A STANDARDIZED EVALUATION TECHNIQUE FOR REACTIVE WARHEAD FRAGMENTS

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Fragmentation is a damage mechanism employed by most warheads: whether produced by natural fragmentation or pre-formed fragments, the warhead produces a spray of high-speed, high-density metal. Traditional approaches to warhead design use inert metals such as steel, tungsten, or tantalum for these fragments. By replacing these inert metals with reactive materials it is possible to augment the kinetic energy effects with chemical energy. However, doing so requires a new approach to the evaluation of the effects of warhead fragments. This paper describes one such methodology that has been developed over the past several years as part of a research program investigating reactive materials.

INTRODUCTION

Traditional warheads use inert metal fragments (e.g. steel, tungsten, or tantalum) as a means to produce most damage along a line defined by their initial velocity vector. Damage of this type is bounded by the initial kinetic energy of the fragment. Reactive fragments add chemical energy and can increase total energy on target by 5 to 10 times that of the kinetic energy, alone. Furthermore, this target damage includes off-shotline regions as a result of the blast wave structure that is produced by the chemical energy release. Though metrics for traditional fragmenting warheads are well established, the novelty of reactive fragments has left them with no such standardization. The Naval Surface Warfare Center, Dahlgren Division has addressed this shortcoming by developing a standardized test technique for reactive fragments. It does so in a representative target engagement scenario in order to capture the effects of the projectile-target interaction.

General Characteristics of Reactive Warhead Fragments

Materials that are suitable for use as reactive warhead fragments are placed into two primary classes: binder-based and binderless. Binder-based materials generally include a polymer binder (e.g. polytetrafluoroethylene, PTFE, or an epoxy) that serves the dual role of mechnical binder and, occasionally, oxidizer. Reactive warhead fragments are intended to perforate a target and produce a detonation-like reaction on the target interior, producing blast and quasi-static overpressures that are damaging to the target structure and internal components. The time scales over which these reactions occur have a number of important consequences. Thin-skinned targets (e.g. air targets) are generally more sensitive to the short-time-scale blast component; harder targets are more sensitive to the quasi-static component and the resulting impulse applied over longer time scales.

The mechanisms by which the materials produce these blast and quasi-static pressures are governed primarily by the amount of "prompt" energy release. When a reactive material impacts a target and begins to react, the material constituents produce an initial reaction that generally occurs on the order of a few microseconds (referred to as the "prompt" reaction). It is usually the case, however, that the material is either fuel rich or inefficient in completing this reaction, the result being a fair amount of unreacted fuel available to combust in the presence of ambient oxygen. Because this secondary combustion reaction is limited by mixing within the ambient atmosphere (assuming one exists), it generally happens on time scales much slower than those obtained during the prompt reaction.

The Need for a Non-Standard Calorimetry Technique

A reactive fragment test technique must include the pertinent characteristics of the projectile-target engagement scenario, including target skin thickness, projectile speed/obliquity, and confinement. The difference in energetic output of a particular reactive material can vary by an order of magnitude in response to changes in target skin thickness and/or impact speed alone (Ref. 1-7). Static calorimetric techniques can be useful to validate a theoretical upper bound but, because they do not capture these effects, they are not suitable for use in conducting evaluations of impact-initiated energetic materials.

THE VENTED CHAMBER CALORIMETRY (VCC) TECHNIQUE

In order to address these requirements, the Vented Chamber Calorimetry (VCC) technique has been developed. The objective of this technique is to provide a well-

defined, standard measurement system by which reactive warhead fragment materials can be evaluated. To this end, the VCC uses an initially sealed chamber with an interior volume chosen to represent targets of interest. On the chamber interior, an impact anvil is placed some distance behind the outer target skin in order to simulate a representative impact surface. The chamber is normally configured such that there is only a single exit point for the high-enthalpy gases produced during the reaction process: that which was produced as the projectile perforated the target skin.

Instrumentation consists primarily of pressure gauges located throughout the chamber, both at the wall and at various locations around the chamber interior. Pressure gauges at the wall provide a record of both the blast and quasi-static pressures but are a function of the geometry of the setup. As such, they are less general than free-field measurements but are still useful as validation data for numerical simulations. Freefield measurements, enabled by pencil-type incident pressure probes, provide a more general measurement but are often difficult to conduct in the chamber interior.

Overview of Impact Phenomenology Using the VCC Technique

When a reactive material projectile encounters a target, there are four primary phases of the projectile-target interaction process: flight, perforation, blast wave propagation, and venting/combustion. These four processes are generic to the interaction but the extent to which effects are produced in each are tightly coupled to the particular reactive material formulation.

The first phase of the fragment-target interaction process is generic for all classes of warhead fragments: flight to the target. Once the fragment reaches the target, it impacts the target skin and begins the perforation process. It is almost always the case that the perforation process includes material reaction to some extent and material erosion and loss to the target exterior. The extent to which a particular material suffers from reaction and erosion during the perforation process is a strong function of two main material properties: reactivity and density. A more reactive material will be ignited more readily and will suffer from greater mass and energy loss to the target exterior. Density also has a role in determining the effectiveness of a given material formulation: more dense materials suffer from less erosion and are able to deposit greater amounts of material on the target interior.

Once through the target skin, most materials exist in a form that is best characterized as a fine-grained loose powder. The higher the density and strength of material, the more likely the fragment is to retain its pre-perforation mass and geometry properties. But, particularly for the weaker binder-based materials, it is not uncommon for a material to expand to a cloud of debris that is an order of magnitude larger in volume than its initial geometry. This cloud of material debris is most often reacting to some extent. Once the debris cloud reaches the anvil (or a hardened component on the

interior of a target), it produces a quick deflagration that, in turn, produces a blast-wave shock structure. As this blast wave propagates, it encounters the walls and produces reflections inside the target chamber.

As time progresses, this initial blast structure continues to reverberate within the test chamber but at much-reduced levels. However, the PdV work done on the chamber gases, combined with a pressure rise due to the afterburn reaction, produces a volumetric pressure rise over much longer time scales. As such, the pressures within the test chamber include a baseline "quasi-static" component with a fluctuating blast component superimposed. Also during this time the high-enthalpy reaction products begin to vent from the chamber. The venting process is a function of the perforation hole size as well as the pressures produced within the target chamber. For most target volumes and projectile sizes, the initial venting process is choked and happens much more slowly (on the order of hundreds of milliseconds) than the pressure rise within the test chamber. As such, up to the point of peak quasi-static pressure, the target interior is essentially a closed system (with regard to mass flux; there may be conductive/radiative heat losses that happen on times scales similar to the reaction rates and pressure rise). If the target fails and suffers massive venting then these assumptions are invalidated.

ANALYZING DATA OBTAINED USING THE VCC TECHNIQUE

As mentioned above, impact on the anvil produces a deflagration and blast wave structure that is characterized by both short time scales (sub-microsecond) and extreme spatial gradients (on the order of the shock structure). Later in time and over longer time scales (100's of ìs to milliseconds), the quasi-static pressures develop and produce a volumetric pressure rise over the entire chamber. The distinction between these phenomena is shown in Fig. 7.
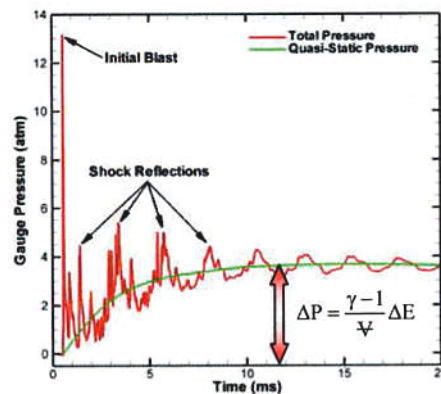

Figure 7: Typical pressure trace showing the distinction between Quasi-Static and Blast Pressures.

Energy Cascade in the VCC Technique

Before beginning the discussion on the energy cascade it is important to define the system to be used as a thermodynamic frame of reference. For most targets of interest, it is the energy deposited into the interior working fluid that is the primary damage mechanism. As such, it is that working fluid that is used as the thermodynamic frame of reference. While there are certainly important energy sinks outside this system (e.g. in any unreacted but deformed solid material) they do not, in general, contribute to the lethality in the reactive fragment application. As such, these energy sinks are grouped into a single category of losses.

In order to relate the pressures to the energy deposition process it is necessary to understand the manner in which energy is distributed within the test chamber. The total projectile energy, including both kinetic and chemical energy, is distributed among three primary sinks (Fig. 8): blast pressure, quasi-static pressure, and losses. As a result of the prompt reaction, some portion of the projectile energy is distributed directly into the localized blast pressures. This energy deposition is a result of a deflagration-type reaction that normally happens over several microseconds after the debris cloud impacts the anvil within the VCC. As stated earlier, most reactive materials will produce a longtime- scale reaction that also deposits energy into the test chamber. Because of the relatively long reaction time scales, however, this energy is not manifested in a shock structure but is distributed globally throughout the chamber in the quasi-static pressures. Finally, there are losses associated with the reaction and energy distribution processes that remove energy from the working fluid within the target chamber. As mentioned above, "losses" here means any amount of energy that does not manifest itself in the working fluid.

The losses include three primary components: heat losses to the chamber, work done on the chamber, and heat losses to and work done on the reactive material, itself. Any solid reaction products are likely to absorb some of the heat produced in the reaction and certainly the energy from work done during the material deformation process. Because this heat is not manifested in the gas pressures, it is not accounted for in this technique. Irreversible work done on the chamber is likely very small: the loads within the test chamber are well within the elastic limit of the chamber materials. Heat loss to the chamber could be significant for materials that produce extreme temperatures and high amounts of thermal radiation. However, because the peak quasi-static pressures are generally obtained within a few milliseconds, it is unlikely that significant heat transfer to the chamber can occur over this time scale. Finally, it is important to note that there are also material and heat losses to the exterior of the chamber as the projectile passes through the outer target skin.

Though the total projectile energy is initially distributed among the blast and quasi-static pressures, the energy in the blast pressures is eventually released into the

quasi-static pressures (excepting the losses). As the blast waves are reflected through the chamber interior, they perform PdV work on the gas into which they are propagating. This gas is initially at the quasi-static pressure and is raised above that pressure as the shock wave passes. The local pressure might then drop as a rarefaction wave follows but overall the global pressure will increase as a result of this PdV work. This is the mechanism by which the localized blast pressures deposit their energies into the global quasi-static pressures. As such, the global quasi-static pressure is the overall sink for all useful energy deposited into the working fluid within the test chamber and is the primary performance metric obtained using the VCC technique.

Relating Pressures to Projectile Energy

Although simply having the pressure measurements is sufficient to conduct lethality analyses, it is also instructive to relate these pressures to the reaction mechanisms. The analysis used in the VCC technique assumes, as stated above, that the energy of the reactive projectile is released first through a prompt detonation/deflagration process and later through an afterburn process. As such, the total energy release rate can be described as

$$\frac{dE_{tot}}{dt} = \frac{dE_d}{dt} + \frac{dE_{ab}}{dt} \tag{1}$$

where t is time, E_{tot} is the total energy release, E_d is the energy release associated with the prompt reaction and E_{ab} is the energy release associated with the afterburn. The assumptions used in the VCC analysis technique are described graphically in Fig. 9 (and taken after Ref. 9).
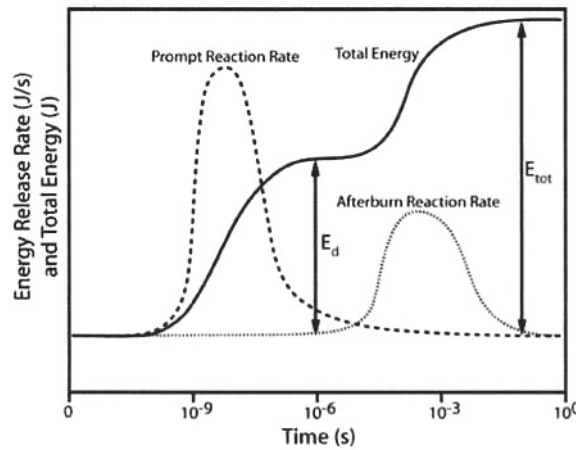

Figure 9: Relationship between early-time and late-time energy release rates

In the very early times, the energy deposition is dominated by the prompt reaction because the afterburn reaction occurs too slowly to have any impact. Once the prompt reaction is complete, the reaction products take time to mix with the ambient oxygen; as such, there is a period of time where there is little additional energy release. Once these materials are sufficiently mixed, however, the afterburn reaction begins and adds more energy to the total within the chamber. Because of the difference in time scales associated with the two reactions, the total energy deposition is characterized by the stair step shape shown in Fig. 9: the height of the first step is a result of the prompt reaction and the height of the second step is due to the afterburn reaction. The total energy rise is, therefore, the sum of the two.

The VCC analysis technique further assumes that the pressures measured on the interior of the chamber can be divided into a spatially dependent blast component) $\tilde{p}(r,t,E_{tot})$ and a spatially invariant quasi-static component $P_{qs}(t,E_{tot})$ as described above (here, r is a spatial coordinate). Using this simple construct, the total free-field static pressure $p(r,t,E_{tot})$ at any time is given by

$$p(r,t,E_{tot}) = \tilde{p}(r,t,E_{tot}) + P_{qs}(t,E_{tot}) \tag{2}$$

If the blast pressures are measured soon enough after the completion of the prompt reaction, it must be the case that

$$\tilde{p}(r,t,E_{tot}) = \tilde{p}(r,t,E_{d}) \tag{3}$$

In other words, the early-time blast component of the pressure is a function only of the detonation energy release because the afterburn reaction has not had sufficient time to release significant energy into the working fluid. This will be true so long as the afterburn energy release occurs on time scales that are many orders of magnitude longer than the prompt reaction (i.e. so long as the behavior shown in Fig. 9 is observed). Finding the appropriate functional form for Eq. (3) is normally done using standard blast scaling laws and other constructs such as TNT equivalence. While it is certainly true that the exact energy deposition is not captured using these techniques, and further that they have applicability only for a certain range of standoffs, it is usually the case that they are sufficiently accurate to capture an idea of the extent of reaction in the very early time. The procedure normally consists of taking a free-field pressure measurement very near the impact point and very early in time. The scaling law model is then used in conjunction with the measured pressure, location, and arrival time to calculate the equivalent early-time energy E_d produced by the prompt reaction.

Once the early-time energy release component is known, it remains to calculate the total energy deposition so that Eq. (1) can be used to distinguish between the two

(normally in integrated form; i.e. relating the difference between the end-state at max quasi-static pressure and the initial condition). Ref. 10 has shown that the total heat addition to the working fluid within the chamber can be related to the quasi static pressure via the relationship

$$\frac{dQ}{dt} = \frac{V\!\!\!\!-}{\gamma - 1} \frac{\partial P_{qs}}{\partial t} + \frac{\gamma P_{qs} V\!\!\!\!-}{m(\gamma - 1)} + \frac{dm}{dt} \tag{4}$$

where Q is heat addition to the working fluid, P_{qs} is quasi-static pressure, $V\!\!\!\!-$ is the volume of the chamber, m is the mass of air inside the chamber, γ is the ratio of specific heats of the gas, and t is time. Note that the term dm/dt is the mass flux from the chamber that is a result of the venting process. If the reaction time scales are much faster than the time scales associated with the venting process (as is usually the case), the effects of venting through the perforation hole can be ignored (the dm/dt term). Furthermore, it must be the case that, in the end state, the heat addition Q is a result of the total energy released into the working fluid E_{tot} and the equation can be integrated to give

$$\Delta P_{qs} = \frac{\gamma - 1}{V\!\!\!\!-} E_{tot} \tag{5}$$

where ΔP_{qs} is the change in quasi-static pressure obtained during the impact and reaction event. As such, this relationship provides a direct link between the measured rise in quasi-static pressure and the total energy deposition into the working fluid within the chamber (the primary damage mechanism).

Summary of Analysis Technique

Based on the analysis technique described above, the VCC technique relies on two primary pressure measurements. The first is a free-field measurement that is very near the impact point and that provides a good measure of the peak overpressure associated with the initial blast. This measurement, along with a functional form such as that given in Eq. (3), provides a measure of the early-time contribution to the energy release, E_d. The second required measurement is of the peak quasi-static pressure, as shown in Fig. 9. This measurement can be used in conjunction with Eq. (5) to provide a measure of the total energy deposited into the working fluid, E_{tot}. Finally, the afterburn contribution is simply the difference between E_{tot} and E_d.

SUMMARY AND CONCLUSIONS

This paper has presented an overview of the Vented Chamber Calorimetry (VCC) technique and why it is a necessary addition to standard calorimetry techniques for reactive fragment materials. Particular attention has been paid to the distinction between quasi-static and blast components of the pressure and how they relate to energy release rates. A detailed description of the reactive fragment target interaction process has also been given. Specific conclusions drawn from the work presented here include the following:

- Standard calorimetry techniques are not sufficient to characterize the energy release produced by reactive warhead fragments
- Most reactive materials produce reactions that occur on two time scales: one very quick (on the order of microseconds) and one relatively slow (on the order of hundreds of microseconds).
- The target interaction process produces overpressures that fall into two main types: blast and quasi-static. Each has a different effect on target response and the relative advantage that each provides is target specific.
- The blast and quasi-static components of the pressure can be directly related to the energy release rates produced by the reactive material. The blast component is directly related to the prompt reaction and the quasi-static pressure is directly related to the combination of prompt and afterburn energy deposition.
- Analysis of data from the VCC technique includes two main parts: one that relates the quasi-static pressure to the total energy deposition (including both chemical and kinetic) and one that relates the blast pressures to the prompt energy release. The difference between the two provides the contribution due to the afterburn reaction.

ACKNOWLEDGEMENTS

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