PERSONNEL PROTECTION AGAINST HEAT EXPOSURE FROM A DEFLAGRATION VIA A RAPID ONE-TIME SURFACE WETTING*

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BACKGROUND

Personnel protection from heat exposure is one of the benefits of the commercial water-based explosion protection systems. A system can be designed to take advantage of all or few of these four mechanisms.

1. Arresting flame propagation completely or partially (thus reducing the size of the hot gas cloud)
2. Cooling the hot gas cloud (thus reducing the radiative heat emission)
3. Generating a water mist and steam cloud that blocks the transmission of radiative energy
4. Wetting the exposed surfaces with a protective water film

Earlier tests reported by Senecal et al. [1] provide dramatic evidence of the protection system bcncfits for an accident scenario initiated by the rupture of a singlc fuel can containing 90 grams of propane. High-speed movies of the tests show that the suppression system knocked down the fireball rapidly.

To evaluate the feasibility of a system design as a local application. a simplified analysis has been performed by ignoring the first three mechanisms and focusing only on the last mechanism. Furthermore. the simplifying assumptions of the analysis are selected to make the results err on the conservative side.

SIMPLIFIED ANALYSIS

This simplified analysis considers the three elements discussed in the following pages.

1. Thermal Assault Created by Fire and Explosions

Thermal assault has convective and radiative components. At the high temperatures typical ot fires and explosions, radiative heat tlux is generally much larger than the convective heat tlux. The radiative heat tlux can he calculated using the equation:

$$q'' = \sigma \quad \varepsilon \quad T^4$$

where:

σ : Stefan-Boltzman constant (5.67×10^{-11} kW/m^2K^4)
ε : Emissivity of the hot gas cloud
T : absolute temperature of the hot gas cloud

The hot gas cloud is assumed to be very close to the target so that the view factor is taken to he unity. If the hot gas cloud is sooty and has a sufficiently large optical path length, then the emissivity will also tend to unity. The maximum fire (turbulent diffusion flame) temperature is typically 1000°C so that the maximum radiant heat flux is 150 to 175 kW/m^2. Fires continue burning for hundreds of seconds. Since the gas or vapor explosions hum as premixed flames, significantly higher temperatures are produced. For example, the maximum premixed flame temperature of propane/air is 1925 "C, which can conceivably produce a radiant heat flux of up to 1300 kW/m^2. Explosions occur typically within a fraction of a second and the burned gases cool down rapidly because of the low thermal inertia of the burned gas compared to any solid or liquid surfaces surrounding it (see DISCUSSION below). Thus, it is seen that the maximum heat flux that can be created by an explosion is several times larger than that can be created by a fire. The levels of the maximum radiant heat flux that can be created by fires or explosions are designated on Figures 1 and 2.

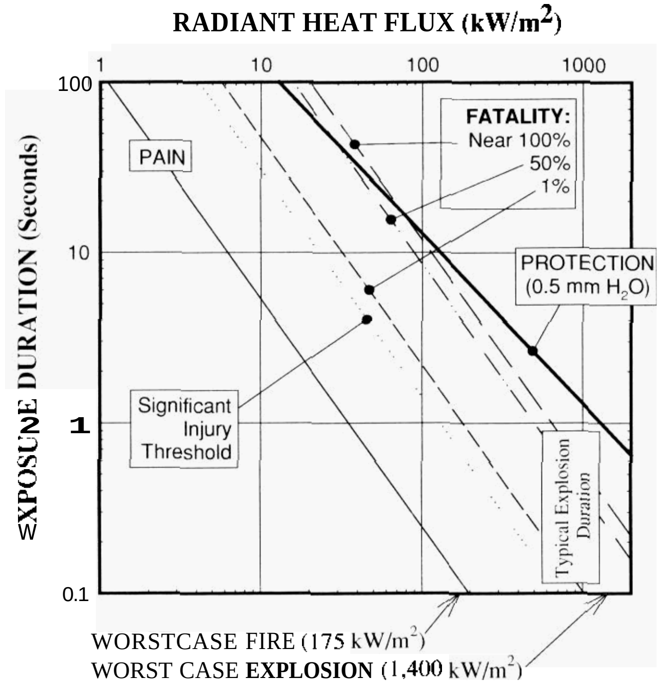

Figure 1. Allowable exposure duration as a function of radiant heat flux.

2. Physiological Response

Two different types of vulnerability criteria for human skin are summarized in Reference 2. The first type of criteria was developed from an analysis of "the data on the relation between thermal radiation intensity and bum injury for nuclear explosions at different yields." These correlations, re-plotted in Figure 1, show that allowable exposure duration for a fixed physiological effect decreases with increasing incident heat flux. (For a prescribed injury level, allowable exposure duration is seen to be inversely proportional to the 4/3 power of the incident heat flux.)

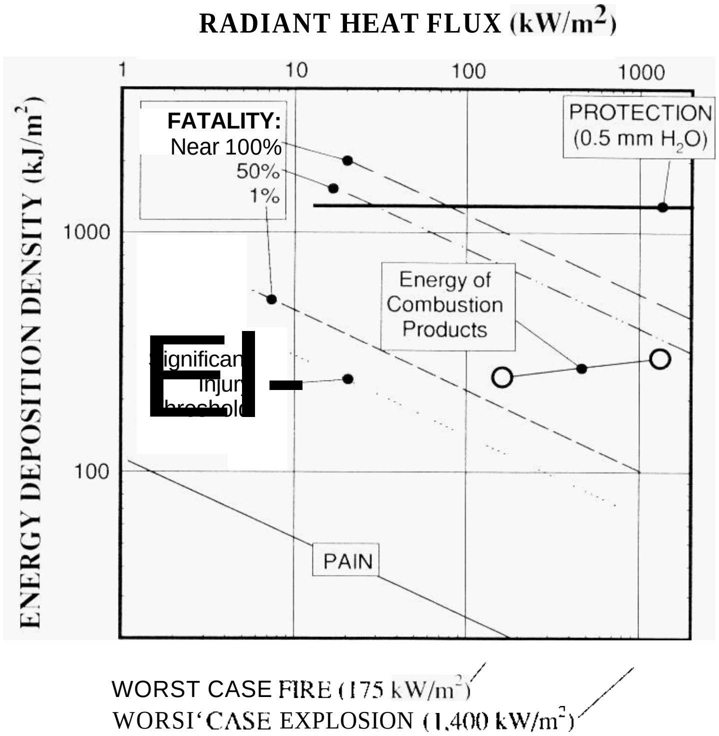

Figure 2. Allowable energy deposition as a function of radiant heat **flux.**

The second type vulnerability criteria (see PREDICTIONS. . . below) is called the "critical energy model" in Reference 2. According to this model, the severity of the burn injury is related to the amount of heat absorbed after the skin surface temperature exceeds *55* °C. The reported critical energy levels are listed in Table I.

TABLE I. CRITICAL ENERGY LEVELS,

Energy absorbed (after *55* °C) per unit surface (kJ/m^2)	EFFECT
Greater than 41.8	Pain, mild second degree burn
Greater than 83.6	Blister, severe second degree burn
Greater than 162.2	Severe third degree burns, permanent injury

3. Protection by a Water Film

In the framework of the simplified analysis presented here, the wetting protection is considered as a 200 to 500 micrometers (0.2 to *0.5* mm) thick layer of water over the exposed skin. Spatial details of the radiant heat absorption across the water and skin layers arc not considered. Instead, the radiation is assumed to be absorbed [1] either at the free surface of the water, or at the skin surface (see PREDICTIONS. . . below). Absorption of the incident radiation by the water vapor (evaporated from exposed surfaces or from discharged droplets) is not considered.

The thermal diffusivity of the water is

$$a = 0.15 \text{ mm}^2/\text{s}$$

If the heat absorbtion occurs at the free surface of the water film, the penetration depth, *6.* of a heat wave over a time period t can be approximated by the equation:

6 = ***(6*** at)”

Calculations show that the penetration depth is the same order of magnitude as the protecting water layer thickness for the typical duration of explosions. Within the framework of assumptions outlined above, the surface temperature of the water layer will increase as the heat wave penetrates and evaporation will begin at the surface. At high incident heat fluxes, the surface temperature of the layer will approach the boiling temperature. Thus. the duration of protection can be estimated from the equation:

$$t_{prot} = \delta_{layer}\, \rho_w\, \Delta H_{vap} / q''$$

where

t_{prot}: protection duration
δ_{layer}: protecting layer thickness
ρ_w: density of water
ΔH_{vap}: enthalpy of vaporization per unit mass
q”: heat flux incident on the layer surface

The duration of protection provided by a 0.5 mm thick water film is calculated using this equation and is also shown in Figure 1. The protection is seen to survive the duration of typical explosions, even at the maximum conceivable heat flux levels.

DISCUSSION

The simplified analysis presented above is based on a number of assumptions. Two of these assumptions make the analysis extremely conservative. First, unmitigated flame temperature was used to express the magnitude of the thermal assault. In reality, a water-based explosion suppression system is expected to reduce the extent of the hot gas cloud and hot gas temperature significantly while also reducing the heat transmission, even in the case of a localized protection.

The second highly conservative assumption is the maintenance of a constant radiant heat flux during the entire exposure period. This is an appropriate assumption for fires since the heat loss is continually replenished by burning of additional fuel. However, in a confined premixed gas explosion, the total amount of fuel, and therefore the total energy that can be released, is fixed. In a vented explosion, energy released inside the room is smaller than the total available chemical energy as some of the unburned and burned hot gases are ejected outside. Afterwards, some amount of gas will be sucked in to keep the pressure near atmospheric, as the gas inside the room cools down. Theoretically, re-admitted gas can be ambient air, hot burned combustion products, or the mixture of the two. The assumption of ambient air admission is more reasonable since the hot gases are ejected at a relatively high velocity during the course of the explosion.

If the maximum energy available in the room is divided by the total exposed surface area, an average value for the "energy deposition density" is obtained. Obviously, the energy deposition density will bound the time integral of the average incident heat flux. Average energy deposition density is proportional to the volume to surface ratio of the enclosure. The effect of the flame temperature is of the second order. since the first order contributions due to higher stored energy arc partially offset by the reduced gas mass at elevated temperature (low reduced pressure).

Examples have been worked out for a vented but otherwise unprotected room explosion scenario. For typical dimensions of 15 by 20 by 12 ft high, the room has 102 m^3 volume and the minimum exposed surface urea (excluding equipment and personnel) is 134 m^2. The complete combustion products of the stoichiometric propane air mixture are considered (i.e., 11.6% CO_2 + 15.5% H_2O + 72.9% N_2).

If this mixturc is assumed to be initially at 2200 K and cooled down to 300 **K,** the total amount ot heat liberated (ignoring condensation) is 71,026 kJ/kmole. The 102 m^3 room volume can accommodate 0.565 kmole mixture at this temperature and at nearly atmospheric pressure. Thus the maximum amount of heat that can he liberated is tlic product of the two parameters. which is equal to 40,123 kJ. The maximum average energy deposition density (299 kJ/m^2) **is** determined by dividing this value by the minimum exposed surface area.

The key results of this calculation **as** well as another calculation for 1300 K initial temperature are tabulated in Table 2.

TABLE 2. EFFECT OF EXPLOSION TEMPERATURE ON AVALABLE ENERGY DEPOSITION DENSITY AT LOW REDUCED PRESSURE.

Initial Temperature (K)	2200	1300
Maximum Initial Radiant Flux (kW/m^2)	**1328**	**162**
Final Temperature (K)	300	300
Molar Composition	11.6% CO_2 + 15.5% H_2O + 72.9%) N_2	
Molar Heat Liberated (kJ/kmole)	71,026	34,756
Number of Moles in the Room (kmolc)	0.565	0.956
Total Heat Liberated (kJ)	40.123	32.226
Average energy deposition density (kJ/m^2)	**299**	**248**

Parameters shown in boldface above are denoted with the open circles in Figure 2. which is obtained by transforming the vertical axis of Figure 1. The allowable duration for a specified damage probability is transformed to allowable energy deposition density by multiplying the duration by the incident heat flux. This is a reasonable approximation since the re-radiation will be small considering the relatively low **skin** temperatures capable of hurting the personnel. The line representing the survival of the protection layer **is** also transformed to the new ordinate of Figure 2.

Since the protection line is above the open circles, Figure 2 indicates that an unprotected premixed gas explosion is capable of causing fatalities due to thermal radiation in a typical room. A *0.5* mm (even a 0.2 mm) thick water film is expected to survive this thermal assault.

PREDICTIONS OF THE CRITICAL ENERGY MODEL

To test the findings against the critical energy model, a conduction calculation has been performed. The temperature gradient across the water film and contact resistance between the water film and the skin were ignored. Constant radiant heat flux was prescribed until the film reached 100 "C. During this phase, evaporation was not allowed. After the moment water film reached the 100 °C mark. the boundary condition was changed to that of constant surface temperature.

The constant incident flux was taken to be 200 kW/m^2, and a modest 250 μm thick water layer was considered. Average thermal properties of skin were taken from Reference 2. In Figure ***3***, calculated values of the heat absorbtion density (after the skin surface exceeds *55* "C) are plotted against the time elapsed after the beginning of the exposure. Figure ***3*** also shows the damaging energy absorbtion in the absence of protection, and the critical energy levels tabulated previously (see 2. Physiological Response).

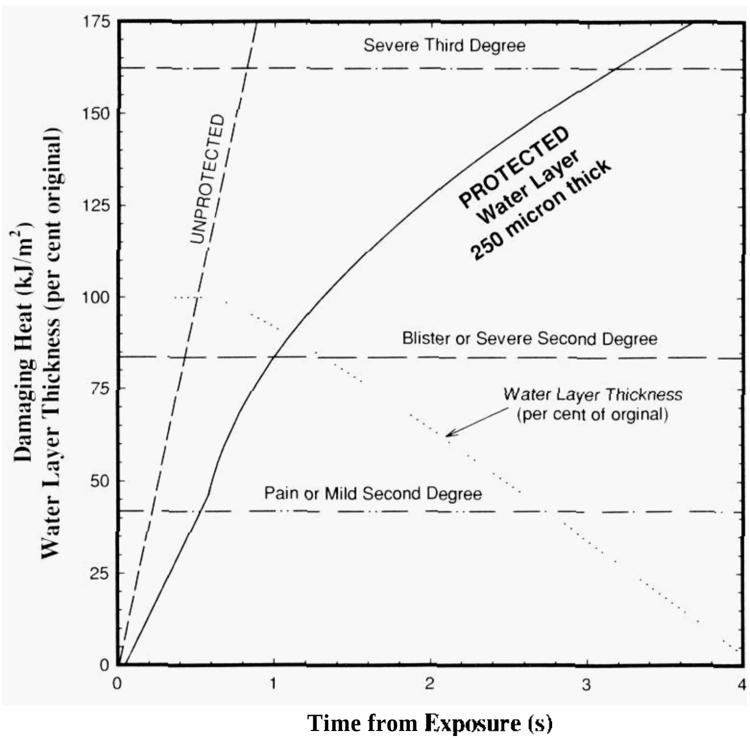

Figure ***3***. Evaluation with the critical energy model.

It is seen that the permanent injury (severe third degree burns) can occur after 0.8 sec if the skin is not protected. On the other hand, a very thin (250 micron) water layer will extend the allowable exposure duration to greater than 3.2 sec at the hypothetical 200 kW/m^2 level. However, typical vented gas explosions are incapable of maintaining this level beyond 1 sec (see DISCUSSION). The dotted line in Figure ***3*** shows the calculated thickness (as a percentage of the initial thickness) of the water layer. The water layer is seen to survive beyond 4 sec.

CONCLUSIONS

Explosions are capable of imparting a heat flux almost an order of magnitude greater than fires. There is a finite probability of fatality due to burns. if any exposed personncl is not protected.

The results ofthe simplified hut conservative analysis show that a 200 to 500 mm thick water film provides adequate personnel protection against severe burns even from an unmitigated large-scale gas explosion. The mitigating effects of a water-based explosion suppression system. especially the effect of cooling the hot combustion products, will significantly increase the estimated duration of the protection beyond that predicted by the simplified yet conservative model, since the radiant heat flux is proportional to the fourth power of the absolute temperature.

REFERENCES

1. J. **A.** Senecal. D. N. Ball, and **A.** Chattaway, "Explosion Suppression in Occupied Spaces," *Proceedings*, Halon Options Technical Working Confercncc, Albuquerque. NM, pp. 79-86, 1994.
3. K. S. Mudan and P. **A.** Croce. "Fire Hazard Calculations for Large Open Hydrocarbon Fires," *SFPE Handbook of Fire Protection Engineering*, Second Edition, Chapters 3-11, pp. 3, 197-3.240, 1995.