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THE CHARACTERIZATION AND EVALUATION OF ACCIDENTAL EXPLOSIONS

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16. Abstract

In this review accidental explosions are discussed from a number of points of view. First, all accidental explosions, intentional explosions and natural explosions are characterized by type so as to form a framework for further discussion. Secondly, the nature of the blast wave produced by an ideal (i.e., point source or H.E.) explosion is discussed to form a basis for describing how other explosion processes yield deviations from ideal blast wave behavior. In this section the current status blast damage mechanism evaluation is also discussed. Thirdly, the current status of our understanding of each different category of accidental explosions is discussed in some detail.

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THE CHARACTERIZATION AND EVALUATION OF ACCIDENTAL EXPLOSIONS

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SUMMARY

This paper contains a comprehensive review of the current status of our understanding of accidental explosions. After a short historical introduction in which all explosions are characterized by type, the first section discusses the general characteristics of explosions in some detail. Here the usually defined properties of blast waves are introduced and the classical point source or ideal wave is used to discuss scaling laws and TNT or point source equivalence in some detail. Following this there is a general summary of non-ideal blast wave behavior which first discusses extant theoretical work on blast waves from non-ideal sources, i.e., sources which are extended in either space or time. Secondly, each different non-ideal source property effect is discussed in detail with examples. Thirdly, atmospheric and ground effects are discussed briefly.

In the next section the mechanisms by which blast waves produce damage are discussed in detail. In particular the new P-I (for pressure-impulse) method of evaluation is described in some detail with examples, the importance of dynamic impulse in producing tumbling and sliding is discussed, our understanding of fragment damage mechanism is presented and the classic TNT equivalence evaluation based on overpressure is described.

In the last main section of the report specific examples of accidental explosions are given by type. The types that are discussed are: Simple pressure vessel failure, Runaway chemical reaction or continued combustion, Explosions in buildings, Internal explosions, Rupture followed by combustion, Vapor cloud explosions, High explosives and propellants, Physical explosions and Nuclear reactor runaway. The length of the discussion for each case is dependent on the potential hazard and extent of our current understanding of that type of explosion.

The conclusion section summarizes the findings of the report. The main conclusions and recommendations are that 1. Accidental explosions are important and they will continue to occur. 2. Certain accidental explosions are more reproducible than others but virtually all of them are non-ideal. 3. TNT Equivalency is not a good criterion for evaluating non-ideal explosions and should be replaced, once our understanding improves. 4. Scaling laws for accidental explosions will be relatively easy to develop once our understanding of non-ideal explosions improves. 5. A considerable amount of work, both theoretical and experimental, is needed in this area.

I. INTRODUCTION

This paper is intended to provide a comprehensive review of the current state of the art relative to the characterization and evaluation of accidental explosions in the atmosphere. It was prompted in part by the recent large increase in both the frequency and destructiveness of all types of accidental explosions and in part by the lack of any comprehensive current survey of the literature in this field. It is hoped that this review will delineate, in a systematic manner, our current understanding of the various facets of explosion and damage producing processes and serve as an impetus for future research in this area.

If one examines the literature, the need for such a review becomes evident. There are only three books, Robinson (1944), Freytag (1965) and Kinney (1962), which attempt to treat the general problem. The first of these is very out of date and the second is more of a handbook of safety techniques than a description of the explosion process itself. The last of these, Kinney (1962), is the most comprehensive but is also out of date. The other texts on explosions, Glasstone (1962), Engineering Design Handbook (1972), Baker (1973) and Baker, et al. (1973), all pertain mainly to the behavior of high explosive charges and do not really treat in detail the more general accidental explosion problem. Furthermore, the majority of the literature in this subject area is not published primarily in open journals but is buried in limited distribution reports.

In general, an explosion is said to have occurred in the atmosphere if energy is released over a sufficiently small time and in a sufficiently small volume so as to generate a pressure wave of finite amplitude traveling away from the source. This energy may have originally been stored in the system in a variety of forms; these include nuclear, chemical, electrical or pressure energy, for example. However, the release is not considered to be explosive unless it is rapid enough and concentrated enough to produce a pressure wave that one can hear. Even though many explosions damage their surroundings, it is not necessary that external damage be produced by the explosion. All that is necessary is that the explosion is capable of being heard.

There are actually many types of processes which lead to explosions in the atmosphere. Table I contains a comprehensive listing of all possible types of explosions including theoretical models, natural explosions, intentional explosions and accidental explosions. The list is by type of energy release and is intended to be exhaustive.

In the following sections of this review, the general nature of explosions, current theoretical models and scaling laws will be discussed. The last section will concentrate on a detailed discussion of the characteristics of the accidental explosions listed in the last column of Table I.

TABLE I. EXPLOSION TYPES

Theoretical Models	Natural Explosions	Intentional Explosions	Accidental Explosions
Ideal Point Source	Lightning	Nuclear Explosions	Pressure Vessels
Ideal gas	Volcanoes	High Explosives	Simple failure (no combustion)
Real gas	Meteors	Blasting	Runaway chemical reaction before failure
Self-similar (∞ source energy)		Military	Internal explosion or detonation before failure
Constant velocity piston		Pyrotechnic separators	Failure followed by immediate combustion
Accelerating piston		Guns	Gaseous Explosions in Enclosures (i.e., Buildings, Cars, etc.)
Bursting Sphere		Muzzle blast	Unconfined Vapor Cloud Explosions
Finite Stroke Piston		Recoilless rifle	High Explosives and Propellants During Manufacture, Transport, Storage or Use
Detonation Driven		Exploding Spark	Physical Explosions
General Discussions		Exploding Wires	Nuclear Reactor Runaway
		Laser Sparks	
		Continuous Source*	
		Contained Explosions**	

* Hypervelocity missile and supersonic aircraft are examples.

** Contained vessel explosions and automotive knock are examples.

II. GENERAL CHARACTERISTICS OF EXPLOSIONS

A. Wave Properties

1. Energy Distribution

One of the most important properties which determine the behavior of any explosion process is the energy distribution in the system and how it shifts with time as the pressure wave propagates away from the source. Initially all the energy is stored in the source in the form of potential energy. At the instant when the explosion starts, this potential energy is redistributed to produce kinetic and potential energy in different parts of the system; the system now includes all materials contained within either the lead characteristic or lead shock wave of the outwardly propagating explosion wave. The system is non-steady, both because new material is continually being overwritten by the lead wave front, and because the relative distribution of energy in various forms and in various parts of the system shifts with time.

In order to consider this problem in more detail in this section, we will idealize the system to some extent. We will assume (1) that the explosion is strictly spherical in an initially homogeneous external atmosphere that extends to infinity, (2) that the source of the explosion consists of both energy containing material (source material) and inert confining material, and that during the explosion process these materials do not mix to any great extent with each other or with the outside atmosphere, and (3) that shock wave formation is the only dissipative process in the surrounding atmosphere. With these assumptions, the originally stored energy is distributed among a number of distinct forms at various times and locations as the explosion process proceeds. These are:

a. Wave energy

The propagating wave system contains both potential energy

$$E_p = \int_v \rho C_v (T - T_o) dv \tag{1}$$

and kinetic energy

$$E_k = \int_v \frac{1}{2} \rho u^2 dv \tag{2}$$

where v is the volume of the atmosphere enclosed by the lead characteristic or lead shock wave. This volume does not include the volume occupied by the products of explosion or by the quiescent atmosphere between the products and blast wave. Furthermore, at late time when the kinetic energy of the source and confining material are zero and the wave amplitude is such that shock

dissipation is negligible, the total wave energy ($E_T = E_p + E_k$) in the system must remain constant with time. This far field wave energy should therefore be a unique property of each explosion process.

b. Residual energy in the atmosphere (waste energy)

In most explosions a portion of the external atmosphere is treated by a shock wave of finite amplitude. This process is non-isentropic and there will be a residual temperature rise in the atmosphere after it is returned to its initial pressure. This residual energy will also reach some constant value at late time. This was first called "waste" energy by Bethe, et al. (1947).

c. Kinetic and potential energy of the fragments (or confining material)

Initially the confining material will be accelerated and will also store some potential energy due to plastic flow, heat transfer, etc. Eventually all this material will decelerate to zero velocity and will store some potential energy.

d. Kinetic energy of source material

In any explosion involving an extended source the source material will be set into motion by the explosion process. This source material kinetic energy will eventually go to zero as all motion stops in the near field.

e. Potential energy of the source

The source originally contained all the energy of the explosion as potential energy. As the explosion process continues a portion of the energy is lost to other forms but a portion of it normally remains in the source as high temperature product gases, etc. While it is true that this stored energy eventually dissipates itself by mixing, etc., these processes are relatively slow compared to the blast wave propagation process, and for our purposes one can assume quite accurately that the residual energy stored in the products approaches a constant value at late time.

f. Radiation

Radiated energy is quickly lost to the rest of the explosion system and reaches a constant value quite early in the explosion process.

Figure 1 summarizes in a schematic manner the way that energy is redistributed in a blast wave as time increases. Note that at late time, when the wave is a far field wave, the system contains potential and kinetic wave energy, residual potential energy (waste energy) in the atmosphere, potential energy in the fragments and potential energy in the products. Also, in general, some energy has been lost to the system due to radiation. However, radiation losses represent an important fraction of the total source energy only for the case of nuclear explosions. A few general statements may be

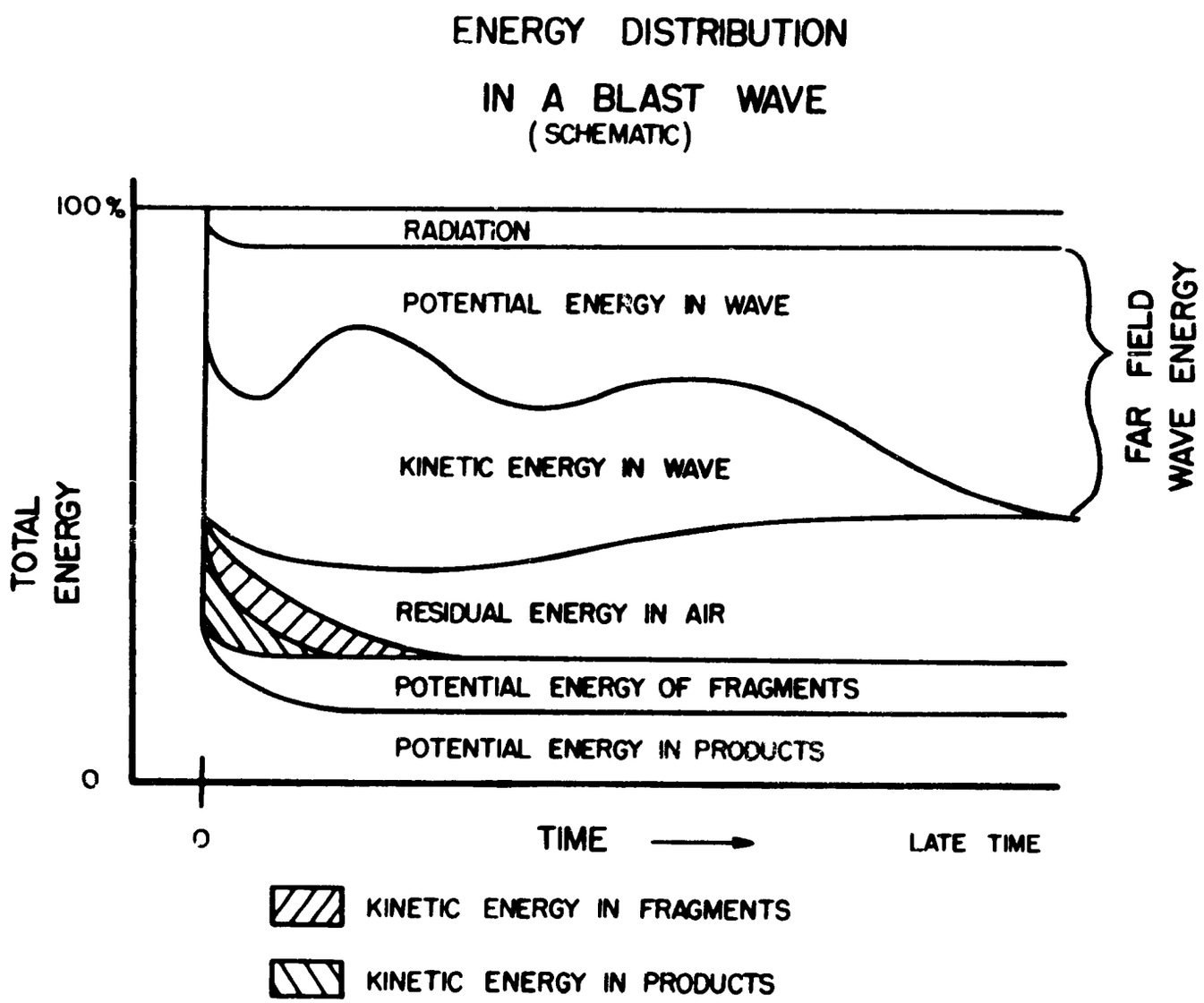

Figure 1. Energy distribution in a blast wave as a function of time after the explosion (schematic)

made at this time about Figure 1.

Firstly, only a fraction of the total energy which is initially available actually appears as wave energy in the far field. Secondly, the magnitude of this fraction relative to the total energy originally available must depend on the nature of the explosion process itself. This is shown for example by the fact that TNT equivalence of nuclear explosions is about 0.5 to 0.7 of that which one would expect on the basis of the total energy available (Lehto and Larson (1969), Thornhill (1960) and Bethe, et al. (1947)). More to the point, in accidental explosions the source normally releases energy relatively slowly over a sizable volume and one would expect this effectiveness factor to be a strong function of the nature of the release process. Unfortunately, there is no extant work which yields any information on this specific problem. Brinkley (1969) and Brinkley (1970) discuss this problem using a theoretical approach but present no experimental verification of the thesis that slow release means that a larger fraction of the energy is lost to the blast wave.

2. Usually Defined Properties

As a blast wave passes through the air or interacts with and loads a structure or target, rapid variations in pressure, density, temperature and particle velocity occur. The properties of blast waves which are usually defined are related both to the properties which can be easily measured or observed and to properties which can be correlated with blast damage patterns. It is relatively easy to measure shock front arrival times and velocities and entire time histories of overpressures. Measurement of density variations and time histories of particle velocity are more difficult, and no reliable measurements of temperature variations exist.

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

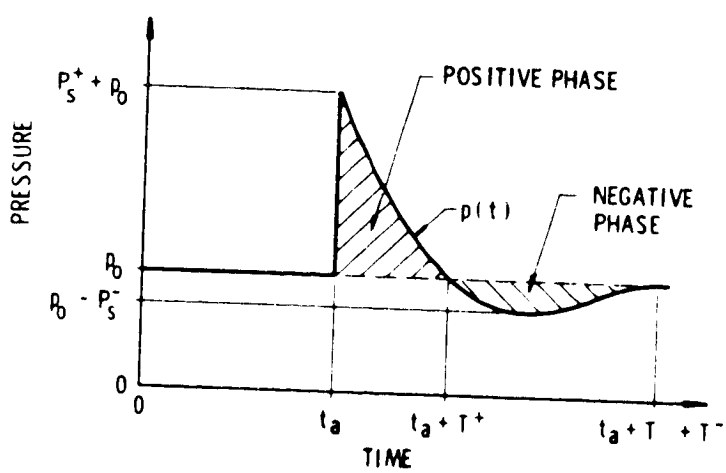

Figure 2. Ideal Blast Wave Structure

(1973)). Prior to shock front arrival, the pressure is ambient pressure p_o. At arrival time t_a, the pressure rises quite abruptly (discontinuously, in an ideal wave) to a peak value $p_s^+ + p_o$. The pressure then decays to ambient in total time $t_a + T^+$, drops to a partial vacuum of amplitude p_s^-, and eventually returns to p_o in total time $t_a + T^+ + T^-$. The quantity p_s^+ is usually termed the peak side-on overpressure, or merely the peak overpressure. The portion of the time history above initial ambient pressure is called the positive phase, of duration T^+. That portion below p_o, of amplitude p_s^- and duration T^- is called the negative phase. Positive and negative impulses, defined by

$$I_S^+ = \int_{t_a}^{t_a+T^+} [p(t) - p_o]dt \tag{3}$$

and

$$I_S^- = \int_{t_a+T^+}^{t_a+T^++T^-} [p_o - p(t)]dt \tag{4}$$

respectively, are also significant blast wave parameters.

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

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

A real target feels a very complex loading during the process of diffraction of the shock front around the target. Figure 3 shows schematically, in three stages, the interaction of a blast wave with an irregular object. As the wave strikes the object, a portion is reflected from the front face, and the remainder diffracts around the object. In the diffraction process, the incident wave front closes in behind the object, greatly weakened locally, and a pair of trailing vortices is formed. Rarefaction waves sweep across the front face, attenuating the initial reflected blast pressure. After passage of the front, the body is immersed in a time-varying flow field. Maximum

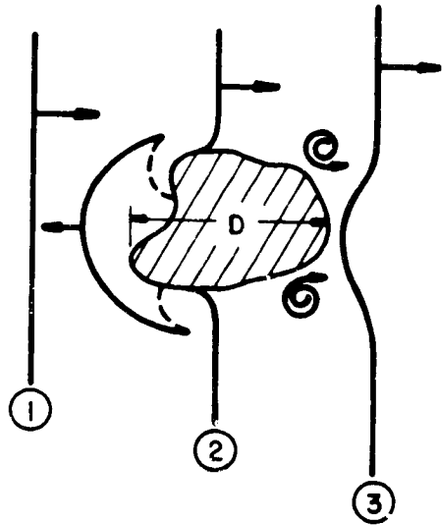

Figure 3. Interaction of Blast Wave with Irregular Object

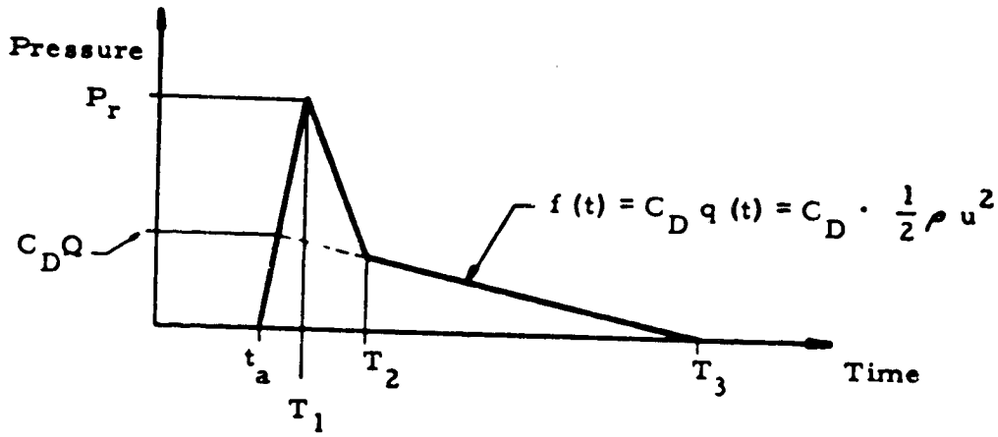

Figure 4. Time History of Net Transverse Pressure on Object During Passage of a Blast Wave

pressure on the front face during this "drag" phase of loading is the stagnation pressure.

We are interested in the net transverse pressure on the object as a function of time. This loading, somewhat idealized, is shown in Figure 4 (details of the calculation are given by Glasstone (1962)). At time of arrival t_a, the net transverse pressure rises linearly from zero to maximum or P_r in time $(T_1 - t_a)$ (for a flat-faced object, this time is zero). Pressure then falls linearly to drag pressure in time $(T_2 - T_1)$, and then decays more slowly to zero in time $(T_3 - T_2)$. This time history of drag pressure q is a modified exponential, with a maximum given by

$$C_D Q = C_D \cdot \frac{1}{2} \rho_s u_s^2 \tag{5}$$

where C_D is the steady-state drag coefficient for the object, Q is peak dynamic pressure, and ρ_s and u_s are peak density and particle velocity respectively for the blast wave. The characteristics of the diffraction phase of the loading can be determined if the peak side-on overpressure P_s or the shock velocity U are known, together with the shape and some characteristic dimension D of the object. The peak amplitude of the drag phase of the loading can be determined if the peak side-on overpressure P_s or the shock velocity U are known, together with the shape and some characteristic dimension D of the object. The peak amplitude of the drag phase, $C_D Q$, can also be determined explicitly from P_s or u_s.

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

$$I_d = \int_{t_a}^{t_a+T} q \, dt = \frac{1}{2} \int_{t_a}^{t_a+T} \rho u^2 \, dt \tag{6}$$

is also reported.

Although it is possible to define the potential or kinetic energy in blast waves, it is not customary in air blast technology to report or compute these properties. For underwater explosions, the use of "energy flux density" is more common (Cole (1965)). This quantity is given approximately by

$$E_f = \frac{1}{\rho_o c_o} \int_{t_a}^{t_a+T} [p(t) - p_o]^2 dt \tag{7}$$

where ρ_o and c_o are density and sound velocity in water ahead of the shock.

B. The Point Source Blast Wave

A "point source" blast wave is a blast wave which is conceptually produced by the instantaneous deposition of a fixed quantity of energy at an infinitesimal point in a uniform atmosphere. There have been many studies of the properties of point source waves, both for energy deposition in a "real air" atmosphere and for deposition in an "ideal gas" ($\gamma = 1.4$) atmosphere. Deposition in water has also been studied (Cole (1965)). Point source blast wave studies date to the second World War (Bethe, et al. (1944), Taylor (1950), Brinkely and Kirkwood (1947), and Makino (1951)). They have been quite adequately summarized by Korobeinikov, et al. (1961), Sakurai (1965), Lee, et al. (1969), and Oppenheim, et al. (1971) and will be briefly reviewed here. Essentially there are three regions of interest as a point source wave propagates away from its source. The first is the near field wave where pressures in the wave are so large that external pressure (or counter pressure) can be neglected. In this region the wave structure admits to a self-similar solution and analytic formulations are adequate (Bethe, et al. (1947), Sakurai (1965)). This region is followed at late time by an intermediate region, which is of extreme practical importance because the overpressure and impulse are sufficiently high in this region to do significant damage, but which does not yield to an analytical solution and therefore must be solved numerically (von Neumann and Goldstine (1955), Thornhill (1960)). There have been approximate techniques developed to extend the analytical treatment from the near field. These have been summarized by Lee, et al. (1969). The intermediate region is followed in turn by a "far field" region which yields to an analytic approximation such that if one has the overpressure time curve at one far field position one can easily construct the positive overpressure portion of the curve for large distances. In this far field region there is theoretical evidence that an "N" wave must always form and that the blast wave structure in the positive impulse phase is unaffected by the interior flow and is self-sustaining (Bethe, et al. (1947) and Whitham (1950)). However, experimentally it is difficult to determine if such an "N" wave actually exists because atmospheric non-homogenieties tend to round the lead shock wave (Warren (1958)).

C. Classical Experimental Work

The classical experimental work on blast waves has mainly revolved about the use of either high explosives or nuclear weapons to produce the waves. This work is quite adequately summarized by Baker (1973). It is found in general that the intermediate and far field waves resemble quite closely those predicted using point source theory and to this extent either high explosive or nuclear explosions can be considered to be "ideal". The questions of blast wave scaling as applied to point source, high explosive and nuclear explosions will be discussed next.

1. Scaling Laws

Scaling of the properties of blast waves from explosive sources is a common practice, and anyone who has even a rudimentary knowledge of blast technology utilizes these laws to predict the properties of blast

waves from large-scale explosions based on tests on a much smaller scale. Similarly, results of tests conducted at sea level ambient atmospheric conditions are routinely used to predict the properties of blast waves from explosives detonated under high altitude conditions. It is not the purpose of this paper to review laws for scaling of blast wave properties, which are adequately summarized in Baker (1973) and Baker, et al. (1973), but we will state the implications of the two laws most commonly used.

The most common form of blast scaling is Hopkinson or "cube-root" scaling. This law, first formulated by B. Hopkinson (1915), states that self-similar blast waves are produced at identical scaled distances when two explosive charges of similar geometry and of the same explosive, but of different sizes, are detonated in the same atmosphere.* It is customary to use as a scaled distance a dimensional parameter, $Z = R/W^{1/3}$, where R is the distance from the center of the explosive source and W is the total energy of the explosive. Figure 5 shows schematically the implications of Hopkinson blast wave scaling. An observer located at a distance R from the center of an explosive source of characteristic dimension d will be subjected to a blast wave with amplitude P, duration T, and a characteristic time history. The integral of the pressure-time history is the impulse I. Hopkinson's scaling law then states that an observer stationed at a distance λR from the center of a similar explosive source of characteristic dimension λd detonated at the same atmosphere will feel a blast wave of "similar" form with amplitude P, duration λT and impulse λI. All characteristic times are scaled by the same factor as the length scale factor λ. In Hopkinson scaling, pressures, temperatures, densities and velocities are unchanged at homologous times. Hopkinson's scaling law has been thoroughly verified by many experiments

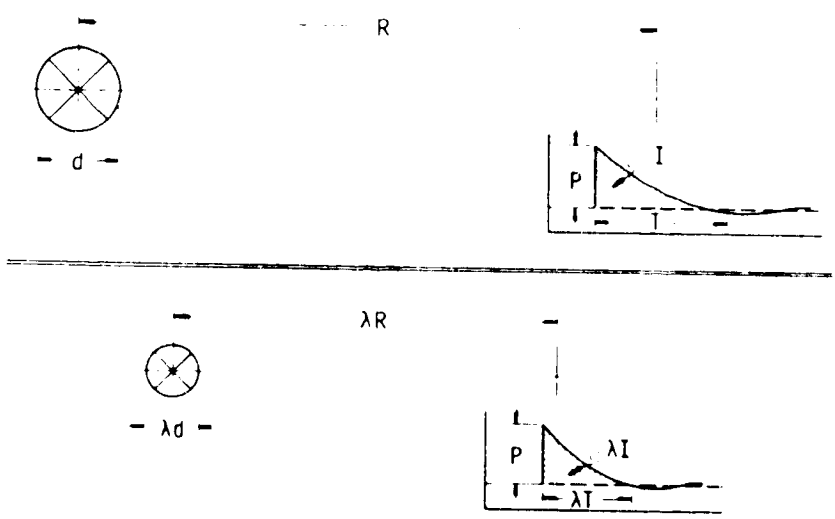

Figure 5. Hopkinson Blast Wave Scaling

* In Germany, this law is attributed to Cranz (1926).

conducted over a large range of explosive charge energies. A much more complete discussion of this law and a demonstration of its applicability is given in Chapter 3 of Baker (1973).

The blast scaling law which is almost universally used to predict characteristics of blast waves from explosions at high altitude is that of Sachs (1944). A careful proof of Sachs' law has been given by Sperrazza (1963). Sachs' law states that dimensionless overpressure and dimensionless impulse can be expressed as unique functions of a dimensionless scaled distance, where the dimensionless parameters include quantities which define the ambient atmospheric conditions prior to the explosion. Sachs' scaled pressure is (P/P_o) (blast pressure/ambient atmospheric pressure). Sachs' scaled impulse is defined as

$$\frac{Ia_o}{(W^{1/3} p_o^{2/3})}$$

These quantities are a function of dimensionless scaled distance, defined as

$$\frac{(Rp_o^{1/3})}{W^{1/3}}$$

The primary experimental proof of Sachs' law is given by Dewey and Sperrazza (1950).

Hopkinson's scaling law requires that the model and prototype energy sources which drive the blast wave be of similar geometry and the same type of explosive or energy source. The law has been used in a modified form to scale the highly asymmetric blast waves generated by muzzle blasts from guns and backblasts from recoilless rifles (see Chapter 4 of Baker, et al. (1973)). These blast sources consist of tubes of hot, high pressure gases suddenly vented to the atmosphere, and so cannot be considered as "ideal" blast sources. Important parameters in the Hopkinson law modified for weapons blast are weapon caliber c and maximum chamber pressure P_C. In contrast to the Hopkinson law, Sachs' law identifies the blast source only by its total energy W, and cannot be expected to be useful for scaling of close-in effects of non-ideal explosions.

No general laws exist for scaling of blast waves from non-ideal explosions, because not all of the physical parameters affecting such explosions are known. However, once a body of data from controlled experiments is available, or once analyses which accurately predict behavior are completed, the development of a scaling law will be straightforward.

2. TNT or Point Source Equivalence

a. Nuclear and high explosive explosions

The standard conversion factors for calculating equivalence of high explosive charges as given in Baker (1973) is repeated here as Table II. With these factors and the scale distance $\bar{R} = Rp_o^{1/3}/W^{1/3}$, we have plotted dimensionless overpressure, $(P_S - p_o)/p_o$, versus $\bar{R}$ on a log log plot in Figure 6 over a very short range, as taken from a number of published sources. It is interesting to note that the overall disagreement between these sources is approximately a factor of ± 2. This was also observed by Baker (1973) and his curve, which is based on experimental data for Pentolite (50/50) is seen to represent a good average of the other curves. Figure 7, which covers a much larger overpressure-scaled distance region, shows the overall extent of scatter. In this curve the shaded regions represent the total range covered by other curves.

There has been controversy about the far field behavior of the wave in the past. Baker (1973) opts for a 1/R dependence, while Bethe, et al. (1947), Thornhill (1960) and Goodman (1960) state that the dependence should be proportional to $1/R(\ln R)^{1/2}$ and Porzel (1972) states that experimental data show an $R^{-4/3}$ dependence. For comparison we have drawn both the $1/\bar{R}(\ln \bar{R})^{1/2}$ and $1/\bar{R}$ dependences on Figure 7 for $\bar{R} > 10^2$ as a dotted line and solid line, respectively, to show how small the differences in far field behavior really are. The question is actually moot for two reasons. Firstly, Warren (1958) has found a spread of measured overpressures in the far field of about a factor of three, this undoubtedly due to refraction and focusing effects in the real atmosphere. He also found that the lead shock disappears in far field and is replaced by a slower pressure rise. This is also to be expected and is due to the non-uniformity of the atmosphere. Secondly, very little damage is done in the far field and therefore it has little practical importance. Techniques for evaluating far field focusing effects due to atmospheric winds and temperature gradients will be discussed in a later section of this review.

b. Non-ideal explosions

The general concept of equivalence for a non-ideal explosion is not well understood at the present time. It is true that usually the near field overpressures are much less than that of a point source explosion which produces the equivalent far field overpressure but it is not obvious exactly what the relationship between near field and far field behavior should be or how this relationship changes as the type of accidental explosion changes. It is also not obvious how one should evaluate the effectiveness for blast damage of any particular type of accidental explosion or how much effectiveness depends on type.

Three approaches to this problem have been taken to date. The first and most practical approach is an *a posteriori* approach involving real accidents. After an accident the blast damage pattern is used to determine the weight of TNT which would be required to do the observed amount of damage at that

TABLE II. EXPLOSIVE PROPERTIES

Explosive	Specific Gravity	Density, ρ_E	Weight Specific Energy, E/W	Volume Specific Energy, E/V	Radius r of 1-lb. Sphere
			English Units		
		$Lb_f sec^2/in^4$	$In\text{-}lb_f/lb_m$	In-lb [illegible] ^{3}	In
Pentolite (50/50)	1.66	1.551×10^{-4}	20.50×10^{6}	1.2[illegible]	1.584
TNT	1.60	1.496×10^{-4}	18.13×10^{6}	$1.048 \times 10^{[illegible]}$	1.604
RDX	1.65	1.542×10^{-4}	21.5×10^{6}	1.283×10^{6}	1.588
Comp B (60/40)	1.69	1.580×10^{-4}	20.8×10^{6}	1.271×10^{6}	1.575
HBX-1	1.69	1.580×10^{-4}	15.42×10^{6}	0.944×10^{6}	1.575
			International Units		
		Kg/m^3	Joules/kg	$Joules/m^3$	M
Pentolite (50/50)		1.658×10^{3}	5.107×10^{6}	8.482×10^{9}	4.023×10^{-2}
TNT		1.599×10^{3}	4.517×10^{6}	7.227×10^{9}	4.074×10^{-2}
RDX		1.648×10^{3}	5.356×10^{6}	8.847×10^{9}	4.034×10^{-2}
Comp B (60/40)		1.689×10^{3}	5.182×10^{6}	8.764×10^{9}	4.000×10^{-2}
HBX-1		1.689×10^{3}	3.841×10^{6}	6.510×10^{9}	4.000×10^{-2}

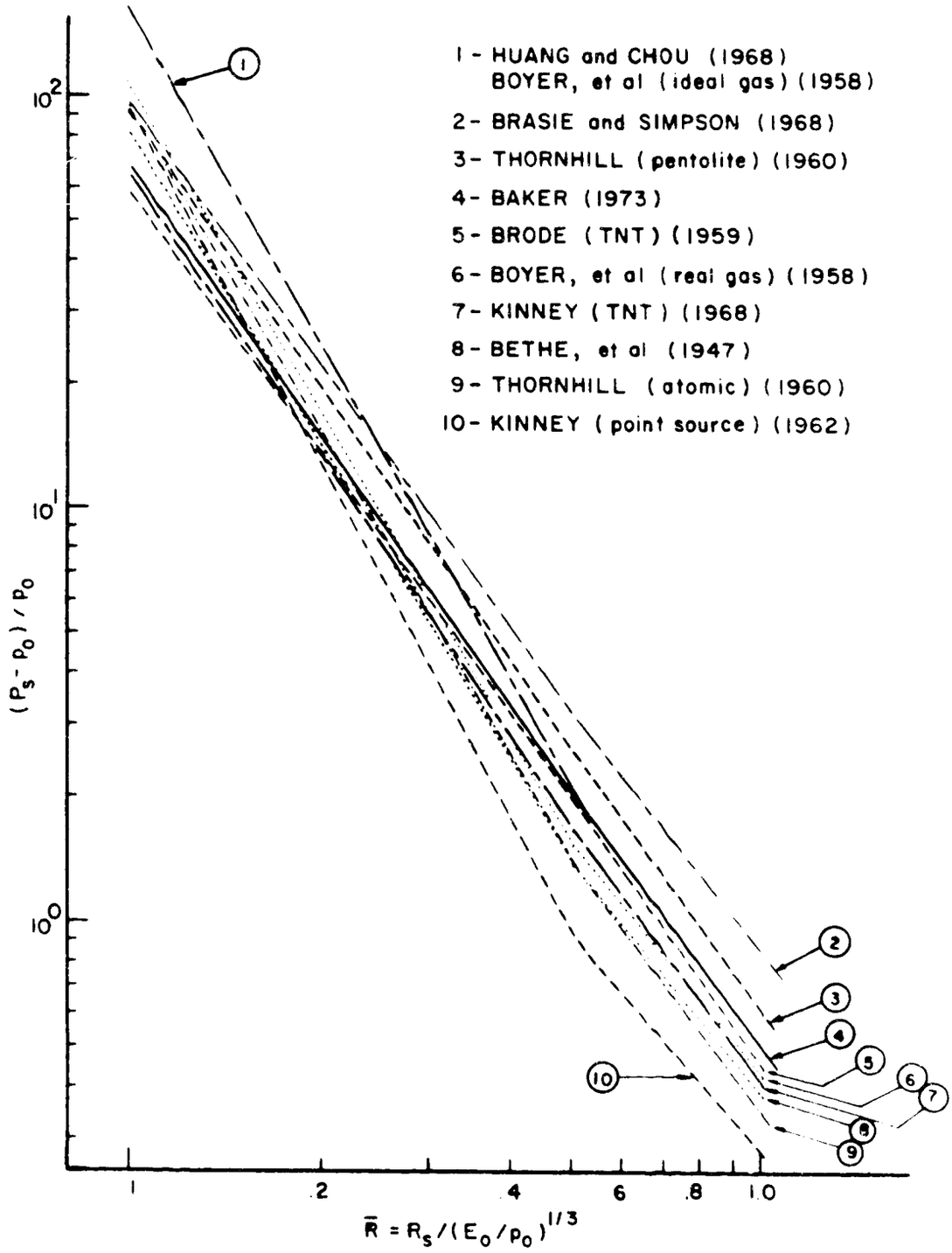

Figure 6. Blast wave overpressure versus scaled distance taken from a number of sources (small range).

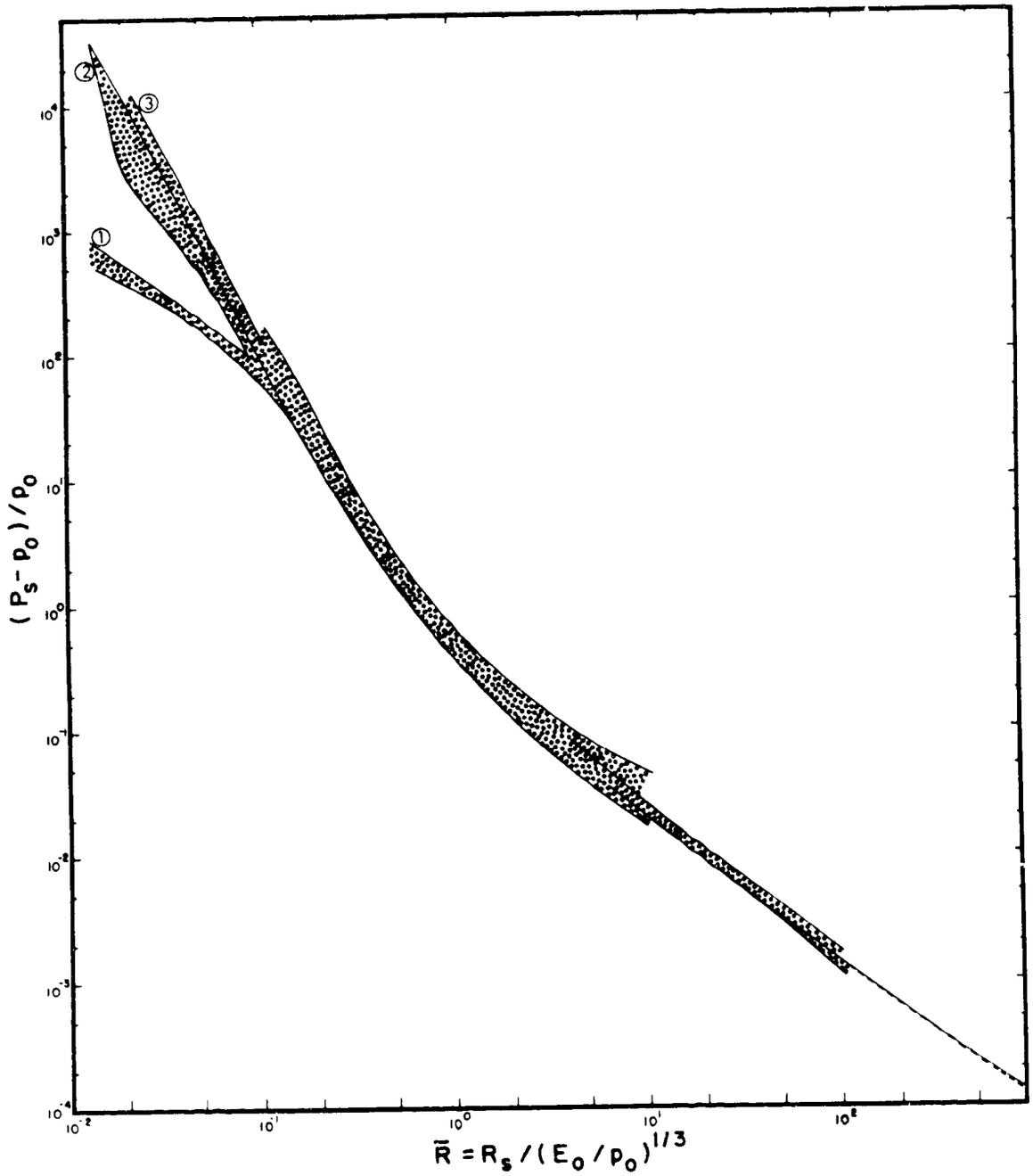

Figure 7. Blast wave overpressure versus scaled distance for blast waves for the sources listed on Figure 6. (1) High explosives; (2) Nuclear explosions; (3) Point source. The dotted line in the lower right is for a $1/[\bar{R}(\ln \bar{R})^{\frac{1}{2}}]$ dependence. The solid line is a $1/\bar{R}$ dependence.

distance from the center of the explosion. If the explosion is chemical in nature, one then usually attempts to determine a percent TNT equivalence by determining a maximum equivalent TNT weight of the fuel or chemical by calculating either the heat of reaction of the mixture or the heat of combustion of the quantity of that substance which was released. Zabatakis (1960), Brasie and Simpson (1968), and Burgess and Zabatakis (1973) have all followed this approach which is probably based on the TNT equivalence concept for high explosives, where relative damage is directly correlatable to the relative heats of explosion of different explosives measured in an inert atmosphere. The formulas are of the type

$$(W_{TNT})_{calc} = \frac{\Delta H_c \cdot W_c}{1800} \tag{8}$$

$$(W_{TNT})_{calc} = \frac{\Delta H_c \cdot W_c}{4.198 \times 10^6} \tag{8a}$$

and

$$\%TNT = [(W_{TNT})_{Blast}/(W_{TNT})_{calc}] \times 100$$

where in Eqn. 8 W_{TNT} = the equivalent maximum TNT weight, lbs; ΔH_c = heat of combustion of the hydrocarbon (or heat of reaction of the exothermic mixture), Btu/lb; W_c = weight of hydrocarbon or reaction mixture available as an explosive source; and 1800 = heat of explosion of TNT, Btu/lb. Eqn. 8a is in SI units (energy in joules, wt in kg). In the same vein, Dow Chemical Co. (1973) in their safety and loss prevention guide advocate evaluating the relative hazard of any chemical plant operation by first calculating a ΔH of reaction or explosion for the quantity of material which is being handled and then multiplying this basic number by factors bas 1 on other known properties such as the substance's sensitivity to detonation

There has also been a considerable amount of work in which non-ideal explosions are deliberately initiated and side-on blast pressure records obtained. The maximum TNT equivalent yield of the explosive is calculated on the basis of a formula like Eqn. 8 and the percent yield in terms of the two variables, overpressure and positive impulse, are plotted versus the scaled distance $\bar{R}$. A detailed discussion of this approach will be presented in Section IV of this report when we discuss each different type of accidental explosion in detail.

The third approach is an *a priori* approach and involves the calculation of the source energy which is available to the blast wave. Eqn. 8 is of this type in a sense. However, to date there has been no proof that this is the correct way to evaluate the maximum available yield for an accidental explosion. Kinney (1962) advocates the use of the work function or Helmholtz free energy, A, of the source to determine the equivalent source energy available for scaling purposes. He presents no proof, however, and at least one case--

that of an exploding frangible vessel--his formula does not yield correct far field equivalence. This will be discussed in the next section under the theory of non-ideal explosions. The only other *a priori* equivalency statements concern frangible vessels and are due to Brode (1955), Brinkley (1970), Baker (1973), and Huang and Chou (1968). They will also be discussed in the next section on non-ideal behavior.

D. Non-Ideal Behavior

1. Theoretical Calculations or Estimations

a. Similarity theories

There have been a relatively large number of attempts to find analytical solutions for the structure of the blast wave produced by different types of energy addition functions. These have all been self-similar solutions. The analytical point source solutions which were discussed above represent the only self-similar solutions which can be generated for the addition of a finite amount of energy. All other solutions which are self-similar, such as the constant velocity piston solution of Taylor (1946) as elaborated on by Kiwan (1970a) or the constant velocity flame solutions of Kuhl, et al. (1973), Oppenheim, et al. (1972a & b), Oppenheim (1973) and Strehlow (1975), represent the eventual addition of an infinite amount of energy if the solution is to remain self-similar. The solution of Dabora (1972) and Dabora, et al. (1973) for a general power law piston motion has the same behavior, i.e. the solution remains self-similar only as long as one continues to add energy in the central region according to the specific power law that was chosen. While the solution of Kuhl, et al. (1973) or its simplification by Strehlow (1975) can be used to predict maximum shock wave Mach numbers for the early stages of some deflagration explosions, they are not useful for discussing how the blast wave decays at later time because this region of the flow is no longer self-similar. To study such late behavior one must resort to numerical techniques.

b. Exploding vessels

A considerable amount of effort has been expended in the calculation of the blast wave structure from exploding vessels. The numerical results of Brode (1955), Boyer, et al. (1958), and Huang and Chou (1968) are examples of calculations in which a vessel containing high pressure quiescent gas is assumed to release its contents instantaneously at time = 0, without the interference of confining walls. The development of the blast wave is followed using a one-dimensional, time-dependent numerical technique and the resulting wave behavior, e.g. overpressure, is compared to elementary point source theory. An example of shock pressure versus scaled distance, taken from Huang and Chou (1968) is shown in Figure 8. Typically the curves for shock pressure start at a pressure, intermediate between the initial chamber pressure and ambient pressure, which can be calculated using a standard one-dimensional flow-patching, shock tube type calculation. The pressure then drops slowly at first and eventually slightly exceeds the point source shock pressure. Then it falls more rapidly with distance than

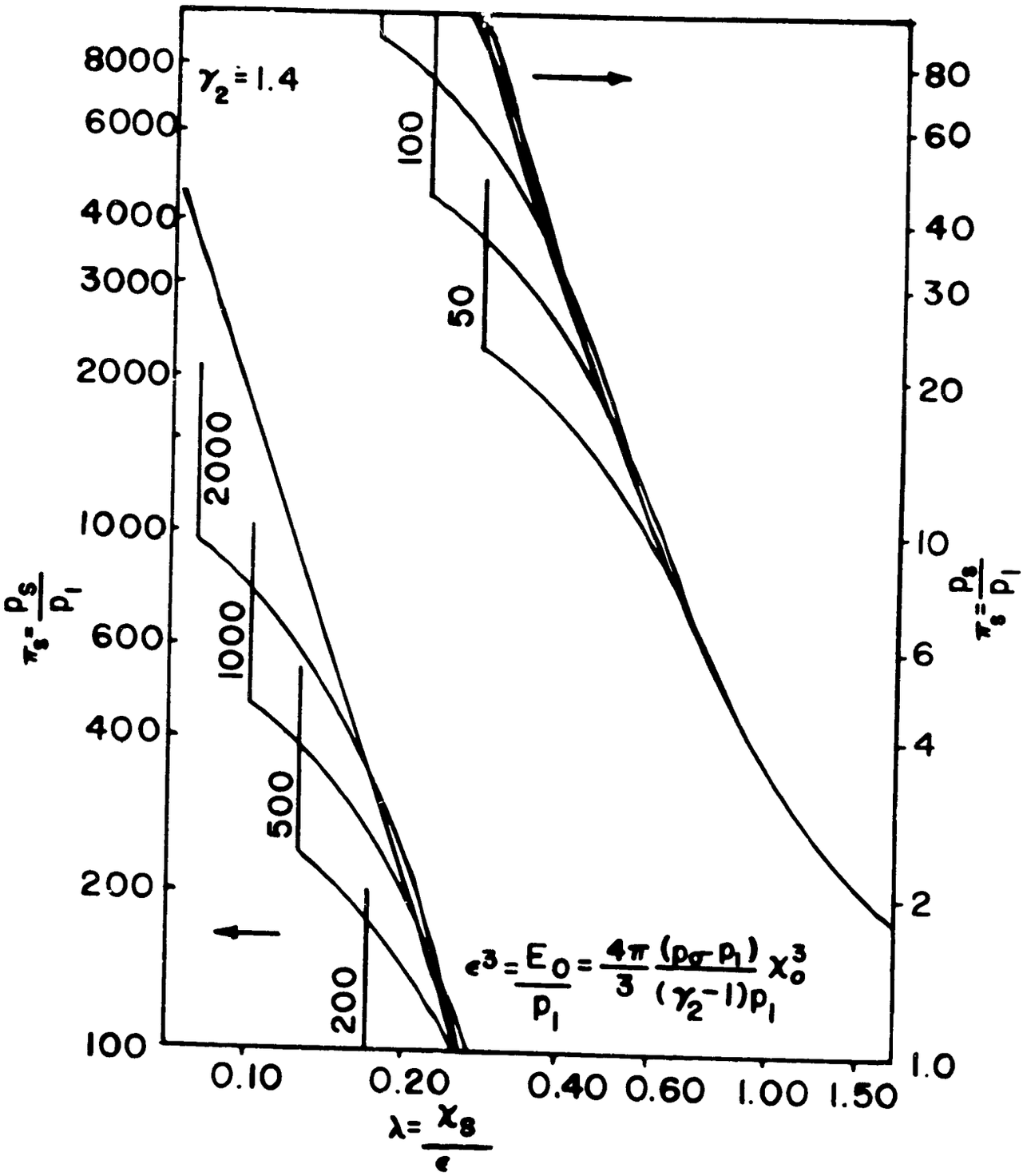

Figure 8. Shock overpressure versus scaled distance for simple sphere bursts (after Huang and Chou (1968)). The line with no vertical section is point source. This is reproduced just as Huang and Chou presented it and the abscissa should be displaced by a factor of $\sqrt[3]{10}$ to the right as explained in the text.

point source--eventually asymptotically approaching the point source solution. Huang and Chou (1968) found this to be true if the energy in the sphere was calculated using the formula

$$\varepsilon^3 = \frac{E_o}{p_o} = \frac{4\pi}{3(\gamma-1)} \frac{(P-p_o)}{p_o} r_o^{\,3} \tag{9}$$

where r_o is the sphere radius and ε is the characteristic length for point source waves. Thus the characteristic dimensionless radius for plotting is given by the formula

$$\bar{R} = R/(E_o/p_o)^{1/3} = R/\varepsilon \tag{10}$$

The $(\gamma-1)$ term enters in Eqn. 9 because Huang and Chou assumed an ideal constant gamma gas in their model. For these assumptions the $(\gamma-1)$ term essentially converts the pressure energy $(P-p_o)V_o$ held in the initial volume to the potential energy needed to raise the pressure and temperature of the stored gases to the pressure P from an initial pressure p_o and to the burst temperature T from some low initial temperature T_o'. This means that the potential energy base for the substance held in the sphere should be the temperature T_o'. In other words

$$E_o = nC_v(T - T_o') = (P - p_o)V_o/(\gamma - 1) \tag{11}$$

where n = the number of moles of substance in the sphere and C_v is the molar heat capacity at constant volume.

It is instructive to compare this potential energy formula to the formulas that have been suggested by Kinney (1962), Baker (1973) and Brinkley (1970). Kinney states that the work function is the available energy.

$$E_o = A = RT \ln P \quad (\text{i.e. } p_o = 1) \tag{12}$$

which, for an ideal gas, can be written as

$$\varepsilon^3 = \frac{4\pi}{3} \frac{P}{p_o} [\ln(\frac{P}{p_o})] r_o^{\,3} \tag{13}$$

Baker (1973) and Brinkley (1970) assume that the available energy is that which is released by the isentropic expansion of the gas in the sphere from the pressure P to the pressure p_o. The formula for this energy is

$$\varepsilon^3 = \frac{4\pi}{3(\gamma-1)} [\frac{P}{p_o} \quad (\frac{P}{p_o})^{1/\gamma}] r_o^3 \tag{14}$$

This is the formula given in Baker (1973) and it differs from that given by Brinkley (1970) in two ways. Brinkley's formula has a factor of two in it because he assumes a surface burst. His equation also has a misplaced bracket which makes it incorrect. It should read (without the 2)

$$\varepsilon^3 = \frac{4\pi}{3(\gamma-1)} \frac{P}{p_o} [1 - (\frac{p_o}{P})^{\frac{\gamma-1}{\gamma}}] r_o^3 \tag{15}$$

Eqns. 9, 13 and 14 (or 15) each has a different functional form and all three cannot be correct. They are plotted in Figure 9. As can be seen from Figure 8, Eqn. 9 agrees well with point source over a sizable range of P/p_o. Unfortunately, Figure 8 has an abscissa which is displaced by a factor of $\sqrt[3]{10}$ to the right in terms of the correct position for the blast wave curves. In other words, the λ of Figure 8 is $\sqrt[3]{10}$ larger than the $\bar{R}$ of Figure 6 and 7. This can be determined by noting that at $t = +0$ the shock is at the surface of the sphere and $x_s = x_o$. Using Eqn. 9 one finds the factor described above. If the curves of Figure 8 are displaced by this amount they uniformly asymptote the far field point source region of Figure 7. The important point here is that one can conclude from these works that Kinney's work function is incorrect for calculating the stored energy available to the blast wave and that the potential energy formula and the isentropic expansion formula give ε/r_o ratios which differ by a factor of 1.5 at the most. This is not sufficient to decide at present which of these two formulas is the correct one (if there is indeed a simple "correct" formula for determining the far field blast wave equivalence of an exploding sphere).

In addition, two questions remain which must be resolved by further theoretical work. In the first place the velocity of sound of the gas in the sphere will determine the maximum shock pressure in the external flow, for fixed internal pressure and stored potential energy. How this change in starting shock pressure will alter the far field equivalence is not known at present. Secondly, the effect of finite opening time on the far field wave, as in the case of a thick walled frangible vessel, is not understood at present.

c. Piston (or flame) driven

As was mentioned earlier, a constant velocity piston or flame generates a self-similar blast wave and the behavior of such a wave after the piston or the flame stop their motion can only be determined by using numerical integration techniques. Kiwan (1970b) and Guirao, et al. (1974) have both performed such calculations. Kiwan (1970b) reports only a single calculation and unfortunately makes no comparisons to either point source or other calculations. Guirao, et al. (1974) have performed such a

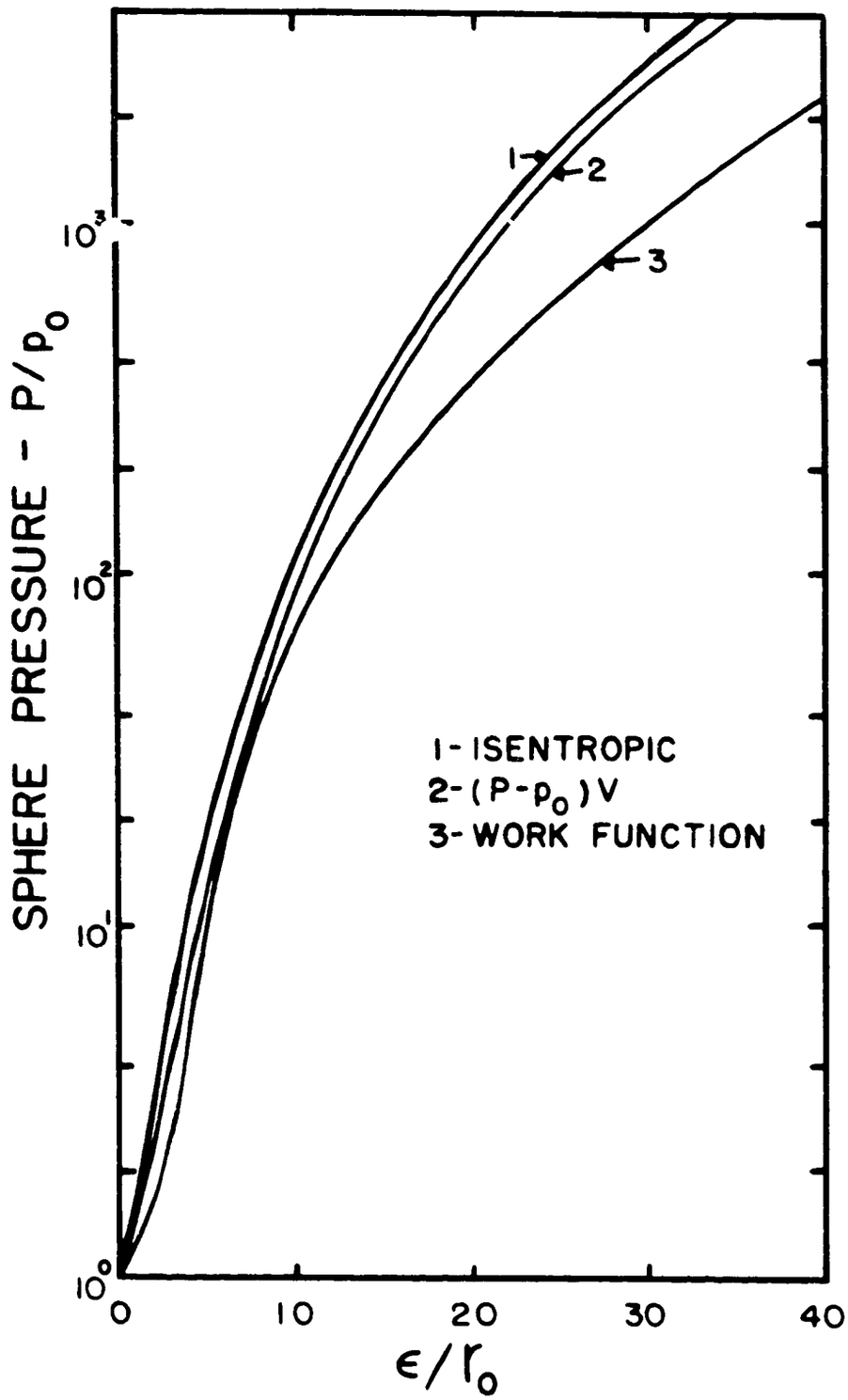

Figure 9. A comparison of the stored energy in a sphere of high pressure gas which is to the blast wave as predicted by Eqns. 9, 13 and either 14 or 15 of the text. From Figure 8, we see that Eqn. 9 agrees well with point source over the range P/p_0 = 2000 to P/p_0 = 50 for room temperature air in the sphere.

comparative calculation. They calculated the rate at which a piston performed work on the surrounding atmosphere and then stopped the piston motion when a certain fixed total energy was added to the system. The resulting flow field was then used as the starting flow field for a numerical calculation. They did this for three different piston velocities and compare the resulting shock pressures to point source for the same total energy. They find that the shock pressure is always higher than point source at fixed $\bar{R}$ but asymptotically approaches the point source shock pressure in the far field. More work is needed in this area to verify these early results and establish generality.

d. More general theoretical studies

There have been very few general studies of the behavior of non-ideal blast waves. Brinkley (1969) and Brinkley (1970) are the only papers which discuss the general behavior of non-ideal blast waves. In both these papers Brinkley discusses the effect of late energy addition by the source. He points out that it is well known that at later times, when the trailing portion of the blast wave contains a negative phase, further energy release by the source will not be able to reach the front and strengthen it. This contention, while interesting, has never been adequately checked.

2. Source Property Effects

a. "Shock up" in the near field

There is some evidence that in combustion driven explosions which are initially unconfin the near field is shock free. Woolfolk (1971), Ablow and Woolfolk (1972), and Woolfolk and Ablow (1973) report that for the deflagrative combustion of hydrogen-nitrogen-oxygen mixtures in hemispherical balloons the near field pressure records were shock free and that the initial shock appearance occurred in the middle of a steepening compression wave. Strehlow and Adamczyk (1974) observed the same type of delayed shock formation when they calculated the blast field produced by a time dependent energy addition function. An example of the flow field associated with such an energy addition function in shown in Figure 10. Energy addition was relatively slow for the first microsecond and then relatively rapid for the second microsecond in this figure. The weak pressure pulse produced by the slow addition of energy did not have time to coalesce into a shock wave before it was overwritten by the shock wave produced by the later, more rapid addition of energy. Zajak and Oppenheim (1971) also found this effect in a calculation of the blast wave produced by the rapid reaction of "reactive center" placed in an inert surrounding atmosphere

b. Multiple shocks

Both Boyer, et al. (1958) and Huang and Chou (1968) have found multiple shock waves propagating away from a bursting sphere in their calculations. A typical example is shown in Figure 11. These results are similar to those of Brode (1959) for TNT explosions. Brode's calculation results are shown in Figure 12 for comparison. It appears from this result

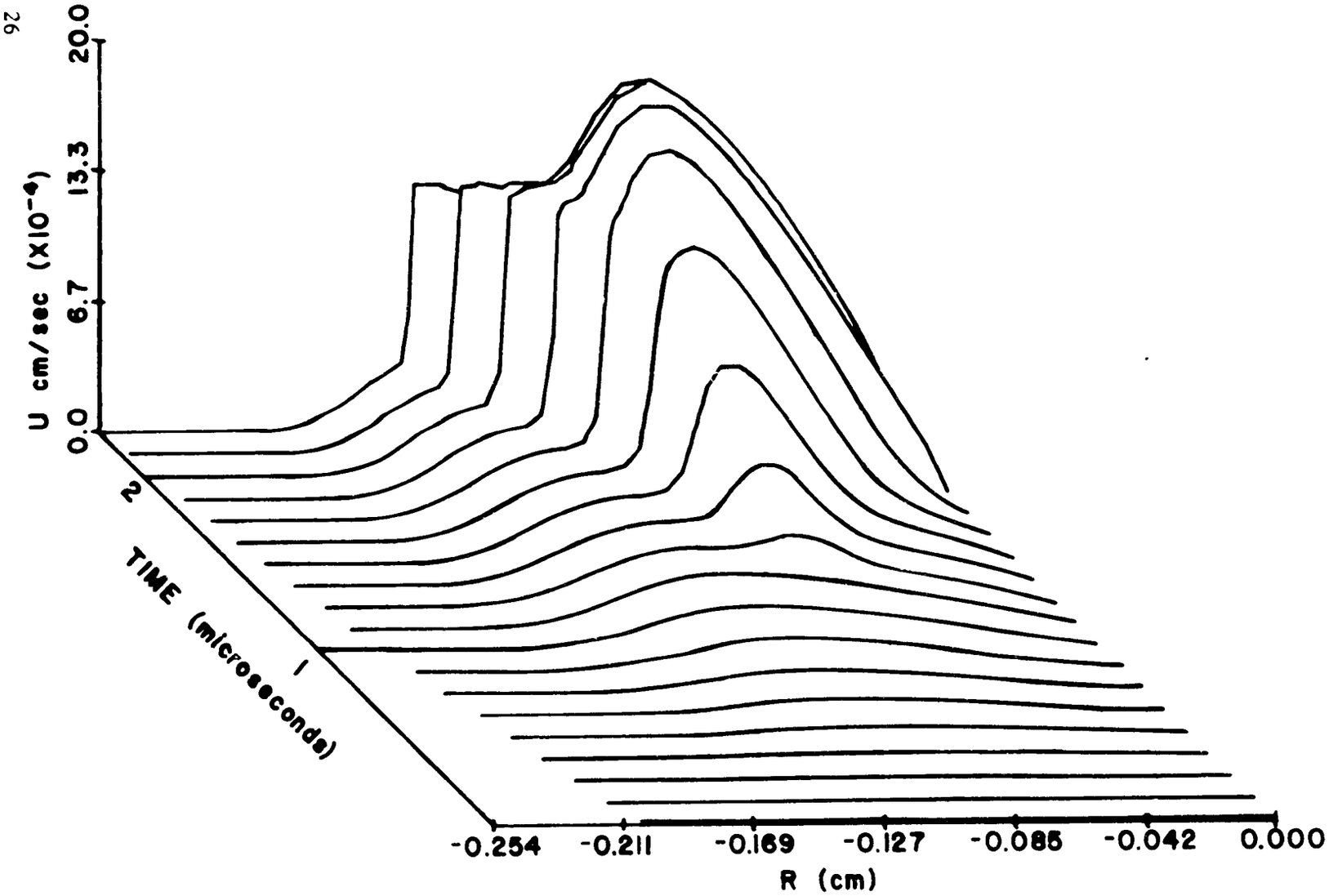

Figure 10. Velocity distribution versus distance and time for the slow addition of energy in the central region. Spherical coordinates. Notice the imbedded shock which appears later in the flow.

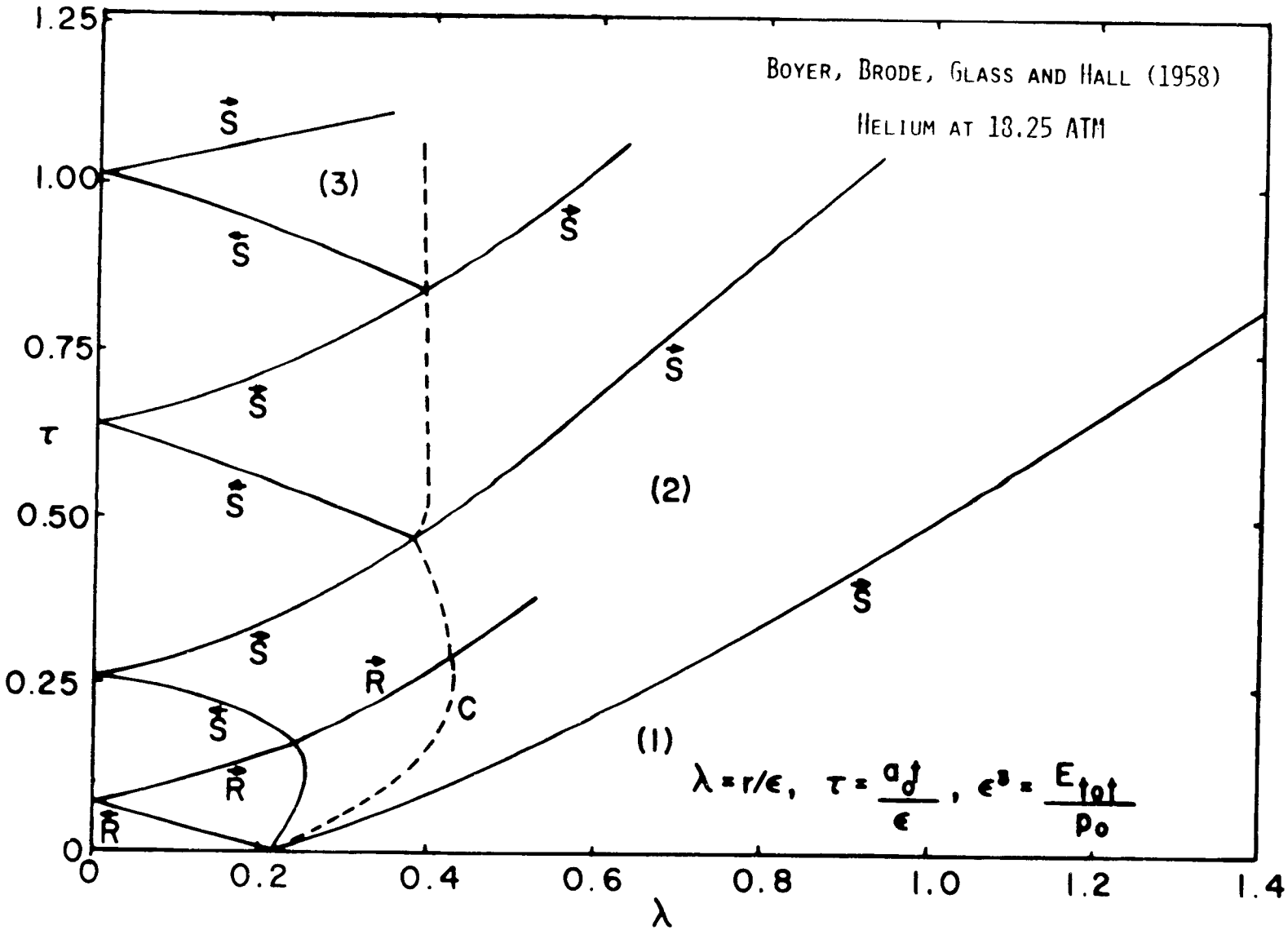

Figure 11. Multiple shocks obtained from the burst of a sphere of helium.

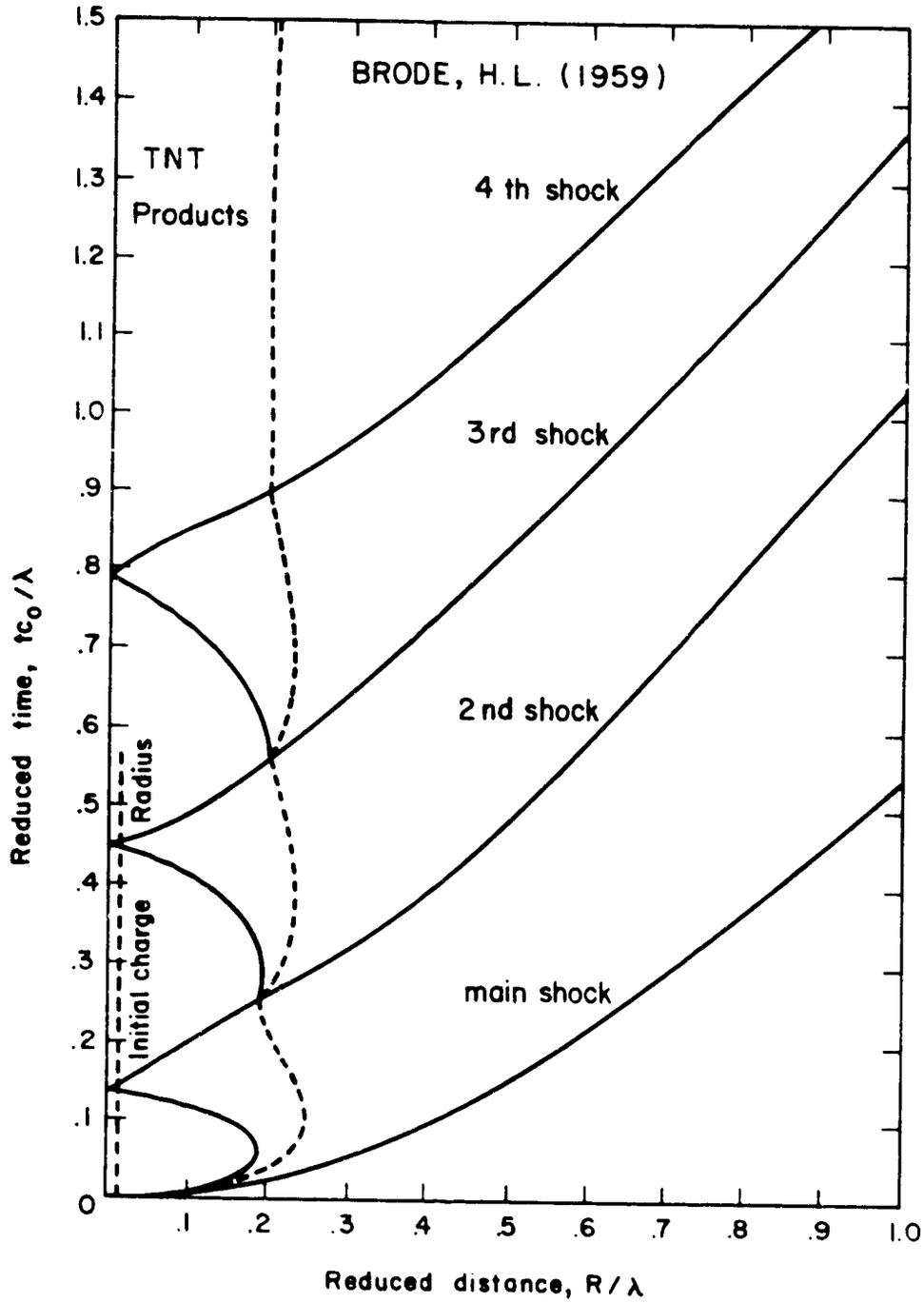

Figure 12. Multiple shocks obtained from a TNT explosion.

that the presence of multiple shocks is related to the finite size of the source. However, Bethe, et al. (1947) and Whitham (1950) have shown theoretically that the far field wave in a homogeneous atmosphere should be an "N" wave and therefore should contain two shocks, even for a point source explosion. Boger and Waldman (1973) have shown that for two sequential high-explosive explosions at the same location there exists a critical delay time between the explosions below which the two lead shocks merge. For larger delays, the two shocks are found to exist as separate shocks out to the far field region. Multiple shocks also appear when the source is non-spherical; see section d. below. No more general statements can be made at the present time.

c. Variations in pressure profile and decay behavior

It is well known that the rate of decay of the lead shock is physically related to the pressure profile immediately behind the shock and the radius of the shock. The exact and approximate mathematical relationships have been given by Brinkley and Kirkwood (1947), Bethe, et al. (1947), and Bach and Lee (1970) to name a few sources. However, no general statements have appeared because the manner in which the profile changes shape and therefore the overall shock decay is determined by the entire flow field, not just by the profile at the shock. The problem is complex and to date only numerical solutions are available.

d. Non-spherical behavior

Any explosion source which is not spherical in free air or hemispherical in contact with a reflecting plane will generate a blast wave which is, at least in its early stages, non-spherical. The wave may well have an axis of symmetry, but requires definition in at least two space coordinates and time. Analytically, the treatment of non-spherical waves requires more mathematical complexity, and experimentally, measurement requires many more tests than for spherical waves.

The simplest type of non-spherical behavior probably results from elevation of a spherical explosion source above a reflecting plane (usually the ground). The resulting reflection process is described in Baker (1973) and Glasstone (1962), and is illustrated schematically in Figure 13. A structure or target on the ground feels a double shock if it is in the region of regular reflection close to the blast source, or a single strengthened shock if it is in the region of Mach reflection. Even this "simplest" case of non-spherical behavior is quite complex.

The second type of asphericity is that caused by sources which are not spherical. Most real blast sources *are* non-spherical, and can be of regular geometry such as cylindrical or block-shaped, or can be quite irregular in shape. Few analyses or experiments have been done for other than cylindrical geometry of solid explosive sources. For cylinders, the wave patterns have been shown (Wisotski and Snyder (1965), Reisler (1972)) to be quite complex, as shown in Figure 14. The pressure-time histories exhibit multiple shocks, as shown in Figure 15, and decay in a quite different manner in the near

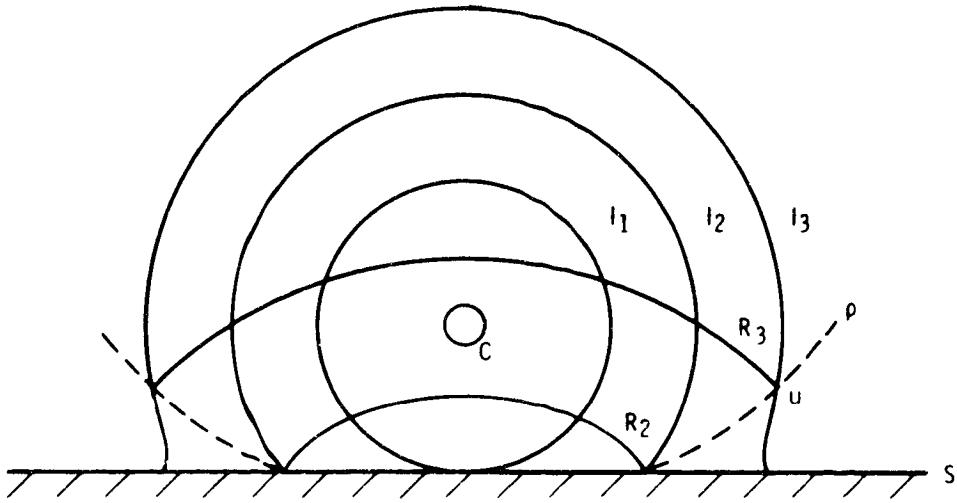

Figure 13. Reflection of Strong Shock Waves

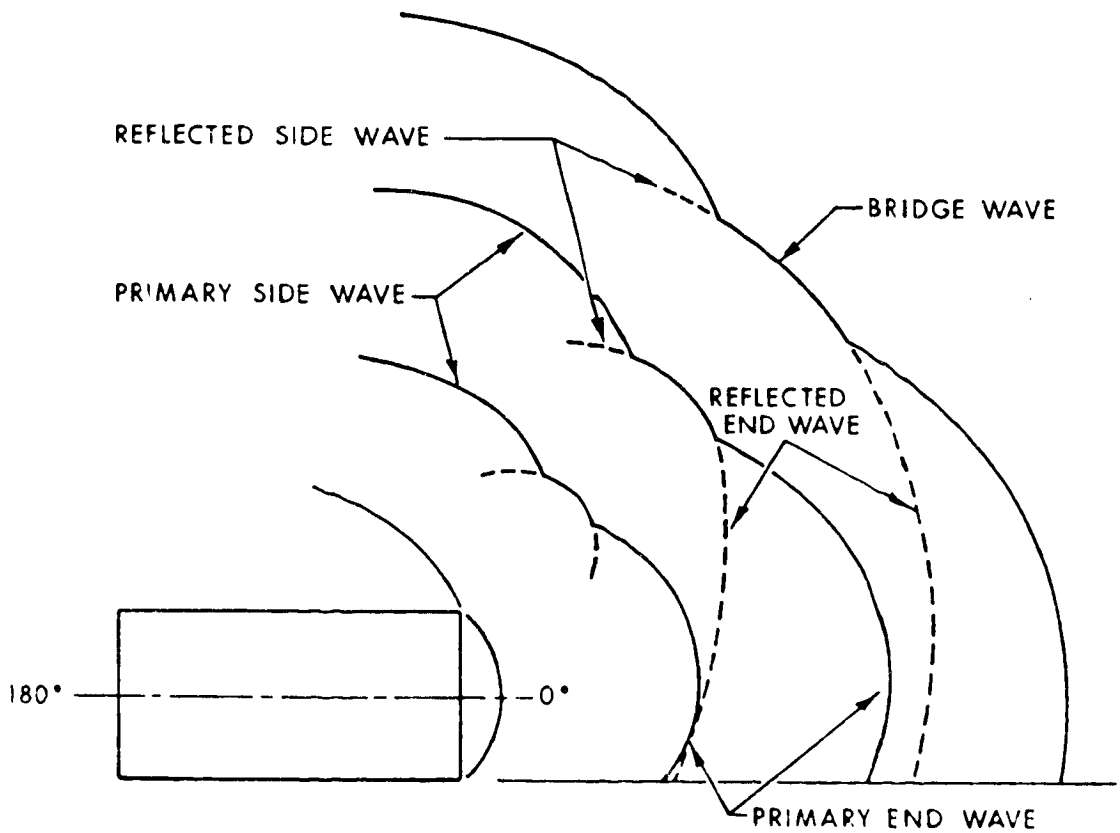

Figure 14. Schematic of Wave Development for Cylindrical Charges (Reisler (1972))

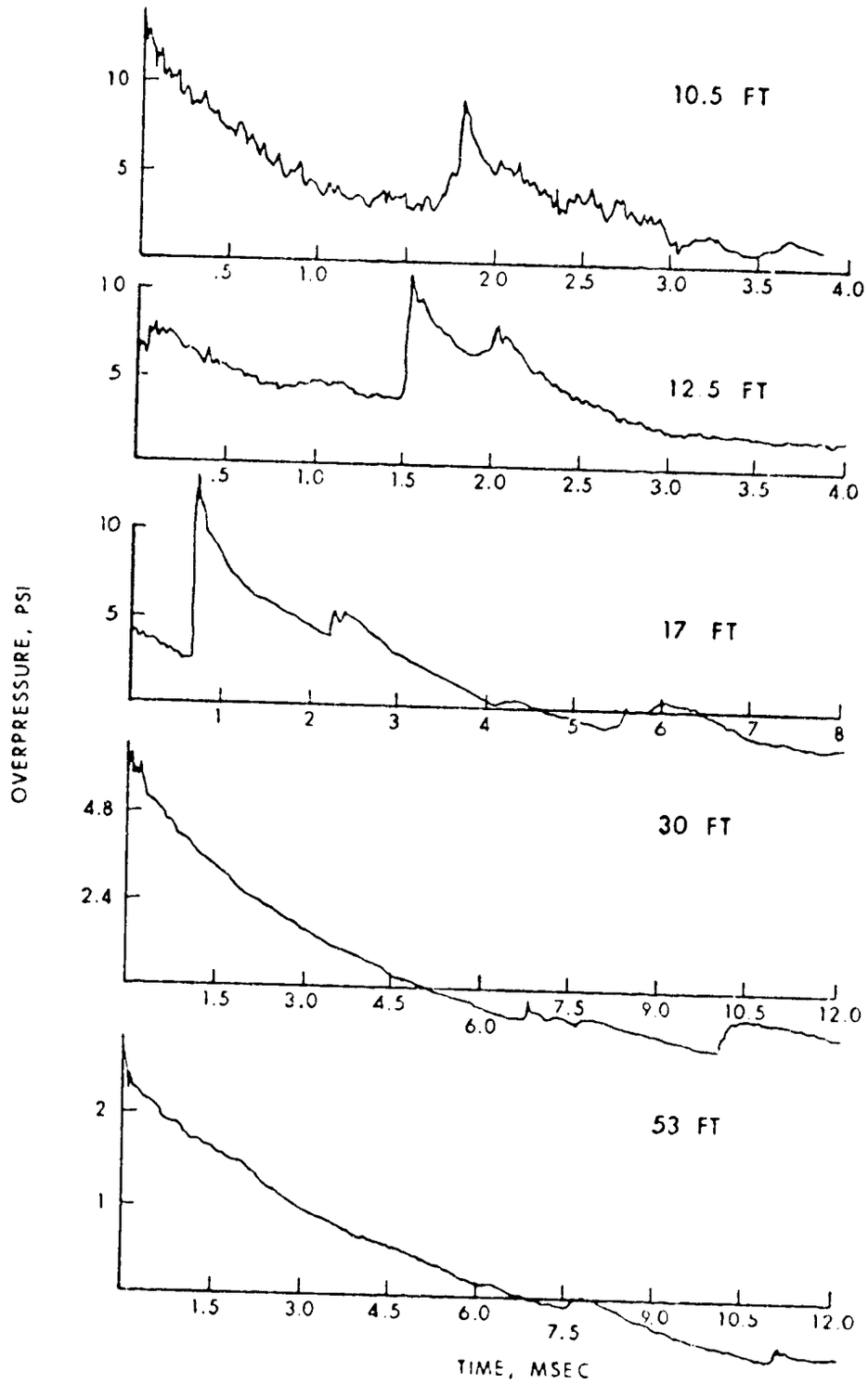

Figure 15. Pressure Time Records from Cylindrical Charges along Charge Axis (Reisler (1972)).

field than do spherical waves.

Another type of non-spherical behavior has been mentioned previously in the section on blast scaling. Gun muzzle blast or recoilless rifle back blast generates waves which consist of essentially single shocks, but shocks with highly directional properties. This type of asphericity is particularly pronounced behind recoilless rifles, where the shock is being driven by supersonic flow of propellant gases expanding through a nozzle (Baker, et al. (1971)).

The above instances are only a few examples of non-spherical behavior. Let us reiterate that, close to most real blast sources, behavior is *usually* non-spherical. Fortunately, these asymmetries smooth out as the blast wave progresses, and "far enough" from most sources, the wave will become a spherical wave.

e. Effect of confinement or partial confinement

The effects of confining explosion sources on blast waves can range from minimal to controlling, depending on the properties of the source. Nuclear weapons blasts in air are almost totally independent of the confinement provided by the weapon casing, and cased warheads or bombs filled with condensed chemical explosives produce blast waves which are relatively little affected by the confinement of the casing. On the other hand, many materials only act as explosion sources when they are confined in some manner. Some solid and liquid chemicals can act as propellants when confined in vented chambers, and as explosives when confined in unvented chambers. (Black powder is an example.) Liquid cryogenic propellants can generate blast waves when mixed and ignited (Willoughby, et al. (1968a, b & c)), but the character and strength of the waves are strong functions of degree of confinement at ignition. Gaseous explosive mixtures produce blast waves which are even more strongly affected by degree of confinement, as will be evident from later discussion in this paper. Finally, the epitome of the effect of confinement is illustrated by blast waves from bursting pressure vessels--no confinement, no blast source.

The design of chambers for confinement and the testing of these designs has proceeded with two purposes in mind. In one case the confining chamber is expected to lessen blast effects in the neighborhood of the chamber or confining configuration, primarily by attenuation (Lesseigne (1973)). The simplest confining method is an overburden of earth and Nicholls, et al. (1971) have discussed this method of confinement. Confining structures have also been designed and experimental measurements on a simple vent structure have been described by [illegible]an and Tancreto (1972). Discussions of the effect of internal explosions on internal pressures (Kennedy (1946)) and venting have also been presented by Sewell and Kinney (1968) and Proctor and Filler (1972). Baker and Westine (1974) and Westine and Baker (1974) have recently presented detailed discussions of how to design suppressive structures which limit the blast loading outside the structure, and Cox and Esparza (1974) present a design which is specific to a melt loading operation for high explosives. Because structures of the type discussed above are intended to

strongly suppress external blast waves, the vent area ratios, usually expressed in the dimensionless form

$$\bar{A}_V = \left(\frac{A_{vent}}{V^{2/3}}\right)$$

where A_{vent} is total vent area and V is internal volume, are small, i.e., $\bar{A}_V < 0.05$. For such small venting, peak gas pressures developed within the structure are independent of vent area ratios and are entirely a function of ratio of explosive energy to volume, W/V (see Proctor and Filler (1972), and Baker and Westine (1974)).

In the other case, the problem of confinement is one of releasing the blast energy rapidly so that the confining structure (the building itself) is not damaged. In the case of building explosions, a first attack on explosion venting has been presented by Runes (1972) and criticized by Howard (1972). Runes' treatment is much more rudimentary than that of Proctor and Filler (1972), but it does account in an approximate way for shock-free internal pressure rises of relatively long rise times. Generally, for the very rapid venting desired to save the building, vent area ratios must be large, say $\bar{A}_V > 0.2$, and maximum internal gas pressures will be a strong function of this ratio as well as W/V.

3. Atmospheric and Ground Effects

Ideal explosions are assumed to occur in a still, homogeneous atmosphere and to be unaffected by the presence of a ground surface. Real conditions in the atmosphere and real surface effects can modify the wave in various ways.

Variations in initial ambient temperature and pressure can affect the blast wave so that noticeably different waves would be recorded from explosions on a high mountain or mesa than from explosions near sea level, or from explosions occurring on a hot summer day versus a cold winter day. These effects are, however, quite adequately accounted for if the Sachs' scaling law described earlier is used to predict the wave properties. For very large explosions such as detonations of multi-megaton nuclear weapons, the vertical inhomogeneity of the atmosphere will cause modification of an initially spherical shock front (Lutzsky and Lehto (1968)). Changes in relative humidity and even heavy fog or rain have been found to have insignificant effects on blast waves (Ingard (1953)).

The more significant atmospheric effects which induce non-ideal blast wave behavior are unusual weather conditions which can cause blast focusing at some distance from the source. A low-level temperature inversion can cause an initially hemispherical blast front to refract and focus on the ground in an annular region about the source (Grant, et al. (1967)). Severe wind shear can cause focusing in the downwind direction. This effect is discussed by Baker (1973) and Reed (1973). Structural damage from accidental

explosions has been correlated with these atmospheric inhomogeneities (Siskind (1973), Siskind and Summers (1974), and Reed (1968)), and claims for damage from explosive testing were reduced when firings were limited to days when no focusing was predicted (Perkins, et al. (1960)). A handbook on how to perform such calculations is available (Perkins and Jackson (1964)).

Ground effects can also be important. If the ground acted as a perfectly smooth, rigid plane when explosions occurred on its surface, then it would reflect all energy at the ground plane and its only effect on the blast wave would be to double the apparent energy driving the wave. In actuality, surface bursts of energetic blast sources usually dissipate some energy in ground cratering and in ground shock, so that only partial reflection and shock strengthening occurs. A good "rule of thumb" is to multiply the effective charge energy by a factor of 1.5 to 1.8 if significant cratering occurs. For sources of low energy density such as gaseous mixtures, very little energy enters the ground, and the reflective factor of 2 is a good approximation.

A ground surface which is irregular can significantly affect the blast wave properties. Gentle upward slopes can cause enhancement, while steep upward slopes will cause formation of Mach waves and consequent strong enhancement. Downward slopes or back surfaces of crests cause expansion and weakening of shocks. These effects are usually quite localized, however, and "smooth out" quite rapidly behind the irregularities. Even deliberate obstructions such as mounded or revetted barricades produce only local effects (Wenzel and Bessey (1969)).

We have noted previously under the heading "non-spherical behavior" that blast sources located above a reflecting plane can generate Mach waves if the shocks are strong enough. The phenomenon of generation and propagation of these waves has been widely studied in blast technology (Glasstone (1962), Baker (1973)), and will not be discussed further here, other than to note that the blast wave in a Mach stem is classical in form but differs markedly in strength from the wave from a free-air source.

III. DAMAGE MECHANISMS

A. The P-I Relation

1. Simple Systems

The blast waves from accidental explosions can cause damage to structures, property or individuals by subjecting them to transient crushing pressures and transient winds which cause drag pressures. Even though the interaction of the waves with the objects they damage involves very complex phenomena, a relatively simple concept has been utilized quite effectively to correlate blast wave properties with damage to a wide variety of "targets". The concept is that damage caused by blast waves (or any transient force-time history) to a given object is primarily a function of the peak overpressure or force (P) and the applied impulse (I). Therefore, for any object, curves of constant damage level can be plotted on a P-I diagram, or empirical or analytical equations developed to describe a P-I relation. An example is shown in Figure 16.

To illustrate this concept, we will first consider a simple system, characterized by a mass (inertia) and a linear spring (resisting force). The development of the P-I diagram for this system is given in Baker, et al. (1973), and will be paraphrased here. Figure 17 shows schematically the

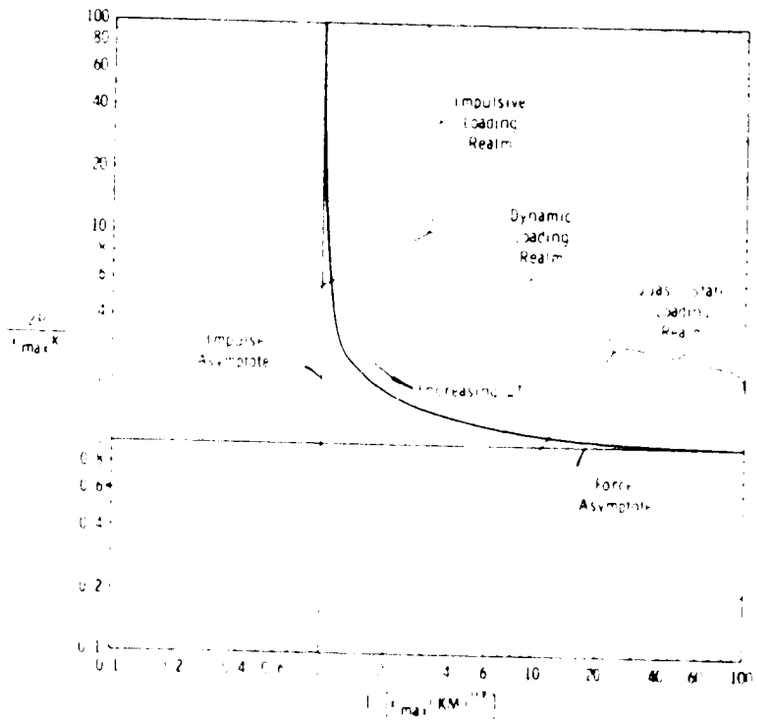

Figure 16. Scaled P-I Curve for Response

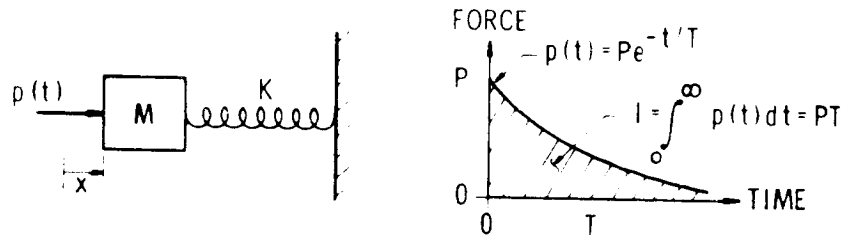

Figure 17. Schematic of Spring-Mass System Under Time-Varying Force

linear spring-mass system to which is applied a specific time-varying force p(t). The equation of motion can be obtained by considering a free-body diagram for the mass. Summing the forces in the x-direction gives

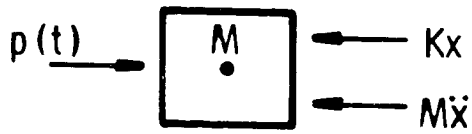

Figure 18. Summation of Forces

$$\underset{\text{Inertial Force}}{M\ddot{x}} + \underset{\text{Spring Force}}{Kx} = \underset{\text{External Force}}{p(t) = Pe^{-t/T}} \qquad (16)^*$$

The initial conditions describing the dynamic state of the mass at zero time must be written. For the mass initially at rest, these are:

$$x(0) = 0 \qquad (17)$$

$$\dot{x}(0) = 0 \qquad (18)$$

Referring to any standard text on mechanical vibrations, we can find that the solution to Eqns. 16 through 18 is

$$x(t) = \frac{1}{\omega M}\int_0^t p(\tau)\sin\omega(t - \tau)d\tau \qquad (19)$$

*Dot denotes differentiation with respect to time, i.e., $\dot{x} = dx/dt$, $\ddot{x} = d^2x/dt^2$.

where

$$\omega = \left(\frac{K}{M}\right)^{1/2} \tag{20}$$

is the "natural" frequency of the system. Or, for the specific form of p(t) which we have assumed,

$$x(t) = \frac{PT^2}{M(1 + \omega^2 T^2)} \left(\frac{\sin \omega t}{\omega T} - \cos \omega t + e^{-t/T}\right) \tag{21}$$

By simple manipulation and use of Eqn. 20, we can render Eqn. 21 dimensionless, as follows:

$$\frac{x(t)}{(P/K)} = \frac{(\omega T)^2}{[1 + (\omega T)^2]} \left[\frac{\sin \omega t}{\omega T} - \cos \omega t + e^{-(\omega t)/(\omega t)}\right] \tag{22}$$

The left-hand side is a ratio of transient displacement to static deflection of the spring under unit load, ωt is dimensionless time, and ωT is a ratio of a characteristic response time ω^{-1} to a characteristic loading time T.

Response is characterized by the maximum displacement x_{max} of the single-degree-of-freedom system. We can operate on Eqn. 22 to determine the *time for maximum displacement*. This time is obtained by differentiating Eqn. 22 with respect to $\omega t = \bar{t}$ for specific values of ωT, setting it equal to zero, and solving by trial-and-error. The resulting transcendental equation for $\bar{t}_{max}$ is

$$\frac{\cos \bar{t}_{max}}{\omega T} + \sin \bar{t}_{max} - \frac{\exp[-\bar{t}_{max}/\omega T]}{\omega T} = 0 \tag{23}$$

The maximum displacement is then obtained by substitution of $\bar{t}_{max}$ in Eqn. 22.

The process just described yields the results shown in Table 3 and Figure 19. An excellent empirical fit can be made to the curve of $\bar{x}_{max}$ as a function of ωT, as can be seen in Figure 19, over the entire range by the formula

$$\bar{x}_{max} = \left[2 - \exp\left(-\frac{\omega^2 T^2}{100}\right)\right] \tanh \omega T \tag{24}$$

The asymptotic values for x_{max} at large and small ωT give, in dimensional form,

TABLE III.

MAXIMUM RESPONSE OF SINGLE-DEGREE-OF-FREEDOM SYSTEM TO EXPONENTIAL FORCE

ωT	$\bar{t}_{max}$	$\bar{x}_{max}$
0.01	$1.580 \approx \pi/2$	0.01
0.1	1.670	0.1
1.0	2.283	0.754
10.0	2.969	1.728
100	3.122	1.969
∞	π	2

The characteristics of the response are as follows:

(1) For small ωT, $\bar{x}_{max} = T$.

(2) For large ωT, $\bar{x}_{max} = 2$.

(3) For intermediate ωT, $\bar{x}_{max}$ is a more complex function of ωT.

(4) Scaled time for maximum response changes relatively slowly from $\bar{t}_{max} \approx \pi/2$ to $\bar{t}_{max} \approx \pi$ as ωT increases.

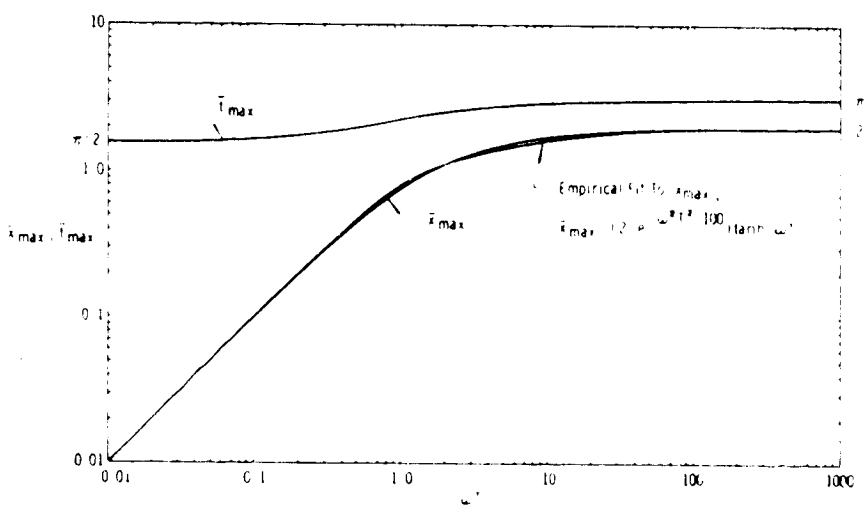

Figure 19. Maximum Response to Force Pulse

$$x_{max} = \frac{PT}{(KM)^{1/2}} \left(\frac{K}{M}\right)^{1/2} \quad T < 0.2 \tag{25}$$

$$x_{max} = \frac{2P}{K} \left(\frac{K}{M}\right)^{1/2} \quad T > 100 \tag{26}$$

In Eqn. 26 the product PT is exactly the *integral under the force-time curve*, which we call the impulse, I. It can be rewritten

$$x_{max} = \frac{I}{(KM)^{1/2}} \left(\frac{K}{M}\right)^{1/2} \quad T < 0.2 \tag{27}$$

For rapidly-decaying force (ωT small), the response is *proportional to impulse* I, while, for slowly decaying force, the response is *proportional to peak force* P. In this latter case, the response is just twice that for static application of the force P, i.e. we have a dynamic load factor of two. Possible dimensionless forms for peak force and impulse are

$$\bar{P} = \frac{2P}{x_{max}K} \tag{28}$$

$$\bar{I} = \frac{I}{x_{max}(KM)^{1/2}} \tag{29}$$

If the empirical fit of Eqn. 24 is used, these become

$$\bar{P} = \frac{2}{[2 - \exp(-\omega^2T^2/100)] \tanh \omega T} \tag{30}$$

$$\bar{I} = \frac{\omega T}{[2 - \exp(-\omega^2T^2/100)] \tanh \omega T} \tag{31}$$

From these last two equations, one can finally generate a scaled response curve, or P-I curve by varying ωT. This has already been shown in Figure 17. The curve represents the *combinations* of scaled force and scaled impulse which cause the *same* scaled response $\bar{x}_{max}$ of the system. It is then an *isoresponse* curve--a similar curve for a system undergoing a given level of damage would be an *isodamage* curve. We can divide the curve into the three indicated regions. In the impulsive loading realm, impulse alone correlates with response. In the quasi-static loading realm, *peak force*

alone correlates with response. In the intermediate dynamic loading realm, both the impulse and the force must be known, i.e. we must know the entire time history of the loading. For the simple system just described, a good fit to the P-I relation is

$$(\bar{P} - 1)(\bar{I} - 1) = C \tag{32}$$

This equation describes a rectangular hyperbola in the $\bar{P}$-$\bar{I}$ plane, with asymptotes (1,1).

Arguments similar to those just presented can be given for the simplest kind of a dynamic permanently deforming system, i.e. a rigid-plastic system with inertia. This is done by Baker, et al. (1973), who show that a scaled $\bar{P}$, $\bar{I}$ curve applies for this system also. The scaled forces and impulses are defined differently for plastically-deforming systems, but the same concept holds.

2. Complex Systems

The P-I curve for describing a given level of damage to a system has also been shown experimentally and analytically to apply for a wide variety of blast-loaded systems. For high explosive blast sources, given combinations of P and I are unique functions of standoff R and charge energy W (see Section II). Westine (1972) has shown that damage to a number of complex targets such as trucks, houses, and aircraft can be presented on an R-W plane, and that such a presentation is equivalent to presentation in the P-I plane. Sewell and Kinney (1968) have also presented a method which is a modified form of the P-I concept.

In a number of instances, the behavior of complex systems under blast loading is too complex to be described by a single hyperbolic P-I diagram. As the combinations of P and I change for such systems, the mechanisms of damage also change. Two examples for widely different "systems" follow.

Thin cylindrical shells subjected to external blast loading from the side will be damaged by plastic buckling. Depending on the duration of loading, two basically different types of buckling failure occur. In one, the shell exhibits longitudinal wrinkles or lobes; in the other, the shell collapses by creasing in the middle of its length. Figure 20 shows a P-I diagram for this dual behavior. This figure, from Lindberg, et al. (1965) also shows different curves for different levels of damage.

The second example of dual damage mechanisms is the threshold response of humans to blast waves. For relatively short-duration waves, the governing criterion is threshold of eardrum damage. For long-duration waves, a standing individual is knocked down. The resulting P-I diagram, from Custard, et al (1970) is shown in Figure 21. This figure also indicates that the impulse asymptote for eardrum damage is very low, because the ear has a very short characteristic response time, i.e. responds to quite high

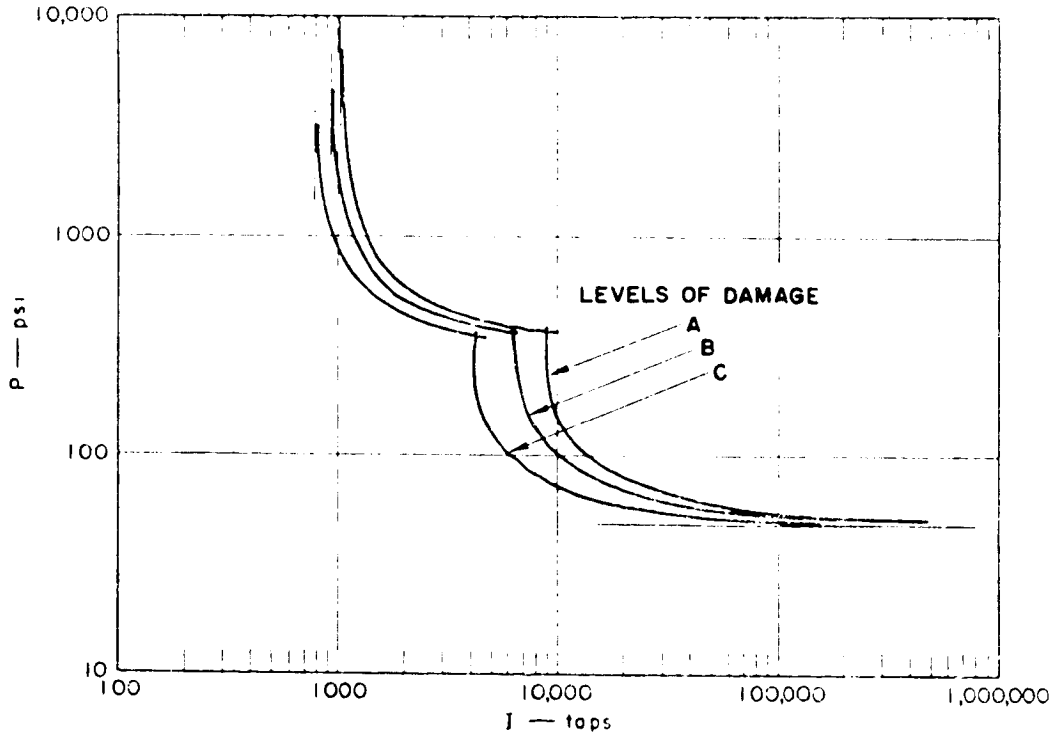

Figure 20. Pressure Impulse Relations for Blast-Loaded Cylindrical Shells (Lindberg, et al.(1965))

frequencies.

A number of analysis methods have been developed to compute response of and damage to a variety of complex structures. These represent a higher degree of sophistication than the P-I concept, but also usually require a large expenditure of manhours and computer time to yield answers. Typical of these methods are Norris, et al. (1959), Baker, et al. (1969), Leigh (1974), and Crocker and Hudson (1969).

B. Dynamic Impulse

The dynamic impulse in blast waves has been defined earlier, and a typical curve given for net transverse pressure applied to an object immersed in a blast wave. For certain systems or objects, the initial diffraction phase of blast loading is unimportant, and the time-history of drag force controls. An object resting on the ground can be accelerated by this loading, and slide or overturn. (An example has already been given in discussing the P-I diagram for humans.) If the object is massive, it will respond slowly to the drag forces, and drag impulse, multiplied by a drag coefficient dependent upon the shape of the object, will determine incipient overturning or sliding. Response of light bodies will depend on the entire history of drag force. An example of a "target" in this latter category is a camper-pickup, which has a lot of side area and a high center of gravity. Custard, et al. (1970) show a

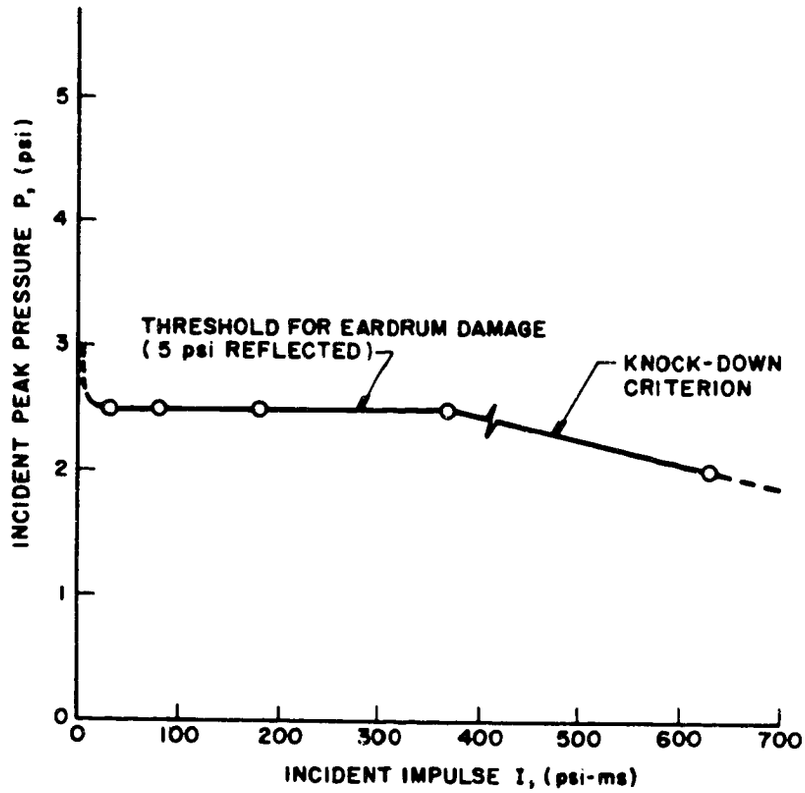

Figure 21. Acceptable Incident Peak Pressure-Impulse Relationship for a 168-Pound Man Explosed to Explosive Blast (Custard, et al. (1970))

P-I diagram for such a vehicle, with overturning being the critical mode of damage (Figure 22).

C. Fragments, Primary and Secondary

An important factor in damage from accidental explosions can be the fragmentation of the container or fracture and acceleration to high velocity of nearby objects or parts of structures. Fragments from containers are usually called *primary fragments*, and those resulting from fracture and acceleration of nearby objects are called *secondary fragments*.

The state of knowledge and our ability to apply it to damage predictions for accidental explosions is much less satisfactory for fragmentation effects than for blast effects. Some of the reasons for this are:

- Fragmentation is inherently statistical in nature,
- Primary fragmentation is very dependent on details of the explosion process,

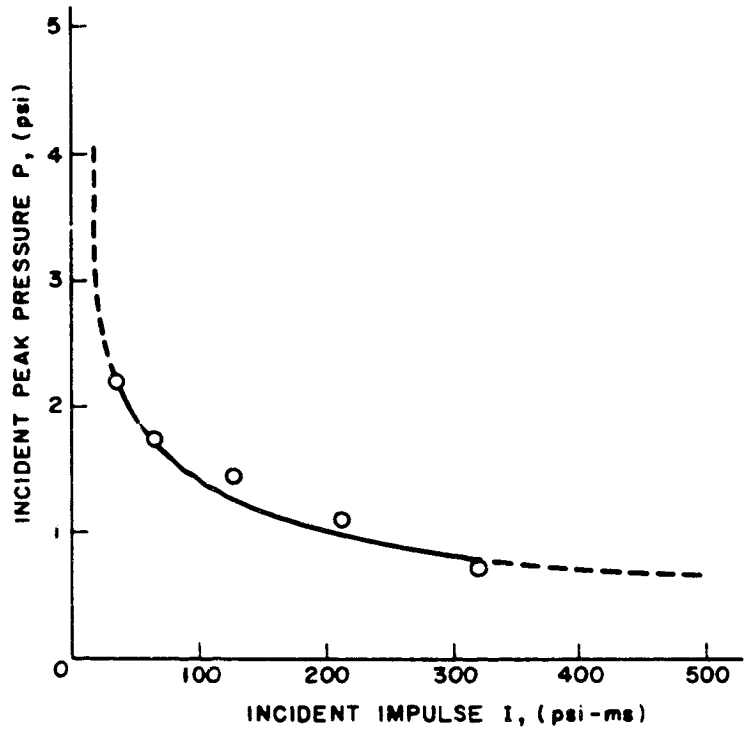

Figure 22. Acceptable Incident Peak Pressure-Impulse Relationship for Constant Damage (80% of Overturning Impulse) to the Camper-Pickup (Custard, et al. (1970))

- Effects of fragments on important "targets" such as humans are highly classified.

Some unclassified studies have been conducted by Feinstein (1972) for fragments from bursting piles of bombs; by Baker, et al. (1974a & b), fragments from bursting liquid propellant vessels; by Pittman (1972a & b), and Taylor and Price (1971) for fragments from bursting high pressure tanks; and by Siewert (1972) for the fragments from ductile tank cars which contain volatile chemicals and fail by pressure burst in fires. Rather than attempt to completely cover this difficult field in this paper, we merely mention the above related papers and note that much further study seems to be required before adequate predictions can be made of fragmentation effects.

D. TNT Equivalence Evaluation Based on Blast Damage

Even though the relatively sophisticated P-I and related techniques that have been developed recently have great generality and give good correlation for blast damage there is still a tendency to evaluate blast damage from accidental explosions by using simpler techniques. One example of a very thorough evaluation from specific indicator evidence is the recent open publication of a paper on the yields from the Hiroshima and Nagasaki bombs by Penny, et al. (1970). Because the blasts from these bombs were of long

duration, the structures whose damages were used to predict yield all fall within the pressure asymptote of their P-I diagrams.

It is usual, however, to relate blast damage patterns directly to overpressure or to scaled distance based on overpressure, thus neglecting positive impulse. Brasie and Simpson (1968) present a typical graph, reproduced here as Figure 23, listing overpressure effects. Notice in particular the large range for glass breakage from about 0.1 to 0.006 PSI side-on overpressure. Reed (1968) in an evaluation of glass breakage from a munitions explosion near San Antonio, Texas, plots his data on a breakage probability versus log overpressure scale and shows, as one would expect, that large plate glass panes, thin glass panes and stressed glass panes are most vulnerable to breakage. Usually if one is using glass breakage, he determines the distance to the location of 50% breakage and uses 0.1 PSI as the pressure level. This yields a scaled range of about 100-200 ft/(lb TNT)$^{1/3}$ so that TNT equivalent weight = $(ft/200)^3$ where ft is the distance in feet from the explosion to the location of 50% glass breakage. The same approach is used in estimating distances for other types of breakage. Errors using this method will be greatest when the actual explosion yield is small, and when the accidental explosion is markedly non-ideal.

E. Non-Ideal Effects

From our previous discussion of P-I relations, it seems apparent that predictions of blast damage from accidental explosions is possible, if the blast wave characteristics are known as a function of distance from the explosion. But, non-ideal effects discussed earlier in this paper can render prediction of these characteristics somewhat uncertain. Similarly, the relatively small amount of information on fragmentation effects indicates that these effects can only be accurately predicted for relatively ideal explosions such as explosions of cased munitions. If one uses TNT equivalency concepts, prediction or correlation of damage effects with real non-ideal explosions may introduce large and unknown errors, given the present state of knowledge.

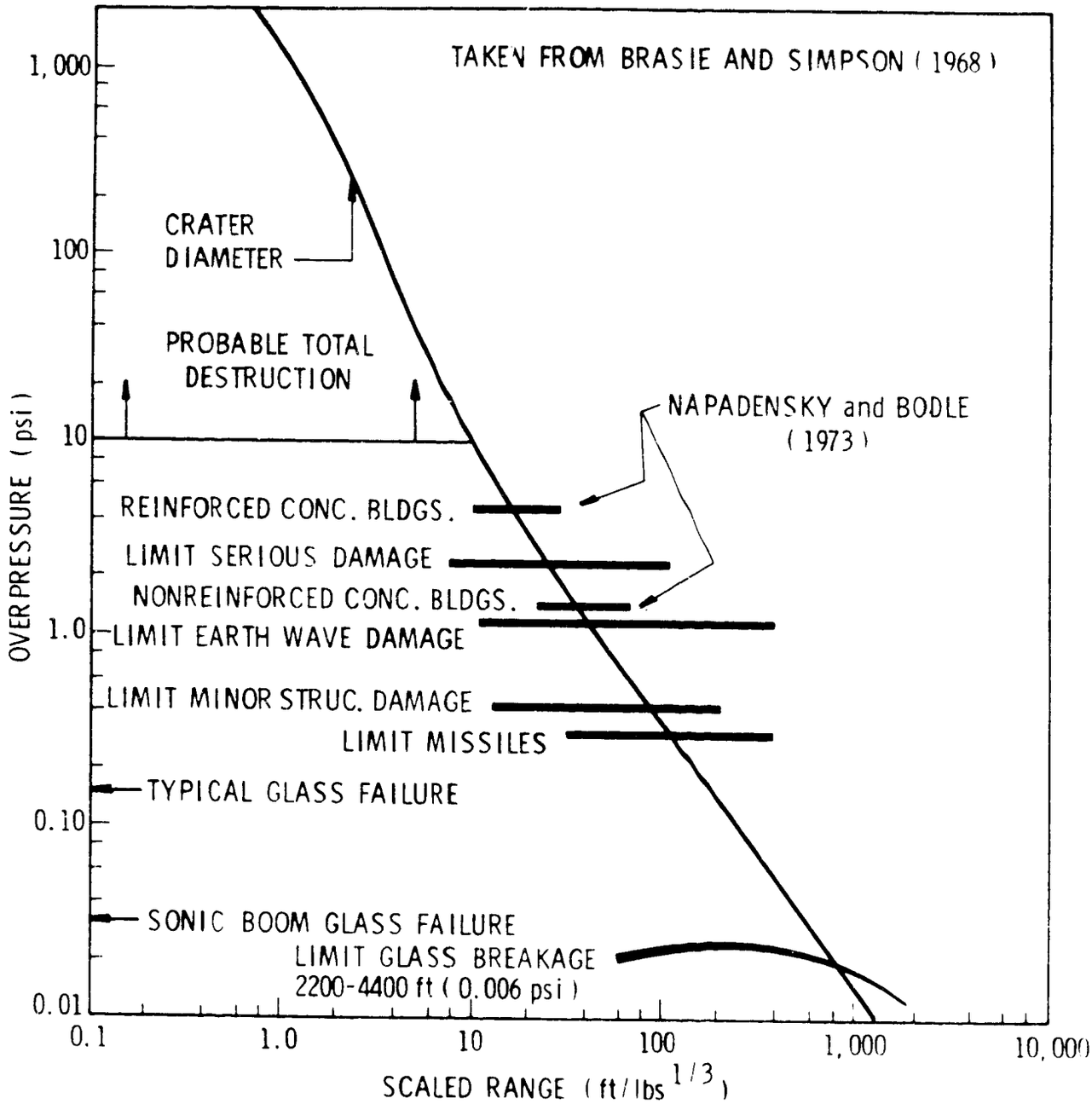

Figure 23. Overpressure Scaled Distance Plot Showing Typical Levels for Blast Damage

IV. SPECIFIC EXAMPLES OF ACCIDENTAL EXPLOSIONS

In this section we wish to discuss either experimental or theoretical results or simply observations that have been made about each of the specific accidental explosion types listed in Table I on page 4. The discussion will range from rather precise to quite vague because of our current understanding of the mechanisms by which these various sources produce non-ideal blast waves. Furthermore, the relative importance or potential hazard of each different type, will determine the length of each discussion.

Before we turn to individual explosion types we will mention two compilations of case histories of accidents which involved explosions. Doyle (1969) has reviewed 83 incidents involving explosions in chemical plants. He found that approximately 50% could be traced to combustion reactions--primarily due to leakage of combustibles from a vessel into a building, with a few due to ignition of the combustible material in the vessel itself. He also found that approximately 40% were due to a runaway chemical reaction in a reactor and that 10% could be labeled as metal failure explosions under otherwise normal operating conditions. Ordin (1974) has compiled information on over 200 accidents involving hydrogen. However, he does not concern himself directly with the occurrence or absence of an explosion or its type; he is more interested in cause. Most of the cases he discusses involve a release during handling.

We now turn our attention to specific cases.

A. Simple Pressure Vessel Failure

1. Frangible Vessels

The blast wave produced by the rupture of a frangible spherical vessel is by far the most reproducible of all possible accidental explosions. Also it has been studied in more detail than the others. The theoretical work of Huang and Chou (1968) and of Boyer, et al. (1958) has already been discussed in some detail in section II.D.1.b. including the problem of how to define the source energy for such a vessel explosion. The arguments of that section show that it is probably best to use the total stored pressure energy, $(P - P_o)V_o/(\gamma-1)$, if one wants to compare the results to far field point source wave properties.

At the present time theoretical work still remains to be done. In particular there has been no systematic study of the effect of the velocity of sound and heat capacity ratio of the gas contained in the vessel on the near field shock produced when it bursts. Since the internal velocity of sound dictates the maximum shock velocity at the time of burst through contact surface balance requirements, and since the velocity of sound can be varied in a manner which is independent of the energy contained in the vessel, it must represent an important additional variable in the determination of near field effects.

Recently there has been some experimental work by Pittman (1972a & b) to complement that of Boyer, et al. (1958). In this work he considers not only the blast wave but also fragmentation patterns from a number of different vessel explosions. He makes comparisons of blast wave overpressure and positive impulse to point source values, but he uses the isentropic relationship given by Eqn. 14 or 15 of this text for this comparison. Conversion to the recommended energy relation would move his experimental data points closer to the theoretical point source curves. Baker, et al. (1974 a & b) have presented calculations of fragment acceleration behavior and review other work in the field on this subject.

There have been a number of accidental explosions which undoubtedly could be represented as simple frangible vessel bursts. A few examples will be discussed. Stephens and Livingston (1973) report on a frangible rupture disk burst due to an exothermic $H_2 + Cl_2$ reaction. Evidence was that there was no contribution to the blast from subsequent reaction. It is true of course that the rupture of a relief disk is strikingly non-ideal because of the explosion's directionality. In this respect they are somewhat like muzzle blast from a gun or the back blast from a recoilless rifle. Munday (1973) is currently working on this problem and there is a publication by the Ministry of Labour (1965) which discusses the design of flame arrestors and explosion relief devices.

Another example is the explosion that occurred on Appollo 13, endangering the lives of the astronauts Anon (1970). In this case an oxygen storage vessel for a fuel cell burst because of overpressure due to an internal fire of electrical insulation and blast and fragment damage to neighboring equipment was extensive. Fortunately, the ground crew and astronauts were able to respond successfully to the crisis and a safe return to earth was effected. This incident dramatically points out the need for safety and hazard evaluation based on the best available information as well as the need to improve our understanding of the near field, non-ideal behavior of blast waves.

Two other examples are the explosion of a liquid oxygen truck (National Transportation Safety Board (1971)), and the explosion of a filter containing chlorine and organics (Statesir (1973)). In both cases the evidence led to the conclusion that a simple pressure vessel burst was involved.

2. Ductile Vessels

There are few examples of ductile failure where subsequent combustion of the products is not involved. Freese (1973) reports one such example of a thin walled vessel with ductile failure and no subsequent combustion. Ductile failure followed by combustion of the products will be discussed later, in section IV.E.

B. Runaway Chemical Reaction or Continued Combustion

A runaway chemical reaction or continued combustion explosion is in some sense similar to the bursting vessel explosion. However in this case

there is the possibility that heat addition due to continued reaction or to flame propagation after the vessel bursts may alter the properties of the non-ideal blast wave that is produced by the burst. Andersen and Louie (1975) have performed a very simplified one-dimensional (i.e., planar) blast wave calculation for the case where the total amount of energy Q is kept constant but is added in different ways. Firstly, they assumed some fraction of Q trapped as pressure energy in a pressure vessel which was assumed to burst at time t = 0. Then they added the remainder of the energy at a constant rate, homogeneously, to all elements of fluid originally contained in the vessel. This represents the continuing chemical reaction or flame propagation. They studied the planar blast wave which is produced as a function of both the fraction of the energy which is added instantaneously and the time required to add the remainder of the energy. Interestingly enough, they found stronger blast waves in the near field when about half of the energy was added over a relatively short period of time after the initial burst. These results are quite intriguing and point to the need for a systematic study of the effects of adding energy over a finite time period in spherical geometry.

Three examples of accidental explosions involving runaway chemical reactions in a pressure vessel are described by Angiullo (1975), Dartnell and Ventrone (1971), and Vincent (1971). Nickerson (1975) discusses a case which involved afterburning in a dryer explosion. In this case the dryer ductwork released the explosive mixture at relatively low pressure and the dryer was not damaged significantly. However, rapid afterburning produced significant blast damage to the building and to a neighboring building.

C. Explosions in Buildings

Explosions in buildings are of three main types. In the first type there is a spill of some combustible material and a slow deflagration wave or "flash back" fire which causes a relatively slow buildup of pressure in the building. In the second type, a piece of equipment explodes, thus producing a blast wave inside the building which damages the structure and/or is relieved by venting. In the third case a leak occurs but the combustible mixture that forms detonates. Severity of damage increases from case 1 to 3. In case 1 or 2 explosive relief or vent design can save the building, as was discussed in Section II.D. Case 3 will be discussed extensively in the following section. For case 3, relief or venting is, in general, not very useful.

D. Internal Explosions

These can be very dangerous. In this case the contents of the pressure vessel, reactor, distillation column, building, car or whatever detonate. It is important to realize that these explosions are uniquely different than those discussed in sections A, B and C above. In those cases the degree of confinement or "bursting pressure" of the vessel or building, etc. determined the nature of the blast wave which is generated and the

damage patterns. However in the case of detonative combustion or reaction, the blast wave behavior and the damage patterns are primarily determined by the behavior of the detonation and are only modified by the confinement.

It appears that very little useful research can be done on these explosions. The major question here is the sensitivity of the exothermic substance or mixture to transition to detonation under confined conditions. Once the transition occurs damage levels are high and have usually been found to correlate well with detonation overpressures. There is the possibility that the P-I technique discussed in section III.A. may be more generally useful for this type of explosion. It appears, though, that whichever technique is used, point source approximations are probably adequate up to overpressure levels which yield light structural damage. Relative to heavy structural damage, the vessel or building, etc., that could not "contain" the explosion is usually extensively damaged and causes major structural damage to nearby equipment, vessels and/or buildings both by fragment and blast. Normally if the explosive material is gaseous (e.g., has low density) cratering does not occur. However, if it has a high density because it is solid or liquid, cratering does occur.

There is one very interesting report by Burgess, et al (1968) which covers this subject very well. It describes the results of numerous experiments and presents guidelines for evaluating such explosions using the point source-overpressure-scaled distance technique discussed in section III.D. Also the nature of the process of acceleration to detonation in pipes and overpressures connected with these detonations is discussed by Craven and Grieg (1968). Howard (1975) discusses the testing of flame arrestors in pipes to stop a propagating detonation in a hydrogen-air mixture. Explosion protection for processing vessels have been discussed by Charney (1967 and 1969), and by Peterson and Cutler (1973).

Examples of case histories in the literature of incidents which involved detonations are numerous: Smith (1959), oil in a high pressure air line; Jarvis (1971a & b), and Freeman and McCready (1971a & b), distillation tower containing vinyl acetylene; Zabatakis (1960), air in dephlegmator; Brasie and Simpson (1968), buildings (3 incidents discussed); Baker (1974), acetylene in a car (see Figure 24); Shepard (1975), methane in an elevator shaft (27 story building, 3 shafts involved, see Figure 25); National Transportation Safety Board (1972c), dynamite in a truck; and Wilse (1974) and Halverson (1975), "empty" super tankers during cleaning or partially full tankers during off loading, to name a few.

E. Rupture Followed by Combustion

This very special type of explosion occurs primarily when a tank of liquified fuel, under pressure, is heated by an external fire following an accident, until it vents and torches. For an explosion to occur the subsequent heating of the venting tank must be sufficiently intense to cause the internal pressure to rise above the tank's bursting pressure, even with venting. This type of explosion produces three distinct damage producing effects. These are 1) a blast wave due to internal pressure

Figure 24. Damage from Acetylene-Air Explosion in a Car. Leaking tank in trunk. Car parked in sun about 1 hr. Ignition source unknown. From Baker 1974.

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Figure 25. Methane air detonation in 3 elevator shafts, central portion, left side of building. New York, NY. Shepard (1975)

relief, 2) a fireball due to subsequent massive burning of the contents of the tank in the air, and 3) large fragments scattered for large distances due to the ductile nature of the tank's rupture and the rocketing of pieces by reaction forces.

The blast from such explosions is usually minor because vessel bursting pressures are in the 200 to 400 PSI range and only a portion of the vessel contains high pressure gas. Estimates of the blast can be made using simple pressure burst formulas if one knows the fraction of the vessel's contents that are in the gas phase and the burst pressure. One can assume that the energy is equal to the pressure burst of a vessel equal to the size of the vapor space plus some contribution from flash evaporation of at least a portion of the liquid phase in the vessel. Flash evaporation is rapid, except as modified by the inertia of the liquid, and contributes to the blast wave. There is no extant work on this aspect of the explosion process and it is doubtful if any will be performed because the blast produced by these explosions is the least damaging of the three effects.

Fireball damage can be severe, particularly if the release of material is large. High (1968) has documented the size and duration of fireballs from a large variety of explosions and finds that they can be predicted quite well with the equations

$$D = 3.86\ W^{0.320}$$

for size and

$$T = .299\ W^{0.320}$$

for duration. Here D is diameter in meters, W is weight of combustible in kg and T is duration of fireball in seconds. The exponent should properly be 1/3, not 0.320; the 0.320 value was obtained from least squares fit to the data. Figure 26 is an example of such a fireball taken by the Champaign Fire Department (1972). The size of this ball agrees well with the correlation of High (1968).

Large fireballs radiate energy at levels which are sufficient to cause severe flash burns to exposed skin and ignite cellulosic materials over a large area. Also, depending on the circumstances, the fireball may entrain firebrands which can ignite multiple fires at a later time.

Fragments from this type of incident can travel large distances. Baker, et al (1974 a & b) have discussed fragmentation patterns for explosions of liquid propellant vessels, and Siewert (1972) has collected fragment distribution data for 84 tank car explosions. He finds that the data for terminal position correlate well on a cumulative probability versus logrithmic radius plot and recommends a safe evacuation radius of 2000 feet (610 m) for all cases where a tank car containing a liquid combustible is being heated by an external fire. Only 5% of the fragments travel beyond this distance.

Figure 26. Fireball from the rupture of one tank car originally containing 33,000 gallons ($120m^3$) of LPG. Crescent City, Illinois, June 21, 1970. Notice water tower on left and train on the right side for scale. The size of the fireball agrees well with the prediction of High (1968). Champaign Fire Department (1972)

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Recent incidents involving this type of explosion include: Crescent City, Illinois (National Transportation Safety Board (1972b)); New Jersey Turnpike Exit 8 (National Transportation Safety Board (1973c)); Houston, Texas (National Transportation Safety Board (1972d)); and Oneonta, New York (National Transportation Safety Board (1974)). There has recently been some research in this area relative to developing techniques to protect tank cars from fire by applying an insulating coating (Phillips (1975)).

F. Vapor Cloud Explosions

Unconfined vapor cloud explosions have been occurring for as long as man has handled large quantities of combustible liquids with high vapor pressure. The usual sequence of events is 1) a massive release of a combustible fuel, 2) a reasonable delay in ignition, of the order of 30 seconds to 30 minutes, and 3) ignition of the cloud to detonation. Strehlow (1973b) reviewed the state of the art relative to our understanding of these explosions two years ago and showed that their frequency and magnitude has increased markedly in the past 10 years. Most of his references will not be repeated here. In addition, Coevert, et al. (1974) have also discussed their behavior in general terms.

There is currently a great deal of interest in these explosions, primarily because of their frequency of occurrence and the damage produced by recent incidents. Table III lists a number of recent incidents in which damaging blast waves were produced. While this list is not exhaustive it does represent typical vapor cloud explosion behavior. Table IV lists five recent incidents involving ignition without explosion. In these cases there were also massive releases and delays to ignition without the production of damaging blast waves. All that occurred for these later cases was a flash of fire back to the leak site followed by torching of the leak. It is interesting to note that one of the incidents listed in Table IV (Anon (1972)) was actually a controlled experiment to determine flame velocity. Raj and Emmons (1975) have recently presented a theory to calculate the flame thickness during flash back of such flames.

The fact that vapor cloud ignition can lead to two very different types of behaviors relative to blast wave production leads one to the conclusion that detonative combustion must always occur before a destructive blast wave is produced. Brown (1973) argues this position rather convincingly and evidence from actual incidents invariably shows that a detonation or detonations had occurred locally in the cloud when severe blast damage was found.

Research which is currently being performed relative to the behavior of these explosions is really of two major types. Firstly, there is considerable effort in the area of assessing the behavior of a deflagrative explosion of the cloud. Here there are two major thrusts to the work. These are 1) overpressures from normal flame propagation are being evaluated, and 2) mechanisms for acceleration to detonation for various degrees of "confinement" are being investigated. Measurement of overpressures and flame behaviors for centrally ignited spherical or hemispherical clouds have been made

TABLE IV

A FEW RECENT VAPOR CLOUD EXPLOSIONS WHICH PRODUCED BLAST DAMAGE

Location and State	Fuel and Quantity	Delay Time to Ignition	Loss Dollars & Fatalities	TNT Yield Based on Overpressure	Evidence for Detonation	References
Berlin, N.Y. July 26, 1962	LPG 1,500 Kg	minutes	$200,000 10	unknown	dwelling exploded	Walls '63
Lake Charles, LA August 6, 1967	Butane Butylene 9,000 Kg	unknown	$35 M 7	9,000 to 11,000 Kg (10%)	not reported	Goforth '69
Pernis, The Netherlands Jan. 20, 1968	H.C. Slops	>13 min.	$46 M 2	18,000 Kg (-)	Fire before severe explosion	MSAPH '68* Fontein '70
Franklin Co., MO Dec. 9, 1970	Propane 30,000 Kg	13 min.	$1.5 M 0	45,000 Kg (10%)	Pump house destroyed by internal explosion	Burgess and Zabatakis '73 NTSB'72a†
East St. Louis, IL Dec. 22, 1972	Propylene 65,000 Kg	> 5 min	$7.6 M	1,000 to -2,500 Kg (.3%)	Box car destroyed by internal explosion	Strehlow '73a NTSB '73a
Elixbourough, England June 1, 1974	Hot Cyclohexane 50,000 Kg	> 1 min.	>$100 M	18,000 to 27,000 Kg (5%)	Fire before severe explosion	Kletz '75 Kinnersly '75 Slater '74
Decatur, IL July 19, 1974	Propane 65,000 Kg	> 5 min.	$15 M	5,000 to 10,000 Kg (2%)	Fire before explosion. Box car destroyed by internal explosion	Benner '75

*MSAPH = Ministry of Social Affairs and Public Health

†NTSB = National Transportation Safety Board

TABLE V. RELEASE, DELAY TO IGNITION, NO EXPLOSION

Location & Date	Fuel & Amount	Delay to Ignition	Fatalities		
Lynchburg, Virginia March 19, 1972	Propane, about 1500 Kg	3-4 min.	1	Flashback fire to torch. Driver killed inside fireball.	NTSB '73b*
Griffith, Indiana September 13, 1974	Propane >100,000 Kg	7 hours	0	.45m vertical pipe at 10^6 Pa connected to a 36,000 m^3 storage cavern blew continuously until ignition. Workmen heard minor "pops" and then plume torched.	Schneidman & Strobel '75 Adderton '74 Shepard '75
Black Bayou Junction, Mississippi September 11, 1969	Viny chloride, monomer ?	6 hours	0	Tank leaked after derailment--no explosion at ignition. Subsequent explosion of tank cars bathed in fire	Kolger '71
Austin, Texas February 23, 1973	Natural gas liq. (Primarily C_3H_8,C_4H_{10})	15 min.	8	Pipe burst--auto engine started fire--800m x 66m burn area--no explosion	NTSB '73d*
France September 1972	LNG ?	?	0	Experiment to measure flame speed--27 m dike with ignition source 50 m away--no explosion	Anon '72

*NTSB = National Transportation Safety Board

by Woolfolk (1971), Ablow and Woolfolk (1972), and Woolfolk and Ablow (1973) using weather balloons of 15 and 90 cubic ft (.42 and 2.5m^3) capacity filled with hydrogen-oxygen-nitrogen mixtures. These mixtures all had relatively large burning velocities compared to ordinary hydrocarbon fuels. For deflagrative (weak) ignition they observed no shocks in the near field and far field overpressures which approached or even exceeded those produced by detonative combustion of the mixture. Unfortunately these experiments were on such a small scale that it is difficult to extrapolate to meaningful cloud sizes. Also, their weather balloons had rather thick walls and quite certainly interferred with the late flow and combustion processes.

Lind (1975) has performed experiments with a number of hydrocarbons in 5 and 10 meter hemispheres of .202" (5×10^{-5}m) thick polyethylene (volumes of 261 and 2094 m^3 respectively) ignited centrally at the ground level. He observed a number of interesting phenomena. Firstly, the flame propagated very rapidly ahead of the main flame ball along the concrete pad. This is probably due to a boundary layer-flame interaction similar to that which is observed in tubes. Secondly, the vertical propagation rate was always somewhat higher than the bulk horizontal rate and was accelerating. This can be attributed to a buoyant rise of the hot combustion products. Thirdly, he observed a very rough flame surface with both large and small roughness and he measured burning velocities (space velocities) which are 3-5 times the space velocity one would calculate from the normal burning velocity or would observe in a laboratory scale experiment. The mechanism which leads to these enhanced burning velocities is not understood at the present time. There is no turbulence ahead of the flame in the bulk gases. There can only be acoustic level disturbances ahead of the flame to possibly trigger flame accelerations. However, there is no theory available for this phenomenon at the present time. Fourthly, pressure levels measured in the flame ball or near it agreed quite well with those calculated using the theory of Kuhl, et al. (1973) while the ball was burning. Finally, they did not observe transition to detonation under any circumstances and they did put obstacles and a number of different shapes to simulate enclosures, etc., in the flame region.

Wagner (1975) has also reported experiments on a relatively small scale using a 1 ft^3 (0.028 m^3) box containing thin transparent walls and central ignition. He finds that when he completely surrounds the ignition source with a spherical coarse mesh screen with a relatively small blockage factor, the flame accelerates instantaneously to a very high velocity as it passes through the screen. He sees accelerated flame velocities as high as 12 times the normal space velocity. Unfortunately, his experiment is rather small scale. However, he did observe that the flame velocity started to decrease after the flame passed entirely through the gas which was rendered turbulent by the screen. Again, acceleration to detonation was not observed.

Calculations of the self-similar (in r/t) pressure and flow fields associated with constant velocity flame propagation have been made by Kuhl, et al. (1974). These require numerical integration of differential equations for solution, and Strehlow (1975) and Guirao (1975) have both obtained approximate solutions which do not require numerical integration. Strehlow's

solution is very simple and yields agreement within about 20% while Guirao's solution is more accurate but yields a more complex analytical relationship. Williams (1974) and Ablow and Woolfolk (1972) have also presented very crude treatments of the blast wave behavior. In addition to these, some calculations for blast behavior after the flame stops burning have been performed by Kiwan (1970b & 1971) and Guirao et al. (1974). Williams (1974) and Sichel and Hu (1974) have also looked in a relatively crude way at blast wave generation from non-spherical clouds both for deflagrative and detonative combustion and Strehlow, et al. (1973) has suggested a way to use shock-free experimental pressure-time curves to estimate the rate of energy release during the deflagrative explosion of a cloud.

The second major area that has been looked at extensively is the area of cloud dispersion. Burgess et al. (1975) used the usual atmospheric dispersion equations and determined that the maximum fraction of the fuel that would be in the combustible range at any one time from either a continuous or massive spill would be about 10%. This agrees quite satisfactorily with the data shown in Table III, where the maximum yield based on TNT equilivant weight is about 10%. In one of these cases (Franklin County, MO), it is known that the entire cloud detonated as a unit.

In addition to the research mentioned above there have been three important papers evaluating the hazard of unconfined vapor cloud explosions and recommending safe distances. Doyle (1970) presents charts giving overpressure levels as a function of distance based on a 2% yield from the massive release. Napadensky and Bodle (1973) specify that petrochemical plants should not be located any closer than 3/4 miles apart based on safety conditions and possible survivability. Finally, Iotti, et al. (1972) discuss safe siting of nuclear plants based on estimates of yield from an unconfined vapor cloud explosion.

The final recent development in the area of vapor cloud explosions has to do with the release and vaporization of liquified natural gas (LNG) particularly when it is spilled on water. The concern is that the contemplated large shipments of LNG into ports located near large population concentrations could lead to a truly massive spill followed by a catastrophic explosion. After all, ships with 5 containers of 50,000 m^3 volume each and single containers of 300,000 m^3 on land near water are either in operation or nearing completion. This development has led to "popular" but primarily hand waving papers concerning this new "danger" by Crouch and Hillyer (1972), Fay and MacKenzie (1972) and Fay (1973). The boiloff rate of LNG on ground has been treated by Burgess and Zabatakis (1962), while spills on water have been measured and dispersion calculations for different size spills have been made by Burgess, et. al. (1970a & b) and Opschoor (1975). Furthermore, it has been found that methane is extremely difficult to detonate. Foster (1974) and Kogarko, et al. (1965) both found that at least 1 kg of C4 or TNT were required to produce a sustained detonation in a stoichiometric methane-air mixture. The import of this work is that the danger of an accidental unconfined methane-air detonation may be slight. However, the final answer to this complex problem has not been reached as yet and more work on flame acceleration processes in large size clouds plus independent verification that transition

to detonation is difficult or impossible is necessary before the danger of handling LNG can be fully assessed.

G. High Explosives and Propellants

The blast waves produced by the accidental explosion of high explosives, black powder, high explosive intermediates or liquid propellants which are accidentally mixed are in general quite unreproducible and difficult to model adequately. This is reflected in the extensive discussion of liquid propellant explosions by Baker, et al. (1974a & b), concerning the results of Willoughby, et al. (1968a, b & c) (i.e., the Project PYRO tests), the modeling work of Farber and Deese (1968), Farber, et al. (1968), and Farber (1969) and the work of Fletcher (1968a & b). A portion of the conclusions by Baker et al. (1974a) are reproduced here directly from their report because they are rather concise and it would be difficult to paraphrase them adequately.

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

(1) The specific energies of liquid propellants, in stoichiometric mixtures, are significantly greater than for TNT (specific energy is energy per unit mass). In fact, all energy ratios are greater than 1, and can range as high as 5.3.

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

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

(4) The geometry of the liquid propellant mixture at time of ignition can be quite different than that of the spherical or hemispherical geometry of TNT usually used for generation of controlled blast waves. The liquid propellant mixture can, for example, be a shallow pool of large lateral extent at time of ignition.

(5) The blast waves from liquid propellant explosions show different characteristics as a function of distance from the explosion than do waves from TNT explosions. This is undoubtedly simply a manifestation of some of the differences discussed previously, but it does change the "TNT equivalence" of a liquid-propellant explosion. Fletcher discusses these differences (we show his curves as Figures 27 and 28). These differences are very evident in the results of the many blast experiments reported in Project PYRO.

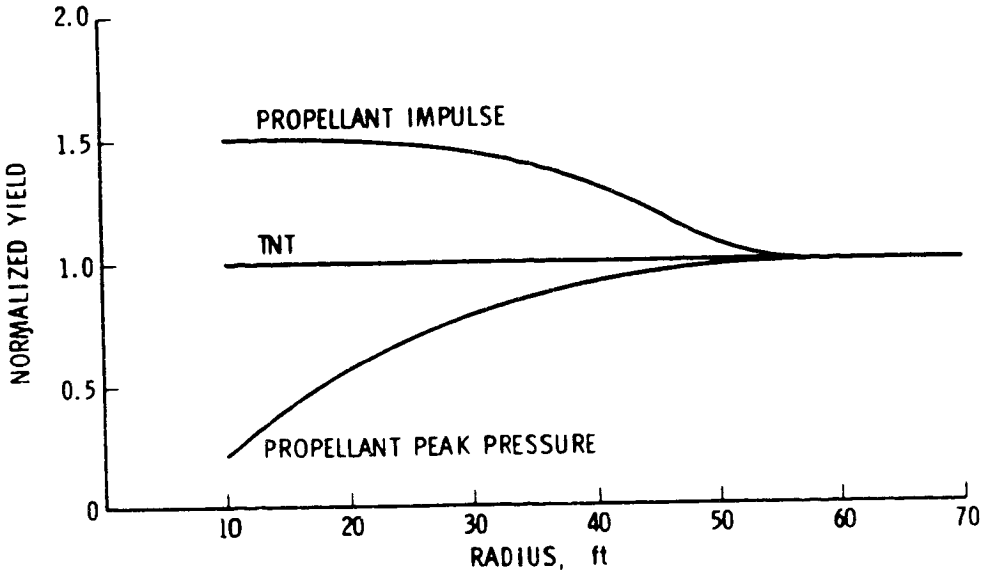

Figure 27. Normalized Pressure and Impulse Yields from Explosion of N_2O_4/Aerozine 50. Fletcher (1968b)

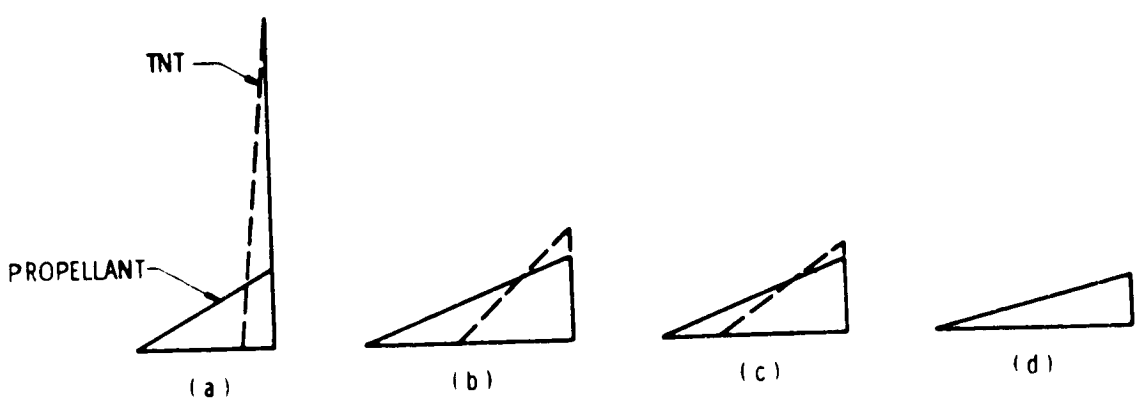

Figure 28. Representative Shock Impulses Showing Coalescence of Shock Waves from Dissimilar Sources (Stages (a) through (d)). Fletcher (1968b)

They have caused the coinage of the phrase "terminal yield", meaning the yield based on blast data taken at great enough distance from the explosion for the blast waves to be similar to those produced by TNT explosions. At closer distances, two different yields are usually reported; an overpressure yield based on equivalence on side-on peak overpressures, and an impulse yield based on equivalence of side-on positive impulses.

There exist at present at least three methods for estimating yield from liquid propellant explosions, which do not necessarily give the same predictions. One method is based on Project PYRO results and the other two are the "Seven Chart Approach" and the "Mathematical Model" of Farber and Deese (1968)."

In addition, Baker, et al. (1974) observed that for liquid propellant explosions:

"(1) The yield is very dependent on the mode of mixing of fuel and oxidizer, i.e., on the type of accident which is simulated. Maximum yields are experienced when intimate mixing is accomplished before ignition. For all cases the yield was found to range over the very large range of from .01% to 3.5% based on propellant weight.

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

(3) The character of the blast wave as a function of distance differs between propellant explosions and TNT explosions, as noted before. There is some evidence that these differences are greatest for low percentage yield explosions.

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

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

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

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

In an earlier report Bracco (1966) presents a calculation for the near field overpressure from the detonation of a mixture of liquid oxygen and liquid hydrogen normalized to far field behavior. He developed a rule of thumb which states that far field equivalence should obtain at a radius which is ten times the charge radius and calculates near field behavior

normalized to this far field behavior. Willoughby, in a response which is attached to Bracco (1966), is critical of this simple approach, primarily of the fact that Bracco assumed that the entire mixture detonates as a unit. He points to some of the (then) current PYRO results to show that some of Bracco's estimations may underestimate blast levels in the near field.

Recently, Sutherland (1974) has presented a simplified technique for estimating near field overpressures from liquid propellant explosions and Farber (1974) has summarized his earlier work which involves techniques he developed for estimating yield. Also Mastromonico (1974) has presented some new data on the carbon monoxide-nitrous oxide system. In short he found that he could not detonate gaseous $CO-N_2O$ mixtures in 33 and 60 m^3 thin walled containers (balloons or tents of thin mylar) but that with proper explosive squib initiation liquid-slush mixtures of $CO-N_2O$ detonated with up to a 60% TNT yield based on propellant weight and overpressure.

There have also been studies of the yield of explosions involving propellants and explosives in configurations which represent manufacturing, transport and storage. Napadensky has been particularly active in this area. In her studies a charge of material is initiated at a site instrumented with blast pressure gauges and the %TNT yield based on overpressure and positive impulse are determined using the weight of propellant or explosive only and not the calculated total energy contained therein. In this respect their technique differs from that used with liquid propellants where the energy is normalized. Percent yield is calculated at each gauge station and is then plotted against scaled TNT distance. Napadensky, et al. (1973) contains a good summary of the technique and results. Two figures from that report are reproduced here as Figures 29 and 30.

Figures 29 and 30 show three interesting general effects. Firstly, the percent positive impulse curves are quite flat for all cases. This is to be expected because for relatively low overpressures the positive impulse represents wave energy to a good first approximation and this is a conserved quantity except for shock dissipation. Thus the ratio between TNT and non-ideal explosion impulse should be a constant to a good first approximation.

Secondly, percent yield based on overpressure uniformly increases as one travels away from the source. This is also to be expected because near field overpressure curves can never be as high as TNT curves because of the slower energy release rate. However because these low pressure curves contain a relatively high impulse they decay more slowly than the TNT curves. Bursting sphere data, Figure 11 and Fletcher's curve in Figure 27, show the same effects only the method of data presentation was different. Finally, the results of Napadensky, et al. (1973) do not show the same far field equivalent TNT yield for overpressure and positive impulse as Fletcher's curve, Figure 27, implies. Analysis of Project PYRO data also shows this type of non-equivalence in the far field for liquid propellant explosions. Fugelso, et al. (1974) present a computational aid for estimating the damage effects due to the accidental explosion of stored munitions.

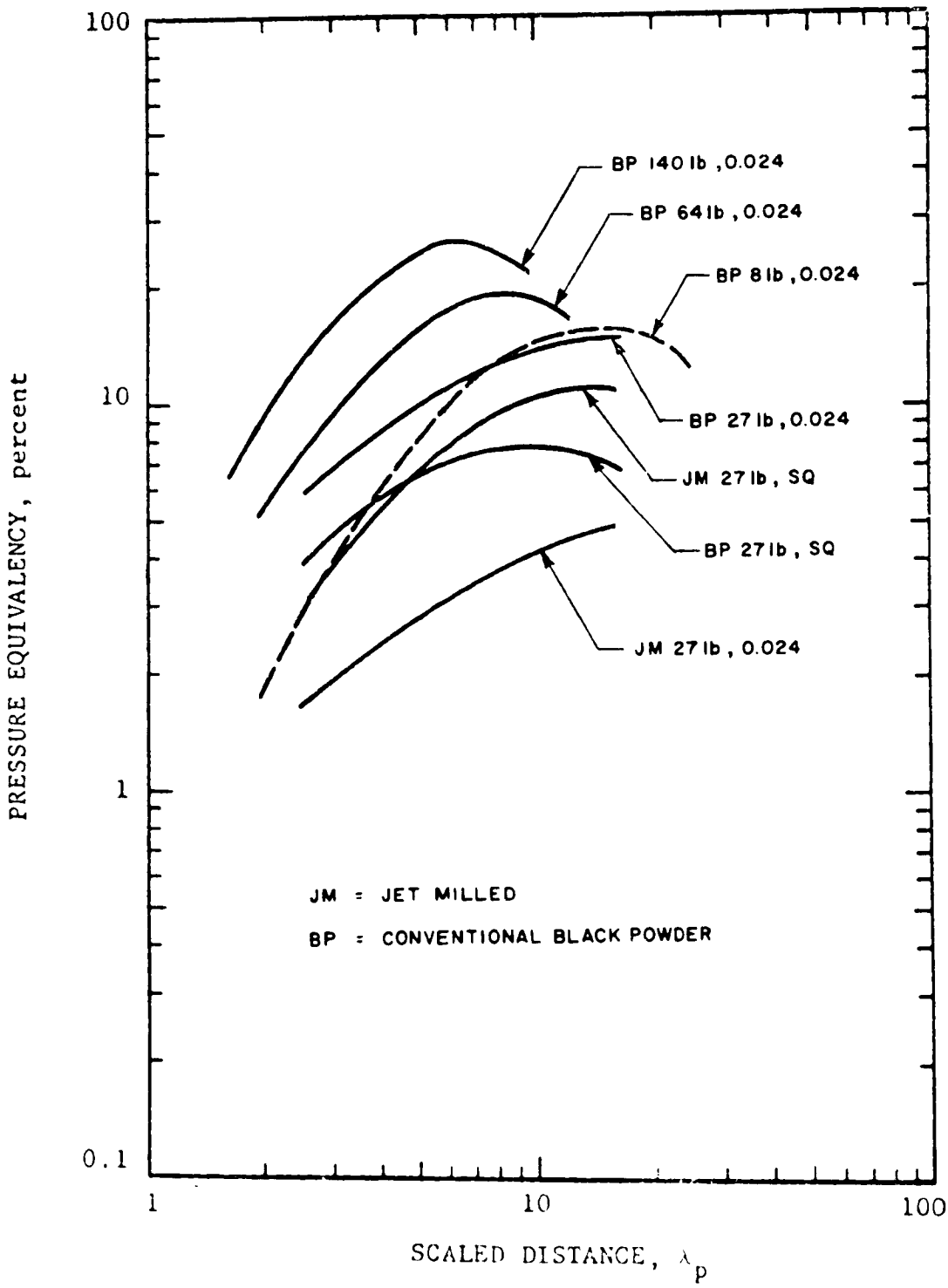

Figure 29. Effect of Black Powder Charge Weight on TNT Pressure Equivalency; Confined Tests, Squib (SQ), or 0.024 lb Booster. Napadensky et al. (1973)

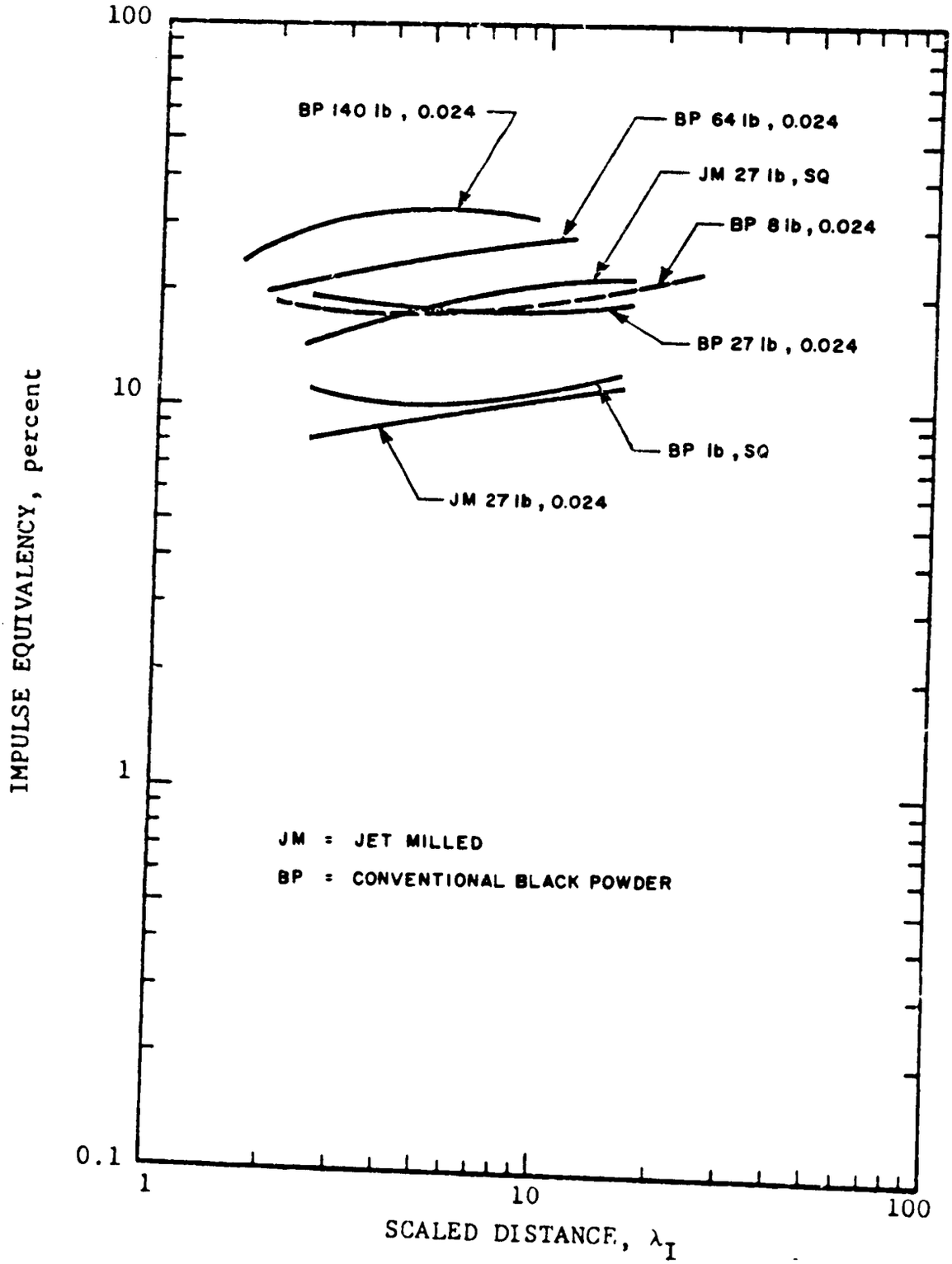

Figure 30. Effect of Black Powder Charge Weight on TNT Impulse Equivalency; Confined Tests, Squib (SQ), or 0.024 lb Booster. Napadensky et al. (1973)

In summary it appears that the highly non-ideal and very irreproducible results which are obtained from liquid propellant and accidental high explosive explosions must complicate the construction of an adequate theoretical model for these explosion processes which fits all the facts. It appears that more work is needed in this area.

H. Physical Explosions

One class of accidental explosion does not involve chemical reaction or the release of the stored energy of a compressed gas. Instead, the explosion occurs upon flash boiling of a cold high vapor pressure liquid when it contacts a high temperature material, usually another liquid. These "physical explosions" or "vapor formation explosions" have occurred in the past when molten or very hot solid metals have been violently mixed with water, or vice versa. They have resulted in a number of serious accidents over the years, primarily in foundries and other industries employing molten metals. Some serious accidents are summarized by Witte, et al. (1970). These authors also describe the nature of this class of explosion, and summarize experiments designated to simulate accidental vapor formation explosions. An apparatus and some test results reported by Witte, et al., for molten aluminum being poured into water are shown in Figures 31 and 32. Other accidental explosions of this type are discussed by Flory, et al. (1969). Nelson (1973) discusses the theory of these physical explosions.

Today, large quantities of the very cold cryogenic liquid LNG (Liquified Natural Gas) are being shipped in specially built and insulated tanker vessels and the projected increase in numbers is large (Hale (1972)). Because these vessels navigate in crowded harbors as well as the open sea, there is a very real possibility of collision or storm damage, and rapid release and mixing of LNG with wate Several years ago, there was serious concern that violent physical explosions could occur during such mixing. The first observations of such explosions were made at the U.S. Bureau of Mines by Burgess, et al. (1970a & b). Since then the problem has been investigated by a number of investigators including Nakanishi and Reid (1971) and Enger and Hartman (1971 and 1972). Katz and Sliepcevich (1971) and Enger (1972) both discuss the mechanism and come to the conclusion that the phenomena is caused by the occurrence of sufficient superheat of the colder fluid at the liquid-liquid interface to cause homogeneous nucleation and "explosive" formation of vapor bubbles. Enger has measured shock pressures in the liquid as high as 1.37 MPa near the "explosions". He reports that LNG must contain less than 40% CH_4 before an explosion will occur. Furthermore, he finds that if the mole ratio of propane to ethane in the LNG is greater than 1.3 "explosions" will not occur. The total energy released by these explosions is rather small, of the order of only 20,000 joules per square meter, and normally in a large spill situation there will be many small explosions rather than one large explosion. The general conclusion is that these explosions do not produce dangerous blast waves in air.

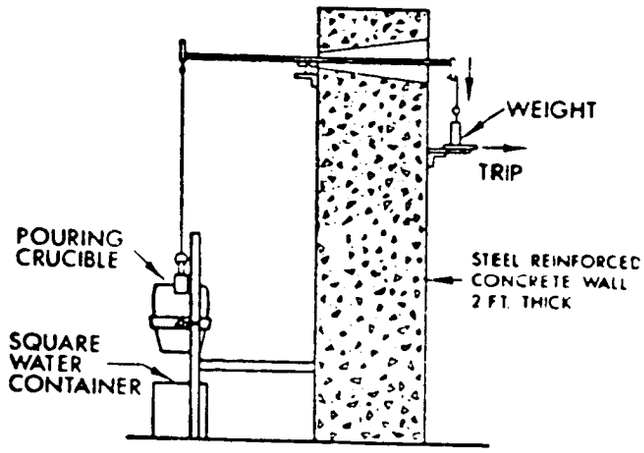

Figure 31. Experimental Apparatus for Molten Aluminum Explosions in Water. Witte et al. (1970

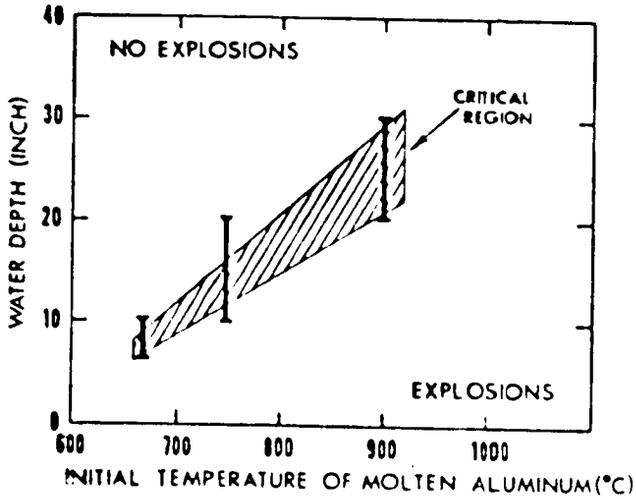

Figure 32. Results for Molten Aluminum Dropped into Water. Witte et al. (1970)

I. Nuclear Reactor Runaway

At first glance, runaway reactions in nuclear reactors would appear to represent very serious explosion hazards. The total amount of energy which could potentially be released is enormous, and the energy source is confined to a relatively small volume. But, reactors are designed so that the magnitudes and rates of real maximum possible energy releases are many orders of magnitude less than for nuclear weapons. Furthermore, they employ many redundant safety features, including massive containment structures designed to withstand strong internal blast and missile impact. The chances of venting to the atmosphere of an explosion resulting from reactor runaway are therefore very remote.

It is quite possible that accidents can occur to nuclear plants which will, however, cause internal explosions. Reactor runaway is essentially an uncontrolled power excursion which increases exponentially until some physical process causes disruption of the reactor core. This disruption can be explosive, as has been predicted analytically [Stratton, et al. (1958), Corben (1958)] and observed in deliberate reactor runaway tests [Dietrich (1954)]. Secondary explosions can occur, either chemical explosions such as sodium-air [Humphreys (1958)], or metal-water reactions as the metallic reactor core melts [Janssen, et al. (1958), McCarthy, et al. (1958), Owens (1959), Bendler, et al. (1958)]. All experimental and analytical evidence to date indicate that explosion hazards in nuclear reactors, although real, can be contained and the effects confined to the containment structure [Baker (1958)].

V. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

The authors draw a number of conclusions from the survey reported here, and also make some recommendations for further work.

We concluded that:

(1) Many damaging accidental explosions have occurred and will occur in industry, transportation and other fields. These explosions are almost always "non-ideal", i.e., they differ significantly from point source or chemical explosive (TNT) detonations.

2. Different types of accidental explosions lead to different types of blast waves. Furthermore, certain accidental explosions, like the simple pressure vessel burst for example, are more reproducible than others and therefore much more ameanable to analysis.

3. Because the comparison between ideal and accidental explosions is inexact, the concept of "TNT equivalence", which is widely used in safety studies, is also very inexact and may be quite misleading. But, this concept will undoubtedly be used to estimate "yields" of accidental explosions until better measures are available.

(4) There is quite a lot still to be learned about the formation and transmission of blast waves from non-ideal explosions.

(5) Scaling laws for non-ideal explosions are not now known exactly but, they can be easily developed once the physics of such explosions are well-known. They will likely be variants on Sach's Law.

(6) If blast wave characteristics can be defined for accidental explosions, correlation with damaging effects on buildings, vehicles, humans, etc. can be made based on existing methods and data in the literature.

(7) Fragmentation patterns from accidental explosions, and the damaging effects of these fragments, are both quite difficult to predict.

Some recommendations for further work seem in order. Some of these studies are already in progress, but others are not. The former are indiacted by an asterisk.

(1) *Analytical study of the physics of non-ideal explosions, and comparisions with test data.

(2) *Development of scaling laws for non-ideal explosions.

(3) Establishment of a method or methods for estimating blast energies of accidental explosions to replace "TNT equivalency."

(4) Careful review of fragmentation effects from accidental explosions, and better definition of these effects.

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