FIRE SCIENCE AT LLNL

A Review

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The LLNL Fire Test Cell

Data Acquisition and Reduction Room

Acknowledgments

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Foreword

Harry K. Hasegawa

The following collection of project summaries is intended to be both a close-out document for a DOE-sponsored research program, "Fire Protection Research for DOE Facilities," and a review of selected studies conducted for Lawrence Livermore National Laboratory (LLNL). Work for the DOE from 1979 to 1984 has been described in year-end reports and other publications. This document covers selected studies conducted between fiscal years 1984 and 1988.

The Fire Science Program

The Fire Science Program multidisciplinary staff conducts and applies contemporary fire research to reduce fire hazard to personnel and fire damage to DOE facilities and equipment. Fire research involves the study of fire inception and growth to define fire risk and develop methods for fire prevention and protection. Because many DOE programs are conducting leading-edge scientific research, their facilities present unique fire-related problems that require solutions that cannot be adequately addressed by traditional fire protection practices or standards. Many DOE facilities and programs represent the most advanced and complex technologies ever assembled, so it is not surprising that the standard fire and building codes used by fire protection engineers are not always sufficient to address the fire risk and to ensure that fire protection systems will in fact negate the predicted hazard. As programmatic design and materials change, both past fire experience and new risk assessment methods must be applied to the development of new codes and standards for the protection of life and property. Fire Science Program studies include full- and lab-scale fire testing; evaluation of the fire performance of laboratory construction materials, equipment, and protective apparel; computer modeling of fire growth in large enclosures; and detailed chemical analysis of smoke and combustion products.

The primary objectives for the DOE program were to define methods to reduce or eliminate fire risk to personnel or high-value equipment in DOE facilities and to develop procedures that prevent release of toxic materials to the environment from fire-related causes. Our primary emphasis has been and is to bridge the gap between fire safety research and traditional fire protection engineering.

The Fire Science Program also provides technical support to LLNL and most specifically to the Fire Safety Division, the Fire Protection Engineering Group, and the Analytical Laboratory of the Hazards Control Department. Most of this support is in the form of short-term applied research projects that provide solutions to specific fire protection needs. A listing of areas of concern addressed by our group but not selected for summarization in this document is included in the table on page vii.

The Fire Science Facilities

The major facilities of the Fire Science Program include

- A full-scale, 100-cubic-meter fire test cell with mechanically forced ventilation and capacity for 200 channels of thermal-fluid dynamic and chemical diagnostics (*Frontispiece*).
- Broad capability in flammability testing—i. e., heat release rate measurements, ASTM* flame-spread and combustibility measurements, fabric flammability tests, ease of ignition, and smoke density analysis.

*American Society for Testing and Materials

- SCBA heat and fire apparatus.
- Means for evaluating fire protection and detection systems and extinguishing agents.
- A complete fire chemistry laboratory with a full range of analytical instrumentation, including a thermogravimetric analyzer, a differential scanning calorimeter, and a gas chromatograph/mass spectrometer unit equipped with both NIST* and Wiley Chemical compound identification libraries.
- Capability to evaluate large-scale fire and smoke performance of in-line air filtration systems.
- Computer systems and databases for contemporary fire models, risk analyses, fault trees, and network algorithms.
- Apparatus for gas-phase flame propagation analysis, fire retardants, mass analysis, and vapor gradient determinations.
- Smoke aerosol analysis using both gravimetric and light scattering procedures.

Other Fire Science Program projects conducted between fiscal years 1984 and 1988.

Fire Properties and Life-Safety Hazard of Exterior Wall Panels
 Static Electricity Generation in Flammable Liquid Transfer Operations
 DC-8 Crash Studies
 Ignition and Flamespread in Treated and Untreated Plywood
 Ammunition Burns
 Flammability of Wire and Cable Insulations
 Evaluation of Quick-Acting On/Off Sprinkler Heads—Phase I
 Reliability Analysis of Sprinkler Systems
 Reliability Analysis of Site Water Supply System
 Fabric Flammability Testing
 Fire Risk Analysis of LLNL Facilities
 Fire Tests of ICC-55 Container to Test for Containment Integrity
 Flammability of an Oil-Soaked Carpet from Bldg 521
 Test and Evaluation of Automatic Portable Halon Extinguishers—Phase I
 Assessment of Flammability of Plastic Cable Trays
 Evaluation of an Air Injection System for Generating Fire Fighting Foams
 Evaluation of the Fire Potential of Plastic Pallets
 Pollutant Identification
 Simple Calculations for Fire Safety in Force-Ventilated Facilities
 Evaluation of the Hazard 1 Software Package
 Unique Procedure of Retardant Application to Wood Materials
 Underfloor Fires (Computer and Control Rooms)
 Protective Clothing for Firefighters
 Fire Fighter Training
 Heat and Flame Testing of Self-Contained Breathing Apparatus

*National Institute of Standards and Technology (formerly the National Bureau of Standards).

Fire Spread in an Office Trailer Complex*

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The number of buildings and portable facilities of all types at LLNL has greatly increased during the past ten years even though the Laboratory has remained fixed at one square mile. It has become necessary to place facilities closer to each other, resulting in an increase in the fire protection measures required for both new and old buildings. In addition, during the past 30 years the use of trailers and other portable structures at field-test sites and as temporary office space at DOE facilities has increased with the cost of general construction and the reduction in building funds. The type of construction of these units, the building materials used, and the irregular clustering of the trailers have all presented numerous problems for fire protection engineers.

The Fire Science Program was presented with the opportunity to perform a full-scale fire test when it came time to demolish an office trailer complex (in use since 1965) to make way for new construction. From these tests we obtained data needed to set a basis for trailer separation guidelines and as input to the

The Fire Science Program secured a trailer complex that was scheduled for demolition and conducted a full-scale fire test to observe and quantify the fire behavior of trailers at separation distances typical at DOE facilities. We undertook this study as a start toward collecting data for a reassessment of safe trailer separation standards under increasingly crowded conditions.

Department of Energy for revising or validating the existing trailer standards.¹

The Experimental Setup

The trailer complex scheduled for demolition consisted of three sections that had been joined together to make a 30 × 52-ft office

complex. We had this complex moved to a remote location on the Livermore site, where we disconnected one of the sections (containing four offices) and placed it opposite the other two, representing the common Laboratory configuration of opposing office complexes. We sealed the open sides of the trailer

Figure 1. The coupling of flames to the wood siding of Trailer B. The space between the trailers is a wall of flames.

* This report, with minor editorial differences, appeared in the Hazards Control Department's *Annual Technology Review* 1988 (UCRL-50007-88) on p. 33, under the title "Fire Exposure to an Office Trailer Complex." The reader is referred to this report for more photographs of the experiments and for graphs of temperature readings and heat flux levels.

with gypsum board and plastic after separation.

The construction of the trailers consisted of walls of wood paneling and siding of white aluminum. We added plywood skirting to the base of the trailers to represent the normal installation practice.

We set the initial distance between the trailers at 40 ft so that we could build kerosene pool fires between them without risking coupling of the flames to the trailers. This enabled us to conduct heat-flux (heat energy) measurements to the trailers to select the final separation distance for the full-scale burn.

We installed our portable Hewlett Packard 3054S data-acquisition system in a motor home so that we could use a portable generator for its power supply. We instrumented the trailers with thermocouples and calorimeters to measure the temperatures and heat flux produced by the fire. After the first test we added instrumentation to measure the internal temperatures of the aluminum siding and any heat transmitted through the windows into the exposed trailer. We used 35-mm cameras and VHS videocameras to record each burn.

The Pool Fires

As mentioned, in the first test the two trailers were separated by 40 feet. We placed a 5-ft² pan on the ground between the trailers with its center 13.3 ft from the closest trailer. By using the 1/3 and 2/3 distances between the trailers for the pan location, we were able to evaluate two

exposure distances for each burn. The fuel for the first test was 20 gallons of kerosene floating on 20 gallons of water. This fire size gave us a calculated heat-release rate of approximately 3600 kW, and it burned for 10 minutes.

This fire reached its peak 7 min into the burn. The highest temperature reached was 110°C and the highest heat-flux level was recorded at 1.5 W/cm², as read by a thermocouple at the calorimeter at the center of the closest trailer. The fire did not couple to either trailer and the heat-flux exposure was not high enough to present an exposure problem.

The second test was conducted with the same 5-ft² pan elevated 3 ft off the ground; the elevation allowed more air to be entrained by the fire. We installed additional instruments in the closest trailer to record the heat transmitted by the aluminum siding and by the fire itself through the two windows. A maximum temperature of 160°C was recorded at the center calorimeter on the closest trailer, from a thermocouple located on the inside surface of the siding; a heat flux of 1.33 W/cm² was recorded at the calorimeter. The burn time was again 10 min with peak temperatures occurring 6 min 30 s into the burn. As in the first test, the exposure from this fire did not couple to either trailer or present an exposure problem.

All the newer office trailer complexes at LLNL are constructed with wood exterior siding, so for the third test we decided to modify the outside of the closest trailer. We covered one half of the trailer's original aluminum siding with Douglas fir T-111 siding and retained

the Test 2 locations of the instrumentation. We placed additional free-standing panels of wood siding north and south of the pan at 5 ft and 10 ft, respectively, to simulate additional trailer fronts.

We employed a 5 × 10-ft pan with 40 gallons of kerosene for this last pan test, during which we calculated the heat-release rate to be 5400 kW. Coupling of the fire to the free-standing panel 5 ft from the pan occurred after 4 min 50 s. The free-standing panel at 10 ft showed some discoloration, but the fire did not attach to it. The fire coupled to the wood siding on the trailer at 6 min 15 s. The heat flux at this time was recorded at 3.0 W/cm² and the temperature at 300°C.

We allowed the fire to burn for an additional 55 s until the aluminum siding above the wood siding started to melt, at which point we applied water to prevent further damage to the trailer. The distance from the edge of the pan to the trailer and the distance from the pan to the panel at about 10 ft was approximately the same, but the angle of view presented by the pan to the trailer was twice that of the panel 10 ft away. This greater view angle produced a larger flame body, causing ignition of the trailer, with a maximum heat flux of 5.5 W/cm² recorded on the central calorimeter in the closest trailer, 6 min and 40 s into the burn. A peak temperature of 460°C was recorded at the same calorimeter location, and estimated flame height was 15 ft at the maximum burning rate. The fire burned for 10 minutes.

The Full-Scale Trailer Fire

We conducted the final test with the trailers parallel to each other 15 ft apart, a distance selected because the LLNL Fire Protection Group found it to be representative of the Laboratory as a whole. The north face of the target trailer was paneled with new T-111 siding. Trailer A, the fire source trailer, was loaded with normal office material found in a typical office, i.e., fuels cellulose in nature (paper, wood, etc.) and typical government furniture composed of metal, plastic and foam.

We started the fire by igniting a wastepaper basket full of computer paper in the southwest corner office. We measured the time to flashover, time to detector activation, and the temperature profile. We instrumented the target trailer, Trailer B, with thermocouples and calorimeters to determine the exposure from Trailer A. Trailer B ignited within 15 min of the original fire, and both trailers were completely burned out in two hours.

We had collected a baseline of 180 s on the data-acquisition system prior to ignition of the full-scale fire. A smoke detector placed in the center of the room of fire origin alarmed 10 s after we started the fire in the wastebasket. Time to flashover was estimated with a thermo-

couple 1 inch below the ceiling, adjacent to the smoke detector. We knew that there would be a hot gas layer of 600°C in the ceiling when flashover occurred²; the time to reach that temperature in the ceiling of the room of origin was 60 s after ignition. The thermal radiation of the hot gases produced a heat flux of 5 W/cm² in the ceiling layer and approximately 2 W/cm² of exposure to the floor. Flashover was noted independently in each office; the fire spread to the skirting of Trailer B 15 minutes after ignition (Fig. 1).

Conclusions

Under the conditions of this single test, it would appear that the LLNL on-site fire department would have had sufficient time after ignition to respond to the fire and protect a second trailer from becoming involved. This would probably not be the case at a remote site where response times exceed the time to coupling. The smoke detector responded fast enough (at 10 s) to give personnel sufficient warning for evacuation. Had the trailer been sprinklered, the fire would most likely not have spread from the room of origin and would have either been extinguished or controlled.

Our tests show that additional work is necessary to evaluate existing trailer separation

standards. This single full-scale test gave us some insight into the performance of LLNL office trailers, but additional work is needed in several areas, including:

- Incorporation of additional trailer separation distances into the test.
- Reevaluation of the type of exterior paneling currently in use with respect to flammability; comparison of older materials to newer substances in terms of fire spread and growth.
- Analysis of fire spread in interior construction materials. (The gypsum-board walls in the center of Trailer A dramatically reduced the fire spread rate from the room of origin to the other end of the trailer. These barriers were standing long after the other walls had collapsed.)
- Comparison of the response times of various types of detectors and sprinkler systems in our facilities for the most efficient and economical factors.
- Evaluation of existing trailer standards against full-scale testing.

References

1. *Standards on Fire Protection for Portable Structures*, U.S. Department of Energy, Washington, D.C., DOE/EV-0043 (1979).
2. S. Martin and S. Wiersma, *An Experimental Study of Flashover Criteria for Compartment Fires*, SRI International, Menlo Park, CA, PRC No. P-77-3-1 (1979).

Thermal and Toxic Properties of Welding Blankets

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We subjected 25 nonasbestos welding blankets to thermal and toxic analysis. Results of our study indicate that most of the blankets will lose a considerable amount of weight and produce substantial amounts of toxic products when exposed to heat. Blankets made of silica cloth, however, are extremely resistant to high temperatures and produce minimal amounts of toxic products, and are therefore the best substitute for asbestos blankets.

Welding blankets are used to protect equipment from the intense heat and sparks of a welding torch. Since asbestos fibers can no longer be used in these blankets because of the health hazards involved, alternative heat-resistant materials have been employed in their manufacture. As a result of an incident involving the thermal failure of a nonasbestos welding blanket, in which welders accidentally exposed the blanket to high temperature and were overcome by toxic fumes, we were asked to conduct a study of the thermal properties of currently available nonasbestos welding blankets. We were particularly interested in determining heat resistance and toxic products generation from these materials at temperatures attained in routine welding and cutting operations. Our experimental approach consisted of the following steps:

1. We conducted a literature search on available nonasbestos blankets. We studied results from Underwriter's Laboratory and looked for information on temperature needed for onset of degradation and formation of toxic products at thermal degradation.

2. We performed thermogravimetric analysis (TGA) on various blanket samples to determine the temperature responsible for the onset of degradation, the rate of weight loss, and the total weight loss.

3. We selected those blankets with the least amount of weight loss and/or the highest heat-resistance (as obtained from the TGA runs) for testing for toxic products formation.

4. We subjected the best blanket (highest thermal resistance and least toxic products formation) to additional testing. This involved exposure of a 1-m² piece to an oxyacetylene torch—the hottest of the commonly used torches—and testing for the presence of toxic products approximately 1 ft away. In addition, we ran a gas-chromatographic analysis of light molecular weight hydrocarbons and a gas-chromatographic/mass-spectrometric analysis of possible liquid thermal-degradation components.

The Literature Search and TGA Analyses

The results of our literature search revealed that most of the heat-resistant fabrics used in welding blankets are made of fiberglass or silica. In many formulations, the fiberglass cloth

is coated with silicon rubber, hypalon, neoprene, or an acrylic fiber. Many of the silica-based blankets are coated with a proprietary substance.

We learned that there is not much information available on the thermal behavior of welding blankets, so we obtained representative samples from various distributors and submitted them to a series of lab tests. We conducted thermogravimetric analysis in air at a heating rate of 20°C/min from ambient to 900°C, and found that the temperature required for initial degradation varied between 40° and 689°C. We also monitored each sample's rate of weight change as a function of temperature, which also varied greatly from sample to sample.

Toxic Products Formation

Based on the TGA results, we chose a number of samples for analysis of toxic product formation at elevated temperatures. We tested Thermonol cloth because of its relative resistance to heat, and we chose Siltemp, Silica fabric #2-3700, Thermoglass cloth, and six other commercially available blankets because of their low overall

weight loss. We also tested an LLNL Central Supply stock blanket.

We utilized Draeger tubes in the screening tests for toxic products formation. We heated the samples to 500°C and tested the resulting smoke for carbon monoxide (CO), carbon dioxide (CO₂), hydrogen cyanide (HCN), hydrogen chloride (HCl), and nitric oxides (NO_x). Two grams of each sample were used for each determination; results of these screening tests are presented in Table 1.

None of the blankets tested were treated with a special organic finish—the HCN and NO_x are degradation products from an organic binder used during the fiber-manufacturing process. If at the end of the process the fibers are not subjected to high temperature to

remove the excess binder from the cloth, both HCN and NO_x will be formed when the fabric is subsequently subjected to great heat. Upon talking to various manufacturers, we also learned that both silica and fiberglass cloths are acid-washed after they are woven, and although most of the acid is washed off, there is a residual amount left on the cloth.

Large-Scale Testing

The best overall performer among the samples tested for toxic products was the Siltemp cloth, so we chose it for our large-scale test. We exposed a 1-m² sample of the Siltemp to the cutting temperature of an oxyacetylene torch and tested for the presence of CO, CO₂, HCN, HCl, and NO_x approximately 1 ft away from the cloth. This test

simulated the worst that a welder could possibly subject a welding blanket to. Results showed negative readings for all gases except NO_x, which at 10 ppm is not in agreement with our aforementioned small-scale test. However, the results from the small-scale test were obtained from products generated at 500°C and sampled directly from the smoke stream. We feel that the 1 ppm of HCN would be diluted at 1 ft away from the blanket to a concentration below the limits of detection of the Draeger tube. We

Table 1. Toxic products formed from welding blanket samples heated in air at 500°C.

Blanket brand	Toxic product				
	CO (%)	CO ₂ (%)	HCN (ppm)	HCl (ppm)	NO _x (ppm)
1. Thermonol	0.5	5	150	>50	N.A. ^a
2. Siltemp	0	0	30	>50	3
3. Silica Fabric #2-3700	0.25	0	9	>20	6
4. Thermoglass	0	0	10	0	3
5. Store Stock Blanket	0.5	5.0	30	>50	10
6. Weld-O-Glass #900FC	0.5	2.5	75	10	7
7. Weld-O-Glass #1000FC	0.5	2.0	75	100	10
8. Weld-O-Glass #2650	0.1	0	15	10	7
9. Weld-O-Glass #1850	0.1	0	30	10	15
10. Zetex-1100	0.5	trace	50	0	trace
11. Zetex-1200	0.4	trace	25	10 ^b	0.5

^aDue to interference by other compounds, we could not interpret results.

^bColor change is due more to CL₂ than to HCl.

Table 2. Light hydrocarbons generated from Siltemp at 750°C in air.^a

Retention time (s)	Components
0.50	methane
0.65	propane
1.50	acetylene
1.65	propylene
1.86	propane
4.21	isobutane
5.07	n-butane
5.53	isobutylene
5.84	cis-2-butene
6.88	ethylacetylene
15.21	pentane
28.40	4-methyl-pentene-2
31.95	4-methyl-pentene-3
44.00	2-methyl-pentene-2
47.50	hexene-1
47.75	hexene-2-cis
57.14	hexene-2-trans
60.42	hexane

^aGC conditions: Separated on 30/100 Carbopack loaded with 0.19% phoric acid in a 2-m x 1/8-inch OD stainless steel collector at a temperature of 50°C and an N₂ flow rate of 30 ml/min. Detector type: FID.

Validation of a Screen Room Sprinkler System

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The Fire Science Group was asked to conduct tests to validate a hybrid dry-pipe sprinkler system slated for installation in an electronic screen room at LLNL (Building 141). Screen rooms are called such because they are electronically shielded from interference from stray rf and other electromagnetic signals. Because complete electrical isolation must be maintained, conductive penetrations, whether liquid or metal, must be avoided—hence, the dry-pipe sprinkler system. The primary objective of these tests was to evaluate the operation and effectiveness of this system. The design, illustrated schematically in Fig. 1, is a candidate to become a standard for the fire protection of all screen rooms at LLNL.

Dry-Pipe Sprinklers

For the reasons mentioned above, this system is designed to allow water into the sprinkler piping only in the event of a fire. This is accomplished through the use of nitrogen gas. The water flows unimpeded until it reaches the check valve outside the screen room (see Fig. 1). Under normal operating conditions, the nitrogen gas is at a higher pressure (796 kPa or 115 psi) than the water (554 kPa or 80 psi), and it is this pressure differential that

We conducted a test series to evaluate a hybrid dry-pipe sprinkler system designed for use in electronic screen rooms—rooms in which all conductive penetrations (including water) must be avoided. We found that the dry-pipe system operates efficiently, effectively, and consistently.

prevents the water from flowing through the check valve. In the event of a fire, one or both of the sprinkler heads will activate and the nitrogen gas will escape through the head(s). The loss of nitrogen pressure will then permit water to flow through the piping and sprinkler head(s) to extinguish the fire. In theory, the 1/4-inch copper line is sufficient restriction to decrease the nitrogen pressure thereby permitting water to flow once a sprinkler head is triggered. If there is a nitrogen pressure loss in

the absence of a fire, water will fill the system but probably not quickly enough to set off the building water-flow alarm.

The Experimental Setup

For our experimental series, we attempted to duplicate the actual system as nearly as possible within the LLNL Fire Test Cell (*Frontispiece*). Some of the critical factors were the following:

- Length of piping and number of bends from check valve to the farthest head.

Figure 1. The setup for the dry-pipe sprinkler tests.

- Size of piping and associated hardware.
- Height of sprinklers from the floor.
- Pressure of the nitrogen gas and water.

Figure 1 illustrates our configuration and shows pertinent dimensions for the test setup. It can be seen that the nitrogen line and all piping up to the check valve are above the gypsum-board ceiling. In addition, although the length of piping after the check valve matches the actual screen room configuration, one extra bend has been added to fit our test cell.

We located thermocouples throughout the test cell to monitor temperature rise during the test. We placed a flow-meter and pressure transducers strategically to monitor water-supply flow and pressure, pressures upstream and downstream from the check valve, and nitrogen-supply pressure. We ignited the test fires directly below the most remote sprinkler head from the check valve.

Tests

We performed a total of four tests, two using a gas burner and two using wood cribs. The ventilation rate for all tests was 0.1 kg/s (175 cfm) with both input and exhaust in the ceiling. Water-supply pressure to the check valve was 554 kPa (80 psi) and the nitrogen gas pressure was set at 796 kPa (115 psi).

We ran two tests using a 57-cm (22-inch) diameter methane-fueled gas burner that uses gravel as a diffusion medium. The fire

strength produced by the burner was 200 kW. The remaining two tests employed a 2 × 2 × 1-ft wood crib, which produces a fire strength of about 350 kW. This second source not only creates a larger fire, but one more difficult to extinguish due to its deep-seated nature and the dense geometry of the fuel bed.

Results

The Gas Burner Tests

We used Exemplar Viking model 589A sprinkler heads rated at 98°C (200°F) for the first test. The head activated in 110 seconds at an air temperature of approximately 180°C (356°F) and extinguished the fire in less than a minute. However, the resultant sprinkler spray appeared to be little more than a mist at less than 30 L/min (8 gpm) of water flow. Our transducers show that the nitrogen pressure dropped to 381 kPa (55 psi), which permitted an unmeasured but reduced water pressure at the head. The competition between the water and nitrogen as they escaped through the orifice of the sprinkler caused an atomization of what little water there was. This was very effective at extinguishing the fire; it would appear that the mechanism for extinguishment is the entrainment of nitrogen gas with water vapor into the fire plume, a combination that both cools and suffocates it.

The second test was identical to the first test with similar results. Sprinkler response was again at 110 s, and it extinguished the fire in less than 40 s using less than 40 L/min (10.5 gpm) of water. Nitrogen gas pressure and water pressure were the same as in the first test.

The Wood Crib Test

To provide a greater challenge for the system, we used wood cribs instead of the gas burner for the final two tests. At sprinkler activation, the nitrogen and water pressure were again identical to the previous experiments. The sprinkler activated at an air temperature of 150°C (302°F) in approximately 200 s, releasing not quite 40 L/min to extinguish the fire in less than 120 s.

The final test was essentially the same as the previous one except that we used a sprinkler with a lower activation rating (68°C or 155°F). Again, all pressures before and after activation were the same. In this case the sprinkler responded in 150 s at an air temperature of 90°C (194°F) and extinguished the fire in less than 120 s.

Conclusions

In light of these experiments, this dry-pipe design appears to be both an effective and efficient fire countermeasure. Not only does it use a unique mechanism to knock down the fire but it uses a minimum of water in the process. The pressure readings below the check valve and above the nitrogen line show how consistently the system operates: the pressure levels were identical in all four tests. In terms of nitrogen supply, we started with a tank containing 2000 lb of pressure, and after four tests we still had 300 lb remaining. Usage averaged about 5 min of activation per test plus a line purge after each test. Therefore, if in actual usage the system is fairly leak-free, the nitrogen pressure should endure for an extended period of time.

Exposure of Firefighter Helmets to Radiant Heat

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In most states firefighter helmets must receive approval by such agencies as Federal OSHA, NFPA, or other safety approving agencies before they can be used in the fire service. This approval is based on standards and criteria outlined by the National Fire Protection Association and the American National Standards Institute, which together specify minimum performance requirements for helmets used in fighting structural fires. Under these standards the helmets are exposed to flame, heat, and impact resistance tests to evaluate their response to a fire exposure. We felt that these tests were not representative of the conditions a firefighter might encounter in a flashover fire, however, where the gas temperature in the ceiling may reach 600°C.¹

The radiant heat-flux (heat energy) under flashover conditions extends from approximately 5 W/cm² at the ceiling to 2 W/cm² at the floor. Extrapolating from these two points, we determined the approximate energy level at the height of a man's head and developed a test procedure to evaluate the performance of helmets exposed to this kind of heat. In the exposure tests we compared new fiberglass-composite helmets of the type now used by the LLNL Fire

Department, the old polycarbonate helmets they replaced, and old-style leather helmets. Although firefighter helmets are exposed to flame and heat resistance tests to evaluate their response to fire exposure, these tests are not representative of conditions a firefighter might encounter in a flashover. We evaluated the thermal endurance of fiberglass-composite, polycarbonate, and leather helmets, and concluded that leather helmets with modern linings and head suspension systems provide the most protection to a firefighter's head in high heat-flux conditions.

Experimental Apparatus and Tests

Small-Scale Tests

The preliminary screening of the materials in the helmets was undertaken in the laboratory. We subjected each helmet's sub-components to thermogravimetric analysis (TGA) and differential scanning calorimeter (DSC) analysis, which give thermal degradation profiles of the material. By heating the material in question and measuring energy and weight loss as a function of temperature, these tests enable us to determine the temperature at which a material will start to degrade, the rate of degradation,

and the residual ash. We are also able to determine if this process is an endothermic (heat absorbing) or an exothermic (heat producing) reaction.

We subjected the TGA samples to a 40°C per minute heating rate from room temperature to 900°C in an air purge, and conducted the DSC analysis at a heating rate of 20°C per minute in a nitrogen atmosphere. Figure 1 compares the thermograms of a fiberglass-composite helmet and a polycarbonate helmet. This plot shows that the fiberglass-composite material starts to degrade at 130°C, with the major onset at 357°C and a weight loss of 54%. The remaining weight is the glass material, which, of course, does not degrade. The polycarbonate material starts to degrade at 182°C, with the major onset at 475°C and a weight loss of 99.08%.

The plot from the DSC for the same fiberglass-composite material displays a major exotherm at about 325°C, corresponding to the point of weight loss on the TGA output. The DSC plot of the polycarbonate material shows an exotherm starting at about 112°C, corresponding to the melting point of the sample. The newer polycarbonate helmets were tested on the DSC for softening point and melting point because of a reported new formulation in the materials. The

Figure 1. Comparison thermograms of the fiberglass-composite material and polycarbonate. The heating rate was 40°C/min.

softening of the new helmets occurred at 175°C, with melting points ranging between 350° and 385°C.

Large-Scale Tests

Our large-scale test apparatus (Fig. 2), which we assembled in the LLNL Fire Test Facility (*Frontispiece*), consisted of a natural gas-fired horizontal radiant panel 24 × 18 inches and a computer data-acquisition system. We installed a head form made of silicone rubber on a movable platform that allows helmet placement under the radiant panel. We mounted two thermocouples on the head form, one on the right ear and the other on the top of the head, to give us the interior temperatures of the helmet. We instrumented each helmet with five thermocouples to measure surface temperatures at the top and outer edges.

We measured thermal energy from the radiant panel at preselected distances from the

panel surface with a water-cooled calorimeter.

We conducted 15 tests on the helmets under the horizontal radiant panel. We selected heat-flux levels of 2.0, 3.0, and 4.25 W/cm² as a range of expected exposure levels that a firefighter might encounter in a compartment fire. At a flux level of 4.25 watts, the fiberglass-composite helmet showed a light darkening of the crown with no other noticeable damage. We removed all of the fiberglass-composite helmets from the radiant panel before the completion of the two-minute exposure, however, because of autoignition of the pyrolyzing gases at approximately 1 minute 30 seconds. All of the helmets had suffered approximately the same extent of thermal damage after this event, the only noticeable difference being the degree of darkening.

The polycarbonate helmet showed signs of softening of the

crown with about one inch of sagging at the top (Fig. 3). The temperature on the top of the head form inside this helmet never exceeded room temperature, but it exhibited melting of the foam lining on the surface next to the helmet shell.

We also conducted tests on older models of polycarbonate helmets without a lining. After a two-minute exposure, the top of the helmet melted and rested on the head form and the polycarbonate shell was heavily charred and blistered. There were also some signs of melting and discoloration on the top of the face shield and brim. The temperature inside the helmet reached 75°C in 120 seconds and reached almost 100°C before we terminated the test.

A test on a leather helmet approximately 25 years old with loose-fitting suspension webbing showed that after two minutes of exposure the crown of the helmet had blistered and was heavily

Figure 2. The experimental setup for these tests, which employed a horizontal radiant panel and a head form for mounting the helmets.

Figure 3. The results of Test 13, in which the polycarbonate helmet showed signs of heavy charring and melting of the interior foam liner.

charred. The temperature inside the helmet reached 100°C in 60 seconds and remained there for the duration of the test. This elevated internal temperature was caused by the steam exuding from the leather—steam that we observed escaping from under the helmet in large quantities during the test.

A test of a new leather helmet that incorporates a modern lining and head suspension system showed signs of charring and blistered paint after the two-minute test. The depth of the char layer was approximately 1/16 inch at the top of the helmet and decreased as it went down the sides. But more importantly, the temperature inside the helmet remained at ambient levels.

Conclusions

Our tests show that of the helmets tested, the new leather helmet provides the most protection to the head of a firefighter when exposed to a high heat-flux environment. This helmet would have to be replaced after repeated exposures to intense heat, as this will eventually cause loss of structural strength.

The fiberglass-composite helmet provided better protection than the polycarbonate, whose softening point of about 112°C in the older ones and 175°C in the newer designs would cause some concern to a wearer in a fire environment. At its softening point, the only protection one would have from a head blow would be from the foam lining. And these temperatures are not uncommon in typical structural fires.

Following a high heat-flux exposure, the outer shell of the fiberglass helmet would have to be replaced because of the loss of the binder and concomitant reduction in strength. The web suspension and foam liners in the newer-design helmets provide a more intimate contact with the head, thereby reducing the air space between the helmet and the head. This contact reduces the transfer of hot gases to the head of the wearer by preventing them from entering under the helmet.

Reference

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Validation of the Fermilab Ignition and Fire-Spread Scenario

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At approximately 1:30 a.m. on October 3, 1987, fire broke out in the E-687 experimental apparatus located on the Wide Band Beam Line in the Proton Area at Fermi National Accelerator Laboratory (Fermilab). The fire was declared out at approximately 4:15 a.m. It resulted in a loss of about \$1.1 million, including cleanup, and the affected experiment

Because of our extensive studies on the flammability of cable insulations, the Fire Science Program was asked to participate in the investigation of a costly fire at the Fermi National Accelerator Laboratory in Batavia, Illinois. Through a large-scale reconstruction of the destroyed cable assembly, we were able to confirm the ignition and fire-spread scenario defined by the investigative team.

suffered a reduction in scope and a five-week program interruption.

After an extensive investigation, it was determined that the fire originated in an assembly of 35 small printed-circuit electronics cards (a Dinode Sum box, which is a power-distribution unit). The cards are interconnected by short foam-clad ribbon cables. One ribbon cable had been reconnected to its mating receptacle

misregistered by one row of pins. This configuration created a ground fault on a 70-ampere-capacity power supply furnishing 5.2 volts to the assembly, which subsequently ignited the ribbon cable. There were no fuses on any of the 35 individual loads.

Once ignited, the quantity of ribbon cable and plastic electronic components provided sufficient fuel for the incipient fire to ignite several bundles of RG 58 coaxial cable running vertically upward from the low elevation of the assembly. These runs communicated the fire to the major fuel supply, which consisted of more than 1000 coaxial cables in vertical runs and horizontal cable trays.

Because the Fire Science Program at LLNL had conducted extensive studies on the flammability of cable insulations, we were asked to participate in the investigation of this fire. We performed large-scale fire tests in the LLNL Fire Test Cell (*Frontispiece*) to validate the ignition and fire-spread scenario as described above. The primary objectives of the fire tests were to answer the following questions:

- Could ignition of the Dinode Sum box and its associated connectors be of sufficient intensity to spread the fire to the cable tray above it?

Figure 1. Our mock-up of the Dinode Sum box, in which the Fermilab fire began.

- Could the resulting fire-spread produce the documented damage patterns?
- Finally, could the above events occur in the time frame indicated by eyewitnesses?

The Tests

In order to address the first question above, we constructed a mock-up of the power-distribution unit to quantify its ignition and burning characteristics. The framework was made of noncombustible materials and matched the dimensions and configuration of the actual assembly, as shown in Fig. 1. We festooned the foamed ribbon cable provided by Fermilab in a manner similar in form and quantity to the actual setup. We then ignited the ribbon cable with a match. The primary parameters monitored and recorded during the test were rate of mass loss, flame height, and temperatures at relevant locations within and above the burning assembly.

The fire burned for approximately nine minutes with flames reaching about 1 foot above the assembly frame. Because our mock-up did not include printed circuit boards, which were part of the actual power supply, the test fire was probably a little less intense and of shorter duration than the real one. However, the results of this test showed that there was more than sufficient energy produced to ignite the cable tray above.

Once we had characterized the burning rate of the power-distribution unit, we programmed a natural gas-fueled burner to reproduce the fire. This program simulated the fire's rate of energy

release, temperatures, and flame volume.

Then, to validate the proposed fire scenario, we constructed a full-scale simulation of the area of origin in the Wide Band facility. As can be seen in Fig. 2, we assembled three horizontal cable trays and a vertical ladder tray in accordance with the dimensions of the actual facility. We then loaded these trays and ladder with 12,000 feet of RG 58 A/U signal wire, which represents only a small fraction of the actual loading. Figure 3 presents the dimensions of the test apparatus and the location of thermocouples for temperature measurements.

Additional measurements taken during the test included:

- O_2 , CO , and CO_2 concentrations.
- Ventilation rate.
- Temperatures throughout the test cell.
- Total hydrocarbon production.

We initiated the test by igniting the gas-burner source fire. Table 1 summarizes the significant events through the course of the test. Ignition of the RG 58 cable occurred fairly rapidly at 1:45 minutes, and the first horizontal cable tray ignited at 3:20 min. It can be seen from Table 1 that the fire spread steadily through the horizontal trays with rapid

Figure 2. The full-scale fire test setup as it looked before festooning with 12,000 feet of cable.

Figure 3. Pertinent dimensions of the full-scale test setup.

acceleration once the large vertical cable run shown in Fig. 4 ignited. Fire-spread to the top of the vertical run at 35:45 min correlates almost exactly with an eyewitness's description of this event in the actual Wide Band fire. Another significant event occurred at 41:05 min when the vertical cable bundle fell to the floor and continued to burn. There were numerous areas within the Fermi facility where fire patterns indicated fires that had burned from the ground. The investigative team had concluded that these fires were the result of vertical cable runs burning through their ties, falling, and igniting adjacent combustibles from ground level. Finally, the

condition of the cable remains following the test looked very similar to those in the actual fire.

Conclusions

Results from this brief study provided sufficient correlations to confirm the ignition and fire-spread scenario defined by the investigative team for the Wide Band facility at Fermilab:

- The burning intensity of the power-distribution unit and the duration of that fire were sufficient to spread it to adjacent cable runs.
- The fire spread vertically through horizontal cable trays until the main vertical cable run became involved.

- The time it took for the fire to spread to the top of the main vertical cable run correlates very well with eyewitness accounts of this event.

- The dropping of the vertical cable bundle to the floor validates the "drop fires" indicated by the fire patterns in the Fermi facility.

- The after-fire condition of the cables in the mock-up looked very similar to the actual damaged cables.

In conjunction with preliminary tests performed at Fermilab to confirm the failure and ignition potential of the mishandled Dinede Sum box, this modest test program proved to be a powerful tool in reconstructing the fire scenario in the area of origin.

Figure 4. Ignition and fire-spread on the vertical cable bundle during the full scale test.

Table 1. Significant events during the reenactment of the 1987 Fermilab fire.

Time (min:s)	Observations
00:00	Burner Ignition (flow rate, 1.2 g/s).
1:30	Burner flow rate, 2.2 g/s.
1:45	Ignition of small vertical cable run.
2:29	Fire-spread to first tray.
3:00	Burner flow rate, 3.8 g/s.
3:20	Ignition of first tray.
6:00	Burner flow rate, 2.2 g/s.
6:30	Ignition of second tray.
8:00	Burner flow rate, 1.2 g/s.
8:30	Ignition of third tray.
15:00	Burner turned off. First (bottom) tray burns out.
16:25	Ignition of right side of vertical run and third tray.
17:00	Fire-spread to top of vertical run.
21:00	Vertical run burns out.
34:30	Ignition of large right-side vertical run.
35:45	Fire-spread to top of vertical run.
41:05	Vertical cable run drops to floor.

Evaluation of Quick-Acting On/Off Sprinkler Heads—Phase II

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Quick-acting on/off sprinkler heads are designed for use in water-sensitive areas containing expensive equipment such as computer facilities and experiment control rooms, or for areas where fire-suppression water must be minimized, such as holding areas for hazardous materials.

In FY 1986 we completed an extensive test series¹ to compare the performance of one company's quick-acting on/off head to conventional on/off heads and standard sprinklers. Our primary concerns were the effectiveness of the sprinklers and the total quantity of water discharged to control or extinguish our test fires. We used a methane gas-fired burner to investigate sprinkler performance as a function of fire size, and we used isopropanol pool fires, wood cribs, and trash fires for fuel-type tests. Results from these tests showed that the quick-acting sprinklers controlled or extinguished the gas burner with minimal water discharge. However, when exposed to our 20-kg (44-lb) wood-crib fire, they failed to operate properly in two consecutive tests; we also experienced one failure during our isopropanol pool fire tests. When the heads did operate properly, they discharged 55 to 90% less water than standard

We evaluated the performance of both pendant-style and flush-mounted quick-acting on/off sprinkler heads for use in areas where fire-suppression water must be minimized. We found that all heads responded and operated smoothly to control all fires. This can be attributed to improvements the manufacturer has made to several critical components since our last test series.

sprinklers to control or extinguish the test fires.

After examining the three failed heads, we returned them to the manufacturer, who dissected and analyzed them. Their conclusion was that these heads were below their normal quality-control standards and should never have been released. They offered to conduct tests similar to ours at an independent testing lab to demonstrate that their product would perform as designed. This test series was never carried out, however, so we performed the study summarized below.

To reevaluate the effectiveness and reliability of the sprinklers,

we investigated the following parameters:

- Air temperature near the sprinkler head at activation and shutoff.
- Time to sprinkler activation as a function of fuel type and fire strength.
- Total quantity of water released to control or extinguish the test fire.

Sprinkler Characteristics

Figure 1 is a photograph of the original quick-acting head and the new, improved model. This style of on/off sprinkler has a two-phase operational mechanism: a eutectic metal seals the deflector housing to prevent water leakage, and a snap disk (to the side) activates the on/off function. The eutectic material holding the deflector in is designed to melt at 57°C, causing the plunger to drop, thereby clearing the path for water flow. The snap disk is set to release water at 74°C. Our previous test series had shown that the mechanism would shut off when the air temperature dropped to approximately 30°C; spray densities were about 12 L./min/m² and the spray patterns were about 3.7 m wide.

Of the three heads that failed during our previous test series, one failed in the "off" position

Figure 1. The original pendant-style quick-acting on/off head (left) and the new model (right), which incorporates the manufacturer's design changes in response to their own and our analyses of failed heads (see Fig. 2).

and two failed in the "on" position. Figure 2 shows schematically the design modifications made by the manufacturer to several critical components of the old-style head, all of which were indicated in the failures we experienced. Our qualitative analysis of the failed heads had indicated the following:

1. Wood crib fire—head failed "off." Although water was dripping from the weep hole, the plunger that drops to clear a path for water flow would not deploy, even though air temperatures around the head were approximately 375°C, or 707°F. Through x rays we noted that the eutectic material had not completely melted out, which prevented the plunger from dropping. It also appeared that the knurled fitting holding the heat-collector fins in place had been torqued on a little too tightly. Finally, water dripping from the weep hole may have had a cooling effect on both the snap disk and the heat-collector fins.

2. Wood crib fire and isopropanol pool fire—head failed "on." These heads cycled four times in response to the crib fire and six times in response to the isopropanol pool fire, and ultimately would not shut off. Because we did not dissect these sprinklers before we returned them to the manufacturer, we base our forensic conclusions on the manufacturer's evaluation. Their findings for these two heads indicated that excessive epoxy flow into the on/off mechanism formed a partial blockage, preventing the snap disk from fully closing. There may also have been some out-of-tolerance problems with the standoff distance of the snap disk housing.

Figure 2. Design modifications made by the manufacturer to the quick-acting on/off sprinkler head.

The Phase II Large-Scale Fire Tests

We conducted six large-scale fire tests in the LLNL Fire Test Cell (*Frontispiece*) to evaluate the performance of the new sprinklers against the two more severe fuel types and fire strengths of our original tests—the wood crib fire and the hydrocarbon pool fire. Four tests involved pendant style heads and two tests addressed the new flush-mounted heads (shown in Fig. 3), designed to be more aesthetically pleasing. Although we did not expect the devices to extinguish all of these fires, we felt that the diversity of challenges would provide a comprehensive evaluation of performance.

A plan and section view of our large-scale test setup is presented in Fig. 4. The 3.05-m high, gypsum-board ceiling with ventilation input and exhaust registers located at opposite ends is representative of typical false ceilings in labs at LLNL. Total cell

volume was 100 m^3 , with a mechanical airflow of $0.1 \text{ m}^3/\text{s}$. For the majority of the tests, we located the fire source in the center of the test cell with a sprinkler head directly over it. We positioned ceiling thermocouples down to the height of the snap disk to monitor air temperature at sprinkler activation. Thermocouples located 1.45 m east and west of the fire simulated additional heads to give an indication of whether remote sprinklers would also activate (except in Test 4, in

which we used two heads). Other standard measurements included oxygen depletion and carbon monoxide and carbon dioxide production. Finally, we installed a water-flow meter in the supply line to monitor flow rates for each test.

The $2 \times 2 \times 1$ -ft wood cribs constructed from cross-piled "2 $\times$ 2s," weighing about 44 lb and producing a fire strength of approximately 350 kW, were identical to those used in the previous test series. The isopropanol pools produced

Figure 3. The new flush-mounted quick-acting on/off head, which is identical in structure to the pendant-style head with the addition of a decorative housing.

Figure 4. One typical setup for our sprinkler head experiments carried out in the LLNL Fire Test Cell.

Table 1. Summary of fire test results.

Test No.	Fuel type	Average activation air temperature (°C)	Average activation duration (s)	Number of cycles	Average flow per cycle (gal)	Total water released (gal)	Comments
1	Wood crib	140	22 ^d	3	15.3	45.4	Controlled fire
2	Wood crib	131	29.5	4	15.6	62.3	Controlled fire
3	Isopropanol pool	139	28	8	14.8	118.9	Controlled fire
4	Kerosene pool	135	30	2	19.8	39.6	2 heads, extinguished fire
5	Wood crib	171	20.3	7	12.3	86	Controlled fire
6	Isopropanol pool	170	20	3	9.6	28.8	Controlled fire, fuel depleted

^dQuestionable reading.

fire intensities of approximately 250 kW. Although we set the kerosene fires in the same size pan as before, we did not calculate their fire strengths.

Results

Table 1 summarizes pertinent results from this test series. Pendant style heads were evaluated in Tests 1 through 4 and flush mounted models in Test 5 and 6. A primary difference in results from the 1986 study was that, with the exception of Test 4, the new sprinklers controlled the fires rather than extinguishing them. In Test 4, we placed a kerosene pool fire between two pendant-style heads, which caused both to activate and immediately extinguish the fire. We conducted all other tests with a single sprinkler, with the fire source directly underneath. In this configuration (fire directly under

the sprinkler), the ceiling thermocouples east and west of the test sprinkler indicated that neither of these remote heads would have activated. Therefore, if the sprinkler is controlling the fire, the total quantity of water discharged will depend on the response time of personnel in extinguishing the residual fire manually. For example, Test 2 (which we stopped after 4 cycles) in approximately 8 minutes produced a total water discharge

of 62.3 gallons, and Test 3 (which we allowed to cycle 8 times) had a total elapsed time of 21.5 minutes and total water discharge of 118.9 gallons. Although the fuel challenges are different, the water flow rates per cycle appear fairly similar.

Figure 5 displays the air temperatures at the snap disk for Test 3. Note the consistency of the on/off temperatures for each of the cycles to keep the fire in check. Toward the end of the test, the

Figure 5. Air temperatures at the snap disk during Test 3.

plot shows that the fire was diminishing and taking longer to reach the sprinkler-activation temperature.

As shown in Table 1, the flush-mounted model required a higher activation temperature than the pendant style by about 35°C. This sprinkler also appears to remain on for shorter times after activation. These differences are most likely caused by the decorative housing placed around the sprinkler, since this probably reduces its sensitivity.

Conclusions

Based on this second test series and manufacturer hardware improvements, we feel that both these quick-acting on/off sprinklers are appropriate for fire control in water-sensitive areas. All sprinklers responded quickly, consistently, and without failure. The design changes have increased both the sensitivity and reliability of the units. One potential shortcoming, which was also apparent with the earlier model, is the brief water-application time for each cycle—typically 20 to 30 seconds. In most

cases this cycle time was sufficient to control the fire until we extinguished it manually. We should, however, point out that the majority of our tests utilized only a single head directly over fires that are inherently difficult to put out. Cribs are difficult to extinguish due to the cross-piling of wood and the resultant deep-seated nature of the fire. Similarly, the liquid hydrocarbon fires typically require a film-forming foam for extinguishment. Therefore, it is not surprising that these sprinklers controlled rather than terminated our test fires.

The only test using more than one head—a much more realistic configuration—gave different results from the others, which leads us to suppose that further testing might reveal valuable information about the effects of various fire locations and more common fuel types. And since Test 4 used only two heads, future tests might include the use of multiple heads.

Reference

1. H. K. Hasegawa, K. J. Staggs, and S. C. Leeds, "An Experimental Program to Evaluate the Performance of Quick-Acting On/Off Sprinkler Heads," Lawrence Livermore National Laboratory, Livermore, CA, UCRL-94224 (1986).

Fire Tests of Fume-Hood Exhaust Ducts Made from Fiberglass-Reinforced Polyester*

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Because of the extremely corrosive nature of the fabrication processes in many of the chemistry labs and clean-room facilities at LLNL, plastic rather than metal ducting is usually used for hood and exhaust systems. In 1987 a new system was installed in one of the Laboratory's many facilities (Building 222) using fiberglass-reinforced polyester (FRP). Polyester typically burns easily and produces large quantities of dark smoke.

The LLNL Plant Engineering Department had required that the FRP material meet the following specifications:

- Composition: Altec 793 or Hetron 693FR resin with 3% antimony trioxide, impregnated at a ratio of 2/3 resin to 1/3 glass fiber.
- Flame-spread index: 25 or less, based on the American Society for Testing and Materials (ASTM) standard No. E-84.¹
- Conformity with the National Bureau of Standard's Voluntary Product Standard No. 15-69.²

However, the material arrived with none of the required labels and it was not clear whether it had met these standards or not. The Fire Science Program was asked to conduct both small- and

We conducted small-scale analyses and large-scale fire tests to determine the burning characteristics of a fiberglass-reinforced polyester ducting system installed in one of our facilities. The tests revealed that this material, used in this configuration, will easily burn and produce large quantities of smoke. Although this material had met certain fire and smoke standards, our tests determined that these standards do not provide a realistic method for evaluating plastic ducting.

large-scale fire tests to determine the composition, smoke characteristics, and burning propensity of the FRP ducting material. The results of these tests would be used to determine if additional fire protection was needed to prevent an in-duct fire.

Small-Scale Tests

We conducted several small-scale tests using sample pieces of the ducting obtained from the building construction site. We subjected them to thermogravimetric analysis (TGA) and differential scanning calorimeter (DSC) analysis in air at a heating rate of 20°C/min. We also measured light hydrocarbons during the main phase of degradation using a gas chromatograph (GC).

We used the TGA, which heats the material and measures weight loss as a function of temperature, to identify the degradation patterns and the glass-to-resin ratio. DSC analysis heats the sample and measures energy given off, revealing endothermic (heat absorbing) and exothermic (heat producing) reactions during degradation. We employed GC analysis to measure the light-hydrocarbon production at the onset temperature of the gross-degradation period.

Results of the TGA and DSC analyses identified the resin as polyester, as expected, with a resin-to-glass ratio of 68 to 32%. (This is the ratio Plant Engineering has requested, but generally, the greater the percentage of resin, the more flammable the FRP will be.) The onset of gross degradation was found to occur at approximately 375°C.

The GC results show that high concentrations of methane, propane, and acetylene are produced during the onset of gross degradation, with a high ratio of acetylene to both methane and propane. (Our preliminary studies of cable insulations suggest that rapid weight losses associated with large quantities of light hydrocarbons with a high acetylene ratio indicate a flammable material³) Although these tests were inconclusive in identifying the presence of a fire retardant, they did indicate that this material is flammable when heated to temperatures above 375°C.

Large-Scale Tests

We conducted two large-scale fire tests in the LLNL Fire Test Cell (*Frontispiece*) to determine the burning characteristics of this material in a realistic configuration.

*For a full report on this study, see *Fume Hood Exhaust Duct Fire Tests: Building 222*, by Kirk J. Staggs, UCID-21675 (1989).

Figure 1. The setup of the first fire test.

Parameters monitored and recorded during these large-scale tests included:

- O_2 , CO_2 , CO , and total hydrocarbon production.
- Inlet and exhaust air flows.
- Pressures within the test cell.
- Rate of mass loss (burning rate).
- Temperatures throughout test cell and fiberglass duct.

All data were monitored and stored at 10-second intervals with a computer-based data-acquisition system.

Test 1

In Test 1 we attached a 6-foot (1.82-m) section of 1-ft (30.5-cm) diameter FRP duct to a section of metal duct 1 ft (30.5 cm) in diameter by 1 ft (30.5 cm) long. We placed this assembly in a vertical position several inches above a 1-ft (30.5-cm) diameter burner. Figure 1 shows this set-up and the location of thermocouples (TCs) for temperature measurements.

Although ventilation was provided to the test cell, there was no air flow induced through the duct; however, we cut holes in the metal duct above the burner to allow air to entrain across the burner and up through the duct.

We ignited the burner and adjusted it to achieve a heat-release rate (HRR) of approximately 20 kW (similar to a small plastic waste-basket fire). After 50 seconds, light smoke was generated on the outside of the duct and heavy black smoke emerged from the top. At 150 s, a smoke layer had formed at the ceiling and had begun to descend to the top of the duct. At 200 s duct thermocouples showed a steep temperature rise (see Fig. 2),

indicating duct ignition. After we shut off the burner at 240 s, the duct continued to burn, and at 340 s it reached a maximum temperature; at the top, of over 750°C. However, within 60 s of reaching this, it fell to below 300°C. The total length of the test from burner ignition was 670 seconds (just over 11 minutes).

Test 2

In the second test we assembled three sections of 18-in. (45.7-cm) diameter duct as shown in Fig. 3. We used a 22-in. (55.9-cm) diameter burner to provide a uniform fire exposure to the interior of the duct. We placed the bottom end of the assembly on a metal skirt above the burner to prevent the fire from prematurely impinging on the duct exterior.

We used a metal snap duct to interface the duct to the test cell ventilation system and positioned the opposite end near the open end of the duct, as shown in Fig. 3. To reduce the velocity of entrained air, we cut holes near the end of the metal interface. We then adjusted the exhaust fan and set it to maintain a constant airflow of 472 L/s (1000 cfm). The airflow through the fiberglass duct was approximately 118 L/s (250 cfm), with make-up air coming from the test cell. We installed a high-efficiency particulate air (HEPA) filter downstream in the test cell exhaust system.

This time we ignited the burner and adjusted the gas flow to produce a HRR of approximately 150 kW. The bottom thermocouple attached to the ducting fluctuated between 300° and 350°C. At about

Figure 2. Duct temperatures during the first fire test.

Figure 3. The setup of the second fire test.

175 s into the test, the temperature recorded by the bottom thermocouple began to increase rapidly (see Fig. 4) and the vertical section of duct above the burner started to smoke. In addition, we could see black smoke being pulled past the holes in the metal snap ducting connecting the duct with the test cell ventilation system.

At 200 s the temperature at the middle and top thermocouple locations started to increase rapidly and flames were visible at the gap between the duct and the interface, and within a few seconds there were small explosions and flareups. Because we were concerned about the generation of combustible gases and the possibility of larger explosions occurring downstream in the test cell ventilation ducts, we shut off the gas burner 220 s into the test and prepared to extinguish the fire. The explosions and flareups continued, increasing in intensity until they destroyed the ventilation interface.

At this point heavy black smoke and fire jetted from the

end of the fiberglass at the interface of the metal and FRP ducts. Ten seconds after the ventilation interface was destroyed, the test cell was completely darkened by heavy black smoke. The pressure in the test cell "went positive," causing the inlet airflow to reverse to the extent that black smoke was forced out the ventilation inlet. The pressure across the HEPA filter increased drastically; however, the automatic flow control maintained a 472 L/s (1000 cfm) rate. At 270 s (four and a half minutes) we manually activated a sprinkler and the fire was extinguished.

Results

The results from the first large-scale test show that FRP material can be ignited and will sustain burning when heated above 375°C. This temperature correlates with the gross degradation temperature identified in our TGA. Once ignited, the material produced large quantities of black smoke and unburned combustible gases.

However, in an under-ventilated configuration (no air through the duct) a fuel-rich condition caused the fire to go out.

The results of the second large-scale test confirmed the ignition, burning, and smoke characteristics produced in Test 1. The greater airflow of 118 L/s (250 cfm) supplied through the duct in Test 2 permitted the combustion of most of the combustible gases pyrolyzed from the duct. However, the small explosions and flareups that occurred in the interface to the test cell duct indicate that a fuel-rich condition still existed in some areas. This was further substantiated by the hydrocarbon concentration of greater than 25,000 ppm (the upper limit of our analyzer) measured in the test cell ventilation system.

The high velocity of the fire, smoke, and unburned gases jetting from the end of the duct showed that a large amount of heat and pressure was being developed. Temperature increases within the duct after the failure of the interface indicated that additional air available to the fire after this event permitted increased combustion.

The tremendous rate of smoke generation from the burning FRP quickly plugged the HEPA filter as illustrated by the rapid rise in pressure differential across the filter.* Although the ventilation system was exhausting air out of the test cell at 472 L/s (1000 cfm), it could not keep up with the production of hot combustion gases. This mismatch caused the air pressure in the test cell to go positive and the inlet airflow to reverse, pushing smoke out of the inlet duct. Temperature data

Figure 4. Duct temperatures during the second fire test.

indicated that the duct was still burning when we activated the sprinklers to extinguish the fire.

Discussion

Although the resin for this ducting had met the criteria for flame-spread and smoke-generation according to the ASTM E-84 test method, the duct system's fire performance in our tests would have been a severe threat to life-safety—and to property: a clean-room's contents would have been covered by smoke particulate. The problem with relying on the E-84 test method is not the test itself, but rather its application (or misapplication): This test standard was conceived to provide relative flame-spread and smoke measurements on building components and finishes that are cellulosic in makeup and typically horizontal (such as ceilings and floors). It cannot assess the flame-spread within a vertical duct section nor simulate the heat feedback generated when the interior surface of a duct is burning. Furthermore, the smoke-generation measurement for this application is questionable, and this is a critical factor for clean-room applications.

The Factory Mutual approval standard for air and fume-handling ducts provides a somewhat more realistic test method.⁴ This standard is designed to evaluate a length of

duct in a horizontal position with induced airflows. However, it does not test various components or vertical runs of ducting in a system. Furthermore, no smoke-density or filter-plugging measurements are taken in this method.

Although either of these standards can be used to screen ducting materials, our tests indicate that actual components of selected duct systems must be independently and collectively tested to determine their fire performance.

Conclusions

Under forced ventilation and exposure to realistic fire conditions, FRP ducting will easily ignite and sustain burning. Air flow through the duct will spread the fire and smoke quickly downstream toward the filters and blower. Unchecked, the fire will burn through the HEPA filters and combustion products will be released into the air. The driving force of the hot gases and smoke produced by the burning duct will eventually overcome the pulling force of the exhaust fan, releasing hot combustible gases and black smoke into all connecting hoods and labs.

The ease with which this material ignited and sustained combustion in our tests indicates that the fire inhibitor used in this material, antimony trioxide, is ineffective in the quantities used in this formulation.

Testing of other fume-hood exhaust duct materials and components might reveal a more fire-resistive material.

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⁴For more information on the smoke-plugging of HEPA filters, see "The Performance of In-Service HEPA Filters When Exposed to Fire" on page 38 of this publication.

An Assessment of Shock Hazard from the Accidental Release of Water from Sprinklers*

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Wet-pipe sprinkler systems are often excluded from areas that contain high-voltage electrical equipment because of the perceived danger of electrical shock should water be accidentally released. We conducted two types of experiments and found that for standard 60-Hz systems this risk is minimal. Conversely, wet-pipe systems reduce the consequences of fires, which kill more than five times as many people as do electrical mishaps.

With the increased use of very-high-power sources in the form of capacitor banks and power-supply units in fusion energy research, nuclear power plants, and high-energy manufacturing processes, the concern has been raised that the inadvertent spraying of water on high-voltage electrical equipment could increase the risk of electrical shock to operation personnel. Electrical engineers tend to perceive fire-protection sprinkler systems as an extraordinary hazard in areas containing high-energy circuits, appliances, and systems. Because of this perception, wet-pipe sprinkler systems are often excluded from these areas.

Is there, in fact, an increased risk of shock that outweighs the risk of fire the sprinklers are there to alleviate? Statistics would indicate otherwise; the accidental death rate caused by fires (26 in 1000) is more than five times that caused by electrical accidents (5 in 1000). Furthermore, analyses indicate that the probability of an inadvertent release of water from properly designed and installed sprinkler systems is very small

(approximately 1 chance in 1,000,000). Ironically, many of these very-high-power stations contain cooling systems, which do tend to release water. Conversely, wet-pipe sprinkler systems will certainly reduce the consequences of fires.

Our literature search revealed several data sources related to

actual electrical conductivity measurements in water spills, sprays, and hose streams. One report sets qualitative distance limits between the hose nozzle and the high-voltage electrical source in terms of voltage levels and water flow rate.¹ However, we could find little applicable research relating to the electrical-

Figure 1. Test chamber to determine shock hazards from the formation of water layers of varying depths.

*This article was excerpted from "Shock Hazards Resulting from the Inadvertent Release of Water from Fire-Protection Sprinkler Systems," by N. J. Alvares and K. J. Staggs in the *Annual Technology Review* 1985 (UCRL-50007-85), on p. 69.

shock potential when both equipment and personnel are exposed to a contiguous spray, so we designed a set of experiments to investigate the issue.

The experiments were confined to two specific areas: (1) The hazard of electrical discharge carried by standing water in and around high-voltage equipment (water-layer formation) and (2) the hazard of electrical discharge carried on water droplets during inadvertent operation of the fire-protection sprinklers or failure of the water cooling lines. Note that in both of these scenarios, ground-fault systems would normally operate before any dangerous conditions could develop.

Experiments

The Water-Layer Test

To determine the hazard imposed by water-layer formation, we constructed and instrumented an acrylic rectangular chamber, shown schematically in Fig. 1. We filled the containment chamber with tap water to selected levels and took voltage measurements across the water between the source electrode and the ground plane.

The Water-Spray Test

We designed an experimental system to address the concern that water spray from fire-protection sprinklers could decrease the dielectric properties of the air between a grounded person and a high-voltage electrical apparatus. We constructed a large chamber from nonconducting materials and equipped it with a water-spraying system, a high-voltage grid, a grounded coil with

electrical resistance similar to that of the average human being, computer-controlled timing and diagnostic circuits, and appropriate safety interlocks for protection of both operator and equipment. Figure 2 shows our test apparatus schematically.

Our experimental plan called for a series of tests in which the control variables were:

1. The separation distance δ between the man-equivalent resistor probe (MERP) and the high-voltage grid ($2.5 \text{ cm} < \delta < 22.5 \text{ cm}$).
2. The potential difference between the high-voltage grid and the ground connection ($\text{cmf} < 12 \text{ kV}\cdot\text{A}$).

3. The water-spray rate ($\dot{v}_{\text{water}} \leq 6.1 \text{ l./min}\cdot\text{m}^2$, where $\dot{v}$ is volume).

4. The water quality, which ranged from distilled water to water from sprinkler pipes that were undrained for several months.

Experimental Results and Discussion

Figure 3 shows examples of our data output for the most severe test conditions. The maximum MERP current for these tests was less than 1 mA.

Results from these tests show that the gradient is very steep

Figure 2. The test chamber for the water-spray test, showing the three main components—the high-voltage grid, the man-equivalent resistor probe (MERP), and the water-spray nozzles.

near the source and ground points. Since water has a linear resistance, we believe this is due to the configuration of the source electrode and ground plate; an extrapolation of these gradients indicates increased gradients as water levels decrease until direct contact is no longer possible. Further analysis indicates that at low water levels, most of the voltage drop between the source and the ground will occur within a few centimeters of the source; inversely, in high water levels most of the voltage drop will occur near the ground. We can extrapolate the gradient for thin

layers, making the assumption that the layer is contiguous and is of uniform thickness.

These results are representative of our experimental apparatus. Changes in electrode shape, cross-sectional area of conduction path, water conductivity, and solid-suspension ratio would change the magnitude, but not the trend of these data.

Conclusions

An analysis of our water-layer and water-spray test data resulted in the following conclusions:

- The relative locations of the electrode and grounding point to the water affected the voltage gradient.
- An increase in the thickness of the water layer inversely reduces the voltage gradient between the high voltage and the grounding electrode.
- At the smallest possible distance between the electrode and MERP, the water-spray test gave minimal indications of current flow (12 kV, 60 Hz).
- Small but measurable changes in current flow occurred with different types of water (tap, sprinkler, deionized) and electrode spacing.

Figure 3. Samples of data output for the most severe test conditions, with sprinkler water (top), city water (middle), and deionized water (bottom graph).

All indications are that for a standard 60-Hz system, risk of an electrical discharge sufficient to create a shock hazard is negligible. Our tests did not investigate the shock hazard involving capacitor systems and dc power sources, which have substantially different current flows. Also, our water-spray tests used only one electrode configuration; other configurations may yield substantially different results.

References

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The Fire Endurance of Borated-Polyethylene Radiation Shielding*

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The Engineering Demonstration System (EDS) was built to extract weapons-grade plutonium isotopes from nuclear power-plant waste. To protect personnel and the surrounding environment, the EDS designers planned to install a shielding material around the plutonium storage boxes inside the glove box line. The proposed material was made of polyethylene with 0.7% boron by weight, boron being a very effective absorber of neutrons. The cost of shielding the entire outside wall of the glove box would have been significant, with substantial savings if the shielding could be placed safely around the storage boxes inside.

Although the manufacturer claims that borated polyethylene is noncombustible, very few materials truly are. When a new material is used in such facilities, fire safety is always a concern. While it is not necessary for a radiation shielding material to be truly noncombustible, it is vitally important to confirm that it would not contribute to or enhance a fire in the glove box. The Fire Science Program of Hazards Control was asked to assess borated polyethylene's ability to resist fire.

Putting a match to this material showed it to be flammable, so we

We conducted chemical analyses and nine exposure tests to investigate the fire endurance of borated-polyethylene shielding, which was proposed for use as protection from radioactive materials. We found that this material melts at 93.5°C, decomposes at 230°C, and ignites at 350°C. The polyethylene never reached ignition temperature in any of the realistic or pessimistic exposure tests we designed. As a result of our work the material was chosen for use.

proposed a set of chemical analyses and exposure tests. The postulated fire source is a plutonium fire burning on the top of a collector plate; the collector plate has stopped or stuck below the stainless steel storage box. The polyethylene mounted on the outside of the storage box would be exposed to this potential heat source.

Chemical Analyses

We began our test series with several routine chemical studies. We conducted a thermogravimetric analysis, which heats the material and measures weight loss as a function of temperature. This revealed that borated polyethylene undergoes decomposition beginning at 230°C, and once decomposed has

a 40% ash content by weight. Differential scanning calorimetry (DSC) analysis, which heats the sample and measures how much energy is given off, revealed that polyethylene melts at 93.5°C and that the decomposition occurs in two endothermic (heat-absorbing) steps, as can be seen in Fig. 1. These reactions required heat from an external source to continue; thus, if the material melts and drops away from the heat source the decomposition will stop.

We then observed the heating behavior of the polyethylene by placing a sample in a ceramic dish and heating it slowly over a Bunsen burner. It expanded in volume as it melted and heated up. At 230°C the polyethylene began to bubble and expanded until it had reached at least four

Figure 1. Differential scanning calorimeter plots of the decomposition of borated polyethylene compared with virgin (or pure) polyethylene and generic polyethylene (which contains stabilizers).

*This article was excerpted from *Investigation of the Fire Endurance of Borated Polyethylene Shielding Material*, by K. L. Foote, UC ID 21338 (1988).

times its cold volume. Much of this increase in volume was due to volatilizing gases trapped in the thick molten material. At 240 °C the polyethylene bubbled vigorously, and above 300 °C it gave off a white smoke that we were unable to ignite with a match.

At 350 °C we were finally able to ignite the molten polyethylene, and the surface temperature quickly rose to 425 °C. It sustained burning in the crucible even after the burner was removed, but the flame died before all of the material had decomposed. We

were able to re-ignite this material easily after stirring and reheating it, and combustion continued until only black and gray ashes were left—40.7% of the original weight of the sample. These observations agree with the data from the thermogravimetric analysis and the DSC.

In Fig. 1, we can see an endotherm at ~250 °C, where the polyethylene began to boil. The final endotherm starts at 320 °C and clearly produces the volatile gases we ignited at 350 °C.

Comparison of the borated polyethylene to other samples (Fig. 4) shows that the borated-polyethylene shielding material has a lower decomposition temperature than either of the other polyethylenes. This lower ignition temperature would be of concern if the shielding were designed for use in an area where it might be exposed to temperatures higher than 300 °C. However, even though the shielding is on the exterior of the storage box, the box flares out above the collector plate in such a way that its stainless steel wall would prevent the polyethylene from reaching such a high temperature during a fire.

Exposure Tests

Figure 2 shows our experimental test setup. To conserve costs, we used 4 × 4 × 4-inch pieces of polyethylene brick instead of the full-sized 24 × 18 × 4-inch shields. We mounted a 1'-ft stainless steel plate to represent the containment wall. We cut a 12 × 12 × 4-inch piece of noncombustible Marinite (which is made from aluminum silicate) to surround the small blocks of

Figure 2. View of the test apparatus with thermocouples leading from it. From the slider device (a) is suspended the 1/2-inch stainless steel plate (b) shielding the small polyethylene block (c), which is embedded in the larger blocks of Marinite (d). The whole apparatus is exposed to intense heat from the burner (e).

Figure 3. Typical temperature plots from thermocouples on the stainless steel face of the apparatus, in the aluminum angle, and at the interface of the steel and the polyethylene.

polyethylene to reduce edge effects caused by using such a small piece. A 12-inch aluminum angle held the Marinlite and polyethylene near the stainless steel.

Five tests were done in "realistic" orientations, similar to the actual EDS glove box geometry. The burner was positioned 5.5 inches to the side of the apparatus. Figure 3 shows typical temperature plots of the data; as can be seen, the temperature of the stainless steel is the first to rise, with the aluminum and the polyethylene lagging behind.

Because of the benign nature of the realistic tests, we also ran four "pessimistic" tests, in which the burner was moved much closer to the apparatus to increase the thermal-radiation exposure factor. This provided a worst-case heat source. In these tests, the polyethylene began dripping out of the apparatus after one hour (Fig. 4). It cooled and solidified before it dropped the short distance to the ground. Eventually, a polyethylene stalagmite formed on the ground and a stalactite formed from the apparatus above. One of these unusual-looking stalagmites is shown in Fig. 5.

Conclusions

Our tests showed that the borated-polyethylene shielding material is stable below 93°C, although it does expand slightly. At 93°C, the material melts and expands further. At 230°C an endothermic reaction begins that continues until the material reaches 350°C, at which point it becomes possible to ignite the molten material with a match. We do not consider this ignition

temperature to be a hazard in light of expected conditions inside the glove box, even though this is a lower ignition temperature than other polyethylene samples; the containment wall prevents the material from reaching even 150°C.

In the "realistic" exposure tests the borated-polyethylene shielding material never got hotter than 70°C, easily passing all five tests. The four "pessimistic" tests showed that there was over an hour of exposure before significant melting of the polyethylene shielding, even with nearly direct thermal exposure. The net result of our work was that this material was chosen for use in the EDS glove box line.

Figure 4. The polyethylene sample began to melt after an hour of exposure to our worst-case heat source. This photograph shows how the polyethylene block appeared when the experiment was over.

Figure 5. The melting polyethylene cooled and solidified before dropping to the ground, forming odd stalagmites.

The Fire Endurance of Sprinklered Glass Walls*

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Barriers of glass are allowed for use as atrium walls by the National Fire Protection Association code. We conducted tests to determine if fires would be likely to shatter this glass and allow smoke and flame to penetrate into adjoining rooms. We used both a large (250-kW) and a small (40-kW) fire source to test tempered glass, ordinary plate glass, and laminated safety glass. The best candidate was the laminated safety glass, which cracked upon exposure to the 250-kW fire but maintained its integrity and did not allow the passage of smoke or flames to the adjoining space.

Chapter 6 of the National Fire Protection Association (NFPA) *Code for Safety to Life from Fires in Buildings and Structures* sets out guidelines for building construction and finishing. Section 6-2, "Construction and Compartmentation," Subsection 6.2.2.3 on floor openings, allows the use of tempered glass walls as fire and smoke barriers in the construction of atriums. Atriums—skylit central courts—have gained much favor among architects in recent years and are widely used in contemporary buildings both inside and outside the Laboratory. Paragraph 6.2.2.3.1.h specifies requirements for the enclosing of atriums:

"(h) Enclosure of Atriums. In new construction, atriums shall be separated from the adjacent spaces by fire barriers with at least a one-hour fire resistance rating.

"Exception No. 1 to (h): Any three levels of the building may open directly to the atrium without enclosure.

"Exception No. 2 to (h): Glass walls may be used in lieu of the fire barriers where automatic sprinklers are spaced 6 ft (182.88 cm) apart or less along both sides of the glass wall, not more than 1 ft (20.48 cm) from the glass, and with automatic sprinklers located so that the surface of the glass is wet upon operation of the sprinklers. The glass shall be tempered glass held in place by a gasket system which permits the glass framing system to deflect without loading the glass before the sprinklers operate."

Because this procedure is allowed by the NFPA, LLNL has adopted the use of tempered glass as a smoke barrier for enclosed atrium spaces. We are quite confident that this method will work for fires that initiate and spread at some distance from the glass barrier; however, fires directly adjacent to the tempered glass could create conditions of intolerable stress in the glass either during the fire exposure or as the result of thermal shock when doused with water. Because of this concern, the Fire Science Group undertook studies in which commercially installed tempered-glass panes were exposed to large and small fires.

Experimental Setup

We conducted the tests in the LLNL Fire Test Cell (*Frontispiece*) by simulating an office space protected by a tempered-glass atrium barrier within the test cell. We selected two fires sizes to simulate a range of conditions. The larger of the fires was an isopropyl pool-fire 0.425 m² in size with a fire strength of about 250 kW. The small-fire source consisted of a gas pipe burner 2.54 cm in diameter and 30 cm long. A natural gas-diffusion flame of 40 kW was produced from holes drilled symmetrically along the length of the pipe. We installed two standard 160°F sprinklers according to the code. Figure 1 is a schematic of the test room showing appropriate dimensions and locations of sprinklers and thermocouples. The door was left open during the tests.

Results

The first test employed tempered glass exposed to the large (250-kW) fire source. The tempered glass remained intact

* This article was excerpted from "Fire Endurance of Sprinklered Glass Walls," which appeared in the Hazards Control Department's *Annual Technology Review 1985* (UCRL-50007-85) on p. 59.

throughout the test and showed no signs of thermal damage. The temperature on the fire side of the glass just before the sprinklers responded was 230°C. We inspected the glass pane under a polariscope to determine thermal damage and found none.

In Test 2 we exposed the same glass panel to the flame of the small-fire source, the 40-kW gas burner. In this test the glass broke into pieces of about $3/8 \times 3/8$ inch after an exposure of 80 seconds. Figure 2 shows the glass wall after the fire was put out and before the glass fell from the frame, which happened several minutes later. The sprinklers did not activate in this test.

The third test was conducted on a pane of standard plate glass exposed to the 250-kW fire. The glass cracked 11 seconds before the sprinkler head activated. The glass remained in the frame but a large crack at the base of the glass would have allowed smoke to penetrate into the next space.

In the fourth test we installed a pane of 0-6-0 laminated safety glass in the frame and exposed it to the 250-kW fire. The laminated glass cracked, but the laminate maintained its integrity, i.e., the crack would not have allowed smoke penetration. The safety glass is approximately 30% higher in cost but may be worth the extra expense where a smoke boundary must be maintained. We expect that the safety glass would also crack when exposed to the 40-kW fire because of the stress generated by direct exposure to the flames before the ambient heat is sufficient to activate a sprinkler.

In the fifth test we repeated the exposure of tempered glass to a small fire, as in Test 2. We called for this repeat performance to rule out the possibility that thermal damage from Test 1 during exposure to the 250-kW fire had caused it to fall in Test 2. Again the glass fractured, as expected, after 216 seconds of

exposure. The sprinkler system was not triggered. The maximum glass temperature at the time of fracture was 950°C.

Conclusions

These tests show that tempered glass performs adequately when exposed to relatively large fires—fires that create a temperature rise in the room fast enough to activate sprinklers before high stresses are generated in the glass. If the fire is concentrated in a small area on the glass and is not large enough to generate a fast gas temperature rise in the room, sufficient stresses can be generated in the glass to cause it to catastrophically fail. This would negate the smoke and fire barriers as required by code. The laminated safety glass appeared to provide the best protection even though the glass cracked during the fire exposure. In this case the glass remained intact and in place, and the fire and smoke boundary was not breached.

Figure 1. The test setup for the glass wall experiments, showing locations of sprinklers and thermocouples (TCs). The fire source was just inside room at the base of the glass wall.

Figure 2. The results of Test 2. When we exposed this pane of tempered glass to our small fire, it shattered and fell from the frame. This test never reached temperatures hot enough to trigger the sprinklers.

Evaluation of an Automatic Halon Fire Extinguisher—Phase II

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Because a fire in an electrical cabinet can severely damage expensive components and can force extended project delays, an efficient, fast-acting extinguishing system is vital. In 1986¹ we tested a Halon 1301 fire extinguisher (a Fireboy 15 GC model) with a head pre-set to activate at 100°C. It did not discharge until the temperature had reached 367°C, at which point the flames were approximately 5 feet high. They were immediately extinguished by the Halon, however, and we noted no subsequent flare-up for the duration of the test (about 10 minutes). Inspection of the cabinet after the test showed moderate to heavy degradation of the cable bundles, but the electronic components on either side of the cable channel appeared to have sustained little or no damage. But since the actual activation temperature was so much higher than the setpoint temperature on this particular extinguisher head, we planned to conduct future tests using extinguishers with lower activation setpoint temperatures. Our goal was to find an extinguisher head that would put out the flames a lot sooner.

In the spring of 1988 we carried out the second set of tests, again using a Fireboy 15 GC model

We tested a Halon 1301 fire extinguisher in a mock-up of an electronics cabinet, using heads set to trigger at 57°C, 74°C, and 100°C in separate tests. Even though the extinguishers did not activate until the temperatures inside the cabinet were well above the setpoint temperatures, they worked efficiently and effectively to terminate the fire with minimal damage to the electronics.

automatic Halon extinguisher, which was originally designed to be used in the engine compartments of small boats. The heads selected for testing were rated to activate at 100°C (212°F) as in our original test, at 74°C (165°), and at 57°C (135°F).

Halon 1301 is a colorless, odorless, electrically non-conductive gas that extinguishes fires by inhibiting the chemical reaction of fuel and oxygen. It was developed in the late 1940s by the U.S. Army in its search for an extinguishing agent with good fire-fighting properties but without the high toxicity of the other materials on hand. Halon 1301 is the least toxic of the halogenated extinguishing agents.

Strong points for choosing this agent over other types of extinguishing chemicals include its effectiveness on three types of fires: Class A (cellulosic materials—paper, wood, cotton, etc.), Class B (flammable liquids), and Class C (electrical). Because it is a gas and can penetrate even the most hard-to-reach places, Halon 1301 is ideal for extinguishing fires in electrical cabinets. In addition, a concentration of only 5% by volume is enough to extinguish most fires, and after discharge it leaves no residue on electrical components.

The Experimental Setup

The Fireboy had been charged with 46 oz of Halon 1301 by the manufacturer and rated to give adequate protection for a compartment up to 75 ft³ in size. To construct a facsimile electrical cabinet for our test, we obtained an empty rack (total volume 38 ft³), representative wire and cables, and electronic components from the LLNL salvage yard. We included a fan for circulation of air within the cabinet.

After setting up the components and cable bundles in the rack, we installed the extinguisher horizontally in the top center of the cabinet, with the head facing down. We installed four thermocouples, placed on the extinguisher head and 12, 32, and 51 inches from the head in the cable channel to monitor the temperature rise during the burn. Finally, we covered the open back of the cabinet with 1/8-inch clear Plexiglas to simulate normal closed-door conditions and still be able to videotape the test in progress.

Test Results

We ran the first test with the extinguisher with the lowest head-activation temperature, 57°C (135°F). To simulate what would happen during a cable

voltage overload, we ignited the wire and cable jacket material with a diffusion flame from a natural-gas burner in the bottom of the cabinet under the cable bundles. Previous small-scale tests had shown that the wire and cable insulation obtained for our tests contained enough fire retardants and inhibitors to sustain burning only if a flame source was kept directly under them. Therefore, we incorporated one 1/4 x 16-inch wooden dowel into each cable bundle to help sustain the flames until extinguisher activation.

As can be seen in Fig. 1, the Halon discharged at 175 seconds at an air temperature of 144°C (292°F). The cable bundles showed moderate damage but only to the lower one-third portion above the gas burner. The flames, which were about two feet high, were extinguished immediately upon Halon discharge and no subsequent flare-up occurred.

We used the extinguisher with the 74°C (165°F) head for the

second test. The gas burner was inadvertently set at a higher rate at the start of this run, causing a higher initial temperature of approximately 100°C for 75 s. This higher heat release rate of the fire caused a faster response time (145 s) than the first test even though the head had a higher temperature rating of 74°C.

The temperature recorded by the thermocouple on the extinguisher head at Halon release was 120°C (248°F). Damage to the cable bundles was similar to the first test, and again there was no re-ignition after Halon discharge.

The third test was a repeat of the 1986 test in which an extinguisher with a 100°C (212°F) head was used. Figure 2 shows a steady temperature rise to the point of activation at 417°C (782°F) at 275 seconds. This temperature correlates well with the original test, in which the extinguisher discharged at 367°C (693°F). The cables sustained much more damage during this test, with heavy degradation

taking place on the lower one-quarter, and moderate to light damage progressing towards the top of the channel. Again, no flare-up occurred after Halon discharge.

Each unit proved to be very effective in extinguishing the fire and in preventing subsequent flare-ups. The rapid response of the 57°C and 74°C extinguishers prevented any damage to electronic components. The 100°C head allowed the flames to reach the top of the cabinet (5 ft) and to burn longer (255 s) than in Tests 1 or 2 before operating. Although the electrical components appeared undamaged following Test 3, a fire of that duration and intensity could prove detrimental to the operation of the components within the cabinet, so we recommend using the extinguisher with the 57° or 74°C heads.

Reference

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Figure 1. Plot of air temperatures during Test 1, which used a head rated to activate at 57°C. The head actually discharged at an air temperature of 144°C, but instantly extinguished the flames.

Figure 2. Plot of air temperatures during Test 3, which used a head rated to activate at 100°C. It actually discharged at an air temperature of 417°C, which correlates well with the 1986 test temperature of 367°C.

The Sensitivity of Fire and Smoke Detectors to rf and Microwave Exposure*

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The primary objective of this project was to define thresholds for fire- and smoke-detector failures resulting from extremes in environmental conditions. These conditions included:

- Unusually high or low temperature.
- Unusually high or low humidity.
- Pressure variations.
- Microwave or radiofrequency (rf) energies.
- Ionizing radiation.
- The presence of volatile fluids or outgassing solids. These include solvents, extracts, and plastics.

Studies of this kind may be used to aid designers in the selection of components for fire-management systems.

We conducted this preliminary work in five phases, beginning with a survey of detector types used at LLNL and an inspection of Laboratory facilities to determine extreme environmental exposure conditions. We then developed a procedure and experimental apparatus for

Certain extreme environments can affect the performance of fire and smoke detectors, either with false alarms or decreased sensitivity. We surveyed the types and placement of smoke detectors in areas of unusual environmental conditions at LLNL. To determine the effects of exposure to radiofrequency or microwave energies, we tested ionization smoke detectors with a small transmitter and a microwave generator. With the low power levels available to our test instruments, we found no change in the smoke detector performance, and we recommend further study.

studies of detector response to these conditions. This was followed by the experiments themselves and the summarization of our findings.

Fire and Smoke Detectors

Several different types of fire or smoke detectors are used at LLNL. Most of these are designed to sense the presence of either heat or smoke. Heat detectors, of course, respond to the thermal energy generated in a fire, and these detectors operate either on the fixed-temperature or the rate-of-rise principle of detection. The fixed-temperature units respond when their operating element reaches a preset temperature; the rate-of-rise units respond when the rate of temperature increase exceeds their preset value (usually around 15°F/min). Optical detectors respond to the infrared and/or ultraviolet light produced in a fire.

Of the several different types of smoke detectors, photoelectric and ionization detectors are the most common. The photoelectric detector responds when aerosol or gases generated during a fire enter the detector and affect the

propagation of light passing between a light source and a sensor. Ionization detectors respond when aerosol or gases enter the sensing chamber and interfere with the electrical current (generated by a radioactive material) to the current-sensing circuitry.

An ionization smoke detector might be affected by rf energies coupling to the leads of the components within the detector. At very high frequencies, the short leads of the electronic circuitry act like antennae, absorbing more and more energy as the rf or microwave energy approaches the leads' resonant frequency—setting off the alarm.

The Literature Search and Facility Survey

Many detector manufacturers place warning labels on their products advising the user not to place the detectors in certain adverse environments. This warning is adequate for ordinary use in offices and other commercial buildings, but the nature of work at research laboratories such as LLNL can lead to unusual conditions. To ensure reliable operation in

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adverse environments, we need to know the exact operating limits for specific detector types. Unfortunately, manufacturers rarely release this type of information; our literature search produced only sparse data.

Information obtained from the Plant Engineering Department at LLNL indicated that heat detectors, water-flow alarms, and ionization smoke detectors are all used at LLNL. We then conducted a survey of the various laboratory buildings on site, including chemistry and electronics labs, fabrication shops, high bays, and other areas where we felt unusual conditions might exist. We recorded the type of fire or smoke detectors used and environmental factors that might influence detector operation.

We learned of false alarms occurring near a microwave capacitor in a vault room of the Physics Research Building. Apparently, during operation of the microwave generator, reflected microwave energy stimulated the detectors and activated the alarm system. To shield the detectors from reflected microwaves, each detector has been covered with aluminum foil. Unfortunately, foil impedes air flow, rendering the detectors useless.

The Tests

We exposed several different models of ionization smoke detectors to varying degrees of rf and microwave energies to determine their susceptibility to false alarms. We employed a hand-held radio transmitter as a fixed-frequency microwave source and a microwave generator as a variable-frequency source. The portable transmitter was a Motorola MX350 FM unit with a 6-W output, which matches the most powerful portable transceiver units used on site and is of the same type used by the LLNL Fire Department. The microwave generator, an HP350, operates at an intensity of 10 mW continuous wave; most normal background sources are at levels of less than 1 mW. The apparatus that supported the detectors during testing consisted of a wood panel with three bases for fastening detectors to it, and a control panel.

We tested each smoke detector with voice transmission from the hand-held transmitter placed six inches away. None of the detectors responded. We then placed each detector against the waveguide tube of the microwave generator. Each detector was exposed to microwaves of less than 10 mW between a range of 1 to 26 GHz in 1-GHz increments.

There was no response from any of these detectors. We repeated these tests while spraying test gas (used by maintenance personnel to provide a detectable aerosol) at the detector to identify any performance change during the transmission of rf and microwave energy. We found no effects.

Study Conclusions

Our survey of detector locations revealed that smoke detectors are seldom placed in areas of extreme environmental conditions at LLNL; these areas are generally serviced with heat detectors and/or sprinkler systems with flow alarms. Smoke detectors are preferable to these other types of alarms because a fire can be detected in its very early stages.

The false alarms from the only smoke detectors we found—those in the microwave vault—probably resulted from reflected microwave energies *several orders of magnitude* above the levels of our tests: the low power levels available with our test equipment were insufficient to trigger them. We feel that further study is required to make recommendations for appropriate fire detection in this and other areas of unusual environmental conditions.

The Performance of In-Service HEPA Filters When Exposed to Fire

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HHEPA filters are used to protect the environment from toxic dust particles in the event that a negative-pressure ventilation system "goes positive" for some reason, such as during a fire. The Department of Energy asked the Fire Science Program to determine whether smoke from a fire would clog these filters and render them useless. We conducted a project in the late 1970s to determine the extent of this danger, but in that test series we used new filters when it is more likely that fire exposure incidents would occur in enclosures served by ventilation systems equipped with used, or "experienced," filters. We therefore conducted a new test series and included filters that we artificially aged.

The range of experience for HEPA filters depends on two factors—time in service and degree of normal loading. These two factors are inversely proportional, i.e., high aerosol concentrations will cause faster filter loading and hence shorter time in service. Extremes of change-out times for experienced filters range from one to three months for incinerating and welding operations to tens of years for final filters of fabrication facilities.

We completed the initial phase of a Department of Energy program to define countermeasures for smoke plugging of in-service high-efficiency particulate air (HEPA) filters. Our large-scale fire tests demonstrated that the synergistic effect of wood and various plastics burning together created aerosols that clogged new, used, and artificially loaded filters, even at very low mass burning rates. This combination and proportion of materials are based on an actual survey of materials in LLNL research labs.

Although we performed an extensive literature search and contacted a number of knowledgeable individuals, we were not able to find a source of data pertaining to typical loadings or physical properties of used HEPA filters at change-out time. Research on the aging of fiberglass filters, however, gave some guidance toward procedures for the acceleration of HEPA media aging. Fiberglass is sensitive to both flexure fatigue and stress corrosion in the presence of water vapor, as would occur in very humid environments or in very humid processes.

In an effort to provide data on the effects of fire and smoke on HEPA filters, we set up the following areas of investigation:

- Small-scale, accelerated aging tests of HEPA filter media.
- Small-scale flame tests on HEPA filter media.
- Small-scale and bench-scale fire tests to determine the nature of combustion products that enhance filter plugging.
- Large-scale fire tests on new and partially loaded filters (at 1000 cfm) to relate the effect of fuel type, burning rate, ventilation, moisture, and fire on filter plugging propensity.

The Small-Scale Tests

Simulated Aging

We designed several small-scale tests to simulate media aging as a result of a number of environmental and mechanical stresses, such as repeated wetting and drying, vibration, and heat and steam. To compare media strength before and after each aging process, we used a specially designed tensile test apparatus. Table 1 summarizes the results of these tests. We compared each reading of tensile strength to the original reading, which is listed in the "As received" column. Although some of the data indicate that the media actually gained strength under certain conditions, it is more likely that these readings are due to the high sensitivity to "noise" of the apparatus and the variation in media manufacture.

Of the various *new* filters listed, elevated pressure *with* humidity, and vibration (by itself) appear to degrade tensile strength the most. Elevated temperature with water soaking does not seem to have significant effects on new filters, but water soaking by itself has a marked effect in decreasing tensile strength in used filters.

Table 2. Summary of the thermal behavior of HEPA media.

Manufacturer	Number of samples	Onset temperature when pyrolyzed in air at 20°C/min (°C)	Weight loss at end of pyrolysis at 550°C (%)
A	4	165–222	8.24–18.08
B	1	152	6.12
C	3	247–372	3.52–7.45
D	4	239–320	4.53–6.41

noted no significant differences amongst the new, used, nor ASHRAE dust-loaded filters. However, further experiments are required to evaluate the filters' performance when exposed to a large flame body (i.e., one that covers the filter face).

Simulated High Humidity

In certain applications and geographical locations,

Table 3. Test parameters and results of the 19 large-scale fire tests.

Test No.	Crib material	Crib size LxWxH (m)	Stick spacing (cm)	Mass loss rate (g/s)	Time period for rate/drop (s)	Pressure drop (Pa/s)	Total mass loss (kg)	Net pressure drop (Pa)	Ventilation inlet/outlet	Comments
1	Wood	0.91x1.22x0.91	^d	108.3	450–650	0.45	79.43	531.51	Lo/Hi	
2	Wood	0.91x1.22x0.91	1.27	40.2	1100–1350	0.03	48.38	82.38	Lo/Hi	
3	Wood	0.91x1.22x0.91	^d	109.9	250–450	0.82	41.37	474.08	Lo/Hi	Plugged (500)
4	Wood	0.91x1.22x0.91	^d	1.0	210–270	0.35	15.53	64.56	Hi/Hi	
5	Wood	0.91x1.22x0.91	^d	57.0	240–420	0.21	23.95	143	Hi/Hi	
6	Wood/PMMA	0.91x1.22x0.91	^d	33.4	480–1020	0.07	59.45	180	Hi/Hi	
7	Composite ^a	0.91x1.22x0.91	^d	19.5	480–960	1.00	18.27	1099	Hi/Hi	Plugged
8	Wood ^b	0.91x1.22x0.91	3.81	31.7	1800–2700	0.02	59.94	63	Hi/Hi	
9	Wood ^c	0.91x0.91x0.91	12.20	31.0	600–1020	0.16	74.54	405	Hi/Hi	
10	Wood ^c	0.61x0.61x0.61	8.90	26.6	420–840	0.09	34.25	148	Hi/Hi	
11	Wood ^c	0.61x0.61x0.61	3.05	27.8	480–1020	0.02	57.49	58	Hi/Hi	
12	Wood ^c	0.91x0.91x0.91	12.20	81.7	360–840	0.71	84.79	1124	Lo/Hi	
13	Wood ^c	0.91x0.91x0.91	7.40	99.8	420–1020	0.44	129.50	818	Lo/Hi	
14	Wood ^c	0.91x0.91x0.91	12.20	31.3	510–990	0.13	60.04	220	Hi/Hi	Repeat of Test 9
15	Wood/PC	0.91x1.22x0.91	^d	62.4	440–860	1.72	48.67	3773	Lo/Hi	FCCI test (plugged)
16	Wood ^c	0.91x0.91x0.91	7.40	111.9	500–710	1.09	67.88	1010	Lo/Hi	Loaded HEPA (plugged)
17	Wood ^c	0.91x0.91x0.91	12.20	86.5	320–680	1.80	70.56	1123	Lo/Hi	Loaded HEPA (plugged)
18	Wood ^c	0.91x0.91x0.91	12.20	42.0	410–1010	0.16	57.14	171	Lo/Hi	Loaded HEPA (derated to 500)
19	Wood ^c	0.91x0.91x0.91	12.20	65.0	200–380	0.65	18.95	273	Hi/Hi	Loaded HEPA (fire went out)

^aWood, PVC, PMMA, Polycarbonate.

^bUnseasoned.

^cNew, rough-cut.

^dIn these cases, we used a screen to support the wood.

environments containing a high moisture content may influence the performance of HEPA filters. To simulate and accelerate this condition, we subjected several unused 1000-cfm-rated filters to atomized water spray within the duct, approximately 5 feet upstream, for 24 to 46-hour periods. The measurements of the pressure across the filter after a 46-hour exposure show that there is only a very slight increase in pressure drop. We have a suspicion that this increase may not be real, but rather a result of instrumentation sensitivity. Thus, further experiments are needed to verify the effects of moisture with dust and smoke on preloaded HEPA filters.

Comparison of New and Partially Loaded Filters

We subjected both new and ASHRAE dust-loaded HEPA filters to fires fueled by cribs of wood (fir) and wood mixed with various plastics in the test cell. (These cribs have long been employed by fire researchers to create controlled and reproducible fires; the all-wood cribs are constructed of "2 × 2s" cross-piled into a fuel array measuring 3 × 4 × 3 ft. The composite cribs are composed of wood, PVC, PMMA,* and polycarbonate.) To evaluate the performance of new and partially loaded 1000-cfm filters, we varied the following parameters:

Rate of airflow out of the fire test cell

- 1000 cfm
- 500 cfm

Ventilation configuration

- high inlet, high exhaust
- low inlet, high exhaust

- high inlet, low exhaust
- low inlet, low exhaust

Fuel crib composition

- all wood
- wood and various plastics

Spacing of sticks within the crib

Table 3 summarizes test parameters and results of the 19 large-scale experiments that we conducted. It can be seen that none of the new 1000-cfm-rated HEPA filters plugged when exposed to a wood crib fire, irrespective of burning rate or mass-loss rate. However, two of the ASHRAE dust-loaded filters (Tests 16 and 17) plugged under the same conditions. Figure 1, which compares an unused filter to a preloaded one, indicates that preloading shifts the baseline ΔP (change in pressure) to cause

plugging of the filter. However, the wood crib must achieve a fairly high mass-loss rate (> 80 g/s) to achieve this plugging.

Table 3 shows that in Test 7 the composite crib plugged an unused filter with a very low mass-loss rate of 19.5 g/s and a high inlet, high exhaust ventilation configuration. This combination of materials had consistently plugged filters in our previous studies. Similarly, a wood and polycarbonate crib (Test 15) plugged an unused filter but with a low inlet, high exhaust ventilation configuration and at a much higher mass-loss rate. This was not the case with the wood and PMMA crib (Test 6). However, the high inlet, high outlet ventilation configuration appears to have significantly reduced the mass-loss rate, due to the lack of oxygen.

Figure 1. Plugging of a preloaded filter compared to that of an unused one.

*Polymethylmethacrylate, or generic Lucite.

Conclusions

Small-Scale Evaluations

It should be noted that these reduced-scale aging tests addressed only the filter media. Further research is needed to determine performance of the entire filter assembly under these conditions.

TGAs performed on various media demonstrated from a thermal aspect that manufacturing processes are not uniform for HEPA filters. Tensile tests of new and used media yielded the following results: For new filter media, vibration alone and elevated pressure with humidity caused the greatest decrease in tensile strength. Water soaking and elevated temperature had only minimal effects. For used filter media, water soaking alone and elevated pressure with humidity caused the largest decrease. Vibration and elevated temperature caused less marked effects.

Large-Scale Fire Tests

When exposed to a spot flame and glowing embers, new, used, and preloaded filter media melted through but did not support combustion. Further testing is necessary to assess the effects of impingement from a large flame body.

No significant change in pressure drop was observed after 24 to 46 hours of filter exposure to atomized water spray. However, because these HEPAs were not subsequently fire tested, we were not able to determine what effect high humidity had on fire performance.

HEPA filters did not plug under the following conditions: When they were unused, 1000-cfm-rated filters exposed to pure wood cribs, irrespective of burning rate. Spacing of sticks in the wood crib appeared to have little effect on burning rate. With the exception of the composite crib, filters would not plug with the high inlet, high exhaust ventilation configuration;

the high inlet restricted the crib burning to a low rate.

The synergistic effect of wood and various plastics in the composite crib enhanced filter plugging by creating aerosols, even at very low mass burning rates. Since this combination and proportion of materials are based on an actual survey of LLNL research labs, our consistent observation of this phenomenon is certainly disturbing. And the low inlet ventilation configuration provided sufficient oxygen to support a high mass burning rate.

The combination of low inlet, low exhaust ventilation on a second composite crib burn caused even more rapid fouling than other configurations. It appears that the low exhaust location extracts larger particles formed by cooling and agglomeration. The filters preloaded with ASHRAE dust were the only 1000-cfm-rated filters to plug from pure wood cribs. The data indicated that preloading to 2-inch ΔP is enough to cause clogging that otherwise does not occur with a new HEPA. However, this last finding is based on only two tests.

How Ventilation Affects Conditions in a Room During a Fire*

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The temperatures in a room in which a fire is burning are affected by several factors, among them the amount of air supplied to and removed from the room and the location of the air vents. The classical two-layer representation often used in fire science and computer fire modeling has a hot layer in the upper part of the room that is almost isothermal (unvarying) and a cool layer near the floor. We have found, though, that the two-layer temperature profile is merely one type of fire environment and not necessarily the norm for fires in forced-ventilated rooms.

Generally, we find two-layer profiles in well ventilated fires and one-layer profiles in underventilated fires, with none of the layers being isothermal. The most important implication of this is that a two-layer profile has a cold layer, and a one-layer profile does not. In other words, the lower part of the enclosure can be relatively cool or dangerously hot, depending on the ventilation rate and pattern. The existence of a cool, smoke-

Fires in enclosed, air-conditioned buildings develop differently from fires in naturally ventilated buildings, often lacking the life-saving cool layer near the floor that allows for breathing and escape. We conducted full-scale fire tests to study this "one-layer" phenomenon and to define ventilation configurations that mitigate this development. We observed a cool layer only in well-ventilated fires that had an air inlet in the lower part of the compartment—a finding that has important implications for the design of enclosed buildings with forced ventilation.

free layer facilitates personnel escape and rescue, and makes fire fighting easier. It also reduces fire damage; electronic equipment, for example, is usually located two to five feet off the floor and will suffer heat and smoke damage when the lower part of the room is contaminated with fire gases. As in the upper part of the room, the smoke in the lower part of the room may contain toxic and corrosive gases and aerosols, which are harmful to both people and equipment.

The parameters that determine temperature profiles are

numerous. In this study we investigated primarily the effects of ventilation rate, ventilation pattern, and the presence or absence of a false ceiling. One may also study the effects of enclosure materials, type of fuel, fire spread and growth, and fires burning near or on a vertical surface—all of which may affect temperatures in the room.

The Experimental Setup

In Fig. 1 we present a schematic of the 100-cubic-meter LLNL Fire Test Cell, showing the air inlet and exhaust locations

Figure 1. A schematic diagram of the LLNL Fire Test Cell.

*This report, with minor editorial differences, first appeared in the Hazards Control Department's 1988 *Annual Technology Review* (UCRL-50007-88) on p. 39. For a description of computer codes for modeling one-layer enclosure fires, please see "Progress in Fire Modeling" immediately following this article.

and the plenum* (when used). A 30-cm-diameter air-inlet duct delivers air near the floor. In experiments with a high air-inlet location, the inlet duct delivers air at a point 3 meters up, aimed downward. The 65 × 65-cm exhaust duct is at a height of 3.6 m on the west wall. We varied the ventilation rate from 100 to 500 g/s (about 200 to 1000 cfm), which corresponds to about 1 to 20 times stoichiometry—the required airflow to sustain the fires.

Methane gas is delivered to a 52-cm-diameter burner that sits in the center of the room. The methane fire provides a constant-heat-release-rate flame that burns by complete combustion over a wide range of ventilation rates. The walls and ceiling of the test cell are 10-cm-thick aluminum silicate refractory brick with a large thermal inertia—that is, they conduct or transfer little heat. In several tests we installed a dropped ceiling made of 2.5-cm-thick Marinite (a noncombustible

material made from aluminum silicate) at a height of 3 m, providing a plenum of 1.5 m. This plenum has a 40 × 40-cm opening to communicate air to the exhaust duct in the ceiling, as shown in Fig. 1.

The cell has two thermocouple racks, 1.5 m in from the east and west walls. The temperatures reported here are those actually measured at the west rack—that is, they are not averaged. The temperature fluctuations range from very low values in the cool layer to highest values in the hot ceiling-jet region and the layer interface region. Despite turbulent fluctuations, the temperatures were always essentially invariant after about 17 minutes (1000 s).

The Results

Development of the One-Layer Temperature Profile

As stated, we observe two ways that gas temperatures in the

room evolve after a fire starts: as one-layered or two-layered. The first case refers to fires that produce only one temperature layer that extends from floor to ceiling and typically has a vertical temperature gradient throughout (Fig. 2). The one-layer case is observed for fires with low ventilation rates, at or below 2 to 3 times stoichiometric, with a low inlet position; we refer to fires with such a ventilation rate as “underventilated” fires.

Figure 2 shows the development of a one-layer temperature profile for an underventilated fire in a room with a plenum. The hot layer expands to the floor within 100 seconds of ignition, and thereafter the shape of the temperature profile does not change appreciably—i.e., the temperatures increase about the same at each height.

Several heat-transfer mechanisms act to produce a temperature gradient, as shown schematically in Fig. 3. Generally,

Figure 2. The quasi-steady, one-layer temperature profile produced by an underventilated fire. This plot is from a 200-kW fire at an air-flow rate of 100 g/s ($2 \times$ stoichiometry), with a low air-inlet location and a plenum at 3 m.

Figure 3. The heat-transfer mechanisms that interact to produce the observed temperature gradients in the hot layer of a fire. This hot layer extends all the way to the floor in a one-layer fire.

*The space above a dropped ceiling.

heat losses to the ceiling and walls, turbulent flow and mixing of gases in the room, and radiative heat exchange inside and outside the layer combine to produce the temperature profile observed. In our tests, which produce little smoke, the radiative transfer is relatively small. In a smoky fire—as most real fires are—smoke will accompany the hot gases that have contaminated the lower layer to cause this heating.

The heat losses to the ceiling and walls are primarily by convection in these tests. The hot gases in the fire plume reach the ceiling, flow along it (as a “ceiling jet”) and are cooled. The gases then flow down the walls, continuing to be cooled. The gases that flow the farthest down along the wall will be the coolest, and this helps maintain the temperature gradient. The turbulent mixing in the hot layer is moderate (if it were very turbulent the layer would be even

more isothermal). The stable stratification of the gases in the room—the gases are hotter as height from floor increases—tends to damp out turbulence.

Development of the Two-Layer Temperature Profile

We observe two-layer temperature profiles when ventilation rates are greater than 2 to 3 times stoichiometric. We will refer to such fires as “well ventilated.” We define a two-layer profile as one having an interface region with a steep vertical temperature gradient in the enclosure (except near solid surfaces). The hot and cool layers are not necessarily isothermal. They can have a moderate temperature variation or even a moderate vertical temperature gradient.

Figure 4 shows the development of a two-layer profile for a well ventilated fire in a room with a plenum. The layer interface, identified by the steep

temperature gradient, stabilizes between 1.1 and 1.4 m after 100 s. The next three plots give temperature profiles at 500, 1000, and 3000 s after fire ignition, at which times the layers are well established.

Ventilation Rate Effects—Low Air-Inlet

Figure 5 illustrates the effect of ventilation rate on the temperatures in the room. Temperature profiles are shown for a 200-kW fire with a high ventilation rate, a low ventilation rate, and no ventilation. (The “no ventilation” fire is one in which the enclosure was unvented except for the opened air-inlet duct in the lower part of the room, which served only to relieve fire-generated pressure.) With the high ventilation rate, a cool layer forms in the lower part of the room, and the temperatures are lower by 25 to 50°C throughout the room. The cool layer extends to about 1.2 m—or about

Figure 4. The development of a quasi-steady, two-layer temperature profile for a well-ventilated fire in a room with a plenum. The only difference between this fire and the one in Fig. 2 is the air-flow rate, at 500 g/s ($10 \times$ stoichiometry).

Figure 5. The effect of ventilation rate on a 200-kW fire with a low air-inlet location. Temperatures are at 500 s.

the height of a desk with a personal computer on it. At that height the gases are 50°C cooler than in the low or no ventilation cases. With low or no ventilation, the hot layer extends essentially all the way to the floor. For the tests shown in Fig. 5, the low and no ventilation cases yield very similar temperature profiles at 500 s because resident air in the room plays a dominant role early in the fire in these two situations.

Figure 6 is similar to Fig. 5 except that there is a plenum at a height of 3 m. With a high ventilation rate (500 g/s), a cool layer about 1.2 m high forms near the floor. At lower ventilation rates (400 g/s and 200 g/s) the cool layer is shorter (about 0.75 and 0.45 m, respectively). At the lowest ventilation rate, Fig. 6 shows no cool layer near the floor; instead, the gas temperature increases rapidly and almost linearly with height from floor to ceiling. At 0.6 m above the floor the temperature has already risen to about 100°C.

Note that for the high ventilation rate, Figs. 5 and 6 show the same cool-layer height.

The cool-layer heights in Figs. 5 and 6 suggest that the extent of the cool layer is determined primarily by the ventilation rate (when the air inlet is low). This is because the layer interface stabilizes at a height such that the total mass of the plume gases entering the hot layer at the interface equals the mass flux of the gases leaving the layer by ventilation. With the same ventilation and the same fire strength, the layer interface stabilizes at the same height from the floor in spite of the plenum.

Ventilation Rate Effects—High Air-Inlet

When the ventilation air comes in through ceiling vents instead of near the floor, the vertical temperature distribution in the room may be altered. Figure 7 depicts the difference for a high-inlet and low-inlet case for a well-ventilated fire. With the "low-

inlet" location we obtain a two-layer profile. In the "high-inlet" case we also obtain a two-layer profile, but the profile is completely distorted and lacks a true cool layer. Instead, within 1.5 meters off the floor (about the height of a person) a temperature bulge of about 50°C is observed. As stated earlier, in a smoky fire—as most real fires are—smoke will accompany the hot gases that have contaminated the lower layer to cause this heating.

Figure 8 illustrates how the ventilation air coming from the ceiling vent may act to bring about the observed heating near the floor by blowing hot gasses downward. The air jet passes through the accumulating layer of hot gases near the ceiling, creating an exchange of fluids between the jet and the hot layer. The jet deposits some cool air in the layer and entrains hot gases and smoke, which are brought into the lower layer along with the rest of the ventilation air. To limit the contamination of the lower part

Figure 6. Varying ventilation rates for a 200 kW fire with a low air-inlet location. At 1000 s, the temperature profiles are quite different.

Figure 7. Varying air inlet locations for a 200 kW fire with a 500 g/s air flow (well ventilated). At 1000 s, the two layer temperature profiles are different.

of the room with hot gases, one must shut off the air supply to the room but maintain a high exhaust rate. This option should be considered in building design when ceiling supply vents are used. This also reduces the risk of smoke transport to adjoining spaces, similar to an emergency containment procedure.

A lesser effect is observed when the ventilation rate is low. Figure 9 shows only a modest difference between cases when the air-inlet is in the ceiling and when it is near the floor. The shape of the temperature profile is similar, but the temperatures are cooler in much of the room when the air enters from above. Apparently, the ventilation air does not have enough momentum at 100 g/s, and deposits most of the air in the upper 2/3 of the room, where it makes the gases generally cooler. The figure shows only a very slight temperature bulge in the

lower third of the room from the gases brought in by any remaining air jet, entrained as it passes through the hot region near the ceiling.

Suspended Ceiling Effects

Figure 10 shows a typical difference in temperature profiles

caused by the presence of a plenum. Because the 200-kW fire is well ventilated, we can see an identifiable two-layer profile for each case. In cases with the plenum, the upper layer is hotter, partly because the room is effectively smaller with a smaller wall area for heat loss. Moreover,

Figure 8. The mechanism behind the distorted two-layer temperature profiles seen in rooms with a high air-inlet location. The inlet cools the upper layer but contaminates the lower layer with hot gases.

Figure 9. Temperatures for under-ventilated fires, showing one-layer profiles. Inlet location for an under-ventilated fire does not affect this profile.

Figure 10. The presence and absence of a plenum in a 200-kW fire with a 500-g/s air-flow and a low air-inlet location. At 1000 s, the temperature profiles are significantly different.

because of different material properties, there is usually less heat loss into the plenum material than into the actual ceiling. The depth of the hot layer is smaller with the plenum, but as we mentioned above, the *height* of the layer interface from the floor (1 to 1.5 m in the near steady state) does not change appreciably with the reduction in room height, because it is primarily controlled by the ventilation exhaust rate.

Conclusions

In experiments with forced-ventilation methane gas fires in the LLNL Fire Test Cell, we made the following observations:

- Lowering the ventilation rate increases the gas temperatures in the room.
- Fires in a room with a plenum produce hotter upper layers than in the same room without the plenum.

- Only well-ventilated fires with the air inlet located in the lower part of the room have a cool lower layer.
- Underventilated fires and fires in rooms where the ventilation air comes in from above lack a cool layer. The absence of a cool layer near the floor is undesirable for rescue, evacuation, and fire fighting. It also increases the potential for heat and smoke damage to the contents of the room, especially electronics and optics.

Our results have implications in the design and operation of ventilation systems for minimizing heat and smoke hazard or damage during a fire emergency. Air inlets should be positioned low in each room, or, if in the ceiling (as is more common), should automatically shut off in the event of a fire. Exhaust vents should be located in the upper part of the room where the hottest gases will be and use an exhaust rate as high as possible.

Progress in Fire Modeling

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Current fire research describes fire and control of fire in buildings with natural ventilation, such as single family homes and office buildings with windows. However, fires in sealed buildings with forced ventilation (air conditioning) are not so well described. These fires present unique problems of detection and attack. Since most new and many current DOE facilities are of this design, we recognized that new strategies would be needed. We have attempted to develop new fire technology to apply to these forced-ventilation enclosures and in particular to nuclear containment facilities.

Starting in 1981, we undertook a series of forced-ventilation enclosure fire tests. Overall, 170 tests have been done in the LLNL Fire Test Cell (*Frontispiece*), covering a wide range of forced-ventilation enclosure fire parameters such as heat-release rate, fire location, fire elevation, ventilation rate, and inlet and outlet ventilation position. We examined natural-ventilation fires, pool fires, and burner fires.

Our first focus was to compare the data from these tests to predictions from natural-ventilation computer models. Participation in this computer

Fires in enclosed, air-conditioned buildings develop different temperature profiles from fires in naturally ventilated buildings. After studying data from 170 full-scale fire tests, we developed an equation to predict upper-layer temperatures, and we defined three characteristic times that relate to this type of fire. In addition, we developed a model to aid us in studying life-safety and fire control technology in forced-ventilated fires.

model evaluation was international in scope and we were able to compare six different models. As might be expected, these natural-ventilation models did not do a very good job of predicting the environment in our forced-ventilation enclosure. Figure 1 shows a comparison of several temperature predictions with data from an LLNL test. These temperature predictions can be seen to vary over a wide range (250°C). Although these models did not do an adequate job of predicting upper-layer temperature, for some parameters such as oxygen depletion they did

very well. Using LLNL forced-ventilation data, several of these codes have been improved and modified in an ongoing process.

Predicting Upper-Layer Temperatures

Out of the forced-ventilation enclosure fire test data, we developed an equation or *simple temperature correlation* to predict steady-state upper-layer temperatures in these types of fires, based on previous work from naturally ventilated fires.¹ The variables needed are: the total surface area A of the enclosure

Figure 1. Plot of upper-layer temperatures and computer-model predictions for a 400-kW fire with 250-g/s forced ventilation. Predictions are from models developed at the California Institute of Technology, Harvard University, Pacific Northwest Laboratory, and Los Alamos National Laboratory.

walls in square meters, the thermal properties of the walls kpc in $\text{kJ}^{-1}/\text{m}^2\text{K}^2\text{s}$, the heat release rate $\dot{Q}$ of the fire in kilowatts, the forced-ventilation air-flow rate $\dot{m}$ in kilograms per second, and the time t in seconds. The resulting answer is the temperature in degrees Celsius.

$$T_{\text{upper}} = 300 + 3 \left(\frac{\dot{Q}}{\dot{m}} \right)^{0.72} \left(\frac{A \sqrt{kpc}}{\dot{m} \sqrt{t}} \right)^{-0.36}$$

Figure 2 shows a comparison of actual fire data with the results predicted from the Simple Temperature Correlation.

The LLNL Simple Temperature Correlation can be applied to a

variety of enclosure fires. It has been used as a tool in risk analysis and incorporated into several LLNL risk analysis protocols. This equation enables any interested person to do a quick calculation and predict, within acceptable parameters, an upper-layer temperature. We have incorporated this correlation into a small-computer program called *STC*, which is available in a variety of formats.

Defining Time Constants

Another product of the enclosure-fire tests is the definition of three characteristic times (Fig. 3) that relate to forced-air fires. We developed these time constants for quick evaluation of enclosure-fire hazards, as many of the facilities we wish to analyze have unique dimensions that make intuitive analysis difficult. The three constants are the *characteristic energy time*, which relates to the growth of the fire and the energy balance in the enclosure, and is expressed as

$$t_e = 3.5PV/\dot{Q}_{me},$$

the *characteristic mass time*, which relates to the approach to chemical species steady-state equilibrium and is expressed as

$$t_m = m/\dot{m},$$

and the *characteristic thermal penetration time*, which defines the time to thermal steady-state equilibrium, expressed as

$$t_p = l^2/4\alpha.$$

In these equations, P is pressure, V is volume, m is mass of enclosure air, l is wall thickness and α is $k/\rho c$. These three

Figure 2. Plot of the actual upper-layer temperature and a prediction from the LLNL Simple Temperature Correlation for a 200-kW fire with 400 g/s forced ventilation.

Figure 3. The four time regions of a forced-ventilated enclosure fire, divided by the characteristic energy time t_e , the characteristic mass time t_m , and the characteristic thermal penetration time t_p .

parameters can be used to predict the times or duration of real events in a forced-ventilation enclosure fire.

Modeling "One-Layer" Temperature Profiles

Much of our enclosure-fire modeling work has focused on upper-layer temperatures because in a "classical," naturally ventilated enclosure fire this is the most important single parameter. But recently we have been analyzing the entire temperature profile (the vertical variation of temperature from floor to ceiling in an enclosure) within a room. The classic temperature profile in an enclosure looks something like Fig. 4(a) and is typically called a two-layer profile, since there is usually a distinct "hot" layer and a distinct "cold" layer. Our forced-ventilation enclosure-fire work has revealed a different type of temperature profile, a unique "one-layer" profile seen only in forced-ventilation enclosures. Figure 4(b) is an

example of one of these one-layer temperature profiles: instead of two layers, we see the temperature vary uniformly from the top of the enclosure to the bottom. This one-layer profile occurs in forced-ventilation enclosures with low ventilation rates and in enclosures where the inlet ventilation air is introduced from the ceiling.*

This type of profile indicates a dangerous fire scenario. In a two-layer fire the air near the floor has ample oxygen for a person to breathe and relatively cool temperatures. It provides an escape route for occupants. In the one-layer fire, the air near the floor is much hotter than it would ordinarily be and is contaminated with toxic combustion products (carbon dioxide, carbon monoxide and hydrogen chloride), making it much more dangerous. This type of profile poses new problems for life-safety and fire control procedures; further research needs to be done in this area to define and evaluate this problem.

Reference

1. B. J. McCaffrey, J. G. Quintiere, and M. F. Harkleroad, "Estimating Room Temperatures and the Likelihood of Flashover Using Fire Data Correlations," *Fire Technology* 17, 2 (1981).

Figure 4. (a) A normal two-layer temperature profile as found in a naturally ventilated enclosure, which provides a cooler layer for breathing and escape, and (b) the more dangerous one-layer temperature profile as found in forced-ventilated enclosures.

*For more information on the two- and one-layer temperature profiles, see "How Ventilation Affects Conditions in a Room During a Fire" on page 43 of this publication.

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