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Quantitative Evaluation of Fire Separation and Barriers

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Abstract

Fire barriers, and physical separation are key components in managing the fire risk in Nuclear Facilities. The expected performance of these features have often been predicted using rules-of-thumb or expert judgment. These approaches often lack the convincing technical bases that exist when addressing other Nuclear Facility accident events. This paper presents science-based approaches to demonstrate the effectiveness of fire separation methods.

Introduction

Fire barriers and fire walls are a common feature of industrial facilities. Usually they are installed to meet prescriptive life safety and monetary protection requirements which differ substantially from the nuclear safety objective to limit radiological releases. The barrier evaluation method presented in this paper is appropriate for use in a variety of safety analysis applications where a quantitative understanding of fire barrier performance is desired. The ability to compare, quantitatively, fire barrier capacity to the expected fire demand consistant with actual facility operations, permits a better understanding of the facility safety margin. This better understanding can be a significant contribution to the process of appropriate safety control definition with the greatest possible of operating flexibility

Standoffs and physical separation are often used to limit fire propagation inside or between buildings. Typically, thermal radiation theory is used to establish the minimum physical separation between a fire and the target to prevent ignition. Two widely-used analytical approaches are compared in this paper. The predictions obtained using the two approaches have been compared and shown to be consistent. In the process, the technical bases for each approach has been reviewed and the safety margin better clarified.

This paper will discuss two separate fire propagation prevention methods (barriers and physical separation) and evaluation techniques to judge their expected performance. There are other fire propagation mechanisms that should be considered in a comprehensive hazard evaluation (e.g., branding, vertical propagation from window to window around a barrier, rocketing of burning cylinders or tanks around or through a barrier, convective propagation of flammable gases through ventilation systems or corridors, propagation along a roof over a barrier, movement of adjacent structural members that damages a barrier). Discussion of these mechanisms is considered beyond the scope of this paper.

Fire Barrier Performance

DOE Order 420.1B, *Facility Safety*[1] establishes the need for fire separation through the requirement to limit the Maximum Possible Fire Loss (MPFL) to specifically defined limits. These limits are established in DOE G 440.1-5, *Implementation Guide for use with DOE Orders 420.1 and 440.1 Fire Safety Program*[2] and DOE-STD-1066-99, *DOE Standard Fire Protection Design Criteria*.[3] These documents prescribe a minimum 2-hour fire rating for fire areas. The documents do not establish or recommend an analytical approach to judge if a greater fire resistance is required. The documents do require that in computing the MPFL "failure of both automatic fire suppression systems and manual fire fighting efforts" must be assumed.[3] As such, there is an implicit risk assumption associated with the use of the 2 hour rating that considers the existence of automatic suppression and fire department intervention.

Documented Safety Analyses (DSAs) for Category 2 and 3 Nuclear Facilities are typically prepared using the safe harbor approach established in DOE-STD-3009-94, *Preparation Guide for U.S. Department of Energy Nonreactor Nuclear Facility Documented Safety Analysis*.[4] A key consideration in the 3009 approach is the explicit identification of the engineered features and administrative controls that provide assurance that the facility may be operated safely. Since the 2-hour minimum rating contains an implicit risk acceptance for monetary protection, there will be facilities where the minimum rating might not be appropriate for the protection of the public or workers from radioactive contamination spread.

There are two basic categories of horizontal fire separation: Fire barrier walls and fire walls.[5] Fire barrier walls are intended to impede the spread of fire, usually to provide occupants sufficient time to exit the facility. They are not intended to remain in place following fire extinguishment. Fire walls are designed to resist fire spread and remain in place following fire extinguishment. While the nomenclature for vertical fire separation (i.e., floors, ceilings and roofs) is not as explicit, the functionality is similar.

The most commonly used fire barrier qualification test is ASTM E-119, *Standard Test Methods for Fire Tests of Building Construction and Materials*.[6] This test, which is used to qualify both fire barrier walls and fire walls, subjects the fire barrier to a specific time-temperature furnace exposure. The primary ASTM E-119 failure criterion is a rise in the temperature on the unexposed surface of more than 139°C (250°F) above the initial barrier temperature, although excessive flame penetration or loss of structural integrity are also failure criteria evaluated in the test. The test is considered to provide a good metric to compare the capabilities of different barrier designs; however, the test is limited to a single time-temperature insult, which is not necessarily the most demanding fire. Specific facility arrangements and fire loadings may create fires that are more demanding than the ASTM test.

A common technique to account for alternate fire severities was developed in the early 1920s based on testing by Ingberg.[7] Table 1 shows the equivalent fire severity for given wood equivalent fire loading. (Nominally taken as 8,000 Btu per pound wood). Based on this table, a building with a 10-psf loading would be expected to have an equivalent fire severity of 1 hour. Care must be taken when using the units of “hours” to report fire severity. The fire severity is sometimes confused with fire duration. The situation is analogous to pounds-force and pounds-mass in the U.S. customary units. In some applications the adoption of d and s subscripts might be appropriate (duration and severity).

Table 1.--Fire intensity and duration.

Wood equivalent combustible loading			Fire severity[7] Hours	E-119 temperature at the specified time[6],°C
psf	Btu/ft^2	kg/m^2		
5	40,000	24	0.5	843
10	80,000	49	1	927
15	120,000	73	1.5	985
20	160,000	98	2	1010
30	240,000	146	3	1052
40	320,000	195	4.5	1121
50	380,000	244	7	1218
60	432,000	293	8	1260
70	500,000	342	9	1260

Harmathy[8] established a methodology to calculate the fire resistance requirements (i.e., fire severity demand) for a specific failure probability based on the normalized heat load:

$$H_d = \frac{1}{\sqrt{k\,\rho\,c}} \int_0^{\tau} q\,dt$$

where k is the thermal conductivity of wall [J/m·K]; c is the heat capacity of wall [J/kg·K]; ρ is the density of wall [kg/m^3]; q is the heat flux to a wall [W/m^2]; t is the time [s]. For a typical wall construction (e.g., concrete, gypsum) heat load capacity was demonstrated to be:

$$H_c = 10^4\left(\sqrt{76.92\tau_s + 29.41} - 6.15\right)$$

where the fire rating of the wall, τ_s, is in units of hour-severity based on the ASTM E-119 curve.

The normalized heat load capacity, H_c; and the normalized heat load demand, H_d; may be used to estimate barrier failure probability, P_f; based on the inverse standard normal distribution function of failure parameter β.[9]

$$\beta = \frac{1}{\sqrt{\Omega_1^2 + \Omega_2^2 + \Omega_3^2}} \ln\left(\frac{H_c}{H_d}\right)$$

where: Ω_1 is the coefficient of variation for the heat load demand, H_d

Ω_2 is the coefficient of variation for the heat load capacity, H_c

Ω_3 is the coefficient of variation for error.

A value of 0.101 has been estimated for the variation in error, Ω_3, and a value of 0.09 for the variation associated with capacity, Ω_2.[9] For simplicity, the variation associated with demand, Ω_1, may be neglected (i.e., set to zero), effectively considering constant combustible load conditions at the maximum level.

Thus, normalized heat load capacity, H_c, can be estimated for a specific wall construction, based on the ASTM E-119 rating (e.g., 2 hours). The normalized heat load demand, H_d, may be estimated using a fire model that predicts the heat flux on the target wall. The failure probability for the target wall can then be estimated from:

$$P_f = 1 - \text{NormalStandard Distribution } (\beta)$$

Figure 1 presents the heat flux predictions to a gypsum wall during a serious fire in a Nuclear Facility at the Savannah River Site,[10] which was generated from a CFAST fire model. The fire compartment is a large (30,000 ft^2, with a 12.5 ft height) unsprinklered concrete structure. The gypsum wall represents the perimeter of a small room within the fire compartment. The combustible loading was approximately 16,000 pounds wood equivalent. The flux predictions assume that the fire will be ventilation limited, intervention by the fire department will not occur, and a limited-combustible zone is established near the gypsum wall (about 20' wide). The limited-combustible zone was established to kept the high heat flux period shown Figure 1 to about 30 minutes.

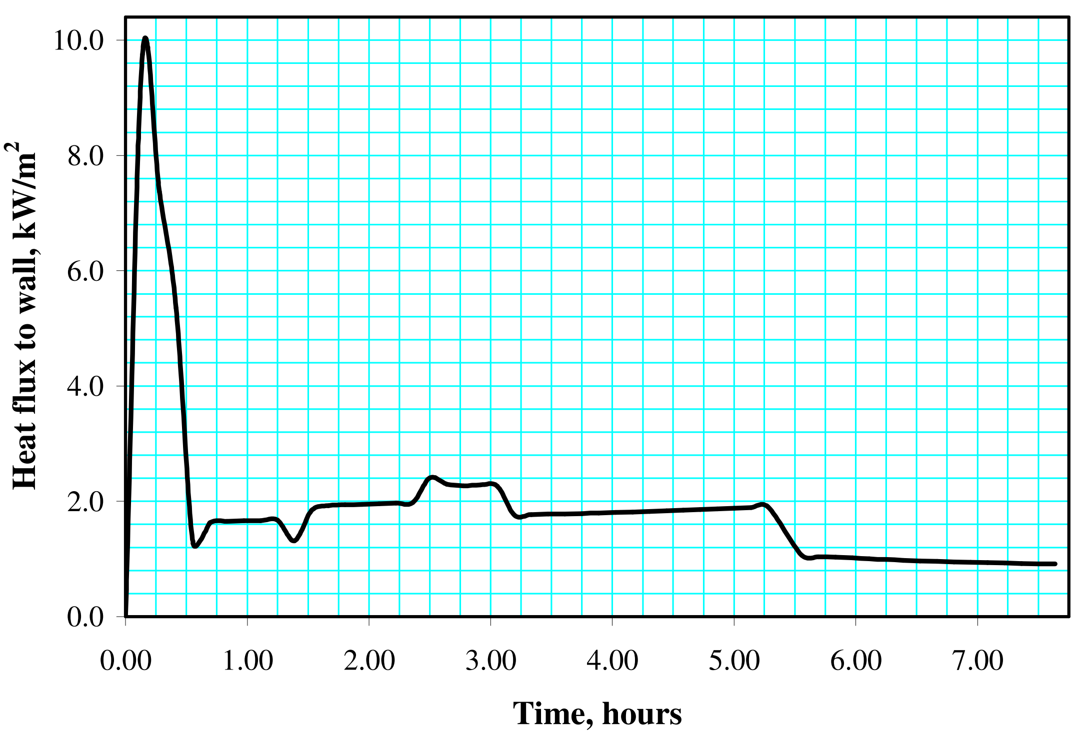

Figure 1, Heat flux to wall during a postulated fire

The probability of target wall failure for the given heat flux demand is developed in Table 2, based on a thermal absorbtivity $(k\rho c)^{0.5}$ for the target wall of 374 W·s$^{0.5}$/m^{2}K, which is a common value for gypsum walls.[9] Predictions are presented for 2, 3 and 4 hour construction. If the fire is extinguished at about 2 hours (first bold row), the probability of fire barrier failure is negligible for all three constructions. If the fire is extinguished at 4 hours (second bold row), the probability of failure for the 2 hour barrier is 62 percent. The probability of the 3 and 4 hour constructions are small (3 percent and 0 percent). At 6 hours, the respective probabilities are 99, 55 and 8 percent. Beyond this duration, the probabilities for any construction are undesirable. In terms of a safety basis strategy it is clear that 2 hour construction will require some form of intervention (e.g., manual fire control). To prevent barrier failure for a 2-hour wall at a 90 percent confidence, suppression will need to occur before 2.8 hours after ignition.

Table 2 – Energy estimates.

Time		Fire flux	Energy absorption by wall		H_d	2 hour barrier $H_c = 73{,}870$		3 hour barrier $H_c = 99{,}798$		4 hour barrier $H_c = 122{,}100$	
sec	hrs	W/m^2	delta	cumulative	$s^{1/2}\cdot K$	β	P_{fail}	β	P_{fail}	β	P_{fail}
0	0.00	0.0	1,937,258	1,937,258	5,180	19.64	0.00	21.87	0.00	23.36	0.00
500	0.14	9.7	3,280,345	5,217,603	13,951	12.32	0.00	14.54	0.00	16.04	0.00
1000	0.28	7.4	2,181,495	7,399,098	19,784	9.74	0.00	11.96	0.00	13.45	0.00
1500	0.42	5.4	1,103,410	8,502,508	22,734	8.71	0.00	10.93	0.00	12.43	0.00
2000	0.56	1.3	1,219,355	9,721,863	25,994	7.72	0.00	9.94	0.00	11.44	0.00
3000	0.83	1.7	1,383,375	11,105,238	29,693	6.74	0.00	8.96	0.00	10.45	0.00
4000	1.11	1.7	1,242,040	12,347,278	33,014	5.95	0.00	8.18	0.00	9.67	0.00
5000	1.39	1.3	1,349,955	13,697,233	36,624	5.19	0.00	7.41	0.00	8.90	0.00
6000	1.67	1.9	1,613,400	15,310,633	40,938	4.36	0.00	6.59	0.00	8.08	0.00
7000	**1.94**	**1.9**	**1,632,055**	**16,942,688**	**45,301**	**3.61**	**0.00**	**5.84**	**0.00**	**7.33**	**0.00**
8000	2.22	2.0	1,824,315	18,767,003	50,179	2.86	0.00	5.08	0.00	6.57	0.00
9000	2.50	2.4	1,949,685	20,716,688	55,392	2.13	0.02	4.35	0.00	5.84	0.00
10000	2.78	2.3	1,887,400	22,604,088	60,439	1.48	0.07	3.71	0.00	5.20	0.00
11000	3.06	2.3	1,679,760	24,283,848	64,930	0.95	0.17	3.18	0.00	4.67	0.00
12000	3.33	1.8	1,481,150	25,764,998	68,890	0.52	0.30	2.74	0.00	4.23	0.00
13000	3.61	1.8	1,491,720	27,256,718	72,879	0.10	0.46	2.32	0.01	3.81	0.00
14000	**3.89**	**1.8**	**1,505,245**	**28,761,963**	**76,904**	**-0.30**	**0.62**	**1.93**	**0.03**	**3.42**	**0.00**
15000	4.17	1.8	1,521,105	30,283,068	80,971	-0.68	0.75	1.55	0.06	3.04	0.00
16000	4.44	1.8	1,538,580	31,821,648	85,085	-1.04	0.85	1.18	0.12	2.67	0.00
17000	4.72	1.9	1,557,180	33,378,828	89,248	-1.40	0.92	0.83	0.20	2.32	0.01
18000	5.00	1.9	1,576,525	34,955,353	93,464	-1.74	0.96	0.48	0.31	1.98	0.02
19000	5.28	1.9	1,237,595	36,192,948	96,773	-2.00	0.98	0.23	0.41	1.72	0.04
20000	5.56	1.1	874,123	37,067,070	99,110	-2.17	0.99	0.05	0.48	1.54	0.06
21000	**5.83**	**1.0**	**847,886**	**37,914,956**	**101,377**	**-2.34**	**0.99**	**-0.12**	**0.55**	**1.37**	**0.08**
22000	6.11	1.0	826,051	38,741,007	103,586	-2.50	0.99	-0.28	0.61	1.22	0.11
23000	6.39	1.0	807,448	39,548,455	105,745	-2.65	1.00	-0.43	0.67	1.06	0.14
24000	6.67	1.0	792,376	40,340,831	107,863	-2.80	1.00	-0.57	0.72	0.92	0.18
25000	6.94	0.9	779,865	41,120,695	109,948	-2.94	1.00	-0.72	0.76	0.77	0.22
26000	7.22	0.9	769,255	41,889,950	112,005	-3.08	1.00	-0.85	0.80	0.64	0.26
27000	**7.50**	**0.9**	**381,082**	**42,271,032**	**113,024**	**-3.14**	**1.00**	**-0.92**	**0.82**	**0.57**	**0.28**

As discussed earlier the minimum acceptable fire separation for monetary protection in the DOE complex is 2 hours. Outside of the DOE community it is common to provide ratings of 4 hours or greater where there is significant potential for large monetary losses.[11] The primary justification for this difference is the strong reliance on good conduct of operations within the DOE community, when compared to general industry. The results in Table 2 validate this safety posture, if sufficient fire department capabilities are available.

Standoff Required to Prevent Ignition

There are two National Fire Protection Association (NFPA) guidance documents that can be used in developing standoff and separation estimates: NFPA 80A, *Recommended Practice for Protection of Buildings from Exterior Fire Exposures*,[12] and NFPA 555, *Guide on Methods for Evaluating Potential for Room Flashover*.[13] Typically, the former is used for exterior building-to-building propagation, while the later is uses for interior package-to-package propagation. The predictions obtained using the two approaches have been compared and shown to be consistent. In the process the technical bases for each approach has been reviewed and the safety margin better clarified.

The fuel packages considered in this evaluation were industrial trailers typical of those containing analytical equipment in exterior material storage facilities. They were comprised of a sheet metal exterior with various combustible and non-combustible interior components (e.g., combustible frames and vinyl interior partitions, ceilings, and floors). The trailer include tires but no tractor unit. The approximate weight of each unit was between 48,000 and 60,000 pounds. The nominal trailer dimensions were 8' (2.4 meters) wide, 46' (14 meters) long, and 12.8' (3.9 meters) high. While detailed combustible representations of the trailers was not developed, the heat release rate (HRR) if the trailers were to become fully involved was judged to be in the range of 10 MW to 50 MW.[14]

Standoff Based on NFPA 80A

Using the method proposed by NFPA 80A, the standoff distance, S, required for exposure from a building of greater or equal height may be estimated as:

$$S = Z \times G + N$$

where: Z is the lesser value of building width (W) or height (H)

G is the guide number [unitless]

N opening protection factor [feet]

The guide number, G, is determined based on fire severity, the percentage of opening in the exposing wall area, and the building exposure face configuration defined as the larger of the width versus height or height versus width ratios. NFPA 80A defines three levels of fire severity (light, moderate, severe) based on the average combustible load per unit of floor area and the characteristics and average flame spread ratings of the interior wall and ceiling finishes. Because the exterior walls of the trailers were not expected to withstand fire penetration in excess of 20 minutes, the percentage of openings in the exposing wall area was taken to be 100% as recommended in NFPA 80A. The building exposure configuration is defined as the larger of the width versus height (W/H) or height versus width (H/W) ratio of the exposing building.

The opening protection factor, N is an additive factor of 5 feet that is included for cases were the openings are not equipped with protective features having a fire protection rating equal to or greater than the expected duration of the fire. Following the NFPA 80A method, the standoff distance required for the inherent heat flux ignition threshold of 12.5 kW/m^2 is presented in Table 3. Qualitative consideration of the generic trailer selected for this evaluation suggests that it would be most realistically represented by the severe fire classification defined in NFPA 80A.

Table 3 – Standoff to Trailer Required by NFPA 80A.

Severity	Lesser of trailer length or height feet	G unitless	Recommended standoff feet	meters
Light	12.8	2.44	36.3	11.1
Moderate	12.8	3.74	52.8	16.1
Severe	12.8	5.48	75.1	22.9

Standoff Based on NFPA 555

Radiant heat flux to a target from a fuel package is described in NFPA 555 as the product of emissive power (E) and a view factor. The emissive power will vary with the size of the fire and type of material involved in the fire. The view factor, which defines the fraction of thermal radiation leaving an emitting surface and intercepted by a target surface, is defined based on the geometric arrangement of surfaces.

The emissive power, E, of a fire may be estimated based on the Shokri and Beyler correlation

$$E = 58 \times 10^{-0.00823D}$$

where D equivalent fire diameter [m]. The fire diameter may be estimated as:

$$D = \sqrt{\frac{4A}{\pi}} = \sqrt{\frac{4(14\ \mathrm{m})(2.4\ \mathrm{m})}{\pi}} = 6.5\ \mathrm{m}$$

where A is the footprint area of the fire [m^2]. The resulting emissive power is 51.3 kW/m^2.

The view factor, F_v, for an elemental area representing the target may be estimated by treating the fire as a flat plate. The view factor for an elemental area to a plane parallel rectangular where the normal to the element passes through the corner of the rectangle is:[15]

$$F = \frac{1}{2\pi}\left[\frac{X}{\sqrt{1+X^2}}\tan^{-1}\left(\frac{Y}{\sqrt{1+X^2}}\right) + \frac{Y}{\sqrt{1+Y^2}}\tan^{-1}\left(\frac{X}{\sqrt{1+Y^2}}\right)\right]$$

where: X = a/c, Y = b/c (See Figure 2.)

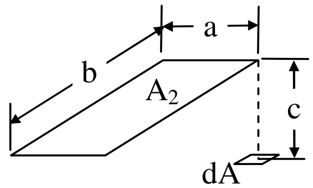

Figure 2, Configuration factor nomenclature for plate and elemental area

For the burning trailer, the plane width may be equated to half the trailer width, the fire height was used to establish half the plane height. (The halves occur because the view factor geometry shown in Figure 2 represents a quarter of the fire surface.) The fire height may be approximated based on the equivalent fire diameter and the fire HRR. Due to the potential variation in actual HRR, a parametric solution is appropriate in which the peak HRR (q) ranges from 10 MW to 50 MW. The associated fire height is then predicted as

$$H = 0.235q^{2/5} - 1.02D$$

The standoff distance, c, may then be calculated for a desired heat flux threshold value based on the view factor relationship and the heat flux estimate:

$$q = E \cdot F$$

Established practice[16] for heat flux calculations estimated using the Shokri and Beyler correlation is to include a safety factor of 2, which is applied to the estimated standoff distance. Thus, the calculated value of standoff distance should be doubled. For the evaluated trailer, the standoff distance required by NFPA 555 for a heat flux ignition threshold of 12.5 kW/m^2 is presented in Table 4. This table was iteratively developed by adjusting the standoff distance until the desired heat flux was obtained.

Table 4 – Standoff required by NFPA 555 for 12.5 kW/m^2 Ignition Threshold.

HRR MW	Fire height, H meters	Standoff, c			geometry constants meters			geometry constants, unitless		f_{total}	heat flux kW/m^2
		With SF*		No SF*							
		feet	meters	meters	a	b	c	X	Y		
10	2.7	31.9	9.7	4.9	1.35	7	4.86	0.28	1.44	0.244	12.5
20	5.7	54.6	16.6	8.3	2.85	7	8.32	0.34	0.84	0.244	12.5
40	9.7	74.9	22.8	11.4	4.85	7	11.4	0.43	0.61	0.244	12.5

*Safety factor

Comparison of Standoff Results

For the defined trailers the fire severity was judged to be severe, the required standoff computed using NFPA 80A was 75.1 feet. For the 40 MW fire, which is judged to be sufficiently conservative for the trailers involved, the required standoff computed using NPFA 555 is 74.9 feet. These two results are considered sufficiently close to validate that either result could be established as the safety basis standoff to prevent fire propagation.

Table 5 presents the required standoff distances based on NFPA 80A, and the HRR estimate necessary to obtain the same standoff distance using the method proposed in NFPA 555. Based on this, it appears reasonable to equate low fire severity with a 10 MW fire, and a severe fire with a 40 MW fire. The moderate fire severity is best equated with a 20 MW fire.

Table 5 – NFPA 80A to NFPA 555 Correlation.

Exposure Severity	NFPA 80A standoff from Table 3		NFPA 555 predicted HRR to achieve a heat flux of 12.5 kW/m^2
	feet	meters	MW
Low	36.3	11.1	11
Moderate	52.8	16.1	19
Severe	75.1	22.9	41

Conclusion

Quantitative analysis approaches have been presented to permit the evaluation of fire barrier capabilities and fire standoff distances. Such methods, when used, can provide reproducible substantiation for fire controls intended to limit fire spread. In addition, by quantifying the key parameters associated with preventing fire propagation, the importance specific parameters can be better understood. Such an understanding can then be used to better tailor the controls strategies to specific operational objectives.

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