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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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TABLE OF CONTENTS

A. ABSTRACT.....	3
B. INTRODUCTION.....	4
C. BACKGROUND.....	6
D. DEVELOPMENT OF THE LLNL TEST CELL FOR CONTAINMENT VENTILATION SYSTEM FIRE ENDURANCE.....	11
E. EXPERIMENTAL PROCEDURES.....	13
F. ENCLOSURE FIRE BEHAVIOR.....	15
G. SMOKE PLUGGING OF FILTERS; RESULTS AND DISCUSSION.....	20
H. FIRE PROTECTION COUNTERMEASURES FOR HEPA FILTERS: RESULTS AND DISCUSSION.....	24
I. DISCUSSION & DESIGN GUIDE FOR SINGLE PASS RPF.....	33
J. ENHANCED PREFILTRATION SYSTEM.....	38
K. CONCLUSION & DISCUSSION.....	38
List of symbols.....	44
Acknowledgements.....	45
References.....	46
Figure Captions.....	48
Figures.....	51
Tables.....	93
Appendix A - Fire Test Cell Data Acquisition System.....	100
Appendix B - Comprehensive Table of All Experimental Data.....	164
Appendix C - Cascade Impactor Data.....	114
Appendix D - Smoke Aerosol Analytical System.....	123
Appendix E - Crib Fire Modeling.....	133
Appendix F - Volatile Degradation Products From Composite Burn Deposited On Both The Prefilter and The HEPA Filter.....	172

The 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.

Initially, methods were developed to cool fire-heated air by fine water spray upstream of the filters. Devices based on this principal, called spray dampers, were constructed and are installed in most new facilities where containment is an issue.

We recognized that smoke aerosol exposure to HEPA filters could also cause disruption of the containment system. Several potential faults could occur. They include plugging of the HEPA filter to 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 non-traditional geometries). Exit duct treatment of aerosols is not unusual in industrial applications and involve 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 Laboratory materials, 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 time duration of the test fires. The reason for success involved the modification of the prefiltration media. Commercially available filter media has 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 have qualified the application of this technique, since it is of use only to protect HEPA filters from fire-generated smoke aerosols. We do not believe this technique is cost effective in the total spectrum of containment systems, 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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B. 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. Upstream of the fan is the final HEPA filter station. This station 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. As such, it generally is remote from operational areas and is naturally protected from enclosure problems because of its relative distance from potential damage sources.

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. Consequently, it's been the subject of several research and testing programs over the past two decades¹. 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. Prior to this time, noncombustible filtration material had been developed and was required for use in facilities containing radioactive materials. Thus, the fire risk considered in the LLNL work did not pertain to the specific 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.

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

We have structured this report chronologically; attempting to illustrate the logical development of factual information that formed the basis for the conclusions and recommendations contained herein.

The Background section contains data from the initial research conducted for this program. At that time foundation was laid for the definition of the risk of fire to containment ventilation systems and their components. To form these definitions, surveys were made of the type and distribution of flammable materials contained in enclosures at risk, and the hazard of fire was estimated. Research was initiated to check the estimates, and preliminary fire risk parameters were defined. The endurance of HEPA filters was found to be compromised by both heat and smoke from fires. Countermeasures were proposed to reduce these effects and some were tested. An apparatus for reducing combustion gas temperature was developed and installed in some LLNL exit duct systems.

A most important result of this work was the realization that ad-hoc testing methods were inadequate for defining critical controlling parameters of smoke logging* of HEPA filters. To rectify this situation, a program was proposed to establish the characteristics and peculiarities of aerosol absorption in HEPA filters, and to define countermeasures to mitigate that effect. A major component of the program was the construction of a facility designed specifically for this application. Section D describes the LLNL fire test cell and associated ventilation test stand that was built in recognition of the need for quantitative data with regard for both the combustion conditions and smoke production rate. This section includes procedures for "shake-down" of the test cell and descriptions of some preliminary tests conducted to gain information on specific (exemplary) fuel configurations. Also described is the development of fuel array we ultimately adopted as standard for most of our countermeasure candidates. Details of instrumentation and diagnostic systems are contained in Appendix A.

A general description of the variety of experiments conducted during last half of this program are contained in Section E, ("Experimental Procedure"). Here we describe the range of measurements used to define combustion

*We define "smoke logging" as the irreversible plugging of HEPA filters by smoke aerosols.

characteristics of the fuel arrays, the resulting smoke production rate, and smoke aerosol absorption on the HEPA filters. A comprehensive table containing pertinent data from most of the tests is contained in Appendix B.

Section F is related to the experimental procedures section. We have emphasized this material because of the uniqueness of fire behavior in enclosures served by negative pressure ventilation systems.* The response of the ventilation flow to the fire heated gases dictates the ultimate combustion process that control the degree and quality of smoke aerosols generated during the tests. It is the aerosol characteristic that is of primary importance in terms of filter plugging potential.

In section G through J we describe and discuss the data and concepts we have developed with regard to: the 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 these sections we developed criteria for the construction of experimental pre-filtration apparatus and guidelines for the development of prototype production models. We also give suggestions as to where these appliances would be best applied.

Appendix C through F give specific information pertinent to these sections.

C. BACKGROUND

The susceptibility of HEPA filters (HEPA's) to fire effects was demonstrated by the occurrence of an insignificant release of radioactive contaminants during the second fire at Rocky Flats in 1969². In this event, investigators concluded that thermal effects caused the final HEPA's, in a specific ventilation circuit, to fault; resulting in the loss of containment. To reduce the probability of a reoccurrence of a similar fault in future fires, induct dampers were proposed as a means to prevent heat exposure. However, during a fire, imposition of impervious dampers in the exit ventilation circuit would cause immediate over-pressurization of the upstream duct and enclosures. Thus, workroom's adjacent passage ways and

*Negative pressure ventilation systems are those where the air-moving pump is the last component of the ventilation circuit.

non-containment enclosures would sustain smoke logging and possible contamination by radioactive aerosols.

Spray Damper Development

Personnel of Dow Chemical Company at Rocky Flats proposed and tested the use of water sprays coupled with demisters as a means of providing effective thermal protection for the HEPA filters. This technique was refined and tested at LLNL for use in a wide variety of containment systems. The experiments showed that combustion heated air at 820°C could be cooled to 175°C upon passage through a region of atomized water (three spray nozzles producing 15 liters/min. of water) and demisters^{3,4}. Design criteria for installation of these ensembles (called "spray dampers") were established. They were required for all new LLNL construction and strongly recommended for retrofit into existing systems at other facilities.

Advantages of the water spray damper are that it reacts to hot gases generated by the fire; i.e., the spray nozzles do not activate until the flowing air temperature in the duct reaches a prescribed magnitude. Moreover, the water spray does not inhibit the air flow unless the concentration of smoke aerosols is high. In the event of high smoke concentration, the coagulated aerosols resulting from the rapid cooling of smoke will collect on demister faces and choke the flow.

At the time of these tests, there was evidence that water spray impingement on HEPA filters would cause plugging of the filters⁵ and to prevent this, the metal screen demisters were installed, on either side of the spray nozzle. However, it has been recently demonstrated that new HEPA filters are not easily wetted by low volume water sprays and consequently do not, under normal conditions experience water spray plugging⁶. A schematic of this apparatus is shown in Figure 1.

The spray damper was applied to LLNL ventilation systems with the full knowledge that the effects of smoke logging of filters, prefilters, and demisters might cause ducts and upstream enclosures to overpressurize during a fire. However, since no other candidate countermeasures to address the problem existed, the planners rationalized that partial protection of HEPA filters was better than none at all. Moreover, in terms of relative risk,

internal pressurization possibly causing contamination of internal enclosures is far more desirable than toxic release to the environment.

Because of the unknown potential of smoke plugging of HEPA filters and the risk of containment system overpressurization, the Atomic Energy Commission was asked to support a modest program with the goal of defining the threat of smoke from accidental fires to the parameters of toxic containment.

Preliminary HEPA Filter Plugging Tests

The experiments were conducted in the apparatus shown schematically in Figure 2. Items shown in the downstream sections of the duct: i.e., prefilters and scrubbing stations, were removed during the initial background tests of smoke plugging of the HEPA filters. These tests involved smoke generation from a variety of fuels.

Guidelines for the selection of materials to be used for smoke production were made by surveying the composition and distribution of flammable materials that were used for construction of enclosures-contained appliances, and materials that were necessary for the operational function of the facility. Qualitative judgments were made relative to the perceived (and sometimes measured) ability of the material to produce smoke. Tables 1 and 2 list the results of the survey in terms of the total fuel load and the quantity of materials considered to produce heavy smoke during combustion or pyrolysis⁷. Using simple enclosure fire models^d, the time dependent quantity of fuel burned was calculated and used to define the rate of material supply to the smoke production furnace.

Selected fuels were fed to a gas-fired burner at rates defined by the model. The method of fuel supply was pragmatic; i.e., packets of fuel materials were dropped into a steel pan heated by a premixed natural gas burner in a modified "Franklin type" stove. Smoke aerosols, so formed, were drawn into the air duct circuit, shown in Figure 2, to provide the challenge aerosol exposure to the HEPA filters. Material with high smoke production potential and heat transfer coupling (like sprayed DTE* oil) should show smoke production rates

*DTE Oil: Medium weight turbine oil.

that are proportional to the amount of unburned material fed to the burner. Permutations in heat transfer coupling and/or smoke production potential should be reflected in the concentration of smoke aerosols produced and ultimately the smoke sorption on the filter.

Figures 3 - 6 show filter plugging rates for various combustible materials that are common to nuclear laboratories⁹. The figures compare the time it takes for the pressure drop across the HEPA (ΔP_H) to reach 5 in wg (1250 Pa), 7 in wg (1750 Pa), and 9 in wg (2250 Pa) respectively. At the highest ΔP_H , the resultant flowrate through the system was less than half of the design flowrate of 500 cfm (250 l/s), which has been defined as the experimental level for filter plugging and the termination point for these tests. Comparison of data contained in the figures show qualitative agreement with the smoke production trends we expected. However, the repeatability for tests at the same fuel rates was poor indicating error causing mechanisms that were not accounted for in the original assumptions. Such factors as:

- Changes in furnace heat transfer due to ash or char build up.
- Chemical reactivity of smoke aerosols with residue from previous tests.
- Physical interactions between smoke aerosols and environmental parameters (evaporation and condensation, phase changes, fallout, coagulation, agglomeration).).
- Environmental interactions with the filter media during exposure to smoke aerosols (high background humidity that can enhance fluid migration of aerosols through filters; gaseous penetration of condensable aerosols, filter wetting due to water surface tension modifications by smoke aerosols).

These factors can change the rate of filter loading in almost any direction. Moreover, since we have no definition of the environmental conditions when these tests were conducted, and the number of replications are sparse, we are unable to define causes for the observed variations. However, the data trends indicate that filter loading is more or less linear with time, at fuel feed rates that do not exceed 0.2 kg per minute.*

*The trends actually hint of a slight decrease in filter loading rate at long times. Moreover, for some materials, the greater the feed rate the less the filter loading. These observations could be caused by poor coupling between the heater pan and fuel, or in fact, incomplete combustion of the fuel. Note, each curve results from a specific experiment.

Effect Of Static Prefilter

In normal operational filtration systems, static prefilters are used to protect the primary HEPA filter stations from large particulates and to increase the normal time span between HEPA filter replacement. To determine the response of a system consisting of a prefilter and HEPA filter in series, the ensemble was exposed to smoke aerosols from a variety of combustible solids. In all cases, the prefilters were rapidly smoke logged and they essentially stopped air flow through the duct. The rate of plugging was many times faster than the corresponding rate for solo HEPA filters facing the same exposure. The difference in total surface area between HEPA's and standard prefilters accounts for this phenomena.

Often the pressure difference across the prefilter exceeded its mechanical strength causing prefilter rupture and subsequent exposure of the HEPA filter to smoke aerosols.. Figure 7 illustrates this behavior for a system at a design flow rate of 1000 cfm (500 ℓ /s) containing a low efficiency furnace prefilter and a properly rated HEPA filter. Note how the air flow fluctuates with the ΔP across both the prefilter and the HEPA filter.

Preliminary Enclosure Fire Tests

To simulate real fire conditions, three tests were conducted in a modified quonset hut to appraise the response of a typical duct system to the smoke aerosol production from an enclosure fire containing a quasi-normal distribution of combustible materials characteristic of LLNL containment spaces¹⁰. Figure 8 is a schematic of this test setup and Figure 9 shows typical test results for a moderately heavy fuel load. In this case, the fuel material was rich in synthetic polymers which produce heavy smoke during normal combustion processes. Post test examination showed that the metal mesh of the scrubber was essentially sealed by solid- and liquid-phase deposits of smoke aerosols.

Three tests were conducted in this configuration using different fuel distributions and fuel material mixes. In all cases, components of the filtration train of the ventilation system were plugged by smoke aerosols and/or products of combustion. The degree of filter plugging appeared to be directly related to the fuel load, fuel type and air available for ventilation.

D. 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.

Figures 10 and 11 are a schematic representation and a photograph of the LLNL facility designed for fire exposure tests on containment ventilation systems and components. The fire test 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 via standard 2 ft X 2 ft ventilation ducting. Diagnostic instrumentation at these locations are "hard wired" to a PDP-11 computer for data addressing, data reduction and final display in hard copy format¹¹. Instrumentation in the fire test cell includes provision for the measurement of:

In the Test Cell

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

Instrumentation In The Exit Duct and HEPA Filter Station Measures

- Temperature (wet and dry bulb)
- Filter parameters
- Total exit gas flow rate
- CO₂ - CO - O₂ - 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 Appendix A.

Preliminary Tests In The Fire Test Cell

The ventilation fire test facility was completed early in 1976. Shakedown and demonstration tests were conducted using hypothetical arrays of laboratory equipment; appliances, furniture and manuscripts. These tests produced ample smoke aerosols which ultimately resulted in plugging of the final HEPA filter. However, because of the nonuniformity of the fuel bed, fire growth was capricious and random so that we were unable to reproduce the time rate of fire growth between individual tests. Moreover, we experienced considerable difficulty in obtaining test exemplars. Pre- and post-fire photographs of selected test arrays are seen in composite figures 12 and 13.

This phase of the project was produced to improve the results of the earlier work under conditions that were closer to reality. But, because of the lack of reproducibility in tests using exemplar fuel arrays, we sought to model fire and smoke production dynamics using simpler fuel systems. Cross piles of fuel called cribs have long been employed by fire research technologists to study the effects of external conditions on fire output parameters. We decided to test cribs in our application to see if they would generate quantities of smoke aerosols. We initially used fir wood cribs for smoke production tests and also to test selected countermeasure arrangements and other combustion parameters. We decided to test cribs in our application, to see if they would generate quantities of smoke aerosols. We initially used fir wood cribs for smoke production tests and also to test selected countermeasure arrangements and other combustion parameters. We ultimately decided to adopt a modified crib arrangement for creating both the thermal exposure and smoke aerosols to challenge the HEPA filters. Surveys of laboratory fuel loads indicate that a large proportion of contained furnishings, finishes and construction materials are composed of synthetic thermoplastics which soften upon heating. These materials would not maintain geometric integrity upon exposure to heat sources or flames because cribs made of such materials would soon lose their shape, thus causing the burning behavior to continuously change throughout the test.

Because of this behavior, we conducted most of our tests using steel frames to define the fuel element layers. These frames were modified according to the type of fuel being burned for specific tests; i.e., for cribs consisting of thermo-plastics each fuel layer was supported by open mesh wire screen, while

for cribs made entirely of wood, no screen support was necessary. Each different fuel has unique properties; i.e., density, conductivity, moisture content, etc. and available geometric form (i.e., most synthetic polymers are economically available in large sheets no thicker than 1/2 inch). We had chosen a specific fuel load for the wood crib fires (1 - 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 14 is an example of a composite crib used as the major fuel source for most of our later tests. Because we needed to make 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 pilot flame to maintain high constant temperatures at the central volume of the crib when the test cell became ventilation controlled.

E. 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. Fuel cribs consisting of various materials formed the basic fuel supply and ultimately, the smoke source for the entire series. 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 potential of smoke aerosols from typical fuels to plug filters and second, to develop practical countermeasures that could be applied to protect the HEPAs from smoke exposure. The data collected from all these tests are tabulated in appendix B.

The characteristics of the smoke aerosols are basically 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. The temperature above the fuel crib is a sensitive indicator of the fuel element type, ventilation rate and crib element spacing (an indicator of fuel geometry) as shown in Figures 15 and 16.¹²

Figure 15 indicates how cribs of various synthetic polymers burn relative to the burning of a fir wood crib. The B-3 curve illustrates the behavior of a fire-retarded PMMA* by its temperature response. Although it takes a relatively long time to ignite, once ignited, it burns with fierce intensity. The combustion response of polycarbonate is shown by the curve labeled B-11. Polycarbonate burns slowly giving relatively low heat release rates.

The effects of crib spacing and ventilation rate on crib burning are shown in Fig. 16. The differences in time to peak burning for PB-8 and B-1 illustrate the effect of crib porosity (A measure of the unfilled volume of a crib), i.e., the time for peak temperature is displaced but the trend of the data are similar because of ventilation control of the combustion processes that is the temperature reduction after a high intensity phase is indicative of oxygen starvation. In test PB-7, the overall ventilation rate was sufficient (500 L/s) to allow active combustion over the entire test period as indicated by the lack of temperature retardation throughout the burn.

Smoke Measurements

We employed cascade impactors to measure the total smoke aerosol mass and mass-size distribution. We recognize the short-comings of this approach and have sought other methods. However, our efforts have not been fruitful since the state of the art of aerosol measurement is not advanced to the degree where dense aerosols can be accurately analyzed 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. Data from these measurements are included in the table containing all test data in appendix B.

Parallel to the general test procedures we inaugurated research into the sampling methods and dilution techniques for rationally assessing the physical properties of dense smoke. Details of our protocol for using cascade impactors for smoke analysis are contained in appendix C and a summary of our efforts in developing techniques for accurate on-line smoke analysis are contained in appendix D.

*polymethylmethacrylate

F. ENCLOSURE FIRE BEHAVIOR

Figure 17 is a composite of data curves from a specially designed wood crib⁺ used for assessing the interaction between a naturally[#] burning fire and the controlling parameters of the forced ventilation test cell. Labelled on the vertical axis of the graph are the parameters of interest:

- Temperature directly over the crib ($^{\circ}\text{C}$)
- Total inlet air flow rate and total exit air- and combustion gas-flow rate (L/s)
- Crib mass loss (Kg)
- Oxygen depletion in the exit duct (%)
- Pressure across the HEPA filter (ΔP_H)

The data trends in Figure 17 describe a temporal portrait of the fire dynamics during this test but, it is not complete since it includes only a sampling of the diagnostic measurements which are used for a complete analysis of both the fire conditions and the HEPA filter performance during each test. However, it serves to illustrate 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 two major groups; (1) control parameters, and (2) 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. Hence they 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 [O]. 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 $\dot{V}_d$), or the magnitude of the initial enclosure

⁺ Contained in a metal pan in which enough propyl alcohol is ignited to expose the bottom surfaces of the crib to flames for a period of 1.0 minute (1.0 L)

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

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

overpressurization (a phenomenon that occurs for almost all substantial fires conducted in the enclosure). From Figure 17 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 out flow from the inlet ducts is over 50% of the design $\dot{V}_a$. $\dot{V}_a$ is nearly 3 times the steady-state $\dot{V}_a$ established after the initial oscillating period of the burn.

The greatest change for both $[O^-]$ and T_c occur near the peak out flow time, and the crib mass loss appears to substantially begin around this period. The gradual reduction in $\dot{V}_d$ corresponds to the increase in pressure drop across the HEPA filter.

One liter of propyl alcohol 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 sec., and will provide ample flaming heat transfer to positively ignite the crib. However, 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 the expansion of internal gases due to the average temperature rise resulting from the fire. This is shown readily in figure 18 during a test where we tightly sealed the fire enclosure to observe the extent of internal pressure rise. The major fuel 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 sec results when one of the seals broke (and was resealed) because of the high ΔP .

Figure 19 demonstrates the importance of the ventilation rate on the magnitude of gas expansion caused flow out of the inlet. In this set of experiments, the pool fire simulator (a method of spraying and burning liquid fuels in a 3 ft. diameter pan at different rates, to simulate fuels of different burning- and heat release-rates) was stepped through 5 spray rates calculated to give a range of potential heat release of 9,566 kJ to 46,150 kJ. This set was run at; 250-500 and 1000 l/s (500, 1000, and 2000 cfm respectively). At all three ventilation rates, thermal expansion caused an initial reduction or indeed reversal of the inlet flow, which corresponds directly with the design

ventilation rate. However, once the fire was established and the average gas temperature in the cell becomes somewhat constant the inflow rate remains relatively constant. Note, in figure 19 the curves are normalized to the design pretest-inflow rate for comparative purposes.

The volumetric expansion resulting from the initial increase in average enclosure temperature can be estimated using the expression:¹³

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

S	= volume expansion
Mole _p	= molecular weight of the combustion products
$\dot{m}_f$	= fuel burning rate
T	= heated gas average temperature
T _{amb}	= ambient gas temperature

Table 3 compares calculated out flow rates with the $\dot{V}_g$ 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 qualitative picture of the dynamics of fires in enclosures serviced by negative pressure ventilation systems: Upon ignition of the accelerant 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 the progress of the fire. Indeed, we observe that gas expansion can account for substantial changes to the inlet flow to the enclosure. As the fire depletes the 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 the fuel burning rate is constant, the air inflow rate and average enclosure temperature resulting from the fire, will approach some intermediate magnitude until fuel depletion becomes a factor.

Figure 20 shows an extreme example of this balance where equilibrium is not established during the steady burn period. Instead, an oscillating response is setup between the crib temperature characteristics and the exit flow parameters as indicated by the oxygen, CO and CO₂ monitors. Note that [O⁻] 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 trends, however, the composition of the combustion gases and the production of smoke aerosols are extremely sensitive to both temperature and oxygen concentration.

Table 4 collects all data pertinent to the combustion dynamics and gross aerosol measurements made during fiscal year 1979. (The data contained in Table 4 are included in the total set of data found in Appendix B). 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 reproductibility, but the trends bare well with the gross conditions of the specific test. As described in table 3, the total air inflow rate is always less than the exhaust rate because of leaks in the test cell. This leak rate (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 initial inflow rate and the relative leakage in and out of the test cell.*

* Appendix E contains theoretical analysis of crib fire phenomenology. This effort was expended to determine how close our procedures agree with the classical crib fire analysis.

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 vary directly with $\dot{V}_d$; and temperature dependent parameters are inverseley proportional to $\dot{V}_c$. 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 element control to ventilation control is very apparent, as there is a net gain of 60% in mass when this occurs (note, both these trends are gross averages only).

One bit of interesting information in Table 4 is the data showing the temperature loss by the combustion gases in transit between the test cell exit and the HEPA station. Excluding tests at $\dot{V}_d$ of 500 l/s, and for experiments where atomized water was introduced into the "up-stream" duct work to artificially cool the gases (tests 60,61,62), the temperature at the HEPA filter was seldom greater than 100C°. * This is an encouraging observation, since temperatures at this level are substantially below destructive temperatures that are potentially available in enclosure fires. Figure 21 shows the endurance of HEPA filters exposed to a range of high temperatures¹⁴. At the temperature levels measured at the HEPA 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 should follow 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 1000C°, 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).¹⁵ By acceptable temperatures we mean temperatures where

* Note that the duct gas temperature at the exit measuring station was generally 40C° to 60C° lower than the average temperature of gas in the test cell which averages about 250C°.

filter endurance is sufficient to provide containment over the period of active fire fighting and until alternate containment ventilation can be provided.

L. SMOKE PLUGGING OF FILTERS; RESULTS AND DISCUSSION

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 22 through 27 show the pattern of HEPA filter plugging for most of the materials used as fuels during this research. The curves relate time dependent pressure difference across the filter resulting from aerosol sorption into the filter media. The time to filter plugging is arbitrarily defined by 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 $\dot{m}$, 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 $\dot{m}$ 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 22 shows the extreme range of response obtained for filter plugging, with the same fuel and ventilation conditions. Note that the measured aerosol mass appears to be inversely proportional to the rate of plugging and the moisture content of the fuel. The effect of fuel

moisture was observed early in the tests and the combustion literature for natural fuels shows a definite physical change in the mechanism of pyrolysis of wood type materials at low and high moisture content.¹⁶ However, in standard wood crib fires, if the fuel moisture content is between 4% and 8%, the time to plug will be between 300 and 400 sec and the data will look very much like the B-32 curve in Fig. 22.

Fig. 23 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 pragmatic 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 2 measurements. Yet under both conditions the HEPA filter plugs in measurable times.

Figure 24 and 25 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, $\dot{m}$ is about 1/3rd to 1/4th the $\dot{m}$ at 500 l/s, but more measurable aerosol was obtained at the low $\dot{V}_d$. The temperature at the HEPA filter is twice as large at $\dot{V}_d = 500$ l/s. ($T_{HEPA} = 1100^\circ$). Two operational factors appear to cause the observed effects. 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 account for aerosols of low concentration to effect 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.

Another very possible cause for the observed phenomena 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 between the crib tests and the Franklin Stove tests. In the case of 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 one case we are making mostly pyrolysis products while in the other method, 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.

One interesting effect was observed concerning the character of the material sorbed on the filter media after tests with the fuels used in Fig. 22 through 25. During the early phases of this program, it was our practice to weigh the plugged HEPA filter as soon as possible after test termination. For tests where wood was the only fuel element, we found the substances soaked in the filter media was highly volatile, it would evaporate rapidly to as low as 1/10th 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 gained during the exposure regardless of the waiting 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 produce very different filter plugging characteristics.

Figure 26 gives the ΔP of HEPA filters exposed to smoke aerosols from a dense fiberboard material fabricated by compression of wood fibers and extracts. Again, the reported 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 8-15, appears to have the potential to plug given enough fuel and time.

Figure 27 contains ΔP data for HEPA filters exposed to smoke aerosols from composite crib fires. In this figure, all 5 curves represent data from crib fires at various $\dot{V}_d$ 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 consistent filter plugging potential of any fuel we used during the entire test series. Thus, we adopted the composite crib as the standard against which we rate the smoke plugging of filter or 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 $110C^0$. 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 define how the filters change abruptly from apparently complete through-put, to complete filter blinding. We have tried unsuccessfully to duplicate the observed phenomena on the small scale. We have also conducted chemical analysis of the materials trapped on the HEPA filters for a range of fuel types. Simultaneously we analyzed the chemistry of combustion gases and pyrolyzates "upstream" and "downstream" of the HEPA filter over the same range of fuels* and searched the literature of filtration technology for examples of similar phenomena; again without success.

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

* Appendix F contains a complete description of the analytical chemistry procedures and results.

cribs, and somewhat longer for cribs formed of synthetic polymers or mixtures of polymers). After this 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 of 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. Specific components of the smoke aerosols are listed in Appendix F.

H. FIRE PROTECTION COUNTERMEASURES FOR HEPA FILTERS; RESULTS AND DISCUSSION

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

- Control the fuel

*Figure 28 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 29 is a SEM of HEPA filter media loaded with solid phase aerosol. Obviously the mechanism, and thus the build-up of pressure will be different with the two types of smoke aerosol exposures.

- 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; e.g., controlling the fuel may involve specified housekeeping procedures, the prohibition of certain classes of materials from a space, or the specification of materials used for internal finishes and appliances. Indeed, This protocol should be mandatory in any Laboratory situation. Control of the fire implies active attack of a fire in its incipient stage. Included in this group are; 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, its 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 its possible to project situations where smoke aerosols from an unprotected space could enter the containment ventilation duct-work of an enclosure containing radioactive materials. Another possible scenerio for smoke exposure to final HEPA filters is for static pre-filters to absorb combustible materials which ignite and produce smoke that is directly communicated to the final HEPA's. An infinite number of low probability fire scenario's 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.

Table 5 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 where attempted. Even those identified for critical testing were limited to a few procedures which showed promise and some practical compatibility in containment duct systems.

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

Another of the listed ideas never used for direct filter protection, but one we used at the termination of every test was our air pollution control system. This device shown in Fig. 8 consists of a cyclone separator and high pressure venturi scrubber, in series. We have never witnessed smoke at the exit diffuser, so we believe the apparatus has sufficient air cleaning capabilities to protect down stream components from quite large fires. However, the cost would be prohibitive for general application to containment ventilation systems.

Table 6 compares the effectiveness of; 4 potential in-duct smoke removal techniques, 1 standard fire protection system and 1 fuel modification example, as countermeasures for the prevention of HEPA filter plugging by smoke aerosols. The first row in Table 6 compares the plugging effectiveness of the combustible materials used as fuel elements for cribs burned in the fire test cell. These examples were selected as being representative of tests conducted with the specific materials. Only two materials (Polycarbonate (PC) and Dense Fiberboard (DF)), failed to plug the HEPA filters at the standard flow-rate of 250 l/s. In the case of PC, when burned at its highest rate, very little smoke was perceived. Review of published listings of combustion and pyrolysis products from PC indicate that they 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 the small volume of smoke aerosols produced to not provide a plugging problem to the HEPA filters. 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 500 l/s. However, the rate of filter plugging was substantially reduced, in some cases because of vapor phase filter penetration of the combustion products.

Fire Protection Sprinkler¹

Of high interest are results with fire protection sprinkler systems. The sprinkler heads used for these tests are rated to fuse at 165°F (75°C). By "fuse" we mean that the temperature sensitive elements of the sprinkler head will fail by design, at a specific temperature range and release water to the site of the fire.

This method was successful in reducing smoke aerosol concentration to non-plugging levels for all tested fuels except PMMA-FR, and PC. The PC which did not produce filter plugging aerosols during the smoke production tests, is a slow burning material with a relatively low heat release. Thus, 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 attempted to repeat this occurrence but were unable to do so. We believe that water spray from the sprinklers mixed with the combustion aerosol such 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 cautiously proposed the above explanation.

The burning behavior of PMMA-FR is responsible for the fact that the filter plugged even though the sprinkler operated upon demand. This material does not ignite until the concentration of bulk retardant falls below a critical value because of thermal erosion. Once ignited, however, the PMMA burns with fierce intensity and produces copious smoke. We believe that sufficient smoke was produced prior to sprinkler fusing to cause the filter to plug.

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

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

Figure 30 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 seconds and HEPA filter plugging is indicated by the complementary response of the air flow and pressure drop signatures.

The generation of aerosols apparently continues at a sufficient rate after the fire plume has been knocked down, or 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., the heat contained in the crib volume was sufficient to allow rekindling of the fire even after the sprinklers operated for 5 to 10 minutes. For the other fuels, exposure of the same duration to the sprinkler shower generally resulted in fire extinguishment.

Chemical Modification To Materials

In a previous section, we discussed the importance of water content of wood fuel elements in influencing the combustion response of the cribs. We were able to explain our observation using research conclusions from work performed elsewhere. These results show 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 the thermal degradation kinetics if impurities in sufficient quantities are intimately distributed through the material.

Our purpose for including the data for wet wood was 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 the proper or random use of additives, impurities, or retardants to generic materials of the same type, reduction or enhancement in the amount of smoke aerosol production is possible.

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 the duration of the test with wood, whereas, it did plug during the composite crib burn with no increase in HEPA endurance time.

Smoke Scrubbing

We know that water scrubbing can be successfully used for the removal 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 water flow rates. We also employed 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.

The last row of Table 6 shows 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.*

We include these results as an indication of 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 3 successive experiments.

* EFB, Inc., Particulate Control Systems,
78 Cummings Park, Woburn, Mass. 01801

Rolling Prefiltration

Early in the project, it was recognized that some form of pre-filtration would be the most desirable method for intercepting the smoke aerosols from unwanted fires before they reached the final HEPA station. Simple tests, using stationary roughing filters, showed that they would afford adequate protection until plugged, which caused either the protected space to be pressurized, or the pre-filter to 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 and a man powered "rolling pre-filter" (RPF), was jury-rigged as a demonstration of the concept. Fig. 31 is a photograph of the RPF installed in the duct-work of the system using the Franklin Stove as a smoke generator. The filter media used in the RPF, was 3 layers of cheese cloth. Figure 32 contains a set of curves demonstrating 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 1/30th of the burning rate of composite cribs).

This technique showed great promise and deserved further exploration. Upon completion of the experiments to define the filter plugging potential of surveyed 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 cell¹⁷. However, since the Anderson unit was designed for filtration of air pollution aerosols, its operation is based on high velocity impaction techniques, requiring high pressure blowers driven by large electrical motors and control systems. Installation of systems of this type in most containment ventilation systems would require complex by-pass 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 to 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 scaleable to a wide spectrum of system types and sizes.
- It should be compatible with a wide variety of filter media.

Based on these criteria, we selected a commercially available RPF, normally used for pre-filtration of ambient air for removal of large particulate matter, ($d > 0.005\text{cm}$). This RPF was modified to fit our experimental duct system and tests were initiated with composite crib fires to define the conditions where it would adequately protect HEPA filters from smoke. Fig. 33 is a view of the entrance of the "as received" RPF. Fig. 34, 35 and 36 show the front, back and filter feed side view of the RPF, 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 first define the filtration properties necessary to meet our requirements and second, purchase bulk filter media and manufacture our own strip filters to use in the RPF. After much Edisonian effort, we developed the laminated system shown in fig. 37. Fig. 38 is a set of curves showing 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.

Parallel to the development of the laminated filter media, was a succession of refinements and modifications to the commercial RPF apparatus. With these modifications, we were ultimately able to demonstrate successful achievement of our goal to trap 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.
- Increase the depth of the edge guides to reduce the filter tip losses.
- Add blinders to upstream filter entrance and outlet slots to reduce aerosol escape and to collimate the aerosol through central regions of the exposed media.
- Control the filter index distance to provide a complete fresh filter area for each index.

Fig. 39 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, $\dot{m}_f$ during a standard composite crib test ($\dot{m}_f = 0.05\text{kg/sec.}$). 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 imposing 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 variance in flow caused by the ΔP changes of the RPF. At approximately 1300 s the RPF media was depleted and smoke aerosol was directed through the HEPA filter, resulting in its plugging and the cessation of flow through the system. Note that fuel was available for at least twice the recorded duration, and if it were possible for us to load more filter media, we are confident that we could have maintained the HEPA filter function during the total burning duration.

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 sec. We

believe that this flow reduction results from a slow loading of the HEPA filter by aerosol leakage of the RPF. This loading is indicated by the regular increase in ΔP_H recorded prior to the time we ran out of media in the RPF. However, at this low rate of loading, it would take an additional 1600 sec. for $\dot{V}_d$ to degrade to 1/2 the design flow rate of 250 l/s.

Fig. 40 compares curves of 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 a RPF, B-40 was equipped with RPF, but the apparatus was not modified to reduce filter tip losses. Both B-45 and B-46 were run with fully modified RPF's and laminated filter media. In these tests the HEPA filter plugging resulted because we could not load enough of the pre-filter media in the modified apparatus to last for the entire burn duration. However, the feasibility of the technique was confirmed. Moreover, its now possible to provide design criteria for induct filtration systems using single pass RPF's*; where justified by circumstances of the enclosure to be protected.

1. DISCUSSION AND DESIGN GUIDE FOR SINGLE PASS RPF'S

The primary goal of this project was 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 in terms of mitigating the smoke plugging threat to the final HEPA filters in containment ventilation systems.

The experimental RPF; i.e., the modified commercial unit, was used as one of several methods to protect HEPA filters from smoke logging. This 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

* Single pass RPF's are defined as an apparatus where the filter media is located across the duct such that the air flow vector is normal to the surface of the filter media.

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 in addition to induct filtration technologies). However, we have definite opinions as to how an operational RPF should be designed and what features it should contain. More important, however, is where and how should single-pass RPF's 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 pre-filter 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 protecting the HEPA filters to maintain their function under any circumstance.

Single Pass Rolling Pre-filter for Fire Protection Only

Our project scope is to consider methods of fire protection. Therefore we will first address the use of single pass RPF's as fire protection devices only. Figure 41 is a sketch of the general features that we envision for an operational single-pass RPF. It is essentially a self contained cassette, 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 are located on a mating duct transition piece that contains the cassette. (Note that this design is patterned after film cassetts 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. However, we will not indulge ourselves by supplying details to figure 41, since the design criteria will vary for different applications. However,

we question the wisdom of recommending installation of this appliance solely for the purpose of protecting HEPA filters from the effects of fire, especially in light of stringent codes imposed on facilities dealing with toxic materials; i.e., 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 for a fire to reach appreciable size before discovery is small. Thus, the utility of the single-pass RPF, to protect 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? Second, if single-pass RPF's are installed as permanent fixtures in containment ventilation systems they would require stringent maintenance with regard to:

- the initiating detector/signalling/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; i.e., the above list of maintenance procedures should occur at frequent intervals to insure operation upon demand. But 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.

Third, the probability of failure of any the automatic systems is finite, regardless of the maintenance schedule. Thus, there must be supervision of the total system to insure trouble-free operation. Finally, since the RPF will generally be installed in remote locations near the bank of final filters, any fault that occurs during emergency operations are essentially unforgiving; i.e., once they occur nothing much could be done to rectify the problem until after the emergency situation is terminated. Any fault,

of course, would result in smoke exposure to the final HEPA station and potentially compromise containment.

Where then would we recommend the use of single pass RPF's should they be relegated only to fire protection duty? We believe that these systems would be cost effective in applications where the containment space includes extreme fuel loads, adjacent to or contiguous with abundant toxic materials. Another application 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 Pre-filter For Pre-filtration Fire and Protection

The logical application of a Single-Pass Rolling Pre-filter is as a Pre-filter! 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 up-stream from the HEPA filter station could serve to 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 contained in Fig 41. 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 insure 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 up-stream spaces.

Because this application of the single-pass RPF requires more-or-less continued 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, then RPF's relegated to fire protection service; e.g., any operation where excessive use of HEPA filters is common should be candidates for these systems:

- 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 to replace a HEPA filter, throughout the country, has been estimated to be \$3000.00, the cost benefit of the dual purpose RPF system for certain operations should be obvious.

J. ENHANCED PRE-FILTRATION PROGRAM

The Waste Management Division of DOE supports a parallel filtration program at LLNL to investigate means of extending the normal operational 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. Thus, 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 concern about fire effects on the newly designed filters and their capability to protect HEPA filters from smoke plugging, tests have continued in the fire test cell using prototype RPF's designed for the enhanced filtration project. Figure 42 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 5 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 have conducted with this apparatus, using the composite crib, we have not used 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 is 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 induct 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.

K. DISCUSSION AND CONCLUSIONS

The primary purpose of this program was to provide guidance and prototype

hardware for protection of components or 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 6)

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

Table 6 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. Both 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 replacement, where possible, 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 are high temperatures at the ceiling resulting from unwanted fire in the space. Should the fire be slow growing, or siting of critical sprinkler leads be inappropriate, (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

* Note, for all flammable materials; if the burning rate was less than 1.0 kg min^{-1} , HEPA filter plugging would not occur during 60 minutes of exposure. This rate corresponds to a fuel load of roughly 0.4 lb. ft.^{-2} , which according to Table 1, is low for laboratories and high for service areas.

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-FY) 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 pip 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 extra ordinary fire protection ploy to consider, is to provide committed detection and suppression systems to facilities or appliances identified to exceed specified fire risk criteria in an enclosure 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 to 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.

* 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 to cause 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 capability 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. Obviously, 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.

We admit the fact that the system described in this report is an experimental prototype that tested the feasibility of a prefiltration concept. We further admit that 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 non-emergency lifetime of HEPA filters exposed to high ambient aerosol concentrations. Naturally, they would still retain the capability to protect HEPA-filter-function in the event of fire in or near the protected enclosure. Continued use of containment protection rolling prefilters of this type would be the most 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. Needed is a prefiltration technique that is universally applicable, and such a system is in current evolutionary development. That is; the electrified-pleated rolling prefilter 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. It's 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.

in wg = Measure of Pressure drop; inches water guage.

Pa = Measure of Pressure drop; pascal

cmf = 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 ($^{\circ}C$).

$[O^-]$ = 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.

$\dot{m}_f$ = fuel burning rate kg/sec.

$\bar{T}$ = Average temperature of the heated gas ($^{\circ}C$).

$\dot{V}_{leak}$ = 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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- Mr. W.B. Donning - Dow Chemical Company
- Mr. I.N. Benjamin - National Bureau of Standards

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- Fig. 1** Schematic diagram of spray damper design.
- Fig. 2** Typical duct arrangement for smoke experiment with "Franklin Stove" smoke generator.
- Fig. 3** Pressure drop across HEPA filters vs. time for HEPA filters exposed to smoke aerosols from DTE oil at various feed rates.
- Fig. 4** Pressure drop across HEPA filters vs. time for HEPA filters exposed to smoke aerosols from neoprene based materials, at various feed rates.
- Fig. 5** Pressure drop across HEPA filters vs. time for HEPA filters exposed to smoke aerosols from PMMA-FR at various feed rates.
- Fig. 6** Pressure drop across HEPA filters vs. time for HEPA filters exposed to smoke aerosols from a variety of flammable material, at various feed rates.
- Fig. 7** Pressure drop and air flow of ventilation system for HEPA filter protected by a stationary furnace pre-filter; the total system smoke exposure from burning neoprene materials.
- Fig. 8** Schematic of preliminary full-scale smoke production test configuration using exemplar laboratory fuels.
- Fig. 9** Temperatures, pressure, and duct flow data for a preliminary full-scale smoke production test (test #2). Note, inverse relationship between fan suction and duct airflow.
- Fig. 10** Schematic layout of LLNL full-scale fire test cell with associated experimental ventilation system and air pollution control system.
- Fig. 11** Photograph of LLNL full-scale fire test cell with associated experimental ventilation system and air pollution control system.
- Fig. 12** Pre- and post-test photograph of fire damage to exemplar fuel load in preliminary fire tests in the new test cell. (Test #1) "Smokey" fuel.
- Fig. 13** Pre- and post-test photograph of fire damage to exemplar fuel load in preliminary fire tests in the new cell. (Test #5) "Non-Smokey" fuel.

- Fig. 14 Standard composite crib in metal support frame.
- Fig. 15 Critical temperature portrait for fires on selected natural and synthetic fuel cribs.
- Fig. 16 Critical temperature portrait for demonstrating the effect of ventilation and fuel element spacing on burning parameters.
- Fig. 17 Fire parameter portrait for a natural burning low porosity wood crib.
- Fig. 18 Temperature and Antenna test cell pressure for a standard wood crib fire in an enclosure tightly sealed, except for exit duct work. Pressure discontinuity results from a seal failure and reseal.
- Fig. 19 Importance of ventilation rate on initial gas expansion out-flow for test with fuel spray fires.
- Fig. 20 Data oscillation during standard wood crib fire. Note, the period of oscillation is relatively constant, where amplitude is some function fire intensity.
- Fig. 21 Effect of air temperature on HEPA filter endurance. The data points indicate average time to failure of HEPA filter at the indicated temperature.
- Fig. 22 Aerosol loading of HEPA filters by smoke from wood fires; effects of burning rate and fuel moisture noted.
- Fig. 23 Aerosol loading of HEPA filters by smoke from PVC fires; effects of burning rate noted.
- Fig. 24 Aerosol loading of HEPA filters by smoke from PMMA fires; effects of burning rate noted (design flow rate at 250 l/s).
- Fig. 25 Aerosol loading of HEPA filters by smoke from PMMA fires; effects of burning rate noted (design flow rate at 500 l/s).
- Fig. 26 Aerosol loading of HEPA filters by smoke from dense fiberboard fires; effects of burning and ventilation rate noted.
- Fig. 27 Aerosol loading of HEPA filters by smoke from composite cribs, effects of various parameters noted.

- Fig. 28 Scanning Electron Micrograph of HEPA filter media loaded with smoke aerosols from composite crib fires.
- Fig. 29 Scanning Electron Micrograph of HEPA filter media loaded with solid phase aerosol (sodium chloride).
- Fig. 30 Flow and temperature portrait of composite crib fire with fire suppression sprinkler application.
- Fig. 31 Hand powered rolling pre-filter using layered cheesecloth as filter media.
- Fig. 32 Airflow and pressure portrait during Neoprene fire tests for a HEPA filter protected by a hand power rolling pre-filter. (burning rate = 100 gm/min).
- Fig. 33 Exit interface of an unmodified commercial rolling pre-filter.
- Fig. 34 Take-up reel side of modified commercial rolling pre-filter.
- Fig. 35 Inlet interface of modified commercial rolling pre-filter. Note, side blinders for flow columnation.
- Fig. 36 Exit interface of modified commercial rolling pre-filter. Note, blinders to prevent tip losses through edges of filters.
- Fig. 37 Photograph of "Home-made" 3 ply rolling pre-filter media.
- Fig. 38 Filtration efficiency of components and composite rolling pre-filter media NaCl as challenge aerosol.
- Fig. 39 Pressure and airflow portraits of prefiltration test with smoke from composite cribs as the challenge aerosol showing prefiltration filter indexing and filter effectiveness.
- Fig. 40 Evaluation of effectiveness of single pass rolling pre-filtration techniques.
- Fig. 41 Conceptual design of single pass rolling pre-filter for containment ventilation systems.
- Fig. 42 Experimental model of pleated rolling pre-filter for the enhanced filtration project

FIG. 1 Schematic diagram of spray damper design.

TYPICAL DUCT ARRANGEMENT FOR SMOKE EXPERIMENTS

Fig. 2. Typical duct arrangement for smoke experiment with "Franklin Stove" smoke generator.

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LAWRENCE LIVERMORE LABORATORY FULL SCALE FIRE TEST FACILITY

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in preliminary fire tests in the
new test cell. (Test#1) "Smoky" fuel

Fig. 13 Pre- and post-test photograph of fire damage to exemplar fuel load in preliminary fire tests in the new test cell. (Test#5) "Non-smoky" fuel.

Fig. 14. Standard composite grid for metal support frame.

B- 1 ⇒ Firwood CRIB, 250 l/S

B- 3 ⇒ PMMA – FR CRIB, 250 l/S

B-11 ⇒ Polycarbonate, 250 l/S

Fig. 15. Critical temperature portrait for fires on selected natural and synthetic fuel cribs.

B-1 $\Rightarrow$ open CRIB, 250 l/s
PB-8 $\Rightarrow$ closed CRIB, 250 l/s
PB-7 $\Rightarrow$ closed CRIB, 500 l/s

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Fig. 40. Evaluation of effectiveness of single pass rolling prefiltration techniques.

Fig. 41. Conceptual design of single pass rolling prefilter for containment ventilation systems.

Fig. 42 Experimental model of pleated rolling prefilter for containment ventilation systems.

MAIN TEXT TABLES

TABLE 1 Fuel Load Summary

TABLE 2 Quantities of Heavy Smoke Producing Materials
in Laboratory Areas

TABLE 3 Test Cell Flow Dynamics for Natural Crib Fires

TABLE 4 Fire, Air Flow and Smoke Release Data for FY1979

TABLE 5 Ideas for Removing or Reducing Fire-Caused Smokes

TABLE 6 Effect of Various Countermeasures on HEPA Filter
Performance

TABLE 1.
Fuel Load Summary
Maximum fuel load, Lb/ft²

	ACTUAL	ADJUSTED ^a
LABS	2.97	3.45
OFFICES	29.7	27.0
EQUIPMENT AREA	0.0127	0.0132
HALL	0.146	0.167

^aAdjusted to the equivalent of wood based on heat of combustion.

TABLE 2
Quantities of heavy smoke producing materials in laboratory areas.

Material	P	V	R	B	U
Maximum area in one lab (ft ²)	319	450	216	119	10
Per floor area (ft ² /ft ²)	0.33	0.46	0.22	0.12	0.008
Maximum weight in one lab (Lb)	1200	40	180	350	2
Per floor area (lb/ft ²)	1.23	0.04	0.19	0.36	0.0002
Distribution - Area					
% of Labs with					
>200 ft ²	19	0	0	0	0
>100 ft ²	24	19	25	5	0
> 50 ft ²	71	35	55	5	0
> 25 ft ²	81	60	80	10	0
Distribution - Weight					
% of Labs with					
>700 Lb	19	0	0	0	0
>300 Lb	35	0	0	0	0
>100 Lb	80	19	25	10	0
> 50Lb	86	20	40	10	0

Totals for heavy smoking materials

Area exposed (ft²/ft² of floor area) - 0.11

Weight exposed (lb/ft² of floor area) - 0.26

P = polymethylmethacrylate

V = PVC film and pipe

R = chlorinated rubber

B = pressed board

U = polyurethane foam

TABLE 3. Test cell flow dynamics for natural crib fires

l/s	51 Wood Crib	52 Wood Crib	53 Composite	54 Composite
Design Air inflow ($\dot{V}_d$)	270 l/s	280 l/s	280 l/s	500 l/s
Measured air inflow ($\dot{V}_a$)	235 l/s	225 l/s	215 l/s	360 l/s
Leak	35 l/s	55 l/s	65 l/s	140 l/s
Measured Out flow (T_{max})	165 l/s	145 l/s	65 l/s	-55 l/s
Calculated Out flow (T_{max})	146 l/s	149 l/s	125 l/s	-180 l/s
Measured STUDY-STATE Flow	90 l/s	100 l/s	85 l/s	200 l/s
Calculated STUDY-STATE Flow	102 l/s	51 l/s	4 l/s	-300 l/s

TABLE 4. Fire, airflow, and smoke release data for FY 1979

Test	$\dot{V}_d$	$\dot{V}_a$	$\dot{V}_{Leak}$	$\dot{V}_{out}$	$\dot{V}_f$	$\dot{M}_F$	T_{cell}	ΔT_0	ΔT_2	$\Delta up/\Delta w$	$\Delta wet/\Delta dry$
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			
51*	280	225	55	-145	100	.036	262	.52	.59	.62	.03
52	280	215	65	-65	85	.028	232	.30	.67	.67	.06
53	560	360	200	+55	200	.028	225	.71	.51	.12	.17
54	255	150	105	-180	50	.066	240	.45	.66	.25	.22
55	255	155	100	-145	40	.06	239	.42	--	.45	.05
56a						.065	229	.50	--	--	.80
56b	230	185	45	-180	80	.031	237	.56	.51	.55	.44
57	250	185	65	-120	135	.033	203	.54	.35	.90	.21
58	250	200	50	-60	90	.063	248	.51		.61	
59	250	190	60	-90	90	.063	232	.50		.88	
60	250	200	50	-105	50	.05	255	.53	.58	.73	.46
61	250				110	.035	235	.75	.45		.15
62	250	200	50	-275	61	.06	240	.61			

*All tests composite cribs
except for 50 & 51

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

Measured initial inflow
(l/s)

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

Peak outflow rate from
inlet ducts (l/s)

Post-outflow-flow
rate (l/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 5
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 6. Effect of various countermeasures on HEPA filter performance

Countermeasure	Fir wood		PMMA-FR		V _d = 250 f/s Polycarbonate		Dense fiberboard		Fiber-reinforced polyester		Polyvinyl chloride		Composite	
	t _{plug} , s	m, kg/s	t _{plug} , s	m, kg/s	t _{plug} , s	m, kg/s	t _{plug} , s	m, kg/s	t _{plug} , s	m, kg/s	t _{plug} , s	m, kg/s	t _{plug} , s	m, kg/s
Forced burn (enclosure)	320	0.12	400	0.03	No plug	0.04	No plug	0.08	880	0.02	590	0.02	400	0.02
Water scrubber (1-100 /min) w/ & w/o surfactant	350	0.11												
Fusing sprinkler	No plug	— ^a	400	— ^a	550	— ^a	No plug	— ^a	No plug	— ^a			265	0.05
Single pass Rolling prefilter	No plug	0.08											No plug	0.07
Wet vocu	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 A
FIRE TEST CELL DATA ACQUISITION SYSTEM

Appendix A

The Lawrence Livermore Fire Test Cell uses the following hardware to acquire data and for data reduction:

- DIGITAL EQUIPMENT CORPORATION PDP 11/10
- PERTEC DISC DRIVE MODEL D3341
- DIGI-DATA TAPE DRIVE MODEL 1609800R
- VIDAR AUTODATA SCANNER MODEL 616
- VIDAR INTEGRATING DIGITAL VOLTMETER MODEL 502B
- TECKTRONIX 4012 DISPLAY TERMINAL
- TECKTRONIX 4631 HARDCOPY UNIT
- ANN ARBOR DISPLAY TERMINAL/ELECTROHOME CRT

Software runs on a 28k PDP-11/10 computer under version 2C of RT11 Foreground/Background Monitor. The foreground runs a program called SCAN which takes millivolt data from a 100-channel Vidar 616/502B scanning digital voltmeter, converts it to floating point, and stores it on a disc or magnetic tape file. SCAN starts a new output file every 60 seconds.

The background may run any non-interfering program, but usually runs Multi-User BASIC in a two-user configuration. User 2 is dedicated to MONITR, a program which converts selected channels to engineering units and displays them in a real time on the Ann Arbor video monitor. User 1 runs either EXPT, a program which starts, stops and controls SCAN; or PLOT, a program which produces graphs of either on-line or off-line data on the Teckronix 4012 display terminal. Auxilliary BASIC programs include U2, which enables MONITR to run under User 2; COMLIST, which list comment files made by EXPT; and CALIBR, which copies, updates, and list files containing calibration constants for various channels.

The Table included in this appendix summarizes diagnostic equipment used for sensing the fire and smoke signatures generated during the tests. The included information is based both on manufacturers' literature and on specific calibrations done by LLNL personnel periodically each year.

Captions - Appendix A

Table A1. Analysis Instrumentation

TABLE A1. Analysis Instrumentation

Measurement	Detector	Manufacture	Type	Range	Typical Response	Sensitivity	Accuracy
Temperature	Thermocouple	Various	Chromel Alumel 1/16 in. 304 S.S. Sheath. Grounded	-300 to 2300°C	~4 sec to 63.2% of Temperature Change	--	4°F 32-53 ±3/4% 530-2
Flow	Inlet: Vane Anemometer	R.W. Young	Propeller Anemometer	±50m/s air Velocity	--	--	±3%
	Outlet: Critical Orifice	LLJ	Sharp edge (5 in.)	25-1200 CFM	--	--	±5%
Pressure	Differential Pressure Transducer	Validyne	Model P24	±0-700 Pa ±0-4000 Pa ±0-10,000 Pa		1/2% full scale	1/2% full scale
Mass loss	Load Platform	Tordid Corporation	Strain Gage Force Transducer	0-500 lbs 0-2000 lbs	(63.2%) 100m sec	.02% full scale	
Heat flux	Heat flux Calorimeter	Medtherm	Gardon Sensor	0-15 Btu/Ft ² /sec	(63.2%)		±3% most Detectors
		114-Cal Engineering	Water cooled Air cooled		.2-2.0 Btu/F ² -sec Less than 1500 msec	±1/2% Full scale	
Gas							
CO ₂	Infrared analyzer	Beckman	Model 864	0-20% 0-5%	90% within .5 sec	±1% of full scale	1% of full scale
CO	Infrared analyzer	Beckman	Model 864	0-10% 0-100%	90% within .5 sec	±1% of full scale	1% of full scale
O ₂	Diffusion cell 0-10% 0-25% O ₂	Beckman	Model 742	0-1% 0-5%	90% within 20 sec	±1% of full scale	±1% of full scale
Unburned Hydrocarbon CH ₄	Flame ionization	Beckman	Model 402	0-250,000 ppm on 8 range switch	90% within 1 sec	Adjustable 5% to 1% CH ₄	1% of full scale

Fuel type and configuration	Initial Conditions			Fuel Parameters			Critical Temperatures				Average Test Cell Temperatures	
	T _{amb} , °C	R _H , %	Exit air flow rate, l/s	Initial fuel weight, kg	Final fuel weight, kg	m fuel, kg/s	T _{max} (cell), °C	T _{max} (duct), °C	T _{DG} (filter), °C	T _{WB} (filter), °C	At t _{plug} Temp., °C	At t _(max) Temp., °C
FB-7 Fir, tight, layers staggered	20	49	500	194	145	.13	670	295	185	70	185	290.5
FB-8 Fir, tight, layers staggered	22	32	250	200	120	.09	700	280	90	62	214.0	265.5
FB-8.2 Fir, tight, layers, staggered	23	—	250	193	108	.10	700	290	100	65	222.5	278.0
B-1 Fir, loose, layers staggered	20	76	250	143	78	.13	800	305	105	60	207.0	317.5
B-2 Fir, loose, layers aligned	20	—	250	147	117	.12	750	310	100	60	223.5	309.5
B-3 Polymethylmethacrylate	20	69	250	94	79	.028	800	175	50	37	68.5	211.3
B-4 Polymethylmethacrylate	17	45	500	79	25	.11	670	215	110	55	213.0	214.5
B-6 Fir, waterspray scrubber	26	38	250	130	60	.10	770	300	59	59	234.3	286.0
B-7 Fir, waterspray scrubber	15	72	250	128	68	.11	750	310	31	31	271.0	298.5
B-8 Fir, sonic nozzle scrubber	21	43	250	132	90	.10	800	130	60	60	278.5	272.0
B-9 Fir, sprinkler	13	70	250	136	—	.05	780	220	100	35	194.0	16.5
B-10 Polymethylmethacrylate sprinkler	8	50	250	81	—	.016	600	185	58	30	16.0	153.0
B-11 Polycarbonate	—	—	250	80	35	.037	700	190	80	50	—	230.3
B-12 Polycarbonate sprinkler	10	56	250	81	—	.01	410	115	65	40	—	154.0
B-13 Fir, loose, leak	—	—	250	135	95	.07	680	250	105	63	183.5	280.5

Fuel type and configuration	Filter Parameters		Upstream Impactor			Downstream Impactor			Gas Analysis			
	tplug secx10 ³	ΔP max, Pa	wet mass, mg	dry mass, mg	Aerosol size trend %	wet mass, mg	dry mass, mg	Aerosol size trend %	[O ₂], %	[CO] _m , %	[CO ₂] _m , %	[CH ₄] _m , ppm
FB-7 Fir, tight, layers staggered	0.9	420	—	1000	>3μ/80	—	—	—	5.4	0.3	—	—
FB-8 Fir, tight, layers	0.7	2700	—	12000	>2μ/70	—	—	—	6.5	3.4	—	—
FB-8.2 Fir, tight, layers staggered	0.7	2300	—	5000	2μ/80	—	—	—	6.0	3.3	—	—
B-1 Fir, loose, layers staggered	0.32	2800	—	7200	1<3μ/77	—	—	—	6.0	2.8	—	—
B-2 Fir, loose, layers aligned	0.3	2750	—	4580	<2μ/87	—	—	—	5.0	3.1	—	—
B-3 Polymethylmethacrylate	0.4	2800	—	4065	>1μ/90	—	—	—	19.4	0.62	0.6	—
B-4 Polymethylmethacrylate	1.45	2075	—	1377	<1μ/72	—	—	—	13.6	—	4.8	400
B-6 Fir water spray scrubber	0.37	2350	—	2196	>2μ/77	—	—	—	5.0	—	12.8	—
B-7 Fir water spray scrubber	0.38	2900	—	3500	<1μ/72	—	—	—	4.0	—	6.2	13600
B-8 Fir sonic nozzle scrubber	0.32	200	—	1480	<2μ/86	—	—	—	3.8	4.0	3.8	1450
B-9 Fir, polymethylmethacrylate loose + sprinkler	—	500	—	—	—	—	—	—	9.0	2.0	13.0	1600
B-10 polymethylmethacrylate	0.4	2350	—	—	—	—	—	—	19.0	1.0	4.0	9600
B-11 polycarbonate	—	1800	—	—	—	—	—	—	9.0	0.2	12.2	1400
B-12 polycarbonate + sprinkler	0.55	2400	—	—	—	—	—	—	16.5	0.2	4.0	—
B-13 Fir, loose, leak test	0.61	2000	—	—	—	—	—	—	5.0	3.2	14.0	—

Fuel type and configuration	Initial Conditions			Fuel Parameters			Critical Temperatures				Average Test cell Temperatures	
	T _{amb} , °C	R _H , %	Exit air flow rate l/s	Initial fuel weight kg	Final fuel weight kg	h fuel kg/s	T _{max} (cell), °C	T _{max} (duct), °C	T _{DB} (filter), °C	T _{WB} (filter), °C	At t _{max} Temp., °C	At t _{max} Temp., °C
B-14 Fir, standard crib	--	--	250	142	109	.12	725	270	120	70	227.5	293.8
B-15 Dense Fiber Board	--	--	250	88	32	.08	630	230	110	90	--	264.5
B-16 Dense Fiber Board sprinkler	--	--	250	88	78	.04	320	110	75	45	--	142.0
B-17 Polyvinyl-chloride	--	--	250	133	128	.02	240	85	60	40	--	85.5
B-18 Fiber reinforced polyester	--	--	250	38	20	.02	560	170	90	50	187.5	187.5
B-19 Fiber reinforced polyester + sprinkler	--	--	250	38	36	.001	410	130	80	40	--	114.0
B-20 Composite crib	--	--	250	161	149	.02	640	200	100	60	183.8	192.0
B-21 Fir, standard crib: low inlet, low output vents	--	--	250	145	100	.10	640	165	90	60	222.8	268.5
B-22 Repeat B-21	--	--	250	145	80	.08	700	170	95	65	213.0	241.3
B-23 Composite Anderson 2000 Rolling Pre-filter (RPF)	--	--	280	180	146	.07	390	130	45	40	--	89.5
B-24 Composite Anderson 2000 RPF	--	--	280	171	116	.07	420	125	35	--	--	48.5
B-25 Composite Anderson 2000 RPF	--	--	380	174	118	.06	370	150	--	--	--	134.0
B-26 Fir, standard crib	--	--	280	135	50	.08	700	210	70	65	--	222.5
B-27 Fir, standard crib	--	--	250	135	88	.09	720	230	80	--	216.5	281.0
B-28 Fir, standard crib, overhead ventilation	--	--	250	130	95	.10 .06	750	280	110	87	172.0	305.0

Fuel type and configuration	Filter Parameters		Upstream Impactor				Downstream Impactor			Gas Analysis			
	η _{plug} mmx10 ³	max, ΔP Pa	wet mass, mg	dry mass, mg	Aerosol size trend %		wet mass, mg	dry mass, mg	Aerosol size trend %	[O] ₂ , %	[CO] ₂ , %	[CO] ₂ , %	[CH ₄], ppm
B-14 Fir, standard crib	0.67	2000	--	--	--	--	--	--	--	1.5	1.9	15.7	16000
B-15 Dense Fiber Board	--	730	--	1663	<2μ/82	--	1666	--	<2μ/88	3.1	3.0	15.0	16000
B-16 Dense Fiber Board + sprinkler	--	--	--	201	<2μ/91	--	--	--	--	17.6	0.2	1.2	900
B-17 Polyvinyl Chloride, loose	0.59	2250	--	2100	<2μ/82	--	1666	--	<2μ/82	17.4	0.2	1.0	--
B-18 Fiber-reinforced polyester	0.88	1530	--	1140	>2μ/73	--	1592	--	>2μ/67	8.3	0.5	11.5	8000
B-19 Fiber-reinforced polyester + sprinkler	--	--	--	226	<2μ/92	--	176	--	>2μ/94	17.5	--	1.0	700
B-20 Composite Crib	0.40	2100	--	6359	>1μ/99	--	4800	--	<2μ/85	13.0	2.0	8.2	--
B-21 Fir, standard crib; Low inlet, Low outlet vents	0.57	1900	--	208	--	--	--	--	--	5.2	1.5	14.0	14500
B-22 repeat B-21	0.76	2080	--	--	--	--	--	--	--	2.8	2.2	15.8	15800
B-23 Composite Anderson 2000 Rolling Prefilter (R.P.F.)	--	--	--	13700	>1μ/91	--	--	--	--	0.8	1.3	9.0	--
B-24 Composite Anderson 2000 RPF	--	200	--	3300	<2μ/79	--	--	--	--	7.0	4.0	10.0	16500
B-25 Composite Anderson 2000 RPF	--	--	--	--	--	--	--	--	--	7.0	4.8	10.5	1250
B-26 Fir, standard crib	--	--	16000	685	<2μ/73	--	--	--	--	2.0	5.6	16.0	15070
B-27 Fir, standard crib	0.2	2000	--	--	--	--	--	--	--	3.2	0.0	15.6	15000
B-28 Fir, standard crib, overhead ventilation	0.4	2250	27000	6000	>3μ/91	11000	2200	--	>3μ/89	7.2	3.8	13.0	13000

Fuel type and configuration	Initial Conditions			Fuel Parameters			Critical Temperatures				Average Test Cell Temperature	
	T _{amb} , °C	R _H , %	Exit air flow rate l/s	Initial fuel weight kg	Final fuel weight kg	m fuel kg/s	T _{max} (cell) °C	T _{max} (duct) °C	T _{D8} (filter) °C	T _{W8} (filter) °C	at t _{plus} Temp., °C	at t _{max} Temp., °C
B-29 Fir, standard crib,	--	--	260	140	105	.10 .05	600	260	100	52	151.8	286.5
B-30 Fir, standard crib,	24	76	260	175	120	.077 .047 .034	700	--	120	55	--	274.0
B-31 Fir, standard crib,	26	64	270	144	--	.060 .043 .013	730	200	100	60	--	221.5
B-32 oven dried > 64	28	50	250	142	115	.120 .030	770	256	112	60	185.0	325.0
B-33 Lexan Repeat sprinklers	36	28	250	135	131	.010	730	125	70	37	--	153.5
-34 Fir,	45	32	500	185	150	.10	775	280	180	70	--	298.5
B-35 Repeat B-34	11	50	500	145	85	.06	720	290	180	160	--	283.0
B-36 Repeat B-35 Sonic Nozzle Upstream Hepa	10	16	500	145	132	.097	740	295	--	70	213.0	302.7
B-37 Low Flow, Large Hepa	28	60	250	145	122	.035	780	230	--	65	--	319.8
B-38 Composite	34	42	500	221	140	.050	430	140	105	90	135.6	143.1
B-39 Composite	35	46	485	190	155	0.080	575	152	105	52	183.3	210.4
B-40 Fir, Standard RFF - 3% moisture content	--	--	250	178	130	.100	738	220	98	68	169.3	357.6
B-41 Fir, Standard R.F.F 8-11% moisture content	--	--	250	175	132	.066	740	--	60	60	181.9	284.3

Fuel type and configuration	Filter Parameters		Upstream Impactor			Downstream Impactor			Gas Analysis			
	ϕplug secx10 ³	max. ΔP Pa	wet mass, mg	dry mass, mg	Aerosol size trend %	wet mass, mg	dry mass, mg	Aerosol size trend %	[O] ₂ , %	[CO] _{1m} , %	[CO ₂] _{1m} , %	[CH ₄] _{1m} , ppm
B-29 Fir, standard crib, overhead ventilation	0.54	2440	10.000	466	>3μ/99	9300	1100	<1μ/50	9.2	3.5	10.8	12000
B-30 Fir, standard crib, overhead ventilation	—	—	4174	258	>3μ	1940	212	>3μ	8.0	2.6	4.6	13500
B-31 Fir, standard crib, overhead ventilation	—	—	15000	2700	<2μ/60	7600	115	>3μ/52	8.0	2.4	6.0	11000
B-32 oven dried > 6h	0.31	2700	3000	—	1-2μ/	332	—	>2μ	6.2	3.0	13.2	14.90
B-33 Lexan, repeat B-12, sprinklers	—	225	—	—	—	—	—	—	16.5	Trace	3.6	2500
B-34 Fir, Hi Inlet	—	300	12400	674	>3μ/75	6500	621	>3μ/71	8.8	1.0	12.2	11900
B-35 Repeat B-34	—	380	24600	2169	>3μ/79	1600	2720	>3μ/76	2.1	1.2	16.0	11500
B-36 Repeat B-35 sonic nozzle upstream hepa	0.64	2000	16250	2100	>3μ/73	13050	1400	>3μ/71	5.2	1.9	12.0	1300
B-37 low flow, large hepa	—	120	19200	2800	>3μ/68	10700	2200	>3μ/55	8.8	1.6	12.4	14000
B-38 Composite	0.44	2250	8600	8300	>3μ/59	6900	6200	>3μ/42	15.2	0.3	5.6	13000
B-39 Composite	0.53	2500	4200	3600	>3μ/42	5300	4060	>3μ/44	—	Trace	5.5	16000
B-40 Fir, standard, R.P.F. 94 moisture content (D.P.)	0.55	1800	6716	296	>3μ/98	6603	3905	<1μ/68	—	—	—	—
B-41 Fir, standard, R.P.F. 8-114 moisture content	0.81	2000	15767	2726	>3μ/64	8176	2218	>3μ/47	—	—	—	—

Fuel type and configuration	Initial Conditions			Fuel Parameters			Critical Temperatures				Average Test Cell Temperature	
	T _{amb} , °C	R _H , %	Exit air flow rate, l/s	Initial fuel weight kg	Final fuel weight kg	Δ fuel kg/s	T _{max} (cell) °C	T _{max} (duct) °C	T _{ps} (filter) °C	T _{ms} (filter) °C	at t _{plug} Temp., °C	at t _{max} Temp., °C
B-42 Fir Standard R.P.F. moisture content 7-11%	--	--	260	180	143	.085	750	250	80	68	171.1	311.9
B-43 Composite crib R.P.F. moisture content 7-8%	--	--	250	185	155	.050	640	160	58	48	162.0	203.9
B-44 Standard Composite Large HEPA	--	--	270	195	175	.050	575	180	65	50	157.9	203.0
B-45 Composite R.P.F.	26	55	250	185	130	.050 .075	670	155	50	60	158.8	228.8
B-46 Composite R.P.F.	--	--	250	195	135	.050	--	--	50	50	153.7	242.9
B-47 Composite R.P.F.	--	--	490	200	170	.070	700	158	58	52	154.0	211.0
B-50 Free Burn (Douglas Fir)	--	--	280	155	130	.042	--	--	--	--	--	259.8
B-51 Free Burn (Douglas Fir)	32	53	270	152	133	.037	720	230	100	55	--	262.7
B-52 Free Burn Composite	--	--	280	155	133	.025	640	200	70	40	172.9	231.6
B-53 Free Burn Composite	33	58	500	155	115	.028	700	210	110	130	--	223.6
B-54 Composite R.P.F.	--	--	255	155	105	.066	655	160	45	70	142.5	239.6
B-55 Composite R.P.F.	38	50	255	178	150	.068	670	165	50	70	154.6	238.9
B-56A Standard Composite Sand Filter #1	--	--	250	175	150	.063	600	180	90	90	196.7	238.6
B-56B Free-Burn Fir Sand Filter #2	34	66	230	147	117	.031	750	190	110	60	--	236.7
B-56C Free-Burn Composite Sand Filter #3	37	56	240	155	132	.031	680	170	95	55	--	203.3

Fuel type and configuration	Filter Parameters		Upstream Impactor			Downstream Impactor			Gas Analysis			
	tpug secs/10 ³	max, ΔP Pa	wet mass, mg	dry mass, mg	aerosol size trend	wet mass, mg	dry mass, mg	aerosol size trend	[O] ₂ %	[CO] ₂ %	[CO] ₂ _{in} %	[CH ₄] _{in} ppm
B-42 Rolling Pre-filter (R.P.F.), moisture content 7-11%	0.51	2150	8556	78	>3μ/98	3344	--	>3μ/61	5.6	4.8	10.5	--
B-43 R.P.F. (Composite) moisture content 7-8%	0.41	540	4315	1384	<3μ/39	1106	1380	<2μ/30	11.5	1.6	5.2	14600
B-44 Composite	0.48	2000	--	--	--	--	--	--	11.5	1.4	5.5	14400
B-45 Composite R.P.F.	0.88	500	--	--	--	--	--	--	7.0	1.8	8.0	17000
B-46 Composite R.P.F.	1.32	2950	--	--	--	--	--	--	8.0	2.4	8.8	--
B-47 Composite R.P.F.	0.75	1500	--	--	--	--	--	--	12.0	1.0	6.0	15800
B-50 Free Burn Douglas Fir	--	--	18337	169	>3μ/92	7041	194	>3μ/86	10.4	0.7	4.0	6000
B-51 Free Burn R.P.F.	--	800	8220	237	>3μ/95	2710	152	>3μ/88	10.5	0.6	--	6500
B-52 Free Burn Composite	0.60	2250	7620	1222	>1μ/92	6713	2141	>1μ/93	12.8	0.7	--	10000
B-53 Free Burn R.P.F. Composite	--	1550	8474	593	>1μ/97	6310	1070	>1μ/95	--	1.0	7.5	--
B-54 Composite Rolling Pre-filter	0.46	2000	18273	731	>2μ/94	10,074	561	>2μ/90	--	1.6	8.5	12500
B-55 Composite R.P.F.	0.50	2000	7472	4354	>2μ/95	7910	6289	>2μ/89	--	Trace	8.5	--
B-56A Standard Composite Sand Filter #1	0.36	--	21706	8425	>2μ/98	9799	4283	>2μ/86	10.5	3.1	9.2	--
B-56B Free burn Fir Sand Filter #2	--	120	14474	2701	>3μ/96	1398	335	>3μ/82	9.5	1.8	11.2	--
B-56C Free burn Composite Sand Filter #3	--	--	10046	1232	2μ/97	3976	816	>2μ/90	10.5	3.0	9.2	--

Fuel type and configuration	Initial Conditions		Fuel Parameters				Critical Temperatures				Average Test Cell Temperature	
	T _{amb} , °C	R _g , %	Exit air flow rate l/s	Initial fuel weight kg	Final fuel weight kg	in fuel kg/s	T _{max} (cell) °C	T _{max} (duct) °C	T _{DB} (filter) °C	T _{DB} (filter) °C	At t _{max} Temp., °C	At t _{max} Temp., °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	168	.063	600	170	83	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	—	80	55	—	—	—

Fuel type and configuration	Filter Parameters		Upstream Impactor			Downstream Impactor			Gas Analysis			
	t _{plug} secx10 ³	ΔP max, Pa	wet mass, mg	dry mass, mg	Aerosol size trend	wet mass, mg	dry mass, mg	Aerosol size trend	[O] ₂ %	[CO] ₂ %	[CO] ₂ %	[CS ₄] ppm
B-57 Composite Pleated R.P.F.	0.45	2000	--	--	--	--	--	--	11.2	3.0	8.2	--
B-58 Composite Pleated R.P.F.	0.43	2000	--	--	--	--	--	--	11.0	2.8	8.8	--
B-59 Standard Composite Pleated R.P.F.	0.41	2000	21868	11716	>1μ/99	2514	1158	>2μ/79	10.5	2.8	8.2	--
B-60 Composite Rolling Pre-filter Sonic nozzle	--	250	17218	1645	>1μ/99	4622	678	>1μ/94	12.5	2.0	7.4	--
B-61 Repeat of B-60	1.05	--	--	--	--	--	--	--	--	--	--	--
B-62 Composite Pleated R.P.F.	0.66	--	--	--	--	12998	678	>1μ/98	--	--	--	--

APPENDIX C
CASCADE IMPACTOR DATA

Appendix C

CASCADE IMPACTOR DATA

The Andersen IACFM particle fractionating sampler is a multi-stage, multi-orifice, cascade impactor which normally is used in the environmental working areas to measure the size distribution and total concentration levels of all enclosure aerosols.

The Anderson IACFM Ambient sampler is comprised of eight aluminum stages that are held together by three spring clamps and gasketed with O-ring seals. Each impactor stage contains multiple precision drilled orifices. When air is drawn through the sampler, multiple jets of air in each stage direct any airborne particles toward the surface of the collection plate for that stage. The size of the jets is constant for each stage, but is smaller in each succeeding stage. Whether a particle is impacted on any given stage depends on its aerodynamic dimension. The range of particle sizes collected on each stage depends on the jet velocity of the stage and the cutoff of the previous stage. Any particle not collected on the first stage follows the air stream around the edge of the plate to the next stage, where it is either impacted or passed on to the succeeding stage, and so on until the jet velocity is sufficient for impaction. Stages 0 - 6 have integral air inlet sections that contain 400 orifices. Stage 7 contains 201 orifice. The inlet sections are approximately 3.125" in diameter. The orifices are progressively smaller from top to bottom stages, ranging from 0.0625" diameter in Stage 0 to 0.0100" diameter in Stage 7. Each stage has a removable stainless steel (3.25"

diameter) collection plate. The exhaust section of each stage is approximately 0.75" larger in diameter than the collection plate, allowing unimpacted particles to go around and into the next stage.

A brief description of the operation of the sampling equipment follows:

1. Weigh filter and use protocol; i.e., specific RH and temperature.
2. Ambient gases enter the inlet cone and cascade through the succeeding stages with successively higher orifice velocities from Stage 0 to Stage 7. Successively smaller particles are inertially impacted onto the collection plates. The submicron particles which are not collected by the last collection plate are caught in the backup filter which is an integral part of the impactor immediately downstream from Stage 7. Stage 0 is an orifice stage only. Stage 8 is a collection stage only.
3. The clean gases are carried through the vacuum tube and into the pump.
4. A constant air sample flow of a ACFM is provided by a continuous duty, carbon vane vacuum pump. Flow rate through the impactor is controlled by an adjustable Fisher Porter flowrator which requires periodic adjustment.
5. After sampling is completed, the sample time is recorded and the tared collection filters and backup filters are removed for subsequent weighing to determine aerosol mass and size distribution.

6. All filter measurements are done in a specially designed enclosure; the filter weighing room where the temperature is always 24° - 25°C and the humidity is constant at 43% - 44% humidity. All sample papers are exposed to the conditioning of the room for at least 24 hours prior to weighing. After the papers are weighed they are placed in the impactors and kept at the condition of the room until ready for use. When ready for use the impactors are sealed and taken out to the sample position at the duct work where they are opened and connected to the sample pumps. The duration of sampling is 1 minute at a flow of 1 CFM. Impactors are then resealed and rushed back to the humidity chamber and the filters are reweighed. The initial weight and post test weight is a measure of the aerosol mass distribution for each size range. All filters are placed in an individual petri dish. After 24 hours of conditioning the filters are weighed a third time. This difference gives us a measure of the volatile fraction of the test aerosols.

Filter papers are Gelman Fiber Filter papers (81mm diameter) and the average weight is 361.7 mg. The backup filter paper is also fiber filter paper (47mm diameter) and the average weight is 127.1 mg. All papers are weighed using a Mettler balance Model #H15.

Figure 1C is a photograph of a typical sampling setup at the HEPA Station of the exit duct of the LLNL Fire Test Cell. Table 1C lists the equipment used for practical testing. Table 2C shows the standard form for recording filter weights and Table 3C is an example of the reduced data generated by the PDP 11.

CAPTIONS - APPENDIX C

TABLE C-1 Impactor Data Sheet

TABLE C-2 Computer Printout of Impactor Calculation Data

TABLE C-3 Cascade Impactor Data Equipment List

Figure C-1 Typical Smoke Sampling Setup at the HEPA Station

IMPACTOR DATA SHEET

DATE _____

TAGE				
0	3rd 2nd Initial	3rd 2nd Initial	3rd 2nd Initial	3rd 2nd Initial
1	3rd 2nd Initial	3rd 2nd Initial	3rd 2nd Initial	3rd 2nd Initial
2	3rd 2nd Initial	3rd 2nd Initial	3rd 2nd Initial	3rd 2nd Initial
3	3rd 2nd Initial	3rd 2nd Initial	3rd 2nd Initial	3rd 2nd Initial
4	3rd 2nd Initial	3rd 2nd Initial	3rd 2nd Initial	3rd 2nd Initial
5	3rd 2nd Initial	3rd 2nd Initial	3rd 2nd Initial	3rd 2nd Initial
6	3rd 2nd Initial	3rd 2nd Initial	3rd 2nd Initial	3rd 2nd Initial
7	3rd 2nd Initial	3rd 2nd Initial	3rd 2nd Initial	3rd 2nd Initial
Bu	3rd 2nd Initial	3rd 2nd Initial	3rd 2nd Initial	3rd 2nd Initial
	Dry Weight (3rd - Initial)	Dry Weight (3rd - Initial)	Dry Weight (3rd - Initial)	Dry Weight (3rd - Initial)
	0	0	0	0
	1	1	1	1
	2	2	2	2
	3	3	3	3
	4	4	4	4
	5	5	5	5
	6	6	6	6
	7	7	7	7
	Bu	Bu	Bu	Bu

IMPACTOR CALCULATION DAT
 8 STAGE IMPACTOR
 SAMPLE C(W)
 VOLUME SAMPLED .02832 CU. METERS

16-OCT-79
 BURN 62

STAGE	WEIGHT (MG)	%
0	1.7	1.4
1	3.3	2.8
2	7	6
3	23.4	20.2
4	49.1	42.5
5	24.4	21.1
6	5.3	4.5
7	1.1	.9
B/U	0	0
TOTAL	115.3	

SIZE	WEIGHT (MG)	%
<1.0	6.4	5.5
1.0<2.0	24.4	21.1
2.0<3.0	49.1	42.5
>3.0	35.4	30.7
CONCENTRATION (MG/CU.METER)	4071.33	

CASCADE IMPACTOR DATE EQUIPMENT LIST

Fiber filter papers - Gelman (81mm) average wt. 361.7 mg.

(47mm) average wt 127.1 mg.

Vacuum Pumps (carbon vane) (2 ea.)

(1) Model #5KH32EG115EX

Serial #Y58996

1/6 H.P. FR 48

(2) Model #5KH32EG115EX

Serial #Y58993

1/6 H.P. FR 49

Fisher Porter Flowrator (2 ea.)

(1) Model #10A3565

Serial #7605A1808A2

(2) Model #10A3565

Serial #7611A1115A5

Cascade Impactors

a ACfm Ambient Particle Sizing Sampler - 8 Stage

Mettler Balance Model #H-15

General Electric 8,000 Btu heater - air conditioning

Sears 30 Pint Automatic Dehumidifier Model #5930

Fig. C1 Typical smoke sampling setup at the HEPA station.

APPENDIX D
SMOKE AEROSOL ANALYTICAL SYSTEM

Appendix D

INTRODUCTION

For the past year the Fire Science Group has been developing an on-the-line Particle Size Spectrometer to evaluate aerosol mass distribution during the growth of a fire. Our major problem is the high density of smoke aerosols generated during the combustion of most materials. Contemporary on-line analyzers are designed to survey diffuse aerosols. Such design appears incompatible for conditions where aerosol concentration is high.

Extensive time was spent to evaluating commercially available particle analyzers for our application. We found no system that would evaluate the smoke concentration produced during our standard tests. Consequently, we identified the need to develop a dilution procedure that would reduce the concentration of aerosols to measurable levels without obliterating the relative size and mass distribution of the virgin smoke. This appendix details our efforts to that end.

Hardware

Figure 1 is a schematic flowchart of the assembled system. The defined components are:

Climet PSA - The Detector

A Climet MODEL 208 Particle Analyzer (PSA) was selected as the detector because of work previously done by Cooke and Kerker¹, and Lewis and Lamothe². The analog voltage output from the photomultiplier tube is connected to the log-amplifier.

AMPLIFIER. A Nuclear Data ND-PSA amplifier was selected for this purpose. The Particle Sizing Amplifier is a pulse amplifier that may be operated in a logarithmic or linear mode. It stretches the event pulse, detecting the peak amplitude and strobes the level of the peak amplitude to the output connector.

PULSE HEIGHT ANALYZER (PHA). A Davidson MODEL 1056A PHA was selected as a data acquisition device. The PHA allows analog to digital conversion and display of spectrum during data acquisition. Digital data is then sent thru a teletype interface to the output terminal.

TELETYPEWRITER. A Texas Instruments Silent 700 model 743 KSR Data terminal is used for hard data storage.

DILUTION SYSTEM. A three stage dilution system was designed and fabricated to reduce the particle number count to the inlet of the sensor to prevent saturation of the detector. The dilution system was based on work done by Kittelson et. al.³ at the University of Minnesota for measurement of Diesel Exhaust Particle Size Distributions.

Calibration

Calibration of the system was conducted using NaCl aerosols and Polystyrene Latex microspheres of .357-, 1.09-, 2.02-, 5.0- and 9- μ m in size.

The source air was pulled thru a HEPA to remove any background particles and background readings were taken to validate air purity. The calibration aerosols were injected into the stream using nebulizers. Particle count was controlled by adjustment of air pressure to the nebulizers.

Figure 2 is a typical curve generated during calibration using latex spheres.

Our research revealed that the 3 stage dilution system was not useful for our work because of the non-linear loss of the larger particles through the system. Figure 3 shows the calibration curve using 4 sizes of latex spheres thru the 3 stages of dilution. The dilution ratio is 39 for the $0.35\mu\text{m}$ spheres and 605 for the $1.0\mu\text{m}$ spheres. This non-linearity in dilution ratio prompted us to seek alternative dilution strategies.

We decided to fabricate a single stage dilution system, of which Figure 4 is a schematic flowchart. Calibration of this system was conducted using the same aerosol systems used previously. The single stage dilution system and particle analyzer system have been used on two full scale fire tests. Comparison of these data and data taken using cascade impactor are very encouraging in that they both show similar size trends and distribution. However, these data are still preliminary requiring further system refinement and verification.

Future Work.

In the FY80 we will continue to gain experience on the Particle Analyzer System in use on our testing programs. Also we will be expanding the system by:

- On LSI-11 microcomputer will be interfaced as a data acquisition system and data reduction device.
- Dual Floppy Disc storage system will be interfaced for data and program storage.
- Development of calibration system to determine true particle diameter vs. aerodynamic diameter and size diameter shift for smoke aerosols.

REFERENCES

1. Cooke, D. D. and Kerker, M. (1975) Applied OPTICS 14, 734.
2. Lewis, C. W. and Lamothe, P. J. (1978) Journal of Aerosol Science, Vol. 9, pp. 391-397.
3. Kittelson, D. B., Dolan, D. F., Diver, R. B., and Aufderheide, E. (1978) Society of Automotive Eng. No. 780787.

- D1 Schematic flowchart of 3 stage dilution system.
- D2 Calibration of PHA with Latex spheres.
- D3 Calibration of dilution system using latex spheres.
- D4 Schematic flowchart of single stage dilution system.

Fig. D1. Schematic flowchart of 3 stage dilution system.

Fig. D2. Calibration of PHA with Latex spheres.

Fig. D3. Calibration of dilution system using latex spheres.

Fig. D4. Schematic flowchart of single stage dilution system.

APPENDIX E

CRIB FIRE MODELING

1. The Characteristics and Burning of Crib Fires
2. Mass Burning Rate in a Wood Crib with a Natural Gas Pre-Burner

Appendix E-1

The Characteristics and Burning of Crib Fires

The selection of cross piles of fuels (cribs) as models for test fires is a logical choice for organizations conducting repetitive fire tests because crib fire characteristics have been well documented and attempts at modeling have been somewhat successful. We naturally gravitated to these sources when exemplar fires proved to be unreproducible. We recognized that to fulfill the mission of our program, we would have to violate the precepts of pure modeling; i.e., to insure the production of dense smoke aerosols, adjustments to crib porosity and burning rate are necessary. And since we wished to assess potential of various flammable materials to produce smoke aerosols to challenge the HEPA filters, they too would have to be burned in crib configuration.

Thus, we decided that a theoretical understanding of crib burning variables was warranted and we secured the talents of Dr. John Creighton of LLNL Chemical Engineering Division, to survey these topics and define the limits to which we could push our experiments.

Two topics are outlined in this appendix; (1) a description of the vent and surface area of a wood crib, a topic necessary to understanding the dynamics of crib burning and analysis of the importance of variables. Using these factors, one of our test fires is analyzed, and (2) a study of the mass burning rate in a wood crib with a natural gas pre-burner. This analysis was done to assess the contribution of the natural gas burner we employed to maintain high fuel consumption rates during the ventilation controlled phase of our test fires.

VENT AND SURFACE AREA OF A WOOD CRIB.

Crib Architecture

Consider a wood crib of N layers, and n sticks per layer b is the width of square stick and l the length of stick.

Let s be the spacing between sticks, there are $n - 1$ such spaces per layer, thus;

$$s = \frac{l - nb}{n - 1}$$

Figure 1 shows these relationships.

Vent Area

Each vent is a rectangular column Nb cm high with a base $s \times s$. The base area is s^2 . There are $(n - 1)^2$ such vents, so the vent area (A_v) is;

$$A_v = (n - 1)^2 s^2 = (\ell - nb)^2 \quad (1)$$

Surface Area

An individual stick has a surface area (S);

$$S = \underbrace{4b\ell}_{\text{sides}} + \underbrace{2b^2}_{\text{ends}}$$

Part of the upper and lower surface of each interior stick is covered by cross sticks from adjacent layers. We want to define the surface area which is free from cover, (S'). The covered area on each interior stick is $2nb^2$, giving the exposed surface area;

$$S' = \underbrace{2b\ell}_{\text{sides}} + \underbrace{2b(\ell - nb)}_{\substack{\text{top and} \\ \text{Bottom}}} + \underbrace{2b^2}_{\text{ends}}$$

In a stack there are $N - 2$ layers of interior sticks. Sticks in the top and bottom layers are uncovered on one side. So the total surface area of the stack, A_s is equivalent to $N - 1$ interior layers and 1 uncovered layer, thus:

$$\begin{aligned} A_s &= (N - 1)nS' + nS \\ &= 2nb [(N - 1)(2\ell + b - nb) + 2\ell + b] \end{aligned}$$

Rearranging

$$A_s = 2nNb\ell [2 - b/\ell (n - 1 - 1/N)] \quad (2)$$

Interpretation of Equation 2

If we neglected the ends of the sticks and the fraction of the area covered, we would get as the exposed area;

$$A'_s = 4nNb\ell,$$

which is the first term of eq. 2. If we add the ends we get;

$$A''_s = 2nNb\ell(2 + b/\ell).$$

If we treat all sticks as interior sticks and subtract the covered area we get;

$$A'''_s = 2nNb\ell [2 - b/\ell(n - 1)]$$

So the $1/N$ term in equation 2 comes from not covering the top and bottom surfaces.

To get an idea of the relative importance of the various terms, assume that in a typical crib $n = N = 10$, and $\ell = 20b$. Then we evaluate equation 2 relative to the importance of the bracketed terms, thus:

$$A_s = 2nNb\ell \left[2 - \frac{nb}{\ell} + \frac{b}{\ell} + \frac{b}{N\ell} \right] \text{ where the value of each term is:}$$

$$2nNb\ell = 4000b^2$$

$$\frac{nb}{\ell} = \frac{1}{2} \text{ which is 25\% of the first bracketed term.}$$

$$\frac{b}{\ell} = \frac{1}{20}, \text{ about a 2\% correction.}$$

$$\frac{b}{N\ell} = \frac{1}{200}, \text{ negligible.}$$

Accuracy

Both A_v and A_s are only approximate quantities. The theory on crib burning by Block (1) assumes uniform flow across a vertical vent channel of area s^2 . Because of drag and the irregular shape of the walls, the effective area will differ from the theoretical value by perhaps 10 to 20%. Similarly, A_s assumes that all exposed surfaces get the same heat flux. This is clearly not true; in particular, the outside surfaces will get less thermal energy. However, the edges are a small fraction of the area. Non-uniform temperature will probably be a bigger factor with regard to the overall error.

Some Comments On Scaling

Burning rate for a large variety of fires can be correlated with $\sqrt{s} A_v/A_s$. We can determine this as a function of stack geometry. If we include only the dominant terms in A_s (discussed above) we get

$$A_s \approx 4nNb\ell \left(1 - \frac{nb}{2\ell}\right) \quad (3)$$

Combining equations 1 and 3 gives

$$\frac{A_v}{A_s} = \frac{1}{4N} \left(\frac{\ell}{bn} - 1 \right) \left[\frac{1 - bn/\ell}{1 - bn/2\ell} \right] \quad (4)$$

This depends only on the stick spacing and the number of layers. The dimensionless parameter

$$\frac{\ell}{nb} = 1 + \left(\frac{n-1}{n} \right) \frac{s}{b} > 1$$

is a function only of the ratio s/b and n , and is independent of the size of the stack so long as s/b and n remain the same. Equation 4 is plotted in Fig. 2, which shows that A_v/A_s is parallel to the dashed line, which is

$(\ell/bn - 1)$. The bracketed term of Eq. 4, is shown in Fig. 3 showing the reason for the curvature. For closely packed cribs we are mainly interested in the region $0 \leq (\ell/bn - 1) \leq 2$, corresponding roughly to $0 \leq s/b \leq 2$. This is shown in Fig. 4.

Burning Rate Of A Close-packed Crib

It is well established, experimentally that the burning rate in a wood crib can be correlated with the parameter $A_v \sqrt{s}/A_s$. In a loosely packed crib the burning rate is independent of the parameter, in a close packed crib

$$\frac{\sqrt{s} \left(\frac{dm}{dt} \right)}{A_s} = \frac{K A_v \sqrt{s}}{A_s} \quad (5)$$

where dm/dt is the mass burned per second and K is an empirically determined constant. Note that the parameter $A_v \sqrt{s}/A_s$ has dimensions of length, and close packed implies a value less than about 0.02 cm. Substituting equation 4 in equation 5 and rearranging gives

$$\dot{m} = \frac{dm}{dt} = K b^{5/2} \left\{ n^2 \left(\frac{\ell}{nb} - 1 \right)^{5/2} \sqrt{\frac{n}{n-1}} \right\} \quad (6)$$

where the dimensionless geometric factors are inside the brackets. Note that the mass burning rate (in kg/sec.) does not depend on the height of the crib.

Another useful quantity is the fraction of the total mass consumed per second. The mass of the crib is

$$M = \rho_w n N b^2 \ell;$$

where ρ_w is the density of the wood. The fractional burning rate is

$$\frac{\dot{m}}{M} = \frac{K}{\rho_w \sqrt{b}} \left\{ \frac{1}{N} \frac{nb}{\ell} \left(\frac{\ell}{nb} - 1 \right)^{5/2} \sqrt{\frac{n}{n-1}} \right\} \quad (7)$$

In both equations 6 and 7 the terms in brackets are dimensionless descriptions of the geometry. If we scale cribs keeping n , N and l/nb constant we preserve the geometry and the size is a function of b , only. We then see from eq. 6 that the mass burning rate scales as $b^{5/2}$; while the volume and mass scale as b^3 . The fractional burning rate varies only as $1/\sqrt{b}$, so the duration of the fire depends mainly on the geometry, not the mass of fuel, provided the crib is close packed.

It has been shown experimentally for loosely packed cribs that $m\sqrt{b}/A_s$ is roughly constant, i.e., the burning rate will be more nearly proportional to the surface area, rather than the volume. Similarly, in a loose packed crib. The fractional burning rate will vary as $b^{-3/2}$ and the duration will be longer for larger cribs.

Value of K

The coefficient, K , in eq. 5 can be evaluated from empirical data. If we use fig. 2 of Croce's 1976 paper(2), we get;

$$K \approx 4 \times 10^{-5} \text{ kg sec}^{-1} \text{ cm}^{5/2}$$

Some of the earlier papers indicate values of K as much as a factor of 2 lower(3); e.g., for loose packed stacks,

$$m\sqrt{b}/A'_s = 1.1 \times 10^{-6} \text{ kg sec cm}^{-3/2}.$$

The boundary between the loose packed and the close packed region is approximately;

$$\sqrt{sb} A_v/A_s = 0.025 \text{ cm.}$$

Criterion For Close Packing

A stack can be considered close packed if

$$\sqrt{s} A_v/A_s < 0.025 \text{ cm.}$$

Substituting eq. 4 and rearranging terms gives a maximum stick width for close packing, as a function of the dimensionless parameter, l/nb .

$$b < 4N \sqrt{\frac{n-1}{n}} \frac{nb^{3/2}}{l} \frac{(1-nb/2l)}{(1-nb/l)^{5/2}} \left(\frac{1.1}{K}\right) \quad (8)$$

The boundary is plotted in Fig. 5 with points below the curve representing close packed cribs. Note that the value of the quantity $\sqrt{\frac{n}{n-1}}$ is nearly unity for $n = 10$ a typical value.

Comparison Of Block's Scaling Parameter With Others

Block scales his fires against a dimensionless parameter

$$\frac{f}{2c} \sqrt{\rho(\rho_o - \rho)ghb} \frac{G(\phi)}{\phi} \frac{\lambda}{\lambda} \frac{1}{\lambda}, \quad (9)$$

whereas nearly everyone else scales fires against $\sqrt{s} A_v/A_s$. Thus, Block's parameter is about 30 times larger. To get this factor Block defines:

$$\phi = \frac{2fsh}{A_{vs}}$$

where f is a friction factor ($f = 0.13$), A_{vs} is the area of a single vent, and h is the height of the stack, equal to Nb . The parameter ϕ , is related to, but not identical to A_s/A_v . The difference comes in the definition of surface area and is illustrated in Fig. 6. Block counts only the areas shown double-cross-hatched, whereas others also include the singly cross-hatched areas. (A factor of 2 in Block's formulation would add the singly cross-hatched strips on the tops of the sticks.) As s becomes smaller it is clear that Block includes a much smaller surface area.

In algebraic terms

$$\phi = f \frac{2N(nb/\ell)}{(1 - nb/\ell)} \left\{ 1 - 1/n \right\} \quad (10)$$

If we rearrange eq. 4 we get

$$\frac{A_s}{A_v} = \frac{4N(nb/\ell)}{(1 - nb/\ell)} \left\{ 1 + \frac{nb/2\ell}{1 - nb/\ell} \right\} \quad (11)$$

The more accurate eq. 2 gives

$$\frac{A_s}{A_v} = \frac{4N(nb/\ell)}{(1 - nb/\ell)} \left\{ 1 + \left(\frac{nb/2\ell}{1 - nb/\ell} \right) \left(1 + \frac{1}{n} + \frac{1}{nN} \right) \right\} \quad (12)$$

The quantities in brackets show the differences, which become significant for small n and nb/ℓ approaching 1 (i.e. for small s). Combining eqs. 9 and 10 gives

$$\left(\frac{\phi}{f} \right) \left(\frac{A_v}{A_s} \right) = \frac{1}{2} \left(1 - \frac{1}{n} \right) \left[\left(1 - \frac{1}{2\ell/nb - 1} \right) \right] \quad (13)$$

If we use eqs. 9 and 11 we get

$$\left(\frac{\phi}{f} \right) \left(\frac{A_v}{A_s} \right) = \frac{1}{2} \left(1 - \frac{1}{n} \right) \left\{ 1 - \frac{1 + \frac{1}{n} + \frac{1}{nN}}{\frac{2\ell}{nb} - 1 + \frac{1}{n} + \frac{1}{nN}} \right\} \quad (14)$$

The bracketed terms of both eqs. 13 & 14 are plotted in Fig. 8. There is little difference in the values obtained from eqs. 13 and 14, but the fall-off for densely packed cribs is significant. Now if we define;

$$\eta(\ell/nb) = \left(1 - 1/n \right) \left\{ 1 - \frac{1}{2\ell/nb - 1} \right\} \quad (15)$$

Then;

$$\phi = \frac{f}{2} \eta \frac{A_s}{A_v}$$

and eq. 9 becomes;

$$\frac{1}{c} \sqrt{\rho(\rho_0 - \rho)} g h b \frac{G(\phi)}{\eta} \frac{A_v}{A_s} \frac{\lambda - 1}{\lambda} \quad (16)$$

The term $\frac{\lambda - 1}{\lambda}$ is a function only of the properties of the fuel. From

experiments Block determined parameters which show that $\frac{\lambda - 1}{\lambda} \approx \frac{2}{3}$ for

typical soft woods. Thus we rewrite eq. 16 as;

$$\frac{2}{3} \frac{\rho_0}{c} \sqrt{\frac{\rho(\rho_0 - \rho)}{\rho_0^2}} g h b \frac{G(\phi)}{\eta} \frac{A_v}{A_s} \quad (17)$$

Block defines

$$G(\phi) = \left\{ \frac{1}{\phi} \left[\frac{1 - e^{-\phi}}{1 - \left(\frac{\rho}{\rho_0 \lambda} \right)^2 e^{-\phi}} \right] \right\}^{1/2}$$

so that $G(\phi) \approx \phi^{-1/2}$; thus for large values of ϕ we can write;

$$\phi = \frac{f}{2} \frac{h P_s}{A_{vs}} = 2 f N b / s.$$

When ϕ is of the order of 1,

$$G(\phi) \approx \sqrt{\frac{s}{2 f N b}}.$$

It is also easy to show that, $\frac{\rho(\rho_0 - \rho)}{\rho_0^2} = 1/4$

so eq. 17 becomes;

$$\frac{1}{3} \frac{\rho_0}{c} \sqrt{\frac{g h s}{2 f N}} \left(\frac{1}{\eta} \right) \frac{A_v}{A_s} \quad (18)$$

where C is a numerical constant

This can be rearranged to a more useful form where;

$$\left\{ \frac{1}{3} \frac{\rho_o}{\eta C} \sqrt{\frac{g}{2f}} \right\} \sqrt{s b} \frac{A_v}{A_s} \quad (19)$$

This is similar to the parameter used by other workers except for the bracketed term, which we wish to evaluate numerically.

Using both empirical data and calculated parameters, Block determined that;

$$C = 1.0 \times 10^{-3} \text{ gm sec}^{-1} \text{ cm}^{-1.5}, \text{ and } f = 0.13$$

The density of air at room temperature is $1.2 \times 10^{-3} \text{ gm/cm}^3$, and $g = 980 \text{ cm/sec}^2$, eq. 19 becomes;

$$\frac{24.6}{\eta} \sqrt{s b} \frac{A_v}{A_s} \quad (20)$$

When $b = s$, $\eta \approx 2/3$, Block's horizontal scale parameter is about;

$$37 \sqrt{s b} A_v/A_s.$$

This agrees with visual comparisons for the position of the knee of the curve. To the left of the knee a straight line on Block's plot will not map to a straight line on other peoples' plots because the factor $1/\eta$ becomes very large as the packing becomes denser. The function $G(\phi)$ partially compensates for the variation with η , but not completely.

It is worth noting that the differences come mainly from different definitions of the exposed surface area. Block clearly doesn't include enough surface, but the definition is rather arbitrary. In particular, some definitions include the outside surface which clearly gets less thermal energy if it gets any at all. Indeed all of the definitions of surface area can be considered approximate at this time.

Based on this analysis we have sited the porosity and burning rate data of a typical wood crib fire in the LLNL test cell on a map of data from crib fires of various porosity. Specific data for our wood cribs are:

$$b = 4.27 \text{ cm,}$$

$$l = 106.8 \text{ cm,}$$

$$n = 12,$$

$$N = 20.$$

The measured burning rate, $\dot{m}$, was 120 gm/sec.

$$s = (l - nb)/(n - 1) = 5.05 \text{ cm.}$$

$$nb/l = 0.480$$

From eq. 4 (or Fig. 5)

$$\frac{A_v}{A_s} = 0.09268$$

$$\sqrt{s}b = 4.644 \text{ cm} = 46.44 \text{ mm}$$

This gives a crib porosity, $\sqrt{s}b A_v/A_s$, of 0.430 mm.

The burning rate must be multiplied by $\sqrt{b}/A_s$. From eq. 3 we get $A_s = 33.55 \text{ m}^2$.

Then $\dot{m} \sqrt{b}/A_s = 0.740 \times 10^{-3} \text{ kg sec}^{-1} \text{ m}^{-3/2}$. This point is shown as an asterisk in Fig. 8.

References for Appendix E

1. Block, J.A., "A Theoretical and Experimental Study of Nonpropagating Free-burning Fires," Thirteenth Symposium (International) on Combustion, The Combustion Institute, 1971.
2. Croce, P.A., "Modeling of Vented Enclosure Fires", Proceedings 5th International Fire Protection Seminar, Karlsruhe, Germany. 22-24, Sept. 1976.
3. Thomas, P.H., "Some Studies of Building Fires Using Models," Proceedings of the International Symposium on the use of models in Fire Research, Nov. 9-10, 1959, National Academy of Sciences, Pub. No. 786, 1961.

Appendix E-2

Mass Burning Rate in a Wood Crib With a Natural Gas Pre-burner

Consider a single vent of cross-sectional area A_v and height h (shown in figure 10). Nitrogen and combustion products will leave the top of the vent with a velocity w_t at a density ρ . Air will be inducted into the bottom of the vent at velocity w_b and density ρ_0 , the density of air at room temperature. A stoichiometric pre-mixed methane-air flame will provide some heat. The total mass flow rate, both nitrogen and combustion products, is $\dot{m}_f$, an input parameter. The heat will pyrolyze the wood, or produce gaseous fuel in some manner, at a mass flow rate $\dot{m}_s$. We wish to solve for $\dot{m}_s$. The variables, ρ , w_t and w_b , are also dependent variables, so we must solve for them, as well as some others that will arise as we develop the equations.

Mass Equation

Figure 10 shows the mass flows. Conservation of mass gives

$$A_v \rho \omega_t = A_v \rho \omega_b + \dot{m}_s + \dot{m}_f \quad (21)$$

This is straightforward.

Energy Equation

The energy equation is equally straightforward. The enthalpy flow out of the top equals the enthalpy associated with the input flows plus the enthalpy of the chemical reactions minus the enthalpy required to pyrolyze the wood.

$$\begin{aligned} C_p T \rho \omega_t A_v &= C_p T_o \rho \omega_b A_v + C_p T_o \dot{m}_f + C_p T_s \dot{m}_s \\ &+ \chi E \dot{m}_s + \dot{m}_f - \Sigma \dot{m}_s \end{aligned} \quad (22)$$

This equation assumes that it requires an enthalpy of ϵ to raise a gram of wood to a temperature, T_s , and pyrolyze it. This is based on the assumption that the wood must be heated to some characteristic temperature, T_s , for pyrolysis to begin. The enthalpy of reaction for methane is Σ per gram of the total pre-burner flow consisting of nitrogen and combustion products. We assume that the air flow is a fraction, χ , of the stoichiometric air flow and that combustion of the fuel releases an enthalpy, E , per gram of pyrolyzed fuel.

We have introduced two new dependent variables, T and χ . The other new variables are assumed to be parameters of the wood or natural gas.

Momentum Equation

The basic momentum equation is a differential equation.

$$A_v d(\rho \omega^2) = -A_v dp - \rho g A_v dz - \tau P_s dz \quad (23)$$

The co-efficient, τ , is a frictional drag co-efficient per unit circumference. The circumference is P_s , equal to $4 \sqrt{A_v}$ for a square vent. We can redefine the friction parameter to give

$$f = 2\tau/(\rho \omega^2).$$

We can also eliminate the variation of pressure with altitude by defining

$$P' = (\rho_o l - gz) - P$$

Substituting these in Equation 23,

$$\frac{d}{dz} (\rho \omega^2) = (\rho_o - \rho)g + \frac{dp'}{dz} - \frac{P_s f}{2A_v} \rho \omega^2 \quad (24)$$

The first term on the right is the buoyancy force and the last is a vertical drag force as the gas rises through the vent. Block¹ has shown that we can neglect the pressure term, and that f is nearly constant over the range of conditions of interest. To obtain an analytic solution we must assume that ρ is constant throughout the vent. This is equivalent to assuming that the temperature and density jump to values of T and ρ at the bottom of the stack and remain at that level to the top of the stack. A more realistic assumption is to require numerical solution of the differential equation. If ρ is constant, we can divide by it.

$$\frac{d\omega^2}{dz} = \left(\frac{\rho_o - \rho}{\rho}\right)g - \frac{\phi}{h} \omega^2 \quad (25)$$

Where $\phi = \frac{P_s hf}{2A_v}$

If we let $U = \omega^2$, we can easily solve eq. 25, obtaining;

$$\frac{\omega_t^2 - a}{\omega_b^2 - a} = e^{-\phi} \quad (26)$$

Where

$$a = \frac{(\rho_o - \rho)gh}{\rho\phi}$$

We will use Equation 26 as the momentum equation, instead of the differential equation.

Chemistry

Pre-Burner

The chemical equation for a stoichiometric methane/air flame is

The coefficient for N_2 is not an integer because it represents the amount of nitrogen accompanying the oxygen in air. It will be simpler to assume that $\dot{m}_f$ consists of products in the proportion on the right side of Equation 27. The pre-burner will also have an enthalpy of reaction sufficient to raise the products to the adiabatic flame temperature, T_a . The enthalpy of reaction can be made consistent with the assumed specific heat by noting

$$C_p (T_a - T_o) \dot{m}_f = \Sigma \dot{m}_f \quad (28)$$

A value of 2500 K for $T_a - T_o$ would be appropriate.

Wood Burning

We could characterize the burning of wood with empirical fits, but our understanding is increased if we look at the chemistry of cellulose combustion.

The coefficient, ν , allows us to consider wood with various moisture contents, since $\dot{m}_s$ includes the mass of water vaporized.

We now define a parameter, γ , for a stoichiometric mixture so that

$$\gamma = \frac{\dot{m}_s}{(A_v \rho_o \omega_b)_{\text{stoich}}}$$

Equation 29 give $\gamma = 0.21$ when $\nu = 0$. Larger values of ν result in larger γ . Block uses $\gamma = 0.27$, corresponding to $\nu = 5.7$ in Equation 29. This represents a moisture content of about 23% by weight if equation 29 is correct. This is an unrealistically high value for most cellulose based materials.

Normally, the vent air flow will not be stoichiometric, so we will let χ be the actual air mass flow rate divided by the stoichiometric mass flux.

$$\frac{\chi}{\gamma} = \frac{A_v \rho_o \omega_b}{\dot{m}_s} \quad (30)$$

Equation of State

Block was able to solve for the mass burning rate without using the equation of state. A complete solution requires an equation of state. We can use an ideal gas equation of state for each component at atmospheric pressure. For example, we can even treat aerosols provided we assign them a huge molecular weight. The ideal equation of state can be written

$$pV = nRT.$$

For a particular molecular species, i ,

$$\rho_i = W_i n_i / V$$

where W_i is the molecular weight. Therefore, the partial pressure of

species i is

$$P_i = \rho_i RT/W_i,$$

and the total pressure is

$$P = \sum P_i = RT \sum (\rho_i/W_i) \quad (31)$$

The pressure at the top of the wood crib is substantially the same as that at the bottom, so if we can determine the ρ_i 's at the top and bottom we can use this equation of state. Further

$$\rho = \sum \rho_i \quad \text{at the top, and}$$

$$\rho_o = \sum \rho_{i0} \quad \text{at the bottom.}$$

To obtain the ρ_i 's at the top, we must make use of the chemistry, along with mass and species concentration. We can rewrite Equation 29, using the fact that the air flow is X times stoichiometric

The mass flow of each product out the top is obtained by multiplying the coefficients on the right side by the appropriate molecular weight and $\dot{m}_s$, then dividing by $\beta = (342 + 18v)$, the effective molecular weight of the two species included in $\dot{m}_s$. We use a similar procedure for Equation 27, except we multiply by $\dot{m}_f$ and divide by the effective molecular weight of the entire left hand side. The result is shown in the first column of Table I.

These mass flows are in terms of $\dot{m}_s$ and $\dot{m}_f$. We can express them in terms of $A_v \rho_o \omega_b$ by using Equation 30 and

$$\dot{m}_f = EA_v \rho_o \omega_b \quad (33)$$

which defines ξ . Note that ξ is an unknown and proportional to $1/\omega_b$. The mass flow rates divided by $A_v \rho_o \omega_b$ are shown in the second column of Table I.

Now;

$$A_v \rho \omega_t = \sum \dot{m}_i \quad (34)$$

which gives

$$\rho_i = \frac{\dot{m}_i}{A_v \omega_t} \quad (35)$$

The partial pressures are obtained by dividing by the molecular weights as shown in the third column of Table I.

A similar procedure is applied to the inlet air flow as shown in the lower part of Table I. Summing the partial pressures gives

$$[1.175 + 1.044\xi + .0175 (\frac{\gamma+1}{\chi})] T = T_o \omega_t / \omega_b \quad (36)$$

If we substitute the definitions for ξ and χ in Equation 21, we get

$$\rho \omega_t = \rho_o \omega_b (1 + \xi + \gamma/\chi) \quad (37)$$

If we had assigned effective molecular weights W_0 to the inlet air and W_p to the products, the equation of state and constant pressure would have given us

$$p = \rho RT / W_p = \rho_0 RT_0 / W_0$$

or

$$\rho T = \rho_0 T_0 W_p / W_0$$

substituting ρ from eq. 37 gives

$$(1 + \xi + \gamma/X) W_0 T / W_p = T_0 \omega_t / \omega_b \quad (38)$$

The principal difference between Equation 38 and the more accurate Equation 36 is the term γ/X , provided we set $W_0/W_p \approx 1.175$. The γ/X term disappears in Equation 36 because of the large molecular weight of $C_{12}H_{22}O_{11}$.

The effective molecular weights are comparable because the principal component is N_2 .

Heat Transfer

An analysis of the heat transfer from the burning gases to the wood will help us eliminate the unknown temperature, T , from the energy equation.

The heat transferred to the surface of the wood is,

$$\dot{m}_s \epsilon = h_c (T - T_s) A_s \quad (39)$$

where h_c is the heat transfer coefficient and A_s is the surface area of exposed wood. In a turbulent flow we can assume that the heat transfer is proportional to the friction coefficient. Then

$$h_c = \frac{1}{2} C_p f \langle \rho w \rangle \quad (40)$$

where $\langle \rho w \rangle$ is the average mass flux. If we let

$$\langle \rho w \rangle = \frac{1}{2} \rho (\omega_b + \omega_t),$$

then

$$\dot{m}_s \varepsilon = \frac{1}{4} f A_s \rho (\omega_b + \omega_t) C_p (T - T_s) \quad (41)$$

Following Block, we define

$$\theta = \frac{C_p (T - T_s)}{\varepsilon} \quad (42)$$

Dividing Equation 41 by $A_v \rho_o \omega_b$, and using Equation 25 to define ϕ , we get

$$\frac{\dot{m}_s}{A_v \rho_o \omega_b} = \frac{\phi}{2} \frac{\rho}{\rho_o} \left(1 + \frac{\omega_t}{\omega_b}\right) \theta \quad (43)$$

This is equivalent to expressing T in terms of other variables.

Solution

It will be convenient to define a new dimensionless parameter,

$$\lambda \equiv \frac{\rho \omega_t}{\rho_o \omega_b} \quad (44)$$

Dividing the energy equation, Equation 22, by $A_v \rho_o \omega_b$ gives

$$\lambda C_p T_o = C_p T_o + (C_p T_o + \Sigma) \xi + (C_p T_s - \varepsilon) \frac{\dot{m}_s}{A_v \rho_o \omega_b} + \chi E \frac{\dot{m}_s}{A_v \rho_o \omega_b}$$

where

$$\xi = \frac{\dot{m}_f}{A_v \rho_o \omega_b}$$

In the last term, substitute $\dot{m}_s = (\gamma/\chi) A_v \rho_o \omega_b$, and in the next to last, use Equation 21 with the definition of λ to get

$$\dot{m}_s = (\lambda - 1 - \xi) A_v \rho_o \omega_b \quad (45)$$

If we define

$$B = [\gamma E - C_p (T_s - T_o)] / \epsilon \quad (46)$$

and

$$\beta = [\Sigma - C_p (T_s - T_o)] / \epsilon \quad (47)$$

We can rewrite the energy equation.

$$\lambda(\theta + 1) = B + 1 + (\beta + 1)\xi \quad (48)$$

Substituting from Equation 42 gives, after some algebra,

$$\lambda = 1 + \xi + \frac{(B + \beta\xi)\phi(1 + \rho/\lambda\rho_o)}{2 + \phi(1 + \rho/\lambda\rho_o)} \quad (49)$$

The unknowns in equation 49 are ξ and the ratio $\frac{\rho}{\lambda\rho_o}$. The latter is equal to ω_b/ω_t and will generally be on the order of 0.1; since this appears as $(1 + \frac{\rho}{\lambda\rho_o})$ it will have little effect on λ , especially for the large values of ϕ in a ventilation controlled crib. In many cases ξ will also be much less than 1 because the pre-burner is normally only a small fraction of the total flow. In principle we can solve for ξ and $\frac{\rho}{\lambda\rho_o}$ and substitute in equation 49. In practice the algebra is rather complex and an iterative numerical solution seems simpler.

Numerical Solution

The first step in the iterative solution involves calculating ϕ , B and β , which characterize the geometry of the stack and the thermochemistry of the fuel. Initial guesses for ξ and $\frac{\rho}{\lambda\rho_o}$ must be made. Having determined λ we can combine equations 42, 43 and 45 to get

$$T = T_s + \frac{2\epsilon(\lambda - 1 - \xi)}{C_p \lambda \phi (1 + \frac{\rho}{\lambda\rho_o})} \quad (50)$$

The equation of state, equation 36, can be rearranged, using

$$\frac{\dot{m}_s}{A_v \rho_o \omega_b} = \frac{\gamma}{X} = \lambda - 1 - \xi, \text{ giving}$$

$$\frac{\omega_t}{\omega_b} = \frac{T}{T_o} = X \left\{ 1.175 + [1.044 - .0175\gamma(\nu+1)]\xi + .0175\gamma(\lambda-1)(\nu+1) \right\} \quad (51)$$

We can now obtain ρ from:

$$\rho = \rho_o \lambda \omega_b / \omega_t \quad (52)$$

The momentum equation (equation 26) gives

$$\omega_b = \sqrt{\frac{a(1-e^{-\phi})}{(\omega_t^2/\omega_b^2 - e^{-\phi})}} \quad (53)$$

with

$$a = \frac{gh}{\phi} \left(\frac{t}{\lambda \omega_b} - 1 \right)$$

New values of $\rho/\lambda\rho_o$ and ξ can now be obtained and the next iteration begins with equation 49. Two or three iterations have proven sufficient except when ξ approaches unity. The iterations can readily be done on a desk calculator.

Example

Calculations have been done for an LLNL crib fire, showing the effect of varying the mass flow rate of the pre-burner. The stack was composed of wood sticks 4.27 x 4.27 x 106.8 cm, with 20 layers at 12 sticks per layer. The parameter B ($\dot{m}_s$ in Table 21) was 1.9, lower than Block's 2.6. The difference is largely due to the large assumed moisture content. Similarly, our γ is 0.23 compared to Block's 0.27. Other parameters were the same. The calculated mass burning rate ($\dot{m}_s$) is about 1.1 gm/sec for each vent, giving a total of about 135 gm/sec for the crib of 121 vents. This compares favorably with the measured 120 gm/sec. The temperature at the top of the stack is also reasonable. Two things are noticeable.

First, about 85% of the fuel is unburned at the top of the crib. Additional fuel should be burned above the top of the stack as air is entrained. This has not been calculated. Second, the density, temperature and mass flux out of the top of the crib are roughly constant. The inlet air flow and the fraction of wood that is pyrolyzed are reduced by the pre-burner mass flux. But since the pre-burner mass flow is about 0.01 times the total measured flow rate, the effect is trivial in the test fires. Should $\dot{m}_f$ become large however, $\dot{m}_s$ would be appreciably reduced.

Conclusion

The model presented here enables us to calculate most of the important parameters of a wood crib fire. By including the equation of state the model permits us to consider the effects of moisture in the wood. (The effects of moisture on ϵ and T_s have been neglected.) The model should be useful for predicting the results of wood crib fires.

The theory appears to breakdown when $\dot{m}_f$ gets large relative to the amount of potential pyrolyzate generated by the fuel, ($\dot{m}_s$). This is apparent when we note the dichotomy between temperature and $\dot{m}_s$. The theory says that $\dot{m}_s$ decreases when T increases, which is not correct. More important however, are the results that show how little effect the pre-burner has on the burning- or pyrolysis-rate at conditions that approximate the experimental conditions in the test cell; i.e., where $\dot{m}_f$ is approximately $0.01(\dot{m}_s)$. Confirming that the pre-burner does not significantly perturb crib fire dynamics makes us more comfortable with our original assumptions; i.e., we assumed that the dominant driver for crib burning is the cross section of the individual elements and the crib porosity. Thus, the differences in the burning of individual materials would be reflected by the dynamics of crib fires made of these materials.

Captions - Appendix E

- Fig. E1. Stick spacing relationship in wood cribs.
- Fig. E2. Plot of equation 4 for the ratio A_v/A_s and the dimensionless quantity (l/nb)
- Fig. E3. Plot of dimensionless bracketed terms of equation 4 to show reason for data curvature.
- Fig. E4. Expanded scale plot of Figure 2.
- Fig. E5. Boundary between close packed and loose packed cribs as defined by equation 8.
- Fig. E6. Cut away view of wood crib showing potential exposure surfaces. Block's model considers only double cross hatch areas.
- Fig. E7. Plot of calculated results for crib density from equations 14 and 15, note: similarity to Figure 3 (from equation 4).
- Fig. E8. Burning rate vs. crib porosity, LLNL wood crib data point shown as asterisk.
- Fig. E9. Mass flow parameters through idealized vent in crib matrix.

Fig. E1. Stick spacing relationship in wood cribs.

Fig. E2. Plot of equation 4 for the ratio A_v/l_s and the dimensionless quantity (l/nb) .

Fig E3. Plot of dimensionless bracketed terms of equation 4 to show reason for data curvature.

Fig. E4 Expanded scale plot of Figure 2.

Fig. E5. Boundary between close packed and loose packed cribs as defined by equation 8.

Fig. E6. Cut away view of wood crib showing potential exposure surfaces. Block's model considers only double cross hatch areas.

Fig. E7. Plot of calculated results for crib density from equations 14 and 15, note: similarity to Figure 3(from equation 4).

Fig. E8. Burning rate vs. crib porosity, LLNL wood crib data point shown as asterisk.

Fig. E9. Mass flow parameters through idealized vent in crib matrix.

CAPTIONS - APPENDIX E

TABLE E-1 Theoretical Computation Parameters

TABLE E-2 Theoretical Mass Flow Results

TABLE E.1.

Species	$\dot{m}_i$	Mass Flow $\dot{m}_i / (A_v \rho_G \omega_b)$	Partial Pressure, p_i / RT
Top			
N_2	$28 \times 45 \dot{X}_{\dot{m}_g} / \beta$ $+ 28 \times 7.5 \dot{m}_f / 290$	$28 \times 45 \gamma / \beta + 28 \times 7.5 \xi / 290$	$\frac{45\gamma}{\beta} + \frac{7.5\xi}{290} \quad \frac{\rho_G \omega_b}{\omega_t}$
CO_2	$44 \times 12 \dot{X}_{\dot{m}_g} / \beta$ $+ 44 \dot{m}_f / 290$	$44 \times 12 \gamma / \beta + 44 \xi / 290$	$\frac{12\gamma}{\beta} + \frac{\xi}{290} \quad \frac{\rho_G \omega_b}{\omega_t}$
H_2O	$18 \times (11\dot{X} + v) \dot{m}_g / \beta$ $+ 18 \times 2 \dot{m}_f / 290$	$18 \times (11 + v/\chi) \gamma / \beta$ $+ 36\xi / 290$	$\frac{11 + v/\gamma}{\beta} + \frac{2\xi}{290} \quad \frac{\rho_G \omega_0}{\omega_t}$
$C_{12}H_{22}O_{11}$	$342 (1 - \chi) \dot{m}_g / \beta$	$342 (1/\chi - 1) \gamma / \beta$	$(1/\chi - 1) \frac{\gamma}{\beta} \quad \frac{\rho_G \omega_b}{\omega_t}$
Bottom			p_i / RT_0
N_2	$\frac{28 \times 3.75}{137} A_v \rho_G \omega_b$	$\frac{28 \times 3.75}{137}$	$3.75 \rho_G / 137$
O_2	$\frac{32}{137} A_v \rho_G \omega_b$	$\frac{32}{137}$	$\rho_G / 137$
$\beta = 342 + 18v, \quad \gamma = \beta / 1644, \quad \chi \dot{m}_g = A_v \rho_G \omega_b,$ $\dot{m}_f = \xi A_v \rho_G \omega_b, \quad \gamma = 0.20803$			

TABLE E-2								
mf	ω_b	ω_t	ρ_g	T	$A_v \rho \omega_b$	$A_v \rho \omega_t$	$\dot{m}_g$	$(1-\chi)\dot{m}_g$
0	27.12	101.7	.00078	943.0	.836	2.026	1.190	0.997
0.001	27.09	101.66	.00078	942.9	.835	2.026	1.189	0.996
0.002	27.06	101.67	.00078	942.9	.834	2.026	1.188	0.995
0.005	26.98	101.67	.00078	942.9	.832	2.026	1.184	0.992
0.010	26.85	101.76	.00078	943.2	.828	2.026	1.179	0.987
0.020	26.58	101.95	.00076	943.4	.820	2.027	1.167	0.978
0.050	25.77	102.10	.00076	944.2	.795	2.028	1.134	0.950
0.100	24.44	102.52	.00076	945.4	.754	2.031	1.077	0.903
0.200	21.79	103.53	.00076	948.6	.672	2.036	0.965	0.810
0.500	13.81	106.40	.00075	957.5	.420	2.051	0.627	0.529

Unburned Pyrolyzate fraction	Mass flow rate of pyrolyzate of wood (gm sec ⁻¹)	Mass flow rate out of vent top (gm sec ⁻¹)	Mass flow rate into vent bottom (gm sec ⁻¹)	Average gas temperature in the vent (°K)	Average gas density in the vent (gm cm ⁻³)	Gas speed at vent top (cm sec ⁻¹)	Air speed at vent bottom (cm sec ⁻¹)	Total mass flow rate of gas, including combustion products and nitrogen (pre-burner)
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The initial conditions for this calculation are given as:

Ambient temperature, T_0 ,	300°K
Heat capacity (gas), C_p ,	0.300 cal gm ⁻¹ °K ⁻¹
Ambient air density, ρ_0 ,	0.0012 gm cm ⁻³
Burning parameters for gaseous fuel, B, gas,	1.523
"B" number for wood, B_{wood} ,	1.936
Heat of gasification for wood, r_p ,	425.0 cal gm ⁻¹
Critical pyrolysis temperature for wood, T_p	643°K
Cross sectional area of the vent, A_v	25.7 cm ²
Exposed fuel surface area, A_g	865.8 cm ²

APPENDIX F
ANALYSIS OF THERMAL DEGRADATION
PRODUCTS OF PLASTIC AND WOOD

APPENDIX F

Chemical Analysis

The purpose of the chemical analysis of the combustion products from wood and composite burns was to determine whether HEPA filter plugging is caused by

- Specific chemicals common to all fuels
- chemicals generated by specific fuels
- The concentration of the degradation products and not their unique chemical make up.

Experimental Method

Wood cribs and cribs constructed of polyvinylchloride, (PVC), wood, polymethylmethacrylate (PMMA), polycarbonate, and fiber-reinforced plastic (composite cribs) were burned in the large fire test cell, and the combustion products were directed into the duct work, which houses a rolling prefilter and a HEPA filter (Fig. F-1). For a better understanding of the combustion products and their effect on the filters, we sampled products upstream and downstream of the HEPA filter and upstream of the rolling prefilter. The various sampling points are shown in Fig. F-1.

We used a vacuum pump to pull the combustion products into glass traps set in a Dewar flask filled with liquid nitrogen. The products were sampled at 5-min intervals, beginning 5 min after the onset of the burn. Each sampling period lasted 5 min. This approach allowed us to include any possible changes in either the quantity or kinds of combustion products generated during the burn. After the products were trapped, they were brought to room temperature.

extracted with chloroform and stored in a refrigerator until gas chromatographic/mass spectrometric (GC/MS) analysis.

In addition, representative samples of the pre-filter and filter were cut out immediately after the burn, sealed in a paint can and stored in a refrigerator. We analyzed for both the volatile, (compounds with boiling points lower than 100°C) and the non volatile components. Prior to analysis a small hole (1cm dia.) was punched in the lid of the paint can and sealed with tape. The can was placed in hot water for ten minutes to allow the lighter components to volatilize and accumulate in the can. An aliquot of the mixture was then drawn out of the can with a syringe and analyzed with a g.c./m.s. The residual filter, coated with the less volatile mixture, was next extracted with chloroform in a soxhlet extractor. In this process hot solvent is vaporized, condensed, and dropped on the solid substance contained in the thimble. The extracted compounds contained in the liquid fill the body of the extractor and automatically siphon into the flask. The process continues repeatedly as the solvent is vaporized and condensed.

The volatile degradation products were analyzed on a 1/8 in (0.32 cm) X 6 ft. (1830 cm) stainless steel column packed with 5% Carbowax on TPA 80/100 Chromosorb WAW. The less volatile products were separated on SE-30 glass capillary column. The column was 30 m long and had approximately 60,000 theoretical plates. The stainless steel column was held at 50°C for 5 min. and then programmed to 110°C at 5°C/min. The capillary column was programmed from 90° to 225°C at a rate of 5°C/min. The injection port temperature was set at 300°C during the analysis of the volatile and the less volatile degradation products. The flame ionization detector oven, its transfer line, and the transfer line between the gas chromatograph (GC) and

the ion source of the mass spectrometer (MS) were maintained at 250°C. Helium was used for the carrier gas with both columns. The flow rate of helium was set at 45 ml/min for the packed column and at 2ml/min for the capillary column. Since the column's effluent was split between a flame ionization detector and the mass spec., we used nitrogen as our make up gas to increase the sensitivity of the FID. The nitrogen flow rate was set at 60 ml/min at the detectors side. A platinum-iridium line split the effluent between our quadrupole MS and the flame ionization detector, allowing simultaneous recording of the chromatographic peaks and total ion counts as a function of time. We used the computerized Wiley library containing the mass spectra* to find the dominant peaks in the chromatograms and then compared the spectra of suspected compounds with the spectra of each chromatographic peak to further identify the components.

Results

The results of the GC/MS analysis are summarized in Tables 1-6. Table 1 lists the more volatile compounds, formed during a composite burn and deposited on both the prefilter and the HEPA filter. We found that this mixture consisted mainly of water and relatively low concentrations of the volatile organics. Some of the physical properties of the chemicals are also included in the table for a better overall portrayal of the mixture. Tables 2-6 list the less volatile compounds from wood and composite burns. Each table shows the burn parameters; the compounds collected on, near, and extracted from the HEPA filter or the prefilter; the retention time for each compound (i.e., the time required for it to elute off the column from the time of injection); and the

* Compiled by Hewlett-Packard.

concentration of each compound. We have expressed the concentrations in terms of peak heights; keep in mind, however, that these are not absolute concentrations because we did not use internal standards in our analysis.

In comparing Table 3 with Table 6, we see that there are a number of similarities between smoke constituents from wood and composite burns. Basically, both types of burns generate a number of aromatic and polynuclear compounds (i.e., cresol, phenanthrene, naphthalene, acenaphthalene); some of which are the dominant compounds formed during the first 5 min. of the burns. Most of the dominant compounds have high molecular weights, high boiling points (above 200°C), are heavier than water, solid in their pure form, and are soluble in organic solvents (Table 7). We detected substantial amounts of the aromatic and polynuclear compounds upstream and downstream of the HEPA filter as well as on the HEPA itself in burns which did not employ a rolling prefilter (Table 2). We further observed that these compounds were drastically reduced downstream the HEPA filter once a rolling prefilter was incorporated in the ductwork (Tables 3-5).

A more detailed examination of the smoke constituents shows that composite burns generate more cresol isomers, phenols, and other aromatics than wood burns, and that wood burns form more polynuclear components. In addition, composite burns generate HCl, HBr, and probably a number of halogenated organics. The halogenated organics, however, were not detected on the columns we used.

If we were to analyze the physical properties of the main constituents of both types of burns, we would probably find that the dominant compounds dissolve in

some of the organic solvents and become airborne through the ductwork in the form of a fine mist that condenses on the walls of the ductwork and the HEPA filter. Furthermore, because the temperature near the HEPA filter is between 50 and 60°C, we could probably expect compounds with higher boiling points to deposit on the filter.

Conclusion and Recommendation

The overall results of this study suggest that filter plugging is not caused by the unique chemical make up of one compound or group of compounds, but rather by a concentration effect.

Because our analytical method was aimed at detecting only the predominant differences among the degradation products of each burn, we did not look at trace components or examine how the various compounds detected were formed. The GC columns used in this analysis were not specific for halogenated compounds, and therefore, a number of the compounds that may have formed in the composite burns may have gone undetected. These could have been irreversibly adsorbed on the columns or perhaps formed in such low quantities that they were masked by other products. In the latter case, they would not have been detected by the MS because of background interference.

A more detailed analysis of the degradation products and their mechanism of formation would require that we:

1. Use capillary columns specific for halogenated compounds and polynuclear compounds.
2. Pyrolyze wood and plastic samples separately and introduce their degradation products directly onto a GC column before they have a

chance to react and form secondary and tertiary reaction products.

3. Develop a sampling system that traps pyrolysis and combustion products as well as trace components.
4. Devise a sample work-up technique to use before we inject the samples onto the analytical column.

However, we believe that we have found the major cause of HEPA filter plugging and that further research in this area would be of secondary importance to filtration chemistry.

LIST OF FIGURES AND TABLES

Fig. F1. Ductwork housing the rolling prefilter and the HEPA filter

TABLE F-1 Volatile degradation products from composite burn deposited on both the pre-filter and the HEPA filter

TABLE F-2 Degradation products from wood burn 41

TABLE F-3 Degradation products from wood burn 42

TABLE F-4 Degradation products from composite burn 43

TABLE F-5 Degradation products from composite burn 45

TABLE F-6 Degradation products from composite burn 46

TABLE F-7 Physical constants of the less volatile organic compounds

TABLE F-8 Compounds which volatilize off the HEPA with boiling points of 100°C and lower

Fig. F1. Ductwork housing the rolling pre-filter and the HEPA filter.

Table F-1 Volatile degradation products from composite burn deposited on both the pre-filter and the HEPA filter.

Compound	Molecular Weight	b.p. °C	Density	Solubility
water	18.02	100	1.0004	
n-pentane	72.15	36	0.6262	alcohol, ether, acetone, benzene, chloroform, heptane
n-hexane	86.18	68	0.6603	alcohol, ether, chloroform
n-heptane	100.21	98.42	0.6837	alcohol, ether, chloroform
methylmethacrylate	100.13	100.	0.9440	alcohol, ether, acetone
1,3-butadiene	54.09	-4.4	0.6211	acetone, benzene, alcohol, ether
1,4-pentadiene	68.11	25.8	0.6608	acetone, benzene, alcohol, ether
cyclohexanone	98.14	155.65	0.947 ^a	ether, acetone, water, alcohol, chloroform

Burn parameters	Retention time, min ^a	Products upstream of HEPA filter	HEPA filter extracts	Products downstream of HEPA filter	Semi-quantitative comparison ^b
Moisture content of wood (Douglas fir) was 8-11%.	1.70		phenol		3
	1.90	<i>o</i> -phenol, benzaldehyde acetophenone			1
Prefilter was not modified.	2.20	2,2- <i>or</i> -methylstyrene, <i>o</i> -methylstyrene, α -methylstyrene			2
Temp max in cell, 740 °C	2.38			<i>o,m,p</i> -cresols	3
in cell at exhaust, 70° C	2.57		<i>o,m,p</i> -cresols		3
in duct at HEPA dry, 60 °C	2.70	<i>o,m,p</i> -cresols, indene methylphenylacetylene			3
wet, 60 °C	3.30	2-methylbenzofuran			2
	3.47		3,4-dimethylphenol methylphenol	3,4-dimethylphenol methylphenol	2, 1
	3.72				2, 1
Ventilation initial, 250 l/s final, 125 l/s	4.05	1-methyl-1H-indene			3
	4.25		naphthalene or azulene	naphthalene or naphthalene	3,5
Time to plugging, 810 s	4.50	naphthalene or azulene			5
	5.62		indane-1-one		1
	6.20		1-methylnaphthalene	1-methylnaphthalene	2
	6.32		2-methylnaphthalene or 5,6-benzobicyclo (2,2,1)-hept-2-ene	2-methylnaphthalene or 5,6-benzobicyclo (2,2,1)-hept-2-ene	2
	6.70	2-methylnaphthalene or 5,6-benzobicyclo (2,2,1)-hept-2-ene			3
	6.90		trans-cinnamic acid		1
	7.47		biphenyl	biphenyl	2

Table F2. Degradation products from wood burn #41.

Burn parameters	Retention time, min ^a	Products upstream of HEPA filter	HEPA filter extracts	Products downstream of HEPA filter	Semi-quantitative comparison ^b
	7.87		benzo (c) clannoline		1
	7.90	biphenyl			2
	8.30	1,2-dimethylnaphthalene			1
	8.80		acenaphthalene	acenaphthalene	4
	9.00	unidentified			2
	9.40	acenaphthalene or biphenylene			3
	9.60			6-methyl-6-phenyl fulvene	1
	10.10	unidentified			1
	10.23		dibenzofuran	dibenzofuran	2
	10.70	unidentified			1
	11.90		4-methyl fluorene		2
	12.10	unidentified			1
	12.30		fluorene or diphenyl diazomethane		2
	12.50	unidentified			1
	15.40		phenanthrene or anthracene	phenanthrene or anthracene	5,3
	16.17	phenanthrene			2
	16.90		1-methyl-3-phenylindane	1-methyl-3-phenylindane	1
	17.70		9,10-phenanthraquinone or 9,10-anthraquinone	9,10-phenanthraquinone or 9,10-anthraquinone	2
	19.00		dibenzoheptafulvene or 2-phenylnaphthalene	dibenzoheptafulvene or 2-phenylnaphthalene	1
	20.70		pyrene or fluoranthene	pyrene or fluoranthene	3,1
	21.00		1,2,3,10B-tetrahydro fluoranthene		2
	21.57		pyrene	pyrene	3,1

^aThe amount of time required for a compound to elute off the column from the time of injection.

^bConcentrations are expressed in terms of peak heights: 5 indicates a very prominent peak (a very high concentration); 4, a prominent peak (a high concentration); 3, a medium size peak (a medium concentration); 2, a small peak (a low concentration); and 1, a very small peak (a very low concentration).

^cTwo numbers signify that (1) the same compounds have emerged from the GC column at the same time or (2) that a peak is comprised of two different compounds.

Table F2. cont.

Burn parameters	Retention time, min ^a	Products upstream of HEPA filter	Products downstream of HEPA filter	Semiquantitative comparison ^b
Moisture content of wood (Douglas fir) was 7-11%.	1.90	<i>o</i> -phenol	No significant peaks	2
	2.80	<i>o,p</i> -cresols		2
	4.00	<i>m,p</i> -ethylphenols		1
Prefilter consisted of a single layer of 50% efficiency media backed by a plastic grid.	4.60	azulene or naphthalene		2
	6.00	indian-1-one		1
	6.40	styrene		1
	6.80	2-methylnaphthalene		1
Temp max in cell, 750°C	9.40	acenaphthalene		3
in cell at exhaust, 250°C	10.40	2-naphthol		3
	10.80	dibenzofuran		3
in duct at HEPA dry, 80°C	11.80	phenalene		2
wet, 68°C	12.23	fluorene		2
	12.67	4-methylfluorene		2
Ventilation initial, 260 l/s	13.50	unidentified		2
final, 198 l/s	14.60	<i>m</i> -phenylphenetole		2
	15.20	unidentified		2
Time to plugging, 510 s	16.30	phenanthrene or anthracene		5
	17.70	dibenzobiphenylene		2
	18.50	9-fluorenone		3
	19.00	1,5-methylene-phenanthrene		3
	19.60	dibutylphthalate		2
	19.90	unidentified		2
	20.60	unidentified		1
	21.60	fluoranthene		4
	22.10	1,3,3,10-β-tetrahydro-fluoranthene		2
	22.70	pyrene		4
	25.15	2,3-benzofluorene		1
	25.17	4-methylpyrene		1
	26.90	2,3-benzofluorene		1
	31.33	2,13-benzofluoranthene		2
	34.30	3,4-benzophenanthrene		2

^aThe amount of time required for a compound to elute off the column from the time of injection.

^bConcentrations are expressed in terms of peak heights: 5 indicates a very prominent peak (a very high concentration); 4, a prominent peak (a high concentration); 3, a medium size peak (a medium concentration); 2, a small peak (a low concentration); and 1, a very small peak (a very low concentration).

Table F3. Degradation products from wood burn #42.

Burn parameters	Retention time, min ^b	Products upstream of HEPA filter	Products downstream of HEPA filter	Semiquantitative comparison ^c
Composite crib made of wood (Douglas fir) with a moisture content of 7-8%, polyvinylchloride, polymethylmethacrylate, polycarbonate, and fiber-reinforced plastic. ^a	1.22	<i>o</i> -xylene	No significant peaks	5
	1.30	cyclooctatetraene		4
	1.67	phenol		3
	1.83	isopropylbenzene		2
	1.93	cyclopropylbenzene or allylbenzene		2
	2.30	methylphenylacetylene		3
Prefilter consisted of two layers of 50% efficiency media and one layer of 10% efficiency media.	3.28	1,2-dibenzonaphthalene		2
	3.60	naphthalene		1
	5.67	biphenyl		2
	10.22	phenanthrene		2
Temp max: in cell, 640°C in cell at exhaust, 160°C in duct at HEPA dry, 58°C wet, 48°C				
Ventilation ^d initial, 250 l/s final, 220 l/s				
Pressure drop across filter ^e initial, 200 Pa final, 540 Pa				
Time to plugging, 410 s				

^aNot fire retarded.

^bThe amount of time required for a compound to elute off the column from the time of injection.

^cConcentrations are expressed in terms of peak heights: 5, indicates a very prominent peak (a very high concentration); 4, a prominent peak (a high concentration); 3, a medium size peak (a medium concentration); 2, a small peak (a low concentration); and 1, a very small peak (a very low concentration).

Table F4. Degradation products from composite burn #43.

Burn parameters	Retention time, min ^b	Products upstream of HEPA filter	Products behind prefilter (sampled in the first 5 min)	Semiquantitative comparison ^c
Composite crib made of wood (Douglas fir) with a moisture content of 8.5%, fiber-reinforced plastic, polycarbonate, and polymethylmethacrylate.	1.20	<i>o,p</i> -xylene		5
	1.27	ethylbenzene		
	1.57	cyclooctatetraene		3
	1.92	phenyl-N-methylcarbonate		3
		1,4-ethoxytricyclo (4,3,2,0)		2
		10- <i>exo</i> -2,4,10-undecatriene		
Prefilter consisted of one layer of 10% efficiency media, one layer of 90% efficiency media, and one layer of 50% efficiency media.	2.37	<i>o</i> -cresol		4
	3.45	methylphenylacetylene		
	4.07	<i>p</i> -ethylphenol		3
	4.35	naphthalene		4
		<i>m</i> -isopropylphenol or <i>o</i> -isopropylphenol or <i>p</i> -isopropylphenol		2
Temp max in cell, 670 °C	5.80	1-methylnaphthalene		2
in cell at exhaust, 155 °C	6.07	5,6-benzobicyclo (2,2,1)		2
in duct at HEPA dry, 50 °C	7.20	hept-2-ene		
wet, 60 °C	8.58	biphenyl		2
Ventilation initial, 250 l/s	11.27	biphenylene		2
final, 230 l/s	11.70	hydroxy-3,6-dimethyl benzaldehyde		
Pressure drop across filter initial, 200 Pa	12.07	1,1-bicycloheptatriene		1
final, 500 Pa	12.65	diphenyldiazomethane		1
	12.97	diphenylpropane		1
	13.67	<i>p</i> -alpha-amyphenol		1
Time to plugging, 880 s	14.20	1,1-diphenylethene		1
	15.20	antlraquinone		1
	19.12	phenanthrene		2
	23.73		di-N-propylnaphthalate	1
	26.98		di-2-ethylhexylnaphthalate	5
			butyl-butoxyethylnaphthalate	3

^aNot fire retarded.

^bThe amount of time required for a compound to elute off the column from the time of injection.

^cConcentrations are expressed in terms of peak heights: 5 indicates a very prominent peak (a very high concentration); 4, a prominent peak (a high concentration); 3, a medium size peak (a medium concentration); 2, a small peak (a low concentration); and 1, a very small peak (a very low concentration).

Table F5. Degradation products from composite burn #45.

Burn parameters	Retention time, min ^b	Soxhlet extract of prefilter	Products sampled behind prefilter			Semi-quantitative comparison ^c
			5 min	10 min	15 min	
Composite crib made of wood (Douglas fir) with a moisture content of 8.5%, fiber-reinforced plastic, ^a polycarbonate, and polymethyl-methacrylate.	1.37 1.40 1.48 1.50 1.60 1.97 2.00	phenol		ethylbenzene	ethylbenzene	3
					styrene, cyclooctatetraene	5
				styrene, cyclooctatetraene		3
				phenol		3
					phenyl-methylcarbonate	4
					isopropyl benzene	2
				4-methylstyrene		2
Prefilter consisted of one layer of 10% efficiency media,	2.22			4-methylstyrene, ar-methylstyrene, allylbenzene cyclopropylbenzene	allylbenzene phenylcyclopropane, ar-methylstyrene	1, 2 ^d
one layer of 90% efficiency media, and one layer of 50% efficiency media,	2.25 2.37		1-(2-ethoxypropoxy) propanol- ⁹			2
Temp max in cell, 800° C	2.90				<i>o,p</i> -cresols	4
in cell at exhaust, 150° C	2.95					5
in duct at HEPA dry, 50° C	3.76	<i>p</i> -ethylphenol				3
wet, 50° C	4.30	naphthalene		<i>m,p</i> -ethylphenols		3
	4.32			1,2-dihydronaphthalene		2
	4.45					2
Ventilation initial, 250 l/s final, 30 l/s	4.57		naphthalene or azulene			2
Pressute drop across filter initial, 250 Pa final, 2950 Pa	4.68 4.93 5.32	<i>m</i> -isopropylphenol		naphthalene, azulene	naphthalene	2 4,4
				<i>o</i> -isopropylphenol or 2,4,5-trimethylphenol or <i>m</i> -isopropylphenol		1
Time to plugging, 1320 s	6.20	1-methylnaphthalene			3-isopropylphenyl-N-methylcarbonate	1, 1
	6.52	1,2,3-trimethyl-5-pyrazolone				3,1
	6.92			1-methylnaphthalene or 2-methylnaphthalene		2
	7.72	biphenyl or acenaphthalene				2
	8.50			acenaphthalene or biphenyl		1
	9.13	acenaphthalene	acenaphthalene			2,2
	9.87	diphenylmethane, allylnaphthalene, acenaphthalene				1
	10.00			acenaphthalene or biphenylene		2
	10.57	dibenzofuran				1

Table F6 Degradation products from composite burn #46.

Run parameters	Retention time, min ^b	Solxlet extract of prefilter	Products sampled behind prefilter			Semi-quantitative comparison ^c
			5 min	10 min	15 min	
	12.42	4-methylfluorene, 1,1-bicycloheptatriene				5
	12.80	diphenyldiazomethane				1
	15.37			fluorene	fluorene	2,1
	15.52		phenanthrene	4-methylfluorene		2
	15.92	phenanthrene				3
	16.88	anthracene			phenanthrene	1,1
	16.93			phenanthrene		2
	17.32	para-alpha-cumylphenol				2
	18.38			unidentified		1
	19.27			1-methylphenanthrene		1
	19.58	dibenzohexafulvene				1
	19.67			4-methylphenanthrene		1
	20.65			2-phenylnaphthalene		1
	21.25	fluoranthene or pyrene				2
	22.28			fluoranthene		1
	22.93	pyrene		1,2,3,4-tetrahydrofluoranthene		5,1
	23.45					
	31.40	naphthalene		pyrene		1

^aNot fire retarded.

^bThe amount of time required for a compound to elute off the column from the time of injection.

^cConcentrations are expressed in terms of peak heights: 5 indicates a very prominent peak (a very high concentration); 4, a prominent peak (a high concentration); 3, a medium size peak (a medium concentration); 2, a small peak (a low concentration); and 1, a very small peak (a very low concentration).

^dTwo numbers signify that (1) the same compounds have emerged from the column at the same time or (2) that a peak is comprised of two different compounds.

Table F6. cont.

Compound	Physical appearance	bp, °C	mp, °C	Density	Solubility
<i>o,p,m</i> -xylenes	liquid, solid	138-144	-47-13	0.8684	alcohol, ether, organic solvents
phenanthrene	blue fluorescent (in solution)	340	101	1.1820	sol in alcohol; slightly CS ₂
ethyl benzene	liquid	136	-94	0.8672	alcohol, ether
<i>o,m,p</i> -cresols	liquid, but solid in the case of <i>p</i>	191-201	11-34.8	1.0460	alcohol, ether, organic solvents
ethyl phenol (para)	solid needles	219	45-46	-	alcohol, ether, benzene, CS ₂
naphthalene	solid monoclinic	210	80.22	1.1450	ether, alcohol, benzene, CS ₂
fluoranthene	pale yellow needles	375	111	1.2520	ether, alcohol (slightly), benzene, CS ₂
pyrene	pale yellow	260	149-150	1.2710	sol in alcohol
acenaphthalene	solid - platelet (alcohol); prism (ether)	265-275	92	0.8988	alcohol, ether, benzene
2-naphthol	monoclinic leaflet	295	122	1.2800	alcohol, ether, benzene, slightly SO ₂
dibenzofuran	leaflet or scales (alcohol);	287	86-87	1.0886	alcohol, ether, benzene, acetic acid
anthracene	solid	340	216	1.2500	benzene, chloroform, toluene

F7. Physical constants of the less volatile organic compounds.

TABLE F8. Compounds which volatilize off the HEPA
with boiling points of 100°C and lower.

1. Water
 2. n-heptane
 3. pentyl ether
 4. methyl methacrylate
 5. methylcyclopentane
 6. 1,3-butadiene
 7. 1,4-pentadiene
 8. 2-cyclohexanone
-

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