Fire and Thermal Effects of HD 1.3 Accidents: History, Research, and Analysis

Jason Floyd and Craig Beyler
Hughes Associates, Inc.
3610 Commerce Dr. #817
Baltimore, MD 21227
410.737.8677 jfloyd@haifire.com

1.0 Introduction

The DoD 6055.9 Quantity-Distance requirements for Hazard Division 1.3 (HD 1.3) materials are based upon the total mass of materials present in a storage location[1]. The QD itself is determined using the cube root of the mass. This approach is reasonable when the hazard results from a very rapid event where the primary hazards are volumetric in nature (pressure, shock). Accidents of HD 1.3 materials can evolve over many minutes and depending upon the initiating event and storage methods used, may or may not have any potential to involve all material being stored in a location. Additionally as events that evolve slowly in time (as compared to a detonation) the primary hazards are not shock related, but rather thermal effects which scales over distance with a one-half power. A proper assessment of the hazards posed by a large component of HD 1.3 material, should reflect damage mechanisms and time scales associated with large quantities HD 1.3 materials. The authors propose an alternate approach to the simple QD relationships in DoD 6055.9 that involves determining credible failure mechanisms resulting in the ignition of HD 1.3 material, analyzing the progression of the accident in time, and finally determining the consequence of the event. Consequences of the event include casualties to personnel, damage to facilities, and interruption of facility activities or loss of mission capability.

This presentation will discuss approaches for modeling the burning of large HD 1.3 components, approaches for determining the time progression of an event, methods for assessing the risk to personnel (skin burns) and methods for assessing the likelihood of facility damage (impact of heat fluxes and high temperatures). The analysis of thermal/fire effects naturally divide into outdoor and interior effects. Outdoor or far field analysis scenarios are typified by the burn off of HD 1.3 materials in the open. Interior analysis scenarios are typified by the burning of HD 1.3 materials within land or sea based storage facilities.

2.0 Accident Scenarios

2.1 Interior Scenarios

Interior accident scenarios involve the burning of HD 1.3 materials in an enclosed space. Typical propellants burning at atmospheric pressures have flame temperatures ranging from 2000 K to greater than 3000 K. Those temperatures can result in structural damage by direct impingement or bulk heating and secondary ignitions of flammable materials (a significant threat on-board a ship where space boundaries are usually constructed of highly conductive materials). Additionally, if the boundaries are sufficiently air tight, the pressure rise due to the energy and mass flux from the propellant can increase enclosure pressure until failure occurs.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
JUL 2010	**N/A**	**-**

4. TITLE AND SUBTITLE	
Fire and Thermal Effects of HD 1.3 Accidents: History, Research, and Analysis	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Hughes Associates, Inc. 3610 Commerce Dr. #817 Baltimore, MD 21227**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002313. Department of Defense Explosives Safety Board Seminar (34th) held in Portland, Oregon on 13-15 July 2010, The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**33**	

Examples of the threat posed by burning propellant inside enclosures can be seen in the attack on the USS *Stark* and the weapons effects tests (WET) conducted for the HULVULL test series.

In 1987, the USS *Stark* was struck by two EXOCET missiles (ASM) while on maneuvers in the Persian Gulf. The first missile, which did not detonate, penetrated on the port side just below the main deck, spreading burning residual propellant in its wake. The second missile struck the ship and detonated just inside the shell. Secondary damage from the first missile exceeded that of the second missile and was attributed to residual propellant remaining in the ship in the case of the first missile but not in the case of the second (hypothesized that blast induced flows removed much of propellant and its associate heat release)[2].

In 1999 the HULVULL test series performed 25 tests propellant burns in simulated shipboard compartments[3]. Quantity and distribution of the propellant was varied along with the loading of additional fuels in the compartment. Results of the testing indicated that burning propellant could ignite other materials in an enclosure resulting in a post-flashover fire sustained beyond the burning time of the propellant.

2.2 Exterior Scenarios

Exterior scenarios result from the burning of large quantities of propellant in the open as might occur during a transportation accident or when an interior accident results in structural failure and allows the burning propellant to be visible from the exterior of the storage facility. There are two consequences for these scenarios: thermal injuries to people exposed to the radiant heat from the burning propellant and the ignition of secondary fires due to the radiant heat from the burning propellant.

3.0 Summary of Analysis Approach

3.1 Determine Maximum Credible Accident Scenarios

The first step in the alternative approach is to determine the maximum credible accident scenario. This is the accident scenario anticipated to have the worst consequences that has some likelihood of actually occurring. This requires performing a review of the types and quantities of propellants stored at a location, the processes occurring at that location (i.e. fabrication, storage, etc.), and how those processes might result in the inadvertent ignition of propellant. Scenarios must be credible. If, for example, the type of propellant being stored has been shown to survive drop tests from 50 ft and heights over 20 ft do not exist during storage or movement, postulating ignition due to dropped propellant would not be credible.

3.2 Evaluate Accident Progression

The second step in the alternative approach is to determine the accident progression. The time-dependent heat release of the initial propellant burn is determined. Heat fluxes and temperature rise from the burn is used to determine if additional propellant ignitions will occur. This process is continued until either all propellant becomes involved or the analysis shows the event terminates. The physical arrangement of propellant as well as its packaging should be included in this evaluation. It should be noted that packaging can result in delayed ignition of additional propellant. That is, the packaging may be successful in preventing the immediate ignition of nearby propellant, but carryover heating from elevated package temperatures could result in ignition at later points in time as heat is conducted to the interior of the packaging.

3.3 Evaluate Consequences

The final step in the alternative approach is to evaluate the consequences of the accident scenario. Internal accident scenarios should be evaluated for the ignition of secondary fires within the building and for structural failure due to high temperatures. External accident scenarios need to have the heat flux at a distance evaluated. The time dependent intensity of the heat flux can be used to determine the likelihood of damage to nearby buildings, ignition of combustible objects, and injury to personnel due to burns.

4.0 Methods of Analysis

4.1 Heat Release Rate

Once ignition of HD1.3 material occurs, there will be a rapid spread of burning over any exposed material. If the burning component is large, this spread time can be short in comparison to the length of time the component burns. Under these conditions, the time dependent burning rate can be computed by applying a constant burning rate to the exposed surface area. For example, if the component were a segment of a large motor, see Figure 1, the heat release rate would be given by the area of the two exposed ends and the area of the bore. As the motor segment burns, the bore will grow in size and the length will decrease. This results in the time dependent heat release rate of:

$$Q(t) = \left(2\pi h(t) r(t) + 2\pi\left(R^2 - r(t)^2\right)\right)\rho \Delta H_c$$
$$h(t) = h(0) - 2\dot{l}t; \quad r(t) = r(0) + \dot{l}t; \quad t_{max} = Min\left[\frac{H}{2\dot{l}}, \frac{R - r(0)}{\dot{l}}\right], \qquad (1)$$

where Q is the heat release rate, h is the instantaneous height, r is the instantaneous radius, R is the maximum radius, $\dot{l}$ is the regression rate, ρ is the material density, and ΔH_c is the heat of combustion.

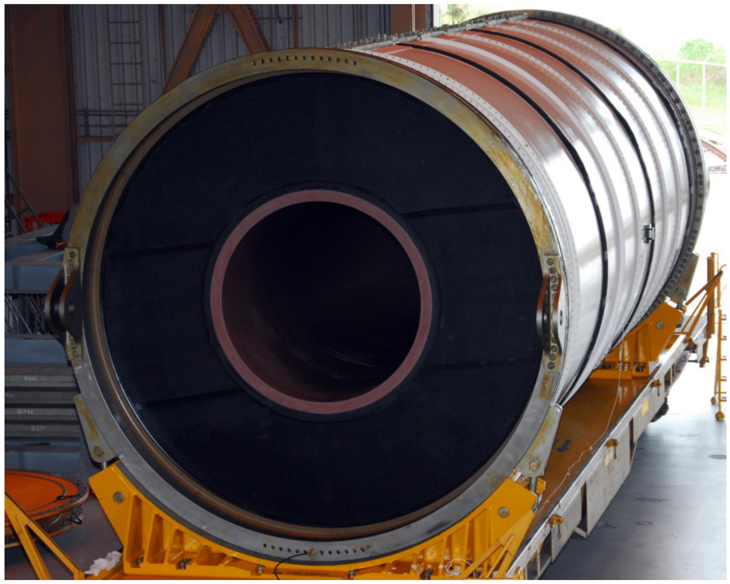

Figure 1: Segment of a large HD1.3 motor

If the accident scenario involves fragmenting of the initial component, this approach could be applied to each individual fragment.

4.2 Ignition of Other Components

In an HD 1.3 event the hazard to nearby components is thermal. Ignition will occur if the temperature of the target HD 1.3 material can be raised to a point where self-sustaining decomposition occurs. Thermal exposure can be via direct flame impingement or via radiative (from the flame and the aerosol cloud) and convective heating from the aerosol cloud. For a large component of HD 1.3 material exposing another large component, the material temperature can be evaluated by performing a 1D heat transfer computation (1D is appropriate as the spatial gradients of temperature and radiative flux for a large component will be small in comparison the heat transfer length scales of the component being exposed).

4.2.1 Determining Ignition Temperature

For propellant materials, existing data on ignition may only be available at high heat fluxes (> 100 kW/m^2), as typical ignition tests focus on the ignition for operational use rather than the ignition due to accidental heating. Additionally, typical testing involves exposing the material to a constant incident heat flux to determine the time to ignition. In an accident scenario with time varying heat flux, a fixed time to ignition would not be appropriate. While the flame temperature of burning propellant could easily result in heat fluxes of over 100 kW/m^2 to bare HD 1.3 material, if that material is within a motor casing, the effective heat flux reaching the material will be significantly lower. To determine an appropriate ignition temperature modeling of the ignition tests can be performed to estimate the surface temperature at ignition. Figure 2 below shows the results of using HEATING 7.3[4] (a Department of Energy heat transfer code), to simulate ignition testing of an AP propellant[5]. The results of these simulations extrapolated to lower heat fluxes suggest an ignition temperature of 260 °C for low heat flux ignition.

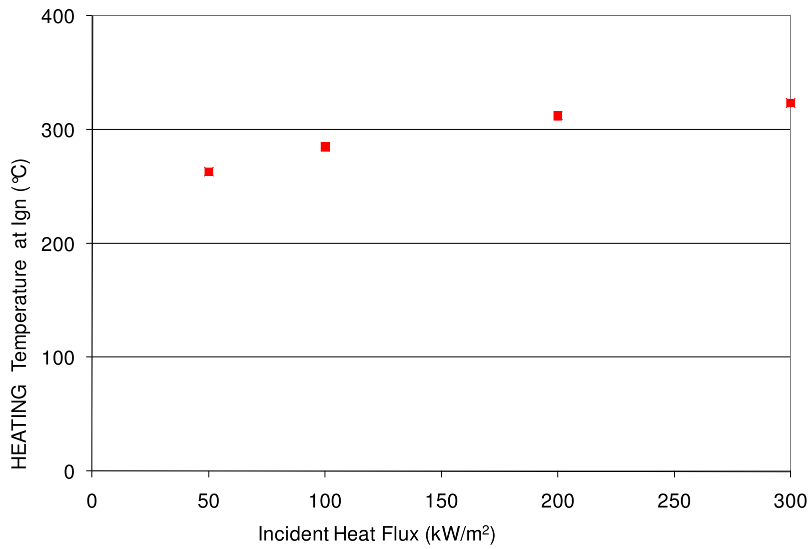

Figure 2: HEATING simulation of AP propellant ignition testing

4.2.2 Accounting for Case Materials

The target HD 1.3 material may not be bare material. In this case a heat transfer computation would need to be performed through a cross section of the casing receiving the actual exposure. As an example, a typical large motor will have an external case of steel, aluminum, or a composite material lined with one or more layers of protective material to keep the casing from being directly exposed to the burning propellant. In this case ignition can occur if enough heat is conducted through the case to cause the propellant reach its ignition temperature. It should be noted that this method of ignition can result in ignition of the target HD 1.3 material after burnout of the initial fire as there will be carry-over heating.

In a recent project the author's had performed cone calorimeter (a device for uniform radiant exposure of 10 cm x 10 cm samples) testing of a large motor mockup. The mockup consisted of a 1.3 cm thick steel plate (representing the external case), two layers of NBR rubber (representing case lining and ablative insulation), and a 2.5 cm thick piece of PMMA plastic (similar thermal properties to propellant). The mockup was exposed to incident heat fluxes of 25, 50, and 100 kW/m^2. The NBR layers will pyrolyze at elevated temperatures. In a real motor, those gases would be contained by the pressure tight case. The test sample was not pressure tight and to prevent ignition of the pyrolyzed NBR, a nitrogen co-flow was used to inter the test sample. The time to 260 °C at the interface of the NBR and PMMA was measured and the tests were simulated using HEATING. The NRB decomposition was not modeled (a process which is endothermic and results in the formation of a vapor layer that reduces heat transfer. Results are shown in Figure 3 below and demonstrate that this approach will conservatively predict a time to ignition.

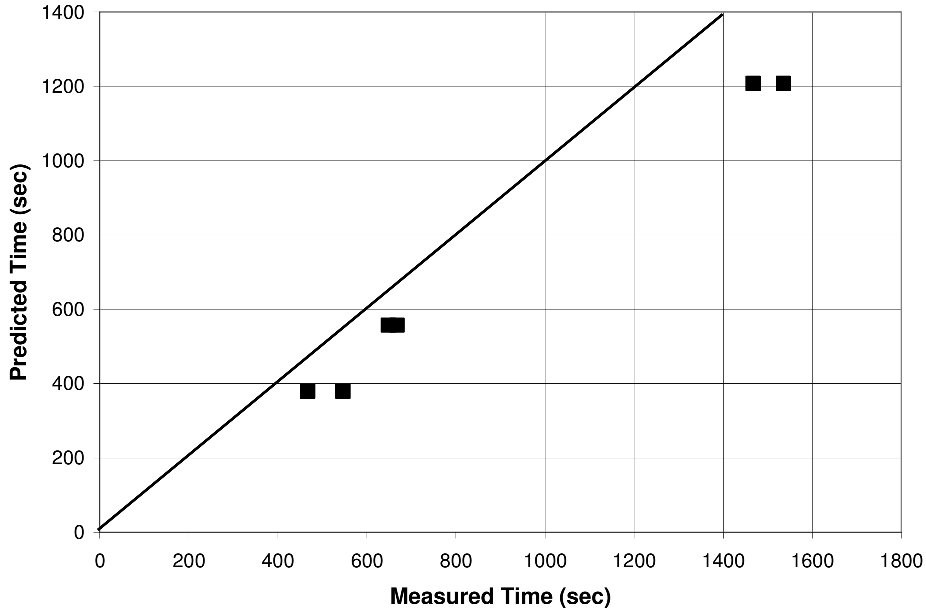

Figure 3: HEATING simulation of motor mockup radiant exposure testing.

5.0 Consequence Evaluation

5.1 Interior

Burning of large quantities of HD 1.3 material will result in a rapid rise of temperature and pressure within an enclosure. The high temperatures can result in the ignition of other material in the compartment or the ignition of materials in adjacent compartments either by heat conduction through the walls or by high temperature exhaust through openings to adjacent compartments. The rapid rise in pressure could result in the failure of doors, walls, and ceilings. Additionally, there could be direct flame impingement on structural members. For a given accident progression, the potential for direct flame impingement on structural members should be evaluated. This may require performing heat transfer analysis for exposed structural members and survivability assessment of structural fire protection given the high temperature and erosion potential of the HD 1.3 fire.

In addition to evaluating the impacts of direct flame impingement, the overall bulk heating and pressure rise of the storage area should be evaluated. Given the burning rate of HD 1.3 materials, it is likely that the flows induced by the burning material will result in well mixed conditions in the compartment of origin. Additionally, the aerosol production will result in a compartment that is optically thick for radiative heat transfer. This means that the use of CFD to evaluate the bulk temperature and pressure rise is not needed and that using a one-zone or two-zone fire model would be appropriate. The combination of the energy and mass release of burning propellant can result in quickly rising pressure in a compartment.

Figure 4 and Figure 5 show the result of using the Fire and Smoke Simulator (FSSIM)[6,7,8,9], a one-zone fire model developed for the Navy, to simulate the HULVUL test series. The test series burned 60 kg to 180 kg of propellant in a 108 m^3 space with a single vent to the outside.

The measured gas temperatures (> 500 °C) and heat fluxes (> 50 kW/m^2) could result in the rapid ignition of light weight combustibles and if sustained for a long enough period of time result in the failure of exposed steel structure.

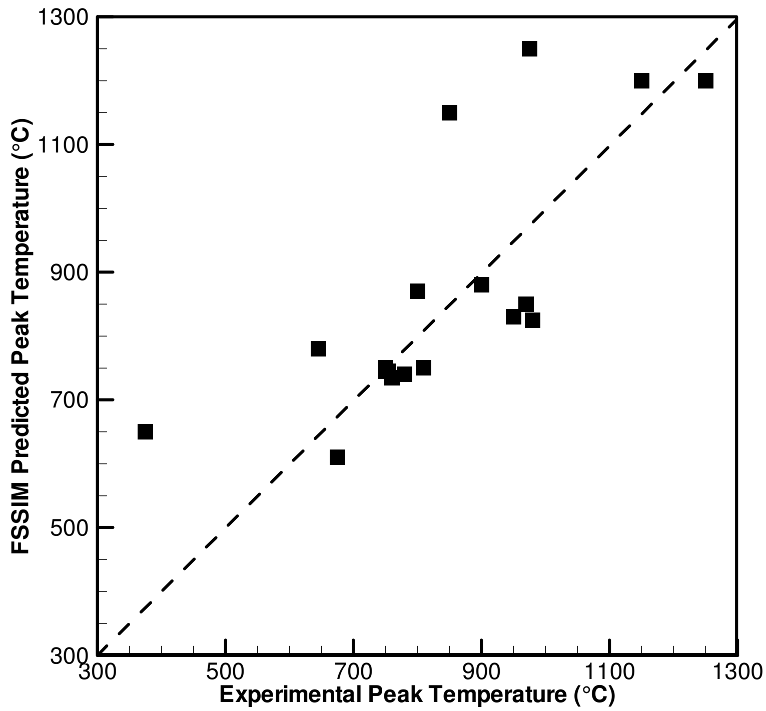

Figure 4: FSSIM vs. HULVUL peak temperature

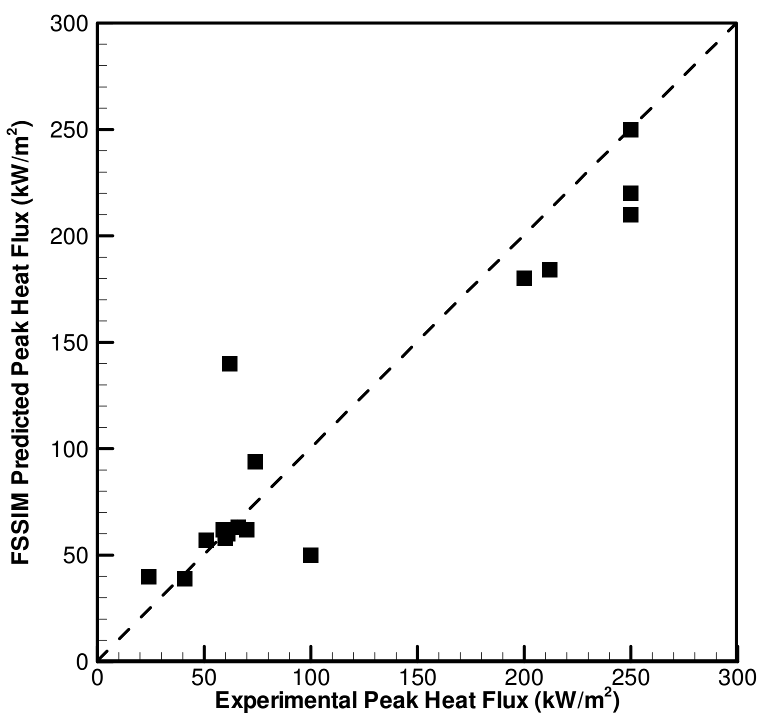

Figure 5: FSSIM vs. HULVUL peak heat flux

5.2 Exterior

For large HD 1.3 components burning in the open, as might occur during a handling accident or if there is major structural failure of a storage facility, the primary hazard is the heat flux at a distance. The specific configuration of the burning component along with ambient conditions can have a significant impact on the hazard. For example, if conditions allow for the formation of an aerosol shroud around the component (as might occur if structural collapse as covered the component in a debris pile), then the cooler and optically thick shroud will act to prevent direct line of sight to the high temperature flame. The shape of the component can also impact the heat flux at a distance. Fragmentation of the component can result in faster burn rates (more exposed surface area). Ignition of a component such as the segment shown in Figure 1 would result in the formation of two jets which would result in an asymmetric pattern of heat flux at a distance. External wind conditions will also affect the plume of combustion products and result in reduced shrouding of the flame. Accounting for these asymmetries suggests the use of a CFD model. Figure 6 shows the predicted heat flux to the ground plane caused by burning a cylinder of propellant as shown in Figure 1, the predictions were made by Fire Dynamics Simulator[10,11] (a CFD fire model).

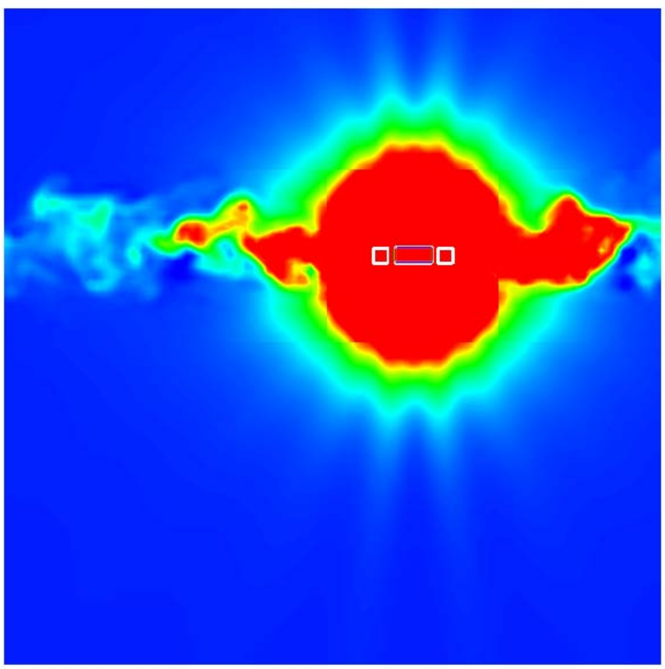

Figure 6: FDS simulation showing jet formation due to burning of a large HD 1.3 component

5.3 Modeling Skin Burns

5.3.1 Model Description

Skin consists of three layers: the epidermis, the dermis, and the subcutaneous tissue, see Figure 7. The epidermis contains no blood vessels. Skin burns are defined based on the level of damage to the skin layers. Skin burns can be modeled by performing a heat conduction analysis of the three skin layers, including the heat removal ability of blood, and using the temperature profiles that result to determine the burn level.

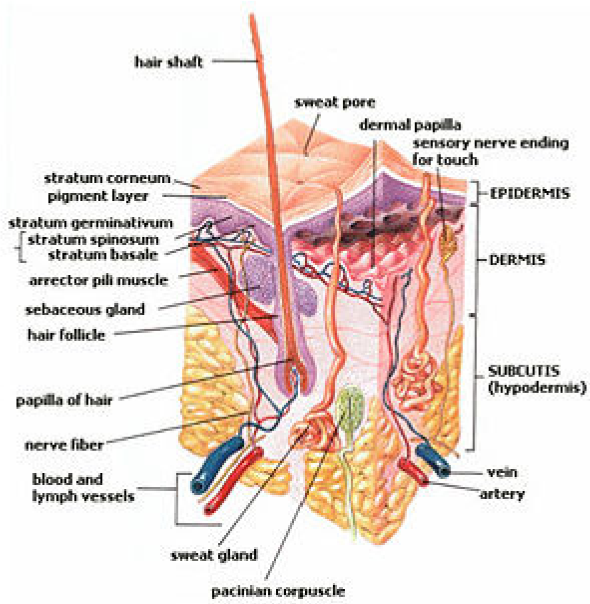

Figure 7: Cross-sectional view of skin

The one dimensional heat conduction equation with blood profusion takes the following form:

$$\rho c \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2} - c_b \rho_b G (T - T_b) \tag{2}$$

Where ρ is the skin density, c is the heat capacity, T is the local skin temperature, k is the skin thermal conductivity, x is the depth below the skin surface, c_b is the blood heat capacity, ρ_b is the blood density, G is the blood profusion rate, and T_b is the blood temperature (taken to be the bulk body temperature). An existing 1D, Crank-Nicolson, heat transfer solver (the solver from FSSIM), was modified to add the perfusion term. When provided with an incident heat flux and thermal properties for the skin, the solver will compute the time dependent temperature profile through the skin. Skin thermal properties from Metha and Wong[12], see Table 1, were used in the analysis.

Table 1: Properties of skin tissues and blood

Property	Epidermis	Dermis	Subcutaneous Tissue	Blood
Thickness (m)	8 X 10^{-5}	2 X 10^{-3}	1 X 10^{-2}	--
Initial Temp. (C)	37*	37*	37*	37
Thermal Conductivity (J/(m·s·K))	2.09 X 10^{-1}	3.69 X 10^{-1}	1.60 X 10^{-1}	--
Heat Capacity	3.60 X 10^{3}	3.22 X 10^{3}	2.30 X 10^{3}	3.77 X 10^{3}

(J/kg·K)				
Density (kg/m^3)	1.2 X 10^3	1.2 X 10^3	1.2 X 10^3	1.06 X 10^3
Blood Profusion Rate (m^3/(s·m^3))	0.0	1.25 X 10^{-3}	1.25 X 10^{-3}	--

* A null transient using these initial values plus the assumed ambient conditions is performed to establish the initial temperature profile in the skin.,

Thermal damage is calculated using the damage integral method originally developed through the work of Mortiz and Henriques[13,14,15,16,17]which models damage as a zero order Arrhenius reaction where the constants are selected so that the integrated damage reaches a value of one at when the skin is irreversibly damaged.

$$\Omega(t) = P\int_0^t \exp\left(-\frac{E}{RT}\right)dt \qquad (3)$$

where Ω is the skin damage variable, *P* is the pre-exponential of the Arrhenius damage kinetics, *E* is the activation energy for damage, *R* is the universal gas constant, and *T* is the absolute skin temperature. Following historical practice integration of damage is accrued at temperatures above 44 °C during both the heating and cooling phases of the exposure. Kinetic constants were taken from the work of Mehta and Wong[12] based upon their reanalysis of the original data of Henriques (P=1.43 x 10^{72} s^{-1}, E= 4.61 x 10^5 J/mol). Damage can be calculated at any depth within the skin, but the typical locations are the front and rear surface of the dermis. Damage at the front surface of the dermis corresponds to the onset of second degree burns, and damage at the rear surface of the dermis corresponds to third degree burn. Pain occurs when the skin temperature at nerve endings at the surface of the dermis reach 44 °C. Skin damage thresholds and the criteria are summarized in Table 2. These values are consistent with SFPE Guide on predicting burns[18], though SFPE did not include third degree burns.

Table 2: Skin damage thresholds

Damage Threshold	Criterion
Pain	44 °C at front surface of dermis
1st Degree Burn	Ω=0.53 at front surface of dermis
2nd Degree Burn	Ω=1.0 at front surface of dermis
3rd Degree Burn	Ω=1.0 at rear surface of dermis

5.3.2 Validation

The core heat transfer solver was extracted directly from FSSIM and has already undergone verification and validation. The skin burn model was tested with two sets of test cases. The first set simulated experiments performed by Derksen[19] in which rats were exposed to constant heat fluxes of varying durations with the surface skin temperature measured. The second set of test cases compares predictions of burn level for constant heat fluxes against the correlations for burn level in the SFPE guide.

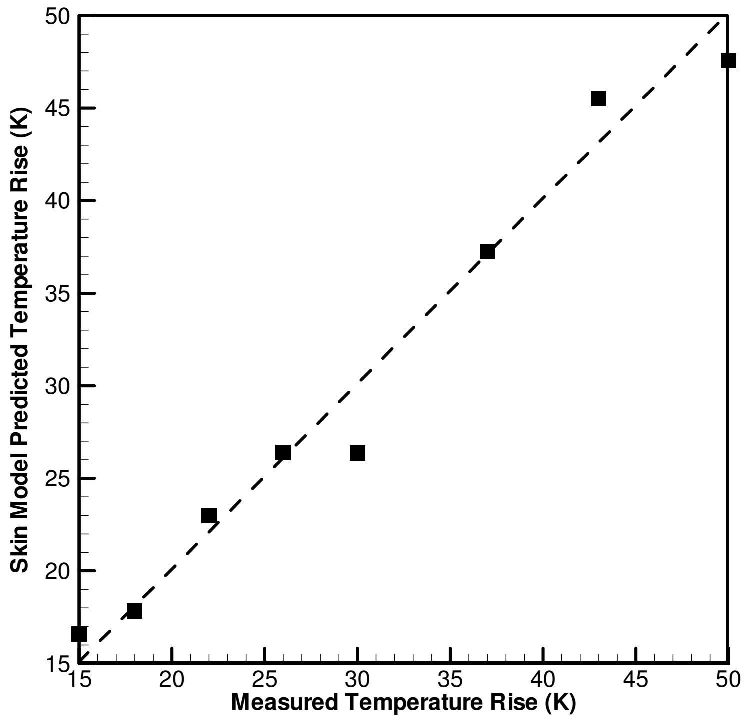

Figure 8: Skin model vs. experimental skin surface temperature rise[19]

Figure 8 shows the predicted vs. measured results for the skin surface temperature rise. As seen the model prediction correlate very well with the measured data. This indicates both that the material properties are reasonable and that the addition of the blood perfusion term did not adversely affect the solver. Figure 9 shows times to various burn level as a function of incident heat flux. Pain, 1st, 2nd, and 3rd degree times are shown for the skin burn model and times to 1st and 2nd degree burns are shown using SFPE recommended correlations. Note that these times do not include the safety factor. There is generally a good agreement between the times to 1st and 2nd degree burns based on the SFPE correlations and the predictions of the skin burn model. Since the correlations represent a fit to a number of datasets and the predictions represent one set of initial conditions and thermophysical properties some difference are expected.

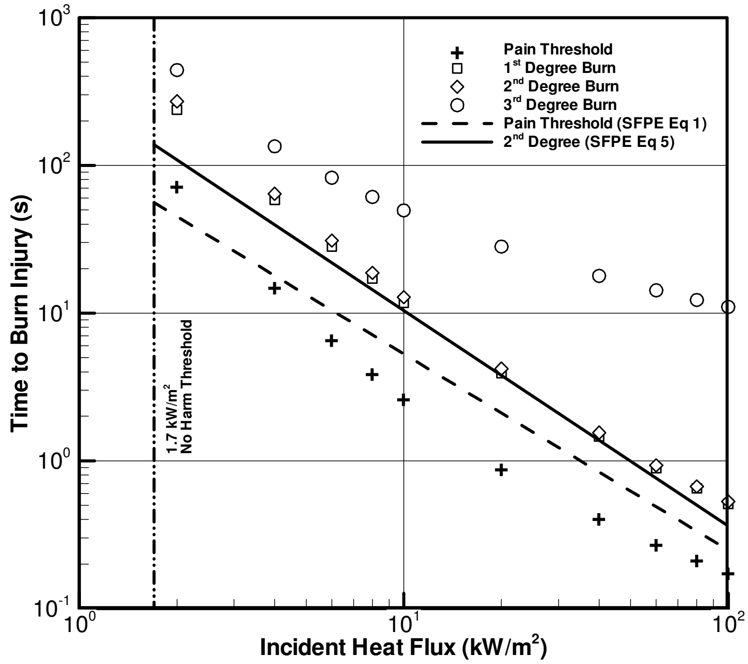

Figure 9: Skin model burn times vs. SFPE correlations for burn times

Since there are a number of uncertainties in skin burn modeling, the SFPE guide recommends a 50 % safety factor be applied.

5.3.3 Use of Model

The skin burn model can be provided with a time and space dependent radiant exposure (such as the output depicted in Figure 6. This exposure should be the sum of both radiant heat from the fire plus radiant heat from any other sources such as the sun (insolation in the southern United States during the summer is close to 1 kW/m^2). A simple analysis approach would be to take the time dependent heat flux as a function of position determined in 5.2 and use it as the input to the skin burn model. A higher lever analysis could presume a person would move away from the fire. Either method will result in the generation of contours of expected burn level as function of the initial position of a person. This result is depicted in Figure 10. In this figure,

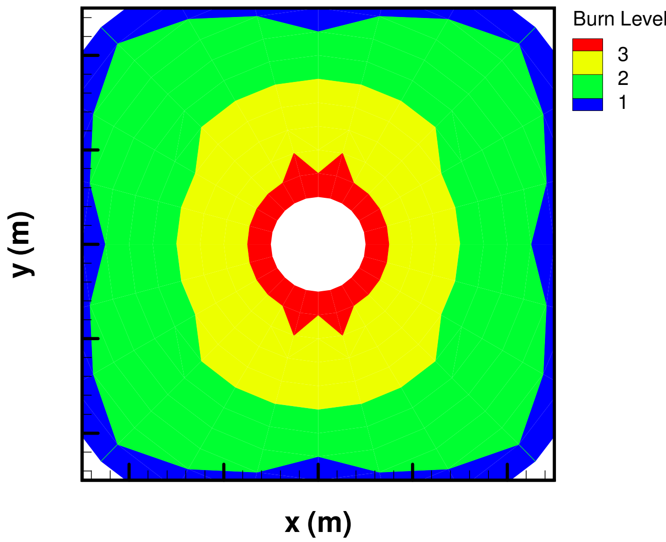

Figure 10: Skin model burn contours for a large component burn in the open

A safe separation distance for personnel can be determined once a tolerable burn level is established. In general, the expectation is that events involving the inadvertent ignition of HD 1.3 materials are rare. As a rare event, for persons not intimately involved in the process that resulted in ignition (i.e. person's whose duties require them to be in close proximity to the material), a typical criterion for acceptable consequence is avoidance of death or permanent injury. Burning of a large quantity of HD 1.3 material, in the absence of shielding, will result in a one-half body exposure. 2^{nd} or 3^{rd} degree burns to large fractions of the body carry a significant risk of death or permanent scarring and, thus, should be avoided. The appropriate criterion, therefore, is avoidance of 2^{nd} degree burns. Large area 1^{st} degree burns will be painful, but would not be expected to result in permanent injury or death. In Figure 10 above, this would be the edge separating the green (1^{st} degree) from the yellow (2^{nd} degree).

6.0 Summary

Currently HD 1.3 hazards are evaluated using a total mass based approach using the QD correlation in DoD 6055.9. This approach presumes a short duration event that consumes the total mass. Depending upon the specific HD 1.3 components and the details of their storage, for very large quantities events may not be short duration and not all mass may be involved. The impact of thermal hazards does not scale in a simple manner with either duration or total mass. Instead, it is proposed to perform an engineering assessment of the hazards and consequences. The steps of this process are identifying accident scenarios, evaluating how those scenarios evolve over time, and finally evaluating the consequences of those time-based scenarios.

Evaluating the evolution of an accident requires determination of burning rates and the spread of fire to other HD 1.3 material. Examples were provided on how to model the burning of large components and how to assess the potential for ignition of other components present in the storage location.

Consequence evaluation includes impacts both on buildings and equipment and on personnel. The potential for collapse or other structure failure should be evaluated for the storage location.

This can be done using low fidelity models given the large mixing that a burning component will cause. External to the storage location, the heat flux at a distance should be evaluated. In most cases it would be appropriate to use a CFD model for this. High heat fluxes can result in the spread of fire to nearby buildings or equipment. Low heat fluxes over longer durations (minutes) can result in fatal burns to exposed personnel at large distances.

Skin burns can be evaluated by computing the time dependent temperature of exposed skin. Doing this a function of position around the storage location will yield a contour map of skin burn level. Establishing an exclusion area to avoid 2nd degree burns will avoid permanent harm to personnel.

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Fire and Thermal Effects of HD 1.3 Accidents: History Research, and Analysis

Jason Floyd and Craig Beyler
Hughes Associates, Inc.

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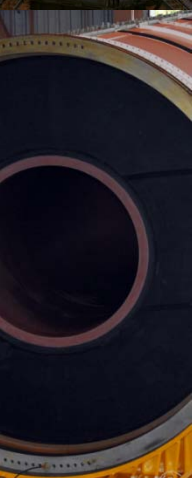
2010 DDESB Seminar

July 13 – 15, Portland


DoD 6055.9 & HD 1.3

- For very large quantities of HD 1.3 QD = C $W^{1/3}$
  - Presumes a rapid reaction
  - Presumes all material present will be involved
- Large components may react over minutes vs. seconds
- HD 1.3 primary hazard at a distance is thermal not shock like HD 1.1. Thermal does not scale as $W^{1/3}$.
- Storage configuration may prevent all material from reacting

DoD 6055.09-STD

DOD AMMUNITION AND EXPLOSIVES SAFETY STANDARDS

Incorporating Change 2, August 21, 2009

February 29, 2008

OFFICE OF THE DEPUTY UNDER SECRETARY OF DEFENSE
(INSTALLATIONS AND ENVIRONMENT)

Alternative Approach

- Hazards assessment and consequence determination
  - Identify credible initiating events
  - Determine the time progression of the accident
  - Evaluate the consequences
    - Damage to facilities
    - Loss of mission capability
    - Personnel casualties

Interior Accident Scenarios

USS *Stark*

- HD 1.3 materials burn from 2000 K to > 3000 K
  - Structural damage
  - Secondary ignitions
- Produce large quantities of gas
  - Over pressure induced failure of enclosure walls or doors
  - Rapid mixing

Exterior Accident Scenarios

- Transportation accident
- Collapse of storage structure
- Radiant heat hazard
  - Secondary ignitions
  - Burn injuries

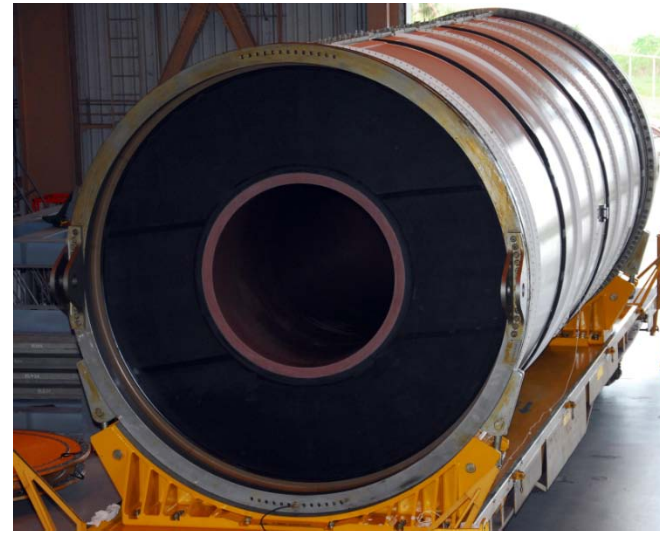
Booster test (Alliant)

Analysis Process

- Step 1: Determine credible events
  - Types of components, sources of ignition
- Step 2: Progression of accident
  - Burning rates and heat release
  - Spread to additional HD 1.3 material
- Step 3: Consequences
  - Structural damage
  - Fire spread to other compartments, buildings, and objects
  - Injuries to personnel

Heat Release Rate

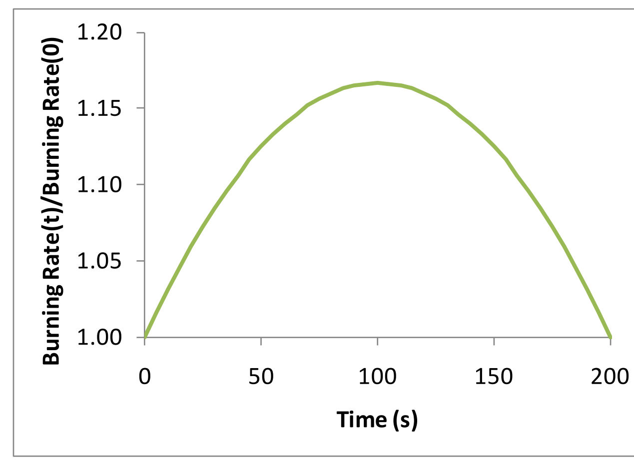
- Approximate as a constant regression rate over the exposed surface area



$$Q(t) = \left(2\pi h(t) r(t) + 2\pi\left(R^2 - r(t)^2\right)\right)\rho \Delta H_c$$

$$h(t) = h(0) - 2\dot{l}t; \quad r(t) = r(0) + \dot{l}t; \quad t_{max} = Min\left[\frac{H}{2\dot{l}}, \frac{R - r(0)}{\dot{l}}\right]$$

- 5 m length
- 3 m diameter w/ 1 m bore
- 5 mm/s regression rate



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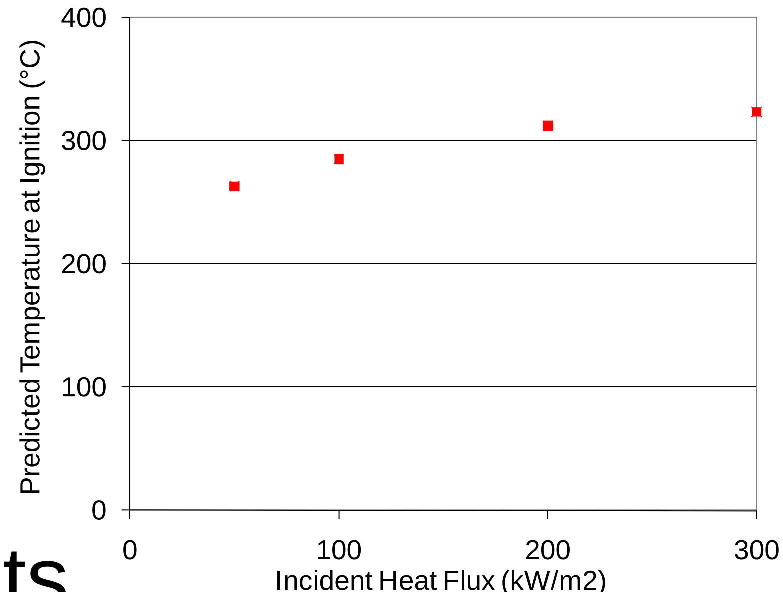
Ignition of Other Components

- Typical ignition testing
  - performed for operational use rather than accidents (> 100 kW/m^2)
  - Uses a constant heat flux
- Typical thermal insult from an accident
  - May be low (<< 100 kW/m^2) either due to protection from packaging or due to separation (no flame impingement)
  - May not be constant over time
- Modeling non-uniform, low heat flux insults is a heat transfer (HT) problem. HT models compute temperature

Determining Ignition Temperature

- HEATING 7.3 simulation of AP propellant ignition testing
- Extrapolation suggests an ignition temperature of 260 °C



(Lengelle, et al. 1991)

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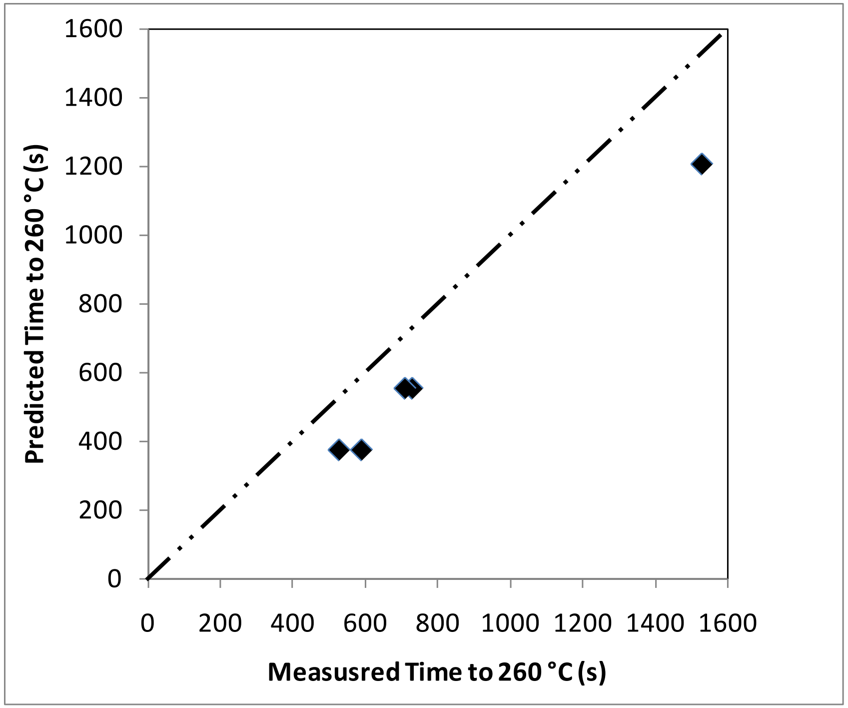
Accounting for Packaging

- Testing of a mockup of a large HD 1.3 component
  - Cone calorimeter (uniform radiant flux over 10 cm x 10 cm sample)
  - 1.3 cm steel plate, 2 layers of NBR rubber, 2.5 cm PMMA
  - Nitrogen co-flow to prevent ignition of NBR layers
- 1D HEATING for prediction



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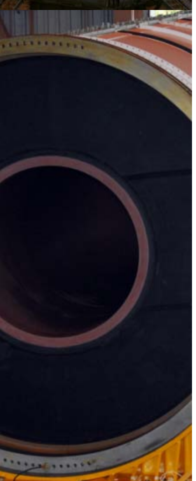
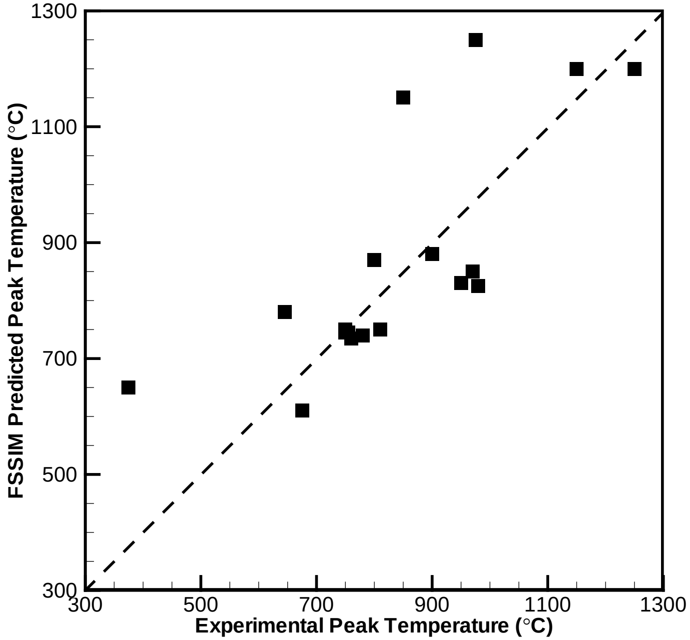



Interior Consequences

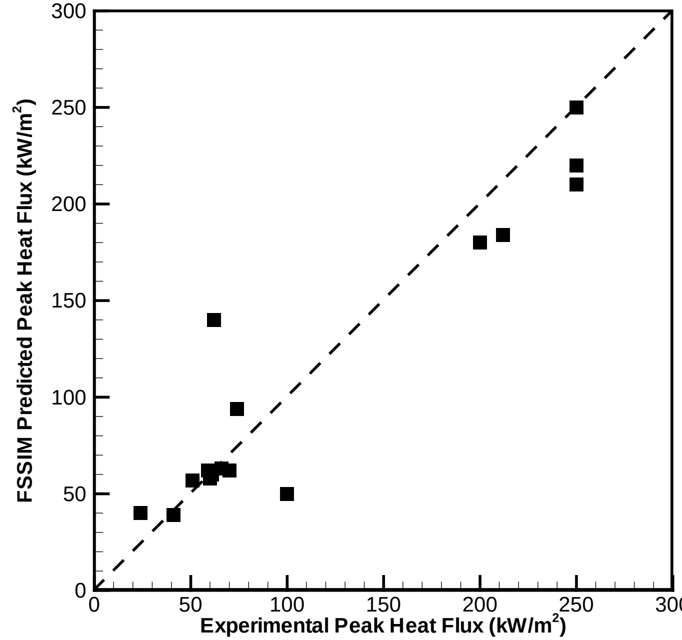
- Propellant will induce mixing
  - Result in well mixed spaces
  - Aerosols will result in optically thick conditions
  - May be able to use low fidelity (zone) models instead of CFD
- Potential for long duration, high temperature exposure of structure
- Flame impingement on structure and walls
- Pressurization of compartment

FSSIM Simulation of HULVUL

Peak Temperature



Peak Heat Flux



- Fire and Smoke Simulator (FSSIM) – 1 zone fire model developed for the Navy
- HULVUL – 60 kg to 180 kg of propellant in a 108 m^3 space

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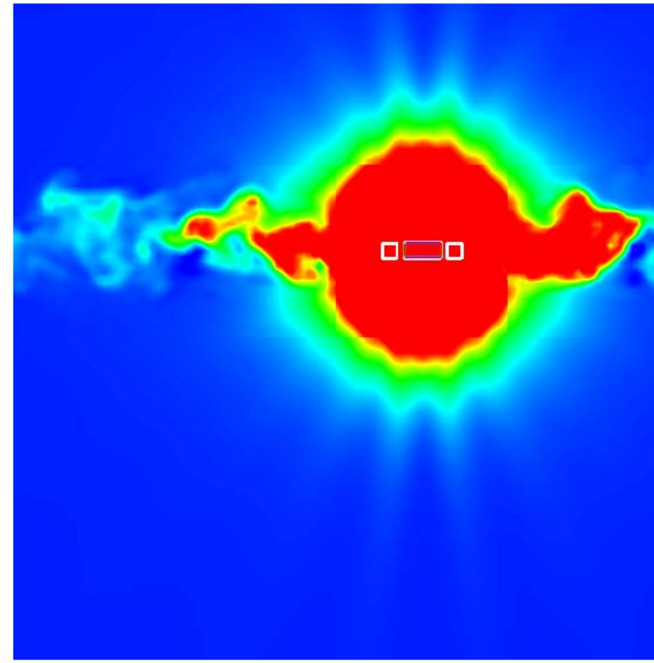
Exterior Consequences

- Component shape may result in non-isotropic radiant emissions
- Rubble piles from collapsed structure or shroud of cooler aerosols may limit direct line of site to the high temperature flame
- Wind will change exposure
- CFD may be the appropriate tool



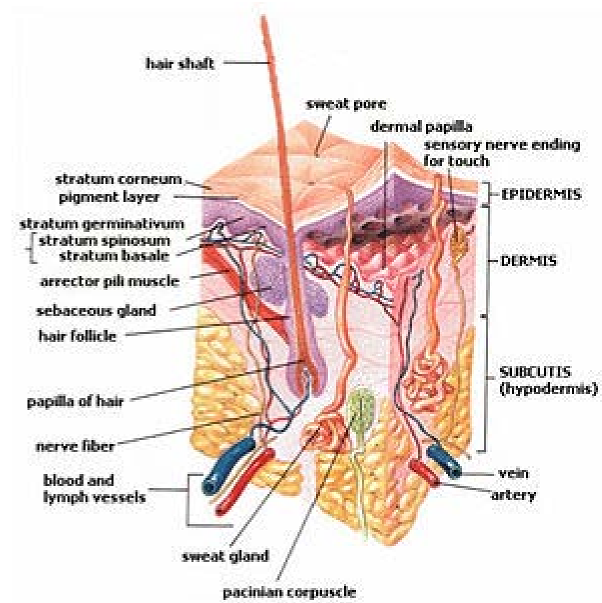
Fire Dynamics Simulator - Heat flux to the ground from a burning motor segment

Skin Burns

- Burns occur when the dermis is damaged due to elevated temperature
- Model skin temperature with 1D heat transfer that includes the effect of blood perfusion

$$\rho c \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2} - c_b \rho_b G (T - T_b)$$

Property	Epidermis	Dermis	Subcutaneous Tissue	Blood
Thickness (m)	8 X 10^{-5}	2 X 10^{-3}	1 X 10^{-2}	--
Initial Temp. (C)	37*	37*	37*	37
Thermal Conductivity (J/(m·s·K))	2.09 X 10^{-1}	3.69 X 10^{-1}	1.60 X 10^{-1}	--
Heat Capacity (J/kg·K)	3.60 X 10^{3}	3.22 X 10^{3}	2.30 X 10^{3}	3.77 X 10^{3}
Density (kg/m^3)	1.2 X 10^{3}	1.2 X 10^{3}	1.2 X 10^{3}	1.06 X 10^{3}
Blood Profusion Rate (m^3/(s·m^3))	0.0	1.25 X 10^{-3}	1.25 X 10^{-3}	--



Skin Burns

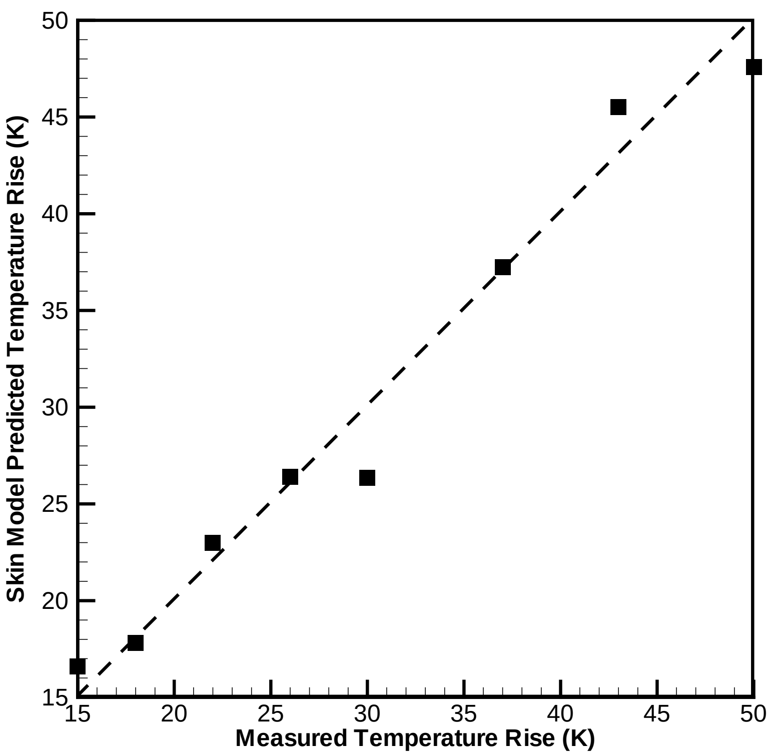
- Burns a result of accumulated damage to cells once temperatures are high enough to cause protein denaturing
- Model as an Arrhenius reaction called a Damage Integral

$$\Omega(t) = P\int_0^t \exp\left(-\frac{E}{RT}\right)dt$$

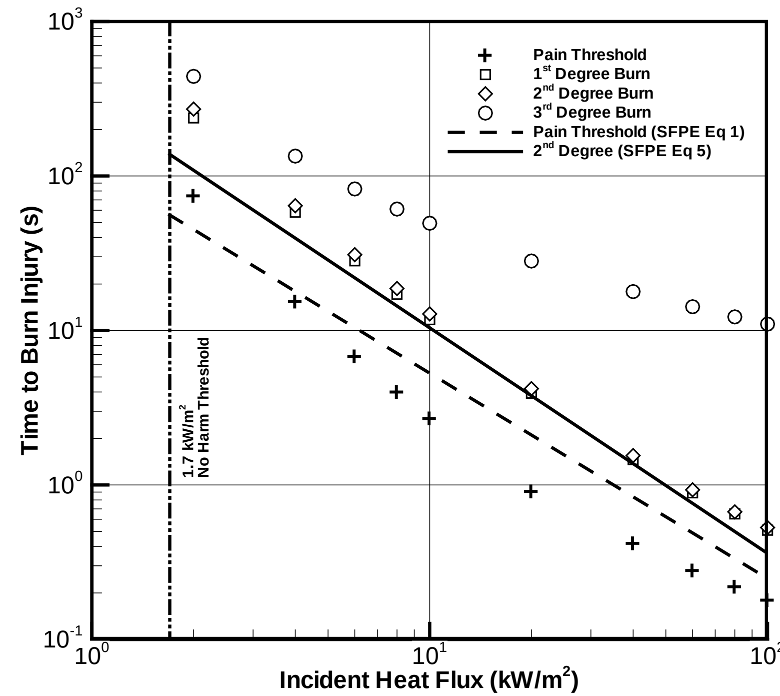
Damage Threshold	Criterion
Pain	44 °C at front surface of dermis
1st Degree Burn	Ω=0.53 at front surface of dermis
2nd Degree Burn	Ω=1.0 at front surface of dermis
3rd Degree Burn	Ω=1.0 at rear surface of dermis

Skin Burns

Skin Temperature of Rats Exposed to Constant Heat Flux



Model Predictions vs. SFPE Burn Guide



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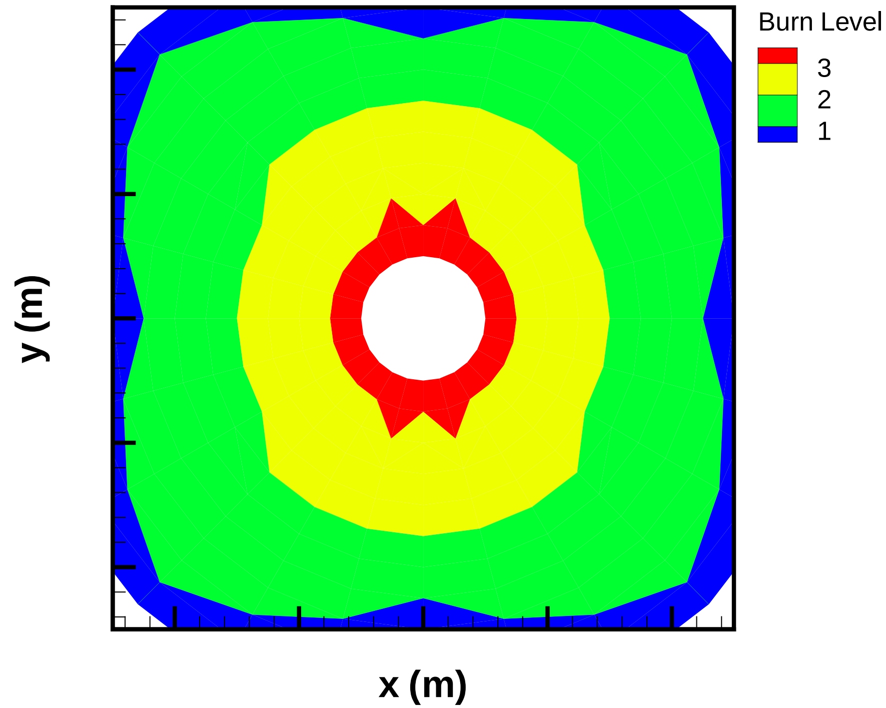
Use of Model

- Use time + space dependent heat flux to generate mapping of burn likelihood
- Account for the sun (as much as 1 kW/m^2)
- Avoid permanent injury
  - Pain is tolerable
  - Large components will result in whole body exposure. Large area 2nd degree burns can be fatal
  - Set safe distance at avoiding 2nd degree



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Summary

- Large HD 1.3 components may not be well characterized by the simple QD rule
- An engineering assessment of credible events can be used instead to establish safe separation distances for buildings and personnel.

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