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IN-DUCT COUNTERMEASURES FOR REDUCING FIRE-GENERATED-SMOKE-AEROSOL EXPOSURE TO HEPA FILTERS *

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Abstract

An experimental program was conducted to assess the endurance and lifetime of HEPA filters exposed to fire-generated aerosols, and to reduce the aerosol exposure by installing engineering countermeasures in the duct between the fire source and HEPA filters.

Large cribs of wood and other potential fuels of interest were "forcefully burned" in a partially ventilated enclosure. In a "forceful burn" the crib of fuel is continuously exposed to an energetic premixed methane flame during the entire experimental period. This tactic serves two purposes: (1) It optimizes the production of smoke rich in unburned pyrolyzates which provides severe exposure to the filters, and (2) It facilitates the ignition and enhances the combustion of cribs formed with synthetic polymers.

The fuel cribs vary in size but have similar weight (~200 kg). The crib elements were natural and synthetic polymers; i.e., polyvinyl chlorides, polymethyl methacrylate (fire retarded), polycarbonate, dense fiberboard, wood, or combinations thereof. These elements are approximately 16 cm^2 in cross sectional area by 90 and 120 cm in length. The elements are either closely packed where the spacing dimensions are identical to the element cross section, or relatively loosely packed where the elements are supported by a metal framework. Some of these materials required a metal framework with a wire screen "floor" at alternate layers to prevent sagging. Wood cribs supported by the same type of framework burned at a faster rate, indicating a somewhat greater lateral crib porosity.

The experiments were conducted in an enclosure specifically designed and instrumented for fire tests. The test cell has a volume of 100 m^3 and includes instrumentation to measure the internal temperature distribution, pressure, thermal radiation field, flow fields, gas concentration, particulate size distribution and mass, fuel weight loss, inlet and exit air velocities, and smoke optical density.

The countermeasure techniques include the use of passively operated sprinkler systems in the fire test cell, of fine and dense water scrubbing sprays, and of rolling prefiltration systems in the exit duct of the fire test cell. Of the countermeasures surveyed, the rolling prefilter system showed the most promise, since it extended HEPA filter lifetimes by factors of two or more.

This paper will concentrate on the effect of control variables; i.e., enclosure air supply, fuel composition and crib porosity on the combustion response; i.e., crib burning rate, enclosure temperature rise, oxygen consumption, and CO, CO_2 and total hydrocarbon production. A discussion of the attempts to rationalize smoke aerosol properties, i.e., aerosol mass-and-size distribution on filter plugging phenomena will be included along with results from the effect of countermeasure application on HEPA filter lifetimes.

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I. Introduction

An unwanted fire in a space containing radioactive materials can compromise containment measures more dramatically than any threat other than explosion as fire can reduce solids and liquids to aerodynamic aerosols and provide the convective flow to distribute them. The methods by which fire defeats standard containment devices and practices include:

- Overpressurizing the space by generating more gas than can flow through the ventilation.
- Overpressurizing the space by plugging the HEPA filters in exhaust ducts with smoke aerosol.
- Breaching the filter by temperature degradation of the filter media.
- Penetrating the filter with evaporated volatile pyrolysis fractions.

We have attempted to identify through testing some practical and cost-effective countermeasures that will, for a reasonable period, protect HEPA filters from the products of such fires. While a normal HEPA filter lasts from 6 to 24 mo depending on exposure conditions, the duration of exposure prior to HEPA plugging or high-temperature breaching during a severe and smoky fire may be reduced to 5 min. Exposure duration is controlled by the type and geometry of the fuel and by the ventilation patterns of the enclosure. Thus, the device or procedure ultimately used as a countermeasure to protect HEPA systems from potentially high smoke and heat exposure must be capable of increasing the smoke exposure filtration so it lasts through the fire brigade attack and until the source fire is controlled.

The primary purpose of our tests then is to make smoke; this we do in the test cell shown schematically in Fig. 1. We described this test cell and its capabilities in detail in the 14th Conference[1] along with details of some preliminary

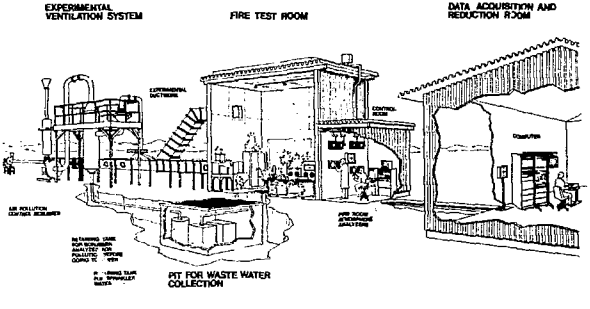

Fig. 1. Full-scale fire test facility.

tests in which we installed laboratory furnishings and appliances in the test cell as fuel items. We indicated a major problem with using such items in a quasi-normal array was the nonuniformity of the flame spread and, consequently, of the smoke production. What we needed was a reproducible but severe source of smoke so we could appraise the effects of various countermeasures to increase the smoke exposure lifetimes of HEPA filters.

Our solution was to employ cribs (cross piles of fuel)—a fuel array traditionally accepted in fire research. We selected our fuel elements from materials abundant in laboratories where radioactive materials are used or stored. We tested several crib arrangements and fuel element distributions, finally deciding on a series of configurations particular to various fuels that would provide a moderate fuel load (1 to 2 lb/ft^2) for the test cell. Figure 2 shows three crib arrays: the top plate shows a natural crib of wood with element dimensions of 1.5 in. on a side and 3.5 ft in length. This "high porosity"[2] factor (i.e., very close element spacing) reduces the burning rate of the fuel. The second plate shows a crib of wood whose alternate layers are supported on a metal framework. The framework supports plastic fuels that soften and flow during flame exposure, as shown in the third plate of Fig. 2. Since a significant proportion of our fuels are synthetic polymers, we have opted to contain all fuel elements in the same type of support grid. This geometry results in a somewhat lower porosity than the natural crib; hence, the burning characteristics are accelerated.

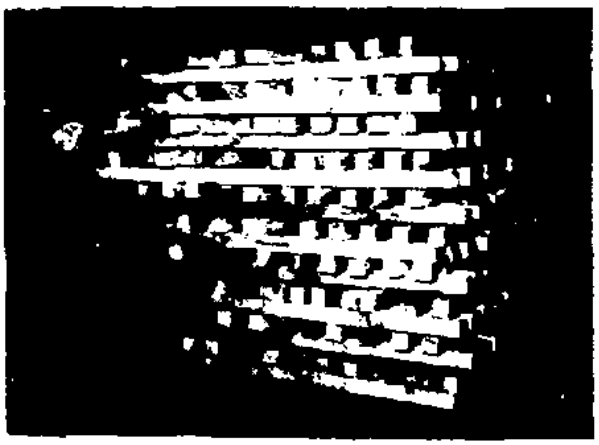

Plate 1

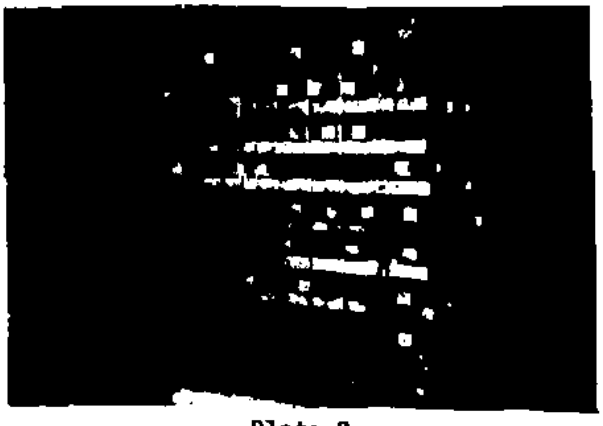

Plate 2

Plate 3

Fig. 2. Crib arrangements for fire tests.

The effects of crib spacing and ventilation rate on crib burning are shown in Fig. 3. The differences in time to peak burning for PB-8 and B-1 illustrate the effect of crib porosity. However, they exhibit a similar trend due to the effects of ventilation control of the combustion processes; that is, temperature reduction after a high intensity phase was indicative of oxygen starvation in tests PB-8 and B-1. In test PB-7, however, the ventilation rate was sufficient to allow active combustion over the entire test period.

Figure 4 indicates how the characters of different burning polymers compared to that of a fir wood crib. The B-3 curve illustrates the behavior of a fire-retarded PMMA* by its temperature response; although it takes a relatively long time to ignite, once ignited it burns with fierce intensity. The combustion response of polycarbonate is shown by the B-11 labeled curve. Polycarbonate material burns with a high heat and smoke release rate.

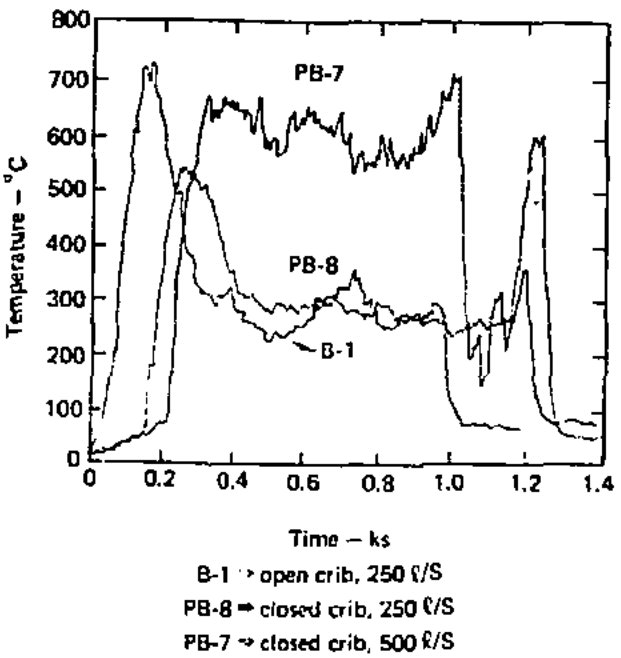

Fig. 3. Effects of crib spacing and ventilation rate on crib burning.

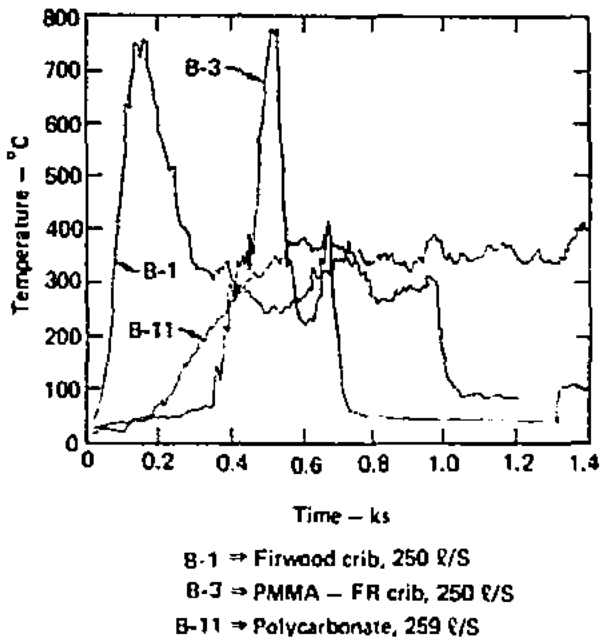

Fig. 4. Comparison of the characters of burning polymers to that of a fir wood crib.

Figure 5 illustrates the selected fir and airflow parameters we surveyed during each test. Burn 29 was a supported wood crib (i.e., the standard fuel array used for correlation tests). The displayed data are: plume temperature (T°C), oxygen concentration [O_2], burning rate or fuel consumption (m), airflow through the ventilation duct (ℓ/s), and pressure drop across the HEPA filter (ΔP HEPA). When airflow through the HEPA filter reached half the initial flow rate, indicated by the cross on the airflow curve, we considered the filter plugged and terminated the test. We conducted comparative analyses with data taken at the temperature peak and again just prior to significant flow reduction. (In Fig. 5, this would be approximately 400 s). Along with the indicated data, we measured total aerosol concentration and rough aerosol size distribution at the exit to the test cell and just upstream of the HEPA filter. Moreover, we used cryogenic techniques to trap grab samples of aerosol and combustion gas both up and downstream of the filter for chemical analysis.

* Polymethylmethacrylate

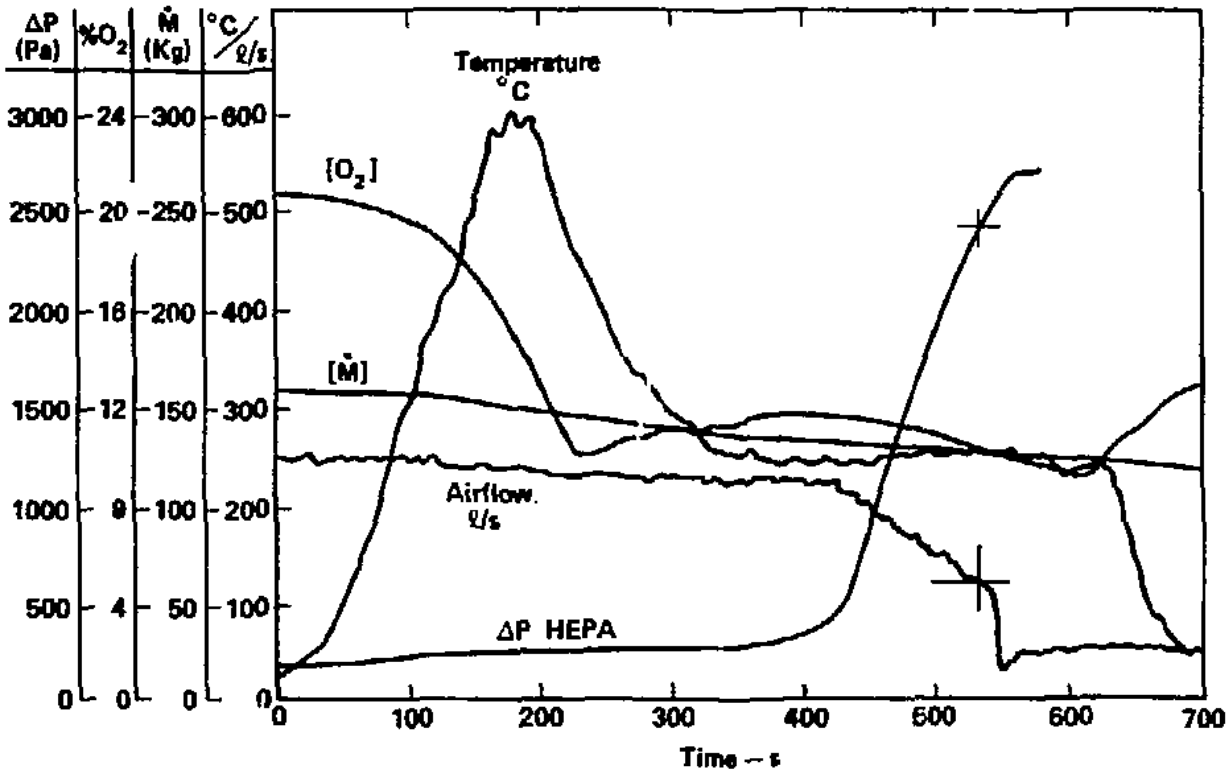

Fig. 5. Selected fir and airflow parameters.

II. Measurements

Because our ignition burner continues to burn throughout the exposure, our crib fires very likely produce more smoke aerosols than would a free-burning crib. For the same reason, the induction period to full burning intensity and, subsequently, to ventilation control is shorter. We are thus able to describe and control the dynamic aspects of our fire source with some degree of success; that is, given the material and a description of the crib parameters, we can approximately predict the combustion response. However, we have been totally unsuccessful in our attempts to characterize smoke aerosols. We can gain some idea of the magnitude of excess pyrolyzate* by comparing the measured weight loss, $\dot{m}$, to the fuel consumption potential as calculated by the oxygen consumption during a stoichiometric combination of fuel and oxygen to products[3]. Table 1 shows this comparison for some early tests and indicates an order-of-magnitude estimate of the unburned pyrolysis, which, in almost all cases, is of the same magnitude or of greater magnitude than the burned fractions.

Our attempts to measure the size and mass distribution of smoke aerosols were fraught with complications, mainly because of the high aerosol concentration as indicated in Table 1. Moreover, the chemical and physical interactions in dense aerosols from any source made such measurements almost impossible. Kinetic processes such as agglomeration, evaporation, deposition, gradiation, fallout electrostatics, chemical change, and adsorption caused the aerosol to change its character during both sampling and measurement procedures. Regardless of these complications, we took a continuous series of aerosol mass and mass distribution measurements using cascade impactors positioned near the exit to the test cell and at the upstream surface of the HEPA filter. Table 2 summarizes these measurements.

* Partially oxidized pyrolysis fractions that can occur during ventilation-limited combustion processes.

Table I. Gross estimates of excess pyrolyzate.

Test	Material	Measured fuel mass loss, $\dot{m}_f$ (kg/s)	Calculated fuel consumption from oxygen depletion measurements, $\dot{m}_o$ (kg/s)	Gross excess pyrolyzate, $\dot{m}_f - \dot{m}_o$ (g/s)
PB-7	Fir wood[a]	0.13	0.086	44
B-1	Fir wood	0.12	0.041	89
B-3	PMMA-FR[b]	0.028	0.003	25
B-11	Polycarbonate	0.037	0.019	18
B-15	Dense fiberboard	0.080	0.049	31
B-17	Polyvinyl chloride	0.020	0.008	12
B-18	Fiber-reinforced polyester	0.020	0.020	0
B-20	Composite[c]	0.020	0.016	4
B-21	Fir wood[d]	0.10	0.043	57
B-28	Fir wood[e]	0.1/0.06[g]	0.038	42[h]
B-36	Fir wood[f]	0.097/0.058[g]	0.089	8
B-38	Composite	0.05	0.023	27

[a] 500-ℓ/s air supply and low-porosity crib.
[b] Polymethylmethacrylate – fire retarded.
[c] Crib made with fir wood, PMMA-FR, polycarbonate, fiber-reinforced polyester, and polyvinyl chloride.
[d] Low air intake and exhaust duct.
[e] High air intake and exhaust duct.
[f] 500-ℓ/s air supply.
[g] Varies with time for high air intake and exhaust duct tests.
[h] Based on average $\dot{m}_f$.

TABLE II. Cascade impactor data

		Impactor at exit of test cell				Impactor at HEPA station			
Test	Material for crib	Conc, mg/m^3	Gross mass distribution d > 3	d > 1	d < 1[a]	Conc, mg/m^3	Gross mass distribution d > 3	d > 1	d < 1[a]
PB-7	Tight fir wood					0.001	82	2	16
B-2	Loose fir wood					0.005	3	60	37
B-3	PMMA-FR					0.001	3	44	53
B-11	Polycarbonate					0.0007	14	58	28
B-15	Dense fiberboard	0.002	12	71	17	0.002	6	67	27
B-17	Polyvinyl chloride	0.002	10	69	21	0.002	10	63	27
B-18	Fiber-reinforced polyester	0.001	61	21	18	0.002	56	15	29
B-20	Composite	0.006	42	57	1	0.005	25	72	3
B-21	Loose fir wood	0.013	62	32	6	0.009	49	23	28
B-28	Loose fir wood	0.006	68	25	7	0.002	89	0	11

[a] d = Aerosol diameter in microns.

The weighing protocol for most measurements listed in Table 2 called for holding the filter papers at 60°C for 24 hr before and after measurement. Obviously, we lost all volatile fractions that vaporize at temperatures below 60°C. Even so, the total concentration of solid-phase aerosol appeared to range around 0.002 kg/m^3 (2 g/m^3). Note, that while we indicate size range, we view these data with reservation. Our total mass measurements of solid-phase aerosol are probably as reliable as anyones.

We knew that by drying the filter after aerosol sampling, we were losing some proportion of the actual in duct aerosol mass. We determined this by sealing the impactors after sampling and by weighing the filters as soon as possible after terminating the test. Then we dried the filters at 60°C and reweighed them. The difference in total mass between the initial and final weighing was a factor of 6 at both the test cell exit and the HEPA exposure surface. Subsequent measurements indicated mass distribution shifts from large (d>3μ) to small (d<1μ) particles - an expected trend.

III. HEPA Filter Performance

Table 3 summarizes HEPA filter performance for all tests conducted during this experimental series. Included in the table are fuel consumption ($\dot{m}$), oxygen depletion ($[O_2]^-$, time to filter plugging (t_{plug}), dry bulb temperature at the filter (T_{DB}), measured total aerosol mass at t_{plug} and calculated excess pyrolyzate These data show the remarkable ability of HEPA filters to perform well even when exposed to very dense aerosol loads. The shortest time to plug, for an unprotected filter was 320 s, and the measured maximum aerosol mass was 7 gm/m^3 (measured from a dry impactor filter array). Since the flow was 250 ℓ/s, the imposed aerosol load was at least 1.75 gm/s and was quite likely much more.

An aspect that modified filter performance was the temperature level at the HEPA station. For dry bulb temperatures of 120°C or higher, the time to plug was significantly longer; in some cases at high temperatures, the filter did not plug. It appeared that some major plugging components of the smoke aerosols remained in gas phase at temperatures greater than 110°C and, consequently, were not adsorbed by the HEPA. This observation was supported by the fact that condensed vapors were observed leaving the exit stack when high-temperature conditions were maintained in the duct and by the chemical determination of hydrocarbon compounds from grab samples taken downstream of the filter.

Table 4 shows that fuel condition and ventilation variables can also affect the HEPA's plugging performance.* The major variable here was supposed to be the ventilation pattern in the test cell, which was equipped with a high and low exit port and two high and low air-inlet ports. [We always use two air inlets (low or high) and one exit port (low or high)]. The first column lists the test number, date, and inlet/exit configuration. The data show that $\dot{m}$ did not vary drastically with the ventilation pattern except for test B-13, where we closed the inlet and found our test cell leaked almost as well as our inlet ducts. [We have subsequently sealed all leaks.]

We also noted that with the Hi/Hi ventilation configuration, the $\dot{m}$ measurement appeared to have a variable character. Most baffling, however, was test B-30; here the filter did not plug. True, the T_{DB} reached 120°C, but we had plugged filters with this condition before. On checking our fuel, we found the wood elements had a 20% average moisture content. Our literature search indicated

* These data are from wood cribs only.

Table III. Review of test data and HEPA filter response for May 28, 1976 to July 15, 1978.

Test	Fuel	Geometry	Countermeasure	Ventilation rate (ℓ/s)	Ventilation geometry Inlet/ Outlet	Rate of measured fuel mass loss, $\dot{m}$ (kg/s)	Oxygen depletion (%)	Dry bulb temperature at HEPA, T_{db} (°C)	Time to plug, t_p (ks)	Calculated excess pyrolysate (g/s)	Measured aerosol mass (g/m^2)
PB-7	Fir wood	Nonporous crib	Free burn	500	Low/High	0.13	16.6	185	0.90	44	1.0
PB-8	Fir wood	Nonporous crib	Free burn	250	Low/High	0.09	14.5	90	0.70	50	12.0
PB-8.2	Fir wood	Nonporous crib	Free burn	250	Low/High	0.10	15.0	100	0.70	58	5.0
B-1	Fir wood	Supported crib	Free burn	250	Low/High	0.13	15.0	100	0.32	89	7.2
B-2	Fir wood	Supported crib	Free burn	250	Low/High	0.12	16.0	100	0.37	76	4.6
B-3	PMMA-FR	Supported crib	Free burn	250	Low/High	0.028	1.8	50	0.40	25	4.1
B-4	PMMA-FR	Supported crib	Free burn	500	Low/High	0.11	7.4	110	1.45	85	1.4
B-5	Diesel oil	3-ft pan	Free burn/scrubbers	250	Low/High	–	–	–	–	–	–
B-6	Fir wood	Supported crib	Scrubber	250	Low/High	0.10	18.0	59	0.37	56	2.2
B-7	Fir wood	Supported crib	Scrubber	250	Low/High	0.11	17.0	31	0.38	63	3.5
B-8	Fir wood	Supported crib	Scrubber	250	Low/High	0.10	17.2	60	0.32	53	1.6
B-9	Fir wood	Supported crib	Fusing sprinkler	250	Low/High	–	12.0	100	No plug	–	–
B-10	PMMA-FR	Supported crib	Fusing sprinkler	250	Low/High	–	2.0	58	0.40	–	–
B-11	Polycarbonate	Supported crib	Free burn	250	Low/High	0.037	12.0	80	No plug	18	–
B-12	Polycarbonate	Supported crib	Fusing sprinkler	250	Low/High	–	4.5	65	0.55	–	–
B-13	Fir wood	Supported crib	Inlet dampers closed	250	Low/High	0.07	16.0	105	0.61	28	–
B-14	Fir wood	Supported crib	Free burn	250	Low/High	0.12	17.5	120	0.67	72	–
B-15	Dense fiberboard	Supported crib	Free burn	250	Low/High	0.08	17.9	110	No plug	31	1.7
B-16	Dense fiberboard	Supported crib	Fusing sprinkler	250	Low/High	–	3.4	75	No plug	–	–
B-17	Polyvinyl chloride	Supported crib	Free burn	250	Low/High	0.02	3.8	60	0.59	12	2.1
B-18	Fiber-reinforced polyester	Supported crib	Free burn	250	Low/High	0.02	12.7	90	0.86	–	1.6
B-19	Fiber-reinforced polyester	Supported crib	Fusing sprinkler	250	Low/High	–	3.5	90	No plug	–	–
B-20	Composite	Supported crib	Free burn	250	Low/High	0.02	8.0	100	0.40	4	6.4
B-21	Fir wood	Supported crib	Free burn	250	Low/Low	0.10	15.8	90	0.57	57	–
B-22	Fir wood	Supported crib	Free burn	250	Low/Low	0.08	18.2	85	0.78	30	–
B-23	Composite	Supported crib	Rolling prefilter	250	Low/High	0.07	12.2	45	No plug	36	13.7
B-24	Composite	Supported crib	Rolling prefilter	250	Low/High	0.07	14.0	35	No plug	32	3.3
B-25	Composite	Supported crib	Rolling prefilter	250	Low/High	0.08	14.0	–	No plug	22	–
B-26	Fir wood	Supported crib	Rolling prefilter	250	Low/High	0.08	18.0	70	No plug	28	16.8
B-27	Fir wood	Supported crib	Prefilter circuit only	250	Low/High	0.09	17.8	80	0.72	41	–
B-28	Fir wood	Supported crib	Free burn	250	High/High	0.1–0.08	13.8	110	0.44	42	27.0
B-29	Fir wood	Supported crib	Free burn	250	High/High	0.1–0.05	11.8	100	0.54	33	10.0
B-30	Fir wood	Supported crib	Free burn	250	High/High	0.077–0.034	13.0	120	No plug	19	4.2
B-31	Fir wood	Supported crib	Free burn	250	High/High	0.08–0.03	13.0	100	No plug	9	13.0
B-32	Kiln dried fir wood	Supported crib	Free burn	250	High/High	0.12–0.01	14.8	112	0.31	34	3.0
B-33	Polycarbonate	Supported crib	Fusing sprinkler	250	High/High	–	4.5	70	No plug	–	–
B-34	Fir wood	Supported crib	Fusing sprinkler	500	High/High	0.1	12.2	180	No plug	33	12.4
B-35	Fir wood	Supported crib	Fusing sprinkler	500	High/High	0.086/0.064/0.035	14.9	180	No plug	0	25.0
B-36	Fir wood	Supported crib	Sonic cooling	500	High/High	0.087–0.068	15.0–11.0	140–75	0.84	8	16.2
B-37	Fir wood	Supported crib	500-ℓ/s filter	250	High/High	0.085–0.42	12.2	106	No plug	30	19.2
B-38	Composite	Supported crib	Free burn	500	High/High	0.05	4.2	103	0.44	27	8.8

TABLE IV. Fir wood crib ventilation and fuel moisture variables.

Test	Date	Ventilation: Inlet / Exhaust	$\dot{m}$, [a] kg/s	t_{peak}, [b] s	t_{plug}, [c] s	t_{peak}/t_{plug}, s	T_{av}, [d] °C	T_{db}, [e] °C
B-2	7/76	Low / High	0.12	160	330	2.07	224	100
B-13	4/77	Leak / High	0.07	210	610	2.9	183	105
B-21	7/77	Low / Low	0.10	140	570	4.0	215	90
B-28	11/77	High / High	0.1 0.05	190	540	2.85	172	110
B-30	2/78	High / High	0.077 0.047 0.038	190	No plug	—	160	120
B-32 (dry)	3/78	High / High	0.12 0.03	160	310	1.9	185	112

[a] $\dot{m}$ = burning rate.

[b] t_{peak} = time to peak temperature above crib.

[c] t_{plug} = time to HEPA plugging.

[d] T_{av} = average highest test cell temperature.

[e] T_{db} = dry bulb temperature at HEPA.

cellulosic fuels of high moisture content would burn at a much slower rate than the sensible removal of water from the cellulose would indicate[5]. To test this finding, we kiln dried enough wood for one crib load. The average moisture content of the dried elements was less than 6%. The results are shown in test B-32 where plugging occurred in 310 s. Obviously, control of the moisture content of porous fuels is very important to ensuring reproducibility in tests.

We have tried several countermeasures to keep the HEPA filter from plugging, including rolling prefiltration, increasing the HEPA surface, water scrubbing, stopping the fire with sprinklers, and controlling the materials. Table 5 summarizes our countermeasure experience and condenses the data given in Table 3 to specifically address the relative merits of different countermeasure techniques.

The rolling prefilter appeared* to offer the most promise as an active control since it can be used for a dual purpose; i.e., enhanced filtration** and HEPA fire protection. A passive control strategy might be to simply double the size of the HEPA relative to the design air throughput.

Scrubbing by in duct spray techniques did not increase filter lifetimes appreciably; in fact, there is some indication that the cooling effects of sprays may enhance the condensation of volatile aerosols, thus making plugging more likely. Fire control sprinklers effectively applied to the crib appeared to reduce the intensity of the fire and consequently the smoke production. In only one case did the HEPA plug after sprinkler application. The fuel was polycarbonate and the effect may be propitious.

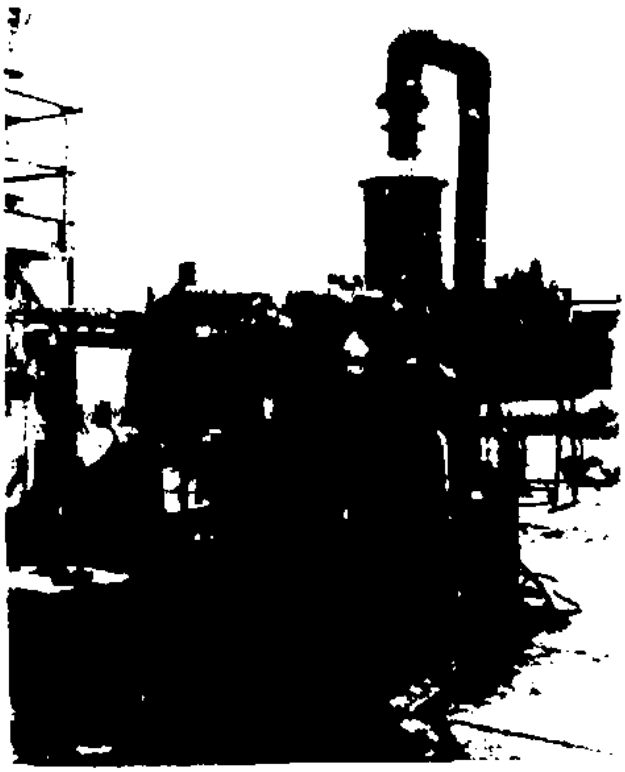

Fig. 6. Rolling prefiltration system installed in the LLL duct system.

IV. Summary and Conclusions

We have exposed HEPA filters to very severe smoke loads from potential fuel materials common in the furnishings and appliances of laboratories containing radioactive materials to identify and test practical filter plugging countermeasures before installing and retrofitting them in DOE facilities. Our tests indicated HEPA filters are inherently capable of handling huge aerosols (equivalent

* In August of 1977, LLL rented a pilot model rolling prefiltration system and operator from the Anderson Corporation. The unit is generally used for filtration of air pollution aerosols and is based on high velocity trapping and scrubbing techniques. In our operations, we circumvented the scrubbing section. Figure 6 shows the unit installed in the LLL duct system. The HEPA was downstream from this unit.

** DOE's Enhanced Filtration Project is aimed at the normal operational HEPA lifetime by unique prefiltration procedures.

to the total aerosol produced from a flashed-over* room), however, the filters will ultimately plug. Attempts to control the fire by passive fire control sprinkler systems reduced the smoke load and generally the filter plugging potential of the aerosol. In the absence of a fire control system, prefiltration techniques appeared to hold a promising means of increasing filter endurance under extreme aerosol exposures. The simple expediency of doubling the filter size relative to the design flow rate of the ventilation system also appeared promising as a passive smoke aerosol countermeasure.

So far, none of our filters have been thermally damaged since the heat lost to the duct was sufficient to reduce the temperature of the combustion products to safe levels (T_{gas}<180°C). However, at gas temperatures greater than 120°C, some volatile components of the combustion products passed through the filter and condensed downstream. We are uncertain if this is a compromise of containment.

We are currently analyzing the chemical components of smoke aerosols responsible for filter plugging. Our gross physical measurements indicate that most fuels tested thermally degrade to specific aerosol mixtures that contain effective filter plugging components. Our efforts in this area will continue at a reduced rate since we intend to concentrate on practical countermeasure techniques unless we can identify a super and universal filter plugging component of all aerosols.

Our future efforts will be directed toward optimizing rolling prefiltration procedures and toward providing scaling guidelines for the inclusion of rolling prefilters in any size containment system.

V. References

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* In this paper we define "flash-over" as the condition when all combustible items in an enclosure are involved in fire.

TABLE V. Effect of various countermeasures on filter performance

	Fir wood		PMMA-FR		Polycarbonate		Dense fiberboard		Fiber-reinforced polyester		Polyvinyl chloride		Composite	
Countermeasure	t_{plug}, s	$\dot{m}$, kg/s	t_{plug}, s	$\dot{m}$, kg/s	t_{plug}, s	$\dot{m}$, kg/s	t_{plug}, s	$\dot{m}$, kg/s	t_{plug}, s	$\dot{m}$, kg/s	t_{plug}, s	$\dot{m}$, kg/s	t_{plug}, s	$\dot{m}$, kg/s
Free burn (enclosure)	320	0.12	400	0.03	No plug	0.04	No plug	0.08	880	0.02	590	0.02	400	0.02
Water scrubber (1-100 ℓ/min)	350	0.11												
Fusing sprinkler	No plug	—[a]	No plug	—[a]	550	—[a]	No plug	—[a]	No plug	—[a]				
Rolling *prefilter*	No plug	0.08											No plug	0.07
Wet wood	No plug	0.03												
Large HEPA surface	No plug	0.035												

[a] For most fires, sprinklers activation occurs before steady-state burning.