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NEED FOR A RELOOK INTO THE THERMAL TEST CRITERIA FOR TYPE-B PACKAGE FOR TRANSPORT OF RADIOACTIVE MATERIALS

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ABSTRACT

Based on statistical data, hazardous materials transport accidents result in releases (78%), followed by fires (28%), explosions (14%) and gas clouds (6%). On the other hand, radioactive materials (RAM) packages in general and Type-B package in particular withstood accident impacts without release. RAM packages need highest level of safety because of its radioactive nature, contamination potential, media attention, public perception, etc. Accordingly, stringent safety protocols are followed since beginning and being improved continually based on experiences gained and new/additional research studies. This study focuses on the need for revising the thermal test criteria given in IAEA's regulations. It is accepted fact that because of significant increase in transport of petroleum products, worst case accident will involve hydrocarbon pool fire. Literature data on pool fire of various hydrocarbon fuels have been analyzed with focus on large pool fires. Study indicates that the flame temperature of majority of hydrocarbon fuel fire will be ≥1000ºC which is higher than the minimum 800ºC stated in regulatory thermal test. Thus, revised thermal criteria have been proposed for consideration of experts.

Keywords: Thermal test, hydrocarbon, pool fire, flame temperature.

INTRODUCTION

Large quantities of flammable materials such as crude oil, gasoline, diesel, etc. are transported through road, rail and sea. The surveys by Oggero et al. [1] and Yang et al. [2] on accidents during three decades (1970-2000) of transport of hazardous materials by road and rail reveals that the most frequent accidents were due to releases (78%), followed by fires (28%), explosions (14%) and gas clouds (6%). This implies that fire might occur during transportation accident. Therefore, a few hazardous materials like explosives, radioactive materials, etc. are transported with additional engineered safety features to protect the package from large-scale pool fires during transport accidents [3].

Though transport of RAM constitutes a very small fraction of overall hazardous materials transport but it has been given highest level of safety because of its nature, contamination potential, media attention, etc. Accordingly, a very stringent safety protocols followed since 1961 including structural and thermal tests for Type-B package simulating severe hypothetical accident conditions. Although there were a few accidents reported during RAM transports, Type-B packages withstood the impact of accidents without any release [4]. It is summarized by Neau [5], "in the last 50 years there has never been an accident due to shortcomings in the regulations which caused significant damage to man or the environment". However, the safety features and protocols followed during transportation are being improved continually based on new/additional studies and experiences gained. There is a significant difference between regulatory temperature of 800°C and average flame temperature of large hydrocarbon pool fire. This study focuses on this aspect and highlights the need for revising the regulatory specifications for thermal test.

ACCIDENTAL FIRE EXPOSURE SCENARIOS

To simulate worst accident scenario, Hypothetical Accident Conditions (HAC) has been described in IAEA's SSR-6 [6] with advisory in SSG-26 [7].With focus on the thermal test, the most important conditions are given in para 728 (a) which states that "Exposure of a specimen for a period of 30 min to a thermal environment that provides a heat flux at least equivalent to that of a hydrocarbon fuel–air fire in sufficiently quiescent ambient conditions to give a minimum average flame emissivity coefficient of 0.9 and an average temperature of at least 800°C, fully engulfing the specimen, with a surface absorptivity coefficient of 0.8 or that value that the package may be demonstrated to possess if exposed to the fire specified".

The actual accident scenario may differ significantly depending prevailing conditions. The fire may initiate due to collision followed by fuel spillage and ignition. The packaging may be exposed to fire from initial stage or suddenly engulfed in large pool fire or exposed to radiant heat from the adjacent fire. Another important factor is duration of fire which is very difficult to predict during accident. Flammable liquid will burn-out quickly as it may spread over large area around the accident site. The blowing wind also plays an important role as it may tilt the flame causing partial engulfment.

WHY TO FOCUS ON LARGE POOL FIRE?

During transportation accident, different type of open fire such as jet type fires, pool fires, vapor cloud fires, etc. may arise depending upon the release scenario. These fires will behave differently and exhibit markedly different radiation characteristics [8]. The commercial fuels such as gasoline, kerosene, diesel, etc. are transported in large quantities through road tankers. Therefore, during transport accidents, probability of these fuels forming spilled pool fire will be highly likely compared to other flammable chemicals. Considering the worst case scenario, it is assumed that accident leads to release of sufficient quantity of hydrocarbon fuel resulting pool fire large enough for full engulfment and to last for minimum 30 minutes. To ensure the engulfment with minimum flame thickness of about 1m beyond the package boundary, a pool of diameter greater than 3m will be necessary even for small package of 1m size. Therefore, thermal test for packaging will invariably involve large pool fire. The characterization of large open pool fire involves the knowledge of mass burning rate, heat release rate, flame temperature, heat flux, radiative power, emissivity, etc.

MASS BURNING RATEOF POOL FIRE

The mass burning rate or flux (m'') is one the most important parameter as it affects heat release rate which has direct bearing flame temperature. It is basically the rate of vaporization of liquid fuel which is determined by the ratio of net heat flux to the pool surface and the heat of vaporization of the fuel. The net heat flux to the fuel is a combination of radiative and convective heat transfer from the flame above the fuel surface [9]. For predicting the mass burning rate, Babrauskas [10] has analyzed and endorsed the formula recommended by Zabetakis& Burgess [11] for pool diameters >0.2 m as given below

$$m'' = m''_{\infty} \cdot \left(1 - e^{-k\beta D}\right) \qquad (1)$$

Where m''_{∞} = asymptotic mass burning rate as pool diameter increases towards infinity, $kg/m^2 \cdot s$; k = extinction coefficient (m^{-1});β = mean beam length corrector and D = diameter of pool, m.

The burning regime for large liquid pools is radiative and optically thick for which mass burning rate asymptote to maximum. Blinov & Khudyakov [12] have carried out large numbers of experiments for various fuels with pool diameter upto 22.9 m but majority of the experiments were done with pool diameter less than 1m. For large pool fire tests, it was stated that "the results for d between 1 and 23 m are few and not very precise". Various authors have reported different pool diameter for reaching asymptotic mass burning rate which also depends on fuel type. For example, Quintiere [13] has reported that the mass burning rate of gasoline becomes steady ~0.055 kg/m^2·s for pool diameter above 1 m whereas Babrauskas [10] observed it to be reasonably constant above 2m pool size. On the other hand, Chatris et al. [14] and Munoz et al. [15] have carried out outdoor large pool fire experiments using gasoline and diesel fuels spread on water in circular pools. The asymptotic mass burning rate reached for pool diameter of about 4 m. It may be noted that the mass burning rates of gasoline and diesel fuels on water were 0.083 and 0.062, respectively, which is higher than of rate measured on land as reported by various authors (Table-1). Mudan [16] has observed that the burning rates for pool fires on water will be slightly higher than land whereas Rew et al. [17] have reported it to be twice for LNG and LPG as their mass burning rates on land are 0.141 and 0.118 and on water are 0.282 and 0.256, respectively. The recent data of mass burning rate of a few common hydrocarbon fuels in large pool fires have been compiled in Table-1, for comparison and their use in general calculations.

Table-1 Mass burning rates of hydrocarbon fuels

Name of Fuel	Mass burning rate, m''_∞, kg/m^2·s		
	[10]	[18]	[17]
LPG-Propane	0.099	-	0.118
Butane, C_4H_{10}	0.078	-	-
Hexane, C_6H_{14}	0.074	0.077	0.075
Gasoline (Petrol)	0.055	0.062	0.067
JP-4	0.051	0.067	0.056
Kerosene	0.039	0.065	0.063
Crude Oil	0.022	0.056	0.051
Diesel	-	-	0.054

The wind speed also plays an important role during fire but its effect was small for velocities below 2 m/s [15]. Whereas, Blanchat & Figueroa [19] have measured the effect of wind speed for large pool fire and found that the mass burning rate of JP-8 fuel on water has increased linearly by 20% with wind speed range of 0.85 to 5.76 m/s.

HEAT RELEASE RATE (HRR)

The heat release rate (Q, MJ) of the pool fire is one of the most important parameter used in determining the impact of afire on its surroundings [20-21]. It is strongly dependent on the calorific value and mass burning rate of fuel as well as thermal properties combustion products. For open pool fire, burning is equated with the rate of supply of gaseous fuel. Accordingly, HRR is commonly expressed as product of heat of combustion (ΔHc, MJ/kg), mass burning rate (m″, kg/m^2·s) and area of liquid pool (A, m^2) as represented by equation (2). For large pool fire, m″ should be substituted by m''_∞.

$$Q = m'' \cdot A \cdot \Delta H_c \qquad (2)$$

The heat of combustion of most of the hydrocarbon liquid fuels such as butane, hexane, gasoline, kerosene, diesel, etc. varies in a narrow range of 43 to 46 MJ/kg [13]. Considering combustion efficiency, the heat of combustion of hydrocarbon liquids is taken as 43 MJ/kg [20]. For gasoline pool fire, taking average mass burning rate as 0.060 kg/m^2·s, the estimated the heat release rate will be 18, 51 and 203 MW for pool diameter of 3, 5 and 10m, respectively.

FLAME HEIGHT

The mean flame height is an important parameter as full engulfment in flame is regulatory requirement. It indicates the zone where the combustion reactions are essentially complete and the inert plume can be considered to begin and defined as the height at which the flame is observed at least 50% of the time. Accidental fire will have low-initial-momentum diffusion flames and is strongly influenced by buoyancy effects [17]. There are several expressions proposed in literatures for mean flame height. Based on data of laboratory-scale wooden crib fire experiments and dimensional analysis, Thomas has formulated a correlation (eqn-3) for the mean visible height of flames in still air. Mudan [16] has stated that Thomas' correlation predicts the visible flame heights better than the other correlations for various fuels.

$$H/D = 42\left[\frac{m''}{\rho_a\sqrt{gD}}\right]^{0.61} \qquad (3)$$

Where m″ = mass burning rate (kg/m^2.s), D = Diameter of pool (m),ρ_a = ambient air density (kg/m^3).

On the other hand, Heskestad has also developed correlation for estimating flame height for zero wind condition and commonly expressed as given in eqn-4 [13].

$$H_f = 0.23\, Q^{2/5} - 1.02D \qquad (4)$$

Where Q= HRR in kW, H_f = Height of flame in m, D = Diameter of pool in m.

Beyler [8] has remarked that the Heskestad correlation under quiescent air conditions best represents large diameter pool fires. Using Heskestad equation, gasoline pool fire of 4 and 6 m size is estimated to have 10.6 and 14.2 m high flames. Wind causes flame to tilt & drag as well as significant variations in thermal radiation to surrounding as well as objects submerged in flames.

FLAME TEMPERATURE

A fire plume has three regions: continuous flame region, intermittent flame region, and thermal plume region [22]. Considering the object engulfed in fire with minimum 1m flame thickness beyond outer surface of package, temperature within the continuous flame region is most important. The flame temperature varies in both space and time as oxygen starved region changes its extent and location with the size of the pool and wind conditions. Further, flame shape and relative sizes of the flame and object engulfed in the flames have a significant influence. Even during steady burning, considerable spatial and temporal flame temperature variations within the fire zones have been observed in many of the pool fire engulfment experiments and these variations were attributed to the influence of prevailing meteorological conditions [23].

The flame temperature of pool fires of various fuels has been analyzed for average flame temperature of large hydrocarbon pool fire. For tall flame in large pool fire, lower portion will have nearly constant temperature and begin to decay in the intermittent upper portion of the flame. Further, the temperature within the flame varies across the width with maximum at the center. The average turbulent flame temperature along the centerline of a fire plume is related with radiative fraction. For large pool fire (ϕ>4m), the radiative fraction is generally <0.20 which indicate that average centre line temperature of flame will be approximately 1150°C [13].

Bainbridge & Keltner [3] have reported extensive experimental data from large pool fire test using JP-4 fuel floating on water with thermocouple at different height between 1.4 to 11 m. During three tests, the average flame temperature at 1.4m elevation within the flame was 870, 921 and 958 °C with maximum temperature of 1280°C. It was further reported that after 30 minutes of fire engulfment, the inside surface temperature of large object was more than 925°C for all the three tests. It clearly indicates that the average flame temperature around the engulfed object was much higher than the 925°C. Mudan [16] has reported the radiation temperature for various hydrocarbons such as gasoline, JP-4, kerosene, etc. and found to vary in the range of 1200 to 1600 K (927 to 1327°C). On the other hand, Mudan & Croce [24] observed that during steady burning the temperature within the flame is reasonably constant about 1150-1250°C in case of hydrocarbon pool fires. Similarly, Sundén & Faghri [25] have noted that the typical time-mean temperatures in a large fire are of the order of 1000°C for many hydrocarbon fuels in air [26]. Reid [22] commented that relying on data obtained from large experimental hydrocarbon pool fire, various studies indicate that flame temperature will be in the range of 1000-1500 ºC. It is pointed out that the flame temperature of pool fire with hydrocarbon fuels have a high calorific value resulting high flame temperature which reaches up to 1400 °C [27]. A typical temperature for fire involving petrol tanker has been stated as 1400 °C [28]. Experimental studies have proved that the flame temperature is a function of time and height and following correlation (eqn-3) is used for the flame temperature in most of the codes for thermal analysis:[29-30]

$$T_f(t,h) = \frac{10^4 \cdot t}{(34+210 \cdot h+8.51 \cdot t)} + 290 \qquad (3)$$

Where 't' represents time in second and 'h' is height in meter within the flame.

The spatial and temporal variations in flame temperature have been determined using equation (3) for fire duration of 60 minutes and plotted in Fig.1 below. It clearly shows that the flame temperature is more than 1200 ºC for large duration of steady fire.

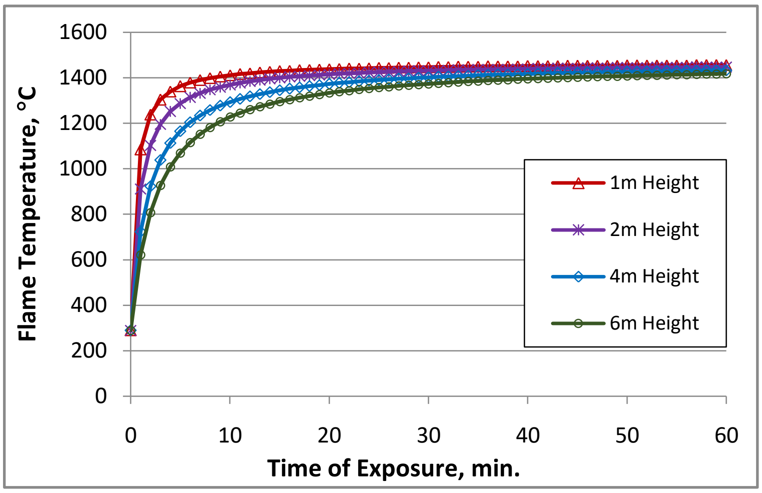

Figure 1 Spatial and Temporal Variations of Flame Temperature in Large Pool Fire

Further, instead of standard cellulosic fire curves [31-32], petrochemical and offshore industries use fire curves simulating hydrocarbon fire termed as 'Standard Large Hydrocarbon Pool Fire Tests'. Based on large pool fire experiments, it is stated that high flame temperature and heat flux conditions are achieved rapidly in hydrocarbon pool fires (typically in less than 1 min) and leveling off to a plateau at 1100ºC. Similarly, in ASTM-E1529 [33], it is stated that test environment temperature shall be between 1010°C and 1180°C at all times after the first 5 minutes of the test. The experimental results of large pool fires by various authors as stated above indicates that the average temperature within the thick continuous flame will vary between 1000 to 1200°C for hydrocarbon fuels.

TOTAL HEAT FLUX

The average heat flux over the area of engulfment of the object is very important for thermal evaluation. When an object such as cylindrical package is fully engulfed in flame, it receives both radiant and convective heat from the flame i.e. hot gases. Therefore, total heat flux is a summation of the both components, as represented in eqn (4).

$$q_T = q_R + q_C \ ; \ q_R = \sigma\, \varepsilon_f \left(T_f^4 - T_s^4\right) \text{ and } \ q_C = h\left(T_f - T_s\right) \qquad (4)$$

Where q_T= total heat flux, kW/m^2, q_R= radiant heat flux and q_C= convective heat flux, other notations have usual meaning.

Though flame temperature is the most important parameter on which total heat flux is strongly dependent, it depends upon a number of parameters such as, nature and type of fuel, size of fire, combustion characteristics, local meteorological conditions, optical thickness of the flame, object size, etc. [23]. Radiant heat is highly dominant mode to transfer heat from flame to an object immersed in a large pool fire [33]. Thermal radiation is contributed by both gaseous species such as water vapor, carbon dioxide and carbon monoxide as well as from soot particles. All luminous flames contain soot particles and their subsequent oxidation produces a high proportion of the flame's radiative power [17] and majority of the radiation in fire plumes (>90%)is derived from the visible part of the flame [34]. For common fuels including hydrocarbon fires, about 3m in diameter or more, the fire gases become optically thick such that the effective emissivity of the fire tends to unity and the emissive power saturates [13, 24, 34].

Convective component from moving hot gases around the object or package is a function of the local temperature difference and velocity of the gases around the package which varies approximately between 1 and 10 m/s with mean near the middle of that range [26, 35]. The effective convective HTC for objects adjacent to fire has been reported by Raj [36] for different wind speeds upto 10 m/s with maximum value approx. 20 W/m^2.K. For fully engulfed object, it will be still higher but for average wind speed of 5 m/s, the convective heat flux of approximately 20 kW/m^2 can be taken and consistent with accepted figure of about 15 to 20% of the total heat flux contributed by convective heat transfer [26].

The heat flux to an object refers to total cold wall heat flux that would be transferred to an object whose temperature is 70°F (21°C) and reasonable average of the experimental values is reported as 158 kW/m^2 during standard large hydrocarbon pool fire tests [33]. On the other hand, IAEA's thermal regulation states that "Exposure of a specimen for a period of 30 min to a thermal environment that provides a heat flux at least equivalent to that of a hydrocarbon fuel–air fire".

Radiative power is highly dependent on the flame temperature and there are large variations in heat flux values reported by various researchers because most of the studies have focused on small-scale pool fires, which differ significantly from large turbulent fires [15]. Moodie [23] stated that hydrocarbon pool fires are usually quoted as having average heat flux in the region of 100-120 kW/m^2. Mudan [16] has stated that the maximum emissive power measured for gasoline fires is in the range of 110 to 130 kW/m^2. Similarly, Bainbridge & Keltner [3] has stated that in spite of the large variations induced by wind, the typical heavy hydrocarbon fires without smoke shielding have an effective surface emission of about 120 kW/m^2. The mean emissive power of large pool fires of gasoline and diesel were measured by Muñoz et al. [15] and found that the average emissive power was varying between 120 and 160 kW/m^2 for continuous flame zone. It is also noted in ASTM-E2230 [26] that "large variations in heat flux depending on both time and location have been observed in actual pool fires. Local heat fluxes as high as 150 kW/m^2 under low wind conditions are routinely observed for low package surface temperatures".

CONCLUSIONS

Accidental fire will involve large hydrocarbon pool fire and its most important fire characteristics such as flame temperature, HRR, heat flux, etc. have been analyzed considering various experimental data available in literatures. Though flame temperature varies spatially and temporally, various studies have shown that the average flame temperature in large hydrocarbon pool fires is more than 1000ºC during steady burning. Since radiation dominates the heat transfer and strongly dependent on flame temperature, regulatory temperature of 800ºC will result significantly lower heat flux during thermal analysis or furnace test of the package compared to actual pool fire test. Moreover, with sooty nature of flame, optical thickness is about 1-2 m. Even near outer edge of the package with minimum 1m flame thickness as per regulation, emissivity of flame will be more than 0.95. The combined effect of lower flame temperature and emissivity will be significant during 30 minutes thermal test. It results disparity between actual open pool fire test and other methods of certification such as Furnace test, Radiant heat test and Qualification by analysis. Based on this study, it can be concluded that changing the regulatory temperature from 800ºC to 900ºC with minimum flame emissivity of 0.95 instead of 0.90 will simulate more realistic flame characteristic of large hydrocarbon pool fires.

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