluids, in addition to rocket propellants. The methods for estimating explosive energy release for flash-evaporating fluids can be used to predict severity of boiler explosions, or severity of blast for any type of liquid and gas mixture stored under high pressure. The data and prediction methods for effects of impact of massive fragments or missiles are not limited to fragments generated by accidental explosions in ground handling systems, and indeed were taken from other related studies.

A number of prediction waves are given in this work for the characteristics of blast waves from bursting gas pressure vessels, and some for bursting vapor spheres. These waves exhibit some characteristics which are distinctly different from blasts from condensed explosives such as TNT, including pronounced negative phases and pronounced second shocks. Most structural response or damage analyses account only for pressures and impulses in the first positive phase, and we therefore recommend further study of responses to waves with characteristics such as in Figure 2-8. It would also be very desirable to conduct more scaled experiments with bursting, pressurized vessels, to generate additional blast prediction curves. These should probably include:

1) Tests with light gases such as helium.

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2) Tests of bursting spheres filled with vapors of higher saturation pressure such as Freon-22, Freon-13, or sulfur hexafluoride (SF6) to better determine the effect of sphere pressure on the overpressures measured.

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- 3) Tests using the same fluids as above but in liquid form just above saturation pressure at room temperature.
- 4) Tests using flash-evaporating fluids in liquid form at a high-pressure heated above room temperature to just below the saturation temperature.

Concurrent with the continuation of study of the character of blast waves from accidental explosions, one should also review, and alter if necessary, the prediction methods for structural response and damage in this workbook, in NASA CR-134906, and related references which assume that the wave can be described as a simple, single pulse. The basic analytic tools to do this are readily available, but application to as complex a loading pulse as Figure 2-8 will require careful application of these techniques, and almost invariably, some increase in complexity of response prediction.

For reasons of economy, this workbook, unlike NASA CR-134906, contains no assessment of accident scenarios for typical situations which have occurred or could occur in ground transport or storage of liquid propellants and compressed gases. A supplement containing evaluations and predictions of blast and fragment effects for a number of cases, should prove useful and instructive to safety engineers.

Several related and potential problems with potentially explosive ground storage and transport systems could perhaps be addressed in following studies. One question concerns planning of in-service testing of pressure storage vessels to avoid or prevent accidental explosions. Many new and effective nondestructive testing methods and equipment have been developed in recent years, and applied in industries such as the nuclear power industry. For storage vessels of large volume and/or high pressure, where the hazards are great in the event of vessel failure, the frequency or thoroughness of such testing might be increased.

This workbook includes a number of prediction methods for fragment and missile impact conditions and locations near explosions, and some relatively new data and prediction curves for effects of impacts of relatively massive missiles. There is still a serious lack of data on massive missile impact effects. Scale model techniques have proven to be efficient in gathering enough data rapidly and relatively inexpensively to generate impact effects curves (see Figures 5-2 through 5-4), but most of the classes of missiles expected in accidental explosions have not been tested against industrial or residential "targets". We would certainly recommend a carefully planned model test program to fill this gap.

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Looking into the future, we can perhaps anticipate an increasing shift to a hydrogen fuel economy. If this occurs, large volumes of hydrogen must be stored either as a compressed gas or as a cryogenic liquid near distribution points. As an aircraft fuel, the hydrogen would most probably be used as a cryogenic liquid, which would necessitate large volume storage near airports. Can this be done safely? A thorough safety study would have to precede any serious plans for such a change, with workbooks like this report providing part of the input to assess the hazards.

#### APPENDIX A

#### Calculations of Blast Wave Properties for Pressure Vessel Bursts

The method for predicting the overpressure and specific impulse from the burst of a thick-walled pressure vessel is the result of the following analysis.

TUTTI [Gentry, et al (1966)], a two dimensional finite difference computer program for compressible fluids, was used to calculate the axisymmetric flowfield surrounding a quadrant of a bursting pressure vessel. The geometry is shown in Figure A-1. During the calculation, the quadrant of the vessel moves along the axis of symmetry at a prescribed velocity. The velocity and position of the vessel are calculated by a computer program called FRAG [see Baker, et al (1975)]. These are supplied to TUTTI. (TUTTI was modified to allow a moving solid boundary.)

Six sets of initial conditions were used (Table A-1), with  $T_1/T_{\bar{a}} = 1$  for all of them. The radius of the sphere is 0.19 m. Increments  $\Delta r = 0.0375$  m, and  $\Delta z = 0.0300$  m were chosen for the flowfield. The rather large  $\Delta r$  and  $\Delta z$  cause the shocks to be spread out, and some accuracy is lost, but this is necessary for economy.

 $\bar{P}_{s}$  vs.  $\bar{R}$  is plotted for these computer runs in Figure A-2. I vs.  $\bar{R}$  is plotted in Figure A-3.

Figure A-2 was used to derive the overpressure prediction method in the text. The point at the end of the dashed line is  $(\bar{P}_{SO}, \bar{R}_O)$ , where  $\bar{P}_{SO}^*$  is defined in the text and  $\bar{R}_O$  is  $\bar{R}$  corresponding to the edge of the sphere. The solid lines show the overpressure behavior after a shock has formed. On the dashed portion of the curves, a shock has not formed yet. Connecting the points of transition to a shock in Figure A-2 gives Curve A in Figure 2-5. It is observed that, for these bursts, the overpressure on curve A,  $\bar{P}_A$ , is related to  $\bar{P}_{SO}$  by  $\bar{P}_A \simeq 0.21 \ \bar{P}_{SO}$ . This permits the location of a starting point for  $\bar{P}_S$  vs.  $\bar{R}$  behavior. A family of  $\bar{P}_S$  vs.  $\bar{R}$  curves has been drawn on Figure 2-5. Once the starting point has been found, the nearest curve(s) can be followed.

As was true for the one-dimensional study in Baker, et al (1975), the  $\overline{I}$  vs.  $\overline{R}$  behavior is not clear, and the pentolite curve

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 $<sup>\</sup>overline{P}_{so}$  is calculated by assuming constant pressure across the contact surface between the stored gas and the atmosphere immediately after the vessel burst. See Baker, et al (1975).

has been extrapolated to small  $\overline{R}$  to provide a conservative estimate for  $\overline{I}$ .

The computer outputs from TUTTI also show the highly directional nature of the blast field close to the bursting sphere. Figs. A-4 and A-5 are indicative of this directionality. The printed output also gives some indication of variation of overpressure along other radial lines from the center in addition to along the plane of symmetry; in particular, along the lines  $\theta =$ 30° and  $\theta = 60°$ . But, the limitations of cell size and computer capability precluded complete mapping along these lines.

TABLE A-1. INITIAL CONDITIONS FOR PRESSURE VESSEL BURSTS

Run Number	Gas	$\frac{p_1}{p_a}$	Υl
1	air	987.2	1.4
2	H <sub>2</sub>	987.2	1.4
3	Не	987.2	1.667
5	co2	987.2	1.225
7	air	98.72	1.4
9	co2	14.81	1.225



FIGURE A-1. QUADRANT OF FLOWFIELD FOR BURSTING PRESSURE VESSEL

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FIGURE A-3.  $\overline{I}$  VS  $\overline{R}$  FOR BURSTING PRESSURE VESSELS

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FIGURE A-4. SAMPLE PLOT FROM TUTTI FOR SPHERE BURSTING AS TWO HEMISPHERES

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# FIGURE A-5. SAMPLE PLOT FROM TUTTI FOR SPHERE BURSTING AS TWO HEMISPHERES

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#### APPENDIX B

### Development of Additional Prediction Methods for Structural Response to Blast Wave Loading

The elastic and elastic-plastic beam solutions which are presented in Figures 3-1 and 3-2 were derived using conservation of energy principles. To illustrate how these relationships can be derived, we will compute Figure 3-2 for an elastic, simplysupported beam. A deformed shape must be assumed in beam and plate like structures. Assuming a deformed shape which corresponds to the static deformed shape for a beam undergoing uniform loads gives:

$$Y = \frac{16}{5} w_{O} \left[ \frac{x}{\ell} - 2\left(\frac{x}{\ell}\right)^{3} + \left(\frac{x}{\ell}\right)^{4} \right]$$
 (B-1)

This deformed shape is then differentiated twice with respect to x so that the elastic bending moment M can be obtained from  $M = -EI\frac{d^2y}{dx^2}$ . This procedure gives for the bending moment

$$M = \frac{192}{5} \frac{E I w_{O}}{2} \left[ \left( \frac{w}{l} \right) - \left( \frac{w}{l} \right)^{2} \right]$$
(B-2)

The strain energy S.E. stored in a deformed beam can then be determined by substitution into S. E. =  $\int_{0}^{\ell} \frac{M^2 dx}{2EI}$ . Substitution gives:

$$SE = \frac{(192)^2 EIw_0^2}{(50) \ell^4} \int_0^\ell \left[ \left( \frac{x}{\ell} \right)^2 - 2 \left( \frac{x}{\ell} \right)^3 + \left( \frac{x}{\ell} \right)^4 \right] dx \qquad (B-3)$$

Or after completing the integration

SE = 24.576 
$$\frac{\text{EIw}_{0}^{2}}{\ell^{3}}$$
 (B-4)

The asymptote which is impulse dependent is determined by equating the kinetic energy KE to the strain energy. The kinetic energy is given by:

KE = 
$$(1/2) m V_0^2 = \frac{I^2}{2m}$$
 (B-5)

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Substituting pAl for m and ibl for I gives:

$$KE = \frac{i^2 b^2 l}{2\rho A}$$
 (B-6)

Equating U to KE gives the impulsive loading realm asymptote

$$\frac{i^{2}b^{2}l}{2\rho A} = 24.576 \frac{EI w_{o}^{2}}{\sqrt{3}}$$
(B-7)

Equation (B-7) relates applied impulse to deformation. To relate impulse to bending stress we must use the moment-curvature relationships. The maximum moment as given by Equation (B-2) occurs at  $x/\ell = 1/2$ . The maximum moment is then given by:

$$M_{max} = \frac{192}{20} \frac{EI w_{o}}{\varrho^{2}}$$
(B-8)

Substituting  $\sigma_{\max} = \frac{M_{\max} H/2}{I}$  and solving for  $\frac{W_O}{\ell}$  gives:

$$\frac{W_{O}}{\ell} = \frac{5}{24} \frac{\sigma_{\max}}{E} \frac{\ell}{H}$$
(B-9)

Finally, taking the square root of Equation (B-7) and substituting Equation (B-9) into Equation (B-7) to eliminate  $w_0$  gives the asymptote for the impulsive loading realm in terms of the maximum bending stress.

$$\frac{\text{ibH}}{\sqrt{\text{pEIA}}} = 1.461 \frac{\sqrt{\text{max}}}{E}$$
(B-10)

Equation (B-10) is the impulsive loading realm asymptote plotted in Figure 3-2. The numerical coefficient 1.461 in Equation (B-10) is the  $\alpha_i$  coefficient for a simply-supported beam. In Equation (B-9), the number 5/24 is the  $C_w$  coefficient in Figure 3-2 to relate stress to deformations in a simply-supported beam.

The quasi-static asymptote in Figure 3-2 is computed by calculating the maximum possible work WK and equating this quantity to the strain energy. This quantity equals:

$$Wk = \int_{O}^{\ell} pb(dx) Y \qquad (B-11)$$

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After substituting Equation (B-1) for Y:

$$Wk = \frac{16}{5} pbw_0 \int_0^{\ell} \left[ \frac{x}{\ell} - 2\left(\frac{x}{\ell}\right)^3 + \left(\frac{x}{\ell}\right)^4 \right] dx \qquad (B-12)$$

Or after integrating:

$$Wk = \frac{16}{25} \text{ pbl } W_{O}$$

The strain energy has already been calculated as Equation (B-4). Equating S.E. to Wk gives the quasi-static loading realm asymptote.

$$\frac{16}{25} \text{ pbl } w_0 = 24.576 \frac{\text{EI } w_0^2}{\ell^3} \tag{B-13}$$

Equation (B-13) relates applied pressure to deformation. To relate pressure to bending stress, we substitute Equation (B-9) for  $w_0$  and algebraically rearrange terms to obtain:

$$\frac{\text{pbHl}^2}{\text{EI}} = 8.0 \ (\sigma/\text{E})$$
 (B-14)

Equation (B-14) is the quasi-static loading realm asymptote plotted in Figure 3-2. The numerical coefficient 8.0 in Equation (B-14) is the  $\alpha_p$  coefficient for a simply-supported beam. The coefficient  $C_v$  relating maximum bending stress to the maximum shear force is obtained by differentiating the moment equation, Equation (B-2), with respect to x to obtain the shear force V with respect to deformation  $w_0$ .

$$V = \frac{dM}{dx} = \frac{192}{5} \frac{EI w_0}{\ell^3} \left[ 1 - \frac{2x}{\ell} \right]$$
(B-15)

The maximum shear occurs at x = 0 or x = l. Setting x = 0 and substituting Equation (B-9) for  $w_0$  gives:

$$V_{max} = 8.0 \frac{\sigma_{max}}{\ell H}$$
(B-16)

Equation (B-16) is the shear equation presented in Figure 3-2. The numerical value of 8.0 in Equation (B-16) is the  $C_v$  coefficient for a simply-supported beam.

The intermediate transition was faired in using a hyperbolic tangent squared relationship which from our practical experience seems to fit quite well. Note that for small values

SE = Wk 
$$\tanh^2 \left[\frac{KE}{Wk}\right]^{1/2}$$
 (B-17)

of the argument, the tanh equals its argument and we obtain the impulsive loading realm asymptote from SE = KE. For large arguments the tanh equals 1.0, and we obtain the quasi-static loading realm asymptote from SE = Wk.

This approach, within the bounds of a Bernoulli-Euler, small deformation, beam solution, gives exact answers for both strain and deformation in the quasi-static loading realm. These "exact" answers occur because the deformed shape is correct in this do-In the impulsive loading realm only approximate answers main. are given because the deformed shape is not quite right; however, the results are sufficiently accurate, especially when one realizes the uncertainties associated with the load. More accurate answers are obtained if a more accurate deformed shape is assumed. Actually the interrelationship of one variable with another remains the same irrespective of the assumed deformed shape. The only effect of using other deformed shapes is to slightly modify the numerical coefficients  $\alpha_i$ ,  $\alpha_p$ ,  $C_v$ , and  $C_w$ .

To compute the p-i diagram for cantilever, clamped-clamped, clamped-pinned, or beams with any other boundary condition, the same procedure can be followed. If the assumed deformed shape corresponds even approximately to a beam with the correct boundary conditions, then fairly accurate answers will result. The only difference in the solutions of beams with different boundary conditions is that different numerical values arise in the  $\alpha_i, \alpha_p, C_v$ , and  $C_w$  coefficients.

At this stage we will not compute the p-i diagram for the elastic-plastic beams as complex integrations are involved which must be performed on a computer. Response of a rigid-plastic beam can, however, be determined using hand calculations. The only differences are that after an assumed deformed shape is assumed and the curvature is obtained by differentiation, the strain energy is determined by integrating the plastic yield moment times the curvature over the entire span of the beam. The procedure of then equating strain energy to kinetic energy to obtain the impulsive-loading realm asymptote, and strain energy to work for the quasi-static asymptote remains the same. The deformations obtained from such a rigid-plastic analysis are residual permanent deformations and strains. In the elastic analysis, maximum deformations and strains are estimated.

Several observations should be noted from these numerical calculations. In the impulsive loading realm, maximum bending stress is independent of span *l*. This conclusion is mathematically correct. It is caused by span entering the strain energy

and kinetic energy expressions to the same power, so that it cancels. In the impulsive loading realm, the response depends only on the impulse or area under the applied pressure time history. In the quasi-static loading realm, response is independent of beam density and duration of the loading.

To derive the graphical solution presented in Figure 3-3, a deformed shape was assumed to be given by:

$$y = w_0 \sin \frac{\pi x}{\ell}$$
 (B-18)

The extensional strain for small deformations is approximated by  $\left(\frac{dy}{dx}\right)^2$ . Differentiating Equation (B-18) and substituting gives:

$$\varepsilon = \frac{\pi^2 w_o^2}{2\ell^2} \cos^2\left(\frac{\pi x}{\ell}\right)$$
(B-19)

The maximum strain occurs when the cosine equals 1.0 or:

$$\varepsilon_{\max} = \frac{\pi^2 w_o^2}{2\ell^2}$$
(B-20)

This equation is the relationship relating strains to deformation in Figure 3-3. If this solution is to be an elastic-plastic one, we need an elastic-plastic constitutive relationship. Equation (B-21) is assumed to be this relationship because it lets stress equal Ee for values of  $E\varepsilon/\sigma_y$  less than 0.5, and lets stress equal  $\sigma_y$  for values of  $E\varepsilon/\sigma_y$  greater than 2.0.

$$\sigma = \sigma_{y} \tanh\left(\frac{E\varepsilon}{\sigma_{y}}\right)$$
 (B-21)

The strain energy per unit volume in an elastic-plastic system is the area under the stress strain curve. Equation (B-22) gives for the strain energy per unit volume

SE/Vol. = 
$$\int_{0}^{\varepsilon} \sigma_{y} \tanh\left(\frac{E\varepsilon}{\sigma_{y}}\right) d\varepsilon$$
 (B-22)

SE/Vol. = 
$$\frac{\sigma_y^2}{E} \log \cosh\left(\frac{E\varepsilon}{\sigma_y}\right)$$
 (B-23)

Substituting Equation (B-19) for  $\epsilon$  in Equation (B-23) and multiplying by the differential volume A, dx gives as an integral for the strain energy:

$$SE = \frac{\sigma y^2 A}{E} \int_0^{\ell} \log \cosh \left[ \frac{\pi^2 E w_0^2}{2\sigma_v^{\ell}^2} \cos^2 \left( \frac{\pi x}{\ell} \right) \right] dx \qquad (B-24)$$

Substituting in a dimensionless variable Z equal to  $\pi x/\ell$  and substituting in  $\varepsilon_{\max}$  for  $\frac{\pi^2 w^2}{2\ell^2}$  (Equation B-20) finally gives an integral for the strain energy:

$$SE = \frac{\sigma_y^2 A \ell}{\pi E} \int_0^{\pi} \log \cosh \left[ \frac{E \epsilon_{max}}{\sigma_y} \cos^2 z \right] dz \qquad (B-25)$$

The asymptotes can now be calculated as before. The impulsive loading realm asymptote is obtained by equating kinetic energy KE to strain energy. The kinetic energy is given by:

$$KE = \frac{I^2}{2m} = \frac{I^2 b^2 l}{2\rho A}$$
(B-26)

Equating Equations (B-26) and (B-24) plus rearranging terms gives:

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$$\left[\frac{ibE^{1/2}}{\rho^{1/2}\sigma_{y}A}\right]^{2} = \frac{2}{\pi} \int_{0}^{\pi} \log \cosh \left[\left(\frac{E\varepsilon_{max}}{\sigma_{y}}\right)\cos^{2}z\right] dz \qquad (B-27)$$

A computer is needed to numerically integrate Equation (B-27) for various constant values of scaled strain  $\frac{E\varepsilon}{\sigma_y}$ . Equation (B-27) does show that the impulsive loading realm asymptote in functional format can be given by:

$$\frac{ibE^{1/2}}{\rho^{1/2}\sigma_{y}^{A}} = \Psi\left(\frac{E_{max}}{\sigma_{y}}\right) \quad (Impulsive Realm) \quad (B-28)$$

Equation (B-28) is plotted as the asymptotes to the impulsive loading realm in Figure 3-3.

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To obtain the quasi-static loading realm asymptote, we calculate the work Wk.

$$Wk = pbw_0 \int_0^{\ell} \sin \frac{\pi x}{\ell} dx \qquad (B-29)$$

Or

$$Wk = \frac{2pblw_{o}}{\pi}$$
 (B-30)

Substituting Equation (B-20) for  $w_0$  in Equation (B-30), equating (B-30) to Equation (B-29), and rearranging terms gives an equation for the quasi-static aysmptote.

$$\frac{\text{pbl}E^{1/2}}{\sigma_{y}^{3/2}A} = \frac{(\pi/2)^{3/2}}{\left(\frac{E\varepsilon_{\text{max}}}{\sigma_{y}}\right)^{1/2}} \int_{0}^{\pi} \log \cosh \left[\left(\frac{E\varepsilon_{\text{max}}}{\sigma_{y}}\right) \cos^{2}z\right] dz \quad (B-31)$$

A computer is also needed to numerically integrate Equation (B-31) for constant values of  $\frac{E\varepsilon}{y}$ . Equation (B-31) shows that the quasi-static loading realm asymptote is functionally given by:

$$\frac{\text{pblE}^{1/2}}{\rho^{1/2}\sigma_{y}^{A}} = \Psi\left(\frac{E\varepsilon_{\text{max}}}{\sigma_{y}}\right) \text{ (Quasi-Static Realm)} \tag{B-32}$$

Equation (B-32) with the proper functional format is plotted as the asymptotes to the quasi-static loading realm in Figure 3-3. An approximation still had to be made to establish a transition between the impulsive and quasi-static loading realms. The same hyperbolic tangent squared relationship, Equation (B-17), was used for this string solution as had been used in the beam solutions.

To derive the solution for buckling of a column, we must assume a deformed shape. If the column is simply-supported without side-sway, a sine wave as in Equation (B-33) is a good assumption

$$Y = w_0 \sin \frac{\pi x}{\ell}$$
 (B-33)

Differentiating Equation (B-33) twice and substituting into  $M = -EI\frac{d^2y}{dx^2}$  gives the moment

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$$M = \frac{\pi^2 E I w_0}{\ell^2} \sin \frac{\pi x}{\ell}$$
 (B-34)

The strain energy is the integral  $\int_{0}^{k} \frac{M^{2} dx}{2EI}$  or:

$$SE = 2 \int_{0}^{\ell/2} \frac{\pi^{4} EIw_{0}^{2}}{2\ell^{4}} \sin^{2} \left(\frac{\pi x}{\ell}\right) dx \qquad (B-35)$$

Which, upon completion, gives:

$$SE = \frac{\pi^4 E I w_0^2}{4 \ell^3}$$
 (B-36)

The load on the column will act through a deflection  $\delta$  equal to S-l, where l is the original length of the column. The differential length ds is given by:

$$ds = dx \sqrt{1 + \left(\frac{dy}{dx}\right)^2}$$
 (B-37)

Upon expanding with the binomial theorem and integrating this gives:

$$\delta = \int_{0}^{\ell} \left[ 1 + (1/2) \left( \frac{dy}{dx} \right)^{2} + \dots \right]$$
 (B-38)

Completing this integration and substracting  $\ell$  from s to obtain  $\delta$  gives as a first approximation:

$$\delta = (1/2) \int_{O}^{\ell} \left(\frac{dy}{dx}\right)^{2} dx \qquad (B-39)$$

We can now proceed to solve for the work:

Wk = pA 
$$\delta = \frac{pA}{2} \int_{0}^{\ell} \left(\frac{dy}{dx}\right)^{2} dx$$
 (B-40)

Substituting in the first derivative of Equation (B-33) to integrate gives:

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$$Wk = \frac{\pi^2 p A w_0^2}{2\ell} \int_0^\ell \cos^2\left(\frac{\pi x}{\ell}\right) dx \qquad (B-41)$$

Or upon completion:

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$$Wk = \frac{\pi^2 p A w_0^2}{4\ell}$$
 (B-42)

The quasi-static asymptote is obtained when the strain energy is equated to the work:

$$\frac{\pi^{4} E I w_{o}^{2}}{4 \ell^{3}} = \frac{\pi^{2} p A w_{o}^{2}}{4 \ell}$$
(B-43)

Or:

$$\frac{pAl^{2}}{EI} = \pi^{2} \quad (quasi-static asymptote \\ S.S. beam-no side sway) \quad (B-44)$$

Equation (B-44) should look familiar. It is the Euler beam buckling solution. The dynamic load factor equals 1.0 instead of 2.0. Because the vertical load pA is independent of  $w_0$ , we have the classical small deformation Euler column instability. The factor  $\alpha_p$  in Figure 3-4 is equal to  $\pi^2$  for this pinned-pinned column without side-sway. The concept of effective column length with  $\ell$  being the distance between points of inflection can be applied in analysis. A review of  $\alpha_p$  for a pinned-pinned column with side-sway shows a column with only one quarter the strength because the effective length of the column is twice as long. Similarly  $\alpha_p$  for a clamped-clamped column without side-sway is four times stronger than the simply-supported column because the effective length of the column is halved.

To compute buckling in the impulsive loading realm, we need the kinetic energy imparted to the overlying mass. This kinetic energy equals:

$$KE = (1/2) m V_0^2 = (1/2) m \left(\frac{iA}{m}\right)^2$$
 (B-45)

Or

$$KE = \frac{i^2 A^2}{2m}$$
 (B-46)

Equating KE to SE gives the impulsive loading realm asymptote.

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$$\frac{(iA)^2}{2m} = \frac{\pi^4 E I w_0^2}{4\ell^3}$$
(B-47)

Notice that, unlike the quasi-static loading realm result, the deformation  $w_0$  does not cancel out of Equation (B-47). This result means that "stable buckling" occurs in the impulsive loading realm. A certain quantity of kinetic energy is being put into the column, which strain energy can dissipate until the deformations are large enough to cause yielding. This observation means that we must use Equation (B-34) to obtain the maximum moment,  $\sin \pi x/\ell$  equal 1.0, and substitute into a  $\sigma = MH/2\ell$  to relate the maximum bending stress (to be limited by  $\sigma_y$ ) to the deformation  $w_0$ . This substitution gives:

$$\sigma_{\rm y} = \frac{\pi^2 \rm EHw}{2k^2} \qquad (B-48)$$

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Substituting Equation (B-48) into Equation (B-47), rearranging terms algebraically, and taking the square root of the result finally gives:

$$\frac{(iA)_{H}\sqrt{E}}{\sigma_{y}\sqrt{m \ell I}} = \sqrt{2.0} \quad (impulse asymptote \\ s.s. beam, no side-sway) \quad (B-49)$$

The numerical coefficient  $\sqrt{2.0}$  is the  $\alpha_i$  coefficient in Figure 3-4. Other  $\alpha_i$  coefficients must be computed independently. The static concept of effective length no longer applies in the impulsive loading realm; hence, it should not be used. We have already mentioned that in the impulsive loading realm, it is a "stable buckling" or actually bending phenomenon that occurs. Permanent deformation does not occur until the column yields. The same Equation (B-17) was used to estimate a transition between the quasi-static and impulsive loading realms as has been used to approximate this transition in all earlier analysis.

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### APPENDIX C

### Model Analysis for Bursting Containment Vessels

The model analysis used here is patterned after the techniques explained by Baker, Westine, and Dodge (1973). The purpose of the model analysis is to devise a method of consolidating the results of the computer runs made to predict velocities of fragments from pressurized spheres and cylinders. Such a consolidation will result in the need for fewer graphs and tables, will be of a more general nature, and will be easier to use.

To conduct the model analysis, it is necessary to list all of the physical parameters which are indigenous to the problem. А listing of these parameters is contained in Table C-1 which includes vessel characteristics, gas characteristics, and a response term. Since only spheres and cylinders with hemispherical endcaps and with an L/D ratio of 10.0 (includes the endcaps) are being considered, one needs to include the vessel's diameter d, thickness h, length 1, volume V, mass  $M_{\rm C},$  the yield strength  $\sigma_{\rm Y}$  of the material of the vessel's walls, and the number of fragments n that the vessel breaks into. It is assumed that the vessel breaks into n equal fragments. Cylinders break into either two equal fragments along a plane perpendicular to the axis of symmetry or n equal strip fragments along the cylindrical wall (endcaps are ignored). The relevant gas parameters are the ratio of specific heats  $\gamma$ , the ideal gas constant  $R_M$  which is adjusted for molecular weight, the speed of sound  $a_0$  of the gas, the pressure  $P_0$  of the gas at burst, the temperature  $\bar{T}_0$  of the contained gas at burst, the energy E of the gas, and atmospheric pressure pa. The response term is the velocity u of the fragment.

There are 11 pi terms or nondimensional ratios which can be created from the above 15 parameters. Table C-2 presents one possible list of these 11 pi terms. This list of 11 pi terms can be reduced to a smaller number of pi terms by examining some interrelationships among variables. Summaries of the various relationships appear in Table C-2 and will be expanded here. There are only two values for  $\ell/d$  ( $\pi_2$ ) being considered, spheres with an  $\ell/d$  of 1.0 and cylinders with hemispherical endcaps and an  $\ell/d$  of 10.0. Since there are so few values of  $\ell/d$ , one might consider putting several curves on one graph. Pi terms  $\pi_7$  and  $\pi_8$  are directly related through the relationship

$$a_{O} = \sqrt{\gamma R_{m} T_{O}}$$
 (C-1)

For the sake of simplicity, pi term  $\pi_{g}$  will be eliminated.

The thickness of the vessel is related to its diameter and the yield strength of the vessel material. Consider a sphere as shown in Figure C-la. For the simplest design where the design thickness is much smaller than the diameter of the vessel,

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## TABLE C-1. PERTINENT PARAMETERS FOR BURSTING SPHERICAL AND CYLINDRICAL CONTAIN-MENT VESSELS

Symbol	Description	Dimensions*
đ	diameter	L
h	thickness	L
L	length	L
v	volume	L <sup>3</sup>
Mc	mass of container	FT <sup>2</sup> /L
σy	yield strength of material	F/L <sup>2</sup>
n	number of fragments	
Ŷ	ratio of specific heats	
R <sub>M</sub>	ideal gas constant (adjusted for molecular weight)	$L^2/T^2\theta$
a <sub>o</sub>	speed of sound in gas	L/T
Po	burst pressure	F/L <sup>2</sup>
То	initial temperature of gas	θ
Е	energy of gas	FL
P <sub>a</sub>	atmospheric pressure	F/L <sup>2</sup>
u	velocity of fragment	L/T

\* L = length

- F = force
- T = time
- $\theta$  = temperature

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TABLE C-2. LIST OF Pi TERMS FOR BURSTING CONTAINMENT VESSELS







(b) Cylinder

FIGURE C-1. DETERMINATION OF VESSEL THICKNESS

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the vessel will burst when the force exerted on the vessel walls by the internal pressure equals the force required to break the vessel. If one considers that the vessel (sphere) bursts in half, one has

$$(P_{o} - P_{a}) \frac{\pi d^{2}}{4} = \sigma_{y} \pi dh$$
 (C-2)

or

$$\frac{h}{d} = \frac{P_o - P_a}{4\sigma_y}$$
(C-3)

Cylinders must have thicker walls than spheres to contain equal amounts of internal pressures. A simplified design for a cylinder can be based on Figure C-lb which shows a cylinder without hemispherical endcaps.

The most likely plane of fracture of a cylinder made of a homogeneous material is along the longitudinal axis as shown in Figure C-lb. For vessels whose thickness is much smaller than its diameter, the vessel will burst when the force exerted on the vessel walls by the internal pressure equals the force required to break the vessel. If one considers that the vessel (cylinder) bursts into two pieces as shown in Figure C-lb, one has

$$(P_o - P_a) d\ell = \sigma_y^{2\ell h}$$
 (C-4)

or

$$\frac{h}{d} = \frac{(P_o - P_a)}{2\sigma_y}$$
(C-5)

Equations C-3 and C-5 indicate that (h/d) is proportional to  $(P_0 - p_a)/\sigma_y$  and thus pi term  $\pi_1$  can be eliminated. If one assumes that only one material with one yield strength will be used in constructing the vessel, then pi term  $\pi_5$  can also be eliminated.

Energy E in the gas is defined as

$$E = \frac{(P_{o} - P_{a})V_{o}}{(\gamma - 1)}$$
(C-6)

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Pi term  $\pi_9$  contains  $p_0$  and  $p_a$ ,  $\pi_3$  contains  $V_0$ , and  $\pi_7$  contains  $\gamma$ . Therefore, the energy of the gas is completely defined by these other pi terms and pi term  $\pi_{10}$  can be eliminated.

Variables in  $\pi_7$  and  $\pi_8$  appear in  $\pi_4$  and  $\pi_{11}$ . It seems logical that the problem has been overdefined and that  $\pi_7$  and  $\pi_8$  can be eliminated from the analysis.

Since  $\pi_3$ ,  $\pi_4$  and  $\pi_9$  have some terms in common, it appeared beneficial to combine them. Thus, one has

$$\frac{\pi_{9} \times \pi_{3}}{\pi_{4}} = \frac{\frac{p_{0}}{p_{a}} \times \frac{V_{0}}{d^{3}}}{\frac{M_{c} \cdot a_{0}}{p_{a}d^{3}}}$$
(C-7)

Rearranging Equation C-7 and substituting Equation C-1 for a<sub>0</sub>, one has

$$\pi_{9} = \frac{P_{O}V_{O}}{M_{C}\gamma R_{m}T_{O}}$$
(C-8)

Substituting  $(P_0 - p_a)$  for  $P_0$  in order to emphasize the importance of the differential in pressure between the inside and outside of the vessel walls, one obtains the abscissa of Figure 4-2. Plotting  $\pi_{11}$  with equation C-1 substituted for  $a_0$ , versus the modified version of Equation C-8 yields the desired result. Figure 4-2 in the text consolidates the presentation of the analysis by allowing one to plot several curves for different L/D ratios and numbers of fragments n on one curve and still maintain accurate estimation of fragment velocity u. Several computer checks have shown that the curves presented in Figure 4-2 can be used for materials of different densities and yield strengths, provided that the thickness of the vessel is less than 1/3 of the diameter of the vessel. For cylinders bursting into three or more "strip" fragments as explained in Baker, Kulesz, et al (1975), the hemispherical endcaps were ignored.

Some cases were run for cylinders with hemispherical endcaps and an L/D ratio of 10.0 which burst into two unequal segments perpendicular to the cylindrical axis of symmetry. It seemed reasonable that the velocity of each fragment would be related to the velocity of the fragments from cylinders bursting in half by some constant k which depends on the unequal fragment's fraction of the total mass of the container. Figure 4-4 in the text was

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plotted from an average of several computer runs for unequal fragments which showed amazing consistency. Note that for equal fragments k equals 1.0. For unequal fragments from bursting cylinders (two fragments total), one must determine the fragment's fraction of the total mass and find k in Figure 4-4. Once k is known, Figure 4-2 can be used to calculate the velocity of the fragment.

### APPENDIX D

Estimate of Initial Velocities of Fragments from Spheres and Cylinders Bursting Into Two Unequal Fragments

The method developed by Taylor and Price (1971) and modified by Baker, et al (1975) for calculating velocities of fragments from bursting spherical and cylindrical gas reservoirs was further adapted to provide velocity calculations for unequal fragments from cylindrical gas vessels. To compute the velocity of fragments from bursting cylinders which contain gas under pressure, the following assumptions were made:

- The vessel with gas under pressure breaks into two unequal fragments along a plane perpendicular to the cylindrical axis, and the two container fragments are driven in opposite directions.
- (2) Gas within the vessel obeys the ideal gas law.
- (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 are too short for drag and lift forces to have a significant effect.

A schematic depicting the essential characteristics of the modified solution for bursting cylinders is shown in Figure (D-1). Before accelerating into an exterior vacuum, the cylinder has internal volume  $V_{OO}$  and contains a perfect gas of adiabatic exponent (ratio of specific heats)  $\gamma$  and gas constant  $R_M$  with initial pressure  $P_{OO}$  and temperature  $T_{OO}$  (Figure D-1a). At a time T = 0, rupture occurs along a perimeter II, 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 D-1b). The masses of the fragments,  $M_1$  and  $M_2$ , are considered large relative to the mass of the remaining gas at elevated pressure (Figure D-1c).

Figure D-2 contains the geometric parameters associated with cylindrical vessels. The generalized fragment velocity solution and subsequent computer program allow for computation of the velocities of both segments of the cylinder. The vessel is assumed

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to break into two unequal segments 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  $C_{\ell}$ , and end cap length  $E_{\ell}$  beyond the cylindrical portion.

The Taylor and Price (1971) solution, generalized to allow for cylindrical vessels bursting into unequal fragments, follows. The equations of motion and initial conditions of the two fragments are

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$$M_{1} \frac{d^{2} x_{1}^{(\tau)}}{d\tau^{2}} = FP_{1}^{(\tau)}, \text{ with } X_{1}^{(0)} = 0, \frac{dx_{1}^{(0)}}{d\tau} = 0 \quad (D-1)$$

$$M_2 \frac{d^2 X_2(\tau)}{d\tau^2} = FP_2(\tau) \text{ with } X_2(0) = 0, \frac{d X_2(0)}{d\tau} = 0 \quad (D-2)$$

where subscripts refer to each fragment and  $X_1$  is a displacement distance taken along the axis of motion. To allow for cylindrical containment vessels, the cross sectional area F over which the force is applied becomes

$$F = \pi (r - C_t)^2$$
 (D-3)

The equation of state for the unaccelerated gas remaining within the confinement of the container fragments is

$$P_{O}(\tau) V_{O}(\tau) = C(\tau) RT_{O}(\tau)$$
 (D-4)

where subscript "o" 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

$$\frac{d C(\tau)}{d(\tau)} = k \Pi X \rho_* a_* \qquad (D-5)$$

where

$$X = X_1 + X_2,$$
 (D-6)

K is the coefficient of discharge of the area between the fragments and  $\rho_{\star}$  is the gas density at critical gas velocity  $a_{\star}$ . The expression for perimeter  $\Pi$  is

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Gas density  $\rho_{\star}$  and  $a_{\star}$  are standard expressions

$$\rho_{\star} = \rho_{O}(\tau) \left(\frac{2}{\gamma + 1}\right)^{1/(\gamma - 1)}$$

$$a_{\star} = a_{O}(\tau) \left(\frac{2}{\gamma + 1}\right)^{1/2}$$
(D-8)

where  $\gamma$  is the adiabatic exponent (ratio of specific heats) for an ideal gas. The volume is assumed to be variable and can be described by

$$V_{0}(\tau) = V_{00} + Fx$$
 (D-9)

where  $x = x_1 + x_2$ .

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,

$$P_{1}(\tau) = P_{0}(\tau) \left( 1 - \left\{ \frac{\gamma - 1}{2 \left[ a_{0}(\tau) \right]^{2}} \right\} \left[ \frac{dx_{1}(\tau)}{d\tau} \right]^{2} \right)^{\gamma/(\gamma-1)}$$

$$P_{2}(\tau) = P_{0}(\tau) \left( 1 - \left\{ \frac{\gamma - 1}{2 \left[ a_{0}(\tau) \right]^{2}} \right\} \left[ \frac{dx_{2}(\tau)}{d\tau} \right]^{2} \right)^{\gamma/(\gamma-1)}$$
(D-10)

To generalize the solution, one can use the following nondimensional forms of the variables:

Dimension: 
$$\mathbf{x}(\tau) = Xg(\zeta), \mathbf{x}_{1}(\tau) = Xg_{1}(\zeta), \mathbf{x}_{2}(\tau) = Xg_{2}(\zeta)$$
  
Time:  $\tau = \theta \zeta$  (D-11)

Pressure:  $P_{o}(\tau) = P_{oo}P_{\star}(\zeta)$ 

From appropriate solutions and initial conditions:

$$\frac{dx_1(\tau)}{d(\tau)} = \frac{x}{\theta} g_1(\zeta) , \quad \frac{dx_2(\tau)}{d\tau} = \frac{x}{\theta} g_2(\zeta)$$

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$$\frac{d^2 x_1(\tau)}{d\tau^2} = \frac{x}{\theta^2} g_1^{(\tau)}(\zeta) , \quad \frac{d^2 x_2(\tau)}{d\tau^2} = \frac{x}{\theta^2} g_2^{(\tau)}(\zeta)$$

$$\frac{dP_0(\tau)}{d\tau^2} = \frac{P_{00}}{\theta} P_{\star}^{(\tau)} \qquad (D-12)$$

Initial conditions:

$$x_{1}(0) = x_{2}(0) = \frac{dx_{1}(0)}{d\tau} = \frac{dx_{2}(0)}{d\tau} = g_{1}(0) =$$
$$g_{2}(0) = g_{1}(0) = g_{2}(0) = 0$$
$$P_{\star}(0) = 1$$

where primes denote differentiation with respect to  $\zeta$ . The pair of characteristic values for dimension X and time  $\theta$  chosen by Taylor and Price are:

$$X = \frac{M_{t}a_{oo}^{2}}{F_{P_{oo}}} \left(\frac{2}{\gamma - 1}\right)$$

$$\theta = \frac{M_{t}a_{oo}}{F_{P_{oo}}} \left(\frac{2}{\gamma - 1}\right)^{1/2}$$
(D-13)

The final derived equations contain two dimensionless groups which define the nature of the solutions, these are

$$\alpha = \frac{\frac{P_{oo}V_{oo}}{M_{t}a_{oo}^{2}}}{M_{t}a_{oo}^{2}}$$

$$\beta = k \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma + 1}{2(\gamma - 1)}} \left(\frac{2}{\gamma - 1}\right)^{1/2} \frac{\pi V_{oo}}{F^{2}}$$
(D-14)

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 (D-3) and perimeter  $\Pi$  given in Equation (D-7) where r is cylindrical 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

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$$V_{OO} = \pi \left\{ (r - C_{t})^{2} C_{l} + (E_{l} - E_{t}) \left[ (r - E_{t})^{2} + \frac{(E_{l} - E_{t})^{2}}{3} \right] \right\} (D-15)$$

for the adiabatic case,

$$\frac{P_{o}(\tau)}{P_{oo}} = \left[\frac{\rho_{o}(\tau)}{\rho_{oo}}\right]^{\gamma} = \left[\frac{T_{o}(\tau)}{T_{oo}}\right]^{\gamma-1} = \left[\frac{a_{o}(\tau)}{a_{oo}}\right]^{\frac{2\gamma}{\gamma-1}}$$
(D-16)

Substitution of Equations (D-10), (D-12) through (D-14), and (D-16) into Equations (D-1) and (D-2) gives

$$\frac{M_{1}}{M_{t}} g_{1}^{\prime \prime} = P_{\star} \left[ 1 - \left( \frac{g_{1}^{\prime 2}}{P_{\star}^{(\gamma-1)/\gamma}} \right) \right]^{\gamma/(\gamma-1)}$$
(D-17a)

by analogy,

$$\frac{M_2}{M_t} g_2^{\gamma} = P_{\star} \left[ 1 - \left( \frac{g_2^{\gamma^2}}{P_{\star}^{(\gamma-1)/\gamma}} \right) \right]^{\gamma/(\gamma-1)}$$
(D-17b)

Differentiation of Equation (D-4) and substitution of Equations (D-5) through (D-9), (D-11) and (D-12) yields

$$\left[\left(\frac{\gamma-1}{2}\right)\alpha + g\right]\frac{P_{\star}}{P_{\star}} = -\frac{\beta\gamma}{\alpha}gP_{\star}^{(\gamma-1)/2\gamma} - \gamma g$$
 (D-18)

In the solution for equal fragments, the fragment masses are equal, and the equations for the motion of the two fragments become identical. However, since the fragment masses in the new solution are unequal, the equations of motion become

$$g_{1}^{\prime\prime} = \frac{M_{t}}{M_{1}} P_{\star} \left[ 1 - \left(\frac{g_{1}^{\prime 2}}{P_{\star}^{(\gamma-1)/\gamma}}\right) \right]^{\gamma/(\gamma-1)}$$

$$g_{2}^{\prime\prime} = \frac{M_{t}}{M_{2}} P_{\star} \left[ 1 - \left(\frac{g_{2}^{\prime 2}}{P_{\star}^{(\gamma-1)/\gamma}}\right) \right]^{\gamma/(\gamma-1)}$$
(D-19)

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Rearranging terms in Equation (D-18) produces

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$$P_{\star} = \frac{\frac{\beta \gamma}{\alpha} (g_{1} + g_{2}) P_{\star}^{(3\gamma-1)/2\gamma} - \gamma (g_{1}^{\prime} + g_{2}^{\prime}) P_{\star}}{\left[ \left( \frac{\gamma - 1}{2} \right) \alpha + (g_{1} + g_{2}^{\prime}) \right]}$$
(D-20)

For initial conditions,  $g_1(0) = 0$ ,  $g_2(0) = 0$ ,  $g_1(0) = 0$ ,  $g_2(0) = 0$ , and  $P_*(0) = 1$ , nondimensional values of distance, velocity, accerlation and pressure as a function of time can be calculated by solving Equations (D-19) and (D-20) simultaneously using the Runge-Kutta method of numerical iteration. Dimensional values can then be calculated from

$$\tau = \theta \ \zeta, \ x_{1}(\tau) = Xg_{1}(\zeta), \ x_{2}(\tau) = Xg_{2}(\zeta),$$

$$x_{1}(\tau) = \frac{X}{\theta} \ g_{1}(\zeta), \ X_{2}(\tau) = \frac{X}{\theta} \ g_{2}(\zeta), \qquad (D-21)$$

$$x_{1}^{\prime}(\tau) = \frac{X}{\theta^{2}} \ g_{1}^{\prime}(\zeta), \ X_{2}^{\prime}(\tau) = \frac{X}{\theta^{2}} \ g_{2}^{\prime}(\zeta), \ P_{0}(\tau) = P_{00}P_{\star}(\zeta)$$

The computer program entitled /UNQL/ was written in BASIC and was exercised on a Tektronix 4051 microprocessor. The computer program requires input in English units and gives output in both English and SI units. Rigorous English measure input is not used for length and mass measurements. Instead, inches are used for length measurements and pounds-force (weight measure) are used 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  $(\gamma)$ , speed of sound  $(a_{00})$ , initial pressure  $(P_{00})$ , external radius of the cylinder of sphere, and the discharge coefficient 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 D-2). The program also requires that a step size and limit be added to allow for the iterative 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 can be found in Baker, et al (1975). This is a standard computer library function which has nine arguments. A list of the program variables, a listing of the program, and sample input and output follow in Table D-1.

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In summary, the solution of the case with two unequal fragments differs from that with equal halves in Equations (D-19) through (D-21) because the masses of the two segments are not identical. The program which follows has been adjusted to account for these differences.



Table D-1. Computer Program Entitled /UNQL/ in Basic

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 unequal fragments 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 English units only and prints output in SI and 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:
  - (CØ) Adiabatic exponent (ratio of specific heats) for gas in the containment vessel
  - $(A\emptyset)$  Speed of sound in gas of vessel
  - (PØ) Initial pressure of gas in vessel
- (B) Vessel characteristics:
  - (RØ) Cylinder radius

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(Z1) =	: 1:	(A)	Cylinder length
		(B)	Length of end cap
		(C)	Cylinder thickness
		(ח)	mbjaknoog of and -

- (D) Thickness of end cap
- (E) Wall density
- (21) = 2:(A) Volume of containment vessel (B) Mass of reservoir (C) Cylinder thickness

(C) Dynamic variables:

- (KØ) Discharge coefficient
- (X8) Nondimensional time increment for calculations
- (X9) Maximum nondimensional time calculation

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(D) Input/Output format:

- (F9) Fraction of total cylinder length (or mass) for first fragment
- (F1) Display nondimensional dynamic variance
   1. = Yes
   2. = No
- (F2) Display dimensional dynamic variance
   l. = Yes
   2. = No

Variables: The definition and units of variables in this program follow.

Program				Units
Variable	Variable	Definition	SI	English
F2		if-l., program displays normal time, distance, velocity, accelerations and pressure		
Cl	с <sub>ℓ</sub>	cylinder length	m	in
El	EL	end length	m	in
C2	ct	cylinder thickness	m	in
E2	Et	end thickness	m	in
DØ		wall density	kg/m <sup>3</sup>	lb-f/in <sup>3*</sup>
vø		outside volume of vessel	m <sup>3</sup>	in <sup>3</sup>
Vl	v <sub>oo</sub>	internal volume of vessel	m3	in <sup>3</sup>
V2		wall volume of vessel	m <sup>3</sup>	in <sup>3</sup>
MØ	Mt	total mass of reservoir	kg	lb-f*
<b>V</b> 5		outside volume of frag #1	m3	in <sup>3</sup>

\*1b-f indicates English weight measurement of pounds of force. Sea level gravitation is assumed.

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Program <u>Variable</u>	Variable	Definition	u <u>si</u>	Inits <u>English</u>
V6		internal volume of frag #1	m <sup>3</sup>	in <sup>3</sup>
V7		wall volume of frag #1	m <sup>3</sup>	in <sup>3</sup>
M7	Ml	mass of frag #1	kg	lb-f*
M8	<sup>M</sup> 2	mass of frag #2	kg	lb-f*
CØ	Υ	adiabatic exponent		
AØ	a 00	sound speed	m/s	in/sec
PØ	Poo	initial pressure	Pa	psi
RØ	r	cylinder radius	m	in
<b>Z</b> 1		<pre>if = 1., input is if = 2., input is</pre>		
КØ		gas discharge coeffi- cient		
X8		dimensionless time interval of iteration		
Х9		maximum dimensionless time of iteration		
F9		fraction of total cy- linder length (or mass) for frag #1		
Fl		if = l., program displays		
F2		if = l., program displays		
P5	Π	perimeter(calculated)	m	in
F5	F	area of cross-section to which force is applied(calculated)	m <sup>2</sup>	in <sup>2</sup>
X2	х	characteristic dimen- sion(calculated)	m <sup>2</sup>	in <sup>2</sup>

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Program Variable	Variable	Definition	SI	Units English
0	θ	characteristic time (calculated)	S	sec
C7		quantity $(\gamma/(\gamma-1))$		
C8		quantity $(3\gamma-1)/2\gamma$		
С9		quantity $(\gamma+1)/2(\gamma-1)$		
Ql	α	dimensionless parameter		
Bl	β	dimensionless geometry parameter		
x		normalized time		
Y(1)		normalized initial displacement of frag #l		
Y(2), F(1)*		normalized velocity of frag #1		
Y(3)		normalized pressure		
Y(4)		normalized initial displacement of frag #2		
Y(5), F(4)*		normalized velocity of frag #2		
F(2)*		normalized accelera- tion of frag #l		
F(3)*		normalized rate of change of pressure		
F(5)*		normalized acceleration of frag #2		
Q2		quantity [(γ-1)/2]α + (g <sub>1</sub> + g <sub>2</sub> )		
U	g´	$(g_1 + g_2)$ quantity		
Т9		normalized time(output)		
*indicates	different:	ial equations solved.		
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Program <u>Variable</u>	Variable	Definition	<u>si</u>	Units English
G	Gl	normalized distance of frag #l (output)		
Gl	a	normalized velocity of frag #1 (output)		
G2	gĩ	normalized acceleration frag #1 (output)		
P9	P <b>*</b>	normalized pressure (output)		
G3	g <sup>2</sup>	normalized distance of frag #2 (output)		
G4	g2	normalized velocity of frag #2 (output)		
G5	9 <u>2</u>	<pre>normalized acceleration of frag #2 (output)</pre>		
Tl, E5		time (output)	S	sec
н1, Еб		distance of frag #1 (output)	m	in
H2, E7		velocity of frag #1 (output)	m/s	in/sec
НЗ, Е8		acceleration of frag #1 (output)	m/s <sup>2</sup>	in/sec <sup>2</sup>
H4, E9		pressure (output)	Ра	psi
H5, S6		distance of frag #2 (output)	m	in
H6, S7		velocity of frag #2 (output)	m/s	in/sec
H7, S8		acceleration of frag #2 (output)	m/s <sup>2</sup>	$in/sec^2$

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SAMPLE INPUT AND OUTPUT

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1143 C2=C 1150 FRIHT "FRACTION OF TOTAL VESSEL MASS FOR FRAG&1 IS "1 1160 FRIHT USING 1170:F9 1170 INAGE 10.40 1170 INAGE 10.40 1180 FRIHT USING 1170:F9 1180 FRIHT USING 1170:F9 1190 FRIHT USING 1190: "ENGLISH INPUT/ENGLISH OUTPUT", A*, B*, D*, C0 1190 FRIHT USING 1200:E*, A0, "IN/SEC", F*, P0, "PSI", G*, R0, O* 1200 FRIHT USING 1210:E*, A0, "IN/SEC", F*, P0, "PSI", G*, R0, O* 1210 INAGE 110, 5X, 3E, 1X, 5A, Y, 1AA, 2X, 3E, 1X, 3A, Y, 5A, 10A, 5X, 3E, 1X, 2A 1220 FRINT USING 1250: "FRAG#1 MASS", M7, "LBF", J*, C2, O* 1220 FRINT USING 1250: "FRAG#1 MASS", M7, "LBF" 1220 FRINT USING 1250: "FRAG#2 MASS", M8, "LBF" 1220 M8=M8/356, C066 1220 M8=M8/356, C066 1200 RFM	1310       NEM         1320       REM         1320       REM         1320       REM         1320       REM         1370       F5=P1±(20-1))         1370       C9=(0+1))         1400       C7=C0+1)         1410       C8=(3*C0-1))         1420       C9=(10+1))         1430       01=P0±(01)         1430       01=P0±(01)         1430       01=P0±(01)         1450       REM         1450       REM         1470       REM

.

REM Y(2)=F(1)=G'#1         REM Y(2)=F(1)=G'#1         REM F(2)=G'#1         REM F(2)=G'#1         REM F(2)=G'#1         REM F(2)=G'#1         REM F(2)=G'#1         REM Y(5)=F(4)=G#2         REM F(5)=G'#2         REM F(5)=G'#2         REM F(5)=G'#2	<pre>REM X=0 Y(1)=0 Y(2)=0 Y(3)=1 Y(2)=0 Y(5)=0 Y(5)=0 PRINT "IHITIAL CONDITIONS" PRINT USING 1689:"X(0)=",Y(1),"G1'(0)=",Y(2) PRINT USING 1689:"X(0)=",Y(4),"G2'(0)=",Y(2),"P-NORM=",Y(3) IMAGE 5A,2D,/,FA,2D,/,FA,2D PRINT USING 1700:"G2(0)=",Y(4),"G2'(0)=",Y(5),"P-NORM=",Y(3) IMAGE 5A,2D,/,FA,2D,/,FA,2D PRINT USING 1700:"G2(0)=",Y(4),"G2'(0)=",Y(5),"P-NORM=",Y(3) IMAGE 6A,2D,/,FA,2D,/,FA,2D PRINT USING 1700:"G2(0)=",Y(4),"G2'(0)=",Y(5),"P-NORM=",Y(3) PRINT USING 1700:"F(1)=Y(1)+Y(4))XY(3)F(1/C7))FC RCD=M0/MBXY(3)X(1)+Y(4))XY(3)FCB-C0X(Y(2)+Y(5))XY(3))/Q2 F(1)=Y(5) F(1)=Y(5) F(1)=Y(5) F(2)=M0/MBXY(3)X(1)-Y(5)XY(5)/Y(3)F(1/C7))FC F(5)=M0/MBXY(3)X(1)-Y(5)XY(5)/Y(3)F(1/C7))FC F(5)=M0/MBXY(3)X(1)-Y(5)XY(5)/Y(3)F(1/C7))FC F(5)=M0/MBXY(3)X(1)-Y(5)XY(5)/Y(3)F(1/C7))FC F(5)=M0/MBXY(3)X(1)-Y(5)XY(5)/Y(3)F(1/C7))FC</pre>	PRINT "CHARACTERISTICS OF MOTION OF FRAGMENTS (NORMALIZED)" PRINT T-NORM G G G G G G G G G G G G G G G G G G G
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<pre>GOSUB 2990 F(1)#Y(2) F(2)=M0/M7#Y(3)*(1-Y(2)*Y(2)/Y(3))+(1/C7))+C7 Q2=(C0-1)/2*Q1+Y(1)+Y(4) F(3)=(-B1*C0/Q1*(Y(1)+Y(4))*Y(3))+C8-C0*(Y(2)+Y(5))*Y(3))/Q F(4)=Y(5) F(4)=Y(5) F(5)=M0/M8*Y(3)*(1-Y(5)*Y(5)/Y(3))+(1/C7))+C7 IF S=1 THEN 1840</pre>	PKINT PKINT USING 1940: "1", X, Y(1), Y(2), F(2), Y(3) IMAGE 10, 1X, 3E, 4(1X, 3E) PRINT USING 1960: "2", X, Y(4), Y(5), F(5) IMAGE 10, 1X, 3E, 3(1X, 3E) J1=J1+1 T9(J1)=Y(1) G(J1)=Y(1) G(J1)=Y(2) G2(J1)=Y(2) G2(J1)=Y(4) G2(J1)=Y(4) G2(J1)=Y(4) G3(J1)=Y	G5(J1)=F(5) IF X=>X9 THEN 2100 IF ABS(LOG(U)-LOG(Y(2)+Y(5)))<=3.0E-5 THEN 2100 U=Y(2)+Y(5) G0 T0 1820 STOP PAGE IF F1=2 THEN 2400 IF F1=2 THEN 2400 K=1+1 IF K)J1 THEN 2350	PRINT USING 2170:"DATE ",2* IMAGE 50,10A PRINT USING 2190:"PAGE NO. ",J9+1
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<pre>2220 PRIMT "CHARAFRETSTICS OF MOTION OF FRAGMENTS (HORMALIZED)" 2220 PRIMT "CHARAFRETSTICS OF MOTION OF FRAGMENTS (HORMALIZED)" 2250 PRIMT USING 2270:"1", T9(1), G2(1), G2(1), P9(1) 2250 PRIMT USING 2270:"1", T9(1), G3(1), G2(1), P9(1) 2260 PRIMT USING 2270:"1", T9(1), G3(1), G4(1), G5(1) 2260 PRIMT USING 21, 31, 31, 31, 31, 31, 31, 31, 31, 31, 3</pre>	L	2200 Jg=J9+I
2250       PRINT *       T-NORM       G	L	2210 PRINT "CHARACTERISTICS OF MOTION OF FRAGMENTS CHARMALIZED." 2220 PRINT "CHARACTERISTICS OF MOTION OF FRAGMENTS CHARMALIZED."
<pre>2220 FRINT USING 2270:"1,"F9(1).G2(1).G2(1).P9(1) 2220 FRINT USING 2270:"1,"F9(1).G3(1).G4(1).G2(1).P9(1) 2200 FRINT USING 23(1%,3E) 2310 FF 1/2=10 FRIN 2140 2310 FF 1/2=10 FRIN 2140 2320 FRINT USING 2430: PDGE N0. ",J9+1 2420 FRINT USING 2430 FRIN</pre>	L	2230 PRINT * T-NORM G C C C C C C C C C C C C C C C C C P-N
<pre>2280 FRINT USING 2200140 2300 IF 1/2=17 THR 2140 2300 IF 1/2=17 THR 2140 2300 IF 1/2=10 THEN 2140 2330 IF 1/2=10 THEN 2140 2330 IF 1/4=10 THEN 2680 2330 IF 1/4=10 THEN 2680 2330 IF 1/4=10 2440 UNIST 2430: "PAGE NO. ", J9+1 2440 UNIST 2430 UNIST 2430: "PAGE NO. ", J9+1 2440 UNIST 2430 UNIST 2430: "PAGE NO. ", J9+1 2440 UNIST 2430 UNIST 2430 UNIST 2430 UNIST 2430 UNIST 2440 UNIST 2430 UNIST 2440 UNIST 2440</pre>	L	2260 PRINT USING 2270:"1",T9(I),G(I),G1(I),G2(I),P9(I)
<pre>2300 IF 1=17 THEN 2140 2320 IF 1/2=10 THEN 2140 2330 IF 1/2=10 THEN 2140 2330 IF 1/2=10 THEN 2140 2336 IF 1/2=10 THEN 2143 2336 IF 1/3 2336 IF 1/3 2338 X=1+1 2338 Y=1+1 2338 Y=1+1 2348 Y=1 2348 Y=1</pre>	L	2280 PRINT USING 2290:"2",T9(I),G3(I),G4(I),G5(I)
2330       IF 1/3=10 THEN 2149         2330       NEXT 1         2350       STOP         2350       PAGE         2440       PAGE         2450       PAGE         2460       PAGE	Ľ	2300 IF 1±10 THEN 2140 2310 IF 1×2±10 THEN 2140
3340 NEXT 1         3350 STOP         3410 INACE 50, 2)         3430 INACE 50, 2)         3430 INACE 50, 2)         3430 INACE 50, 2)         3430 STATULUSING         3430 STATULUSING         3450 STATULUSING      <	H	2320 IF I/2=10 THEN 2140 2330 IF I/4=10 THEN 2149
<pre>2350 PAGE 2350 I=0 2350 IF KJJ THEN 2680 2350 IF KJJ THEN 2680 2350 PRINT USING 2410: "DATE ", Z* 2420 PRINT USING 2430: "PAGE NO. ", J9+1 2420 PRINT USING 2430: "PAGE NO. ", J9+1 2430 PRINT USING 2430 PRINT USING 2430 2430 PRINT USING 2430 PRINT USING 2430 PRINT USING 2430 PRINT PRINT</pre>	L	2340 NEXT 1 2350 STOP
2383 K=1+1         2393 IF K>J1 THEN 2680         2410 INGE 50.0         2420 PRINT USING 2419: DOTE ", 2*         2430 INGE 50.10         2440 INGE 50.10         2430 INGE 50.10         2440 J9-1         2440 J9-1         2440 J9-1         2440 J9-1         2450 IF F2=2 THEN 2680         2460 J9-19+1         2460 J9-19+1         2460 J9-19+1         2460 J9-19+1         2460 J9-19+1         2460 J9-19+1         2460 J9-10+1         2460 PRINT "SYNCTERISTICS OF MOTION OF FRAGMENTS CENGLISH UNITS)"         2460 PRINT         2650 PRINT         2650 PRINT         2510 H1=AZZYCOTION         2510 H1=AZZYCOTION         2510 H2=AZYCOTION         2510 H2=AZYCOTION         2510 H2=AZYCOTION         2510 H2=AZYCOTION         2510 H2=AZZYCOTION         2510 H2=AZZYCOTION	Ц	2370 I=8 2370 I=8
740       FRINT USTME 2410: "DATE ", 24         2410       IMAGE 50, 10         2420       PRINT USTME 2430: "PAGE NO. ", J9+1         2430       J9=J9+1         2440       J9=J9+1         2450       IFFE22         2450       IFFE	1	2383 K=I+1 2390 te kyli tuen yaad
<pre>2420 PRINT USING 2430: "PAGE NO. ", J9+1 2440 J9=J9+1 2440 J9=J9+1 2450 IF F2=2 THEK 2680 2460 PRINT "CMCPCTERISTICS OF MOTION OF FRAGMENTS (ENGLISH UNITS)" 2450 PRINT "CMCPCCTERISTICS OF MOTION OF FRAGMENTS (ENGLISH UNITS)" 2500 H1=X2*000 2500 H1=X2*000 2500 H3*X2*(000*52KI) 2500 H3*X2*(000*52KI)</pre>	U	2400 FRINT USING 2410: "DATE ", 25
7430       1000000000000000000000000000000000000	K	2420 PRINT USING 2430:"PAGE NO. ",J9+1
2450       IF       F2=2       THER       2680         2460       PRINT       2460       PRINT       2460         2460       PRINT       CHAPACTERISTICS       OF       MOTION       OF       PRAGMENTS       CENGLISH       UHITS>"         2460       PRINT       TIME       DIST.       UEL.       PRESSURE         2450       PRINT       TIME       DIST.       UEL.       PRESSURE         2450       PRINT       CHAPACTERISTICS       DIST.       UEL.       PRESSURE         2500       T1=0*TSCO       DIST.       UEL.       PRESSURE         2500       H1=X2*GCD       S200       S200       H3=X2×COOSTCD         2500       H3=X2×COOSTCD       S200       S200       S200       S200	Ц	Z438 IMR6N 2A,40 2446 J9=19+1
<pre>2400 FAINT "CHARTERISTICS OF MOTION OF FRAGMENTS (ENGLISH UNITS)" 2450 FOR 1=K TO U1 2450 FOR 1=K TO U1 2550 T1=0#T9(1) 2550 T1=0#T9(1) 2550 H3=X2/0701(1) 2550 H3=X2/0700000522(1) 2550 H3=X2/070000522(1) 2550 H3=X2/070000522(1) 2550 H3=X2/070000522(1) 2550 H3=X2/070000522(1) 2550 H3=X2/070000522(1) 2550 H3=X2/070000522(1) 2550 H3=X2/070000522(1) 2550 H3=X2/070000522(1) 2550 H3=X2/0700000522(1) 2550 H3=X2/0700000522(1) 2550 H3=X2/0700000522(1) 2550 H3=X2/0700000522(1) 2550 H3=X2/0700000000000000000000000000000000000</pre>	1	2450 IF F2=2 THEN 2680
2483         PRINT         TIME         DIST.         UEL.         MUCCEL.         PRESSURE           2503         T1=0±T2<1         DIST.         UEL.         MUCCEL.         PRESSURE           2503         H1=X2±GC.         DIST.         UEL.         MUCCEL.         PRESSURE           2503         H2=X2×GC.         DIST.         UEL.         MUCCEL.         PRESSURE           2503         H3=X2×CC.         DIST.         UEL.         MUCCEL.         PRESSURE	L	2450 FXINT "CMAPACTERISTICS OF MOTION OF FRAGMENTS ZENCLISU UNLIEN"
2559 T1=0+T955 2510 H1=X24552 2529 H2=X2X055151 25509 H3=X2X(99095521)	11	2483 PRINT " TIME DIST. UEL. ACCEL. PRESSURE
2529 H2=X2/0001(1) 2509 H3=X8/(0001(1) 2509 H3=X8/(0001(1))	Ц	2000 11=0米15(1) 2010 11=20米15(1)
2539 H3#X2<(210)~522(1)	4	ないため、日本になるというという。そので、「「「「「「」」」、「「」」、「」、「」、「」、「」、「」、「」、「」、「」、
	K	2523C H3#X6×(000000000)/2X#2H 5552
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<pre>Diffict 130, 35, 70, 36, 75, 70 Diffict Usit 230, 37, 56, 10 Diffict Usit 2900; 700051, 01 Diffict Usit 2920; 700051, 01 Diffict Usit 2920; 7000550 Diffict Usit 2920; 7000550 Diffict Usit 2920; 7000550 Diffict Usit 2920; 7000550 Diffict Usit 2900; 7000550 Diffict Usit 2000; 7000 Diffict Usit 2000; 7000 Diffict Usit 2000; 7000 Diffict Usit 2000 Diffict 2000 Diffi</pre>

**3230 S=2** 3240 G0 T0 **3309** 3250 F0R L=1 T0 N 3250 V(L)=Y(L)+AAXB\*F(L)-Q(L)) 3250 Q(L)=2\*AAXB\*F(L)+(1-3\*A)\*Q(L) 3259 NEXT L 3259 S=1 3300 RETURN 3310 END

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### APPENDIX E

### MODEL ANALYSIS FOR FRAGMENT TRAJECTORIES

In order to generalize the analysis for determining the range of a flying fragment from a bursting spherical or cylindrical container, a model analysis was performed. The analysis for calculating the fragment range and the subsequent computer program (FRISB) are presented in detail in Baker, et al (1975). However, for the sake of clarity, a brief discussion of this analysis is presented below.

The equations for calculating the horizontal and vertical (X and Y) accelerations of a fragment are as follows:

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$$\ddot{Y} = -g - \frac{A_{\rm D}C_{\rm D}^{\rho} (\dot{X}^2 + \dot{Y}^2) \sin \alpha}{2M} + \frac{A_{\rm L}C_{\rm L}^{\rho} (\dot{X}^2 + \dot{Y}^2) \cos \alpha}{M}$$
(E-1)

$$\ddot{x} = \frac{-A_D C_D \rho_0 (\dot{x}^2 + \dot{y}^2) \cos \alpha}{2M} - \frac{A_L C_L \rho_0 (\dot{x}^2 + \dot{y}^2) \sin \alpha}{M}$$
(E-2)

where

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at t = 0

$$\dot{X} = V_i \cos \alpha_i$$
 (E-3)

 $\dot{Y} = V_{i} \sin \alpha_{i}$  (E-4)

By solving the two second-order differential equations simultaneously, one can obtain velocity, and by numerically integrating the velocities, one can obtain the displacement, i.e., fragment range.

The first step in performing the model analysis was to list all of the pertinent physical parameters in the analysis, i.e., drag coefficient, drag area, lift coefficient, lift area, mass, etc., together with their fundamental dimensions, in a mass, length, and time (M, L, T) system. This list is presented in Table E-1. It should be noted that since the coefficient of lift, the lift area, and the density of air are interrelated as are the coefficient of drag, the drag area, and the density of air, they were combined as shown in Table E-1. These dimensional parameters were than combined into a lesser number of dimensionless groups (pi terms) by the methods of dimensional analysis as outlined in Baker, et al (1973). Table E-2 presents the dimensionless parameters in pi terms. It should be noted that this set of pi terms is not a unique set and that other combinations of pi terms are possible. It should also be noted that the number of pi terms equals the number of original dimensional parameter minus the number of fundamental dimensions.

For the special case of the fragment whose geometry is such that there are no lift forces acting on it, the fourth pi term listed on Table E-2 drops out of the model analysis.

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## TABLE E-1

### LIST OF DIMENSIONAL PARAMETERS

Parameter	Dimension
CD <sup>A</sup> D <sup>p</sup> o	M/L
$C_L^A L^\rho O$	M/L
v	L/T
М	М
g	L/T <sup>2</sup>
R	L
α	-

TABLE E-2

DIMENSIONLESS PARAMETERS (PI TERMS)



$$\pi_{3} \qquad \qquad \frac{\rho_{O}C_{D}A_{D}R}{M}$$

$$\mathbf{T}_{\mathbf{4}} \qquad \qquad \frac{\mathbf{C}_{\mathbf{L}}^{\mathbf{A}}}{\mathbf{C}_{\mathbf{D}}^{\mathbf{A}}\mathbf{D}}$$

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#### APPENDIX F

#### ROCKETING OF STORAGE AND TRANSPORTATION VESSELS

In an accident involving propellant (propane, butane, etc.) storage systems, fragments are often generated and propelled by the force of an explosion. The fragments generated in an explosion which travel large distances typically are of much smaller mass than that of the storage vessel. However, in some instances, a large portion or portions of the vessel (greater than onefourth) will break free intact and will travel larger distances than would be possible solely from the force of the explosion. These large fragments exhibit a rocketing behavior (see Appendix H) which results from the changing of the liquid propellant into a gas when the external pressure is released during the fracturing of the vessel. The gas escapes from the opening in the vessel in a manner similar to gas exiting a rocket motor and propels the, somewhat stabilized, fragment to great distances.

Figure F-1 schematically demonstrates the fragment rocketing process. After a portion of the vessel breaks off, the remaining portion of the tank emits gas out of its open end as the fluid in the tank vaporizes. This mass flows out of the aft end of the tank and produces a force F(t) in the direction opposite to the mass flow which varies as a function of time t, and the tank accelerates along a trajectory angle  $\theta$  with respect to the horizontal axis (ground). The force of gravity Mg also acts on the vessel inhibiting its vertical ascent. Since every action has an equal and opposite reaction, the vertical and horizontal inertial forces  $M_{y}^{u}$  and  $M_{x}^{u}$ , respectively, complete the simplified free-body diagram in Figure F-1. Note that for the purposes of this analysis, drag and lift forces are assumed to be much smaller than the thrust and gravitational forces and are ignored. It is also assumed that the "rocket" never changes its angle of attack  $\theta$ during its flight.

The equations of motion for this simplified rocketing problem are then

$$M(t)g + M(t)y - F(t)\sin \theta = 0$$
 (F-1)

and

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$$M(T)x - F(t) \cos \theta = 0 \qquad (F-2)$$

Note that the mass (mass of the fragment and its contents) as well as the force, changes with time. From basic rocketry, the thrust F is

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FIGURE F-1. ROCKETING FRAGMENT



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$$F = A_{e} \left( \frac{U_{e}^{2}}{v_{e}g} + p_{e} - p_{o} \right)$$
 (F-3)

where

 $A_e = exit area$   $U_e = exit velocity$   $v_e = specific volume of the gas$  g = gravity constant  $p_e = exit pressure$  $p_o = atmospheric pressure$ 

Balancing the energy in the system, one has

$$h_{i} + q = h_{e} + \frac{U_{e}^{2}}{2g}$$
 (F-4)

where

h<sub>i</sub> = enthalpy of the gas at time t<sub>i</sub> q = energy expended in heating the gas h<sub>e</sub> = enthalpy of the gas at the nozzle (exit)

If the gas expansion is isentropic, q = 0, and Equation (F-4) reduces to

$$\frac{V_e^2}{2g} = h_i - h_e \qquad (F-5)$$

Flow continuity gives

$$\dot{w}v = AU$$
 (F-6)

where  $\dot{w}$  is the mass flow rate.

To determine the fragment's trajectory, one starts with a wet vapor in a tank having known initial state conditions of pressure  $p_i$ , specific volume  $v_i$ , entropy  $s_i$ , and enthalpy  $h_i$  which can be determined from tables of thermodynamic properties. One next assumes isentropic expansion through the nozzle, That is,

$$\mathbf{s}_{i+1} = \mathbf{s}_e = \mathbf{s}_i \tag{F-7}$$

where  $s_e$  is the entropy of the gas at the nozzle (exit) and  $s_{i+1}$  is the entropy at time  $t_{i+1}$ .

When the backpressure  $\mathbf{p}_{\mathrm{O}}$  is less than the critical pressure  $\mathbf{p}_{\mathrm{O}}$  given by

$$p_{c} \simeq 0.58 p_{i} \qquad (F-8)$$

the flow will be sonic and  $p_e$  in Equation (F-3) equals  $p_c$ . When the backpressure  $p_o$  is greater than the critical pressure  $p_c$ , then  $p_e$  equals  $p_o$  in Equation (F-3). Also, the pressure in the vessel at time  $t_i + 1$  is given by

$$\mathbf{p}_{i+1} = \mathbf{p}_{e} \tag{F-9}$$

Equations (F-7) and (F-9) allow one to obtain the value for  $h_2$ , the enthalpy at time  $t_i + 1$ , from the table of thermodynamic properties once one knows the values of  $s_e$  and  $p_e$ . Equation (F-5) gives  $U_e$ , and the thrust obtained by substitution into Equation (F-3). At the exit, Equation (F-6) gives

$$\dot{w}v_e = A_e U_e$$
 (F-10)

where  $v_e$  is also obtained from the thermodynamic tables. In reality, the state variables of the gas within the tank change continuously, but, for computational purposes, we will assume quasi-steady flow. From Equation (F-10), one can obtain the mass flow rate  $\dot{w}$  and calculate a new total mass of the fluid after a small time  $\Delta t$  from

 $M_{i + 1} = M_{i} - \frac{\dot{w}}{g} \Delta t$  (F-11)

After this time, a new specific volume can be determined from

$$v_{i} + 1 = \frac{V}{gM_{i} + 1}$$
 (F-12)

where V is the total volume of the fragment. Knowing  $v_{i+1}$  one can then obtain  $p_{i+1}$  from the table of thermodynamic properties of the gas and start a second iteration.

The above iteration process continues until backpressure  $p_0$  is greater than the critical pressure in Equation (F-8). Then the flow becomes subsonic and Equation (F-3) reduces to

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$$F = A_e \frac{U_e^2}{V_e g}$$
 (F-13)

Some thrusting will continue until the internal pressure  $p_n$  equals  $p_0$ , and the state of the gas in the vessel after n iterations lies on the  $p_0$  isobar.

To complete the process of calculating tank acceleration, velocity, and position one must solve Equations (F-1) and (F-2) during each iteration. The acceleration in the y and x directions is given by

$$\ddot{y}_{i} = \frac{F_{i} \sin\theta}{M_{i}} - g \qquad (F-14)$$

and

$$\ddot{x}_{i} = \frac{F_{i} \cos \theta}{M_{i}}$$
 (F-15)

Assuming the thrust  $F_i$  and mass of the vessel and enclosed substance  $M_i$  to be constant during the time step  $\Delta t$ , one can obtain velocity for time  $t_i + 1$  by integrating Equations (F-14) and (F-15) obtaining

$$\dot{y}_{i+1} = \Delta t \left( \frac{F_{i} \sin \theta}{M_{i}} - g \right) + \dot{y}_{i}$$
 (F-16)

and

$$\dot{\mathbf{x}}_{i+1} = \Delta t \left( \frac{\mathbf{F}_{i} \cos \theta}{\mathbf{M}_{i}} \right) + \dot{\mathbf{x}}_{i}$$
 (F-17)

where

$$\dot{y}(0) = \dot{x}(0) = 0$$

Integrating Equations (F-16) and (F-17), one can obtain displacement from

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$$Y_{i+1} = \frac{\Delta t^2}{2} \left( \frac{F_{i} \sin \theta}{M_{i}} - g \right) + \dot{Y}_{i} \Delta t + Y_{i} \qquad (F-18)$$

and

$$x_{i+1} = \frac{\Delta t^2}{2} \left( \frac{F_i \cos \theta}{M_i} \right) + \dot{x}_i \Delta t + x_i \qquad (F-19)$$

where y(0) = x(0) = 0.

The thermodynamic processes followed by the expanding fluids are shown on the pressure-volume (p - v) plane and temperatureentropy (T - s) plane in Figures 1-1 and 1-2, respectively.

A computer program entitled "THRUST" was written to perform computations for determining acceleration, velocity, and position of a thrusting fragment as a function of time, as explained. The program was written in BASIC and was run on a Tektronix 4051 microprocessor. The program was exercised using the state properties of propane gas to compare with measurements made after propane/butane accidents (Appendix H). The program was written with enough flexibility to allow for rocketing calculations of large portions of vessels containing other types of gases. TO change the contained gas, one merely inputs the state variables of the appropriate gas at the beginning of the program. Linear interpolation was used to estimate values of the state variables between those acquired from the thermodynamic properties tables [Din (1962)]. Table F-1 contains a list of the program variables, a listing of the program, and sample input and output.

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#### TABLE F-1

#### COMPUTER PROGRAM ENTITLED "THRUST" IN BASIC

FUNCTION: This program computes the acceleration, velocity, and displacement of a fragment containing a vaporizing liquid. It is assumed that a large portion of a vessel containing a liquid/gas mixture in equilibrium at greater than atmospheric pressure separates from the rest of the storage vessel. As the liquid underpressure converts to a gas when exposed to atmospheric pressure, thrust is produced causing the fragment to "rocket".

<u>INPUT-OUTPUT CONSIDERATIONS</u>: This program is written in BASIC computer language and is compatible in its existing form with a Tektronix 4051 microprocessor. Thermodynamic properties of the gas to be considered are stored in arrays on files using the program for storing data arrays contained in Table F-2. Input data follow.

- A. Thermodynamic properties of the liquid/vapor:
  - entropy (S) in cal/mole, °K
  - 2) enthalpy (H) in cal/mole
  - 3) specific volume (V) in  $cm^3/mole$
- B. Vessel characteristics:
  - 1) launch angle (Al) in degrees
  - 2) volume of the vessel (VO) in cubic meters
  - 3) volume of the fragment enclosure (V1) in cubic meters
  - 4) exit area (A) in square meters
  - 5) mass of the fragment (M) in kilograms
- C. Initial conditions of the liquid/vapor:
  - 1) initial pressure (Pl) in Pascals
  - 2) volume of the liquid (V8) in the vessel in cubic meters
  - 3) volume of the vapor (V9) in the vessel in cubic meters

D. Dynamic variable:

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1) time step (T) in seconds

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## VARIABLES

The program variable, identifying variable in the derivation above, definition, and units of variables in this program follow.

									Pre	cedir	ig pa	ge b	lan <b>k</b>			177		
U	L	L	L	L	L	Ľ	L	E	Ц	Ľ	K	H	H	П	ų	K	Ľ	L

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Ľ	178	PROGRAM VARIABLE	VARIABLE	DEFINITION	<b>UNIT'S</b>
1		S	ø	Array of entropy liquid/vapor values for propane	cal/mole, °K
1		Н	۲	Array of enthalpy liquid/vapor values for propane	cal/mole
I		^	>	Array of specific volume liquid/vapor values for propane	cm <sup>3</sup> /mole
		Al	;	Array for storing launch angles to be tested	degrees
]		Id	pl	Initial pressure	Pa
L		ØN		Volume of the container	°∈ '
		٧١		Volume of fragment enclosure	m E
E		<b>V</b> 8		Volume of liquid in the container	ົ∈່
		60		Volume of vapor in the container	ొ౬ౕ
L		۲		Exit area .	Z E
		Σ		Mass of fragment	kg
Ľ		£		Time step	S
L		BØ	Ð	Current launch angle	degrees
Ľ		IJ	ł	Counter used once to determine mass of gas and specific volume of frag portion immediately after breakup	-
		6d	ď	Atmospheric pressure	Pa
K		El	þ	Horizontal velocity at current time	m/s
		<b>E</b> 1		Vertical velocity at current time	m/s
Ŀ		TL		Current time	ŝ
		Z		Unit conversion constant for interpolations in specific volume	J • mole/cal • kg
R		IN	!	Unit conversion constant for interpolations in entropy or enthalpy	m <sup>3</sup> · mole/cm <sup>3</sup> · kg
Ŀ		8d		Nondimensional internal pressure	
Į	6	E A		Interpolated liquid specific volume	m <sup>3</sup> /kg
L	)RI OF	V4		Interpolated vapor specific volume	m <sup>3</sup> /kg
5	.GI P	IW		Initial mass of gas/liquid	kg
I	NA 00	V2		Initial specific volume	m <sup>3</sup> /kg
]	L R	01		Initial quality (based on specific volume)	;
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		ilume)	1	U)	Ē	E	hed 1	Ē	5/E	ht s	20 CD		<b>ت</b> :	
NOTLINI	ressure at nozzle	uality after pressure release (based on specific vo	uality after pressure release (based on entropy)	tabilization time (no more thrust)	tabilization distance (no more thrust)	tabilization height (no more thrust)	ime from stabilization until maximum height is read	laximum height reached by fragment	inal vertical velocity	ime from point of maximum height to the end of fligh	otal time fragment is in air	otal range of the thrusting fragment	orizontal (X) position of fragment at maximum height	
VARIABLE							-			-	-	•	-	• • • • •
PROGRAM VARIABLE	БЧ	80	60	ťa .	D2	D3	Т2	Н	¥З	Т3	T4	۵	6X	
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180 <b>L</b>	PROGRAM VARIABLE	VARIABLE	DEFINITION	
L	M2		Mass of gas/liquid in thrusting portion of tank	
	53		Interpolated liquid entropy	
U	S4		Interpolated vapor entropy	
	S5		Calculated entropy	
L	H3		Interpolated liquid enthalpy	
	H4		Interpolated vapor enthalpy	
1	HS		Calculated enthalpy	
	U		Constant (1/0.58)	
]	6đ		Nondimensional exit pressure	
L	S6		Interpolated liquid entropy at nozzle (exit)	
	S7		.Interpolated vapor entropy at nozzle (exit)	
F	02		Quality at nozzle (exit)	
	9H		Interpolated liquid enthalpy at mozzle (exit)	
L	H7		Interpolated vapor enthalpy at nozzle (exit)	
	6H		<b>Calculated enthalpy at nozzle (exit)</b>	
IJ	9A		Interpolated liquid specific volume at nozzle	
Ĩ	٧٦		Interpolated vapor specific volume at nozzle	
L	V5		Calculated specific volume at nozzle	
5	n		Exit velocity	
	ſL		Thrust	
Ţ	3		Mass flow rate	
1	X2		Horizontal acceleration	
	Y2		Vertical acceleration	
	X1		New horizontal velocity	
H	хı		New vertical velocity	
	×		Worizontal distance (range)	
L	Υ		Vertical distance (height)	
	P2		Pressure in container	
K				
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F.,				
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COMPUTER PROGRAM LISTING AND SAMPLE OUTPUT

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OR STORE DATA BELOW PROGRAM ING 230:A(I,1),A(I,2),A(I,3),A(I,4) 6D.2D,1X) P •,A(I,2),A(I,3),A(I,4) >,A(I,2),A(I,3),A(I,4) REN PROGRAM FOR STORING DATA ARRAYS-IN REST CHECK STORED DATA FILE ABOVE "DATA STORAGE FILE?" CORRECTIONS "FILE NO.?" ā 90 mm MAKE a ef 05 **END** STOP MAGI LOSI PAGE PAGE NLac PRIN IdN INI Id **dN** X REH х ш Х Ш Ř SO: à 40,-201 ē Ō 400 390 385 0 0 0 180 190 269 361 38 ЗÄ 4 M M M M M Ø Ö ORIGINAL PAGE IS OF POOR QUALITY 182 E К Ľ Ц L Ц Ľ Ľ R Ľ Ľ E Ľ Ľ Ľ K L

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B REN THRUSTTHIS PROGRAM CALCULATES THE ACCELERATION, VELOCITY, AND B REN DISTANCE TRAVELED BY A THRUSTING LIQUID B REN HYDROCARBON STORAGE TANK B REN B REN B PAGE	SET DEGREES B SET DEGREES B REM INPUT ENTROPY(S),ENTHALPY(H), AND SPECIFIC VOLUME(V) LIQUID/ B REM UAPOR VALUES B DIM S(18,4),H(18,4),U(18,4),A1(5) B DIM S(18,4),H(18,4),U(18,4),A1(5) B FIND 5	INPUT 033:S   FIND 6   INPUT 033:H   FIND 7   INPUT 033:H   FIND 7   INPUT 033:H   PATA 5, 10, 15, 30, 45	PRINT "INITIAL PRESSURE (PA) = "; INPUT PI PRINT "UOLUME OF CONTAINER (CU M) = "; INPUT UO INPUT UO PRINT "UOLUME OF FRAG ENCLOSURE (CU M) = "; PRINT "UOLUME OF FRAG ENCLOSURE (CU M) = "; PRINT "UOLUME OF LIQUID (CU M) = "; PRINT "UOLUME OF LIQUID (CU M) = ";	INPUT U8   PRINT "UOLUME OF UAPOR (CU M) = ";   INPUT U9   INPUT 0   PRINT "MASS OF FRAG (KG) = ";   INPUT M   A*="DATE "
REN T REN T REN T REN PAGE	SET D SET D REN I DIM S FIND S	FIND FIND FIND FIND FIND FIND FIND FIND	PRINT PRINT PRINT PRINT PRINT PRINT PRINT	INPUT PRINT PRINT PRINT PRINT PRINT PRINT PUT PUT
11111 00-00 00-00 00-00 00-00 00 00-00 00 00-00 00	2000 2000 2000 2000 2000 2000 2000 200	2000 2000 2000 2000 2000 2000 2000 200	33000000000000000000000000000000000000	00000000000000000000000000000000000000

<pre>B#="PAGE ND. " PRINT TIME STEP (SEC) = "; PRINT TIME STEP (SEC) = "; P</pre>
¥¥¥¥¥¥¥¥KKKKKK&&&&&&&&&&&&&&&&&&&&&&&&

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<pre>38 S4=(S(I-1,4)+(P8-S(I-1,1))/(S(I,1)-S(I-1,1))*(S(I,4)-S(I-1,4)))*H 98 S5=S3+Q1*(S4-S3) 98 IF P8(1 THEN 1582 98 IF P8(1 THEN 1582 188 IF E1=0 THEN 1210 188 FOR I=1 TO 18 18 IF U(I,1)=&gt;P8 THEN 1150 18 NEXT I</pre>	<pre>0 U3=(U(I-1,3)+(P8-U(I-1,1))/(U(I,1)-U(I-1,1))*(U(I,3)-U(I-1,3))/H1 0 U4=(U(I-1,4)+(P8-U(I-1,1))/(U(I,1)-U(I-1,1))*(U(I,4)-U(I-1,4)))/H1 0 D1=(U2-U3)/(U4-U3) 0 REM 0 REM 0 REM DETERMINE INITIAL ENTHALPY</pre>	<pre>B H3=CH(I-1,3)+(P8-H(I-1,1))/(H(I,1)-H(I-1,1))*(H(I,3)-H(I-1,3)))*N B H3=CH(I-1,4)+(P8-H(I-1,1))/(H(I,1)-H(I-1,1))*(H(I,3)-H(I-1,3)))*N B H5=H3+Q1*(H4-H3) B F5=H3+Q1*(H4-H3) B C=1/0.58 B F7 P8&lt;=C THEN 1280 B F9=0.58*P8 B G0 T0 1290 B G0 T0 1290</pre>	0 FOR I=1 TO 18 0 IF S(I,1)=>P9 THEN 1350 0 NEXT I 0 REM 0 REM DETERMINE QUALITY AT NOZZLE (EXIT) 0 REM	<pre>8 S6=(S(I-1,3)+(P9-S(I-1,1))/(S(I,1)-S(I-1,1))*(S(I,3)-S(I-1,3))*N 8 S7=(S(I-1,4)+(P9-S(I-1,1))/(S(I,1)-S(I-1,1))*(S(I,4)-S(I-1,4))*N 8 22=(S5-S6)/(S7-S6) 8 REM 8 REM DETERMINE ENTHALPY AT NOZZLE (EXIT) 8 REM</pre>	<pre>0 H6=(H(I-1,3)+(P9-H(I-1,1))/(H(I,1)-H(I-1,1))*(H(I,3)-H(I-1,3))*N 0 H7=(H(I-1,4)+(P9-H(I-1,1))/(H(I,1)-H(I-1,1))*(H(I,4)-H(I-1,4))*N</pre>
800		12121212121212121212121212121212121212		135 135 135 135 135 135 135 135 135 135	185

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T SE	1430 H3=H6+Q2‡(H7-H6)
Ľ	1440 REM 1450 REM DETERMINE SPECIFIC VOLUME AT NOZZLE (EXIT)
U	1450 KEH 1470 V6=(V(I-1,3)+(P9-V(I-1,1))/(V(I,1)-V(I-1,1))*(V(I,3)-V(I-1,3))/HI 1480 U7=(V(I-1,4)+(P9-V(I-1,1))/(V(I,1))/(V(I-1,1))*(V(I,2))/V(I-1,4))//HI
L	1490 US=U6+Q2±(U7-U6) 1490 US=U6+Q2±(U7-U6) 1500 REM DETERMINE EXIT VELOCITY, THRUST, AND MASS FLOW RATE
Ц	1510 REM 1520 U=SQR(2#(H5-H9))
Ľ	1538 F=AI(UIU/U5+(P9IPU-PU)) 1548 W=AIU/U5 1550 M2=M2-UII
Ľ	1560 REM DETERMINE ACCELERATION
L	1580 REM 1581 IF P8>1 THEN 1590
Ľ	1582 P8=1 1583 F=0
Ľ	1590 X2=F*COS(B0)/(M+M2) 1600 Y2=F*SIN(B0)/(M+M2)-9.80665
K	1620 REM DETERMINE VELOCITY
Ш	1630 KEH 1640 X1=F‡COS(B0)/(M+M2)#T+E1 1650 Y1=(F‡SIN(B0)/(M+M2)-9.80665)#T+E2
Ц	1660 REM DETERMINE POSITION
11	1680 KEA 1690 X=F\$COS(80)/(M+M2)\$T\$T/2+E1\$T+X 1740 Y=(F\$CIN(R4)/(M+M2)+9,80665)\$T\$T/2+F2%T+Y
K	1710 P2=P8#P8 1720 P3=P9#P8
LL LL	1730 TI=TI+T 1771 E1=X1
<u>k.</u>	
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1918 1918	URE AT WHICH QUALITIES Q8(SPECIFIC VOLUME) AND ITROPY) ARE EQUALTHIS IS THE NEW INTERNAL URE. 1,4)-U(J,3))	ORIGINAL PAGE IS OF POOR QUALITY 100 POOR QUALITY 100 POOR QUALITY	2020 P8>/{V(J,1>-V(J-1,1>)*(V(J,3)-V(J-1,3>)>/44094 P8>/{V(J,1>-V(J-1,1>)*(V(J,4>-V(J-1,3>)>/44094
E2=Y1 IF F=0 THEN 2091 REM REM REM DETERMINE NEW MASS OF REM IF Y<=0 THEN 2091 IF Y<=0 THEN 2091 IF Y<=0 THEN 2091 IF P8=1 THEN 1590 U2=U1/M2 U2=U1/M2 IF J>0 THEN 1910 FOR J=1 TO 18 IF U(J,1)=>P8 THEN 1910 NEXT J	REM DETERMINE PRESSURE AT I REM DETERMINE PRESSURE AT I REM PRESSURE. REM PRESSURE. RE	G0 T0 1960 F8=1 G0 T0 1100 IF X>0 THEN 1970 P8=U(J,1) IF ABS(Q9-Q8)<=1.0E-3 THEN IF P8=>2 THEN 1980 P8=P8-T#0.1 G0 T0 1990	P8=P8-I IF P8>U(J-1,1) THEN 2020 J=J-1 G0 T0 1910 U6=(U(J,3)-(U(J,1)-P8)/(U( U7=(U(J,4)-(U(J,1)-P8)/(U(
	1868 1888 1988 1988 1988 1988 1988 1988		1988 1998 2008 2018 2018 2028 2028 2038 2038

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2009 Sefs(J,4)-(S(J,1)-PB)/(S(J,1)-S(J-1,1))*(S(J,3)-S(J-1,3)))*94.96 2010 Dief 2010 D
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USING
2457; "STABILIZATION
DISTANCE", D2, "M"

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228, 2X, 4E, 1X, 1A
MIT
USING
2459; "STABILIZATION
HEIGHT", D3, "M"

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228, 2X, 4E, 1X, 1A
MIT
USING
2459; "STABILIZATION
HEIGHT", D3, "M"

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228, 4X, 4E, 1X, 1A
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2470; "TOTAL
RANGE", D, "M"

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RANGE", D, "M"
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2470; "TOTAL
RANGE", D, "M"

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2470; "TOTAL
RANGE", D, "M"
MSEC"
MSEC"

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USING
2490; "FINAL
UELOCITY", Y3, "M/SEC"
MSEC"

NT
USING
2520; "TOTAL
TIME", T4, "SEC"
M/SEC"

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USING
2520; "TOTAL
TIME", T4, "SEC"
M/SEC"

NT
USING
2520; "TOTAL
TIME", T4, "SEC"
M/SEC"

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USING
2540; "MAXIMUM
HEIGHT", H1, "M"
M/SEC"

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2540; "MAXIMUM
HEIGHT", H1, "M"
M/SEC"

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2540; "MAXIMUM
 "STABILIZATION X-UEL.",E1,"M/SEC" с щ S VERT. VELOCITY, Y3, M/SEC . "M/SEC Ì. Ľ. Y-UEL.", TIME", D1 200,4X,4E,1X,50 USING 2452: "STABILIZATION USING 2455: "STABILIZATION "FINAL UALUES" 9.80665\*H1> 0665 2452 DNISO X9=D-E1X dS= IMAGE PRINT PRINT IMAGE PRINT IMAGE PRINT INAGE PRINT PRINT PRINT PRINT PRINT **<u><u></u>**</u> <u></u> <u></u> <u></u> <u></u> <u></u> <u></u> <u></u> + <u>×</u>=0 PRINT IMAGE PRINT PRINT IMAGE COPY NEXT PRIN IMAGE PRINT PRINT \* 7=V 74=7 e N D 

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DATE 9/30/77 PAGE NO. 1 INITIAL CONDITIONS		
INITIAL PRESSURE VOLUME OF CONTAINER VOLUME OF FRAG ENCLOSURE	7.0120E+005 3.8020E+001 2.8230E+001	PASCALS CU M CU M
VOLUME OF UAPOR EXIT AREA MASS OF FRAG		
LAUNCH ANGLE TIME STEP	5.0000E+000 5.0000E+000	DEGREES
FINAL VALUES STABILIZATION X-VEL.	1.9383E+002	M/SEC
STABILIZATION Y-VEL. STABILIZATION TIME	6.0238E+000 1.1150E+000	M/SEC SEC
STABILIZATION DISTANCE STABILIZATION HEIGHT	1.0779E+002 3.3347E+000	T T :
FINAL VERT. VELOCITY	4.2617E+002 1.0084E+001	M = 1398 ft M/SEC
FINAL HORZ. VELOCITY TOTAL TIME	1.9383E+002 2.7576E+000	M/SEC SEC
MAXIMUM HEIGHT X POSITION AT MAX.HT.	5.1848E+999 2.2686E+902	M = 17.01 ft M
TIME AT MAX.HT. Internal pressure	1.7293E+000 1.0135E+005	SEC PASCALS
actual range = 1029 ft = befor	e first hittin	g ground

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## TABLE F-2

## PROGRAM FOR STORING DATA ARRAYS

Function: This program stores data arrays in files on tape. The program is written in BASIC and is compatible with a Tektronix 4051 microprocessor.

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ORIGINAL PAGE IS OF POOR QUALITY STORE DATA BELOW-PROGRAM 18 230:A(I,1),A(I,2),A(I,3),A(I,4) 20.1X) 50 **),A(I,2),A(I,3),A(I,4)** :A(I,1),A(I,2),A(I,3),A(I,4) PROGRAM FOR STORING DATA ARRAYS~ REM CHECK STORED DATA FILE IN REST PAGE g ABOUI CORRECTIONS TA STORAGE "FILE NO.?" "DATA NAKE ł Ħ I HAGE PRINT Indn. PRIN CLOSE PRIN' STOP **N**PU QNI: NPU STOP NEXT REM NPI PAG NEX NEX 20: NEX. REA 10R NEX 20 D B C 281 22 IN Z 375 385 385 98 288 00 6 すららいの Õ -NM 192

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#### APPENDIX G

#### MODEL ANALYSIS FOR ROCKETING OF STORAGE AND TRANSPORTATION VESSELS

The model analysis used here is patterned after the techniques explained in Baker, Westine and Dodge (1973). The purpose of the model analysis is to devise a method of consolidating the results of the computer runs made to predict the ranges of fragments which exhibit "rocketing" behavior as explained in Appendix F.

To conduct the model analysis, it is necessary to list all of the physical parameters which are indigenous to the problem. It is better to overdefine the important parameters initially than to leave out potentially pertinent items. Unnecessary parameters or parameters which weakly affect the results can be eliminated after the nondimensional pi terms are ascertained. A listing of these parameters is contained in Table G-1 which includes vessel characteristics, gas characteristics, and response parameters. Since we will ignore drag and lift forces (see Appendix F), the pertinent vessel characteristics can be limited to the internal volume V of the fragment, the exit area A, the mass M of the fragment, and the initial launch angle  $\alpha$ . Relevant gas parameters are the ratio of specific heats  $\gamma$  of the gas, the ideal gas constant  $R_M$ , the temperature T of the liquid/vapor at rupture, the volume of vapor to volume of liquid ratio  $V_V/V_1$ , the pressure P of the gas at rupture, and the atmospheric pressure pa. The acceleration g due to gravity is also important since it affects the vertical travel of the thrusting fragment. Pertinent response terms are the velocity u of the fragment and the distance X traveled by the fragment.

There are nine pi terms or nondimensional ratios which can be created from the above 13 parameters. Table G-2 presents one possible list of these nine pi terms. This list of nine pi terms can be reduced by making some simplifying assumptions. Since we were unable to readily locate the thermodynamic properties of butane and since most of the accidents examined involved propane for which we did have the thermodynamic properties, only rocketing due to the expansion of propane was considered. Since the ratio of specific heats  $\gamma$  in this case is constant,  $\pi_1$  can be eliminated. Since the gas is constant, R<sub>M</sub> is constant. The acceleration g due to gravity is nearly constant on earth and is also contained in  $\pi_6$ , temperature T is proportional to pressure P and V which are contained in  $\pi_5$ ,  $\pi_6$ ,  $\pi_7$ , and  $\pi_8$ . Thus  $\pi_2$  can be eliminated. If one assumes that atmospheric pressure pa is constant nd one observes that internal pressure P is contained in  $\pi_6,\ \pi_8$  can also be disregarded. Finally, we are not concerned with the velocity u of the fragment, a response term, and the volume V of the fragment is contained in  $\pi_6$ . Thus  $\pi_7$  can also be eliminated. No other simplifications are readily discernible.

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# TABLE G-1

# Pertinent Parameters for Rocketing Fragments

Symbol	Description	Dimensions*
v	internal volume of the fragment	r <sub>3</sub>
A	exit area	L <sup>2</sup>
М	mass of the fragment	FT <sup>2</sup> /L
α	launch angle	
Y	ratio of specific heats of the gas	
R <sub>M</sub>	ideal gas constant (adjusted for molecula weight	ar $L^2/T^2\theta$
т	temperature of the liquid/vapor at ruptur	<b>ε</b> θ
v <sub>v</sub> /v <sub>1</sub>	volume of vapor to volume of liquid ratio	)
Р	pressure of the gas at rupture	F/L <sup>2</sup>
Pa	atmospheric pressure	F/L <sup>2</sup>
g	acceleration due to gravity	L/T <sup>2</sup>
u	velocity of the fragment	L/T
х	distance traveled by the fragment	L

\* L = length

F = force

- T = time
- $\theta$  = temperature

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### TABLE G-2

# LIST OF PI TERMS FOR ROCKETING FRAGMENT



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Therefore, one finds that the distance traveled by a fragment experiencing rocketing due to the expansion of a single gas (propane in this case), depends upon the relative volumes of the vapor and liquid at fracture  $(V_V/V_1)$ , the launch angle ( $\alpha$ ), a vent area to fragment volume  $(A/V^{2/3})$ , and a ratio of inertial force to the force of the gas inside the vessel  $(Mg/PV^{2/3})$ . Representing these observations in equation form, one has

$$\frac{X}{V^{1/3}} = f\left(\frac{V_{v}}{V_{1}}, \alpha, \frac{A}{V^{2/3}}, \frac{Mg}{PV^{2/3}}\right)$$
(G-1)

Several computer runs were made to simulate actual accidents recorded in accident reports. Because these accidents were not experimental tests, some parameters such as launch angle and internal pressure of the tank at rupture had to be assumed. In spite of these obvious obstacles, the predicted values for distance traveled by the fragments, in most instances, correlated well with accident report observations. A summary of these comparative computer runs is contained in Table G-3. When one observes the sensitivity of fragment range to launch angle in this table and in Table 4-2 and keeps in mind the limitations on predicting launch angle from the accident reports, one can readily appreciate the apparent accuracy of the computer program.

Due to the complexity of the thrusting process (explained in greater detail in Appendix F) and limitations on the number of computer runs performed, no reduction of the five parameter space described by Equation (G-1) was readily apparent. Until further analysis can be performed for propane and other gases, it is recommended that the reader use the results contained in Table G-3 and Table 4-2 where appropriate or actually exercise the computer program.

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COMPARISON OF COMPUTER PREDICTED RANGES AND REPORTED	RANGES FOR ACCIDENTS INVOLVING ROCKETING FRAGMENTS	
G-3.		
TABLE		

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BEST ESTI- MATE FOR LAUNCH AN- GLE (degrees)	ي م	۰ <b>۲</b>	ν	5-10	01-5	5-10	5-10
PERCENT DIFFERENCE IN RANGE (2)	9E	18	-6.7	266	- 588		\$ ?
ACTUAL RANGE (m)	314	398	165		621	123	123
CALCU- LATED RANGE (m)	426	471	154	450	846	6	179
CALCULATED IMPACT VELOCITY (m/s)	194	189	76	159	154	72	11
LAUNCH ANGLE (degrees)	Ś	'n	Ś	Ś	10	Ń	01
NASS OF FRAGNENT (kg)	3885	5083	652	171	171	171	171
EXIT AREA (m <sup>2</sup> )	3.75	3.41	3.41	2.336	2,336	0.6567	0.6567
VOLUME OF VAPOR BE- FORE RUPTURE (m <sup>3</sup> )	4.916	10.56	10.56	0.3067	0.3067	0.3067	0.3067
VOLUME OF LIQUID BE- FORE RUPTURE (m <sup>3</sup> )	01.66	27.29	27.29	1.586	1.586	1.586	1.586
VOLUME OF FRAGMENT ENCLOSURE (m <sup>3</sup> )	28,23	30.32	1.28	0.5513	0.5513	0.2002	0.2002
VOLUME OF CONTAINER (m <sup>3</sup> )	38.02	37.85	37.85	1.8927	1.8927	1.8927	1.8927
INITLAL PRESSURE (P <sub>a</sub> )	701,197	1,034,214	1,034,214	1,378,951	1, 378, 951	1, 378, 951	1, 378, 951
SOURCE OF ACTUAL DATA	NTSB- HAR- 76-4 4/29/75	NTSB- HAR- 73-4 9/21/72	NTSB- HAR- 73-4 9/21/72	Propane Tank Explosion in San Antonio	Propame Tank Explosion in San Antonio	Propane Tank Explosion in San Antonio	Propane Tank Explosion in San Antonio
EXAMPLE NUMBER	Т	3	<b>m</b>	4 B	Ą 7	0 4	P4

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#### APPENDIX H

Accident Data and Statistical Fitting to Fragment Data

A literature search was conducted in which accident reports and other available, related data sources were reviewed for information on characteristics of fragments and pressure waves of bursting thick-wall, compressed fluid storage and transportation vessels. Fluids and gases considered in the survey were propane, anhydrous ammonia, oxygen, argon, air and propylene. Organizations and contractors contributing sources included the National Transportation Safety Board, Naval Surface Weapons Center, NASA Langley Research Center, Department of Transportation, National Technical Information Service and Ballistic Research Laboratory. Also, an incident which occurred in San Antonio, Texas during the accumulation of data, in which a propane storage tank exploded, was personally investigated by two staff members, W. E. Baker and L. M. Vargas, for information on energy release. The missile map developed as a result of this investigation proved very useful in determining effects of fragment impact. Data obtained from this literature were organized in a logical manner for the subsequent analysis. Records of the data include the reference and date of the explosion; the quantity of the explosion source; the estimated energy release; the shape, volume, mass, material and dimensions of the container vessel; the number of fragments; the masses, ranges, trajectory elevations (if given), drag coefficients and shapes of the fragments; and any additional pertinent information. Each vessel is assigned an identifying number. Twenty-five vessel explosions form the data base. These data are given in Tables H-1 and H-2.

In order to uncover any trends in terms of different variables which affect the chracteristics and effects of fragment impact and pressure waves, all the data were tabulated in terms of absolute numbers, percentiles, means, standard deviations and variations in information. The tabulations and analyses of different combinations of variables follow. A bibliography of sources utilized is also included.

#### Derivation of Fragment Range Distributions

#### (Figures 4-6 and 4-7)

The fragment range data for each of the six event groups (see Table 4-3) were sorted in ascending order. For event groups 1, 2, 3, 4 and 6, the values for the range for the 10th to the 90th percentile in 10% steps were identified. For event group 5, the values from the 14.3 percentile to the 85.7 percentile in 14.3% steps were identified. Table H-3 is a listing of these values.

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 _		r	1 1		1	1			4			r	r - 1														 	
	MATERIAL	A 212GrB Steel												TC128GrB Steel														
	MASS (KG)	235,000 kg												162,000 kg														
VESSEL	VOLUME (M <sup>3</sup> )	30.07m <sup>3</sup>												20.71m <sup>3</sup>														
	DIMENSIONS	Inside	diameter:	2.61m & 3.06m	Surface	Area:	183.14m <sup>2</sup>	Thickness	sheets 0.0190	0.02m	Outage:	0.34m	Length: 21m	Inside	Diameter:	3.02m	Surface	Area:	181.53m <sup>2</sup>	Thickness	sheets:	0.016m,	0.011m	Outage:0.30	Length:	19.lm		
	SHAPE	Railroad Tank	Car #27 with	Hemispherical	heads									Tank car #28	with	Hemispherical	heads											
	ESTIMATED ENERGY (JOULES)	5.417 × 10 <sup>5</sup>	Joules											5.954 × 10 <sup>5</sup>	Joules													
DURCE	OTHER DATA	Temp:	83°F	Specific	Gravity:	0.507								Temp: 88°F	Specific	Gravity:	0.507											
EXPLOSION SC	QUANTITY (M <sup>3</sup> OR KG)	62,700	kg =	31,300 m <sup>3</sup>										64,900 kg	= 32,400 <sup>m3</sup>													
-	MATERIAL	Propane												Propane														
	REFERENCE	NTSB-RAR-	72-2	Train	Derailment	6-21-70								NTSB	RAR-72-2	Train	Derailment	6-21-70										
	1.D. VUMBER	1												2														

TABLE H-1. LISTING OF EXPLOSION EVENT SOURCE AND VESSEL DATA

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(CONT.)		MATERIAI	TC128CBB Steel												A212GrB steel												
DATA (		MASS (KG)	37 800 ke	94 000 17								•			95,600 kg												
VESSEL	VESSEL	( <sub>2</sub> W) Norn <del>we</del>	4 افس <sup>3</sup>	m2 T · L											12.21m <sup>3</sup>												
CE AND		DIMENSIONS	Inside	Diamerer :	3.01 <b>m</b>	Surface	Area:	182.18m <sup>2</sup>	Thickness	sheets:	0.019m, 0.02m	Outage:	0.36m	Length:19.3m	Inside	Diameter:	2.66a-2.96a	Surface	Area:	618.13m <sup>2</sup>	Outage:	0.36m	length#70m				
ENT SOURC		SHAPE	Tank Car #30	with Hemispheri-	cal heads										Tank Car #32	with hemispheri-	cal heads										
SION EV		ESTIMATED Energy (Joules)	1.272 × 10 <sup>5</sup>	Joules							-				3.030 × 10 <sup>5</sup>	Joules											
EXPLC	JURCE	OTHER DATA	Temp = 78"F	Specific	Gravity:	0.507									Temp: 80°P	Specific	Gravity:	0.507									
ISTING OF	EXPLOSION SC	guantity (M <sup>3</sup> Or KG)	64,800 kg	32,300 <b>m</b> <sup>3</sup>											64,600 kg	- 32,200m <sup>3</sup>											
H-1. LJ		MATERIAL	Propane												Propane												
TABLE		REFERENCE	NTSB-	RAR-72-2	Train	Derailment	6-21-70								NTSB-	RAR-72-2	Train	Derailment	02-12-9								
		I.D. NUMBER	٣												4												
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			EXPLOSION SC	JURCE				VESSEL		
I.D. NUMBER	REFERENCE	MATERIAL	GUANTITY (M <sup>5</sup> OR KG)	OTHER DATA	ESTIMATED ENERGY (JOULES)	SHAPE	DIMENSIONS	VOLLIME (M <sup>3</sup> )	MASS (KG)	MATERIAL
<b>.</b>	NTSB	Propane	65,400	Temp: 80°F	.288 × 10 <sup>6</sup>	ank Car 133	Inside 1	10.73m <sup>3</sup>	83,900 kg	TC128GrB Steel
	RAR-72-2		ke =	Specific	loules	with hemispheri-	Diameter:			
	Train		32.600m <sup>3</sup>	Gravity:		cal heads	2.997m			
	lere ( ment			0.507			Surface			
	6-21-70						Area:			
							604.42m <sup>2</sup>			
							Thickness			
							Sheets			
							0.016m.0.017m			
							Outage:			
							0.36m			
							Length: 64.2m			
								1		
6	NTSB	LPG	114 <b>=</b> 3	Specific	3814	Section of Tank	About 18.29m	3.253m <sup>3</sup>	25.400kg	ASTMA212
	1-25-69			Gravity:	Joules	car (POTX car	long	(estimated from		Grade B or
	Train			0.505		261) with		BRL report)		AAR TC128
	Derailment			Temp: 157°F		hemispherical				Grade B steel
	1+-;					heads				
	fracture)									
1	NTSB	LPG	114m <sup>3</sup>	Specific	3814	Section of tank	About 18.29m	3.253m <sup>3</sup>	25,400 kg	ASTHA212
	1-25-69			Gravity:	Joules	car with hemis-	long	(estimated		Grade B or
	Train			0.505		pherical heads		from BRL re-		AAR TC128
	Derailment			Temp: 157°F		(POTX 269)		port)		Grade B steel
	(wheel									
	fracture)						_			

LISTING OF EXPLOSION EVENT SOURCE AND VESSEL DATA (CONT.) TABLE H-1.

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	TABLE	H-1. LIS	TING OF ]	EXPLOSI	ON EVEN	T SOURCE	AND VE	SSEL DA	TA (CC	NT.)
<u>.</u>			EXPLOSION SC	JURCE				VESSEL		
I.D. NUMBER	REFERENCE	MATERIAL	guantity (M <sup>3</sup> or Kg)	OTHER DATA	ESTIMATED ENERGY (JOULES)	SHAPE	DIMENSIONS	volume (Å <sup>3</sup> )	(90) Kass Kass	MATERIAL
8	NTSB	DATI	114m <sup>3</sup>	Specific	3814	Section of tank	About	3.253" <sup>3</sup>	25.400 kg	ASTH AZ12
	1-25-69			Gravity:	Joules	car with hemis-	18.29	(estimated		Grade R or
	Train			0.505		pherical heads	long	from BRL re-		AAR TC128
	Derailment			Temp: 157°F		(GALX car 557)		port)		Grade B steel
	(wheel									
	fracture)									
6	NTSB	LPG	114m <sup>3</sup>	Specific	3814	Section of Tank	About	3.253m <sup>3</sup>	25.400 kg	ASTH A212
	1-25-69			Gravity:	Joules	car with heads-	18.29 <b>m</b>	(est imated		Grade B or
	Train			0.505		pherical heads	long	from BRL		AAR TC128
	Derailment			Temp: 157*F		(POTX 162)		report)		Grade B Steel
	(wheel									
	Fracture)									
10	NTSB	947	114m <sup>3</sup>	Specific	3814	Section of tank	About 18.29	3.253 <b>m</b> <sup>3</sup>	25,400 kg	ASTH A212
	1-25-69			Gravity:	Joules	car with hemis-	long	(estimated		Grade B or
	Train			0.505		pherical heads		from BRL re-		AARTC 128
	Derailment			Temp: 157°F		(CATX 89971)		port)		Grade B steel
	(wheel									
	fracture)									- -

T.T.STTNG OF FXPLOSION FVFNT TARLE H-

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												_	_														_
4T.)		MATERIAL	Steel	(pipe was not	cathodically	protected)						Steel								DOT 112A340W &	DOT 114A340W	Tank cars	steel				
A (CON		MASS (KG)										3520 kg								 25,400kg	OB BRL		-				
SEL DAT	VESSEL	vollume (MJ)										0.45m <sup>3</sup>								3.253m <sup>3</sup>	(estimated fi	report)					
AND VES		DIMENSIONS	Diameter:	0.3048m	Thickness:	0.00254m	(corroded	from	0.0064m)	Length?		1.524m	hieh	Diameter:	0.61m	Length:?				None	given						
SOURCE		SHAPE	Cylindrical	pipe								Cylindrical	tank; concave	bottom, convex	top; designed	to operate at	maximum pres-	sure of 75	psig	Cylindrical	tank car #27	with hemis-	pherical heads	(1704EXTAN)			
N EVENT		ESTIMATED ENERGY (JOULES)																		3920	Joules				from BRL		
XPLOSIC	DURCE	OTHER DATA	Pressure:	3.427 ×	10 <sup>6</sup> Pa	Temp:	40°F-50°F					Pressure:	1.2066 ×	10 <sup>6</sup> Pa						 Pressure:	2.41 ×	10 <sup>6</sup> Pa	Temo: 157	ŭ.	(estimated	report)	
ING OF E	EXPLOSION SO	QUANTITY (M <sup>3</sup> Or KG)									;									125m <sup>3</sup>			-				
-1. LIST		MATERIAL	Natural gas									AIR	(Tank partial-	ly filled with	water)					LPG							
<b>FABLE H-</b>		REFERENCE	NTSB	PAR-75-3	Pipeline	Accident	3-15-74					NTSB-	PAR-76-2	Pineline	Accident	4-22-74				NTSB-	RAR-76-8	9-1-75					
.,		I.D. NUMBER	11									17								 13							

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			LING OF	TCOTAS	UN EVEN	L SOURCE	AND VE	SSEL DA	ra (co	NT.)
			EXPLOSION S	OURCE				VESSEL		
I.D. Vumber	REFERENCE	MATERIAL	guantity (M <sup>3</sup> or Kg)	OTHER Data	Estimated Energy (Joules)	SHAPE	DIMENSIONS	(M2) Vollume	Mass (KG)	MATERIAL
14	NTSB-	LPC	125m <sup>3</sup>	Tank	3920	Cylindrical	None	3.253m <sup>3</sup>	15 LOOL-	
	RAR-76-8			Pressure:	Joules	tank car #32	given	(estimated fy	on BRI.	DOT 114A3404
	9-1-75			2.41 × 10 <sup>6</sup>		with hemis-		report)		tank care
				Pa		pherical heads				
				Temp: 157*		(GATX 83347)				1101 P
				P.						
			(estimated fro	m BRL report)						
51	NTSB-	541	125m <sup>3</sup>	Tank	3920	Cylindrical	None	3.253m <sup>3</sup>	25,400kg	DOT 112A340W &
	RAR-76-8			Pressure:	Joules	tank car #33	given	(estimted fr	om BRL	DOT 114A340W
	8-1-75			2.41 x 10 <sup>6</sup>		vith heats-		report)		Tank cara
				Pa		pherical heads				steel
				Temp: 157°P		(GATE 83340)				
			(estimated fr	M BRL report						
16	NTSB-	Liquified	8.21m <sup>3</sup>	Pressure	~	Cargo tank	None	8.97ª <sup>3</sup>	70.200kg	Tank surroun-
	HAR-71-6	Oxygen		in tank:		assembly with	etven			ded by about
	5-30-70	(TOX)		at time of		henispherical				0.15m of pow-
				delivery		heads				dered inert
				68,948Pa-						insulating ma-
				82,737Pa						terial con-
				Temp: vas						tained in a
				refrigerated						steel jacket
			-	in tank at						
				290°F						
				Purity in						
				tank:						
				2 67.99						

TICTING OF TARLE H-

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	MATERIAL		USS T-1	Carilloy steel																										
	MASS (KG)	10111	145,800 kg																											-
VESSFL	VOLUME (M <sup>3</sup> )		~ 18.63m																											
	DIMENSIONS		Three 2,44m	in diameter	spheres	(0.032 <b>m</b>	thick) con-	nected hv	1.22m dia-	meter ofo-	tne (0.013=	thick) -dis-	tribute air	to 6 of 12	large stor-	age bottles	thru 0.91m	diameter man-	ifolding	m(0,0095m	thick)									
	SHAPE		Air system	manifolds;	Composed of	series of cylin-	drical pipes	and spheres																						
	ESTIMATED ENERGY (JOULES)	"UL × 10".	AT 4 0/717	Joules	-																									
OURCE	OTHER Data		ressure:	0T X 66.7	Pa	Outside	temp:	72°F-75°F																						
EXPLOSION S	guantity (M <sup>3</sup> or Kg)	47 400 <b>t</b>	34,200 86	71.900m																										
	MATERIAL	ATR	AIR																											
	REFERENCE	Report of		Accident	Investigating	Board to MASA	Langley Re-	search Center	9-30-21			-																		
	I.D. Number	17																												

TABLE H-1. LISTING OF EXPLOSION EVENT SOURCE AND VESSEL DATA (CONT.)

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			Γ		Γ																									
Т.)		MATERIAL	Steel plate																											
A (CON		MASS (KG)	25,500 kg																											
SEL DAT	VESSEL	VOLUME (M <sup>3</sup> )	3.263 <mark>m<sup>3</sup></mark>																											
ND VES		DIMENSIONS	18.26m long	tank	3.023m in-	side diame-	ter shell	thickness;	0.016m	tank head	thickness:	0.017m	car length:	19.28	wheels =	0.91	100 ton	trucks	15.95m apart	- <b>s</b>	other train	was travel-	ing about	52 mph at	time of de-	railment (max	speed at	that section	of track was	(1 m f)
SOURCE A		SHAPE	Cylindrical Tank	car with hemis-	pherical heads -	struck when an-	other train	derailed;	released gas to	form amonia	cloud																			
N EVENT		estimated Energy (Joules)	1.487 × 10 <sup>5</sup>	Joules																										
(PLOSIO)	JURCE	OTHER DATA	Temp: 4°F	(amb1ent	temp)	Pressure:	1.37 × 10 <sup>5</sup>				-																			
NG OF E	EXPLOSION SC	guantity (M <sup>3</sup> or Kg)	72,400 kg =	93,800m <sup>3</sup>																										
I. LISTI		MATERIAL	Anhydrous	amon1a																		-								
ABLE H-		REFERENCE	NTSB-	RAR-71-2	Train	Derailment	é Collision	2-18-69																						
F		I.D. Number	18																											

чт.)		MATERIAI	TC-128 steel								Quenched-and-	tempered steel															
A (CON		MASS (KG)	25,400 kg								7840 kg																
SEL DAT	VESSEL	vollume (M <sup>3</sup> )	3.253m <sup>3</sup>								1.001m <sup>3</sup>																
AND VES		SNOISNEWID	18.3m long	3.05 <b>m</b> in	diameter	shell	thickness	0.0159	Avg. tank	temp: 157°F	Cylinder	wall thick-	ne88 :	0.0119	head thick-	Deas:	0.00635m	tank length	11.57	sentrailer	length:11.83	tank dime-	ter: 2.11m	(outside)			
SOURCE		SHAPE	Cylindrical	tank car with	ellipsoidal	heads (RAX	201)				Cylindrical	cargo tank	semitrailer	with hemis-	pherical heads												
N EVENT		Estimated Energy (Joules)	3920	Joules							۰.																
ULCULTS	OURCE	OTHER DATA	Pressure:	9.63 × 10 <sup>5</sup>	Pa	Temp: 70°F	rank nres-	sure at	rupture:	2.41x10fra	Vapor	Pressure:	1.034x10 <sup>6</sup>	Pa	Temp:65°F	We1ght:	14,217.7	ke									
TING OF E	EXPLOSION SI	guantity (M <sup>3</sup> or kg)	About 125m <sup>3</sup>								27.29 <sup>m<sup>3</sup></sup>																
		MATERIAL	9471	(97.96% Pro-	pane)						Propylene	DAT															
		REFERENCE	RRI R 1935	September	1976						NTSB-	HAR-73-4	Multiple-	vehicle	collision	9-21-72											
		1.D. NUMBER	19								8																

ILISTING OF EXPLOSION TABLE H-1

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		[	1	1		Г	1																					
гг.)		MATERIAL	T-l steel								T-1 steel								T-1 steel									
A (CON		MASS (KG)	46.2 kg								136 kg								187 kg									
SEL DAT	VESSEL	VOLUME (M3)	0.0283m <sup>3</sup>	(internal)						-	0.0283m <sup>3</sup>	(internal)							0.0283m <sup>3</sup>	(internal)								
AND VES		DIMENSIONS	Internal	radius:0.19m	Shell	thickness:	0.012m	External	Red tue 10.203		Internal	radius:0.19m	Shell	thickness:	0.025	External	radius:	0.216m	Internal	radius:0.19m	Shell	thickness:	0.044m	External	radius:	0.23 <del>m</del>		
SOURCE A		SHAPE	Spherical								Spherical								Spherical									
N EVENT		ESTIMATED ENERGY (JOULES)	2.438 × 10 <sup>9</sup>	Joules							6.078x10 <sup>9</sup>	Joules							1.133×10 <sup>10</sup>	Joules								
<b>(PLOSIO</b>	JURCE	OTHER DATA	Pressure:	1.034 × 10 <sup>8</sup>	Pa	Temp: 17°C					Pressure:	2.068x10 <sup>8</sup> Pa	Temp:17°C						Pressure:	3.447×10 <sup>8</sup> Pa	Temp:17°C							
ING OF E	EXPLOSION SC	guantity (M <sup>3</sup> or Kg)	28.2 kg =	15.8 <sup>m<sup>3</sup></sup>							35.2 kg =	19.7m <sup>3</sup>							39.3 kg =	22.0m <sup>3</sup>							- -	
1. LIST		MATERIAL	Ar Ron								Argon								Argon									
ABLE H-		REFERENCE	NSHC/	NOL./TR	7587	2-9-76					NSWC/	HOL/TR	75-87	2-9-76					NSWC/	WOL/TR	75-87	2-9-76						
L		1.D. Number	21								22								23									

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NT.)			MATERIAL	U.S. Steel T-1																	Steel									
A (CO		MASS	(KG)	6340 kg																	512 kg									
SEL DAT	VESSEL	AOLUME	(M3)	0.810m <sup>3</sup>																	0.0654m <sup>3</sup>									
AND VES			DIMENSIONS	Tank length:	10.87mm	Inside	diameter;	2.18m	Thickness:	0.0096m(min)	Tank head	thickness:	0.0064m	Design	Pressure:	1.724x10 <sup>6</sup> Pa	at 150°F	Actual inter-	Del Dressure	5.998x10 <sup>5</sup> Pa	External	diameter	.955 m	Thickness:	0.0794mm	Head thick-	ness:.00508m	Tank length:	3.089m.Cyl.	Licthes 13/
SOURCE			SHAPE	Cylindrical	cargo tank on	semitrailer	vich hemis-	pherical heads	attached to	tractor											cylindrical	ank with	lemispherical	sede						
DN EVENT		ESTIMATED ENERGY	(JOULES)	549.6	Joules																24.78	Joules t	-	-	-					
XPLOSI(	ource	OTHER	DATA	Temp:	80°F																Relief	valve trig-	gers at 200	psi, vide	at 225 psi					
ING OF E	EXPLOSION S	QUANTITY	ניוא אט דוו	33.11m <sup>2</sup>																	 1.586m <sup>3</sup>									
-l. LIST		MATEDIAL	ria I EK I AL	LPG	(Half propane	half butane)															Propane									
TABLE H-		DEFERENCE		NTSB-	HAR-76-4	4-29-75															Propane tank	Explosion	8-9-77							
		I.D.		24																	25									

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	reparks	First in a series of ex	plosions-dug a crater	in track structure	Struck & collapsed roof	of a gag station	hurled southwesterly	Hurled southwesterly.	The force caused the	next car (#28) to ro-	tate with the north end	elevated 10 ft higher	than south end.	hurled southward; en-	tered a brick apartment	hurled northwest over	several bodises i landed	in a field & continued	to roll					
	SHAPES OR OTHER Description	East end hurled-	eastward		West end hurled-	Bouthwestward	Large Portion - (0.762m wide)	large portion -						South end -		north end -								
AGMENTS	DRAG COEFFICIENT C <sub>D</sub>	1.20			1.20		0.82	0.82						0.82		0,82								
E	APPARENT TRAJECTORY ELEVATION																							
	RANGE (M)	182m			91.4m		182m	228m						61.0m		487¢								
	MASSES (KG)						· · · · · · · · · · · · · · · · · · ·						•											
	TOTAL NUMBER Fragments	7												2										
	I.D. NUMBER	-												,										

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r.)		REMARKS	destroyed 2 buildings	after going through	them & came to a stop	in a third one	remained in general	derailment area	The remaining cars of	the train were rear-	ranged with this ex-	- Dioston	both fragments re-	mained stationary;	did not separate into	hurl fac at acas		did not travel beyond	general area; struck	next car	piece bounced off #39	é ignited propane in	11S					
DATA (CONT		SHAPES OR OTHER Description	about 1/2 of the	tank (north end)			other end -						car split	longitudinally				west end -			other end -							
JENT FRAGMENT	RAGMENTS	DRAG COEFFICIENT Co	0.82																		1.20							
XPLOSION EV	LL.	APPARENT TRAJECTORY ELEVATION											H		1													
ING OF E.		Range (M)	182m				20.0						0.0		0.0			5.0 <del>a</del>			15.24m							
H-Z. LIST		MASSES (KG)																										
TABLE		TOTAL Number Fragments	2										2					2										
		I.D. NUMBER											4					1										

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	TABLE	H-2. LIST	ING OF E	XPLOSION EV	JENT FRAGMENT	DATA (CON	т.)
				ι <b>τ</b> .	PAGMENTS		
1.D. NUMBER	TOTAL NUMBER Fragments	MASSES (KG)	RANGE (M)	APPARENT TRAJECTORY ELEVATION	DRAG COEFFICIENT C <sub>b</sub>	SHAPES OR OTHER DESCRIPTION	REMARKS
9	2	3/4 of total tank	487 <del>a</del>	low	0.82	11.28m long	First fragment bounced
						section	at 304.8m, then again
							at 396.24m, coming to
							rest at 487.68m on
		1/4 of tank	30.5m	lov	0.82		top of a house.
							Smaller section was
							not carried as far
1	3	3/4 of tank	335m		0.82	11.28m long -	struck a roof of a
						section	mill at 243.24m from
							the track; then it
							bounced at 274.32m,
							304.8m, and landed at
							335.28m
		1/4 of tank	15.24m		1.17		
		Ú	30.51m		1.17		
8			213m		1.20		none of these rose
							much in the air:largest
			182m		1.20		one traveled the
							fartheat 5 destroyed
			161-		1.17		a building

LTANT 1 Ę Ē 502 LISTING OF EXPLOSION EVENT TABLE H-2.

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	REMARKS	cår ruptured	circumferentially	without prior puncture	d <b>ama</b> ge	fragments were ap-	proximately equal	in size; car ruptured	without prior damage	by puncturing		fragment dug a crater	12.19m long, 5.18m	wide, and 3.048m	deep - 91.44m	dismeter area was	charred; 2 people	killed 10.06m from	the fragment; one	victim was almost 20m	avay				
	SHAPES OR OTHER DESCRIPTION											2.44m long -	section split	in 2 pieces											
PAGMENTS	DRAG COEFFICIENT C,	0.82	1.20			1.20		1.20				1.20													
E	APPARENT TRAJECTORY ELEVATION																								
	RANGE (M)	30.5 <del>u</del>		30. 5m		22.9m		a0.5m				29.9m													
	MASSES (KG)											23.2kg		23.2kg											
	TOTAL NUMBER Fragments	2				2						2													
	I.D. NUMBER	6				10						п			-								-		

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					AGMENTS		
TOTAL NUMBER MASSES RANGE FRAGMENTS (KG) (M)	MASSES RANGE (KG) (M)	RANGE (M)		APPARENT TRAJECTORY FI FVATTON	DRAG COEFFICIENT	SHAPES OR OTHER	
				906	۹, -	DESCRIPTION	KEFWIKKS
			<b>_</b>		0 * * 1		DOLLOW DIEW OUT OF
			_				the tank, rocketing
							it upward to strike
			_				a 0.1524m sas
			$\square$				service line above
							4
2 0.0m	0.0m	0.0			1.20	16.15m long -	found next to track,
						piece	split open on top. up-
							richt
27.4	27.4	27.4=			1.20	6.096a lone	
						piece	
3 4.57m	4.57m	4.57m	_		1.98	<b>esin section</b> -	tank shell flattened
							into a sheet
19.88	19.8m	19.8m			1.20	end piece (a-	found upright
						bout 3.048m	
						long)	
19.8m	19,8m	19.8m			1.20	other end (a-	located 39.62m
						bout 3.048m	from flust end
						long	piece
		-					

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TABLE H-2. LISTING OF EXPLOSION EVENT FRAGMENT DATA (CONT )

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		T	T		1	T		_		-		T	T	<b></b>	_		-		_	_	_		_		 _	 	
	REMARKS						reduction in thickness:	about 63kg of metal min-	sing from inner wall					- soared over a building.	struck the sidewalk,	broke, <b>6 destroyed</b> 2	cars totally				see diagrams						
	SHAPES OR OTHER DESCRIPTION	13.41m long	piece	2.74m by	1.524m piece		Osection of -	cargo tank wall		Qspray	header fragment	Obaffle plate		Outnot teal pipe	Dlameter:0.61m	Thickness:0.0095m	Length:11.95m	D Pipe diameter:0.61m	Thickness;0.0095	Length:3.302m	0.61m diameter	pipe	Thickness:0.0095	Length:0.57m			
PAGMENTS	DRAG COEFFICIENT C.D	0.82		1.17			1.20			1.20		1.17		1.20				1.20			1.20						
Ľ	APPARENT TRAJECTORY ELEVATION																										
	RANGE (M)	65.23 <b>m</b>		60.96m								4.1m		19120				206m			233m						
	MASSES (KG)							-						Q1703kg				Q470kg			Q2.22kg						
	TOTAL NUMBER FRAGMENTS	2					8							35													
	I.D. NUMBER	15					16							11													

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r.)		RFMARKS		see diagrams							-				-					=										
DATA (CONT		SHAPES OR OTHER DESCRIPTION	BO TITUL	0.91m diameter	Cylindrical pipe	THITCHIESS :	0.0095m	tengtn: 66 Verv small piece	of 0.91m in dia-	Beter pipe	60 Very small piece	of 0.91m in dia-	meter cylindri-	cal pipe	60 0.91m in diame-	ter cylindrical	pipe; thickness	0.0095m; Length	6.33m	fong piece of	0.91m in diame-	ter pipe;thíck-	ness:0.0095m	Length:6.77m	fig piece of	0.91m in dlame-	ter pipe; thick	ness: 0.0095ms	Length:7.65m	
ENT FRAGMENT 1	RAGMELITS	DRAG COEFFICIENT C	4) 0.82					1.17			1.17				0.82					1.20					1.20					
XPLOSION EV	ι.	APPARENT TRAJECTORY ELEVATION																												
ING OF E		RANGE (m)	208m					14600			185m				40.0 <b>m</b>					44.0 <b>m</b>					54.2m					
H-2. LIST		MASSES (KG)	@ 1930ke					Ø			0				Ø 1340kg					B 1440kg					(g) 1627kg					
TABLE		TOTAL NUMBER Fragments	35																											
		I.D. Number	17	Conr 'd																										

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					JAGMENTS			
I.D.	TOTAL NUMBER FRAGMENTS	MASSES (KG)	RANGE (M)	APPARENT TRAJECTORY FI EVATION	DRAG	SHAPES OR OTHER DESCRIPTION	DCWADVC	
17	35	0 1082kg	63.00m		1.20		Con Nacros	
cont 'd.						cylindrical pipe;	000 17071 000	
						Thickness:0.0095m		_
						Length:5.089m		
		00 1039kg	66.4m		0.47	612 Z.44m in dlameter	=	<del>.</del>
						sphere:thickness		-
						= 0.032 <b>m</b>		<b>.</b>
		(2) 2020ks	73.1m		1.20	(11) long piece at	=	
						0.91m diameter		
						cylindrical pipe;		
				/		Thickness:0.0091		
						Length:9.5m		
		0	67.7ma		1.17	eld wery small piece	-	_
						of 0.91m in dis-		_
						meter cylindrical		
						pipe, 0.0095m		_
						thick		
		(d) 93.6kg	63.7 <del>m</del>		1.17	Stall piece of	11 11	
						0,91m diameter		· · · ·
						pipe; 0.0095m		
						thick		
						Length:0.44m		
		G 2007kg	68.4ma		1.20	616 0.91m diameter	Ŧ	
						cylindrical pipe		
						0.0095m thick		
						Length: 9.44m		
								_

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-		RFMARKS		See Diagrams			=				=				=					=			b <b>a</b> dly crumpled; does	not even look	cylindrical			
ATA (CONT		SHAPES OR OTHER DESCRIPTION	C	U.YLB in diageter	0.0095m thick	Length: 10.45m	<b>BIB</b> Very small piece	Of 0.91m diameter	pipe, 0.0095m	thick	Very small piece	of 0.91m diameter	pipe, 0.0095 <b>m</b>	thick	620 connecting cy-	lindrical pipe.	1.22m diameter,	0.013m thick	Length: 3.29	B2D 2.44m diameter	sphere, 0,32m	thick	0.91m diameter -	cylindrical pipe	0.0095m thick;	Length: 5.334m		
ENT FRAGMENT D	PAGMENTS	DRAG COEFFICIENT C B	1.20				1.17				1.17				0.82					0.47			0.82					
PLOSION EVE	L	APPARENT Trajectory Elevation																										
NG OF EX		RANGE (M)	75.9				67.1ma				88.0m				97.5m					112m			110m					
1-2. LISTI		MASSES (KG)	(i) 2220kg				Ŵ			e	9			0	U 1280kg				<u>60</u>	C 1040kg			4 1130kg					
TABLE 1		TOTAL Number Fragments	35																									
		1.D. NUMBER	17	Cont'd.																								

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	REMARKS	- demolished several	buildings while still	connected to B12, then	broke apart & destroyed	a car in the parking lot																				
	SHAPES OR OTHER DESCRIPTION	(823) 11.28m long piece	of 0.91m diameter	cylindrical pipe.	0.0095m thick		<b>624</b> very small piece	of 0.91m diameter	pipe. 0.0095m	thick	625) 0.91m diameter	cvlindrical pipe	0.0095m thick	Length: 1.82m	625 5.08m long piece	Of 0.91m diameter	cylindrical pipe	0.0095m thick	0.91m diameter	cylindrical pipe	0.0095m thick	Length: 4.25m				
PAGMENTS	DRAG COEFFICIENT C <sub>D</sub>	0.82					1.17				1.20	-			0.82				1.20							
E	APPARENT TRAJECTORY ELEVATION																									
	RANGE (M)	32.5m					22.4m				29.1 <del>m</del>				65.7m				69.8m							
	MASSES (KG)	22) 2400kg					\$				69 <sub>387kg</sub>				29 1080kg				69 903kg							
	TOTAL NUMBER Fragments	35																								
	I.D. NUMBER	17	Cont'd.																							

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r.)		DEMADUC														does not annear on		does not annear on	does not appear on	reconstruction picture							
DATA (CONT		SHAPES OR OTHER DESCRIPTION	429	U.YIm dlameter	cylindrical pipe	0.0095m thick	630 830 small piece of	0.91m diameter	cylindrical pipe	0.0095m thick	Length: 1.14m	612 0.91m diameter	cv indrical nine	0.0095m thick	Length: 1.12m	(63) Very small frag-	8	037 Verv small frae-	(838) věry small frag-	ment	(839) very small piece	of 0.91m diame-	ter cylindrical	pipe, 0.0095m			
ENT FRAGMENT	PAGMETITS	DRAG COEFFICIENT C	1.20				1.17					1.20				1.17		0.82	1.20		0.82						
KPLOSION EV	LL.	APPARENT TRAJECTORY ELEVATION																									
ING OF E		RANGE (M)	5.42m				292m					116m				110m		48.1m	40.6m		102.3m						
H-2. LIST		MASSES (KG)	(21) 399kg				28) 24.2kg				¢	29 238kg				60		6)	(5)	(	69						
TABLE		TOTAL NUMBER Fragments	35																								
		I.D. Number	17	Cont'd.																							

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		REMARKS										remained intact; came	to rest north of the	track siding	landed in front yard	of a residence	hurled northward		hurled toward north	side of track	hurled toward north	side of track				
		SHAPES OR OTHER DESCRIPTION	Welly small piece	of 0.91m diameter	cylindrical pipe,	0.0095m thick	amall piece of	0.91m diameter	cylindrical pipe	0.0095 m thick.	Length: 1.06m	longer section of	rønk, about	9.1m long	top portion of -	shell, 4.88m long	bottom portion -	of tank head	other section -	of tank	other section -	of tank				
	PAGMENTS	DRAG COEFFICIENT C <sub>b</sub>	0.82				0.82					1.20			0.82		1.05		1.05		1.05					
	Ē	APPARENT TRAJECTORY ELEVATION																								
		RANGE (M)	1.12m				4.06ma					0.0			61.0 <del>m</del>		42.7m		40 <del>m</del>		161 <b>m</b>					
		MASSES (KG)	ଞ				0.9 244kg					10,800kg			4800kg		1910									
ſ		TOTAL NUMBER Fragments	35									7														
		I.D. NUMBER	17	Cont'd.								18														

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	RFMARKS	hurled toward north	side of track	hurled toward north	side of track	located in pit		located in pit			located in nit		located west of pit			located west of pit			located southeast	of pit				
	SHAPES OR OTHER Description	other section -		other section -		Item 76: portion	of tank car shell	Item 58: portion	of ellineoidal	to the sector sector.	Ttem 116 - Addad		Item 15: Portion	of ellipsoidal	head	Item 16: Portion	of tank car	shell	Item 1: Standard	manway				
PAGMENTS	DRAG COEFFICIENT G	1.05		1.20		1.20		1.17					1.17			1.20								
L	APPARENT TRAJECTORY ELEVATION																							
	RANGE (M)	174m		183m		15.4 <b>m</b>		21.2m	-		19.9m		104.2m			112.9 <del>m</del>			94.5m					
	MASSES (KG)					U 7470kg		Q 150kg			3 94.8kz		G 1150kg			S 74.8kg		¢	6 220.0kg					
	TOTAL NUMBER Fragments	7				6	major ones	(63 total of RAX	201)	(127 total of	entire test struc-	ture)												
	1, D, Number	18	cont'd.			61																		

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	REMARKS	located southeast of	pít	located south of pit			located south of	pit		northeast of	explosion point			southwest of	explosion point	southwest of	explosion point		found along eastern	embankment of	turnpike				
	SHAPES OR OTHER DESCRIPTION	Item 4: Portion	of tank shell	Item 7: Portion	of ellipsoidal	head	Item 9: Portion	of ellipsoidal	head	front section of-	tank shell:8.23m	in length(3/4 the	length of tank)	rear head		rear 1/4 of	cylindrical sec-	tion:3.34m long	part of trailer-	suspension					
PAGMENTS	DRAG COEFFICIENT C <sub>D</sub>	1.20		1.17			1.17			0.82				1.17		0.82			1.55						
E	APPARENT TRAJECTORY ELEVATION																								
	RANGE (M)	133m		146ш			73.6m			398m				165m		85.0 <del>m</del>			15.2m						
	MASSES (KG)	D 12,200kg		B 1180kg			④ 183kg			© 5080kg				2 652kg		③ 2060kg			9						
	TOTAL NUMBER Fragments	6									main ones														
	I.D. NUMBER	19	cont'd.							20															

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					RAGMENTS		
TO NU FRAG	ntal. Mber Ments	MASSES (KG)	RANGE (M)	APPARENT TRAJECTORY ELEVATION	DRAG COEFFICIENT C <sub>5</sub>	SHAPES OR OTHER Description	REMARKS
		୭	15.2 <b>m</b>		1.98	the two axles -	found along eastern
						(with the tires	embankment of turnp1ke
						burned off)	
		9	54.9		1.17	front pair of -	southeast of
	Ĩ					trailer wheels	explosion point
		(Shot No.)					
	2 each	e.)	max. of 512.06m	54°	0.165	top half of sphere	- never found
from	3 different	(b) 23.8kg	202.69m	54*	0.165	bottom half of	- avg. measured velocity
shot	60					sphere	96.93m/sec
		ම	max. of 423.37m	64*	0.165	top half -	never found
		29 23.9kg	168.25m	64*	0.165	bottom half -	avg. velocity =
							98.76m/sec
		6a 23.2kg	0.0		0.165	top -	impacted rear wall of
							steel
		6b 23.2kg	0.0		0.165	bottom -	confining structure;
							both halves remained
							inside the arena
		(Shot No.)					
	2 each	3a) 69.2kg	max. of 346.25m	70°	0.165	top -	never found (probably
for	2 shots						landed in wooded area)
		(Jb) 66.9kg	<b>B</b> 0.0		0.165	bottom -	found inside the arena;
							mean fragment velocity
							= 107.59m/mec

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	REMARKS		both found inside	arena; average ve	for bottom sectio	83.52m/sec		found inside aren	<b>velocity = 63.84</b>	never found	both found inside	the arena	struck on elevate	first hit ground	313.64m, bounced	touched again aft	84.73m and demoli	a mobile home; by	into the air & w	another 105.77m (	a second mobile	which caught fir	struck a third m	home to stop 504	from explosion p	
	SHAPES OR OTHER DESCRIPTION		top	bottom				large portion -		small portion -	large portion 7	small portion	large forward -	section												
AGMENTS	DRAG COEFFICIENT C <sub>5</sub>		0.165	0.165				0.165		0.165	0.165	0.165														
FR	APPARENT TRAJECTORY ELEVATION									78*																
	RANGE (M)		0.0m	0.0				0.0m		mex. of 220.07∎	0.0	-0°0	504m													
	MASSES (KG)	(Shot No.)	(a) 42.4kg	(b) 49.0kg			(Shot No.)	🕰 117kg		6 70. 3kg	(3) 123kg	(B) 64. 4ke	Ø													
	TOTAL NUMBER FRAGMENTS		2 each	for 2 shots				2 each	for 2 shots				25													
	I.D. NUMBER		22	cont'd.				23					24													

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	REMARKS																								
	SHAPES OR OTHER DESCRIPTION	aft section	(split in 3	parts actually)	Tractor frame	Tractor engine	Tractor fuel tank	Rear tank baffles	Spare tire	Trailer hose rack	Fifth wheel	plate	Tractor drive	shaft	Trailer spare	Trailer landing	gear assembly	Left door of	trailer	Tank vapor pipe					
PAGMERITS	DRAG COEFFICIENT CD								1.17																
ι.	APPARENT TRAJECTORY ELEVATION																								
	RANGE (M)	244 <b>m</b>			39,9ш	39,9m	51.5m	163 <b>m</b>	76.0m	85.0m	57.3m		66.1m		137m	37.3m		60.0 <del>8</del>		32.0m					
	MASSES (KG)	0			0	¢	Ø	0	Ø	9	0		9		0	0		0		69					
<u> </u>	TOTAL Number Fragments	25																							
	I . D. NUMBER	24	cont'd.																						

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(-		REMARKS																									
ATA (CONT		SHAPES OR OTHER DESCRIPTION	Trailer rear	bumber assembly	Trailer relief	valve system	Tractor radiator	Right seat of	tractor	Portion of bot-	tom tank shell	Portion of bot-	tom tank shell	Trailer front	tandem axle	wheels	Trailer rear	tandem axle	vheels	Portion of tank	shell (rear	head)	Right door of	tractor	Tractor	muffler	
ENT FRAGMENT I	RAGMENTS	DRAG COEFFICIENT C <sub>D</sub>																									
PLOSION EV	١L	APPARENT TRAJECTORY ELEVATION																									
ING OF EX		RANGE (M)	57.9m		67.7m		81.7m	89.0m		106m		230m		160m			169m			255m			220m		2391		
H-2. LIST]		MASSES (KG)	©		<b>(</b>		£Ĵ	6		6		ම		(I) (I)			20			0			24		3		
TABLE		TOTAL NUMBER Fragments	25																								
		I.D. NUMBER	24	cont'd.																							

LISTING OF EXPLOSION EVENT FRAGMENT DATA (CONT.) 0 Ħ

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	REMARKS		struck wall 2.8448m	above ground level:	also included	one attached	end can					located in creek	3.05m from the	main portion of the	cvl (nder	tank was sitting on	these concrete blocks				12.2m from a van								
	SHAPES OR OTHER DESCRIPTION		hemispherical end	can dissort	.0144m, .00508m thick	ma≴in por-	tion of cylinder	2.1336m long;	as circuan-	ference; .07144m	thick	section of	end cap (about	1/2)		cubical section	of cement block	fairly	rectangular	section of block	pie-shaped	piece of block	Pie-shaped	piece of block	sort of cubical	section of block	rectangular	section of block	
PAGMENTS	DRAG COEFFICIENT C		0.47			1.20						0.47				1.05		1.55			2.05		1.55		0.80		2.05		
	APPARENT TRAJECTORY ELEVATION																												
	Range (m)		31.4m to	wall, then	another 4.57m	12 <b>3</b> m						<b>119</b>				31.4m		40.2m			17.78		25.2m		15.2		28.3m		-
	MASSES (KG)	(Fragment ID)	① 104kg			(J) 171.1kg					(	(III) 52.2kg				(1) 0.0341kg		(2) 1.56kg			(J) 1.22kg		(4) 0.998kg		(5) 1.22kg		6 0.967kg		
	TOTAL NUPBER FRAGMENTS		11	main ones																									
	I.D. Number		25																										

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(•)		REMARKS	found across the	street against the	curb	struck wall about	3.96m above ground	level											
ATA (CONT		SHAPES OR OTHER DESCRIPTION	fence pipe;	5.77m long		1.96m long	fence pipe												
ENT FRAGMENT I	PAGMENTS	DRAG COEFFICIENT C <sub>b</sub>	1.20			1.20													
PLOSION EV	E	APPARENT TRAJECTORY ELEVATION																	
ING OF EX		RANGE (M)	58.8m			41.8m													
H-2. LIST		MASSES (KG)	(A) 9.3kg			B 1.00kg													
TABLE 1		TOTAL NUMBER Fragments	11																
		I.D. NUMBER	25	cont'd.															

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		Ev	vent Grou	ıp Number	s	
Percent	1	2	3	4	5	6
10.0	20.00	15.24	22.35	32.00		15.24
14.3	-				168.27	
20.0	40.00	19.81	40.64	51.51		17.68
28.6					202.69	
30.0	60.96	27.43	54.19	60.65		25.20
40.0	91.44	30.48	66.38	76.02		28.35
42.9					220.07	
50.0	161.00	60.96	68.41	85.04		31.39
57.1					346.25	
60.0	182.88	94.50	88.05	136.86		41.76
70.0	182.88	133.40	109.73	164.59		58.83
71.4					423.37	
80.0	228.60	167.64	115.82	238.96		119.79
85.7					512.06	
90.0	487.68	335.28	206.59	373.73		122.83

#### TABLE H-3. PERCENTILES FOR PLOTTING FRAGMENT RANGES OF THE SIX EVENT GROUPS

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Figures H-1 through H-6 are plots of the percentile points on log normal probability paper for each of the respective six events groups.

Table H-4 is a listing of the estimated means and standard deviations for the log normal (to the base e) distributions.

A "W" statistic [see Hahn and Shapiro (1967)] 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 H-5.

### Deviation of Fragment Mass Distributions

(Figures 4-8 and 4-9)

Sufficient pertinent mass data were available only from event groups 2, 3 and 6. Table H-6 is a listing of the percentiles of these event groups.

Figures H-7 through H-9 are plots of the percentile points on log normal probability paper for each of the respective event groups.

Table H-7 is a listing of the estimated means and standard deviations for the log normal (to the base e) distributions.

The calculated "W" statistic along with the approximate probability of obtaining the calculated test statistic, given that the chosen distribution is correct are presented for each of the three event groups in Table H-8.

## Correlation Analyses of Fragment Range and Fragment Mass Within Event Groups

(Figures 4-11 and 4-12)

For each of the three event groups (2, 3 and 6) with sufficient fragment range and mass data, three models were exercised to determine the degree of correlation between fragment range and mass. The three models and equivalent equations were:

1) Linear -

2)

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R = a + b M Power Curve -

 $R = aM^{D}$ 

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FIGURE H-2. EVENT GROUP 2 (EVENTS 6,7,8,9,10,13,14,15 and 19) PROBABILITY DISTRIBUTION, RANGE

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FIGURE H-3. EVENT GROUP 3 (EVENT 17) PROBABILITY DISTRIBUTION, RANGE

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FIGURE H-4. EVENT GROUP 4 (EVENTS 20 and 24) PROBABILITY DISTRIBUTION, RANGE

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FIGURE H-5. EVENT GROUP 5 (EVENTS 21, 22, 23) PROBABILITY DISTRIBUTION, RANGE

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FIGURE H-6. EVENT GROUP 6 (EVENT 25) PROBABILITY DISTRIBUTION, RANGE

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Event Group No.	Estimated Mean	Estimated Standard Deviation
1	4.569939	0.906041
2	4.103086	1.062895
3	4.275966	0.646206
4	4.633257	0.785540
5	5.660840	0.446785
6	3.668606	0.758061

TABLE H-4. LISTING OF ESTIMATED MEANS AND STANDARD DEVIATIONS FOR LOG-NORMAL RANGE DISTRIBUTIONS (TO THE BASE e) FOR THE SIX EVENT GROUPS

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#### TABLE H-5. SUMMARY OF "W" TEST ON NORMALITY FOR FRAGMENT RANGE DISTRIBUTIONS FOR EVENT GROUPS 1 THROUGH 6

Event Group No.	"W "	<b>Probability</b>
1	.964	.82
2	.951	.68
3	.986	.98
4	.980	.95
5	.936	.57
6	.917	.28

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 the six event groups are more than adequate.

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	Eve	nt Group Numbe	rs
Percent	2	3	6
10	74.8	93.61	.0341
20	94.8	241.98	.967
30	220.0	399.28	.998
40	350.0	1,039.52	1.00
50	1.180.0	1.080.29	1.22
60	3,183.0	1,281.78	9.30
70	7,470.0	1,439.81	52.23
80	12.200.0	1,935.88	104.46
90	19,098.0	2,020.84	171.38

TABLE H-6. PERCENTILES FOR PLOTTING FRAGMENT MASSES OF EVENT GROUPS 2, 3 AND 6

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8, 9, 10, 13, 14, 15, EVENT GROUP 2 (EVENTS 6, 7, 8, 9, ] PROBABILITY DISTRIBUTION, MASS

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FIGURE H-8. EVENT GROUP 3 (EVENT 17) PROBABILITY DISTRIBUTION, MASS

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TABLE H-7. LISTING OF ESTIMATED MEANS AND STANDARD DEVIATIONS FOR LONG-NORMAL FRAGMENT MASS DISTRIBUTIONS (TO THE BASE e) FOR EVENT GROUPS 2, 3 AND 6

Event Group No.	Estimated Mean	Estimated Standard Deviation
2	7.049131	2.117124
3	6.617446	1.051264
6	1.418576	2.784658

TABLE H-8. SUMMARY OF "W" TEST ON NORMALITY FOR FRAGMENT MASS DISTRIBUTIONS FOR EVENT GROUP 2, 3 AND 6

Event Group No.	<u>"₩"</u>	Probability
2	.920	. 37
3	.860	.10
6	.914	.32

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3) Logarithmic Curve -

$$R = a + blnM$$

Table H-9 is a listing of fragment range and mass for the three event groups. Table H-10 contains a listing of the estimated parameters and correlation coefficients for each model for each event group.

From Table H-10, the largest correlation coefficients over each of the three models are .79, .35, and .68 for the event groups 2, 3 and 6, respectively. These values of r can be transformed to a normal variate, Z, by the following formula [Arkin and Colton (1950)]:

$$Z = .5 [ln (l + r) - ln (l - r)]$$
(H-1)

The standard error of  $Z, \sigma_Z$ , is:

$$\sigma_{Z} = 1/(N - 3)$$
 (H-2)

where N is the number of fragment range-mass pairs in Table H-9 an event group.

A 95% confidence limit ( $L_Z$ ) on the range of sampling variation on Z can be set by:

$$L_{7} = Z + 1.96 \sigma_{7}$$
 (H-3)

Then, the 95% confidence limit on r can be established by substituting the two values of  $L_Z$  (one at a time) into Equation (H-1) for Z, and solving for r.

The 95% confidence limits on r for the three event groups are:

- 1) Event group 2
  - .70 < r < .85
- 2) Event group 3
   .39 < r < .43</pre>

3) Event group 6

.61 < r < .74

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TABLE H-9.	LISTING	OF FRAGME	ENT	RANGE	AND	MASS
	FOR EVEN	NT GROUPS	2,	3 AND	6	

Event C	roup 2	Event C	roup 3	Event G	roup 6
Range	Mass	Range	Mass	Range	Mass
112.9	74.8	233.0	2.22	31.39	.0341
19.9	94.8	63.37	93.61	28.35	.0967
73.6	183.0	115.82	237.66	25.2	.998
94.5	220.0	4.064	224.70	41.76	1.00
21.2	350.0	292.61	241.98	15.24	1.22
104.2	1150.0	29.13	387.18	17.68	1.22
145.7	1180.0	5.42	399.28	40.23	1.56
15.24	3183.0	206.59	470.70	58.83	9.3
30.48	6366.0	69.77	903.18	119.79	52.23
15.4	7470.0	112.44	1039.52	31.39	104.46
133.4	12200.0	66.38	1039.52	122.83	171.38
487.68	19098.0	65.70	1080.29		
335.28	19098.0	63.00	1082.13		
		110.41	1134.30		
		97.54	1281.78		
		39.96	1345.72		
		44.03	1439.81		
		54.19	1627.08		
		191.69	1703.20		
		207.94	1935.88		-
		64.41	2007.72		
		73.15	2020.84		
		75.86	2223.24		
		32.51	2399.70		

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ESTIMATED PARAMETERS FOR REGRESSION MODELS FOR CORRELATION BETWEEN FRAGMENT RANGE AND MASS FOR EVENT GROUPS 2, 3 AND 6 TABLE H-10.

				EV	ent Group				
Modal *		2			m			9	
Tapoli	ŋ	q	r	a	p q	r	a	q	ч
Linear	37.5572	.01558	.79	731.72	-0.5789	.18	34.2328	0.4534	. 68
Power Curve	20.3775	.16782	. 30	101.93	-0.0640	60.	31.3277	0.1692	. 63
Logarithmic Curve	-9258.7	3472.05	.56	210.41	-17.4501	. 35	32.9911	10.2442	. 60

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- a is the range axis intercept \*
- b is the slope
- r is the correlation coefficient

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Since one can be 95% confident that the correlation coefficient for event group 3 is less than .43, there would be little benefit in using the corresponding prediction model for fragment mass given fragment range, or vice-versa. However, for event groups 2 and 6 a sufficient degree of correlation between fragment range and fragment mass is indicated to make the prediction models worthwhile. These models are shown on Figures 4-11 and 4-12.

### Correlation Analysis of Fragment Range to the Ratio of Mean Fragment Weight to Vessel Weight For Cylindrical Tanks

Five events with cylindrical tanks contained sufficient fragment mass information to determine the degree of correlation of fragment range to the ratio of mean fragment weight to vessel weight. It was necessary to group events 6 and 7 to have a sufficient sample size.

Table H-11 presents the data by event number, the ratio of the arithmetic mean fragment weight  $(\overline{W})$  to the vessel weight (W(T)), and the arithmetic mean fragment range  $(\overline{R})$ . Figure H-10 is a plot of the points in Table H-11 along with the prediction equation. The sample correlation coefficient is .987. Using the same techniques as described earlier, one can be 90% confident that the true population correlation coefficient is greater than .74.

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TABLE H-11. MEAN RANGE AND RATIO OF MEAN FRAGMENT WEIGHT TO VESSEL WEIGHT FOR CYLINDRICAL TANKS

Event	<u>w/w(t)</u>	R
6,7	.644	179.83
18	.242	110.30
19	.100	80.08
25	.0612	39.20



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# LIST OF SYMBOLS

# English Symbols

A	<pre>= cross-sectional area; loaded area; differential   volume</pre>
Aa	= speed of sound in surrounding atmosphere
<sup>A</sup> D	= drag area
<sup>A</sup> e	= exit area
A <sub>L</sub>	= lift area
a	= conditions in surrounding atmosphere; range axis intercept
a <sub>*</sub>	= critical gas velocity
a gas	= sound speed of gas
<sup>a</sup> o	= speed of sound
b	= loaded width, slope
C <sub>D</sub>	= drag coefficient
C <sup>L</sup>	= lift coefficient
$\frac{{}^{C}{}_{L}{}^{A}{}_{L}}{{}^{C}{}_{D}{}^{A}{}_{D}}$	= lift/drag ratio
c <sub>l</sub>	= cylindrical length
c <sub>t</sub>	= cylindrical thickness
С(Т)	= mass of gas confined at high pressure as a function of time
C <sub>v</sub>	= coefficient relating maximum bending shear stress to the maximum
с <sub>w</sub>	= coefficient to relate stress to deformations
$D = M/d^3$	= caliber density of the projectile
đ	<pre>= coefficient; projectile diameter; pipe outside diameter</pre>
ds	<pre>= differential length</pre>
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		Is	<pre>= side-on specific impulse</pre>
		Ŧ	<pre>= scaled (dimensionless) impulse</pre>
		I	<pre>second moment of area</pre>
		h <sub>i</sub>	= enthalpy of gas
		<sup>h</sup> e	= enthalpy of gas at nozzle
		h	<pre>= enthalpy; concrete panel thickness; height</pre>
		ਸ਼ੁ	= scaled gage height
		Ħ	= scaled height
		H	= total depth
		subscript	= gas (saturated vapor)
		√ g	= square root of the acceleration of gravity
		q	= acceleration of gravity; gravity constant
		-c subscript,	= fluid (saturated liquid)
		f'	= ultimate concrete compressive strength
		ਸ	thickness
		e	<pre>= specific energy; specific work; perforation thickness</pre>
		E <sub>t</sub>	= end cap thickness
		е Е	<pre>= energy of detonation of l gram of TNT</pre>
		E,	= end cap length
		e E <sub>v</sub>	= kinetic energy of the fragment
		<sup>2</sup> C E	= effective blast vield
		F	Tessels
		E	<pre>= blast yield (energy) for bursting pressure </pre>
		E	= blast yield (energy); elastic modulus
		$\left(\frac{dv}{dx}\right)$ max	= maximum slope

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	I <sub>s</sub> (-)	<pre>= negative phase impulse for first shock</pre>
	I <sub>s</sub> (+)	<pre>= positive phase impulse for first shock</pre>
	Īs	<pre>= scaled (dimensionless) side-on overpressure</pre>
	i	= impulse
	<sup>i</sup> r	= reflected impulse
	is	= positive impulse
	K	= coefficient of discharge; constant; concrete penetrability factor
	KE	= impact kinetic energy
	L/D	= length-to-diameter ratio
	LZ	= confidence limit
	٤	= length; span
	М	= total mass; mass of the overlying floor
	м <sub>с</sub>	= mass of the container
	Mg	= force of gravity
	M	= enclosed substance
-	M Y	<pre>= vertical inertial force</pre>
	M X	= horizontal inertial force
	(MW)	= molecular weight
	m	<pre>= mass of the liquid in the vessel</pre>
	N	= number of fragment-mass pairs; projectile nose-shape factor
	n	= number of fragments
	0	= reservoir conditions immediately after failure
	Ρ	<pre>= peak applied pressure; pressure; internal     pressure</pre>
	P	= average burst pressure

Pa	= atmospheric pressure
₽ <sub>A</sub>	<pre>= starting overpressure</pre>
P-i	= nondimensionalized pressure impulse
P <sub>oo</sub>	= initial pressure
Pr	<pre>= peak reflected overpressure</pre>
P <sub>s</sub>	= peak side-on overpressure
₽s	= dimensionless overpressure
Psl	<pre>= first shock side-on overpressure</pre>
P <sub>s2</sub>	<pre>= second shock side-on overpressure</pre>
₽V/E <sub>o</sub>	= normalized yield
P	= absolute pressure
p <sub>1</sub>	<pre>= initial absolute pressure in the vessel</pre>
p <sub>1</sub> ,V <sub>1</sub> ,S <sub>1</sub> , U <sub>1</sub> ,h <sub>1</sub>	= initial state variables
pA	= vertical load
Pa	<pre>= outside atmosphere absolute pressure; ambient pressure; atmospheric pressure</pre>
P <sub>c</sub>	= critical pressure
°e	= exit pressure
P <sub>n</sub>	= internal pressure
P <sub>O</sub>	<pre>= atmospheric pressure; back pressure</pre>
p-v	= pressure-volume plane
q	<pre>= energy expended in heating gas</pre>
R	= range
R	<pre>= dimensionless distance; scaled distance; mean fragment range</pre>
R <sub>M</sub>	= ideal gas constant

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, r	= correlation coefficient; cylindrical radius; distance along the plane of symmetry from the center of tank
S	<pre>= entropy, scabbing thickness</pre>
s <sub>2</sub>	= final entropy
s <sub>e</sub>	<pre>= entropy of gas at the nozzle (exit)</pre>
Т	= absolute temperature
Ŧ	= scaled (dimensionless) time
т <sub>о</sub>	= temperature of the gas
Too	= temperature
T-s	<pre>= temperature-entropy plane</pre>
T <sub>s</sub> (-)	= duration of negative impulse for first shock
T <sub>s</sub> (+)	= duration of positive impulse for first shock
t <sub>w</sub>	= pipe wall thickness
U	= mean fragment velocity
Ue	= exit velocity
u	<pre>= internal energy; velocity</pre>
v	= maximum shear force; shear force
v <sub>l</sub>	= vessel volume
vo	= internal volume
v <sub>oo</sub>	= internal volume
vs	<pre>= missile striking velocity</pre>
v <sub>v</sub> /v <sub>1</sub>	= volume of vapor to volume of liquid ratio
v	= specific volume
v <sub>2</sub> , u <sub>2</sub> , h <sub>2</sub>	= thermodynamic parameters
<sup>v</sup> e	= specific volume
$v_{f}$	= final volume occupied by the gas originally in the vessel
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	1	- ratio of specific heat for gas in the vesser
	T	= ratio of specific heat for cas in the vessel
	αp	= numerical coefficient
	-	simply-supported beam
	α <sub>i</sub>	= initial trajectory angle, coefficient for
	α	= trajectory angle
	Greek Symbols	-
	z	= plastic section modulus
	Y Z	= normal variate, dimensionless variable
	¥ •	= vertical acceleration
	Ŷ	= altitude
	×	= horizontal velocity
	×2	= final quality
	×ı	= initial quality
	x	= quality of the vapor; characteristic dimension; total penetration depth; the depth a missile will penetrate into an infinitely thick target
	X	= horizontal acceleration
	x <sub>l</sub>	= displacement distance along the axis of motion
	x	= distance traveled by the fragment
	wo	= maximum elastic deformation
	ŵ	= mass flow rate
	w	= deformation
	W(T)	= sphere weight, vessel weight
	WK	= maximum possible work
	$\overline{w}$	<pre>= geometric mean fragment mass; mean fragment weight</pre>

Δt	= small time
σ	= deflection
<sup>e</sup> max	= maximum strain
θ	= trajectory angle, characteristic time, temperature
Π	= perimeter
ρ	= mass density
ρ <b>*</b>	= gas density
ρgA	= weight per unit length quantity
ρ <sub>o</sub>	= density of air
omax	= scaled stress
σt	= yield strength
σ <sub>u</sub>	= ultimate stress
σy	= yield point
σ <u>y</u> E	= yield strain
$\frac{\mathrm{E}\varepsilon_{\max}}{\sigma_{y}}$	= scaled strain
σ <sub>z</sub>	= standard error of Z
τ	= time
<sup>ψ</sup> p,i,ε,w <sub>o</sub>	= coefficients

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#### 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 =  $2.54 \times 10^{-2}$  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. The accepted abbreviation in Système International (SI) is given in parentheses in the second column.

To convert from	to	multiply by
atmosphere	Pascal (Pa), <sub>2</sub> Newton/meter <sup>2</sup>	+05 1.013 25*
bar	Pascal (Pa), <sub>2</sub> Newton/meter <sup>2</sup>	+05 1.00*
British thermal unit (mean)	Joule (J)	+03 1.055 87
calorie (mean)	Joule (J)	+00 4.190 02
dyne	Newton (N)	-05 1.00*
erg	Joule (J)	-07 1.00*
Fahrenheit (temperature)	Celsius (C)	$t_{c}^{=}(5/9)(t_{F}^{-}32)$
foot	meter (m)	-01 3.048*
inch	meter (m)	-02 2.54*
<pre>lb<sub>f</sub>(pound force, avoirdupois)</pre>	Newton (N)	+00 4.448 221 651 260 5*
lb <sub>m</sub> (pound mass, avoirdupois)	kilogram (kg)	-01 4.535 923 7*
Pascal	Newton/meter <sup>2</sup> (N/m <sup>2</sup> )	+00 1.00*
pound force (lb <sub>f</sub> avoirdupois)	Newton (N)	+00 4.448 221 615 260 5*

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To convert from	to	multiply by
pound mass (lb <sub>m</sub> avoirdupois)	kilogram (kg)	-01 4.535 923 7*
poundal	Newton (N)	-01 1.382 549 543 76*
slug	kilogram (kg)	+01 1.459 390 29
foot/second <sup>2</sup>	<pre>meter/second<sup>2</sup>  (m/s<sup>2</sup>)</pre>	-01 3.048*
inch/second <sup>2</sup>	meter/second <sup>2</sup> (m/s <sup>2</sup> )	-02 2.54*
gram/centimeter <sup>3</sup>	kilogram/meter <sup>3</sup> (kg/m <sup>3</sup> )	+03 1.00*
lb <sub>m</sub> /inch <sup>3</sup>	kilogram/meter <sup>3</sup> (kg/m <sup>3</sup> )	+04 2.767 990 5
lb <sub>m</sub> /foot <sup>3</sup>	kilogram/meter <sup>3</sup> (kg/m <sup>3</sup> )	+01 1.601 846 3
slug/foot <sup>3</sup>	kilogram/meter <sup>3</sup> (kg/m <sup>3</sup> )	+02 5.153 79
lb <sub>f</sub> /foot <sup>2</sup>	Pascal (Pa), <sub>2</sub> Newton/meter <sup>2</sup>	+01 4.788 025 8
lb <sub>f</sub> /inch <sup>2</sup> (psi)	Pascal (Pa), <sub>2</sub> Newton/meter <sup>2</sup>	+03 6.894 757 2
foot/second	<pre>meter/second  (m/s)</pre>	-01 3.048*
inch/second	meter/second (m/s)	-02 2.54
foot <sup>3</sup>	meter <sup>3</sup> (m <sup>3</sup> )	-02 2.831 684 659 2*
inch <sup>3</sup>	meter <sup>3</sup> (m <sup>3</sup> )	-05 1.638 706 4*

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- <u>appurtenance</u> 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 released in an explosion inferred from measurements of the characteristics of blast waves generated by the explosion.
- burst pressure the pressure at which a gas storage vessel bursts or fails.
- concrete penetrability factor measures the resistance of concrete to impact penetration.
- <u>drag coefficient</u> ratio of drag force to dynamic force exerted by wind pressure on a reference area.
- 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.
- <u>far field barricade</u> a barricade located near the protected structure.
- FRAG a computer program for predicting velocities of fragments from bursting cylindrical and spherical pressure vessels.
- FRISB a computer program for predicting trajectories of fragments with both lift and drag aerodynamic forces.
- <u>lift coefficient</u>- ratio of lift force to dynamic force exerted by wind pressure on a reference area.
- LPG liquified petroleum gas, usually liquified propane.
- <u>mound</u> An elevation of earth having a crest at least 3 ft. wide with the earth at the natural slope on each side and with such elevation that any straight line drawn from the top of the side wall of a magazine or operating building or the top of a stack containing explosives to any part of a magazine, operating building or stack to be protected will pass through the mound. The toe of the mound shall be located as near the magazine, operating building or stack as practicable.

near field barricade - barricades located near an explosive source

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overpressure - pressure in a blast wave above atmospheric pressure

- perforation thickness the maximum thickness of material which will be completely penetrated by a missile at a given velocity.
- reflected impulse integral of reflected pressure-time history.
- <u>risk assessment</u> the estimation of effects of some potentially dangerous operation or situation; but also the estimation of the probability that the event will occur and cause some level of damage.
- rocketing propulsion of large fragments from liquid propellant vessels resulting from the change of the liquid propellant into a gas when the external pressure is released during the fracturing of the vessel.
- scabbing thickness thickness of a target required to prevent scabbing of material from the backface for a missile with a given velocity.
- side-on impulse integral of time history of side-on overpressure.
- <u>side-on overpressure</u> blast wave overpressure in an undisturbed blast wave.
- single-revetted barricade a mound which has been modified by a retaining wall preferably of concrete of such slope and thickness as to hold firmly in place the 3 ft. width of earth required for the top, with the earth at the natural angle on one side. All other requirements of a mound shall be applicable to the single-revetted barricades.
- spalling or scabbing the process of projection of pieces of material from impacted plates or walls by stress wave reflection.
- stable buckling bending of a column under axial impulsive load.
- starting overpressure a curve on a graph of dimensionless overpressure versus dimensionless distance used as a starting point to compute the overpressure at a given distance from the center of the vessel.
- THRUST a computer program for predicting trajectories of large parts of pressure vessels containing flash-evaporating fluids.
- total penetration depth the depth a missile will penetrate into an infinitely thick target.

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- <u>TUTTI</u> two dimensional finite difference computer program for compressible fluids.
- unconfined vapor cloud explosion a quantity of fuel released to the atmosphere as a vapor or aerosol, subsequently mixed with air and then exploded by some ignition source.
- <u>UNQL</u> a computer program for predicting velocities of two unequal fragments of a failed pressure vessel.
- vapor density the ratio of the density of the vapor to that of air at standard temperature and pressure.
- vapor dome the dome-shaped curve on a plot of thermodynamic properties of a fluid which represents the boundary between wet vapor and superheat.



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