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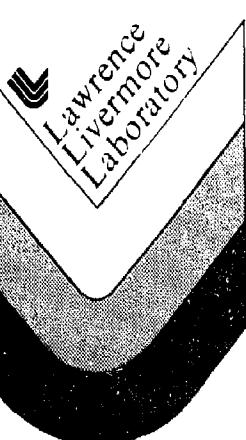
Fire Protection Countermeasures For Containment
Ventilation Systems

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FIRE PROTECTION COUNTERMEASURES
FOR
CONTAINMENT VENTILATION SYSTEMS*

by

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Abstract

The goal of this project is to find countermeasures to protect HEPA filters, in exit ventilation ducts, from the heat and smoke generated by fire.

Methods developed to cool fire-heated air by fine water spray upstream of the filters are available and are currently installed in some new facilities where containment is an issue. Since exposure of HEPA filters to smoke aerosols could also cause disruption of the containment system definition of the problems, and modes of mitigation were sought.

Several potential faults could occur, including plugging of the HEPA filter which would cause overpressurization of the ventilated space, filter breakdown due to extreme pressure differential across the filter media, and penetration of the filter by condensable gas-phase pyrolyzates which could carry chemically combined toxicants with them.

We have identified, through testing and analysis, several methods to partially mitigate the smoke exposure to the HEPA filters. These independently involve controlling the fuel, controlling the fire, and intercepting the smoke aerosol prior to its sorption on the HEPA filter. Fuel and fire control involve standard fire-protection practice (with some modifications for new materials and nontraditional geometries). Exit duct treatment of aerosols is not unusual in industrial applications and involves the use of scrubbers, prefilters, and inertial impaction, depending on the size, distribution, and concentration of the subject aerosol. However, when these unmodified techniques were applied to smoke aerosols from fires on materials, common to experimental laboratories of LLNL, we found they offered minimal protection to the HEPA filters. Ultimately, we designed a continuous, movable, high-efficiency prefilter using modified commercial equipment. Our technique is capable of protecting HEPA filters over the total duration of the test fires. The reason for success involved the modification of the prefiltration media. Commercially available filter media has a particle sorption efficiency that is inversely proportional to media strength. To achieve properties of both efficiency and strength, we laminated rolling filter media with the desired properties. Our approach was Edisonian, but we truncated in short order to a combination of prefilters that were effective for our purposes. We do not believe that the use of rolling prefilters solely to protect HEPA filters from fire-generated smoke aerosols is cost effective in every type of containment system, especially if standard fire-protection systems are available in the space. But in areas of high fire risk, where the potential fuel load is large and ignition sources are plentiful, the complication of a rolling prefilter in exit ventilation ducts to protect HEPA filters from smoke aerosols is definitely justified.

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Introduction

High-efficiency particulate air (HEPA) filters, used in ventilation systems of toxic-containment facilities, have functional life times of months to years, depending on the normal resident background aerosol concentration.

The ventilation circuit for containment facilities may include several filtration stations, in specific application to the risk operations in various enclosures of the containment facility. The systems are necessarily negative pressure systems; i.e., the air-moving fan is the last component of the ventilation circuit, and ventilated enclosures have negative pressure relative to the ambient atmospheric pressure. The final HEPA filter station is upstream of the fan. It generally contains two series sets of HEPA filters (the number and size of filters depends on the design and throughput of the system) and is the last protection component of the containment system. Because it generally is remote from operational areas and potential damage sources, it is naturally protected from enclosure problems.

Several natural and man-made occurrences can jeopardize the integrity of the total ventilation system including the final filters*. Fire in a protected space provides a risk potential somewhat greater than other hazards, and, consequently, has been the subject of several research and testing programs over the past two decades (1-4). The Lawrence Livermore National Laboratory (LLNL), in contract to the various agencies that evolved to become the Department of Energy (DOE), has been conducting research into the protection of HEPA filters from fires for about 10 years. Noncombustible filtration material had been developed earlier, and was required for use in facilities containing radioactive materials. Thus, the fire risk considered in the LLNL work did not pertain to the flammability of the filters, but to the effects of products of combustion (thermal damage and smoke plugging) on HEPA-filter performance. The goals of the program were to survey the practical response of production HEPA filters to combustion-product exposure and to assess the effectiveness of existing or newly developed countermeasures to reduce or negate the effect of such exposure.

This paper contains a general description of the experiments conducted during the last three years of this program; including descriptions of the facility developed for the experiment and of the measurements used to define combustion characteristics of the fuel arrays, the resulting smoke-production rate, and smoke aerosol absorption on the HEPA filters. The initial work has been reported elsewhere (5,6).

The test facility included a fire-test cell with dimensions approximating containment-laboratory scale and a corresponding ventilation test section flexible enough to survey the range of ventilation systems used throughout the industry. Because we are dealing with containment ventilation circuits, we have designed the test cell to be served by a negative-pressure ventilation system. The response of the ventilation flow to the fire-heated gases in such enclosures dictates the ultimate combustion processes that control the degree and quality of smoke aerosols generated during the experiments. The aerosol properties are of primary importance in terms of filter plugging potential.

* Tornadoes, hurricane, seismic activity, explosions, fire, sabotage.

The unique behavior of fires in negative-pressure ventilation systems is described in this paper, along with data and concepts we have developed with regard to smoke plugging of HEPA filters, tested countermeasures for preventing smoke exposure to the final HEPA filters, and the techniques that we believe to have the most promise for mitigating the effect of smoke on HEPA filters. In later sections we describe criteria developed for the construction of experimental prefiltration apparatus and guidelines for the development of prototype production models. We also give suggestions as to where these appliances would be best applied. A comprehensive table containing pertinent data for most of the tests is contained in the Appendix.

Development Of The LLNL Test Cell For Containment Ventilation System Fire Endurance

To define the effects of enclosure-fire parameters on the production of the smoke aerosols, a test facility was designed and constructed to incorporate the best characteristics of a fire-research laboratory, while maintaining the essential geometric and ventilation configuration found in most laboratories that contain radioactive materials.

Figure 1 is a schematic representation and Fig. 2 is a photograph of the LLNL facility designed for fire exposure tests on containment ventilation systems and components. The facility consists of the negative-pressure ventilation test area, the fire test cell, and the computer diagnostic room. The ventilation test area is coupled to the fire test cell by standard 2 ft x 2 ft ventilation ducting. Diagnostic instrumentation at these locations is "hard wired" to a PDP-11 computer for data addressing, data reduction, and final display in hard-copy format. (5) Instrumentation in the fire test cell measures:

- Temperature
- Pressure
- Thermal radiation for fire and adjacent wall surfaces
- Fuel weight loss
- Total air-flow rate into the test cell
- Fire portraits by video camera

Instrumentation in the Exit Duct and HEPA filter station measures:

- Temperature (wet and dry bulb)
- Filter parameters
- Total exit gas flow rate
- CO_2 - CO - O_2 - Total hydrocarbon gases in exit gas flow
- Optical density in the exit duct
- Total aerosol mass
- Aerosol size distribution

Details and descriptions of the instrumentation and diagnostic equipment are contained in Ref. 5 and 6.

Experimental Procedures

Sixty-two full-scale smoke production tests have been conducted in the fire-test cell since its inauguration in the summer of 1976. All tests had the same basic anatomy and were aimed at providing a severe smoke flux to HEPA filters with the objective of defining first, the filter-plugging potential of smoke aerosols from typical fuels, and second, to develop practical measures for

protecting the HEPA filters from smoke exposure. The data collected from all these tests are tabulated in Appendix. The characteristics of the smoke aerosols a direct function of the fuel type, the fuel air supply, and the fuel geometry. Dependent on these parameters are: the fuel consumption rate, local and average product gas temperatures, product gas composition, oxygen depletion in the exhaust gases, smoke aerosol size distribution, and phase.

Preliminary Tests In The Fire-Test Cell

We initially used fir wood cribs for smoke production tests and also to test selected countermeasure arrangements and other combustion parameters. We ultimately adopted a modified crib arrangement for creating both the thermal exposure and smoke aerosols to challenge the HEPA filters. A large proportion of the furnishings, finishes, and construction materials in LLNL laboratories is composed of synthetic thermoplastics that soften upon heating. These materials would not maintain geometric integrity upon exposure to heat sources or flames, and cribs made of them would soon lose their shape, thus causing the burning behavior to change continuously throughout the test. Therefore, we conducted most of our tests using steel frames to define the fuel layers. These frames were modified according to the type of fuel being burned for specific tests; open mesh screens supported fuel layers consisting of thermoplastics, while no screen support was necessary for cribs made entirely of wood. Each different fuel has unique properties; i.e., density, conductivity, moisture content, etc., and available geometric form (for example, most synthetic polymers are economically available in large sheets no thicker than 1/2 in.). We had chosen a specific fuel load* for the wood crib fires (1 to 2 lb/ft²), and we elected to maintain the same fuel loading for all standard smoke production tests. Thus, crib size varied over a small range proportional to the fuel density.

Eventually we adopted a fuel array made up of specific proportions of fuel materials common to physical science laboratories. Figure 3 is an example of a composite crib used as the major fuel source for most of our later tests. Because we needed dense smoke aerosols to challenge the HEPA filters, we provided the fuel array with a constant premixed flame source (100 l/min natural gas with 57 l/min air), centrally placed in the crib base. This burner acted both as the ignition source and a thermal driver to maintain high constant temperatures in the crib when the test cell became ventilation controlled.

Smoke Measurements

We used cascade impactors in our attempts to measure the total smoke-aerosol mass and mass-size distribution. We recognize the short coming of this approach and have sought other methods. However, the state of the art of aerosol measurement is not advanced to the degree that dense aerosols can be analyzed accurately either on-line or by grab sampling. Because of this gap in the technology, we continued to use cascade impaction methods for gross smoke analysis. The results are included in the table containing all test data in the Appendix.

Results and Discussion

Enclosure Fire Behavior

Figure 4 is a composite of data curves from an assessment of the interaction

* The fuel load is defined as the weight of combustable material contained in an enclosure divided by the unit area of the open floor surface.

between a naturally burning fire* and the controlling parameters of the forced-ventilation test cell, using a specially designed wood crib.** The parameters of interest are:

- Temperature directly over the crib (°C)
- Total inlet air flow rate and total exit air- and combustion gas-flow rate (l/s)
- Crib mass loss (kg)
- Oxygen depletion [O₂]⁻ in the exit duct (%)

Although Fig. 4 gives a temporal portrait of the fire dynamics during this test, it is not a complete one, since it includes only a sampling of the diagnostic measurements used for a complete analysis of both the fire conditions and the HEPA-filter performance during each test. However, it does illustrate the controlling features of natural fire behavior in enclosures ventilated by negative pressure systems and the corresponding response of the filtration system. The data curves can be divided into control parameters and dependent parameters. Note that all these data are interdependent to a degree, but factors such as the total exit air-flow rate and the initial burning rate of fuel*** are predetermined conditions, and hence are somewhat independent of the dynamics of the test cell.

A striking feature of this figure is the dynamic but interrelated response of the inlet air flow rate (\dot{V}_a), the air temperature over the crib, T_c , and the oxygen depletion at the exit port [O₂]⁻. We note first that \dot{V}_a is not equivalent to exit (design) flow rate (\dot{V}_d), indicating that the test enclosure is leaky. We were aware of air leaks in the system because of the smoke that escapes when the HEPA filters plug, but we did not know the leak rate (which depends on the fire size and \dot{V}_d), or the magnitude of the initial enclosure overpressurization (a phenomenon that occurs for almost all substantial fires conducted in the enclosure). From Fig. 4 we see that the leak is roughly 20% of \dot{V}_d , and that \dot{V}_a actually becomes substantially negative early in the fire sequence; i.e., there is a net outflow of gas escaping through the inlet ducts. The peak outflow from the inlet ducts is over 50% of the initial \dot{V}_a , and is nearly 3 times the steady-state \dot{V}_a established after the initial oscillating period of the burn. The greatest change for both [O₂]⁻ and T_c occurs near the peak outflow time, and the crib mass loss appear to begin substantially around this period. The gradual reduction in \dot{V}_d corresponds to the increase in pressure drop across the HEPA filter.

One liter of propylalcohol is used as the accelerant to ignite these cribs to positive burning. This volume provides a layer of accelerant 1-cm thick over the surface of the pan containing the crib. The layer will burn away in roughly 60 s, and will provide ample flaming heat transfer to positively ignite the crib. The enclosure "breathing" manifested in the induction period of the burn is not unique to either the ignition source or the major fuel components. What occurs is simply expansion of internal gases due to the average temperature rise from the fire. This is shown readily in Fig. 5 during a test where we tightly sealed the fire enclosure to observe the extent of internal pressure rise. The fuel in this case was a fir crib with the natural gas ignitor. The peak pressure of 170 Pa (0.7 in. wg) is sufficiently greater than atmospheric pressure to cause gas propulsion to any region of lower pressure. In this test, the discontinuity in the pressure data at 500 s resulted when one of the seals broke because of the high ΔP and was resealed.

* By naturally burning fires, we mean fires positively ignited and allowed to burn without further acceleration by contained sources.

** Contained in a metal pan in which enough propylalcohol is ignited to expose the bottom surfaces of the crib to flames for a period of 1.0 min. (1.0 liter).

*** Caused by the amount of accelerant used for ignition.

The volumetric expansion resulting from the initial increase in average enclosure temperature can be estimated using the expression:(7)

$$S = (\text{Mole}_p) \dot{m}_f \left[\frac{\bar{T}}{\bar{T}_{\text{amb}}} \right] ,$$

where:

S = volume expansion,
 Mole_p = molecular weight of the combustion products,
 \dot{m}_f = fuel burning rate,
 \bar{T} = heated gas average temperature, and
 T_{amb} = ambient gas temperature.

Table 1 compares calculated outflow rates with the \dot{V}_a measured at the period of peak overpressurization of the cell for tests with naturally burning cribs. The calculated values are remarkably close to the peak values measured for the wood cribs and the data trends are in the right direction for the composite cribs. The calculated values for volume expansion during the steady state phase of burning do not agree nearly as well, which is understandable because we know neither the dynamic fuel composition nor the products of combustion accurately.

These experiments begin to give us a quantitative picture of the dynamics of fires in enclosures serviced by negative pressure ventilation systems: upon ignition of the accelerator fuel, the average temperature in the space increases rapidly. Ideal gas laws tell us that this condition should increase either the pressure in the space or the volume of the gas, and that this response will in some way influence enclosure fire dynamics. Indeed, we observe that gas expansion can account for substantial changes to the inlet flow to the enclosure. As fire depletes available oxygen in the space, it becomes ventilation controlled and the average temperature is lowered, resulting in a corresponding reduction of low-density combustion gases and heated air. Hence, more inlet air enters the space available for combustion. If fuel burning rate is constant, the air inflow rate and the average enclosure temperature, will approach some intermediate magnitude until fuel depletion becomes a factor.

Figure 6 shows an extreme example of this balance, where equilibrium is not established during the steady burn period. Instead, an oscillating response is set up between the crib temperature characteristics and the exit flow parameters as indicated by the oxygen, CO, and CO₂ monitors. Note that [O₂] is nearly completely out of phase with the CO and CO₂ data, as it should be. Oxygen depletion and production of combustion gases follow similar, but reciprocal trends, where the composition of the combustion gases and the production of smoke aerosols are extremely sensitive to both temperature and oxygen concentration.

Table 2 collects all data pertinent to the combustion dynamics and gross aerosol measurements made during fiscal year 1979. (The data contained in Table 2 are also included in the total set of data in the Appendix). The table delineates the tests where instruments were available to measure the variable inflow rate and thus we were able to compute the leak rate (\dot{V}_{leak}). The data do not show good reproducibility, but the trends bear well with the gross conditions of the specific test. As described in Table 1, the total air inflow rate is always less than the exhaust rate because of leaks in the test cell. \dot{V}_{leak} , (determined by the difference between \dot{V}_d and \dot{V}_a) varies with the magnitude of the design flow rate and with the intensity of the fire source, e.g., for a \dot{V}_d of 500 l/s, \dot{V}_{leak} is about 200 l/s, while for forced burn tests where \dot{V}_d is 250 l/s, \dot{V}_{leak} varies between 50 and 100 l/s. In the "natural burn" tests with a \dot{V}_d of 250 l/s, the leak rate ranged between 25 l/s and 65 l/s, thus the fire intensity along with the \dot{V}_d dictates both the variable inflow rate and the relative leakage in and out of the test cell.

The variable magnitude of leakage makes it impossible for us to quantify the combustion mass balance through the test cell/duct flow system. However we can show qualitative correlations of the data trends:

Most of the gas flow data varies directly with V_d ; and temperature dependent parameters are inversely proportional to V_c . Aerosol mass measurements are very sensitive to both the distance that the sample was taken from the fire and the condition of the fire, e.g., 60% of aerosol mass is lost between the sampling station at the exit to the test cell and the sampling station at the HEPA filter. On the other hand, the difference in aerosol production when the fire changes from fuel control to ventilation control is very apparent, as there is a net gain of 60% in aerosol mass when this occurs (note, both these trends are gross averages only).

One bit of interesting information in Table 2 is the data showing the temperature loss by the combustion gases in transit between the test-cell exit and the HEPA filter station. Excluding tests at V_d of 500 l/s, and for experiments where atomized water was introduced into the "upstream" duct work to artificially cool the gases (tests 60,61,62), the temperature at the HEPA filter was seldom greater than 100 $^{\circ}$ C.* This is an encouraging observation, since temperatures at this level are substantially below destructive temperatures that are potentially available in enclosure fires. Figure 7 shows the endurance of HEPA filters exposed to a range of high temperature.(8) At the temperature levels measured at the HEPA filter station of our duct system, the endurance time for the conditions encountered during our tests is of the order of days. Since our testing conditions are probably far more severe than most natural enclosure fires, it follows that the risk of thermal damage to the final filters of most containment systems is very small. In fact, heat transfer calculations show that if the gases that enter the duct are somewhat less than 1000 $^{\circ}$ C, the heat transfer along the duct is sufficient to reduce the gas temperature at the final HEPA filter station to acceptable temperatures (so long as the duct length is greater than 10 times the duct diameter).(9) By acceptable temperatures, we mean temperatures where filter endurance is sufficient to provide containment over the period of active fire fighting and until alternate containment ventilation can be provided.

Smoke Plugging of Filters

Aside from the gas temperature, the major threat to the normal operation of HEPA filters during fires in protected enclosures is plugging by smoke aerosols. Most of the tests conducted in the LLNL fire test cell were to determine what materials and what conditions of combustion (fuel geometry and degree of ventilation) produce smoke aerosols with the most potent filter-plugging potential. Most materials burning under well-ventilated conditions produced more gas-phase combustion products at relatively high temperatures, which have low filter-plugging potential. When the air becomes vitiated by combustion products, condensed-phase aerosols, composed of high-vaporization-temperature pyrolyzates, prevail.

Figures 8 through 13 show the pattern of HEPA filter plugging for most of the materials used as fuels during this research. The curves show the time-dependent pressure difference across the filter resulting from aerosol sorption into the

* Note that the duct gas temperature at the exit measuring station was generally 40 to 60 $^{\circ}$ C lower than the average temperature of gas in the test cell which averages about 2500 $^{\circ}$ C.

filter media. The time to filter plugging is arbitrarily defined as the time at which the flow rate is reduced to 1/2 its design value. For most tests, this condition is achieved when ΔP is greater than 1500 Pa. The curves in each figure are labeled with information specific to the conditions of test; e.g., the average burning rate of the fuel m , the measured gas temperature at the HEPA filter station (T_{HEPA}), the time of filter plugging, (t_p), and other pertinent information that might apply to that experiment. Included with the m data are indications of the measured total aerosol mass taken by cascade impactor during the ventilation-controlled portion of each fire when such measurements were made. We have reservations about the value of these measurements because of the nature of dense smoke aerosols where both temperature and pressure changes can cause extreme changes in aerosol character.

Figure 9 shows plugging data for a test where the crib is made up of polyvinylchloride (PVC) elements. These data are compared to an earlier test conducted by hand feeding the fuel to a Franklin stove, modified to be a practical smoke generator. The fuel consumption difference is a factor of 12 between the experiments, and \dot{V}_d differs by a factor of 2. Thus we have provided a dilution factor of greater than 20 between the two measurements. Yet under both conditions the HEPA filter plugs in measurable times.

Figures 10 and 11 contain data for cribs and Franklin stove burns with fire-retarded polymethylmethacrylate (PMMA-FR), at \dot{V}_d of 250 l/s and 500 l/s respectively for the crib tests. At 250 l/s, m is about 1/3 to 1/4 the m at 500 l/s 1680 g/min to 6600 g/min respectively, but the measured aerosol mass was greater at the low \dot{V}_d (4.1 g/m³ to 1.4 g/m³ respectively). The temperature at the HEPA filter was twice as large at $\dot{V}_d = 500$ l/s ($T_{HEPA} = 110^{\circ}C$).

Two factors appear to cause the appearance of more effective plugging at the low ventilation rate; the most important factor is the temperature of the combustion-gas-smoke aerosol complex at the HEPA filter. At low temperatures, more volatile components of the mixture will be in the condensed phase and available for blinding of the filter media. This can also account for the fact that aerosols of low concentration cause plugging at $\dot{V}_d = 500$ l/s; i.e., the greater dilution at the high \dot{V}_d , the more cooling of the smoke mixture, hence the more condensed-phase aerosols.

The other cause for the observed phenomenon is that the chemistry of pyrolysis is changed because of the higher temperatures of combustion throughout the test period. We must be very cautious in proposing this mechanism since the observed behavior of fuel during PMMA-FR fires showed that maximum smoke production occurs during most active combustion. Moreover, the mechanism of fuel pyrolysis and combustion is entirely different in the crib tests than in the Franklin stove tests. In the crib tests, the fuel elements are exposed directly to premixed flames, whereas in the Franklin stove, chunks of fuel are dropped into a fire-heated pan at prescribed intervals to dictate the fuel consumption rate; thus in the crib tests we are making mostly pyrolysis products while in the Franklin stove tests the yield is a combination of pyrolysis and combustion products. However, it is clear that given the proper conditions, PMMA-FR produces potent filter-plugging aerosols.

The character of the material sorbed on the filter media was different for the different fuels used. During the early phases of this program, weighed the plugged HEPA filter as soon as possible after test termination. When wood was the only fuel, the substance absorbed by the filter media was highly volatile--it would evaporate rapidly to as low as a tenth of its initial weight. After the filter

dried, it could again pass--and filter--air with only a slight increase in the ΔP . However, the filter had no longer any endurance to smoke exposure. It would plug almost instantaneously, even during the initial fully ventilated phase of the tests.

Where the fuel elements were either PVC or PMMA-FR, the deposits on the filter media were dry to the touch after the test, moreover, they maintained the initial weight regardless of the post exposure period; once plugged, the filter was always plugged. Thus the type and very likely the composition of smoke aerosols from synthetic polymers are very different from the smoke aerosols of wood or cellulosic based materials; moreover they have very different filter plugging characteristics.

Figure 12 gives the ΔP of HEPA filters exposed to smoke aerosols from a dense fiberboard made by compression of wood fibers and extracts. Again, the data comes from both crib fires and tests done in the Franklin stove. Neither of these tests caused filter plugging over the test period, but the slope of the ΔP curve for B-15 appears to show a potential for plugging, given enough fuel and time.

Figure 13 contains ΔP data for HEPA filters exposed to smoke aerosols from composite crib fires. The five curves represent data from crib fires at various V_d and for both free and forced-accelerant fires. The fuel elements consist of a mixture of materials with the distribution:

Fir wood	40%
Fiber-reinforced polyester	29%
PVC	14%
PMMA-FR	9%
Polycarbonate	8%

The fuel proportions are based on the general material distribution found in enclosures containing radioactive materials. Moreover, we found this combination to have the most consistant filter-plugging potential of any fuel we used during the entire test series. Thus, we adopted this composite crib composition as the standard against which we rate the smoke plugging of filters and the countermeasures to protect HEPA filters from smoke aerosols.

The only burn that failed to cause filter plugging was B-53, a free-burn test. All conditions appear to be favorable for filter plugging except the T_{HEPA} of 110°C. The other curves show typical response of ΔP vs time for this fuel combination regardless of the variability of the burning rate and the measured aerosol mass at the HEPA station.

We have attempted to determine the nonlinear plugging signature of the filters; i.e., how they change abruptly from apparent complete throughput to complete filter blinding. Trying to duplicate the observed phenomena on a small scale was unsuccessful. Chemical analysis of the materials trapped on the HEPA filters for a range of fuel types, combined with analysis of combustion gases and pyrolyzates "upstream" and "downstream" from the HEPA filter, revealed no selective sorption of components of the products of combustion and pyrolysis on the filters.(10) A search of the literature of filtration technology for examples of similar phenomena were unrewarding in terms of locating cause or theoretical analysis of the observed event.

A qualitative description of the phenomena, based on our observations, follows: during the well-ventilated induction period of the fire, no plugging aerosols are formed (this period will be 2-3 min for dry wood

cribs, and somewhat longer for cribs formed of synthetic polymers or mixtures of polymers). After the induction period, the air supply to the fuel is vitiated by combustion products and the character of the aerosol changes and becomes rich in condensed-phase materials that can adhere to the filter media.* Exposure to this smoke aerosol continues and filter plugging proceeds at an exponential rate. Comparison of this response with that of earlier tests of filter plugging (the Franklin stove tests) indicates that the rate of plugging will be linear if the smoke production rate is linear and exponentially fast as the filter becomes more efficient because of sorbed aerosols.

Chemical analysis shows that the materials collected by the filter media have the same gross distribution as does the aerosol collected "upstream" of the filter. There is also no great difference in the composition of the aerosols from burning cribs of wood or from composite materials. (We have no data on the composition of smoke from single-component synthetic materials because we did not have the analytical tools available when we were making those tests.)

The results of chemical analysis suggest that filter plugging by smoke aerosols is dominated by the overall concentration of the aerosol. We were unable to identify any specific pyrolyzate or combination of combustion and pyrolysis products with unique capability for filter plugging.

Fire Protection Countermeasures for HEPA Filters

Three methods of protecting HEPA filters from fire and fire products are generally available:

- Control the fuel.
- Control the fire.
- Intercept the smoke before it reaches the filter.

The first two techniques are accepted fire-protection concepts where a choice of methods are available for affecting the countermeasure. For example, controlling the fuel may involve specified housekeeping procedures, prohibiting certain classes of materials from a space, or specifying the materials to be used for internal finishes and appliances. Indeed, this protocol should be mandatory in any laboratory situation. Control of the fire implies actively attacking the fire in its incipient stage, and involves alarm systems, professional and portable fire fighting equipment and procedures, and automatic fire suppression apparatus.

However, to provide ultimate protection to the filters in containment ventilation systems, it is necessary to ensure that the final filters can maintain their function under any circumstance. Because fire plumes can cause extreme disruption of normal ventilation patterns, it is possible to project situations where smoke aerosols from an unprotected space could enter the containment ventilation ductwork of an enclosure containing radioactive materials. Another possible scenario is that static pre-filters might absorb combustible materials which could ignite and thus produce smoke that is directly communicated to the final HEPA filters. An infinite number of low probability fire scenarios can be proposed that would compromise active fire protection systems, thus, even if rigid fire protection protocol is observed, some method of intercepting smoke aerosols before they reach the final filter station may be required.

* Figure 14 is a scanning electron micrograph (SEM) of HEPA filter media loaded with a liquidous material from a composite crib test. It appears to generally thicken the fibers, as well as forming globules at specific locations. For comparison, Figure 15 is a SEM of HEPA filter media loaded with solid-phase aerosol. Obviously the mechanism, and thus the buildup of pressure, will be different with the two types of smoke aerosol exposures.

Table 3 lists a variety of techniques for removing or reducing the concentration of smoke aerosols within the duct circuit. These techniques were thought to be technically feasible, but only those identified by asterisks were attempted. Even those identified for critical testing were limited to a few procedures which showed promise and some practical compatibility with containment duct systems.

One concept we attempted, but soon rejected, was to convert smoke particulate to gas using an afterburner. The problems of this technique, even on a small scale, are many; for example, igniting the afterburner flame in a constant flow of air was tricky. Ignition to combustion was nearly impossible if the flow rate or the composition of exposure gases changed. Moreover, small detonations were both common and quite loud. These events quickly quenched our fervor for this procedure.

Another of the listed ideas (no. 4) was never used for direct filter protection, but was used at the termination of every test as our air-pollution control system. This device (shown in Fig. 1) consists of a cyclone separator and high pressure venturi scrubber in series. We have never seen smoke at the exit diffuser, so we believe the apparatus has sufficient air cleaning capabilities to protect downstream components from quite large fires. However, the cost for general application to containment ventilation systems would be prohibitive.

Table 4 compares the effectiveness of four potential in-duct smoke removal techniques, one standard fire protection system, and one fuel modification example as countermeasures to prevent HEPA filter plugging by smoke aerosols. The first row in the Table gives representative data for the plugging effectiveness of the combustible materials burned in the fire test cell, without countermeasures. Only two materials, polycarbonate (PC) and dense fiberboard (DF), failed to plug the HEPA filters at the standard flowrate of 250 l/s. When PC was burned at its highest rate, very little smoke was perceived. A review of published listings of combustion and pyrolysis products from PC indicates that these products consist of mostly light gases and low-molecular-weight condensed-phase materials. Such components have little potential for filter plugging. The burning rate of the DF cribs is very low, thus producing a small volume of smoke aerosols that does not cause HEPA filter plugging. At higher flow rates, the DF did cause a HEPA filter to plug. We did not burn PC cribs at high ventilation rates because the results of our tests and literature studies indicate that hotter PC fires produce products that would be less likely to cause filter plugging. All other materials produced plugging aerosols at both 250 l/s and 500 l/s. However, the rate of filter plugging at 500 l/s was substantially reduced (in some cases because the combustion products passed through the filter as vapors).

Fire Protection Sprinkler. The results with fire protection sprinkler systems are of high interest. Sprinkler heads used for these tests are rated to fuse at 1650 F (750 C), that is, the temperature-sensitive elements of the sprinkler head will fail by design at the specified temperature and release water to the site of the fire.

The sprinkler system successfully reduced smoke-aerosol concentration to nonplugging levels for all tested fuels except PMMA-FR and PC. The PC, which did not produce filter-plugging aerosols during the smoke production tests, did produce plugging of HEPA filters after sprinkler activation. It is a slow burning material with a relatively low heat release, and in the test in question; the sprinklers did not reach fusing temperatures until nearly 10 minutes of the burn had elapsed. Very shortly after the sprinklers activated, the filter plugged! We were unable to

repeat this occurrence. We believe that water spray, from the sprinklers mixed with the combustion aerosol so that the surface tension of the water changed to the range where it could wet and hence plug the filter.* Since we were not able to verify the occurrence, we propose this explanation cautiously.

The burning behavior of PMMA-FR is responsible for filter plugging during tests where this material was used, even though the sprinkler operated upon demand. PMMA-FR does not ignite until thermal erosion reduces the concentration of bulk retardant below a critical value. Once ignited, however, the PMMA burns with fierce intensity and produces copious smoke. We believe that enough smoke was produced before the sprinkler fused to plug the filter. We also believe that the surface tension reduction of the water spray carry over through the duct could operate during the burning of PMMA-FR. Thus, two independent effects could be responsible for the observed phenomena.

The combustion patterns of composite cribs are intermediate between those of synthetic polymers and fir wood. The acceleration to peak heat release is somewhat slower than for wood and the maximum temperature attained is correspondingly less. Following this, the time to ventilation control conditions is longer. Consequently, the time for the plume gas to reach fusing temperatures is longer than for wood cribs.

Figure 16 is a map of a composite-crib fire test where sprinklers were employed as fire control countermeasures. The plotted parameters are: temperature above the crib, exit-duct flow rate, and pressure drop across the filter. The time at which the sprinklers fuse is noted by the abrupt temperature reversal at 180 s and HEPA filter plugging is indicated by the complementary response of the air flow and pressure drop signatures. Filter plugging results from either the generation of aerosols that continues at high rates after the fire plume has been knocked down or because the characteristic of the aerosol-water vapor complex has been changed to provide a more potent smoke-exposure challenge to the HEPA filter.

One point of interest for wood-crib fires sprayed by automatic sprinklers is that the combustion reaction was seldom quenched; i.e., enough heat was contained in the crib volume to allow rekindling of the fire even after the sprinklers operated for 5 to 10 min.. For the other fuels, exposure to the sprinkler shower for the same duration generally extinguished the fire.

Chemical Modification of Materials In the past, we have shown the importance of water content of wood fuels in influencing the combustion response of the cribs.(6) We can explain these results by using research conclusions from work performed elsewhere,(11) which shows that absorbed water appears to be chemically active under pyrolyzing conditions. The reduction in burning rate and the change in the type and numbers of pyrolyzates points to chemical interaction of the water with the pyrolyzates during thermal degradation of the material. This process is not exclusive to wood. Almost all flammable materials will exhibit changes in thermal degradation kinetics if impurities in sufficient quantities are intimately distributed through the material.

We mention the results for wet wood here to illustrate that the materials we used for the tests are unique; i.e., they are materials in common use at LLNL. Should other materials with the same name be used for similar smoke production tests, the results may not be the same. Moreover, by either planned or random use of additives, impurities, or retardants to generic materials of the same type, smoke-aerosol production can be reduced or enhanced.

*We conducted water spray tests with HEPA filters early in the series and found that the only way we could cause water to affect the flow through the filter was to reduce the surface tension of the water.

Increasing Filter Area. One technique considered for reducing the rate at which HEPA filters clog is to "derate" the filter relative to the design-mass air-flow rate, i.e., use a filter rated for 500 l/s in a system where the flow rate is 250 l/s. We tested this concept as a possible counter measure for both composite crib fires and for cribs of wood only. The results show partial success, in that the large filter did not plug over during the test with wood, whereas it did plug during the composite crib burn with no increase in HEPA filter endurance time.

Smoke Scrubbing. We know that water scrubbing can successfully remove of aerosols of any size and concentration, so long as sufficient power and water volume are used. We thought that it might be possible to use simple water spray systems to remove some of the smoke aerosols and to some degree extend the life time of HEPA filters. We used a wide range of spray configurations, and flow rates, and different modes of atomization (high-pressure nozzles) for distributing the water. In addition, we added surfactants to the sprayed water to test the possibility of enhanced smoke removal by reducing polar forces between the atomized water and the smoke aerosol. These experiments were conducted using smoke from diesel fires (test B-5.1 through test B-5.27) and smoke aerosols from plain wood cribs (tests B-6 through test B-8). None of these "scrubber" tests showed any appreciable effect with regard to protecting the HEPA filters from plugging. Indeed, in some cases the presence of water spray in the duct appeared to cause the filter to plug faster, possibly by surface-tension reduction effects.

Sand-Bed Filter. The last row of Table 4 gives the results of unsuccessful tests conducted with a static sand-bed filter (augmented by electrified grids upstream of the sand bed to intensify particulate collection) marketed by the EFB, Inc.* These results indicate the plugging potential of smoke aerosols generated during ventilation-control fires. The electrified sand filters have successfully cleaned the "blow-by" from asphalt production plants. However, in our tests, the smoke aerosols completely clogged the surface layer of a 10-cm-thick sand filter during three successive experiments.

Rolling Prefiltration. Early in the project, it was recognized that some form of prefiltration would be the most desirable method for intercepting the smoke aerosols from fires before they reached the final HEPA station. Simple tests with stationary roughing filters showed that they would afford adequate protection until they plugged, at which point either the protected space became pressurized or the prefilter burst because of the high ΔP , thus admitting smoke to the HEPA. A filter that could be changed in-duct, or moved as the pressure drop increased to intolerable levels, would offer a tentative solution to this dilemma. A man-powered "rolling prefilter" (RPF) was jury-rigged as a demonstration of the concept. Figure 17 is a photograph of the RPF installed in the ductwork of the system using the Franklin stove as a smoke generator. The filter media used was three layers of cheese cloth. Figure 18 shows the utility of the system as the RPF is indexed. The fuel used for this test was synthetic rubber fed at a rate of 0.1 kg/min (about a thirtieth of the burning rate of composite cribs). This technique shown great promise.

Upon completion of the experiments to define the filter-plugging potential of laboratory materials, we sought sources of commercial RPF systems. The Anderson Corporation* maintained a pilot-model RPF system to test the feasibility of RPF's for a variety of industrial air-cleaning applications. We rented the system with operator, and demonstrated the ability of automated RPF's to remove smoke aerosols and protect HEPA filters under the severe smoke loads provided by all composite cribs in the test cell(6). However, since the Anderson unit was designed to filter

* Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

air-pollution aerosols, its operation is based on a gravitational impaction technique, requiring high-pressure air flow driven by large electrical motors and control systems. Installation of systems of this type in most containment ventilation systems would require complex bypass circuits, including dampers and associated hardware. Our charter requires the development of a simpler and more cost-effective system that could be installed as part of the containment ducting and ideally would not add unnecessary maintenance to the total containment system. Thus, we decided to seek a simpler system for further research and testing.

We set several requirements as selection criteria for the experimental in-duct system:

- It must be simple and easily modified as the experiment progresses.
- It should be compatible with the existing duct system.
- It should be reasonably inexpensive.
- It should be cleanable.
- The design should be compatible with ultimate containment criteria.
- The design should be flexible and scalable to a wide spectrum of system types and sizes.
- It should be compatible with a wide variety of filter media.

We selected a commercially available RPF, normally used to prefiltration ambient air for removal of large particulate matter ($\text{d} > .005\text{cm}$), modified it to fit our experimental duct system, and tested it with composite crib fires to define the conditions where it would adequately protect HEPA filters from smoke. Figure 19 is a view of the exit of the as-received RPF. Figures 20, 21, and 22 show the front, back, and filter-feed side view of the RPF, as modified to join to the experimental duct system.

The filter media supplied with the RPF had very low efficiency, but it was designed to tolerate the tension stresses caused by the force of the take-up reel. We soon learned that the range of media available for use in sizes comparable to our RPF was very limited and that the only way we could conduct our research was to define the filtration properties required and then to purchase bulk filter media and manufacture our own strip filters. After much Edisonian effort, we developed the laminated system shown in Fig. 23. Figure 24 shows the individual filtration efficiency of each component of the lamination and the resultant composite efficiency. The total ensemble resulted in an average pressure drop of 250 Pa.

We also refined and modified the commercial RPF apparatus. With these modifications, we were ultimately able to achieve our goal of trapping smoke aerosols from composite cribs by in-duct filtration using a continuous-filter media. The set of changes necessary to reach this goal include:

- Development of adequate filter media.
- Removal of sharp edges and prominences that could contact and tear the filter media.
- Sealing leaks in the clean-filter cassette and the dirty-filter reservoir.
- Increasing the depth of the edge guides to reduce the filter-tip losses.
- Adding blinders to upstream filter entrance and outlet slots to reduce aerosol escape and to collimate the aerosol through the central regions of the exposed media.
- Control the filter index distance to provide a complete fresh filter area for each index.

Figure 25 is a portrait of duct flow parameters, showing the pressure drop across both the HEPA filter and the RPF and the total exit flow rate during a standard composite-crib test ($\dot{m} = 0.05 \text{ kg/s}$). The RPF did not start loading until 300 s, at which time it was allowed to attain ΔP of 800 pa before it was indexed. Even though we were exposing a complete area of new filter media at each index, it was not feasible to reduce the RPF ΔP to the pre-loading value because we did not wish to be extravagant with the filter media. The oscillations in \dot{V}_d and in ΔP across the HEPA reflect the variation in flow caused by the ΔP changes of the RPF. The RPF media was depleted at approximately 1300 s and smoke aerosol was directed through the HEPA filter, causing filter plugging and the cessation of flow through the system. Note that fuel was available for at least twice the recorded duration, and we are confident that if it were possible for us to load more filter media, we could have maintained the HEPA filter function for the total burning time.

There is a slight degradation in the \dot{V}_d after steady-state RPF indexing is established. This rate of flow reduction is 10 l/s over 400 s. We believe that this flow reduction results from a slow loading of the HEPA filter by aerosol leakage through the RPF. This loading is indicated by the regular increase in P_H recorded before we ran out of media in the RPF. However, at this low rate of loading, it would take an additional 1600 s for \dot{V}_d to degrade to 1/2 the design flow rate of 250 l/s.

Figure 26 compares ΔP across the HEPA filter for separate tests of composite-crib fires, with and without RPF's inserted between the test cell and the HEPA filter. The B-20 burn was conducted without an RPF; B-40 was equipped with an RPF, but the apparatus was not modified to reduce filter-tip losses; and both B-45 and B-46 were run with fully modified RPF's and laminated filter media. In the B-45 and B-46 tests, HEPA filter plugging resulted because we could not load enough of the prefilter media in the modified apparatus to last for the entire burn. However, the feasibility of the technique was confirmed. Moreover, it is now possible to provide design criteria for in-duct filtration systems using single-pass RPF's*, where justified by circumstances of the enclosure to be protected.

Single-Pass Rolling Prefilters*: Design and Applications

The primary goal of this project were to: (1) define the smoke-production potential of materials in common use in laboratories where radioactive materials are stored or worked with, (2) determine the susceptibility to plugging of HEPA filters exposed to these smoke aerosols, (3) develop countermeasure techniques and test their feasibility for mitigating the smoke-plugging threat to the final HEPA filters in containment ventilation systems.

The experimental RPF (i.e., the modified commercial unit), is a simple filtration procedure which was bound to work, given the right balance of flow and filtration conditions. We were able to provide these conditions using the modified RPF and thus prove the feasibility of the technique. The scope of this program did not require that we develop a prototype apparatus based on the optimum methods identified for protecting the HEPA (indeed the optimum procedure appears to follow the dictates of good fire prevention and to use available in-duct filtration technologies). However, we have definite opinions as

* A single pass RPF is defined as an apparatus where the filter media is located across the duct so that the air-flow vector is normal to the surface of the filter media.

to how an operational RPF should be designed and what features it should contain. More important, however, is where and how a single-pass RPF should be used. If it is employed solely as a fire protection device, its use mode would be entirely different than if it were used as a permanent prefilter with the general purpose of increasing the lifetime of the final HEPA filters. In this latter employment the RPF could also serve as a fire protection device by protecting the HEPA filters to maintain their function under any circumstance.

Single Pass Rolling Prefilter for Fire Protection Only

Figure 27 is a sketch of the general features that we envision for an operational single-pass RPF. It is essentially a self-contained cassette made of any inert and thermally stable material. The filter-media reservoir should contain enough media to allow continued operation during any possible fire in the protected space(s). A linkage between the filter reservoir and the take-up reel is provided across the duct air path using either steel cables or wide mesh-metal screen. Frangible plastic film isolates the filter reservoir and the spent-filter take-up space from the flow of contaminated gases. Upon command of a fire detection system, the filter media is drawn across the duct (through the frangible membranes) to intercept the smoke aerosols. The pressure-indexing control causes new media to enter the duct at prescribed ΔP values. The driving force for the take-up reel and control/detection circuits is located on a mating duct transition piece that contains the cassette. (Note that this design is patterned after film cassettes used in small cartridge cameras.) We believe that our research gives us the necessary background to design and construct a single-pass RPF for most practical containment systems, but we will not indulge ourselves by supplying details to Fig. 27, since the design criteria will vary for different applications. We question the wisdom of recommending installation of this appliance solely for to protect HEPA filters from the effects of fire, especially in light of stringent codes imposed on facilities dealing with toxic materials: e.g., in areas where radioactive materials are stored or worked with, amounts of potentially combustible materials are controlled and contemporary fire-detection and fire suppression systems are required. The chance of a fire reaching appreciable size before discovery is small. Thus, the utility of the single-pass RPF for protecting HEPA filters from fire effects is correspondingly small. In addition, several factors must be considered before deciding on the applicability of this concept to "standard" containment ventilation systems.

First, would the addition of RPF systems in the ventilation circuit increase the complexity of the circuit so that the probability of accidental release of toxic materials is also increased? Each time filter media penetrates the duct during filter injection checks, we face an increased potential for toxic release because we have penetrated the integrity of the containment.

Second, if single-pass RPF's are installed as permanent fixtures in containment ventilation systems they would require stringent maintenance for:

- The initiating detector/signaling/RPF-starter solenoid circuits.
- The filter-injector linkage.
- The condition of the filter media (compressed, as a roll, in the filter feed reservoir).
- The pressure indexing control.
- The filter drive system.
- The drive motors and power-switch contacts.

If the single-pass RPF is designed to be used only when a fire occurs, its very dormancy creates problems for the containment system, and maintenance should be performed at frequent intervals to insure operation upon demand.

Third, the probability of failure of any of the automatic systems is finite, regardless of the maintenance schedule. Thus, there must be supervision of the total system to insure trouble-free operation.

Forth, since the RPF's will generally be installed in remote locations near the bank of final filters, any fault that occurs during emergency operations is essentially unforgiving, and once a fault occurs nothing much can be done to rectify the problem until after the emergency situation is over. Any fault, of course, would result in smoke exposure to the final HEPA filter station and potentially compromise containment.

Where then would we recommend the use of single-pass RPF's should they be relegated to fire protection duty only? We believe that these systems would be cost effective in applications where the containment space includes extreme fuel loads, adjacent or contiguous to abundant toxic materials, or is in areas where explosive research or potentially explosive reactions are routinely being conducted.

The common denominator of these activities is that they require constant supervision, hence, all support equipment and safety systems should be well maintained. Moreover, all automatic safety circuits should have parallel override systems to provide safety redundancy.

In general, we would only recommend the use of a single-pass RPF as a fire protection device where it:

- Receives frequent maintenance.
- Is subject to constant supervision.
- Is easily accessible during emergency operations.

Single-Pass Rolling Prefilter for Prefiltration Fire and Protection

The logical application of a single-pass rolling prefilter is as a prefilter! There are many situations in laboratories and fabricating plants where HEPA filters are exposed to heavy aerosol loads. Consequently, they require frequent replacement and because they generally are contaminated with toxic materials, they create bulky waste-disposal problems. A continuously operating RPF located upstream from the HEPA filter station could significantly reduce both the HEPA filter replacement costs and the volume of toxic waste. Moreover, a permanently installed RPF would also protect the final HEPA filters from smoke logging should a fire occur in spaces served by the ventilation system. The only difference between normal and emergency operations would be the indexing frequency of the prefilter media which is controlled by its pressure difference.

The design of the permanently installed single-pass RPF would not be too different from the sketch in Fig 27. Provision would have to be made for removing the contaminated media and for loading new filter material (we have not done the engineering design for these operations but we do not think they present limiting problems). A protocol would be established to ensure that an adequate supply of clean media was always available in the filter-feed reservoir to trap smoke aerosols in the event of fires in upstream spaces.

Because this application of the single-pass RPF requires more-or-less continual operation of the apparatus, many of the problems identified for the fire protection RPF's disappear; i.e., no signaling circuits are required and no transient stresses are imposed on the system during start-up sequences. Maintenance schedules should be routine, since only the filter driving motor and indexing system would require servicing. In fact, monitoring the filter use rate should provide information about the concentration of aerosol produced in the normal operation of the facility.

At least two additional benefits are gained by use of a permanently installed RPF: the reduction in the volume of contaminated waste and the potential for recovery of expensive or accountable materials that are generally unrecoverable when trapped by HEPA filters.

Permanent-operating single-pass RPF's in containment system have a much larger set of applications than RPF's relegated to fire protection service; therefore, any operation where excessive use of HEPA filters is common should be candidates for these systems, for example:

- Dry scrubbing of acid mists.
- Incineration of toxic waste materials.
- Areas of high dust loading.
- Pre-scrubbing of aerosols from mining, refining, fabricating and reprocessing systems.

Since the cost of replacing a HEPA filter, throughout the country, has been estimated to be \$3000, the cost benefit of the dual-purpose RPF system for certain operations should be obvious.

Enhanced Prefiltration Program

The Waste Management Division of DOE supports a parallel filtration program at LLNL to investigate means of extending the normal operating lifetimes of HEPA filters by enhanced-filtration techniques. These techniques involve increasing the efficiency of low-efficiency filters by imposing an electric field across the media. So that the aerosol is preferentially attracted to the media fiber, as influenced by the lines-of-force patterns established by the electric field. Both static and moving filters are the subject of this research. Because the Waste Management Division has concerns about the effects of fire on the newly designed filters and about their ability to protect HEPA filters from smoke plugging, we tested prototype RPF's designed for the enhanced-filtration project in the fire-test cell. Figure 28 shows a recent RPF prototype tested in this program. Note that the filter media appears pleated in the duct opening. These pleats are actually the path of the filter, directed by offset rollers to increase the surface area of filter exposed to air flow. The surface area for the pleated RPF is five times greater than the area of the single-pass RPF. The main reason for the larger filter area is to reduce the aerosol transit velocity through the filter so that the electric field can act on the particulate.

In tests we conducted with this apparatus, using the composite crib, we did not use electric-field enhancement of the filter because we do not need the degree of efficiency required for diffuse aerosols. While we have been able to show some effect with regard to protecting the HEPA from smoke aerosols, we have not repeated the effectiveness of the single-pass RPF. Tip leakage across the filter edges was identified as the cause for our problems, and the latest model of the pleated RPF has shields to prevent this fault. Note that once this apparatus is developed, it

will have all the desirable qualities required for permanent in-duct prefiltration installation; it will increase normal endurances of standard HEPA filters many fold and will act as a fire protection system for protecting the HEPA from smoke aerosols, when required.

Summary and Conclusions

The primary purpose of this program was to provide guidance and prototype hardware for protection of components of containment ventilation systems from fires and their products in enclosures containing toxic materials.

Our approach included:

1. Defining the magnitude of the problem (the parameters of fire).

- The type and size range of enclosures to be protected.
- The kinds of flammable materials used as furnishings and finishes in laboratories.
- The distribution of flammable materials in containment facilities (using LLNL laboratories as models).
- The relative smoke-production potential of enclosure materials.
- The enclosure ventilation patterns and range for different applications.

2. Defining the damage potential created by the fire.

- Destruction of final HEPA filters by heat or excessive pressure drop, resulting in toxic release to the environment.
- Plugging of final HEPA filters by smoke aerosols or water vapor modified by chemical constituents of smoke; resulting in overpressurization of the ventilation system and potential spread of contamination throughout the facility.
- Enclosure fire overpressurization causing breaches in enclosure containment without compromise of the ventilation system or filtration components.

3. Defining a set of countermeasures to mitigate the problem.

- Control the fuel: materials management to reduce the concentration of combustible materials to the minimum necessary amount in an enclosure.
- Control the fire: application of contemporary fire-detection and fire-suppression procedures to quench or control the fire to reduce thermal damage and possible smoke-release rate.
- Control the smoke: smoke removal or treatment by some means in the exit duct of the enclosure, down stream from the final HEPA filter station.

4. Designing experiments to verify the damage potential.

- Thermal damage to HEPA filter system.
- Smoke logging of HEPA filters by selected flammable materials identified during laboratory survey.

5. Testing of countermeasure procedures that are both promising and cost effective (see Table 4 and the appendix).

The last step in this process was to develop recommendations for the application of the proposed countermeasures.

Table 4 shows that under the standard conditions of our fire test, only two materials common to LLNL did not produce smoke aerosols capable of plugging HEPA filters. They were polycarbonate and dense fiberboard. But these materials ignited to self-sustained combustion, but their burning rates were low, and the resulting smoke aerosol apparently contain more lower molecular weight fractions than do the fuels that produce plugging aerosols.*

Thus, where possible, replacement of materials with high burning rates and high smoke aerosol production by polycarbonate and dense fiberboard would be a logical materials-control measure to reduce the risk of smoke and heat damage to HEPA filters.

The positive fire suppression action of wet-pipe sprinkler systems is accepted as the primary defense against fire spread in enclosures. The required driver for fusing of sprinkler heads is a high temperature at the ceiling. If the fire is slow growing, or the siting of critical sprinkler heads inappropriate, (e.g., shielded from spreading fire plume or in the cooling flow of inlet HVAC ducts) the fire can grow to appreciable size before sprinklers fuse. Thus, it is possible to challenge the containment-protection filters of the ventilation system even though the protected enclosure is equipped with sprinklers. Moreover, fast-growing fires (e.g., our standard test fires) on both flammable and fire-resistant synthetic materials (respectively polycarbonate and PMMA-FR) produce sufficient aerosol during the sprinkler induction period to positively plug HEPA filters after the sprinklers have actuated. These results are accentuated by similar responses during fire tests with composite cribs where over half the fuel mass is fir wood.

To effectively apply the fire-protection attributes of wet-pipe sprinkler systems for primary protection of ventilation containment systems, materials control must also be practiced to reduce the quantity of potential fuels that can produce filter-plugging aerosols regardless of the presence of water sprays.

An extraordinary fire-protection ploy to consider, is to provide committed detection and suppression systems to facilities or appliances identified as exceeding specified fire-risk criteria in enclosures where nonflammable materials and low-fire-risk activities are generally in practice. This technique** could be quite cost effective and should definitely reduce the smoke aerosol exposure of the containment filters.

In areas where the fuel load is moderate and inspection is frequent, standard house-cleaning protocol and contemporary fire-management systems should be more than adequate to protect in-duct filters from smoke aerosols generated in that space. But several conditions can exist which negate the potential of standard techniques to operate effectively; e.g.:

- Volumes containing high resident fuel load on tiered surfaces.
- Volumes for storage of high-energy fuels, explosives, or propellants.
- Laboratories in which explosive experiments are conducted.
- Facilities conducting combustion research.
- Incineration activities.
- Containments near, or adjacent, to any of the above activities.

* Note, for all flammable materials: if the burning rate was less than 1.0 kg/min, HEPA filter plugging would not occur during 60 min. of exposure. This rate corresponds to a fuel load of roughly 0.4 lb/ft, which, according to Table 1, is low for laboratories and high for service areas.

** This is not a new idea; deluge systems for fire protection of individual facilities in petrochemical plants and independent suppression and detection systems for computers, are good examples.

The last item on this list has the greatest potential for causing failure of general ventilation-containment systems since the requirement for ventilation protection may be overlooked in spaces where fire risk is perceived as being negligible.

Clearly, some in-duct appliance is needed to intercept smoke aerosols before they challenge the ability of the containment filters to perform their function. This is especially necessary for operations where loss of containment would be detrimental to the environment, or where internal spread of contamination could perturb productivity in the mission of the facility. The single pass rolling prefilters designed and tested during this program can provide this protection. This capability is demonstrated by the period of protection afforded the HEPA filters in series with RPF, during both wood- and composite-crib fires. The apparatus was a modified commercial unit, containing empirically coupled filter media. This is, in fact, the most encouraging aspect of the research; i.e., the most promising overall countermeasure is nearly an "off-the-shelf" item. Modification for application to containment ventilation systems should entail only precision in manufacture and sealing criteria since the conceptual models exist and are in current use as roughing filters. Another attribute of this system is that the design is scalable to commercial size, making the appliance applicable to the range of common ventilation ducts.

The system described in this report is so far just an experimental prototype that tested the feasibility of a prefiltration concept. Also, single-pass RPF's refined for containment systems would have limited application as a pure fire-protection device. However, they would enjoy much broader use as high-efficiency RPF's, used practically for increasing the nonemergency lifetime of HEPA filters exposed to high ambient aerosol concentrations. Naturally, they would still be able to protect HEPA-filter function during a fire in or near the protected enclosure. Continued use of containment-protection rolling prefilters of this type would be the optimum application of this concept.

We reiterate that single-pass RPF's will have limited application over the spectrum of containment ventilation systems in current use; however, the feasibility of the technique has been proven. A prefiltration technique that is universally applicable is needed, and such a system is currently being developed--the electrified-pleated RPF under development by the Enhanced Filtration Program at LLNL. Optimization of this RPF will provide an appliance that can be used on almost any containment ventilation system, regardless of the ambient aerosol load. Its most cost effective application would be where the background aerosol concentration is not high, resulting in minimum attention or changing of both the prefilter and the HEPA filter. However, because of the wide variety of facility types and applications, both single-pass and pleated RPF's provide fuller options in the range of contemporary and future containment ventilation systems.

List Of Symbols

ΔP_H	=	Pressure drop across the HEPA filter (p_a).
in. wg	=	Measure of pressure drop; inches water gauge.
P_a	=	Measure of pressure drop; pascal.
cfm	=	Measure of volumetric flow rate; cubic feet per minute.
ℓ/s	=	Measure of volumetric flow rate; liters per second.
\dot{V}_a	=	Total inlet air flow to test cell (ℓ/s).
T_c	=	Temperature directly over the burning crib ($^{\circ}C$).
$\{\alpha\}$	=	Oxygen depletion in exit duct (%).
\dot{V}_d	=	Exit (design) air flow rate (ℓ/s).
kJ	=	Kilo-joules
S	=	Volume expansion of gas due to ambient temperature rise (ℓ).
Mole _p	=	Molecular weight of the combustion products.
M_f	=	Mass of fuel (kg).
\dot{m}_f	=	Fuel burning rate (kg/s)
T	=	Average temperature of the heated gas ($^{\circ}C$).
t_p	=	Time of filter plugging (time at which flow rate is reduced to 1/2 its design value)
\dot{V}_{leak}	=	Calculated test cell leak rate. (ℓ/s).
T_{HEPA}	=	Measured gas temperature at the HEPA filter sampling station ($^{\circ}C$).
t_p	=	Time to filter plug (sec)

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Captions

1. Schematic layout of LLNL full-scale fire test cell with associated experimental ventilation system.
2. Photograph of LLNL full-scale fire test cell with associated experimental ventilation system.
3. Standard composite crib in metal support frame.
4. Fire parameter portrait for a natural-burning low-porosity wood crib.
5. Temperature and internal test cell pressure for a standard wood crib fire in an enclosure tightly sealed, except for exit duct work. The sudden drop in pressure was due to HEPA filter rupture.
6. Data oscillations during a standard wood crib fire. Note that the period of the oscillations is relatively constant, with the amplitude some function of fire intensity.
7. Effect of air temperature of HEPA filter endurance. The data points indicate average time-to-failure of HEPA filters at the indicated temperature.
8. Aerosol loading of HEPA filters by smoke from wood fires; effects of burning rate and fuel moisture noted.
9. Aerosol loading of HEPA filters by smoke from PVC fires; effects of burning rate noted.
10. Aerosol loading of HEPA filters by smoke from PMMA fires; effects of burning rate noted. Design flow-rate at 250 l/s.
11. Aerosol loading of HEPA filters by smoke from PMMA fires; effects of burning rate noted. Design flow rate at 500 l/s.
12. Aerosol loading of HEPA filters by smoke from dense fiberboard fires; effects of burning and ventilation rate noted.
13. Aerosol loading of HEPA filters by smoke from composite cribs; effects of various parameters noted.
14. HEPA filter media loaded with smoke aerosols from composite crib fires.
15. HEPA filter media loaded with solid phase aerosol (sodium chloride).
16. Flow and temperature portrait of a composite crib fire with fire-suppression sprinkler application.
17. Preliminary design of a hand-powered rolling prefilter using layered cheesecloth as filter media.
18. Air flow and filter pressure drop during Neoprene fire tests for a HEPA filter protected by a hand-powered rolling prefilter (burning rate = 100 gm/min).

19. Exit interface of an unmodified commercial rolling prefilter.
20. Take-up reel side of modified commercial rolling prefilter.
21. Inlet interface of modified commercial rolling prefilter. Note the side blinders for flow collimation.
22. Exit interface of modified commercial rolling prefilter. Note the edge blinders to prevent tip losses through edges of filters along the slide path.
23. Three-ply rolling prefilter media.
24. Filtration efficiency of components and composite rolling prefilter media.
25. Pressure and airflow portraits of prefiltration test showing prefiltration in indexing and effectiveness.
26. Evaluation of effectiveness of rolling prefiltation techniques.
27. Conceptual design of a rolling prefilter for a containment ventilation system.
28. Pleated rolling prefilter: experimental model for the enhanced filtration project.

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LAWRENCE LIVERMORE LABORATORY
FULL SCALE FIRE TEST FACILITY

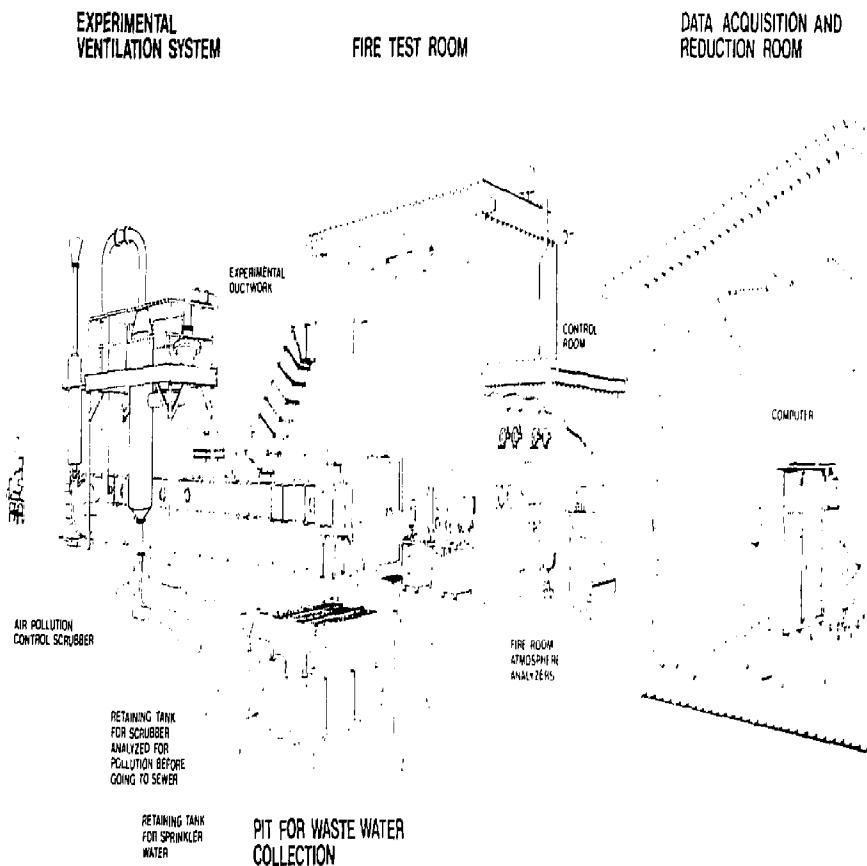


Fig. 1. Schematic layout of LLNL full-scale fire test cell with associated experimental ventilation system.

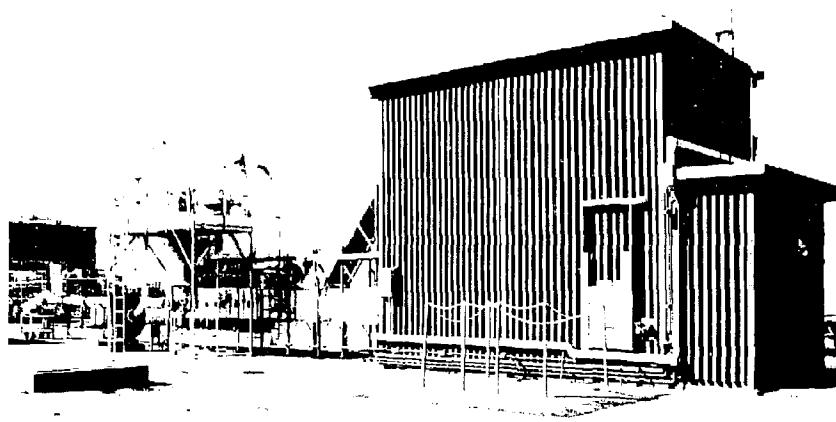


Fig. 2. Photograph of LLNL
full-scale fire test cell with
associated experimental
ventilation system.

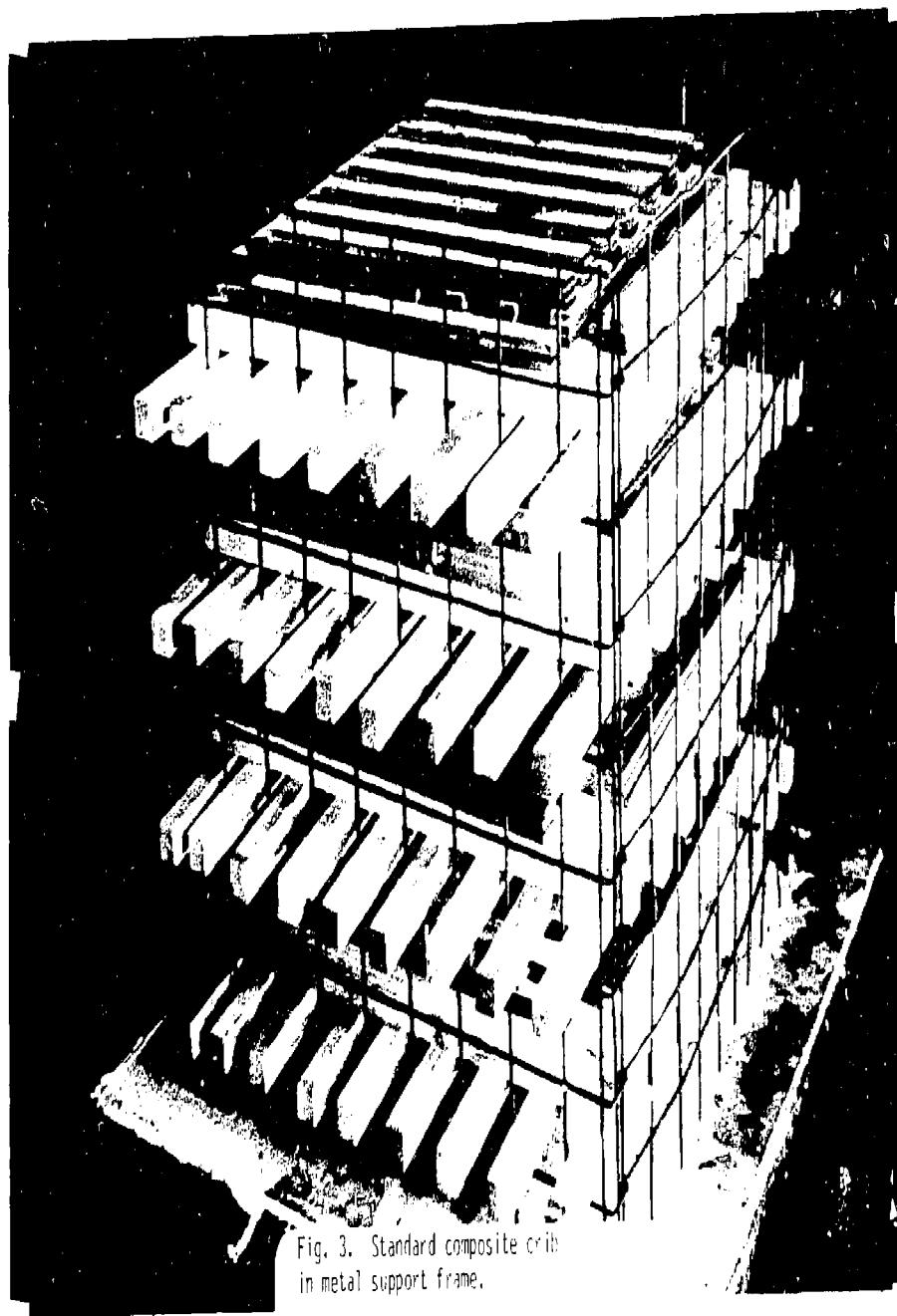


Fig. 3. Standard composite crib
in metal support frame.

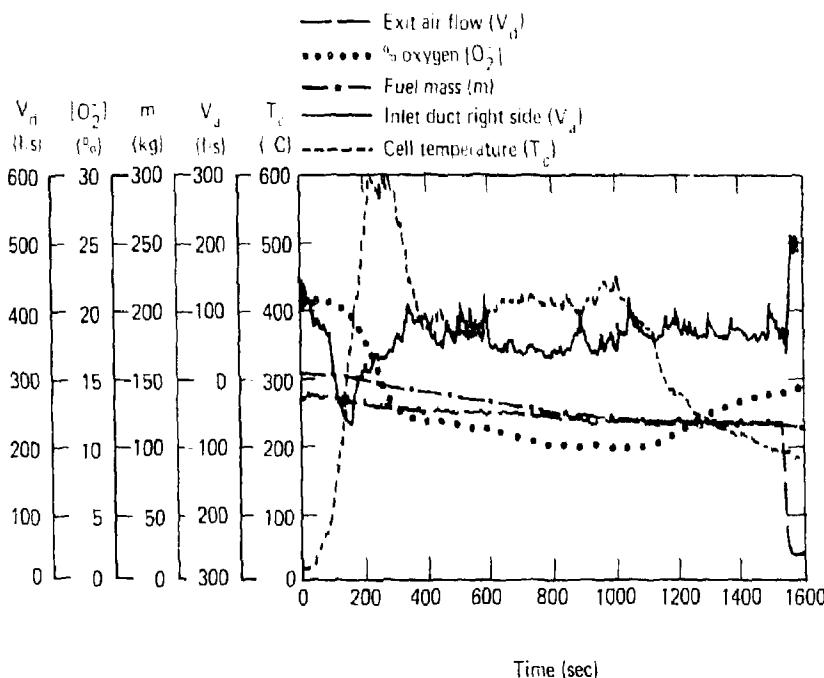


Fig. 4 Fire parameter portrait for a natural-burning low-porosity wood crib.

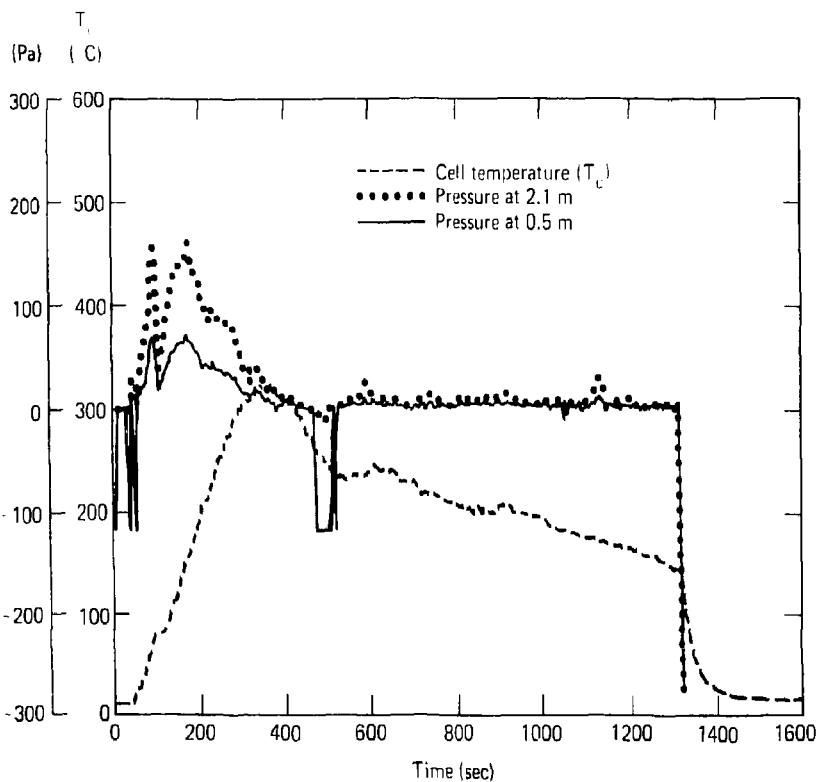


Fig. 5 Temperature and internal test cell pressure for a standard wood crib fire in an enclosure tightly sealed, except for exit duct work. The sudden drop in pressure was due to HEPA filter rupture.

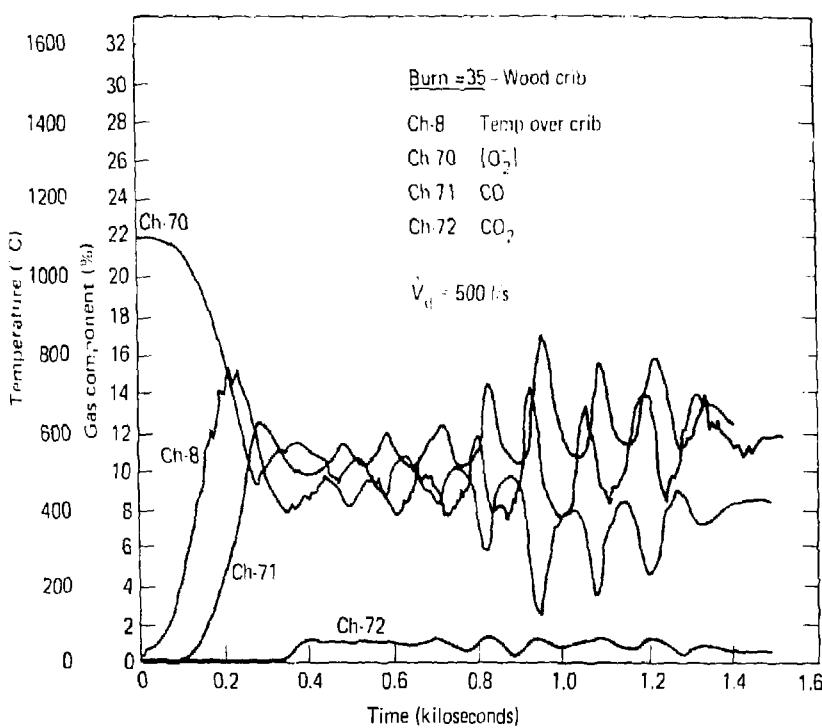


Fig. 6 Data oscillations during a standard wood crib fire. Note that the period of the oscillations is relatively constant, with the amplitude some function of fire intensity.

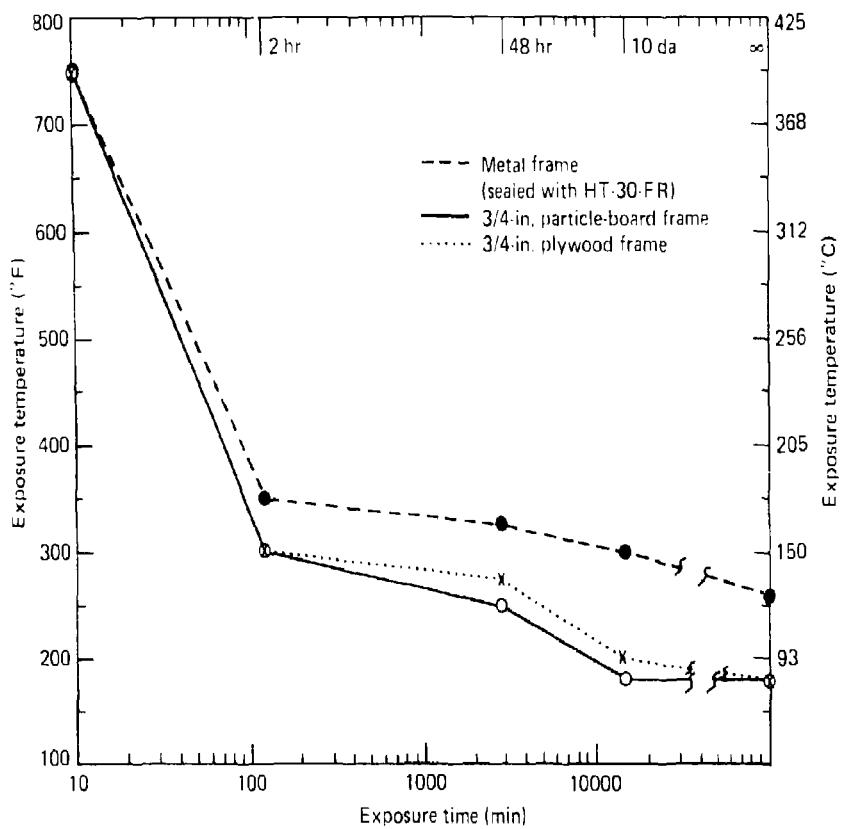


Fig. 7 Effect of air temperature of HEPA filter endurance. The data points indicate average time-to-failure of HEPA filters at the indicated temperature.

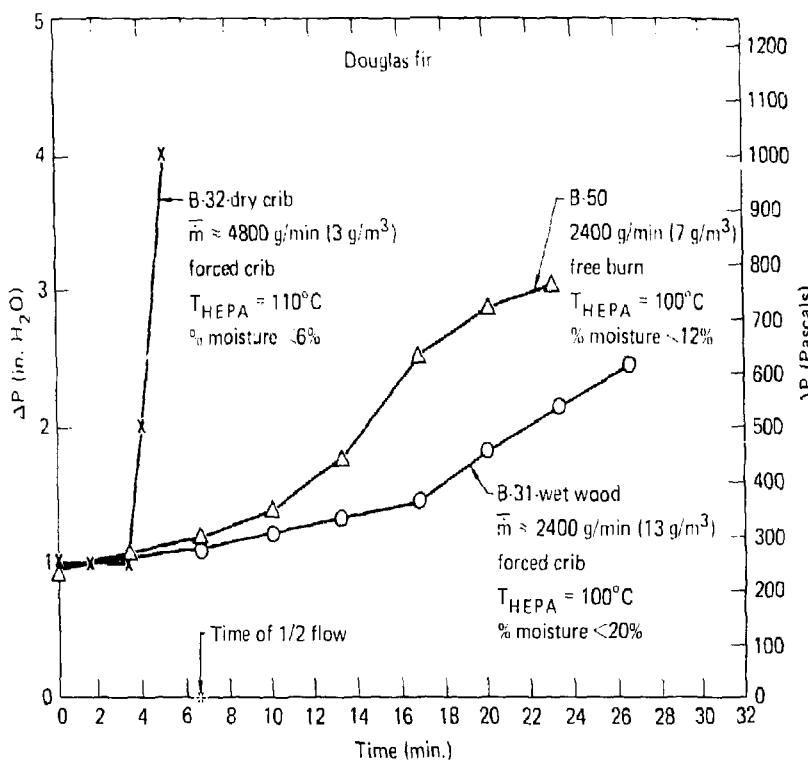


Fig. 8 Aerosol loading of HEPA filters by smoke from wood fires; effects of burning rate and fuel moisture noted.

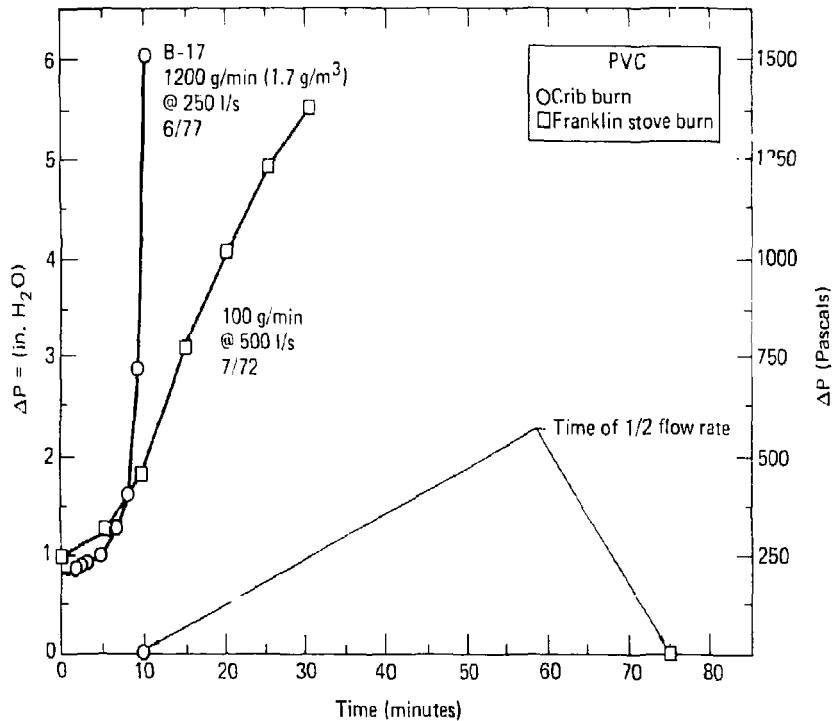


Fig. 9 Aerosol loading of HEPA filters by smoke from PVC fires; effects of burning rate noted.

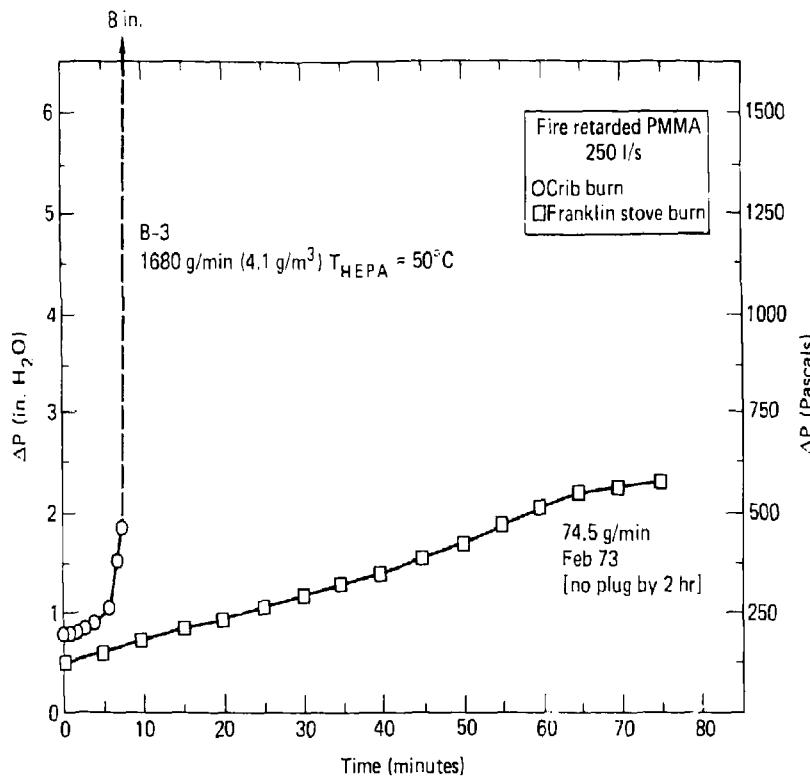


Fig. 10 Aerosol loading of HEPA filters by smoke from PMMA fires; effects of burning rate noted. Design flow-rate at 250 l/s.

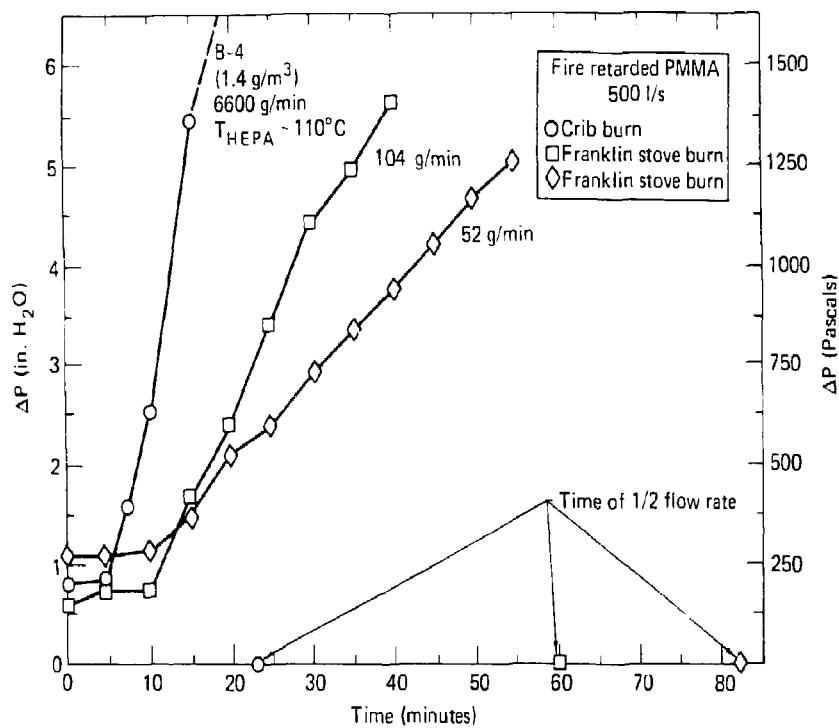


Fig. 11. Aerosol loading of HEPA filters by smoke from PMMA fires; effects of burning rate noted. Design flow rate at 500 l/s.

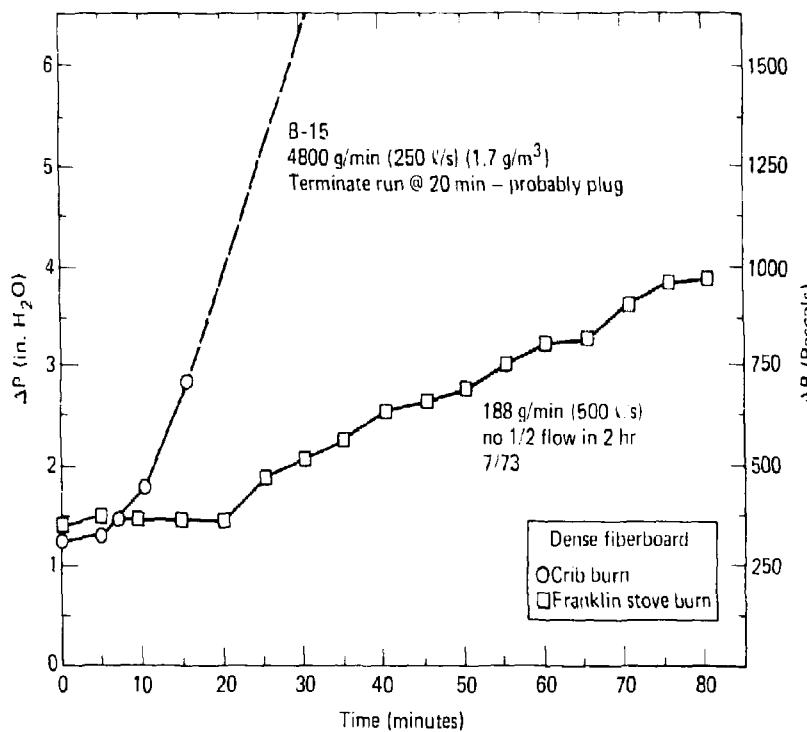


Fig. 12 Aerosol loading of HEPA filters by smoke from dense fiberboard fires; effects of burning and ventilation rate noted.

					HEPA	Wood
		W ₁ (g/min)	W ₂ (g/m ²)	T _{exp} (°C)	wt gain (g)	moisture (g)
	B 44	250	3000	6.4	65	470
1500° C fire	B 20	250	1200	4.8	86	
	B 38	500	3000	8.6	105	574
	B 52	250	1500	7.6	70	106
Fire burn	B 53	500	1680	8.4	110	550
Fire burn					8	

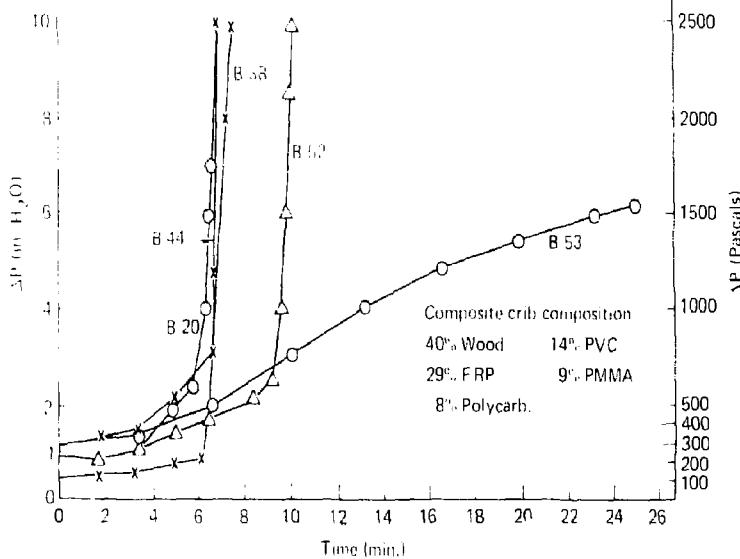


Fig. 13 Aerosol loading of HEPA filters by smoke from composite cribs; effects of various parameters noted.



Fig. 14 HEPA filter media loaded with smoke aerosols from composite crib fires.

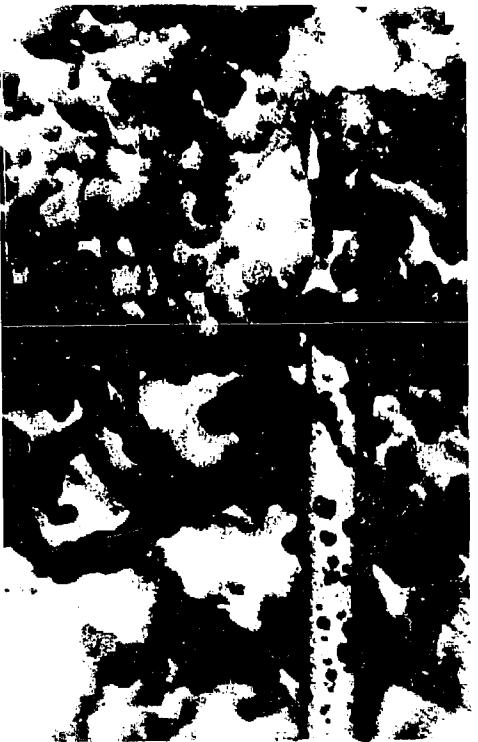


Fig. 15 HEPA filter media loaded with solid phase aerosol (sodium chloride).

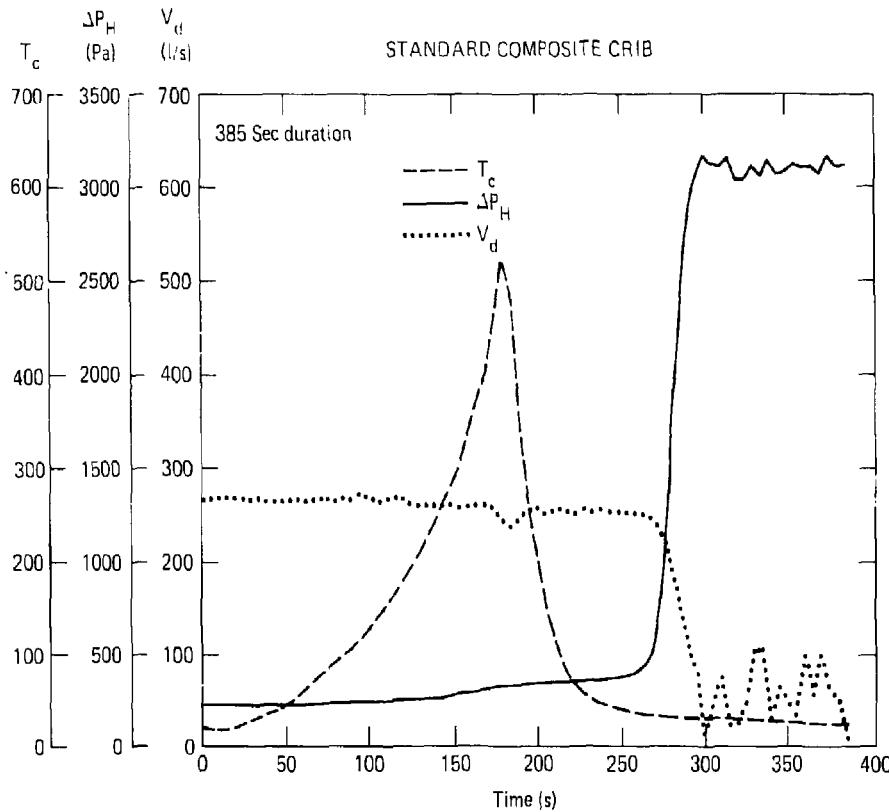


Fig. 16 Flow and temperature portrait of a composite crib fire with fire-suppression sprinkler application.

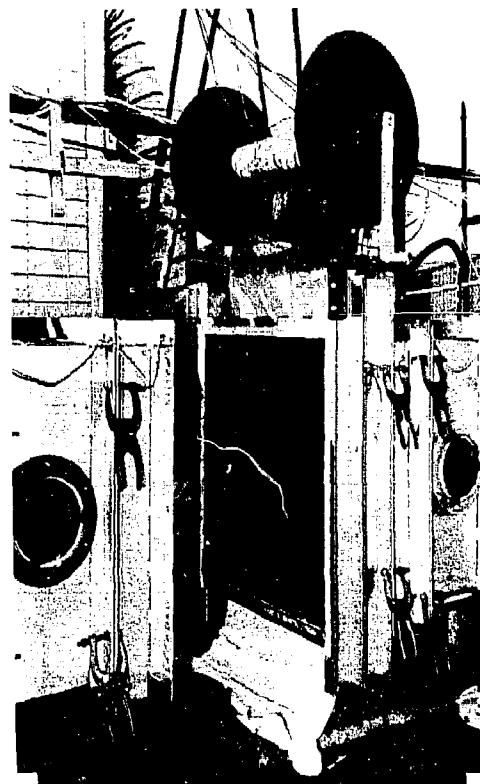


Fig. 17 Preliminary design of a hand-powered rolling prefilter using layered cheesecloth as filter media.

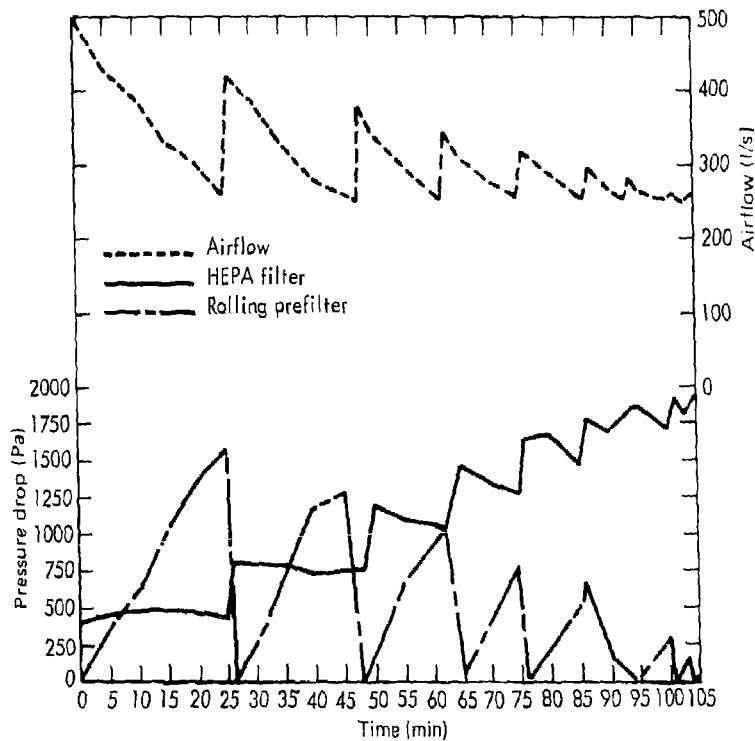


Fig. 18 Air flow and filter pressure drop during Neoprene fire tests for a HEPA filter protected by a hand-powered rolling prefilter (burning rate = 100 gm/min).

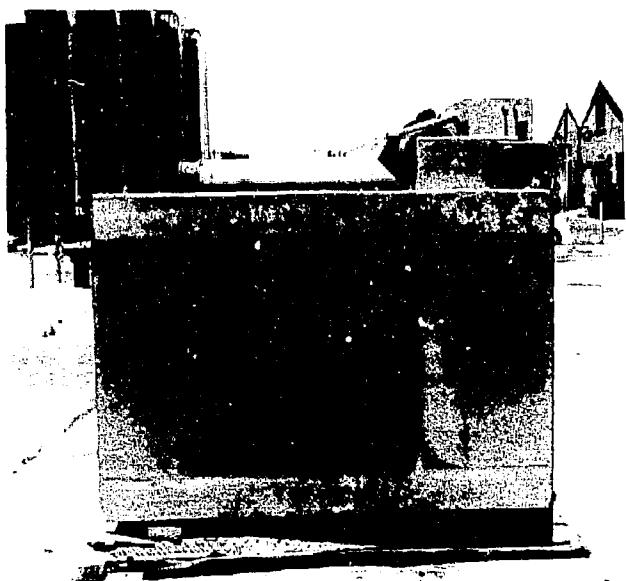


Fig. 19 Exit interface of an unmodified commercial rolling prefilter.

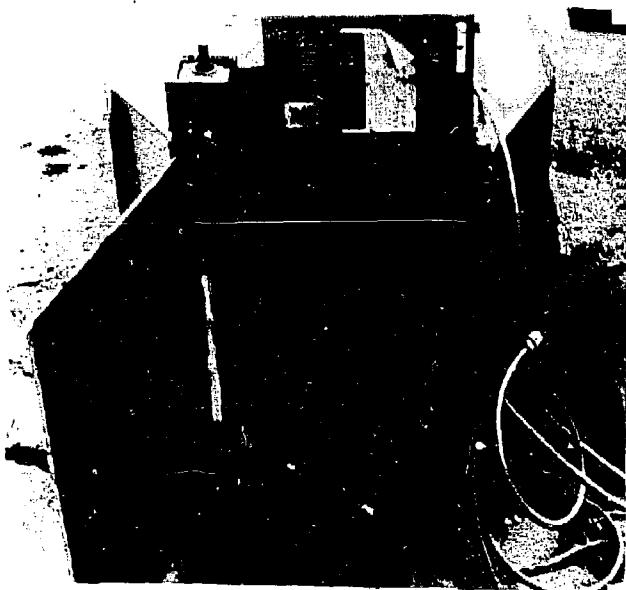


Fig. 20 Take-up reel side of modified commercial rolling prefilter.

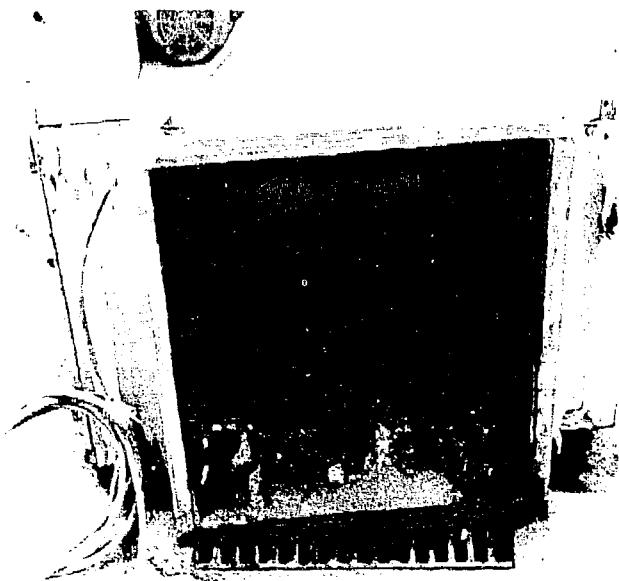


Fig. 21 Inlet interface of modified commercial rolling prefilter. Note the side blenders for flow collimation.

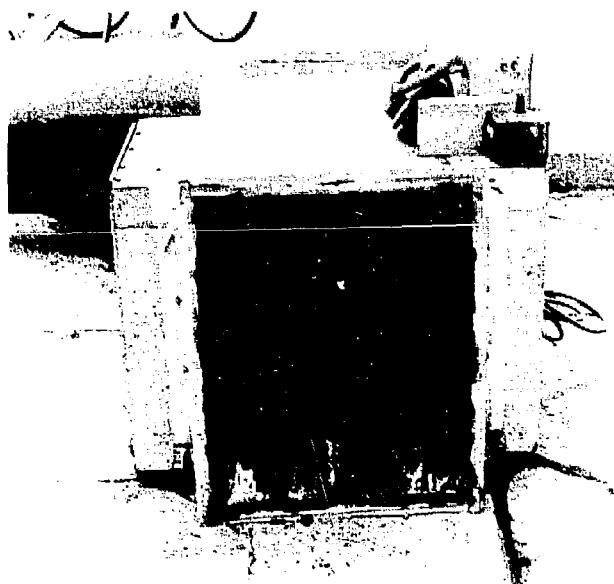


Fig. 22 Exit interface of modified commercial rolling prefilter. Note the edge blinders to prevent tip losses through edges of filters along the slide path.

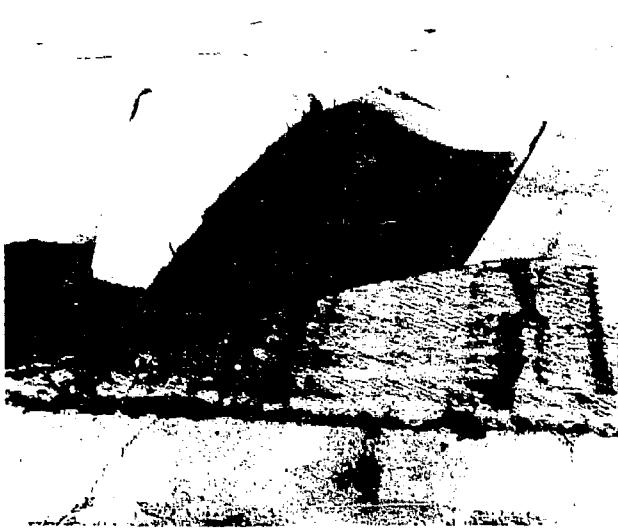


Fig. 23 Three-ply rolling prefilter media.

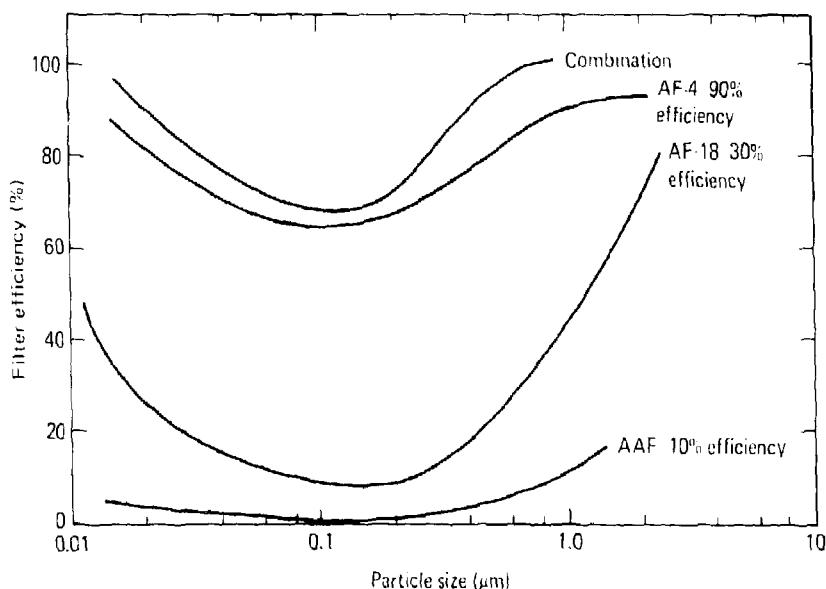


Fig. 24 Filtration efficiency of components and composite rolling prefilter media.

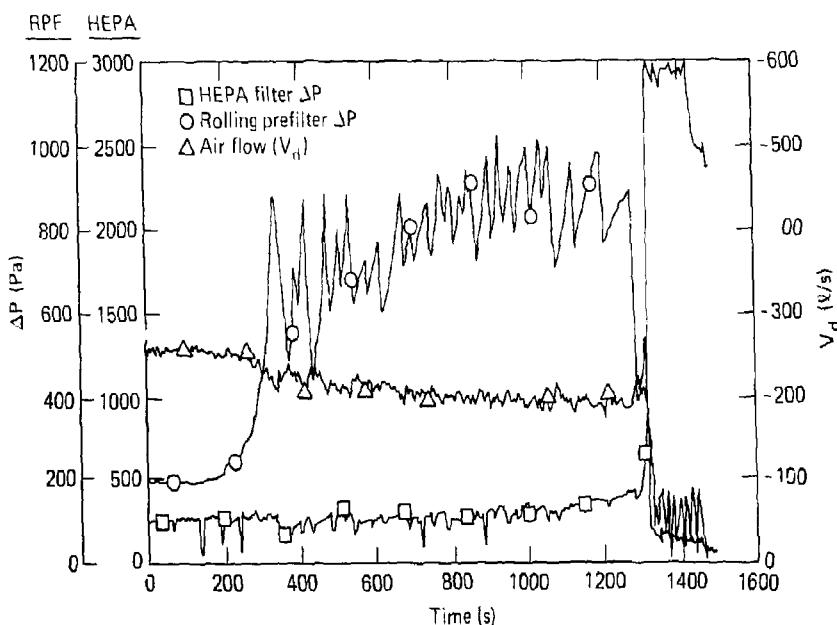


Fig. 25 Pressure and airflow portraits of prefiltration test showing prefiltration in indexing and effectiveness.

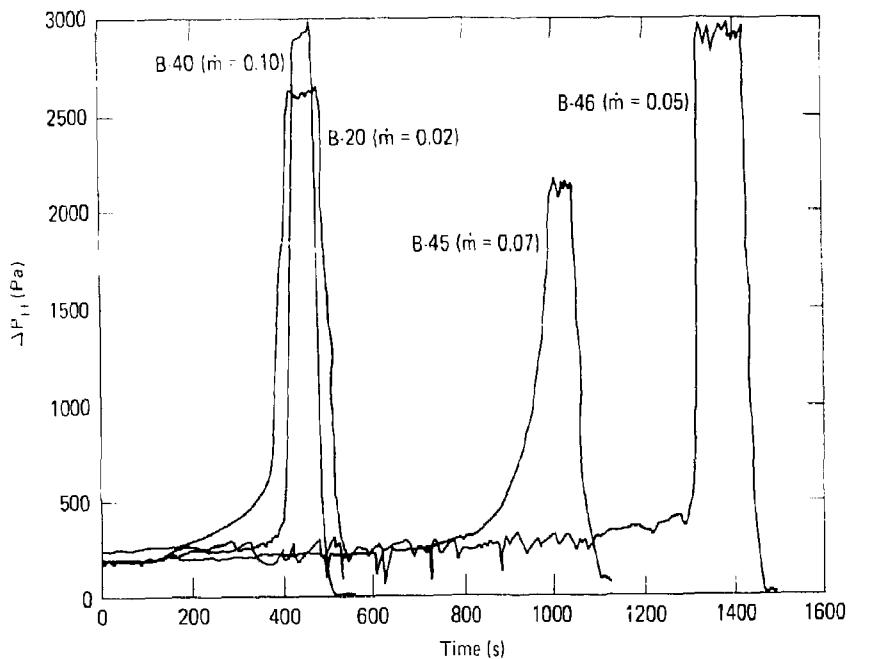


Fig. 26 Evaluation of effectiveness of rolling prefiltration techniques.

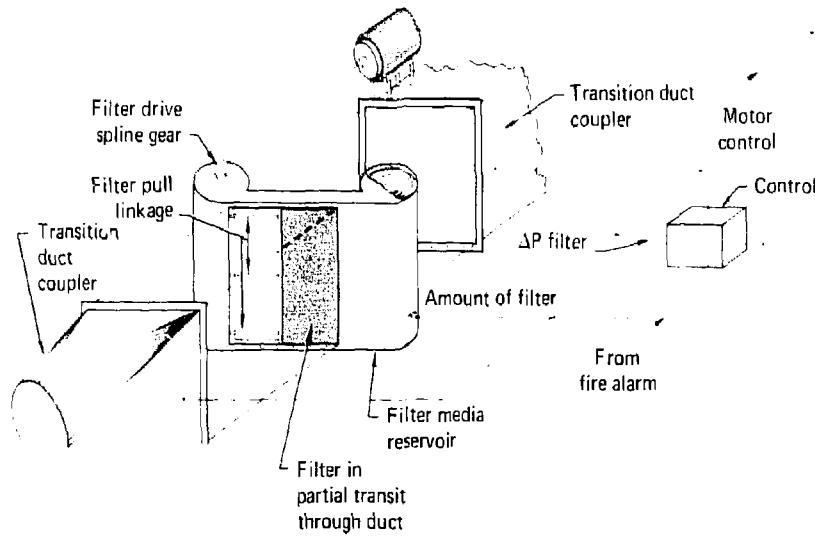


Fig. 27 Conceptual design of a rolling prefilter for a containment ventilation system.

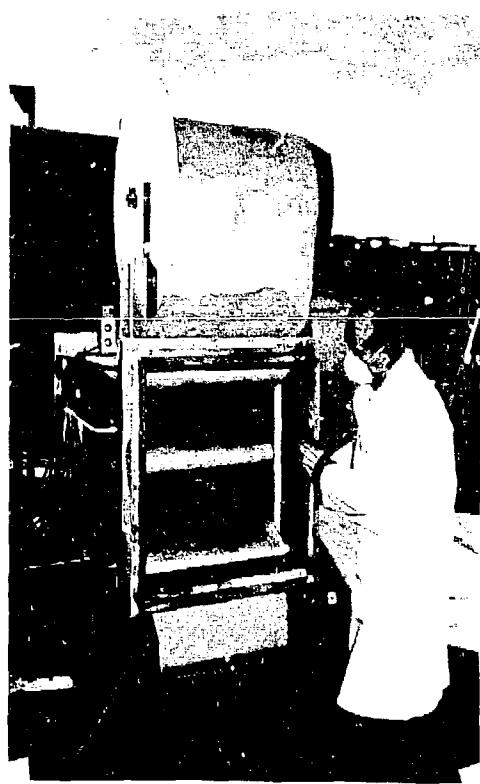


Fig. 28 Pleated rolling prefilter;
experimental model for the enhanced
filtration project.

TABLE I. Test cell flow dynamics for natural materials, in liters/second.

	51	52	53	54
	Wood chip	Wood chip	Composite	Composite
Design air inflow (V_d)	111	280	240	500
Measured air inflow (V_a)	235	225	115	360
Leak	35	55	65	140
Measured outflow (T_{max})	165	145	65	55
Calculated outflow (T_{max})	146	149	125	130
Measured steady-state flow	90	100	85	200
Calculated steady-state flow	102	51	4	-300

Table 2. Fire, airflow, and smoke release data for FY 1979

Test	Vd	Va	V Leak	V out	Vf	Mf	Tcell	ΔT ₀	Δt _{1/2}	Δup/dw	Δwet/dry
45	250	175	75	-30	95	.075	229	.42			
46	250	197	53	-		.05	243	.36			
47	520	340	180	-20	120	.07	211	.63			
50*	260	235	25	-165	90	.042	260	.52	.59	.62	.03
51*	280	225	55	-145	100	.036	262	.52		.67	.06
52	280	215	65	-65	85	.028	232	.30	.67	.12	.17
53	560	360	200	+55	200	.028	225	.71	.51	.25	.22
54	255	150	105	-180	50	.066	240	.45	.66	.45	.05
55	255	155	100	-145	40	.06	239	.42	--	--	.80
56a						.065	229	.50	.51	.55	.44
56b	230	185	45	-180	80	.031	237	.56	.74	.90	.24
56c						.033	203	.54	.35	.61	.21
57	250	185	65	-120	135	.063	248	.51			
58	250	200	50	-60	90	.063	232	.50			
59	250	190	60	-90	90	.05	255	.53	.58	.88	.46
60	250	200	50	-105	50	.06	235	.75	.45	.73	.15
61	250					.035					
62	250	200	50	-275	61	.06	240	.61			

*All tests composite cribs
except for 50 & 51

Design air flow rate
(actual out flow) (g/s)

Measured initial inflow
(g/s)

Apparent test cell
leakage ~1/4 to 1/3 of
total flow

Peak outflow rate from
inlet ducts (g/s)
Post-outflow-flow
rate (g/s)

Fuel burning rate
(kg/sec)

Average test cell (°C)
Temperature (exclude fire)

Percent of duct entrance
temperature at 19' down duct

Aerosol gain from fully
ventilated to ventilation
control (%)

Percent aerosol lost
through 19' of duct (%)

Percent aerosol mass
remaining after 24 hours of
drying at ambient
temperature

Table 3.
IDEAS FOR REMOVING OR REDUCING FIRE-CAUSED SMOKES

1. Use HEPA Filter in series
2. Increase filter area *
3. Use less efficient filters (prefilters) ahead of HEPA Filter *
4. Use moving filter "tape" *
5. Electrostatic precipitation
6. Active resident fire protection *
7. Scrubbing with water sprays with or without surfactant *
8. Acoustical agglomeration
9. Natural aging
10. Chemical additives *
11. Minimize quantity of materials which smoke (fuel control) *
12. Convert smoke particulates to gas *
13. Recirculate smoke
14. Use high pressure Venturi scrubbers *
15. Control ventilation (oxygen starvation) *
16. Electrophoresis in filter media
17. Dilute aerosol

Note: The above ideas are given on the basis that they are technically possible-not that they are necessarily practicable or cost effective.

Table 4. Effect of various countermeasures on HEPA filter performance

	Fir wood	PPVA-PR	$V_d = 250 \text{ f/s}$	Polycarbonate	Dense fiberboard	Fiber-reinforced polyester	Polyvinyl chloride	Composite				
Countermeasure	t plug, n, t plug, s, t plug, n, t plug, s, t plug, s, t plug, s, t plug, n, t plug, s,	kg/s	kg/s	kg/s	kg/s	kg/s	kg/s	kg/s				
Forced burn (enclosure)	320	0.12	400	0.03	No plug 0.04	No plug 0.08	680	1.01	590	0.02	400	0.02
Water scrubber (1-100 /min)												
w/ & w/o surfactant	350	0.11										
Fusing sprinkler	No plug	^a	400	^a	550	^a	No plug	^a	265	0.05		
Single pass Boiling prefILTER	No plug	0.08					No plug	0.07				
Wet wood	No plug	0.03										
Large HEPA surface	No plug	0.035										
Electrified Sand Filter							360	0.06				

^aFor most fires, sprinkler activation occurs before steady-state burning.

Appendix

Fuel type and configuration	Initial Conditions			Fuel Parameters			Critical Temperatures			Plug, Temp., °C	Peak, Temp., °C	
	T _{init} , °C	R _{in} , %	Exit air flow rate, l/s	Initial fuel weight, kg	Final fuel weight, kg	q, kg/s	T _{max} (cell), °C	T _{max} (duct), °C	T _{DP} (filter), °C	T _{DP} (filter), °C		
PE-7 Fir, tight, layers staggered	20	49	500	194	145	.10	674 0.37	295	145	70	145.5	290.5
PE-5 Fir, tight, layers staggered	22	12	250	200	120	.09	700 0.24	280	90	62	214.0	265.5
PE-4.2 Fir, tight, layers, staggered	21	--	250	183	108	.10	700 0.34	290	100	65	224.5	278.0
B-1 Fir, loose, layers staggered	20	76	250	143	78	.11	800 0.16	105	105	50	201.0	317.5
B-2 Fir, loose, layers aligned	20	--	250	147	117	.12	750 0.16	110	106	60	223.5	304.5
B-3 SE-1 Fir, loose, layers aligned	20	69	250	94	79	.028	800 0.52	175	50	37	68.5	211.3
B-4 SE-2 Fir, loose, layers aligned	17	45	500	79	25	.11	670 0.70	215	110	55	211.0	214.5
B-6 SE-3 Fir, loose, layers aligned	26	38	250	130	60	.10	770 0.16	300	59	59	234.3	286.0
B-7 SE-1 Fir, loose, layers aligned	15	72	250	128	68	.11	750 0.15	310	31	31	271.0	298.5
B-8 SE-3 Fir, loose, layers aligned	69	43	250	132	90	.10	800 0.17	130	60	60	278.5	272.0
B-9 Fir, loose + sprinkler	55	70	250	136	--	.05	780 0.14	220	100	35	194.0	16.5
B-10 SE-3 + sprinkler	45	50	250	81	--	.016	600 0.13	185	58	30	16.0	153.0
B-11 Lexan	--	--	250	80	35	.037	700 0.55	190	80	50	--	230.3
B-12 Lexan + sprinkler	49	56	250	81	--	.01	410 0.35	115	65	40	--	154.0
B-13 Fir, loose, leak	--	--	250	135	95	.01	680 .021	250	105	63	183.5	280.5

Fuel type and configuration	Filter Parameters		Upstream Impactor			Downstream Impactor			Gas Analysis			
	t plug	Δ P max, pascals	wet mass, mg	dry mass, mg	Aerosol size trend	wet mass, mg	dry mass, mg	Aerosol size trend	[O ₂] %	[CO] _g %	[CO] ₂ _g %	[CH ₄] _n ppm
PB-7 Pir, tight, layers staggered	0.9	420	--	1000	>3μ/80	--	--	--	5.4	0.3	--	--
PB-8 Pir, tight, layers	0.7	2300	--	12000	>2μ/70	--	--	--	6.5	3.4	--	--
PB-8.2 Pir, tight, layers staggered	0.7	2300	--	5000	2μ/80	--	--	--	6.0	3.1	--	--
B-1 Pir, loose, layers staggered	0.32	2600	--	7200	1<3μ/77	--	--	--	6.0	2.8	--	--
B-2 Pir, loose, layers aligned	0.33	2750	--	4500	<2μ/80	--	--	--	5.0	1.	--	--
B-3 SE-3, layers aligned	0.4	2800	--	4065	>1μ/90	--	--	--	19.4	0.62	0.6	--
B-4 SE-3, layers aligned	1.45	2075	--	1377	<1μ/72	--	--	--	13.6	--	4.8	400
B-6 SE-3, layers aligned	0.37	2350	--	2196	>2μ/77	--	--	--	5.0	--	13.8	--
B-7 SE-3, layers aligned	0.38	2900	--	3500	<1μ/72	--	--	--	4.0	--	6.2	13600
B-8 SE-3, layers aligned	0.32	200	--	1400	<2μ/96	--	--	--	1.8	4.0	3.8	1450
B-9 Pir, loose + sprinkler	--	500	--	--	--	--	--	--	9.0	2.0	13.0	1600
B-10 SE-3 + sprinkler	0.4	2350	--	--	--	--	--	--	19.0	1.0	4.0	9600
B-11 Lexan	--	1600	--	--	--	--	--	--	9.0	0.2	10.2	1400
B-12 Lexan + sprinkler	0.55	2400	--	--	--	--	--	--	16.5	0.2	4.0	--
B-13 Pir, loose, leak test	0.61	2000	--	--	--	--	--	--	5.0	3.2	14.0	--
			--	--	--	--	--	--	3.5	3.9	15.7	16000

Fuel type and configuration	Initial Conditions			Fuel Parameters			Critical Temperatures			Plug	Peak	
	T_{amb} , °C	R_f , %	Exit air flow rate, L/s	Initial fuel weight	Final fuel weight	\dot{m} fuel/s	T_{max} °C	T_{max} (duct), °C	T_{CB} (filter), °C	T_{AB} (filter), °C	Temp., °C	Temp., °C
				Kg	Kg	Kg/s	°C	°C	°C	°C		
B-14 Fir, loose, crib.	—	—	250	142	100	.12 0.22	725	270	120	70	227.5	293.8
B-15 Benglex	—	—	250	88	32	.09 0.42	630	230	110	90	—	264.5
B-16 Benglex + sprinkler	—	—	250	88	78	.04 0.27	120	110	75	45	—	142.0
B-17 PVC, loose	—	—	250	133	128	.02 0.50	240	85	60	40	—	65.5
B-18 FRP, loose	—	—	250	38	20	.02 0.43	560	170	90	50	187.5	187.5
B-19 FRP + sprinkler	—	—	250	38	36	.001 0.25	410	130	80	40	—	134.0
B-20 Composite	—	—	260	161	149	.02 0.24	640	200	100	60	181.8	192.0
B-21 Fir, standard crib	—	—	250	145	100	.10 0.14	640	165	90	60	222.8	268.5
B-22 Repeat B-21	—	—	250	145	80	.08 0.15	700	170	95	65	213.0	241.3
B-23 Composite Anderson 2000	—	—	280	180	146	.07 0.13	390	130	65	40	—	89.5
B-24 Composite Anderson 2000	—	—	280	171	116	.07 0.13	420	125	35	—	—	48.5
B-25 Composite Anderson 2000	—	—	380	174	118	.06 0.40	370	150	—	—	—	134.0
B-26 Fir, standard crib	—	—	280	135	50	.08 0.10	700	210	70	65	—	222.5
B-27 Fir, standard	—	—	250	135	88	.09 0.06	720	230	80	—	216.5	281.0
B-28 Fir, standard crib, overhead ventilation	—	—	250	130	95	.10 0.06	750	280	110	87	172.0	305.0

Fuel type and configuration	Filter Parameters		Upstream Impactor			Downstream Impactor			Gas Analysis			
	t plug	Δ P max, pascals	wet mass, mg	dry mass, mg	Aerosol size trend	wet mass, mg	dry mass, mg	Aerosol size trend	[O_2] ₀ %	[CO_2] ₀ %	[CO_2] _a %	[CH_4] _a ppm
B-14 fit, loose, calib.	0.67	2000	--	--	--	--	--	--	3.5	3.9	15.7	16000
B-15 Bonelex	--	750	--	1663	<2p/22	--	1666	<2p/22	3.1	3.0	15.0	16000
B-16 Bonelex + sprinkler	--	--	--	201	<2p/91	--	--	--	17.6	0.2	3.2	900
B-17 PVC, loose	0.59	2250	--	2300	<2p/22	--	1666	<2p/98	17.4	0.2	1.8	--
B-18 PVC, loose	0.88	1500	--	1140	>2p/73	--	1592	>2p/67	8.3	0.3	11.5	8000
B-19 PVC + sprinkler	--	--	--	226	<2p/92	--	176	>2p/94	17.5	--	3.0	700
B-20 Composite	0.40	2100	--	6359	>1p/99	--	4800	>2p/85	13.0	2.8	8.2	--
B-21 Pfr, standard crib	0.57	1900	--	208	--	--	--	--	5.2	1.5	14.0	14500
B-22 repeat B-21	0.76	2080	--	--	--	--	--	--	2.8	2.1	15.8	15000
B-23 Composite Anderson 2000	--	--	--	13700	>1p/91	--	--	--	8.8	1.3	9.0	--
B-24 Composite Anderson 2000	--	200	--	3300	<2p/79	--	--	--	7.0	4.0	10.0	16500
B-25 Composite Anderson 2000	--	--	--	--	--	--	--	--	7.0	4.0	10.5	1550
B-26 Pfr, standard crib	--	--	16800	685	<2p/73	--	--	--	7.0	5.5	16.0	15000
B-27 Pfr, standard crib	0.2	2000	--	--	--	--	--	--	1.1	0.8	15.6	15000
B-28 Pfr, standard crib, overhead vents	0.4	2250	27000	6600	>3p/91	11000	2200	>3p/89	7.2	3.8	13.0	11000

Fuel type and configuration	Initial Conditions			Fuel Parameters			Critical Temperatures			Plug		Peak	
	T _{amb} , °C	B _H , %	Exit air flow rate, l/s	Initial fuel weight, kg	Final fuel weight, kg	h, kg/s	T _{max} (cell), °C	T _{max} (duct), °C	T _{DR} (filter), °C	T _{DB} (filter), °C	Temp., °C	Temp., °C	
B-29 Fir, standard crib, overhead ventilation	-	-	260	140	105	.10 .05	600 0.19	260	100	52	151.8	286.5	
B-30 Fir, standard crib, overhead ventilation	24	76	260	175	120	.077 .043 .034	700 0.19		120	55	--	274.0	
B-31 Fir, standard crib, overhead ventilation	26	64	270	144	--	.060 .043 .013	730 0.32	200	100	69	--	221.5	
B-32 oven dried - Et	28	50	250	162	115	.120 .030	770 0.16	256	112	63	185.0	325.0	
B-33 Lexan Repeat B-15, sprinklers	16	28	250	135	111	.010	730	125	70	37	--	153.5	
B-34 Fir, Hi inlet	40	32	500	185	150	.10	775	280	150	71	--	298.0	
B-35 Repeat B-34	52	50	500	145	85	.36	720	290	160	14	--	251.0	
B-36 Repeat B-35 Sonic Nozzle Upstream Hepa	48	16	500	145	112	.097	740	295	70	213.0	301.7		
B-37 Low Flow, Large Hepa	28	60	250	145	122	.035	780	210	65	--	119.8		
B-38 Composite	34	42	500	221	140	.050	430	140	105	90	135.6	131.1	
B-39 Composite	35	46	485	190	155	.030	575	152	105	52	161.2	210.8	
B-40 Rolling prefILTER - 3% moisture content	-	--	250	178	130	.100	738	220	46	68	163.2	157.6	
B-42 R.P.P (D.E) 2-11% moisture content	--	--	250	175	117	.066	740		50	60	151.5	164.2	

Fuel type and configuration	Initial Conditions			Fuel Parameters			Wall Temperatures			Plug	Peak
	T _{amb} , °C	R _H	Exit air flow rate, L/s	Initial fuel weight, kg	Final fuel weight, kg	fuel flow rate, kg/s	T _{max} (cell), °C	T _{max} (duct), °C	T _{DB} (filter), °C	T _{WB} (filter), °C	Temp., °C
B-42 R,P,P (D,P) moisture content 7-11	--	--	260	180	143	.085	750	250	80	60	171.1
B-43 R,P,P (Comp.) moisture content 7-8	--	--	250	185	155	.050	640	160	58	48	162.0
B-44 Composite R,P,P	--	--	270	195	175	.050	575	180	65	50	157.9
B-45 Composite R,P,P	26	55	250	185	130	.050	670	155	50	60	158.8
B-46 Composite R,P,P	--	--	250	195	135	.050			50	50	153.3
B-47 Composite R,P,P	--	--	490	200	170	.070	700	158	58	52	154.0
B-50 Free Burn (Douglas Fir)	--	--	260	155	130	.042					-- 259.8
B-51 Free Burn (Douglas Fir)	32	53	270	152	133	.067	720	230	100	55	-- 262.7
B-52 Free Burn Composite	--	--	280	155	133	.025	640	200	70	40	172.9
B-53 Free Burn Composite	33	58	500	155	115	.028	700	220	110	130	-- 223.6
B-54 Composite R,P,P	--	--	255	155	105	.066	655	160	45	70	142.5
B-55 Composite R,P,P	38	50	255	178	150	.060	670	165	50	70	154.6
B-56A Sand Filter #1	--	--	250	175	150	.063	600	180	90	90	196.7
B-56B Sand Filter #2	24	66	230	147	117	.031	750	190	120	60	-- 236.7
B-56C Sand Filter #3	37	56	240	155	112	.031	680	170	95	55	-- 203.1

Fuel type and configuration	Filter Parameters		Upstream Impactor			Downstream Impactor			Gas Analysis			
	t sec	JP max, pascals	wet mass, mg	dry mass, mg	Aerosol size trend	wet mass, mg	dry mass, mg	Aerosol size trend	[O] %	[CO] _n ppm	[CO] _d ppm	[CH ₄] _n ppm
B-42 Rolling Pre-filter (D,P), moisture content 7-11%	0.51	2150	8556	78	>3 μ /98	3344	>3 μ /61	5.6	4.8	19.5	--	--
B-43 R.P.F (Composite) moisture content 7-8%	0.41	540	4315	1384	>3 μ /39	2186	1380	1<2 μ /30	11.5	1.6	5.2	14600
B-44 Composite	0.40	2000	--	--	--	--	--	--	11.5	1.4	5.5	14400
B-45 Composite R.P.P	0.88	500	--	--	--	--	--	--	7.0	1.8	6.0	17000
B-46 Composite R.P.P	1.32	2950	--	--	--	--	--	--	8.0	2.4	6.8	--
B-47 Composite R.P.P	0.75	1500	--	--	--	--	--	--	12.0	1.0	6.0	15800
B-50 Free Burn Douglas Fir	--	--	18337	169	>3 μ /92	7041	194	>3 μ /96	10.0	0.7	4.0	6000
B-51 Free Burn R.P.F	--	800	8220	237	>3 μ /95	2730	152	>3 μ /88	10.5	0.6	--	6500
B-52 Free Burn Composite	0.60	2250	7620	1222	>1 μ /92	6713	1141	>1 μ /91	12.8	0.7	--	10000
B-54 Free Burn H.P.F Composite	--	1550	8404	593	>1 μ /97	6310	1070	>1 μ /95	--	1.0	7.5	--
B-54 Composite Rolling Pre-filter	0.46	2000	18273	711	>2 μ /94	10,074	561	>2 μ /90	--	1.6	6.5	12500
B-55 Composite R.P.P	0.50	2000	7472	4354	>2 μ /95	7915	5289	>2 μ /89	--	Trace	6.5	--
B-56A Sand Filter #1	0.36	--	21706	8425	>2 μ /98	9789	4283	>2 μ /86	10.5	1.1	9.2	--
B-56B Sand Filter #2	--	320	14474	2701	>3 μ /96	1398	135	>3 μ /82	9.5	1.8	11.2	--
B-56C Sand Filter #3	--	--	10046	1232	2 μ /97	3976	816	>2 μ /80	10.5	3.0	9.2	--

Fuel type and configuration	Initial Conditions			Fuel Parameters			Critical Temperatures			Average Test Cell Temperature		
	T _{amb} , °C	R _H ,	Exit air flow rate /s	Initial fuel weight kg	Final fuel weight kg	m kg/s	T _{max} (cell) °C	T _{max} (duct) °C	T _{DB} (filter) °C	T _{WB} (filter) °C	A _t t _{plug} , °C	A _t t _{plug} , °C
B-57 Composite, Pleated-RPF	--	--	250	175	150	.063	650	190	68	48	151.7	247.7
B-58 Composite Pleated RPF	27	67	250	187	166	.063	600	170	63	52	156.7	232.3
B-59 Composite Pleated R.P.F.	43	32	250	182	160	.050	680	188	80	50	157.3	254.7
B-60 Composite Pleated RPF + Sonic nozzle	27	88	250	176	155	.060	740	80	50	40	--	235.0
B-61 Repeat B-60			250	--	--	.035	--	55	50	--	--	--
B-62 Composite Pleated RPF	25	19	250	--	--	.060	--	90	55	--	--	--

Fuel type and configuration	Filter Parameters		Upstream Impactor			Downstream Impactor			Gas Analysis			
	t plug	Δ P max, pascals	wet mass, mg	dry mass, mg	Aerosol size trend	wet mass, mg	dry mass, mg	Aerosol size trend	[O] %	[CO] _n ppm	[CO ₂] _n ppm	[CH ₄] _n ppm
B-57 Composite Rolling Pre-filter	0.45	2000	--	--	--	--	--	--	11.2	3.0	6.2	--
B-58 Composite Rolling Pre-filter	0.43	2000	--	--	--	--	--	--	11.0	2.8	6.0	--
B-59 Standard Composite R.P.F.	0.41	2000	21068	11716	>1μ/99	2514	1158	>2μ/99	10.5	2.8	6.2	--
B-60 Composite Rolling Pre-filter Sonic nozzle	--	260	17218	1645	>1μ/99	4622	678	>1μ/94	12.5	2.0	7.4	--
B-61 Continuation of B-59	1.05	--	--	--	--	--	--	--	--	--	--	--
B-62 Composite Rolling Prefilter	0.68	--	--	--	--	12988	678	>1μ/98	--	--	--	--