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FULL-SCALE FIRE EXPERIMENTS: PRIOR WORK

Experimental Design

Earlier research at Battelle-Columbus was based on the recognition that more deaths occurred in residential fires because of anoxia and the inhalation of toxic gases than because of burns. In an approach to this problem, a major source of these toxic gases was assumed to be the processes of smoldering and pyrolysis that occur in room-type fires, especially those involving some types of synthetic materials. Experimental examination of means for modifying the pyrolytic decomposition of furnishing materials raised the need for a more exact specification of the temperature and environmental conditions to which materials might be exposed during residential-type fires.

With the cooperation and assistance of the Columbus Fire Department, a program was initiated for development of techniques and procedures that would permit observation of the way furnishing materials respond to the periods of fire and smoldering in fires set for this purpose. Using a selection of furniture loadings, several room-type fires were set in plaster on lath wall residences scheduled for destruction of the Fort Hayes military complex located in Columbus, Ohio. These buildings had been occupied in recent times and were in excellent condition for examination of fires under the limited ventilation conditions that would be typical of residences in this part of the United States in winter months.

This experience demonstrated that the early stages of a room fire exhibit stage-wise development of smoldering, fire flareup, oxygen depletion, combustion and pyrolysis product accumulation, and oxygen-level recovery through air circulation. To a considerable degree the gaseous accumulations, such as CO, are linked to the degree of oxygen depletion and hence to the ventilation circumstances. The particular degree of stage-wise and cyclic fire development that is obtained clearly will depend on the choice of room characteristics and the arrangement of furnishings.

More recently a new series of fires was carried out in order to establish the need for materials of improved fire safety in some domiciliary settings and to demonstrate the potentials for new materials arising from the latest technology.

Two concepts for application of the new materials were explored. In one concept, the room surfaces and furnishings were totally equipped with new materials so that the performance of these could be observed under the conditions of the best use for each candidate material. In this case, fire spread from an igniter load might be anticipated to be small or nonexistent and, because the choice of igniter load may determine the result in this fire, several levels of igniter load were envisioned. In the other concept, the probability was considered that only partial substitution by new materials might be achieved in many buildings for reasons of cost, decor, existing practice, and similar factors. Because fire hazard is a complex matter relating to many factors other than fire spread rate, there are many significant variations in partial substitution that can be tried. For that series of fires only a single demonstration was made so that the new material would show

(1) Its effectiveness in controlling fire spread when located in the normal path for fire development

(2) Its capacity for contribution to other hazards, e.g., smoke, toxic gases, if the room fire develops anyway as a result of the combustibility of the other furnishing materials.

Arrangements were made with the Columbus Fire Department to use an existing six-story concrete building, designed and used as a fire tower, as the site for the experimental fires. The fire tower is a concrete building with casement window frames on each of three sides. The arrangement for using this structure in the experimental program is illustrated in Figure 1. The volume of the fire room, 968 ft^3, is about 35 percent of the residual volume left for circulation of air and gases into and out of the fire room. Communication of such gases between the fire tower volume and the fire room occurred by an open doorway and a duct opening located in the ceiling of the fire room. An opening was maintained in one window of the fire tower to provide a continuing supply of air and to relieve pressure fluctuations during the fire.

To minimize cost, the series of fires were carried out on as rapid a schedule as possible. This required that each fire in the series was carefully planned in advance; extensive iterative use of the results of one fire to dictate those of a subsequent fire could be done only by addition of fires at the end of the planned sequence. Further, to maintain a rapid schedule, the fire rooms were prefabricated in sections for storage and then subsequently used by bolting the sections together. Thus, the manpower and instrumentation were committed to this program for an experimental period of about 4 weeks, during which the four experimental fires and a few trial burns were made using various igniter loads.

Ventilation

Various possibilities exist for ventilation of the fire room and the choice may be anticipated to have considerable bearing on the results obtained in

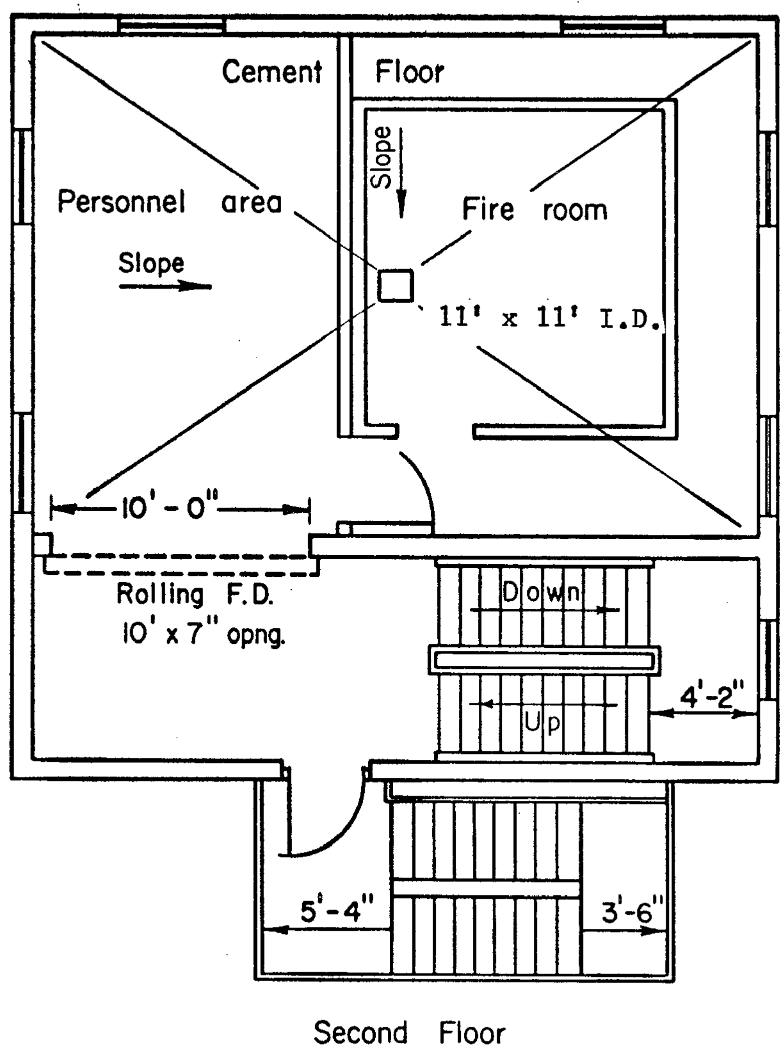

FIGURE 1. ARRANGEMENT FOR FIRE ROOM AND BARRICADE

the experimental fires. In our earlier experience, air entered the fire room by way of a doorway and, because it was cooler than the room air, flowed along the floor, thus forming a layer through which it was possible to see entirely across the fire room. At the same time the accumulation of smoke in the room had reduced visibility above this layer to only a few feet and the smoke could be seen leaving the room by the same doorway that admitted the fresh air. Similarly, in the corridor experiments at NBS, measurements of air flow in the bottom one-third of the door opening show air entering the fire room while gas motion was demonstrated to be outward in the top two-thirds of the opening. Thus door openings serve simultaneously to supply air to the fire and to vent the combustion products; in many circumstances, this is the major opening for such transport to occur. In the earlier Battelle full-scale room fire experiments at Ft. Hayes, the outside doors and windows of the building were sealed so that, in the early stages of the fire, only the air contained in the building was available to circulate through the open doorway of the fire room. Later in each fire an opening was made to increase air circulation and thus accelerate the second flare up of fire; at first such openings tended to occur naturally as a result of cracks that formed in a window in the fire room, and in later experiments these openings were created to repeat the circumstances of fire development.

For the latest program the doorway to the fire room was planned to be the major source for circulation of air and gases but, in contrast to our earlier work, an open window in the corridor leading to the fire room insured a continued supply of fresh air and served to vent gases from the fire room.

One ventilation duct opening was used for the fire room which connected to a few feet of duct terminating in the space above the fire room. This duct was used without blower so that the relative importance of natural convection through this opening could be observed. At the normal blower circulation rate of four room volume changes per hour, the impressed circulation of a blower would be expected to be relatively unimportant during the fire periods compared to the circulation through the open doorway, and would serve only to shorten somewhat the smoldering periods that were anticipated. Thus, if the blower is not needed for achievement of suitable fire development, it is otherwise undesirable for observations of the toxic gas evaluation problem.

Further, in modern structures smoke detection equipment in such ducts may be used to turn off the blowers at an early stage of the fire so as to diminish the spread of smoke and toxic gases.

Instrumentation and Sampling Considerations

The continuous coverage of selected products of combustion in the earlier Battelle experimental fires provided information on the stage-wise development of conditions in the fire room, and similar coverage was used for the latest series of experimental fires.

In order to keep sampling probes as short as possible, one wall of the fire room was built adjacent to the barricade. Sample collection for monitoring purposes was made at three locations: inside the fire room at about the middle of the wall adjacent to the barricade and about 30 inches from the floor, at the doorway, and at the ventilation duct. The information collected at each of these was as follows:

	Inside Room	Doorway	Duct
Smoke density	--	X	X
Ventilation rates	--	X	X
$CO/NO_x/O_2/HC/SO_2/CO_2$	X	--	--
Radiant heat flux	--	X	--
Particulate/Aldehydes	X	--	--
HCl	X	X	--
HCN	X	--	--
HF	X	--	--

Smoke Density. Photomultiplier arrangements, similar to those used in the NBS smoke test chamber provided for transmission estimates between 100 and 0.01 percent. These were located vertically in doorway and in duct. Because of the complications that arise from smoke deposition on the windows of both source and photocell, tubulature extensions were provided on each window with a slow flow of air provided normal to the windows to flush out these extensions and maintain them as free of smoke as possible.

Ventilation Rates. Transducerized pitot tubes seem to offer the best possibility for measurement of air flows in the range of temperatures anticipated. The locations of these pitots within the openings must be regarded as compromise choices to provide maximum information with a minimum number of sampling sites. For the doorway, the opening is visualized as being divided into thirds: the top and middle thirds were monitored at their centers to provide data on the efflux of combustion gases, and the bottom third was monitored at its center to provide data of air flow into the room. For the ventilation duct, a single pitot was located at the center of the duct cross section.

Heat Flux. The measurement of radiant heat flux at the room openings was made using a Gorden-type radiometer similar to those used in corridor fire experiments at NBS and in a study of heat transfer and fire spread by the Forest Service of the U. S. Department of Agriculture. The radiometer was used with a sapphire window to protect it from convected heat, and was located near the doorway.

Gas Analyses. Continuous monitoring equipment available at Battelle was used to sample the atmosphere inside the fire room.

HCl and HCN can be analyzed using indicator tube techniques but, because of the temperature limitation on such tubes, considerable error can be anticipated due to absorption of the HCl or HCN vapor in water condensate formed when the atmospheric gases are cooled prior to entering the indicator tube. For this reason such techniques have been avoided. Instead equipment developed and used for combustion gas sampling for the Environmental Protection Agency was adopted to the purpose. Thus a standard EPA stack-sampling arrangement and an SO_2/SO_3 sampling train were employed in this program. In the stack-sampler particulate material collected in the heated probe is combined with the filter catch as an estimate of particulate matter per m^3 of gas sampled. The filter can be made of high-purity quartz and, if necessary, can be analyzed to determine the presence of elements of special toxicological interest in the particulate matter. Usually very little solid particulate is found in the impingers, which serve instead to collect condensable materials present.

In the stack sampler, particulate material collected in a heated probe is combined with that caught on a filter as an estimate of particulate matter per cubic meter of gas sampled. If necessary the filter can be analyzed to determine the presence of elements of special toxicological interest. Vapors passing through the filter then enter a train of four cold glass impinger tubes which may contain H_2O or other solvents to collect mists and soluble vapors from the gas stream. In this research the impingers contained 1N NaOH solution to retain gases such as HCl, HF, HCN for analysis. A separate impinger train was used with 1 percent $NaHSO_3$ solution for aldehyde collection.

Temperature Measurements

Chromel-alumel thermocouples were located at over thirty points in the room and the outputs were logged automatically at the rate of about 2-1/2 points per second by a Digitem datalogging device. Where practical, the heads of the thermocouples were placed below the surface layer of the furnishing item being monitored so that the actual use in temperature would be detected rather than the transient levels of incident radiant heat. Other thermocouples measured air temperatures at velocity and heat measuring sites, and at sampling probes.

APPENDIX

PERTINENT FACILITIES AND EQUIPMENT

Generally speaking, all the facilities at Battelle-Columbus are available to any project that may have need of them. However, there are certain groupings of facilities that appear more pertinent to fire research problems; these are described specifically herein.

Facilities or equipment generally used for combustion and air pollution research will be useful in monitoring building fires. Brief descriptions of facilities and equipment follow.

Battelle's Mobile Air Quality Laboratory

Battelle's extensive analytical facilities for conducting air pollution research programs include a mobile air quality laboratory. The mobile monitoring unit, housed in a 30-foot trailer, is designed for field sampling in rural and urban areas, and for specific source sampling, such as in the neighborhood of industrial or municipal facilities, or direct stack analysis. The trailer is outfitted with continuous air-quality monitors, a wet-chemistry laboratory for batch-sample analysis, and facilities for collecting gas and particulate samples for more detailed analysis at the Columbus Laboratories.

Continuous monitors, interchangeable with those used with Battelle's smog chambers, are available for most of the common air pollutants such as NO, NO_2, SO_2, total oxidant, ozone, total hydrocarbons, CO, NH_3, and acid gases. Using the wet-chemistry laboratory, standard batch-sample analyses may be performed in the trailer for formaldehyde, total aldehydes, SO_2, NO_x, oxidant, and many other pollutants. Gas chromatographs are used to analyze for specific organic compounds.

Gas and Particle Sampling and Analysis Equipment

Battelle is currently using a variety of monitoring techniques for gaseous measurements, both in the field and in the laboratory. These techniques are listed in Table 1. As is well recognized, monitoring devices with 100 percent reliability are still wanting in air-pollution technology. On the other hand, most of the equipment available today, when used properly, can be quite reliable. The monitoring techniques selected for this program are

TABLE 1. GASEOUS EMISSION INSTRUMENTATION AVAILABLE AT BATTELLE-COLUMBUS

	Instrument			
Pollution	Name	Range, ppm	Principle of Operation	Comments
NO_x	Faristor	10-5000	Electrochemical (dry)	Continuous, fast response, portable, SO_2 correction required
	Mast	0.1-250	Electrochemical (wet)	Continuous, fast response, portable, SO_2 correction required, NO oxidizer required
	Beckman K-76	0.01-10	Colorimetric (wet)	Continuous, response time delay (accountable), not portable
	Atlas	0.1-5000	Electrochemical (wet)	Continuous, response time delay (accountable), poor portability
NO*	Beckman Model 215A	Various (0-1250)	NDIR	Continuous, portable, water-vapor correction required
	Thermo Electron Model 12A	0-10,000	Chemiluminescent	Continuous, semiportable
	AeroChem Model M-5B	0-10,000	Chemiluminescent	Continuous, semiportable
NO_2	Mast	0.1-200	Electrochemical (wet)	Continuous, portable, SO_2 correction required
SO_2	Faristor	10-5000	Electrochemical (dry)	Continuous, fast response, portable, no NO_x interference
	Beckman Model 906	0.01-5	Coulometric (wet)	Continuous, poor portability, water and particulate interference
	Beckman Model 315A	Various (0-6000)	NDIR	Continuous, portable
	Mast	0.05-1	Electrochemical (wet)	Continuous, portable, NO_2 correction required
CO	Beckman Models 215 & 315	Various (0-10%)	NDIR	Continuous, portable, water and CO_2 interference can be accommodated
	Union Carbide Air Monitor (Stevens technique)	0-200	Ni-catalyst/gas chromatogram	Also yields methane, batch
Hydrocarbon	Beckman Model 109	0-120,000	Flame ionization	Continuous, fast response, portable
	Beckman Model 402	0-120,000	Flame ionization	Continuous fast response, semiportable, selectable elevated temperature sampling line and oven
	Varian HiFi III	Variable	Gas chromatography	C_2 - C_6, choice of columns, semiportable batch operation, flame-ionization detectors
	Varian Series 2800	Variable	Gas chromatography	ditto
CO_2	Beckman Model 215A	0-20%	NDIR	Continuous, portable, water interference can be accommodated
O_2	Beckman Model 715	0-5% 0-25% 0-10 ppm	Amperometric	Continuous, portable
Aldehyde	--	Variable	MBTH wet chemical	Batch--aliphatic aldehydes
O_3	REM Model 612	0-2 ppm	Chemiluminescent	Continuous, portable
Various	Varian Model 1720		Gas chromatography	Choice of columns, semiportable batch operation, thermal conductive detectors
Data logger	Digitem			Output to teletype consol 20 channels
Integrator	Infotronics Model IRS-204			Integrates G.C. output

* All NO instruments can be used to measure NO_x when a converter (NO_2 to NO) is included in the sample line.

based primarily on the concentration range anticipated, interference correction requirements, and ease of use in the field.

To meet the objectives of the program described above, it is necessary to monitor rather accurately a number of gaseous, particulate, and general parameters. Measurements may be made of oxygen, carbon dioxide, carbon monoxide, nitric oxide, and nitrogen dioxide sulfur dioxide, gaseous hydrocarbons, smoke, and particulate emissions and temperature.

Although numerous "standard" monitoring procedures and instruments are available at Battelle-Columbus for these analyses, it would be misleading, however, to ignore the fact that the current state of the art does not permit all of these procedures to be accepted without consideration of their limitations. Battelle's experience, and the experience of many others in air-pollution instrumentation, has shown that gas analysis problems can be very vexing. In the following paragraphs, considerations are presented for how samples can be removed from gas streams and possible means for analysis.

Sampling

In order to ensure that losses--by condensation, reaction, or adsorption--be minimized, it is proposed that, where feasible, all gaseous analyses be made directly; that is, portions of the combustion gas be fed directly to continuous monitoring units set near the fire to minimize sampling line losses. For some analyses where direct monitoring techniques are not available, 1 to 2 cubic feet samples of combustion gas can be collected in Mylar or Teflon bags, and transported directly to Battelle's Columbus Laboratories for analysis.

Because of the high water-vapor content of the product gases and the solubility of some of the species in aqueous media, sampling combustion products is done with a heated probe at about 300 to 400 F. Sampling in flames may require unheated or cooled probes. Battelle has constructed many probes of all designs for various programs.

Particulate Analysis

Battelle has several particulate analysis trains similar in design to that specified by EPA for emission measurements. This train provides separate weight measurements of dry filterable particulate and "condensable" particulate caught in impingers.

Carbon Monoxide

Carbon monoxide will be monitored using a nondispersive infrared analyzer. The NDIR unit uses a condenser for removal of water vapor. An Ascarite column would be used to remove the carbon dioxide interference. Battelle also has a "Stevens" methane/CO analyzer.

Carbon Dioxide

Nondispersive infrared analyzers are available for CO_2 analyses.

Oxygen

Oxygen would be monitored as needed with a Beckman amperometric detecting unit.

Nitrogen Oxides

Currently Battelle is using a variety of procedures for nitrogen oxide (nitric oxide and nitrogen dioxide) analysis. These include nondispersive infrared analyzers, chemiluminescent analyzers, Mast electrochemical procedure, the Faristor electrochemical procedure, and Saltzman colorimetric procedures. All of these procedures have certain good and bad features. It is important in all of these procedures to partially dry the gases with minimum solution of the combustion-produced nitrogen dioxide. NDIR and chemiluminescent analyzers can be used to measure NO (and NO_x with NO_2 to NO converters), the Mast procedure can be used to measure NO (and NO_x with an NO to NO_2 oxidizer), and the Faristor to measure NO_x.

Sulfur Dioxide

Sulfur dioxide can be analyzed by nondispersive infrared or by an electrochemical technique. Battelle uses a Beckman Model 315A NDIR and a Faristor unit for analyses of SO_2 at high levels. With the proper precautions, removing excess water vapor for the NDIR but not completely drying the gases for the Faristor, these procedures work smoothly.

Sulfur trioxide can be analyzed by wet chemical techniques such as the modified Shell method or the barium chloranilate method.

Total Hydrocarbons

Unburned hydrocarbons in the combustion gas streams can be measured with a Beckman 109A hydrocarbon analyzer that measures total hydrocarbons by flame ionization. This instrument has full-scale ranges from 0-1 to 0-3000 ppm and has been used extensively on air-pollution projects. It is suitable for continuous monitoring of combustion products. If needed, Battelle has Beckman 402 high-temperature hydrocarbon analyzers with a sampling train maintained at 300 F.

It may be desirable in some instances to obtain detailed information on the makeup of the hydrocarbon emissions. For hydrocarbons in the C_2-C_6 range, gas samples for these analyses would be concentrated in liquid nitrogen and carbon dioxide freeze-out traps and analyzed by standard gas chromatographic techniques. A variety of columns are available for these separations. Chromosorb and dimethylsulfone columns have been used effectively for the C_2-C_6 range of hydrocarbons.

Aldehydes. Aldehydes may be analyzed by the bisulfite techniques of described above (total hydrocarbon section) and by batch wet-chemical procedures using MBTH (3-methyl-2-benzo-thiazolone hydrazone). The MBTH procedure is limited to aliphatic aldehydes, so the bisulfite scrubbing procedure with hydrocarbon FID analysis will be used for most of the aldehyde analyses.

PNA-Benzo(alpha)pyrene. There is no method of analysis for total PNA's as a class. However, benzo(alpha)pyrene (BaP) is generally regarded as one of the most important, and BaP is the PNA most widely analyzed.

Many techniques have been employed in analysis for BaP. Combination of thin layer or paper chromatography with fluorimetry has been widely used and is probably the most sensitive technique. In work at Battelle one such method has been found to be sensitive to slightly less than 10^{-9} g. Gas chromatography has also been used for analysis for BaP. Although more rapid, gas chromatography generally is not as sensitive as the thin layer chromatography/ fluorimetry method, and is only used where its greater resolution is required and its lower sensitivity can be tolerated.

For this program the thin-layer chromatography method can be used initially. If the amount of BaP found is small, this method can be used throughout the project. If relatively large amounts of BaP are found (i.e., 0.1 μ per sample or more) gas chromatography can probably be used.

Smoke

Smoke number can be measured by the ASTM D-2156-65 filter paper method, as provided by the Bacharach smoke meter. Transients and traversing for stratification can be checked by operation of the continuous-tape Von Brand smoke sampler.

Other Compounds of Interest

Most other compounds of interest can be detected by using wet chemical techniques on batch samples. Specific techniques would depend to some extent on the concentrations of compounds present,

Temperature-Measuring Instrumentration

High-speed single and multipoint recorders
Precision potentiometers
Optical and contact pyrometers.

Additional Equipment Being Constructed or Proposed at Battelle

Research Flammability Chamber (Laboratory Size)

Battelle has been constructing a laboratory size research flammability chamber which embodies features of both the Michigan Chemical Smoke Densitometer, and of equipment described in ASTM D2843-70 and other relevant ASTM specifications. It will be initially used to guide development of carpeting formulations, although its versatility will enable flammability evaluations of a wide-range of materials.