Protective Construction Design Criteria for HD 1.3

Arturo Luna, PE; Naval Facilities Engineering and Expeditionary Warfare Center; Port Hueneme, CA USA

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Abstract

United Facilities Criteria (UFC) 3-340-02 is the governing document that prescribes criteria for the design of protective construction to resist the effects of accidental explosions. It provides design criteria for the effects of Hazard Class/Division (HD) 1.1 explosives materials. It does not consider the effects of HD 1.3 explosives systems. Some protective construction design guidance exists outside of UFC 3-340-02 but has significant limitations. This paper discusses a number of existing gaps and necessary developments for HD 1.3 protective construction design criteria. Global HD 1.3 protective construction design considerations are presented. NFPA's fire protection rating system and its applicability and limitations to HD 1.3 protective construction is discussed.

Introduction

Within the Department of Defense, protective construction is used to protect personnel and assets from the effects of intentional or accidental explosions, or to delay the propagation of explosions. For accidental explosions, governing protective construction design criteria is provided by Unified Facilities Criteria (UFC) 3-340-02, "Structures to Resist the Effects of Accidental Explosions" [1]. UFC 3-340-02 design and analysis procedures address the effects of Hazard Division (HD) 1.1 mass-detonating explosives. It presents methods to determine the energetic output and explosion effects of HD 1.1 materials. It also presents procedures to design protective construction to resist these effects. These methods are accessible to designers on the basis of equivalent weight of TNT, and determining TNT equivalencies for HD 1.1 materials is generally feasible.

Currently, UFC 3-340-02 does not provide guidance for the design of protection construction to resist the reaction effects from HD 1.3 systems. Although some simplified protective construction design guidance exists outside of UFC 3-340-02, limitations inherent to some of these procedures may make them undesirable to use by designers. This paper discusses a number of existing gaps and necessary developments for HD 1.3 protective construction design criteria. Global HD 1.3 protective construction design considerations are presented. Additionally, the NFPA's fire protection rating system and its applicability and limitations to HD 1.3 protective construction is discussed.

Reaction Effects of HD 1.3 Energetic Materials

Department of Defense (DoD) Manual 6055.09-M, "DoD Ammunition and Explosives Safety Standards" [2], provides governing explosives safety standards to manage risks with DoD-titled ammunitions and explosives (AE) by providing protection criteria to minimize serious injury, loss of life, and damage to property. It states that hazards associated with HD 1.3 systems include fireball and thermal flux effects, gas pressures, fragments and debris.

A more detailed consideration of the hazards of HD 1.3 materials is likely to be reflected in future explosives safety standards. The Department of Defense Explosives Safety Board (DDESB) has recognized that that current HD 1.3 criteria does not represent the hazards associated with fire initiated (combustion) reactions [3, 4, 5]. Boggs et al. [3] conducted a review of mishaps occurring from the beginning of the 20th century to March 2012. The results of this review indicate that over 75% of the mishaps had fire as the primary initiation hazard, which can be present all throughout an AE's lifecycle.

HD 1.3 covers a broad range of munitions. These include articles such as grenades, gun propellants, and large diameter solid rocket motors. The reaction violence of a combustion initiated HD 1.3 system can vary widely and is dependent on several factors. Romo et al. [6] summarize the influence of combustion properties on the hazards potential of HD 1.3 systems. Depending on the properties of the stimulus (in this case combustion), properties of the HD 1.3 system, and the system's environment, the system may not react at all, burn mildly, burn rapidly (deflagration), explode, or detonate.

The factors that drive the reaction violence of an HD 1.3 system (stimulus, sample properties, and environment) vary throughout its lifecycle. In recognition of this fact, the National Fire Protection Association (NFPA) Explosives Material Code, NFPA 495 [7], recommends that a process hazards analysis be conducted throughout an AE's lifecycle. This type of process hazards analysis would serve as design load basis for protective construction to designed to resist or manage the effects of HD 1.3.

Of particular importance to protective construction is the role that structural confinement (environment) plays in contributing to the reaction violence of HD 1.3 systems. Recent testing and research efforts in Farmer et al. [4, 5] indicate that high loading densities and low vent ratios associated with HD 1.3 systems can lead to rapid pressure rise in robust structures resulting in rupture. This process is known as choked flow.

These tests were conducted at the Naval Air Warfare Center Weapons Division with HD 1.3 M1 gun propellant. The M1 propellant underwent combustion inside of 2 meter cubed reinforced concrete structures with a vent opening on one side. The results of these tests showed that at sufficiently high loading densities, and when vent ratios are low, combustion of the M1 gun propellant will result in a rapid increase in internal pressure until it ruptures the containment structure (choked flow condition).

The pressurization occurs as the solid energetic material reacts to product gases. This pressure is relieved by gases leaving the structure through venting. The rate at which gases may be vented out from the structure depends on available vent area as well as the atmospheric pressure outside the structure. Choked flow occurs when the pressure inside of the structure is about twice that of the pressure outside the structure.

The occurrence of choked flow can be related to quantitative parameters characterizing the HD 1.3 reaction event. These are *vent area ratio* and *loading density*. Vent area ratio is a non-dimensional parameter defined as the vent area divided by the chamber volume to the 2/3 power. The loading density is defined as the weight of the energetic material divided by the chamber volume. A choked flow condition occurs when loading density is high and vent ratio is low.

The distinction between an HD 1.3 reaction event resulting in choked flow and one that results in un-choked flow is important because of the impact this has on expected hazards. When flow is un-choked, the rise in internal pressure does not result in a rupture of the chamber structure. When flow is choked, the rise in internal pressure causes the structure to rupture soon after the reaction has started, projecting large structural debris hundreds of feet beyond sited safe-separation distances.

From the perspective of protective construction, it is clear that a choked flow event presents an untenable design scenario, and future design criteria may benefit from quantitative provisions that allow designers to avoid this response regime.

Existing HD 1.3 Protective Construction Design Guidance

In 1993, the US Army Corps of Engineers (USACE) Huntsville Division published HNDED-CS-93-7, "Hazard Division 1.3 Passive Structural Systems Design Guide" [8]. The purpose of this design guide is to present procedures for designing new structures as well as evaluating and modifying existing facilities for the effects of HD 1.3 reaction events.

The design guide provides simplistic procedures for the determination of HD 1.3 reaction effects in containment structures. This includes procedures to determine both fireball volume and how it is channeled throughout the containment structure and out of vent openings. It also presents procedures to determine gas pressures by calculating equivalent weights of TNT from which pressure and impulse characteristics may be generated.

Limitations associated with these procedures pose significant challenges for designers. The design guide makes a qualitative distinction between confinement and non-confinement structures. It defines a confinement structure as a building, room, part of a structure, or other enclosure that sufficiently encloses an HD 1.3 system to permit the development of significant gas pressures. This distinction is based on a literature search of tests and accidents involving HD 1.3 material.

In general, DoD explosives operating rooms are designed either to provide full containment or are designed with at least one lightweight, frangible surface (e.g., exterior wall or roof). Historically, confinement rooms with relatively low vent ratios have been rare, but some recent designs have used this configuration. If a room only has a few small vent paths or openings for the release of combustion gases, significant gas pressures may develop. Unfortunately, our available test data are limited, so USACE HNDED-CS-93-7 criteria for determining what constitutes ‘significant’ gas pressures inside a confinement structure are subjective and conservative. By contrast, non-confinement structures are not capable of developing significant internal gas pressures. Typically, non-confinement structures have multiple vent paths, some of which can be large openings relative to the enclosure’s dimension.

The procedures to calculate fireball volume expansion are challenging for designers to use for similar reasons. The procedure applies a safety factor equal to 1.2 on the weight of the HD 1.3 material, and the diameter of the fireball is calculated as 10 times the cube root of the effective explosive weight. The fireball volume is then amplified a factor F_1 that accounts for the level of confinement in the enclosure. F_1 increases with increasing levels of confinement , and based on a review of available accident and test data, the design guide recommends values between 2 and 5 be used. However, no quantitative guidance is provided to determine F_1, and thus application of this procedure will likely result in overly conservative design requirements.

The design guide also provides procedures for determining gas pressures in confinement structures. It provides equations to determine equivalent weight of TNT based on the heats of combustion and detonation of the HD 1.3 material in question. The equivalent weight of TNT is intended to be used to feed into a load analysis using UFC 3-340-02 procedures. However, the accuracy of these equivalency calculations is unclear and designers often find it preferable to assume the entire weight of the HD 1.3 material is equivalent to TNT, which may result in overly conservative designs.

Protective Construction Design Basis for HD 1.3 Systems

The design of protective construction to resist or manage the effects of HD 1.3 systems depends on the degree of protection that is required. In some scenarios, it may be necessary to provide a high degree of containment of the reaction effects of HD 1.3 systems. This can include operating cells or control rooms adjacent to laboratories and test chambers. Other scenarios, such as storage, may not require containment and can instead allow the HD 1.3 system to react in a controlled manner.

If containment is required, the structure must be designed to resist any internal gas pressures that may develop. They must also safely contain or vent any flames and fireballs. This requires an accurate determination of the pressurization rate and thermal output characteristics of the HD 1.3 system as it reacts inside the structure. The pressurization rate and thermal output of the HD 1.3 system depend on the initiation stimulus, sample properties, and environment [6]. An environmental factor of significant concern in the case of a containment structure is the degree of confinement. The design loading density and vent ratio must be designed such that a choked flow condition is avoided. A process hazards analysis of the type recommended by NFPA 495 would serve to develop this design basis.

Protective construction designs not required to provide containment, such as storage structures, are likely to have higher loading densities by comparison. They should therefore be designed to have high vent ratios and many frangible surfaces in order to prevent the buildup of significant gas pressures. In addition, the construction method for non-frangible elements of these structures need not be overly heavy or robust. In this scenario, too, it is important to rule out the potential for choked flow conditions.

A challenge in developing these kind of design bases is the lack simplified load prediction tools to determine the rate of pressurization. Improvements in this area will be of great benefit for the design of protective construction going forward.

NFPA Fire Protection Codes and Standards

A limited search through existing NFPA design codes and standards was conducted to determine if additional guidance may be used or readily adapted for HD 1.3 protective construction applications. Although relevant findings from this code search are presented below, additional code and literature search efforts are warranted as HD 1.3 protective construction criteria are further developed.

Existing safe-distance siting criteria are intended to assist facility planning efforts, and thus these distances are meant to be applied between separate facilities. However, typical DoD operations can also require HD 1.3 protective construction design criteria that is applicable between separate rooms or operating cells within a common building envelope, such as in the case of laboratories, test chambers, or production and processing bays. If, for example, an accidental HD 1.3 explosion occurs inside of a laboratory, it may be necessary to protect personnel and assets in an adjacent control room. In such scenarios, preventing the HD 1.3 reaction effects from propagating through penetrations and openings into adjacent rooms becomes a primary design objective. NFPA standards may provide some utility for designers trying to prevent the spread of fire from HD 1.3 explosions through penetrations and openings.

<u>NFPA Fire Door Ratings and Standard Temperature-Time Curve.</u> NFPA 252 [9] is a standard that prescribes fire test procedures that apply to fire door assemblies intended to be used to stop the spread of fire through door openings in fire resistive walls. The result of the test is a fire protection rating for the door assembly quantified in units of time. For the duration of the fire rating, it is expected that the door assembly resists the spread of fire to the protected side while meeting standardized performance requirements (gaps developed between door and frame, size of flames passing onto protected side, etc.). NFPA 252 prescribes a standardized temperature-time for a severe design fire event reproduced during the test as shown in Figure 1. Fire ratings for other fire resistive components are also based on this standardized curve.

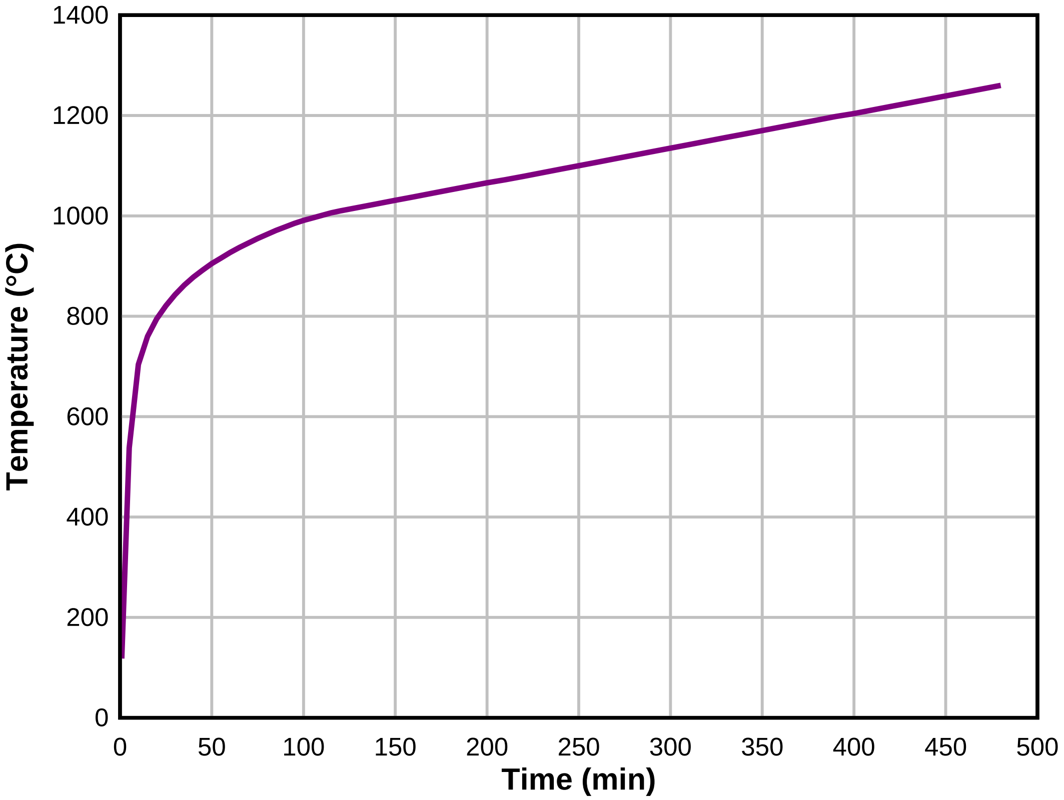

Figure 1. NFPA 252 Standard Temperature-Time Curve for Fire Resistance Tests.

In situations where there are negligible gas pressures, such as when loading densities are sufficiently low and vent ratios are high, the fire ratings for non-blast resistant components such as door assemblies may be provide adequate fire protection. The temperature-time curve shown in figure 1 shows temperatures that are comparable to those expected during HD 1.3 explosions. However, in some instances, an HD 1.3 deflagration may have a much faster temperature rise time than that which is shown on the standard NFPA curve. This introduces the risk of thermal shock, the effects of which should be further investigated prior to adopting NFPA fire ratings for use in resisting thermal hazards from HD 1.3 explosions.

NFPA 221 Standard on Firewalls. NFPA 221 [10] specifies requirements for the design and construction of high challenge fire walls, fire walls, and fire barrier walls including protection of openings and penetrations. This standard requires the use of firestop systems and devices at all penetrations, such as for pipes, cables, cable trays, exhaust vents, wires, and other similar systems. There are a wide variety of commercially available firestop devices, all of which are tested to meet the requirements of ASTM E814 or UL 1479 standards. They are designed to seal off any exposed gaps in a penetration, thus limiting the spread of fire. These devices are fire rated but are generally not tested under significant positive pressure environments.

NFPA 80 Standard for Fire Doors and Other Opening Protectives. NFPA 80 [11] is a standard that regulates the installation and maintenance of assemblies and devices used to protect openings in walls, floors, and ceilings against the spread of fire and smoke within, into, or out of buildings. These assemblies and devices include doors, elevator hoistways, fire shutters, fire windows , fire dampers, and fire curtains. Where overpressures are minimal, these standards may be useful to prevent the spread of fire from HD 1.3 deflagrations.

NFPA 68 Standard on Explosion Prevention by Deflagration Venting. NFPA 68 [12] is a standard that applies to the design, location, installation, maintenance, and use of devices and systems that vent the combustion gases and pressures from a deflagration within an enclosure so that structural and mechanical damage is minimized. The requirements it prescribes to prevent structural failure of the enclosure due to internal overpressure are superseded by UFC 3-340-02 structural design criteria. However, standards on vent closure operation and the effects of vent discharge ducts and stacks are directly applicable to HD 1.3 deflagration events.

Use of NFPA Rated Non-Blast-Resistant Fire Protection Devices and Assemblies within Vestibules. Although the potential for thermal shock to impact the performance of non-blast-resistant fire rated assemblies and devices requires investigation, one possible way to allow for their use is by eliminating the gas overpressure effects of HD 1.3 events through the use of vestibules. These are antechambers, halls, or lobbies outside of rooms containing HD 1.3 systems. The rooms themselves would be designed to resist gas overpressures and prevent them from leaking into the vestibule space. This would require the use of blast doors between the room and vestibule. However, this type of floorplan would leave the vestibule to act strictly as a fire resistive barrier without having to resist any significant overpressures.

Conclusions

Current design criteria to protect personnel and property from the reaction effects of HD 1.3 systems are limited and simplistic. The reaction violence from HD 1.3 systems varies widely depending on the nature of the initiation stimulus, sample properties, and environment. Current simplified methods to predict the fireball and gas pressure effects may prove challenging to use in some design scenarios as they ignore many of these factors. Tools to predict these effects require significant development.

The design bases for protective construction are well served by process hazards analyses of the type recommended by NFPA 495. In general, structures designed to contain the effects of HD 1.3 systems should ensure low loading densities, adequate venting ratios, and be designed to resist conservatively calculated internal gas pressures. Non-containment structures benefit from generous venting, frangible surfaces, and don’t require heavy construction methods. Both types of structures must be designed to avoid choked flow conditions, and additional quantitative criteria on the occurrence of choked flow is of great value going forward.

NFPA fire ratings and provisions on preventing the spread of fire through penetrations and openings may be of benefit in providing protecting from HD 1.3 systems. However, two caveats should be noted: 1) although HD 1.3 deflagrations may result in comparable temperatures to standard NFPA temperature-time curves, their rise times may be substantially shorter, and so the effects of thermal shock on fire-rated components and devices requires investigation, and 2) non-blast-resistant fire rated components cannot be assumed to provide overpressure resistance, but the use of vestibules may provide an indirect way around this limitation.

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