AD-A085 048 NAVAL POSTGRADUATE SCHOOL MONTEREY CA F/G 19/4
ATTENUATION EFFECTS OF THERMAL RADIATION ON INTERNAL BLAST OVER--ETC(U)
DEC 79 D E SMITH

UNCLASSIFIED NL

1 OF 1
AD A
085048

END
DATE
FILMED
7-80
DTIC

5

②

NAVAL POSTGRADUATE SCHOOL

Monterey, California

THESIS

ATTENUATION EFFECTS OF THERMAL RADIATION ON INTERNAL BLAST OVERPRESSURE

by

Douglas Edwin Smith

December 1979

Thesis Advisor: Richard A. Reinhardt

Approved for public release; distribution unlimited.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO. AD-A085 048	3. RECIPIENT'S CATALOG NUMBER (9)
4. TITLE (and Subtitle) (6) Attenuation Effects of Thermal Radiation on Internal Blast Overpressure.		~~5. TYPE OF REPORT & PERIOD COVERED~~ Master's Thesis, December 1979
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) (10) Douglas Edwin/Smith		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940		(11) ~~12. REPORT DATE~~ December 1979
		13. NUMBER OF PAGES ~~41~~ (12) 42
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) Naval Postgraduate School Monterey, California 93940		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Blackbody Radiator
Chapman-Jouguet Detonation
Condensed Explosive Detonation
Internal Blast
Thermal Radiation

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The determination of overpressure yield from internal blast has been the subject of prior investigations. Models have been developed to predict explosion thermodynamic parameters, based on equations of state, mass and energy conservation, and rate laws, utilizing high speed digital computers. Typically, thermodynamic equilibrium was assumed, an equilibrium temperature was determined, ideal gas law behavior was ascribed to product gases, and a

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
(Page 1) S/N 0102-014-6601

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

251450

pressure was computed. Reports of the results of these studies have typically contained a disclaimer that radiation effects have been ignored. In this investigation, a blackbody radiator model was developed and, utilizing the parameters reported in the literature for a number of explosives of common interest, a determination was made of the effect of thermal radiation as an attenuation mechanism on explosive energy and the existence of thermodynamic equilibrium. Energy losses of less than .5% were calculated and thermodynamic equilibrium was demonstrated through statistical considerations.

Approved for public release; distribution unlimited.

Attenuation Effects of Thermal Radiation on Internal Blast Overpressure

by

Douglas Edwin Smith
Lieutenant Commander, United States Navy
B.S., New Mexico Institute of Mining and Technology, 1966

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN PHYSICS

from the

NAVAL POSTGRADUATE SCHOOL
December 1979

Author

Approved by: Richard A. Reinhardt
Thesis Advisor

Second Reader

J. N. Dyer
Chairman, Department of Physics and Chemistry

William M. Tolles
Dean of Science and Engineering

ABSTRACT

The determination of overpressure yield from internal blast has been the subject of prior investigations. Models have been developed to predict explosion thermodynamic parameters, based on equations of state, mass and energy conservation, and rate laws, utilizing high speed digital computers. Typically, thermodynamic equilibrium was assumed, an equilibrium temperature was determined, ideal gas law behavior was ascribed to product gases, and a pressure was computed. Reports of the results of these studies have typically contained a disclaimer that radiation effects have been ignored. In this investigation, a blackbody radiator model was developed and, utilizing the parameters reported in the literature for a number of explosives of common interest, a determination was made of the effect of thermal radiation as an attenuation mechanism on explosive energy and the existence of thermodynamic equilibrium. Energy losses of less than .5% were calculated and thermodynamic equilibrium was demonstrated through statistical considerations.

TABLE OF CONTENTS

I. INTRODUCTION

Internal blast is the term applied to the concussion effect resulting from highly exothermic reactions occurring in a confined space. Examples of internal blast are dust explosions in grain elevators and coal mines; gas pocket explosions in buildings and underground systems such as sewers and mines; and the detonation of high explosives, either accidently or through proper fuse function, in a charge hole in a mine ore face, or in a shipboard ordnance stores magazine or other compartment. Substantial effort has been devoted to the study of explosive phenomena during the past century; internal blast investigation has been particularly intense during the past two decades.

Various computer codes have been developed to predict the thermodynamic properties of the detonation products generated by explosive materials. Typically, these codes have been used to determine a product composition and condition based on chemical reaction rate equations and other thermodynamic and conservation considerations applied to a system of equations of state, such as the STRETCH code, which is based on the Becker-Kistiakowsky-Wilson (B-K-W) equations of state, reported by Mader of the Los Alamos Scientific Laboratory [Ref. 1).

Other work has been very specifically directed to the determination of internal blast overpressure yield. Previous investigations were conducted by G. F. Kinney, R. A. Reinhardt and K. J. Graham of the Naval Postgraduate School, working in conjunction with personnel from the Naval Weapons Center, China Lake, California, on determination of peak overpressure yield of various explosives and fuels, with and without the incorporation of blast-augmenting reactive metals [Ref. 2, 3 and 4]. The technique for determining internal blast overpressure used by Kinney, Sewell and Graham and by Reinhardt is to solve a system of simultaneous equilibrium equations to determine a product composition, based on a selected trial temperature. The sum of the internal energies of each product gas species at this trial temperature is then computed, using a polynomial form for c_v for each species. The value of the sum is compared to the previously determined value of the maximum energy available for release in the explosion. The value of the trial temperature is varied until energy balance is achieved. This temperature is an equilibrium flame temperature. Ideal gas law behavior is then ascribed to the mass of product gases, and a peak overpressure is computed.

A second major effort was undertaken at the Naval Ordnance Laboratory, White Oak, Maryland, with a focus on the production of a computer program capable of predicting damage mechanism due to internal blast [Ref. 5]. A common disclaimer made in the reports of these investigations has been that the effects of thermal radiation as an energy loss mechanism can be ignored. Additionally, an assumption of thermodynamic equilibrium was made in the determination of flame temperature.

The validation of the assumption of thermodynamic equilibrium establishment in the detonation reaction zone and the magnitude of the thermal radiation losses are the subject of this investigation. Examination of open literature reports of investigations conducted on luminosity of explosions was made to determine if thermal radiation energetics in conventional high explosive detonations had been quantified.

Inconsistencies of values which various sources cite for the same parameters is noted in examining the literature reporting explosives experimental results. A remark by Rudlin [Ref. 6] to the effect that statistical deviations within explosives data sets ostensibly reporting replicate measurements average about 10 to 15%, and that agreement to within 5% was unusually good, provides a basis for the order of magnitude and two digit precision used in the model development for this investigation. The best experimental or computational values available are used, the best being defined as having been cited in more than one source, or being internally consistent with other data cited in more than one source.

A model of a detonating explosive is developed to explore the existence of thermodynamic equilibrium and to quantify expected radiant exitance from the detonation. This model is established as a blackbody, with size and temperature characteristics determined by the detonation parameters of the explosives considered, as found in the literature. Utilizing these parameters, a determination is made of the effects of thermal radiation as an attenuation mechanism on the explosive energy available for generation of overpressure, and of the existence of thermodynamic equilibrium.

II. DETONATION THEORY

A brief discussion of the theory of detonation and terms used in detonation literature is considered appropriate prior to discussion of the specific model developed. Condensed explosives are solids which consist of materials or mixtures of materials which are capable of undergoing highly exothermic chemical reactions at extremely fast rates, producing gaseous and, usually, solid reaction products at high pressures and temperatures. "CHNO" explosives are organic materials whose molecules contain atoms of carbon, hydrogen, nitrogen and oxygen. These complex molecules undergo a decomposition reaction, followed immediately by oxidation-reduction reactions which produce low molecular weight detonation products, such as H_2O, CO, CO_2, N_2 and C. The exact quantity of each reaction product, per mole of explosive, is dependent on such factors as the initial composition and density of the explosive, the fuel-to-air ratio and initial conditions of the environment. Detonation of an explosive results from rates of reaction which are so rapid that the heat evolved in the exothermic decomposition and subsequent oxidation-reduction processes cannot be carried away before there is an energy build-up of such magnitude that a shock front results. This shock front propagates through the explosive material; it is called the detonation wave, and propagates at a characteristic velocity of detonation, D.

The detonation shock front separates the unreacted explosive material from the material undergoing reaction. One description (the model adopted for this investigation) considers three areas in an explosive undergoing detonation, separated by two planes, as depicted in Figure 1. In this description, the shock wave initiates the decomposition reaction of the complex "CHNO" molecule. Decomposition reactions are completed and oxidation-reduction reactions proceed to completion in the reaction zone. When the "C-J plane" is reached, reaction products are at thermodynamic equilibrium, and are of composition and condition predictable by appropriate equations of state.

Part of the net energy in the reaction zone pumps the detonation wave to sustain it as it propagates through the explosive. The rest of the net reaction energy is taken up as internal energy of the reaction products. When the detonation wave reaches the surface of the explosive, it shocks the surrounding medium, setting up the initial shock wave in the medium, and establishes a transient reflected shock wave back into the material, which results in a compression. Thus, the net energy released in the detonation is partitioned, with some going into the surrounding medium as the initial shockwave, and the rest being retained in the explosive material.

The values of specific heat of detonation, q, reported in the literature are often based on constant volume bomb calorimetric measurements. Values of heat of detonation experimentally determined in calorimetric devices are lower

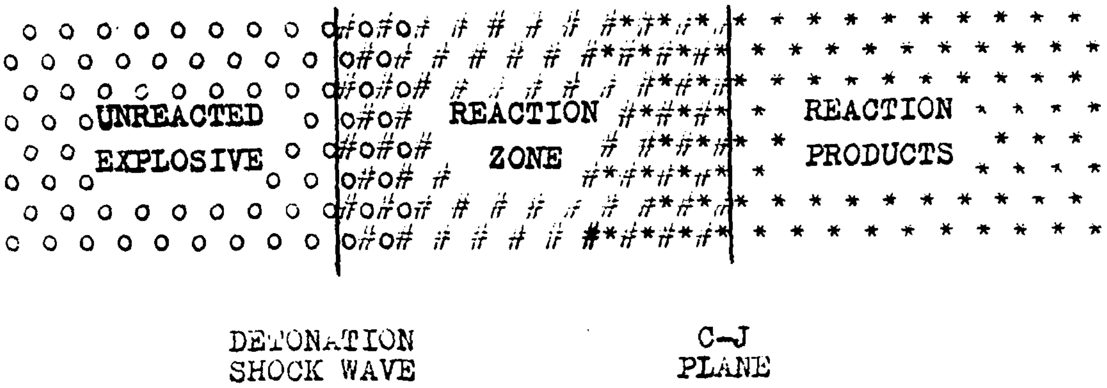

UNREACTED
EXPLOSIVE
REACTION
ZONE
REACTION
PRODUCTS
DETONATION
SHOCK WAVE
C-J
PLANE

FIGURE 1

than the maximum heat of detonation calculated for the enthalpy of the reactions transforming the explosive to its detonation products [Ref. 8]. The bomb calorimeter values are lower than calculated values because the products formed in the bomb differ from those in the Chapman-Jouguet (C-J) detonation state. The final products achieved in the bomb calorimeter are not the C-J products but, rather, reflect approximate equilibrium at low pressures. The relative amounts of H_2O, CO_2 and solid carbon formed in the reactions, as compared to CO and H_2, are determined by pressure dependent equilibrium equations. The formation of H_2O, CO_2 and solid carbon are preferred over the formation of CO and H_2 at the very high pressure of a C-J detonation state. The detonation products analyzed from bomb calorimeter tests, even when confined, show much higher concentrations of CO and H_2 than predicted, at the expense of H_2O, CO_2 and solid carbon [Ref. 8]. The enthalpy of the C-J detonation products is more negative than that for the bomb products. Since the object of this investigation is to determine the thermal radiant loss from the more energetic detonation state, calculated values are used [Ref. 7], where applicable.

A brief review of the pertinent points of the theories which have been advanced to explain explosive behavior provides definition to the terminology and concepts presented above. Reference 8, chapter 6, contains a satisfactory development of the elementary theory of the plane wave detonation. Extension of the concepts presented there to a spherical wave is straightforward [Ref. 8, ch. 9]. The detonation wave, in the framework of elementary thermodynamic-hydrodynamic theory, is assumed to be a shock wave, treated as a mathematical discontinuity, with full application of the general conservation laws which apply across any such discontinuity. As such, then, the detonation wave obeys the Rankine-Hugoniot equation for a shock wave:

$$e_1 - e_o = \tfrac{1}{2}(p_1 + p_o)\ (v_o - v_1)$$

where the subscript o refers to the unreacted material and 1 to the reaction products; e is the specific internal energy function, p is the pressure and v is the specific volume. This equation will be referred to as the Hugoniot. If the products are assumed to be in thermodynamic equilibrium, then their thermodynamic state is specified as

$$e_1 = e(p_1,v_1)$$

where e(p,v) is some known function of the state variables. In terms of specific enthalpy,

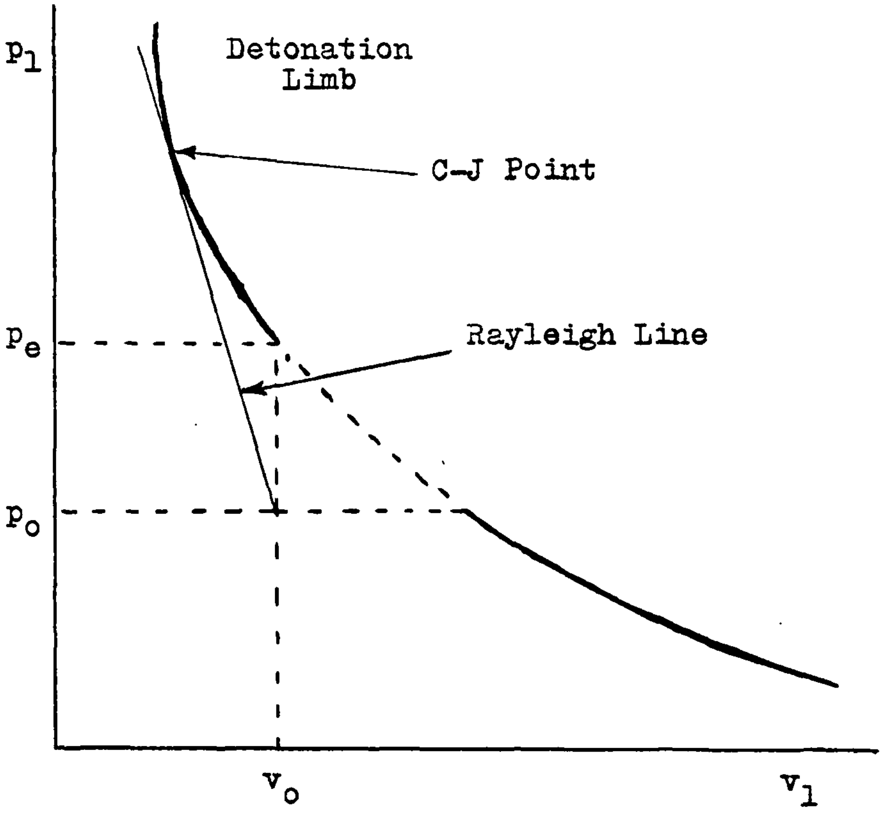
$$h = e + pv,$$

the Hugoniot can be written in an alternative form

$$h_1 - h_o = \tfrac{1}{2}(p_1 - p_o)\ (v_1 + v_o).$$

A plot of the Hugoniot in the p_1-v_1 plane provides a framework for definition of the Chapman-Jouguet (C-J) point (see Figure 2).

Consider the point on the Hugoniot curve for which v_1 is equal to v_o, corresponding to conversion of the explosive to its products at constant volume. The value of pressure



HUGONIOT CURVE

FIGURE 2

p_1 for this volume v_o on the Hugoniot, p_e, is the minimum value of pressure for detonation, and defines the lower point (p_e, v_o) of the detonation limb of the Hugoniot. Mass and momentum conservation conditions yield the relationship

$$- \rho_o^2 \; D^2 = \frac{(p_1 - p_1)}{(v_1 - v_o)}$$

which describes a straight line in the $p_1 - v_1$ plane; it is called a Rayleigh line, and is the chord connecting some point (p_1, v_1) to the point (p_o, v_o). The propagation velocity, D, is proportional to the square root of the negative slope of the Rayleigh line. One Rayleigh line passes through (p_o, v_o) and is tangent to the Hugoniot on the detonation limb. The point of tangency is called the Chapman-Jouguet point (p_{C-J}, c_{C-J}), and the explosion at this point has several important properties. The C-J state detonation, from some specified initial state (p_o, v_o), has a minimum value for the propagation velocity D, relative to the unreacted material, and a stationary minimum value of entropy. The Hugoniot curve is tangent to the isentrope through the C-J point, and therefore the Rayleigh line is also tangent to that same isentrope. The flow of the reaction products relative to the reaction front is sonic behind a C-J detonation. The Chapman-Jouguet hypothesis states that the detonation wave for which the wave flow proceeds at a sonic velocity is the one that actually occurs when the reaction wave is unsupported. Subsequent arguments by Becker [Ref. 9] showed, through entrophy considerations, that only the C-J detonation is stable. The C-J plane is the locus of C-J points, where the chemical reactions have come to thermodynamic equilibrium and the detonation properties predicted by the equations of state exist.

III. MODEL DEVELOPMENT

A. GENERAL DESCRIPTION AND GEOMETRY

This investigation is concerned with the centrally initiated detonation of spheres of condensed organic explosives of "CHNO" composition both with and without aluminum. A standard mass of ten kilograms is modeled, contained in a sphere of about 10 to 15 centimeters radius, depending on the density of the explosive. The volume taken up by the initiator at the center is ignored as is any energy contribution from the initiator, since both are very small compared to those quantities for the main charge. The explosive is detonated in a rigid container of irregular geometry, with an average distance from the charge to the wall of five meters, filled with normal air at standard conditions. When the detonation shock wave reaches the surface of the explosive, the initial shock wave is established in the surrounding air, there is a contraction of the surface of the explosive due to the reflected shock wave, and the reaction zone is the surface of the sphere. The shock wave displaces the air slightly away from the surface of the sphere and the compression of the surface itself results in a rarefaction; any chemical interaction of the medium with the material in the reaction zone is initially ignored, for reasons developed below. The reaction zone, at the surface, is referred to as the fireball in some contexts; after the hot gases produced by the detonation reaction have begun expansion and encounter material from the surrounding medium, the surface does indeed burn in some cases. This is called afterburn and is most evident in oxygen-poor explosives or those mixed with reactive metals. For purposes of this model, any medium-product reactions that occur do so after the beginning of the hot gas expansion and are considered to slow down the decay of the high temperature-high pressure conditions when volume expansion occurs.

The surface of the explosive is modeled as a blackbody. This requires thermodynamic equilibrium, which is demonstrated below. Spherical geometry is selected for several reasons. An isotropic blackbody obeys the Stefan-Boltzmann law, and a spherical surface is isotropic. For most explosive configurations of interest, at some time after completion of detonation, the expanding mass of hot gases assumes an approximately spherical geometry. The true geometry of a real system of explosive and confining chamber can be transformed into a spherical coordination description. Spherical geometry greatly facilitates computations of radiant energies. Additionally, the experimental results reported in the literature for many explosives of interest have been for spherical masses of explosive.

The initiation of detonation of a spherical mass of condensed high explosive from the center produces an expanding spherical detonation shock wave which propagates through the explosive. Although several sources have indicated a problem with maintaining a spherically diverging finite reaction zone of constant width [Ref. 8], because it would of necessity decrease in width as it expands, Cook [Ref. 10] employs a spheriform shock front model, and photographic evidence for such an expansion was reported by Rudlin [Ref. 11]. A point of consideration to resolve this quandry is that the value of the propagation velocity, D, builds up to the stable C-J value more slowly in the spherical case than in the case of plane wave propagation through an end-initiated cylindrical charge, and is a function of the radial distance out from the center [Ref. 8, ch. 9]. For purposes of the model used in this investigation, the C-J conditions are considered to exist at the surface of the sphere at the instant of departure of the initial shock wave into the medium. A minimum size exists below which this model does not apply, due to not reaching C-J conditions by the time the detonation wave has reached the surface, and due to an unfavorably small mass-to-surface area ratio (since heat of detonation and, therefore, the energy evolved, is a function of the mass of explosive and the radiant energy emitted is a function of the surface area and temperature).

B. THERMODYNAMIC EQUILIBRIUM

Existence of thermodynamic equilibrium in the detonation reaction zone during a sensible time period is an essential element of the foundation of assumptions upon which internal blast studies have been built. Sensible time is chosen to be that time required for the reaction zone to move through the detonating explosive a distance equal to the width of the reaction zone. Although an exact value for the width of a reaction zone is dependent on a number of variables, such as initial conditions of the explosive (density, packing, configuration, temperature, etc.) and the chemical composition and experimental measurement is, at best, very difficult, values on the order of 0.1 millimeter have been reported, based on pressure distribution in the reaction zone determined by shockwave measurements in thin layers of inert material placed in contact with the end surface of the charge [Ref. 12]. In Ref. 10, Cook makes a correlation between the reaction zone width and an area of ionization which exists immediately behind the detonation front. Using this correlation, reaction zone widths on the order of centimeters are reported. The reaction zone does propagate through the explosive immediately behind the detonation wave, with essentially the same velocity, D. As a typical case, TNT is considered. (Appendix A is a glossary of explosive acronyms; the common names of the explosives considered in this investigation are defined, and their compositions are given.) Reported reaction zone widths of 2.5 cm [Ref. 10] and 0.1 mm [Ref. 12] are used to give an upper limit value for the sensible time of 3.7×10^{-6}s and a lower limit value of 1.5×10^{-8}s, based on a reported detonation velocity value of 6830 m/s [Ref. 1]. If a large number of collisions occur between molecules of the product gases during this sensible time, it is reasonable to conclude that thermodynamic equilibrium exists.

Geometric collisional diameters of product species have been reported in the range of one to five Angstroms (1 to

5×10^{-10}m), determined by viscosity, heat conductivity and diffusion experiments [Ref. 13] or molecular beam apparatus experiments [Ref. 14]. Values of such collision diameters for diatomic and polyatomic molecular species are found to be, for example, 2.47×10^{-10}m for H_2 and 4.82×10^{-10}m for CO_2, with many values reported in the range of 3.5 to 5.0×10^{-10}m for molecules of the species found in detonation product gases. Order of magnitude agreement was found throughout the literature examined.

The number of particles, their collisional cross sections and thermal velocities can be combined to give a measure of the average time between collisions, through the relationship

$$t_c = \frac{1}{n \sigma v}$$

where n is defined as the number density of particles in the gas, v as the average velocity and σ as the collisional cross section. Reference 15 contains a form of expression for v (the Maxwell mean speed); using the variables of this analysis, $v = (8kT/\pi m)^{1/2}$. Reference 16 cites an equivalent expression, and provides a method to obtain an estimate of cross section for collisions between molecules of different species if molecular radii are known: $\sigma = \pi (r_a + r_b)^2$, where r_a is the radius of molecule species "a" and r_b is that of molecule species "b." Variations of molecular diameters, and the large number of possible varieties of collision events that could occur between the dozen species usually found in product gases, call for a simplifying approximation. An average molecular collision diameter of 4×10^{-10}m is selected, which results in a value for σ of $50 \times 10^{-20}\text{m}^2$ ($5 \times 10^{-15}\text{cm}^2$).

Composition of product gas for a large number of organic chemical high explosives is reported by Mader [Ref. 1]. An average molecular weight for these gases was determined to be 30 (28.8 for TNT of density 1.60 gm/cm^3, as an example). The particle density, n, is determined by multiplying the Loschmidt number (2.69×10^{19} particles/cm^3) by the detonation pressure in atmospheres and by the fraction 273/(detonation temperature). For condensed TNT of density 1.60 gm/cm^3, Ref. 1 reports detonation pressure of 194 kbars and detonation temperature of 2971 K. Using these values and an average molecular weight of 28.2, n was calculated to be 4.73×10^{23} particles/cm^3, v was calculated to be 1.49×10^5 cm/s, and a value of t_c was calculated to be 2.84×10^{-15}s. Comparison of t_c to the shortest sensible time value of 1.5×10^{-8}s demonstrates that a very large number of collisional events, on the order of millions, occur during the sensible time. Thermodynamic equilibrium thus exists in the reaction zone at the C-J plane.

C. BLACKBODY APPROXIMATION

The maximum radiant energy emitted by any isotropic body at thermodynamic equilibrium is, by definition, that radiated by a blackbody. A determination of the spectral energy given off by a blackbody at the detonation temperature for some explosive provides a measure of the maximum energy which could be lost from the product gases through thermal radiation. The surface of a sphere of detonated explosive, immediately after the departure of the shock wave into the surrounding medium, is modeled as a blackbody made up of hot gas which emits the spectrum characteristic of the temperature of detonation (the C-J temperature). Justification of this model follows order of magnitude comparisons between the excited state lifetimes and the time between collisions in the gas.

The lifetime of an excited state is defined as the average time an atom spends in this state before making a transition. Radiation can be given off by the atom when transition to a lower state occurs. Lifetimes for many states are on the order of nanoseconds (10^{-9}s) [Ref. 17]. Comparison of typical excited state (radiator) lifetimes (10^{-9}s) to the average time between collisions for the gas molecules in a detonation (10^{-15}s), as computed above, leads to the conclusion that the individual spectral line widths for the dozen or so species present in the detonation reaction zone will be collisionally broadened to the point of showing a continuum. Consider, as an example, the case of the 10.2 micron CO_2 line. It has a center frequency of 2.94×10^{13}Hz. CO_2 has a collision diameter of 4.84×10^{-10}m. At a C-J temperature of 3000 K and pressure of 2×10^{5} atmospheres, a time of collision of about 10^{-15}s is calculated. The line width (frequency spread) due to collisional broadening is about

$$\Delta\nu_o = \frac{1}{\pi\,\tau_c} \qquad \text{[Ref. 18].}$$

In this example, a line width of about 3×10^{14} Hz results, as compared to a room temperature width of about 50 MHz. This collisional broadening smears the 10.2 micron line from about 10^{6} Hz through 10^{20} Hz. The line spectrum of an explosion is very rich [Ref. 19]; such collisional broadening is operating on all species line widths to some comparable degree, causing them to smear together into an apparent continuum. Within the excited state lifetime, hundreds of thousands of collisions occur. Thus, thermodynamic equilibrium and continuum radiation are characteristic of the reaction zone, and application of a blackbody model is quite justified.

The radiant exitance of a blackbody is given by the Stefan-Boltzmann law,

$$M = \sigma T^{4} \quad \text{where} \quad \sigma = 1.36 \times 10^{-12} \text{cal cm}^{-2}\ \text{K}^{-4}\ \text{s}^{-1}.$$

Using this relationship, the energy emitted by the model blackbody can be found if the surface area, temperature and time of radiation are known.

The radiant surface of the detonation is the surface of a sphere occupied by a ten kilogram mass of condensed explosive, and a function of the density of the explosive. Different loading techniques produce different densities for the same explosive. Initial density is a necessary parametric input to any solution of the equations of state and is reported, for example, by Mader [Ref. 1]. The surface area for the reaction zone is somewhat reduced initially because of the condensation which occurs in reaction to the departing shock wave; subsequent pressure driven expansion of the reaction zone will provide a compensating increase in surface area. The surface area of the unreacted mass is considered to be a good approximation. As the fireball expands, the surface area increases; the temperature, however, decreases. The rate of energy radiation is a linear function of the radiator area, but depends on the fourth power of the temperature, as seen above in the Stefan-Boltzmann law. Thus, as the fireball expands, exitance decreases. Some argument could be advanced that the fireball would encounter additional oxygen from the air as it expands, thus helping to maintain the temperature through exothermic formation of additional oxides. This has been ignored for three reasons: (1) since air is only 20% oxygen, for every unit of mass of oxygen taken into the fireball, four units of mass of neutral (non-reacting) gas are also taken in and all the new material taken in must be raised to the equilibrium flame temperature, thereby compensating for any exothermicity of the oxide formation; (2) except in the case of very oxygen deficient or highly metallized explosives, formation of additional oxides may not be particularly dominant because of the decrease in pressure which would accompany the expansion; and, (3) the number of oxygen molecules in the air immediately surrounding the surface available for reaction is small compared to the number of product gas molecules. Although afterburn does indeed contribute to overall yield in some explosives [Ref. 20], the consideration made is that the temperature at the C-J plane (the detonation temperature) is the maximum, and that the exitance computed for that temperature and for the surface area of the original explosive mass represents a maximum power level; total maximum energy loss through thermal radiation is then established for a time period. The numerical value used for this time period varies for each explosive, dependent on available data. Actual light-intensity measurements are available for only some materials; the narrow bandwidth of the sensors used to obtain these data make them of marginal value. Experimental times of arrival of steady overpressure level or other time of significance is used where available. The maximum time of significance is in all cases determined to be the time to establish the relative quiescent peak overpressure which is considered the primary damage mechanism in the studies reported by Kinney, Sewell and Graham [Ref. 2].

D. OPACITY OF THE REACTION ZONE

Thermal photons emitted interior to the surface do not contribute to the radiant flux emanating from the fireball. The reason for this is the opacity of the reaction zone. The radiation, as photons, is absorbed or scattered before it can cross out of the sphere through the reaction zone. Time between events for photon-molecule interaction is found using the previous relation:

$$t_c = \frac{1}{n \sigma v} \quad ;$$

v in this case is the velocity of a photon traversing the body of gas. As an approximation, c_o, the speed of light in vacuum is used. σ in this case is the cross section of the molecules, an admittedly smaller number than the effective cross section seen by the radiation as an E-M wave. An order of magnitude comparison is again employed; a too-small σ, which results in a too-large t_c, is inconsequential to the outcome of the comparison since, using the average molecular diameter of 4×10^{-10}m and the n from the thermodynamic equilibrium calculation above, t_c is found to be on the order of 5×10^{-22}s (4.72×10^{-22}s in the case of TNT of density 1.60 gm/cm^3, from the Mader data). The time for the photon to cross the reaction zone of typical 2.0 cm width is 6.7×10^{-11}s, minimum. Thus, it is not probable that a photon from the interior would not be scattered or absorbed in the reaction zone transit, thereby escaping to contribute to the radiant flux.

E. REFLECTION AND ABSORPTION

In this model, all thermal radiation emitted by the fireball is considered to be absorbed by container surface. Typical reflectivity profiles for substances used as coating material, such as linseed oil based paints, show a maximum reflectivity of about 80%, with values under 50% more common; reflectivity is, of course, wavelength dependent. Reference 21 contains a number of graphs of reflectivity vs. wavelength for many coating materials. Radiation emitted from the fireball will encounter surfaces tens of thousands of times per millisecond in the container, and be partially reflected and partially absorbed at each encounter. After 25 reflections, even wavelengths with a reflectivity as great as .8 would be absorbed to less than .5% of their original intensity. About .05% of the equatorial cross section of the container is composed of the fireball cross section, under the model. Absorption in the fireball, with subsequent re-radiation, can be assumed for only some small portion of the radiated energy, and is ignored. Atmospheric attenuation within the container is likewise ignored because of the small path length involved to virtual extinction through surface absorption.

F. TIME OF RADIATION

Determination of the actual length of time for which thermal radiation losses are a mechanism reducing peak overpressure, and at what rate, involves complexities beyond the scope of this investigation. As an absolute maximum, the amount of time, called t_r, that this radiant flux reduces the internal energy available for overpressure generation is that from the time of arrival of the reaction zone at the surface of the explosive to the time of establishment of a level of quasi-static overpressure at the surface of the container. During this time, the temperature decreases from the C-J temperature, although by how much is a function of the amount of afterburning.

As a maximum, the total possible exitance is considered to be that from a blackbody, radiating at the C-J temperature, with surface area equal to that of the unreacted explosive mass, for a time, t_r, as described below. Radiant power decreases as the fireball grows because the temperature decreases with volume expansion and exitance is a function of the fourth power of the temperature. This power decrease due to temperature drop dominates the power increase attributable to greater radiator surface area and afterburning where present.

Times of arrival of the initial shock and quasi-static overpressure level have been reported for TNT [Ref. 6]. These times are each about five milliseconds. If the shock had maintained the C-J detonation velocity for the transit across the five meter average distance to the container wall, its time of arrival (a little over half a millisecond) would have been about one order of magnitude smaller than the measured arrival time. Application of the same 10:1 ratio and approximate equality of initial shock and quasi-static overpressure arrival times to other explosives is an artificiality, although not unreasonable for inclusion in the model since the mechanisms which cause velocity decay operate on both the initial shock and overpressure waves. When no experimental data are available, a time of radiation is chosen to be twenty times the idealized initial shock transit time as computed from the C-J detonation velocity. Where available, actual reported arrival times are used.

IV. RESULTS

A. DATA

Determination of the energy of detonation contained in a ten kilogram mass of explosive was rather direct since values of q, the specific heat of detonation, are reported in the literature, and Q is qxm. The value of q depends, to some extent, on the condition of the explosive; where full data are available for more than one set of initial parameters for a given explosive, calculations were made for each set. Specific volume, v, the reciprocal of density, was determined, since the surface area is a constant times the 2/3 power of the specific volume ($A_s = 2245\ (v_o)^{2/3} \mathrm{cm}^2$) for a constant ten kilogram explosive mass.

As noted above, the explosive energy is partitioned, with some portion going into the initial shock wave. The precise partition is highly variable, dependent in part on the density of the surrounding medium. Cole [Ref. 22] reports that 53% of the explosive energy of TNT is transmitted to the surrounding medium in an underwater explosion. Cook [Ref. 10] examines these variances in fluid and condensed media in some detail, although no empirical relations are established, per se. For purposes of this investigation, an examination of the ratio of the total radiant energy emitted to half the total explosive energy is deemed appropriate. Division of this $(\mathrm{Mxt}_r)/Q$ ratio by the decimal fraction of Q retained in the explosive after departure of the initial shock wave, were it known, would provide the percentage energy loss; it is not considered probable that this decimal fraction would be less than .50 in air. Thus, the maximum radiant energy loss reported in the data represents the evaluation of $(Mxt_r)/.5Q$.

Data and calculation results are contained in Table I. Sources of the numerical values used are cited, by reference number in parentheses. If no reference is cited, values are computed from other entries in the table, using a formula or technique described above. The value of q for ALEX is estimated on the basis of values for similarly aluminized explosives.

B. ANALYSIS

Limited luminosity data are contained in the literature for comparison. Rudlin [Ref. 6, 11 and 19] reported some observations on radiant emissions from TNT and pentolite. His analysis of data from a series of multi-ton TNT explosions, and a scaled comparison to data obtained on a series of eight pound sphere detonations are inconclusive due to an absence of quantitative measurements of thermal radiative power for the smaller charges. In addition, the instrumentation used on the smaller masses was band centered toward the shorter wavelengths in the visible and near infrared region of the spectrum. Rudlin observed that there was substantial energy in the infrared not accounted for in his investigation, due to the instrumentation red cut-off, at about .7 microns. Some data are available for multi-ton TNT events which give an integrated, broad bandwidth radiant energy measurement and percentage of explosive yield [Ref. 19]. Unfortunately, to quote Rudlin [Ref. 19], "scaling.....from small charges to multi-ton charges, does not, in general, hold." Of interest is that luminosity times reported are on the order of a millisecond for the smaller charges. Reference 17 also contains luminosity data. Although no units of power or energy are given, luminosity times in a no-afterburn environment (N_2 filled explosion chamber) are also very short, again on the order of a millisecond or two for lightly aluminized or non-aluminized explosives.

The times of radiation used in Table I are longer than those reported for the small explosive charges and may result in an overestimate of the total radiant energy emitted. A precise correlation is not possible because of the fact that the sensors used to determine the reported experimental times were not sensitive to the infrared radiation which makes up the majority of the radiant energy emitted. Since maximum attenuation effect determination is the object of this study, the t_r is, within the other model criteria, considered to be of an appropriate magnitude.

TABLE I

Explosive	ρ_o (gm/cm^3)	q (cal/gm)	D (m/s)	T_{C-J} (^oK)	Loss (ρ)
	v_o (cm^3/gm)	Q (Mcal)	t_r (ms)	$\dot{M}$ (Mcal/s)	
RDX	1.78 (7)	1480 (7)	8000 (1)	2970 (1)	.03
	.562	14.8	12.2 (23)	0.162	
PETN	1.67 (1)	1510 (7)	8180 (10)	3400 (1)	.05
	.578	15.1	12.2 (10)	0.283	
TNT	1.54 (7)	1290 (7)	6950 (1)	2940 (1)	.03
	.649	12.9	11.3 (6)	0.171	
HMX	1.89 (7)	1480 (7)	9124 (23)	2364 (1)	.01
	.529	14.8	11.0 (23)	0.0624	
COMP B	1.69 (7)	1400 (7)	7840 (23)	2770 (1)	.02
	.592	14.0	12.8 (23)	0.127	
Tetryl	1.71 (7)	1450 (7)	7850 (23)	2917 (1)	.03
	.585	14.5	12.7 (23)	0.155	
TATNB	1.89 (1)	1080 (7)	7500 (23)	2128 (1)	.01
	.529	10.8	13.3 (23)	0.041	

TABLE I
(cont.)

Mannitol Hexanitrate	1.73 (23)	1390 (10)	8260 (23)	6040 (10)	.49
	.578	13.9	12.1 (23)	2.82	
DATNB	1.80 (7)	1150 (7)	7559 (1)	2667 (1)	.02
	.555	11.5	13.2 (1)	0.104	
ALEX 20	1.80 (1)	1800	7451 (1)	5142 (1)	.21
	.556	18.0	13.4 (1)	1.44	
Tritonal 80-20	1.42 (10)	1100 (10)	4930 (10)	4100 (10)	.25
	.704	11.0	20.3 (10)	0.683	
Tritonal 80-20	1.79 (10)	1750 (10)	7020 (10)	5410 (10)	.29
	.559	17.5	14.2 (10)	1.77	
45/30/25 RDX-TNT-Aluminum	1.51 (10)	1060 (10)	5470 (10)	4400 (10)	.29
	.662	10.6	17.4 (10)	0.869	
45/30/25 RDX-TNT-Aluminum	1.82 (10)	1630 (10)	6760 (10)	5700 (10)	.39
	.549	16.3	14.8 (10)	2.16	

V. CONCLUSIONS

The basic assumption made in previous investigations of internal blast [Ref. 2, 3, 4 and 5] that explosion products are in thermal equilibrium is shown to be valid. By utilization of a blackbody radiator model, it is shown that explosive energy losses through thermal radiation from the surface of the explosion fireball are small, ranging from about .5% to under .01%. Demonstration of the validity of a second major assumption made in these prior investigations, that thermal radiative losses could be ignored, is thereby achieved.

With the recent development of detector systems which operate in the infrared, better experimental data on the spectral intensity profile of detonating explosives may be obtainable to the end of experimentally verifying detonation temperatures predicted by thermo-hydrodynamic codes. It is probable, however, that the experimental error induced by the apparent irreproducibility of explosive results to within a tolerance finer than five percent shall remain a major impediment to consistently accurate prediction of explosive parameters.

APPENDIX A

GLOSSARY OF EXPLOSIVE ACRONYMS

ALEX 20	Aluminized Explosive; 20% aluminum in 80% Composition B; empirical formula, based on 100 grams per mole, is $C_{1.873}H_{2.469}N_{1.613}O_{2.039}Al_{7.338}$.
Comp B	Composition B; mixture of 64% RDX and 36% TNT; empirical formula, based on 347.07 grams per mole, is $C_{6.85}H_{8.75}N_{7.65}O_{9.30}$.
DATNB	Diamino trinitrobenzene; chemical formula is $C_6H_5N_5O_6$.
HMX	Cyclotetramethylene tetranitramine; chemical formula is $C_4H_8N_8O_8$.
PETN	Penta erythritol tetranitrate; chemical formula ia $C_5H_6N_4O_{12}$.
RDX	Cyclotrimethylene trinitramine; chemical formula is $C_3H_6N_6O_6$.
TATNB	Triamino trinitrobenzene; chemical formula is $C_6H_6N_6O_6$.
Tetryl	Trinitrophenyl methyl nitramine; chemical formula is $C_7H_5N_5O_8$.

TNT	Trinitrotoluene; chemical formula is $C_7H_5N_3O_6$.
Tritonal	Aluminized TNT; numbers index percentages of TNT and aluminum (e.g., 80-20 is 80% TNT with 20% aluminum).

LIST OF REFERENCES

1. Mader, Charles L., Detonation Properties of Condensed Explosives Computed Using the Becker-Kistiakowsky-Wilson Equation of State, Los Alamos Scientific Laboratory, 1963.

2. Naval Weapons Center, NWC TP 6089, Peak Overpressure for Internal Blast, by G. F. Kinney, R. G. S. Sewell and K. J. Graham, June 1979.

3. Naval Weapons Center, NWC TM 3820, Adiabatic Computation of Internal Blast from Magnesium-Cased Charges in Air, by Richard A. Reinhardt, April 1979.

4. Naval Weapons Center, NWC TM 3429, Reactive Metals in Internal Explosions: The Combustion of Magnesium in Air, by Richard A. Reinhardt, February 1978.

5. Air Force Systems Command for Joint Technical Coordination Group for Munitions Effectiveness, Report 61-JTCG/ME-73-3, Internal Blast Damage Mechanisms Computer Program, by James F. Proctor, 10 April 1979.

6. Naval Ordnance Laboratory, NOLTR 63-13, On the Origin of Shockwaves from Condensed Explosions in Air, Part 2: Measurements of Airshock Pressures from 8-lb TNT Spheres of Various Densities at Ambient Pressures, by L. Rudlin, 21 January 1963.

7. Dobratz, Brigitta M., Properties of Chemical Explosives and Explosive Simulants, p. 5-2 - 5-3, Lawrence Livermore Laboratory, 1974.

8. Principles of Explosive Behavior, AMC Pamphlet 706-180, Engineering Design Handbook series, Army Material Command, 1972.

9. Becker, R., "Stosswelle und Detonation," Zeitschrift fur Physik, v. 8, p. 321-362, 20 December 1921 (1922).

10. Cook, Melvine A., The Science of High Explosives, p. 61-170, 265-282, 284-310, 322-330, Reinhold Publishing Corporation, 1958.

11. Naval Ordnance Laboratory, NOLTR 62-182, On the Origin of Shockwaves from Spherical Condensed Explosions in Air, Part 1, Results of Photographic Observations of Pentolite Hemispheres at Ambient Conditions, by L. Rudlin, 9 November 1962.

12. Johansson, Carl H., and Persson, P. A., Detonics of High Explosives, p. 28-31, Academic Press, 1970.

13. Glasstone, Samuel, Textbook of Physical Chemistry, 2d ed., p. 276-285, D. Van Nostrand Company, Inc., 1946.

14. Daniels, Farington and Alberty, Robert A., Physical Chemistry, 4th ed., p. 273-299, John Wiley & Sons, Inc., 1975.

15. Kittel, Charles, Thermal Physics, p. 203-220, John Wiley & Sons, Inc., 1969.

16. Richards, James A., and others, Modern University Physics, p. 362-372, Additon-Wesley Publishing Company, Inc., 1960.

17. Eisberg, Robert Martin, Fundamentals of Modern Physics, p. 468-472, John Wiley & Sons, Inc., 1961.

18. Svelto, Orazio, Principles of Lasers, p. 47-51, Plenum Press, 1976.

19. Naval Ordnance Laboratory, NOLTR 69-179, Luminosity from Multi-Ton TNT Explosions, by L. Rudlin, 22 June 1970.

20. Naval Ordnance Laboratory, NOLTR 61-178, The Contribution of Afterburning to the Airblast from Aluminized Explosives, by C. C. Matle, E. M. Fisher and T. O. Anderson, 22 June 1967.

21. Wolfe, William L., and Zissis, George J., editors, The Infrared Handbook, p. 3-102 - 3-105, The Infrared Information and Analysis (IRIA) Center, Environmental Research Institute of Michigan, for Office of Naval Research, 1978.

22. Cole, Robert H., Underwater Explosions, p. 146, Princeton University Press, 1948.

23. Properties of Explosives of Military Interest, AMC Pamphlet 706-177, Engineering Design Handbook series, Army Material Command, 1971.

INITIAL DISTRIBUTION LIST

		No. Copies
1.	Defense Technical Information Center Cameron Station Alexandria, Virginia 22314	2
2.	Library, Code 0142 Naval Postgraduate School Monterey, California 93940	2
3.	Department Chairman, Code 61 Department of Physics and Chemistry Naval Postgraduate School Monterey, California 93940	1
4.	Professor R. A. Reinhardt, Code 61Ri Department of Physics and Chemistry Naval Postgraduate School Monterey, California 93940	1
5.	LCDR Douglas E. Smith, USN 363 Linden Court Herndon, Virginia 22070	1
6.	Mr. R. G. S. Sewell, Code 3835 Detonation Physics Division Naval Weapons Center China Lake, California 93555	1
7.	Technical Library Naval Weapons Center China Lake, California 93555	1
8.	Mr. James F. Proctor, Code R12 Explosives Division White Oak Laboratory Naval Surface Weapons Center Silver Springs, Maryland 20904	1