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Modeling Ventilation System Response to Fire

D. Allan Coutts, Ph.D., FSFPE
Washington Group International, Savannah River Site
2131 S. Centennial Drive, Aiken, SC, 29803
(803) 502-9811, Fax (803) 502-2811
allan.coutts@wsms.com

Abstract

Fires in facilities containing nuclear material have the potential to transport radioactive contamination throughout buildings and may lead to widespread downwind dispersal threatening both worker and public safety. Development and implementation of control strategies capable of providing adequate protection from fire requires realistic characterization of ventilation system response which, in turn, depends on an understanding of fire development timing and suppression system response. This paper discusses work in which published HEPA filter data was combined with CFAST fire modeling predictions to evaluate protective control strategies for a hypothetical DOE non-reactor nuclear facility. The purpose of this effort was to evaluate when safety significant active ventilation coupled with safety class passive ventilation might be a viable control strategy.

Introduction

Ventilation is a commonly credited system to limit the release of radioactive contamination from Category 2 Nuclear Facilities. For facilities with unmitigated radiological consequences challenging or exceeding 25 rem total effective dose equivalent (TEDE), it is common to assign a Safety Class (SC) designation to these systems. For Category 2 facilities that have unmitigated consequences in the 1 to 20 rem range, the need for SC designation is less clear. The need is dependant on the conservatism in the unmitigated consequence estimate and the interpretation of what is considered to challenge the 25 rem evaluation guideline (EG). This paper focuses on the subclass of Category 2 facilities where active ventilation might be needed to protect workers during the facility evacuation, but the unmitigated offsite consequences do not significantly challenge the 25 rem TEDE EG.

Industrial (i.e., internally initiated) fire events in nuclear facilities can be grouped into four basic scenarios:

1. Fires that start in a process cabinet (e.g., hood, glove box), spread contamination to the process room but don't expand further

2. Fires that start in a process room (i.e., room containing significant quantity of radioactive material), cause the spread of radiological contamination, but don't expand further

3. Fires that start in a process room, cause the spread of radiological contamination, and expand to involve other rooms in the facility

4. Fires that start in a non-process (i.e., a room that does not contain significant quantity of radioactive material), spreads to a process room, and cause the spread of radiological contamination

The basic premise of this paper is the facility is relatively small (~1,200 m^3, 42,000 ft^3 in volume), with an air flow of about 10 changes per hour and fewer than 10 rooms. Such a facility will have a limited quantity of active HEPA filters, thus there will be a finite amount of time prior to filter pluggage and the subsequent potential for contamination spread. To assure adequate protection, workers and co-facility workers will need to be in a protected location (e.g., upwind, or sheltered) prior to filter pluggage.

In evaluating these scenarios the applicable receptors are: workers in the room where the fire starts, facility workers in neighboring rooms, co-located workers outside of the facility, and the off-site public. The demarcation for facility workers is associated with the notification process. For workers in the room of origin, notification will be through physical observation of the fire in scenarios 1, 2 and 3. For other facility workers, co-located workers, and most workers for scenario 4, some form of notification system will need to exist (e.g., automatic alarm to a central control room with subsequent PA announcement) to assure prompt evacuation. Regardless of the scenario and the notification mechanism, it is expected that workers will evacuate to a safe location or don protective gear. If workers choose to stay and manually suppress the fire, they are assumed to understand the potential for contamination spread and wear the appropriate personnel protective equipment (PPE). If the correct PPE is not available, then the workers should evacuate, and not attempt to suppress the fire.

Co-located workers (i.e., workers outside of the facility or in neighboring facilities), will also need to be notified in a timely manner so they can evacuate to an upwind rally point or to a shelter location. Notification can be through a combination of devices including automatic notification devices (e.g., fire alarms), a public address system, pagers, radios, etc. The definition of timely notification will be explored later in this paper.

Facility Description

The example facility was taken to have three basic rooms, each with a floor area of approximately 85 m^2 (910 ft^2) and a volume of 400 m^2 (14,000 ft^3). The total facility volume was taken as 1200 m^2 (42,000 ft^3). To achieve 10 air changes per hour will require a facility flow of 3.35 m^3/s (7100 scfm). If the facility has two 100 percent redundant ventilation trains each filter housing will require an approach area of six standard filter units (24” x 24”), based on a filter design capacity of 1,200 cfm per filter unit.

The CFAST model, version 5.1.1,[1] was developed for a single room, with a fan exhaust taken at an elevation of 4 meters. (See Figure 1.) The fan was considered a constant flow device (1.12 m^3/s). The ceiling and floor of the room were taken as concrete, and the walls gypsum.

The facility was considered to have both a wet-pipe sprinkler system and photo-type smoke detectors. The spacing between sprinklers was taken as 15 feet (4.6 meters), and the spacing between each sprinkler and each wall was taken as 7.5 feet (2.3 meters). Each detector was located 7.7 feet (2.35 meters) from each wall, just inside the room from each sprinkler. (See Figure 2.)

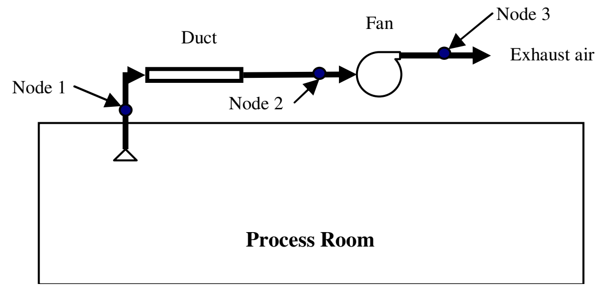

Figure 1, Model Process Room Ventilation System

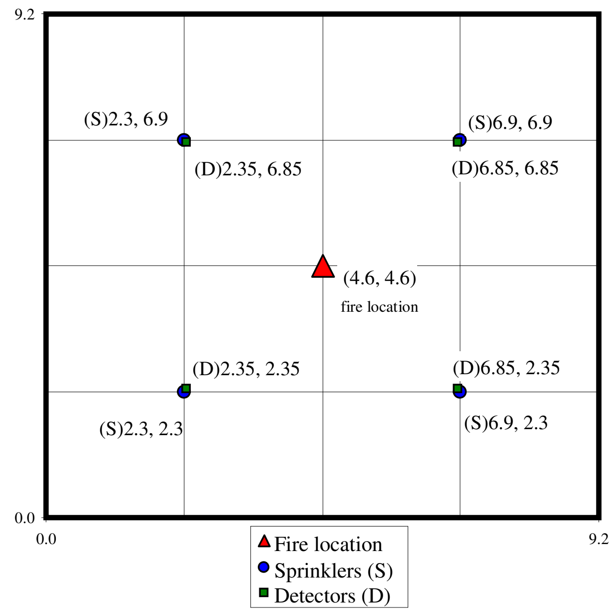

Figure 2, Simplified sprinkler and detector layout for CFAST compartment

The sprinkler system was modeled as being an ordinary hazard (Group 1) design with a sprinkler activation temperature of 57 to 77°C. [NFPA 13, Table 6.2.5.1]. The higher value was used in the model. The sprinkler Response Time Index (RTI) was taken as 200 $m^{1/2}\cdot s^{1/2}$. This value is in the upper range of Ordinary temperature rating solder type sprinklers.[2] The distance between the ceiling and the sprinkler deflector was taken as 6 inches (0.15 meters).

The elevation of the detector sensors was taken as 15.3 feet (4.67 meters), which is 3 inches below the room ceiling. The activation temperature for the detector was taken as 7.2°C above ambient for fast and ultra-fast growth rate fires and 27.8°C for medium and slow growth fires. (See NFPA 72, Table B.4.7.5.3). The Response Time Index (RTI) for the detectors was taken as 98 $m^{1/2}\cdot s^{1/2}$. While the value is not used by CFAST for smoke detectors[3] this placeholder value was used to accommodate future analysis with alternate detector types.

Modeling Inputs

The fire was considered to occur in the center of the room and involve polyethylene, which has a net heat of combustion of 43 MJ/kg and the molar weight of 28.0[4] The gaseous ignition temperature (393.15 K) was set 100 K higher than the default value of the initial fuel temperature in CFAST (i.e., 100 K higher than 293.15 K). The lower oxygen limit was taken as 12% and represents the level at which the HRR will be limited and excess pyrolysis gases will occur. The oxygen concentration threshold for this condition is in the range of 8 to 15 percent by volume[5]. CFAST has a default value of 10 percent. The 12 percent value has been accepted as good practice by the *International Collaborative Project to Evaluate Fire Models for Nuclear Power Plant Applications*.[6] The HRR from a fire is the total energy release rate, which consists of both radiation and convective terms. Typically, the radiation term is 20 to 40 percent of the total energy release rate.[7] The radiative fraction (0.3) is the midpoint of this range. The growth period of the fire was taken to have the form established in NFPA 72:[8]

$$\dot{Q} = Kt^2$$

where: $\dot{Q}$ is the HRR of the fire [kW]; t is the time from free burning [seconds]; and K is a constant established based on materials present [kW/s^2]. Table 1 provides typical values used to establish fire growth curves where the constant K is established based on the time to achieve 1,055 kW (1000 Btu/sec). Figure 3 presents the growth curves.

Table 1.—Parameters defining each fire curve.

Growth rate	NFPA 72 growth time range [Table B.2.3.2.3.6] seconds	Growth time to 1,055 kW used in fire model seconds (minutes)	K kW/s^2
Slow	$t_g \geq 400$	600 (10)	0.0029
Medium	$150 \leq t_g < 400$	300 (5)	0.0117
Fast	$t_g < 150$	150 (2.5)	0.0469
Ultra-fast	...	60 (1)	0.2931

Temperature Response

Figure 4 presents the upper layer temperature predictions for the room of origin, neglecting the effect of the sprinkler system. These temperatures are bulk average values. Local fire conditions in and near the flames will range from 900 to 1200°C.[9] The detector and sprinkler system activation times are presented in Table 2. In all cases the automatic sprinkler system is expected to control the fire before conditions become severe. For the medium, fast and ultra-fast curves, if the fire is not controlled, the room temperature approaches flashover conditions, thus flashover is assumed to occur. The effect would be ignition of most of the combustibles in the room and severe fire conditions.

For the slow growth HRR variation the room temperatures stay low, and the fire stresses will not be severe. If a control could be identified to prevent the other fire growth HRR variations, a possible safety basis strategy would be to limit the fires to the slow growth HRR curve. However, such an approach is often operationally restrictive, since contamination controls materials (e.g., plastic and paper waste) often have medium or fast growth profiles.

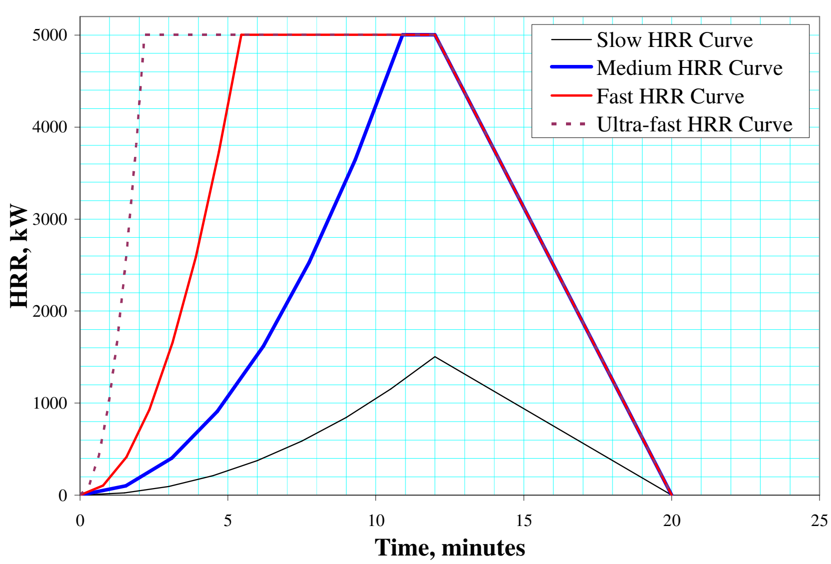

Figure 3, Growth rate curves for fire detection system design

Table 2.—Conditions at sprinkler system activation, peak temperatures and pluggage times

	Activation time, seconds		Conditions at sprinkler system activation			Maximum upper layer air temperature °C	
Growth rate	Detector system	Sprinkler system	Upper layer air temperature °C	Cumulative mass loss kg	Soot produced kg		Time at pluggage seconds
Slow	170.7	363.7	85	1.7	0.34	269	794
Medium	88.9	229.5	101	2.0	0.4	583	471
Fast	51.1	150.5	119	2.1	0.42	593	297
Ultra-fast	22.9	86.2	152	2.4	0.48	598	171

Contaminated HEPA filters have been demonstrated to successfully perform at temperatures not exceeding 150°C. Above this temperature releases from the filters were observed. The release rate in these tests started at 1E-6/min.[10] Thus, the safety basis approach should limit filter approach temperatures to 150°C, if possible. If this temperature is exceeded, it would be necessary to estimate a release from the material that is on the filter. The *Air Cleaning Handbook*[11] recommends that while HEPA filters can withstand a temperature of 399°C for an extremely limited time (on the order of 5 minutes), they should not be subjected to continuous exposure to temperatures higher than 121°C. Thus, the following evaluation criteria are proposed:

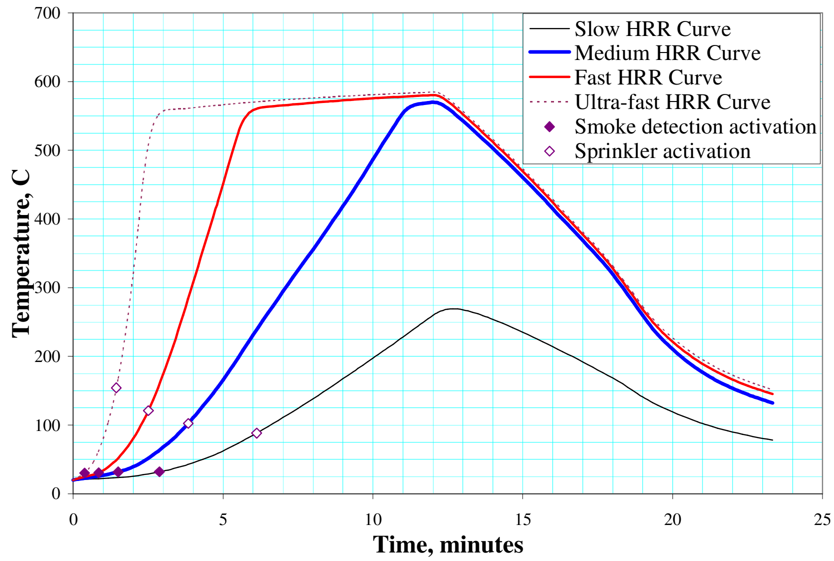

Figure 4, Temperature predictions for each HRR variation

- Filter not affected if approach temperature is below 150°C
- Limited release if approach temperature is below 399°C and does not exceed 121°C for more than 5 minutes.
- Filter does not function if approach temperature exceeds 399°C or exceeds 121°C for more than 5 minutes.

The uncertainty of temperature predictions using CFAST, where the prediction is less than 500°C, has been estimated as -30% and +40°C. For predictions greater than 500°C, the uncertainty is estimated to be -30% and +90°C.[12] Thus, temperature predictions should be adjusted appropriately to reflect the uncertainty of the predictions. When the fire is limited to a single room, the filter bank approach temperature will be approximately the weighted average of the air temperature in the three rooms (where Q_i is the volumetric flow rate). Since the rooms for the example are the same size, the weighted average is:

$$T_{filter} = \frac{T_{fire}Q_{fire} + T_2Q_2 + T_3Q_3}{3Q} \approx \frac{T_{fire} + T_2 + T_3}{3}$$

For the slow growth HRR variation, the maximum temperature without suppression system credit is 269°C (309°C with uncertainty), so the filter approach temperature based on 20°C from the other two rooms is 116°C, which is below the threshold for filter damage. For the other three variations the filter approach temperature was about 240°C, which while above the 150°C, is below the 399°C value. Thus, if filter shutdown could be accomplished in a timely manner, it would reduce the potential for an unfiltered release through the ventilation system. The timing of such an event, for the fast fire variation would be about 10 minutes (i.e., 5 minutes to reach severe fire conditions and 5 minutes to approach filter damage). Timely system shutdown or transition to the second filter bank may be a viable control strategy and provide an additional 5 minutes of evacuation time. Switching could be based on measured temperatures in the filter bank, or time from fire detection. The controls system could be automatic or manual. Given the complexities in predicting possible fire HRR variation, the better approach may be to use manual switching based on measured plenum temperatures.

Using the approach from above, the suppressed filter approach temperature predictions for the four modeled growth rates range from 128 to 194°C. The duration of this exposure will be very short (< 5 minutes) because the sprinkler system water flow will rapidly cool the room. Since the 194°C prediction is below the short term exposure criterion of 399°C for 5 minutes, the short term filter performance in terms of temperature stress is expected to be good. Thus, a control strategy combining filtration early in the event with rapid fire control would limit work consequences.

Soot Response

Table 3 presents the results from filter testing conducted at Clemson University.[13] The flow section through the HEPA bank had a flow area of a single filter unit (2’ x 2’). The tests were conducted by batching material representing a mix of combustibles that were heated in a combustion chamber. The resulting soot was drawn through the filters by an exhaust fan. Soot production was continued until the pressure drop across the filter housing reached 50 inches of water. The amount of soot deposited on each filter was determined by comparing the pre- and post-test filter weights.

Significant observations from these tests are:

- The total loading for the filter bank ranged from 570 to 740 grams.

- The prefilters absorbed most of the soot and experienced the majority of the pressure drop for the filter bank.

Table 3.—Soot captured by the filter bank during the Clemson HEPA testing[13]

	Test Run 1		Test Run 2		Test Run 3	
	Soot, grams	Percent	Soot, grams	Percent	Soot, grams	Percent
HEPA Filter	200	35.1	240	36.4	270	36.5
Prefilter	308	54.1	350	53.0	310	41.9
Roughing filter	62	10.9	70	10.6	160	21.6
Total	570	100	660	100	740	100

The average value from the three tests is 0.657 kg with a standard deviation of 85. The 90 percent coverage value for this data (single-tailed, degrees of freedom = 2, $p_{one\text{-}tailed} = 0.1$, t-statistic = 1.89).

$$m_{90\%} = \left[(657\ g) - (1.89)(85\ g)\right] = 500\ g = 0.5\ kg$$

Thus, the six filters in the example facility will have a combined soot capacity of 3 kg at 90 percent confidence. This value neglects the preloading of the filter prior to the fire. If accounted for, the mass loss to cause pluggage will be lower, perhaps by a factor of 30 percent (adjusted soot capacity would be 2.1 kg).

Soot production during a fire will vary with the type of material burning, the fuel size and the fire environment. During the early growth period (up through sprinkler activation) the fire will exhibit flaming combustion and the later items (size and environment) will not have a significant effect. Fuel size, because the fire will not have adequate time to become large, and environment, because the room conditions will not become oxygen limited. Butler and Mulholland[14] tabulated the soot fraction for flaming combustion for a variety of materials. The overall range was 0.00009 to 0.227, although for practical purposes the value ranges from 0.01 to 0.2, with plastics being in the upper part of the range and woods being in the lower portion. The actual soot fraction value of polyethylene in flaming combustion ranges from 0.015 to 0.06.[14]

When the combustion behavior is not flaming, the soot production fraction will often increase. For most circumstances with non-flaming combustion (e.g., oxygen limited combustion) the recommended soot fraction range is 0.1 to 0.3. Thus, depending on the desired degree of conservatism in the analysis, for flaming combustion a soot fraction of 0.1 or 0.2 is recommended. For non-flaming combustion the recommended value would be 0.2 or 0.3. For purposes of this paper, the value will be taken as 0.2 for both flaming conditions.

The soot production during the fire may be estimated by combining the soot fraction, f_{soot}, and the mass loss, m. The mass loss can be estimated from the pyrolysis (i.e., mass loss) rate which is coupled with the heat release rate:

$$\dot{m} = \frac{\dot{Q}}{\varepsilon \Delta H_c}$$

where: $\dot{m}$ is the mass loss (pyrolysis) rate [kg/s]; ΔH_c is the heat of combustion [kJ/kg]; and ε is the combustion efficiency [unitless]. The combustion efficiency was taken as 0.65, since the value was expected to be similar to that of a flammable liquid, and such liquids typically burn with an efficiency in the range of 60 to 70 percent.[7] Figure 5 was derived from Figure 3, estimating the cumulative mass as:

$$m_i = \frac{(\dot{m}_i + \dot{m}_{i-1})}{2}(t_i - t_{i-1})$$

where: m is the cumulative mass loss (pyrolysis) [kg]; t is the time elapsed from fire ignition [seconds]; and the subscript i represents the incremental value noted in Figure 3.

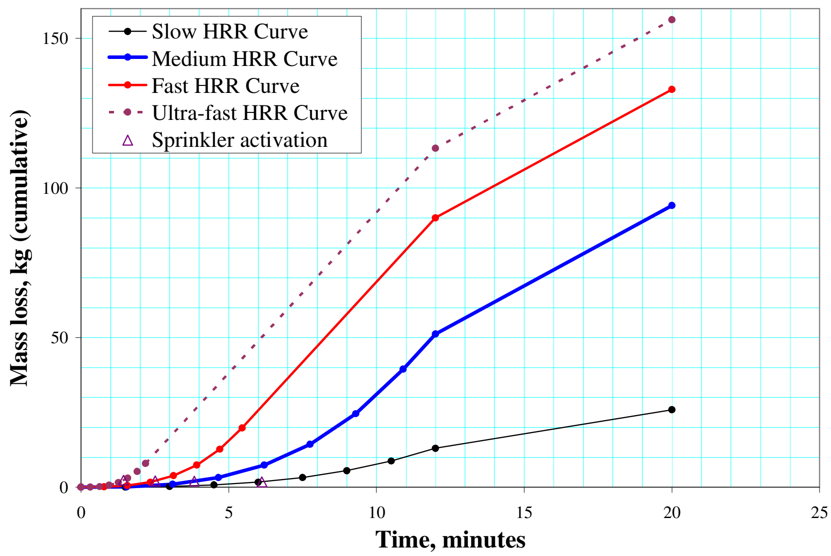

Figure 5, Cumulative mass loss for each HRR variation

The soot generation may be estimated from:

$$s = f_{soot} m$$

where: s is the soot generation [kg]; and f_{soot} is the soot fraction [unitless]. Since a value of 0.2 was used for the soot fraction, the soot estimates in Table 2 overstate the expected soot generation for fires extinguished by the sprinkler system. The margin associated with this overstatement has not been quantified. It is important to recognize that all values presented to this point would typically be considered best-estimate. For safety basis purposes, it is suggested that the soot fraction estimates at suppression system activation may be considered reasonably conservative.

The time to pluggage values presented in Table 2 were estimated from the Figure 5 data for a mass loss of 15 kg (3 kg soot ÷ 0.2). With the exception of the slow growth HRR variation, the conclusion that the filter will plug is not sensitive to the soot fraction (i.e., 100 kg mass loss x×0.05 = 5 kg, which exceeds the capability of the filters). For a soot fraction of 0.2, the total mass loss from the fire would need to be 15 kg. Thus, the soot fraction assumption has little affect on the conclusion about pluggage (It should be expected if the fire is not extinguished by the suppression system), but it will affect the timing of pluggage.

Results

In selecting the controls for the hypothetical facility in this paper, the need for active ventilation to protect workers early in the event during evacuation is apparent. The required evaluation timing is on the order of about 10 minutes, if the sprinkler system is not credited to limit fire growth, automatic switching between filter banks occurs on high pressure drop, and ultra-fast fires are avoided. The latter requirement (ultra-fast fire prohibition) is required because the predicted pluggage time for the first filter bank is about 3 minutes, which is judged insufficient to provide worker evacuation. The avoidance of ultra-fast fires could be accomplished through a programmatic control that limited the quantity of flammable and combustible liquids permitted into the facility. If reduced reliance on evacuation timing is desired, consideration to assigning an SS designation to the suppression system should be considered

If the sprinkler system is credited to extinguish or control the fire, the soot generation rate will be reduced, combustibles involving ultra-fast fires can be permitted, and the timing of the worker evacuation becomes less critical. For either approach, the active ventilation system would be considered to be SS as a minimum.

For public protection, the nature of the stated problem implies an SC control may not be warranted, however it is recognized that an SC control may be desirable for facilities with unmitigated doses in the 5 to 20 TEDE rem range. For the hypothetical facility the ventilation system operating in a passive mode, coupled with the building envelope will limit the off-site consequences. If these features are designated to be SC, consideration should be given to a qualitative evaluation of the mitigated consequences. Such an approach is technically defensible, and cost effective.

Conclusion

Analytical methods have been demonstrated to estimate room fire conditions, the timing of fire protection system activations, and the expected timing of ventilation system degradation. The analysis was conducted using conservative techniques that account for the expected fire protection system responses. From this information, it is possible to evaluate the effectiveness of safety basis controls strategies involving combinations of active ventilation, combustible controls, automatic suppression, and building evacuation. This provides a foundation to support discussions of the pros and cons of various safety basis strategies, which can be used to establish facility-specific safety basis strategies.

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