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CONVECTIVE HEAT EXPOSURE FROM LARGE FIRES TO THE FINAL FILTERS OF VENTILATION SYSTEMS

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ABSTRACT

The Fire Science Group of the Hazards Control Department, Lawrence Livermore Laboratory has been asked to design a probable fire scenario for a fuel-pellet fabrication facility. Using this model we were to estimate the potential for thermal damage to the final HEPA filters. These filters would not experience direct fire exposure because they are the last component of the ventilation system before the exhaust air pumps. However, they would be exposed to hot air and fire gases that are drawn into the ventilation system. Because fire is one of the few occurrences that can defeat the containment integrity of facilities where radioactive materials are stored and processed, the fire scenarios must be defined to ensure that containment systems are adequate to meet the threat of such events.

Fire-growth calculations are based on the measured fuel load of materials within the fabrication enclosure and on semi-empirical fire-spread models. We assume that the fire never becomes ventilation controlled. The temperature rise of ceiling gases and heat transfer from ventilation ducting are calculated using accepted empirical relationships, and the analysis shows that even under the most severe exposure conditions, heat transfer from the duct reduces the fire gas temperatures to levels that would not hamper filter function.

INTRODUCTION

In facilities where toxic materials are handled or stored, a large portion of maintenance and safety funds are devoted to ensuring the containment of the hazardous materials. The containment criteria usually involve several safeguard systems. Of these, the ventilation system is of prime importance.

Standard procedures and guidelines for installing and maintaining ventilation systems have been developed for nuclear material fabrication facilities. These systems ensure that potential toxic particles are contained by passing the air through several high-efficiency filters located in the exit-duct network. The filters, known as high-efficiency particulate air filters (HEPA), are in the ventilation system downstream of the protected enclosures where, to prevent leakage of the hazardous materials to the environment, the ambient pressure is maintained lower than that of the atmosphere.

Because these filters are intricately designed and must function flawlessly over a wide range of operational conditions for long periods, they must be protected against the heat and smoke aerosols from fires that occur within the enclosures. Therefore, in order for the system to perform its primary function—protect the environment during normal or emergency operations—it must be equipped with its own protection system.

The Lawrence Livermore Laboratory (LLL), supported by the Department of Energy, is currently conducting a research program to investigate the protection systems for HEPA filters that are exposed to products from enclosure fires. Early experiments¹ have proven that the filters are susceptible to thermal damage and to blockage by smoke aerosols. Because heat exposure may be reduced simply by installing the filters at a sufficient distance from the heat source, most studies of fire effects on HEPA filters have focused only on the mechanisms of smoke-plugging and developing countermeasures to reduce the concentration of the plugging aerosols. However, to be relicensed by the Nuclear Regulatory Commission, existing nuclear

materials facilities must demonstrate that their ventilation systems can remain functional during a defined, maximum-credible fire experience. Yet, no guidelines have been established to predict either fire growth and size or the heat balance between combustion gases and ventilation components.

The Fire Science Group of the Hazards Control Department, ILL, was asked to help design a maximum credible fire portrait for a facility that was due for relicensing. We were also asked to estimate the heat exposure to the final HEPA filters of the main ventilation system. A schematic of a glove-box processing station shown in Fig. 1 is an example of the containment system of a nuclear-processing plant. Figure 2, a photograph of a glove-box facility, shows a major potential fuel source—glove boxes. Glove boxes usually have windows made of materials (usually PMMA*) to allow good visual contact of the item being handled. Other major flammable materials in a nuclear processing plant include

- Rubber gloves
- Window materials (PMMA or polycarbonate)
- Paper materials
- Wooden furniture and structural materials
- Polyvinyl chloride (PVC) ducts and hoods
- Polyethylene film and components
- Electrical and thermal insulators
- Solvents

*Polymethyl methacrylate

FIG. 1. Typical ventilation system for a glove-box processing station in a nuclear-processing plant. a—final high-efficiency filter; b—air-supply duct; c—perforated ceiling tile; d—high-efficiency filters; e—air-supply grills; f—prefilter; g—glove box; h—exhaust filter; i—inlet filter; j—air attenuator (mixing box); k—air-supply ducts.

FIG. 2. Glove-box facility.

In our pragmatic analysis we used currently accepted fire models and scaling criteria based on empirical data to simulate the hypothetical burning behavior of combustible materials in the analyzed space designated as FAB 1. From time-dependent growth-rate models, which predict the freely ventilated heat-release rate of the various fuels in FAB 1, we estimated both the average heat-release rate at the peak of burning and the minimum duration of the fire (assuming that the burning rate remains constant after it achieves its maximum value). Using this information, we can calculate the approximate temperature rise of the combustion-heated air and combustion products above the fuel at appropriate vertical and horizontal distances from the combustion zone. Assuming that these hot gases are drawn into the exhaust-duct network, we can calculate the heat lost to the duct by the gas as it transits the main ventilation system. As a result of the heat loss, the gas temperature gradually decreases. The temperature of the gas as it reaches the filter stations is assumed to be the exposure temperature.

ANALYSIS

The endurance of HEPA filters to hot air flow is shown in Fig. 3. These data are for standard, pressed, fiberglass filters encased in metal or wood frames. A high-temperature sealant (HT-30-FR) is used to attach the filters to the frames. We have drawn straight lines between data points because we extracted this information from tabular data.² The endurance of the filter is nearly inversely proportional to the exposure temperature above 300°F (148°C); the effect of exposure temperature below this temperature is minimal. These data indicate that the filters may be expected to last indefinitely if the air temperature is below approximately 180°F (82°C).

The parameters that determine fire spread and heat-release rate, and ultimately the temperature of the combustion gases that enter the ventilation system, are shown in Fig. 4. A large surface-to-volume ratio of the fuel source is a conservative condition that will ensure maximum temperature rise; the burning is never

FIG. 3. Effects of air temperature on HEPA filter endurance.

curtailed from lack of ventilation. Figure 5 shows the fire growth (in terms of heat-release rate) of three empirically derived models.³⁻⁵

Although each model is based on sound technical reasoning and empirical data, they differ from each other in the induction period between initiation and maximum steady-state burning by a factor of five. The measured fuel loads of materials in FAB 1 (Table 1) were used in these calculations. The fuel weight is converted to total potential heat release based on data from Ref. 2. The time to total fuel consumption for the Coulbert A model (the fastest growth rate) is approximately 30 min for the Alger model (slowest growth rate), the time to total fuel consumption is 70 min. Note, these durations include the growth period up to and including the steady-state burning period but not the reduction in burning rate during the burnout phase. Although the actual duration of burnout would be longer for these fuel arrays, their rate of heat release would be reduced.

For a conservative analysis we have used the heat-release rate derived from the Coulbert A model, averaged over the steady-state burning period until burnout (about 25 min) to define the temperature gradient

FIG. 4. Factors influencing rate of fire spread.

TABLE 1. Measured fuel loads of materials in FAB 1.

Material	Total weight, lb (kg)	Heat of combustion Btu (W·s/gm)	Heat content BTU (W·s)
Polyvinyl chloride	490 (223)	7,720 (17,910)	3.8×10^6 (4.0)
Wood (cellulose)	340 (155)	7,160 (16,680)	2.4×10^6 (2.6 $\times 10^9$)
Polymethyl methacrylate (PMMA)	520 (236)	11,470 (26,610)	6.0×10^6 (6.3 $\times 10^9$)
Rubber gloves (butadiene/styrene copolymer/GRS/rubber)	210 (95.5)	19,010 (44,100)	4.0×10^6 (4.2 $\times 10^9$)
		Total heat content	16.2×10^6 (17.1 $\times 10^9$)

FIG. 5. Heat-release rates from freely ventilated fires for three empirically derived fire models.

in the FAB 1 ceiling. The total energy released during this period is 274 MW; therefore, the average heat-release rate is:

$$\dot{Q} = \frac{274 \text{ MW}}{25 \text{ min}} = 11.0 \text{ MW/min}$$

The temperature gradient in the induced ceiling flow field resulting from the fire plume can be found, knowing the average heat release rate.⁶

We are vitally concerned with the air temperature introduced into the inlet of the exhaust duct in FAB 1. However, not knowing the horizontal location of the fire relative to the location of the inlet duct in the ceiling, we will choose two hypothetical locations: (1) the inlet duct is not directly above the fire, but displaced laterally to a radial location in the ceiling (the chosen radius is compatible with the dimensions of the critical area of FAB 1); (2) the inlet duct is directly above the fire.

In Case 1, the equivalent radial distance of the hypothetical exhaust inlet is 20.5 ft (5.65 m) from the point in the ceiling directly over the fire. Figure 6 schematically shows the most important dimensions of FAB 1 and the two hypothetical exhaust-duct entrances. The temperature of the fire gases at the ceiling is known to depend on the radial distance away from the stagnation plane of the ceiling jet. The temperature level at both hypothetical positions are calculated using the following equations⁷:

Case 1

$$T - T_{\infty} = 4.74 \frac{(\dot{Q}/r)^{2/3}}{H}, \text{ for } r > 0.18 H \quad (1)$$

Case 2

$$T - T_{\infty} = 14.9 \frac{\dot{Q}^{2/3}}{H^{2/3}}, \text{ for } r \leq 0.18 H \quad (2)$$

where

$\dot{Q}$ = heat-release rate,

r = radial distance along the ceiling—20.5 ft (5.65 m) for Case 1 and 0 ft for Case 2,

H = room height,

T = temperature,

T_{∞} = ambient temperature—approximately 72°F (22°C).

As calculated in Eq. (1) for Case 1, the air temperature at the exhaust-duct entrance is 343°F (173°C), a temperature most HEPA filters could effectively perform at for more than an hour. With moderate heat loss along the duct, the decrease in the gas temperature between the entrance and the filter location is expected to be substantial; therefore, thermal damage to the filter would be minimal.

In Eq. (2) for Case 2, the air temperature at the exhaust duct entrance is 1039°F (560°C). Given this inlet temperature, we need to calculate the gas temperature reduction as it transits the duct, considering the heat losses to and through the duct.

Figure 7 is a schematic of the exhaust duct and HEPA filter arrangement of FAB 1. Indicated on the schematic are the duct dimensions and the normal flow rate of the air. Reynolds number calculations show that the flow is turbulent.

FIG. 6. Diagram of a fire-induced ceiling jet. Dashed lines indicates boundary of plume or ceiling jet with ceiling air.

The heat loss from horizontal tubes such as these, by natural convection, is the subject of considerable analysis. The analysis, however, becomes more difficult when the heat-transfer coefficient is a complex combination of both radiative and convective mechanisms. Fortunately, these conditions are similar to heat exchanger problems, and empirical data are available on combined heat-transfer coefficients for heat exchangers.

FIG. 7. Exhaust duct and filter arrangement for FAB I.

From the simple heat exchanger treatment in Giedt,⁸ we note that the thermal balance between the hot and cold fluid of a co-flow heat exchanger is

$$dq/dT = h dA, \quad (3)$$

where dq and dT are respectively the heat transfer rate and differential gas temperature (both parameters of the fluid temperatures); dA is the incremental area; and h is the overall heat transfer coefficient, considered constant over the length of the duct. We can manipulate this relationship in terms of enthalpy exchange between the heat exchanger fluids and assume that the cooling fluid (in our case, the outside air) remains at a nearly constant temperature (i.e., convection from an infinite reservoir). By integrating this relation, we get the equation for the cooling of gases in a horizontal duct by convection and radiation:

$$\Delta T_{out} = \Delta T_{in} \exp(-hA/WC_p). \quad (4)$$

where

A = total outside pipe area,

W = air mass flow rate (weight time),

C_p = air-heat capacity,

$\Delta T = T - T_x$

The subscripts *out* and *in* represent the condition of the fluid at the entrance and exit of the heat exchanger, respectively. As mentioned previously, the overall heat-transfer coefficient must include components for both radiation and convection losses. Experimental values of *h* for combined radiation and convection heat transfer are given in Table 2⁹ for horizontal pipes of various diameters and for different magnitudes of ΔT between the pipe temperature and the outside air. The duct temperature at the entrance will be higher than that at the exit because of the heat transfer. Consequently, to define the heat-transfer coefficient, we must estimate an average ΔT . The temperature drop of the combustion gases is estimated to be about 600°F (316°C) over the length of the duct; thus, the estimated average duct-surface temperature is 700°F* (492°C). By interpolating the data in Table 2 for a 1.5-ft-diam (0.48 m) pipe, we arrive at a combined heat-transfer coefficient: $h = 6.6 \text{ Btu/hr}\cdot\text{ft}^2\cdot^\circ\text{F}$ ($3.7 \times 10^{-3} \text{ W/cm}^2\cdot^\circ\text{C}$).

The data used to calculate the gas temperature at the filters is shown in Table 3. Using Eq. (4) we calculate T_{out} (the gas temperature exposure to the HEPA filter) to be 332°F (167°C). Figure 3 indicates that

$$\frac{1000 + 400}{2} = 700 \text{ (}^\circ\text{F)}$$

TABLE 2. Measured combined radiative and convective heat transfer values from circular ducts ($h_c + h_r = h$).

Nominal pipe diameter in. (cm)	Temperature difference between pipe surface and outside air (ΔT , $^{\circ}\text{F}$)														
	50 (10)	100 (35)	150 (65)	200 (94)	250 (121)	300 (149)	400 (204)	500 (260)	600 (316)	700 (371)	800 (427)	900 (482)	1000 (538)	1100 (593)	1200 (649)
1.2 (1.27)	2.12	2.48	2.72	3.10	3.41	3.75	4.47	5.30	6.21	7.25	8.40	9.73	11.20	12.81	14.65
1 (2.54)	2.03	2.38	2.65	2.98	3.29	3.62	4.33	5.16	6.07	7.11	8.25	9.57	11.04	12.65	14.48
2 (5.08)	1.93	2.27	2.52	2.85	3.14	3.47	4.18	4.99	5.89	6.92	8.07	9.38	10.85	12.46	14.28
4 (10.16)	1.84	2.16	2.41	2.72	3.01	3.33	4.02	4.83	5.72	6.75	7.89	9.21	10.66	12.27	14.04
8 (20.32)	1.76	2.06	2.29	2.60	2.89	3.20	3.88	4.68	5.57	6.60	7.73	9.05	10.50	12.10	13.93
12 (30.48)	1.71	2.01	2.24	2.54	2.82	3.13	3.83	4.61	5.50	6.52	7.65	8.96	10.42	12.03	13.84
24 (60.96)	1.64	1.93	2.15	2.45	2.72	3.03	3.70	4.48	5.37	6.39	7.52	8.83	10.28	11.90	13.70

TABLE 3. Data used in calculating gas temperatures at the filters.

Parameter	Value
Hot gas temperature (T_{Hot})	1040°F (560°C)
Ambient air temperature (T_{∞})	72°F (22°C)
$T_{\text{Hot}} - T_{\infty} = \Delta T_{\text{in}}$	960°F (516°C)
$h_{\text{convection}} + h_{\text{radiation}} = h$	6.6 Btu/hr/ft ² ·°F ($3.7 \times 10^{-3} \text{ W}\cdot\text{s/cm}^2\cdot^\circ\text{C}$)
Hot gas mass flowrate ($\dot{W}$)	11,160 lb/hr (5070 kg/hr)
Hot gas heat capacity (C_p)	0.25 Btu/lb·°F (1.0 W·s/gm·°C)

this temperature level will not hamper the filter's performance for periods up to 100 min. Moreover, if we arbitrarily reduce h to half of the estimated value, or $3.3 \text{ Btu/hr ft}^2 \text{ }^\circ\text{F}$ ($1.9 \times 10^{-3} \text{ W/m}^2 \text{ }^\circ\text{C}$), the exposure gas temperature would be $T_{\text{gas}} = 574^\circ\text{F}$ (301°C), which indicates a HEPA filter temperature endurance time of more than 30 min.

DISCUSSION

From the preceding analysis it is obvious that cooling the combustion gases entrained in ventilation ducts is extremely important in reducing the severity of thermal exposure to the final filters of a ventilation system. This analysis is extremely conservative, because we prescribe very severe burning experiences without including heat losses to enclosure surfaces. Further omitted are variations in burnout dynamics; energy partitions for heat feed-back; smoke-aerosol conversion; and the poor flammable characteristics of the polyvinyl chloride ducts and other construction materials.

Most facilities containing toxic substances are constructed of very sturdy materials with uncluttered and orderly interiors to reduce the opportunity for poor housecleaning. Moreover, because sophisticated fire-protection systems are generally adopted to prevent catastrophic fires in fabrication spaces, there is a low probability of substantial fire growth. If a large fire does occur, and fire gases enter the ventilation systems, the present analysis shows that the heat losses in long ducts will allow continuous filter protection until active fire-fighting measures are taken.*

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*Note again, this paper studies only the effects of heat on filter endurance. Studies on smoke plugging phenomenon are in progress at this laboratory and elsewhere.