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RESEARCH AND DEVELOPMENT DIVISION

LARGE SCALE FIRE TESTING OF
LOW COMBUSTIBILITY RIGID PVC COMPOUNDS

by

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CORPORATE RESEARCH

RESEARCH REPORT

4007A-78 - JULY 3, 1979

22012001

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Large Scale Fire Testing of
Low Combustibility Rigid PVC Compounds

by

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SUMMARY

In the past several years, joint Corporate Research-Chemical Group programs have led to the development of low combustibility rigid PVC compounds. The first compounds were Geon 87234 and 87235. And most recently Geon 87265 and 87266 based on SS-50 technology were developed. The improvements in fire test performance ratings claimed for these compounds were all based on what are now termed "small-scale" fire tests. This study, a joint program involving Corporate Research, Corporate Technical Support, and different segments of the Chemical Group, was designed to answer questions about the "large-scale" fire performance of these compounds compared to a Geon 8750 Grey control compound. The program was conducted at Brecksville using the Room Burn Facility built for tests of this type. The compounds were tested as sheet products (.030 to .125 in thick) which covered two adjacent 8' high walls making up a corner within the room. Amounts of PVC involved in the tests ranged from 12 lb. to 46 lb. The ignition source for the tests were 14 lb. wooden cribs located in the corner.

Under these test conditions, which are among the most severe used today in fire testing, the low combustibility PVC compounds showed substantial reductions in smoke generation (60-90% reduction), carbon monoxide generation (24-87% reduction), and hydrogen chloride generation (up to 90% reduction) over the Geon 8750 control. None of the rigid PVC compounds tested (control or improved) added significant heat to the fire buildup. Observations of the low combustibility rigid PVC compounds during the tests indicated that the large amount of intumescent char formed during the fire exposure played a key role in their improved performance. We also tested a .030 in. commercial Tuffak® polycarbonate sheet under the same conditions. The fire was so intense that flashover almost occurred, generating the highest levels of smoke and carbon monoxide measured during our series of tests.

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CONCLUSIONS

1. Low Combustibility rigid PVC compounds developed by BFG over the last few years (Geon 87265, 87266, 87234, and 87235) were tested as sheet products (.030 to .125 in thick) in the Brecksville Room Fire Test Facility using 14 lb. wooden cribs as ignition sources. The tests were a joint Corporate Research/Corporate Technical Support/Chemical Group program. Under these severe large scale fire testing conditions the low combustibility compounds showed (a) lower smoke, (60-90% reduction), (b) lower CO generation (24-87% reduction), (c) lower HCl generation (up to 90% reduction), and (d) slightly lower or equal fire involvement when compared to our commercial Geon 8750 Grey control compound. A corner test configuration was used within the room.

2. A sample of Tuffak® polycarbonate sheet when tested under similar conditions almost led to flashover and generated the highest levels of smoke and CO measured during our program.

3. Reductions in smoke generation (over Geon 8750 Grey) seen in our large scale tests of the low combustibility PVC compounds are very similar to that seen in the small-scale NBS Smoke Chamber test. This was not true for the polycarbonate sheet which had exceptionally low NBS Smoke Chamber smoke ratings but generated considerable smoke in the large scale test we ran.

4. The low combustibility rigid PVC compounds, and in particular Geon 87265 (which uses SS-50 as a smoke retardant), formed thick layers of intumescent char in the area exposed to the crib ignition source.

5. A test of thin gauge Geon 87265 sheet (0.030 in.) using a 20 lb. crib ignition source showed increases in fire involvement but did not approach a flashover condition.

6. Measurements of the heat flux experienced by the samples mounted on the wall surfaces indicated peak heat fluxes experienced during the test to be 8 watt/cm² for a 14 lb. crib and 10.8 watt/cm² for a 20 lb. crib. These heat fluxes are substantially above those seen by plastic materials in small-scale flammability tests (2-3 watt/cm²) and help to explain the poor correlation seen between small-scale and large-scale fire tests.

7. Small-scale toxic gas protocols measure only the inheritant toxic gas generation of a material without addressing the combustibility and fire involvement of the material. Our tests showed big differences between regular PVC (8750G) and low combustibility PVC's in CO and HCl generation which had not been predicted from our small-scale toxic gas protocol studies. These differences are rationalized based on the char formation and lack of fire involvement seen in the low combustibility PVC compounds.

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8. A two-fluid hydraulic flow model was used to allow calculation of flows out of the test facility. This model worked well and gave values in line with our experimental measurements of the flow velocity out of the room.

RECOMMENDATIONS

Key parts of and conclusions drawn from this study were included as part of a review paper presented by R. Brown and J. Tanzilli at the Fourth International Conference on Fire Safety, University of San Francisco, January 18, 1979. This paper over-viewed the performance advantages of BFGCG low combustibility rigid PVC compounds (basically 87265 without identifying it). The large-scale results reported here were an important confirmation of our condensed-phase additive (char-formation) philosophy on reducing combustibility.

Consideration will be given towards publishing this study. Additional analysis of the temperature data is needed before we prepare a manuscript, however.

PATENT SITUATION

All of the low combustibility PVC compounds tested and discussed in this report are already proprietary to BFGoodrich.

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ACKNOWLEDGEMENTS

This program was the result of a joint effort of several R&D groups within BFGoodrich. Bob Bloor and Randy Brown (Plastic Division, Chemical Group, ALTC) were responsible for preparing the PVC samples and providing part of the financial support; Greg Smith, Bob Yount, and Bob Jackson (Flame Lab, Chemical Group, ALTC) designed and installed the equipment, took the data on site, and provided analysis of all of the toxic gas data generated in this study; Jim Tanzilli (Fire Affairs, Chemical Group, Oak Tree) helped in the choice of overall design and philosophy used to conduct this study; Floyd Myers and Dan Hasman (Corporate Technical Support) were responsible for preparation of the actual Burn Room facility for this series of tests and helped in the coordination of the preparation of the room and the actual tests; and finally we wish to thank Art McRowe (Latex R&D, Chemical Group, Brecksville) for useful comments and coordinating help.

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INTRODUCTION

A primary function of model and local building codes is the regulation of materials used in structures to assure adequate performance and safety in their use. The normal means used by building codes to accomplish regulation of materials are (1) specify which performance tests are to be run on the materials, (2) the manner in which they are to be conducted, and (3) specify allowable ratings from these tests for the use of materials in various situations covered by the building code. Two groups have contributed heavily towards our understanding of the relationship between the choice of test method (and ratings) and the "quality" of the resulting regulation. They are ASTM and independent testing labs such as Underwriters Laboratories.

The fire safety of buildings is an important concern of local and model building codes. And has been dealt with for many years by classifying the performance of materials under various ASTM tests. In the early 1970's a key assumption underlying this method of regulating materials was shown to be incorrect, or at least highly misleading. It was shown that for several commercially important materials their ASTM test ratings and real fire hazard were significantly different. This led to a lawsuit by the Federal Trade Commission against a number of plastic manufacturers, ASTM, and SPI. The consent agreement signed by all parties has led to a number of changes in the way in which plastic materials are marketed and ASTM has put caveats on all ASTM fire test methods noting that the test ratings may not represent the real fire hazard of the material being tested. A key phrase introduced in these actions was "real fire hazard". Unfortunately, there is no such thing as a typical fire and all "real" fires are different, so how is one to obtain the "real fire" performance of a material?

At present the only answer to this question is to test materials in realistic, full-scale environments using a variety of fire scenarios. The cost of doing this is prohibitive except in the case of high volume commercial products. Both the SPI Urethane Safety Group^(1a) and the SPI Polystyrene Safety Group^(1b) have funded extensive full-scale tests of products representative of their industries. BFGoodrich, through the Chemical Group, has been involved in several industry sponsored programs on full-scale fire testing of products important to us such as vinyl house siding and wallcoverings. As an educational measure, BFG and Battelle-Columbus collaborated with the Columbus Fire Department in burning down some abandoned houses in Columbus in 1970⁽²⁾.

In searching for a means to test materials under more realistic, full-scale conditions, the plastics industry in recent years has started using what are known as corner-burn tests and room-burn tests for wall surfacing and ceiling materials. It was found by members of the fire-research community that the heat transfer from an ignition source to a material coating both sides of a vertical inside corner (like the corner in a typical room)

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was the highest of any of the possible combinations encountered in typical furnished living quarters. This was particularly true if the material being tested had tendencies of melting and dripping, like many commercial plastics.

The corner burn test is conducted by lining both sides of a typical eight-foot high inside corner with the test material. An area four-foot out from the corner in both directions is normally covered. A 4 foot x 4 foot piece in the ceiling over the corner can also be covered if desired. An ignition source (wastebasket, wooden crib, etc.) is located in the corner adjacent to the wall surfaces and ignited. Performance is measured by lateral flame propagation from the corner across the surface of the test material or equivalently by the heat, smoke, and toxic gases generated during the test. Figure 1 shows a typical corner burn arrangement.

The room-burn version of this test simply encloses the test corner in a well defined room and allows better control of the ventilation of the fire.

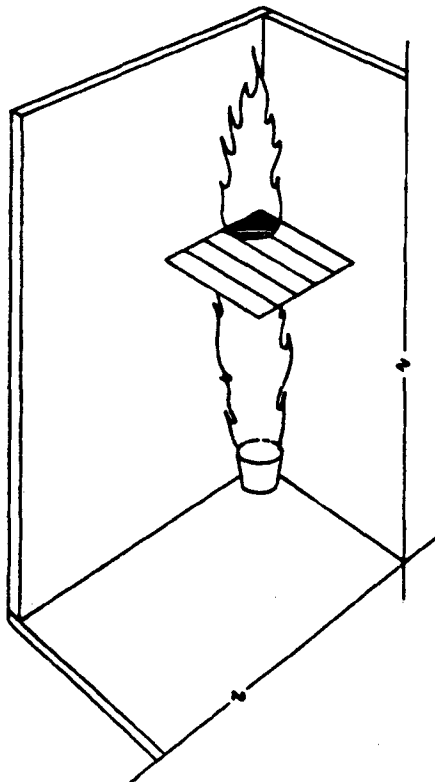


Figure 1. CORNER TEST ARRANGEMENT

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A large number of studies(3-14) have been carried out on corner burn tests and related room-burn tests with corner ignition. Several years ago, in response to requests by marketing people in the Chemical Group, we upgraded a small building at Brecksville to serve as a facility for room-burn testing⁽¹⁵⁾. Current practice guidelines(12-14) were followed in its size, geometry, and facilities. However, to cut out the major element of cost, we did not house the room-burn facility within a larger facility such as UL and FMRC have done. This limits the number of days available for testing but saved us about \$1 MM in capital outlay. Other companies such as GE have built facilities similar to ours.

The work reported here is a comparative study on smoke retarded PVC (Geon 87265 and 87266) against regular untreated PVC (Geon 8750) using the room-burn test. Factors taken into consideration in the study were sample thickness, ignition source intensity, and the repeatability of the experiment. It was a co-operative venture sponsored by the Plastic Materials Division of the Chemical Group (R. Brown, G. Smith and R. Yount of ALTC) and Corporate Research New Ventures (D. Dickens and R. Evans) using the facilities of D/8505 (F. Myers and W. Chambers). Motivation for this series of tests was the impending commercial introduction of Geon 87265 and the need to assure ourselves (and potential customers) that the improvements seen over regular PVC in small-scale combustibility tests are present in large-scale, more severe, fire tests.

To illustrate how this test methodology can be misused, we also carried out a test on a polycarbonate sheet using a more realistic sized ignition source than the one pictured in GE advertisements on the room-burn fire performance of Lexan® polycarbonate sheet. In small-scale ignition and smoke tests the polycarbonate sample appeared to be difficult to ignite and to produce little smoke under standard NBS Smoke Chamber conditions. In our larger scale room burn test, an intense fire was observed with massive amounts of smoke.

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RESULTS AND DISCUSSION

Samples tested in this program were used as received except for trimming for proper mounting in the test corner. Samples were prepared by sheet die extrusion from cube compound at ALTC under the direction of R. Brown. Materials tested were:

- (a) Geon 8750 Grey (40, 100 mils)
- (b) Geon 87265 (30, 70, 125 mils)
- (c) Geon 87266 (30 mils)
- (d) Geon 87234 (125 mils)
- (e) Geon 87235 (125 mils)
- (f) Rohm and Haas Tuffak® polycarbonate (30 mils)

Where possible, tests were run in duplicate. Geon 87234 and 87235 were added to this series of burns to compare different strategies for smoke-retarding PVC. Geon 87265 and 87266 use the new additive, SS-50, at a 4 phr loading level as the smoke retarding system. Geon 87234 has 35 phr alumina trihydrate ($\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$) as filler and smoke retardant while Geon 87235 has 3 phr $\text{Bi}_2\text{O}_3\text{CO}_3$ and 35 phr alumina trihydrate as the smoke retarding system. Geon 87234 and 87235 represent earlier technology which has good performance but very poor processing and physical properties. Geon 87265 and 87266 have a more desirable balance of high performance (in small-scale tests) and easy processing with reasonable physical properties.

I. Test Facility and Instrumentation

The building used in our test program is shown in Figure 2. Basic construction used was a block wall building with the block reinforced and filled with concrete. The inside walls were prepared for use by first putting a $\frac{1}{2}$ " layer of transite over the block walls and then 2 x 4 framing studs on 16" centers. Normal 5/8" drywall is used over the framing studs. Both the drywall and framing studs require replacement. The ceiling was of similar construction as the walls. A 30.5 cm (12") diameter circular duct was cut in the center of the ceiling and connected to a scrubber and fan to provide forced ventilation when desired. The interior dimensions of the room (width = 242 cm (7.94 ft.), length = 395 cm (12.96 ft.), height = 235 cm (7.71 ft.)) give a volume of 22.43 m³ (793 ft³). Ventilation into the room is controlled by a dutch steel door. With both parts of the door fully open, we have an opening 213 cm (83.3 in.) high by 90.2 cm (35.5 in.) wide. With the top part of the door closed we have a reduced opening in the bottom 90.2 cm (35.5 in.) wide by 100 cm (39.4 in.) high.

The purpose of reducing the opening height through the use of the dutch door was to contain as much of the smoke and toxic gas as possible within the room. Furthermore, most tests were conducted with the fan off for the same reason. However, these steps were not sufficient as we found out and we were forced to model

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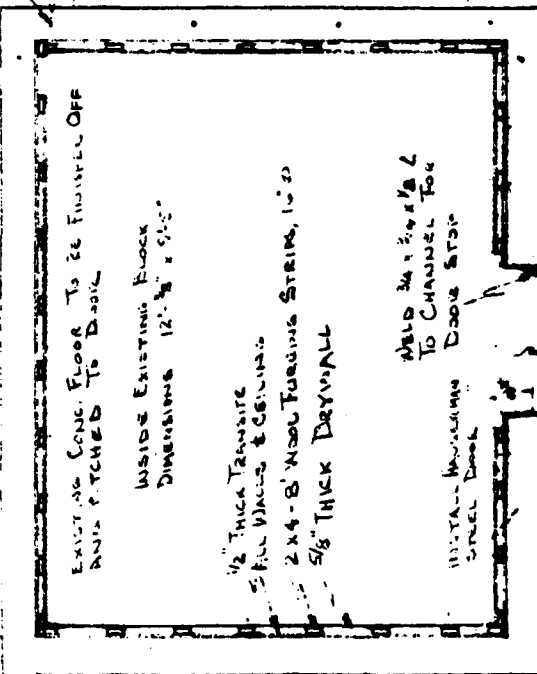
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REVISION

EXISTING 8" CONC. BLOCK WALLS
REINFORCED EVERY COURSE WITH
DUR-O-WALL VERTICAL REINFORCING
#5 ROD EVERY 16". ALL CORES FILLED WITH CONCRETE?

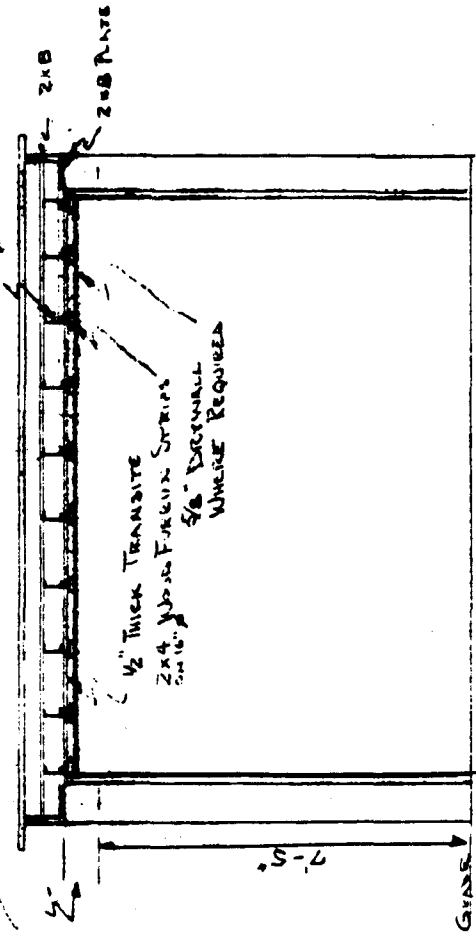
4 ANCHOR BOLTS/SIDE
1/2" x 8" L

EXISTING CONC. FLOOR TO BE FINISHED OFF
AND PITCHED TO DRAIN



A

NEW ONE COURSE 8x8x16 BLOCK
TO EXISTING WALL



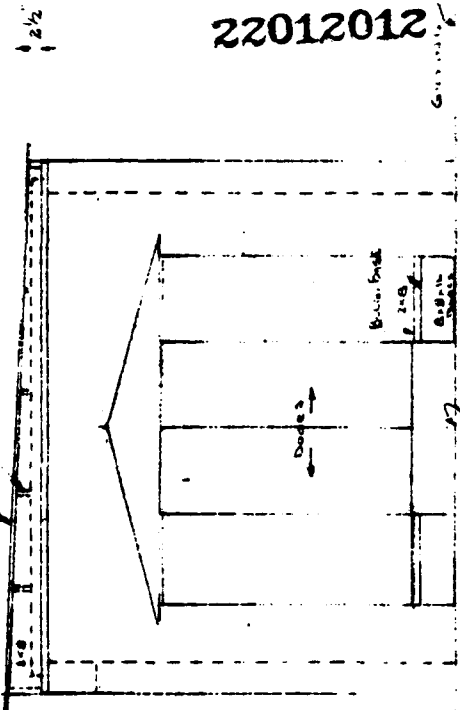
7'-5"

GRADE

FIGURE 2. Burn Test Facility

METAL OUTSIDING BLOCK
7 1/2" x 12 1/2" HIGH
SEALS #32 K. COULSON OR EQUIV.
SET UP ON 1-K. JOIST & 2x8 PLATE

4" CORRUGATED TRANSITE ROOFING
NAILER STRIPS



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3" SLOPE FLASHING
1/2" METAL BLOCK

SECTION A-A

REFERENCE DRAWINGS

THIS DRAWING IS THE PROPERTY OF THE B.F. GOODRICH COMPANY. NO PART IS TO BE REPRODUCED OR TRANSMITTED IN ANY FORM OR BY ANY MEANS, ELECTRONIC OR MECHANICAL, INCLUDING PHOTOCOPYING, RECORDING, OR BY ANY INFORMATION STORAGE AND RETRIEVAL SYSTEM, WITHOUT THE WRITTEN PERMISSION OF THE B.F. GOODRICH COMPANY. FOR THE B.F. GOODRICH COMPANY, THE ENGINEER HAS REVIEWED THIS DRAWING AND APPROVED IT FOR THE BURNING TEST FACILITY.

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RESEARCH CENTER

BURNING TEST FACILITY

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REV.

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the tests as flowing systems in order to make comparisons between materials.

The instruments were housed in another block building adjacent to the burn room. This room is shown in Figure 3. Sampling probes and thermocouple wiring were bundled and passed through the east wall of the instrument building. The closeness of the two buildings allowed us to shorten the probe lines. However, it also posed fume problems if the wind switched during a test.

Thermocouple Locations -- The thermocouples employed were chromel-alumel, 24 gauge, with a fiber-glass/asbestos jacket. The thermocouples were staged such that replacement of any one required only replacing a short length of wire in the burn room. The choice of 24 gauge was a compromise between fast response and long lifetime under our test conditions. It proved to be quite adequate. Recording of the thermocouple data was done on several standard multipoint recorders, grouped by the temperature ranges employed on the recorder and the sampling time.

The philosophy behind the layout used for the thermocouples is similar to that employed by W. Fitzgerald of Monsanto⁽¹⁶⁾ and UL⁽¹³⁾. The room was divided into three layers, (1) a ceiling layer with 19 thermocouples placed 1.3 cm ($\frac{1}{2}$ ") below the ceiling and 4 thermocouples buried in the gypsum board, (2) a layer 157.5 cm (62") above the floor (national average nostril height of standing adults) with 16 thermocouples sensing the air temperature and 6 thermocouples buried in the gypsum wall, and (3) a layer 81.3 cm (32") above the floor, nominally below the neutral density plane for most tests, with 14 thermocouples sensing air temperature and 6 thermocouples buried in the gypsum wall. The layouts and numbering system of the thermocouples employed are shown in Figure 4.

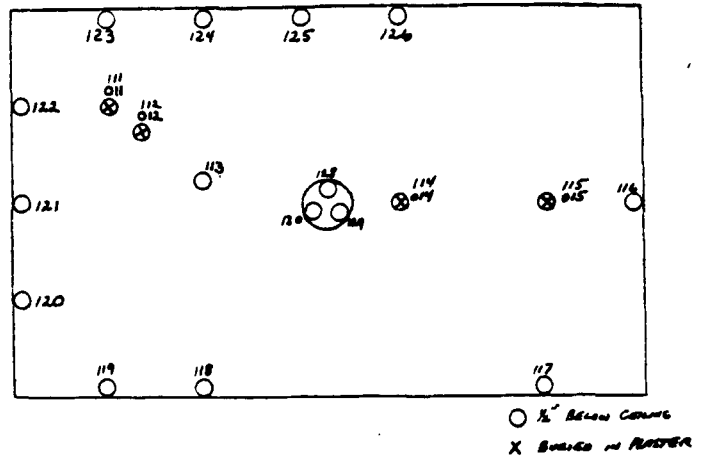
Gas Sampling System -- G. Smith, R. Yount, and R. Jackson installed a three-level gas probe system in the burn room. The probe lines were $\frac{1}{2}$ " stainless steel with Swagelok® fittings. The location of the gas sampling points within the burn room are shown on Figure 5. Probes heights were 107 cm (42"), 168 cm (66"), and 219 cm (86") from the floor. An additional probe was located 5 cm (2") below the door jamb. The probe lines were wrapped with heating tapes to prevent condensation of gases during their transport from the burn room to the sampling valve in the instrument room.

Each gas probe line coming into the instrument room was connected to soot filters, passed through a HCl scrubbing system, dried and fed to a four way sampling valve into a Miran gas analyzer for an IR measurement of CO. Syringe gas samples were taken from the gas probe lines before the soot filters for HCl analysis. An ion-specific electrode technique was used for the HCl measurements which were analyzed at the end of each run. Carbon monoxide sampling occurred 15 seconds of every minute for each of the four probe locations. HCl samples were taken from each probe line at 3, 5, 7, 10 and 14 minutes during the test. Data for the determination of CO content was read off of a single channel recorder coupled to the Miran IR analyzer.

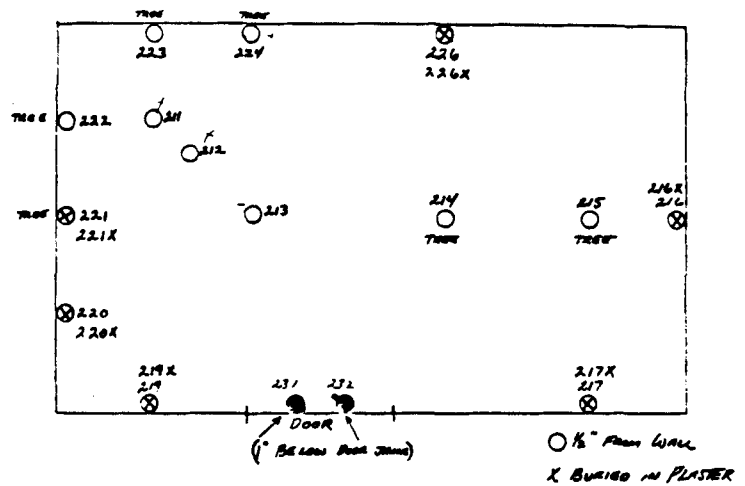
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Ceiling



62" above floor



32" above floor

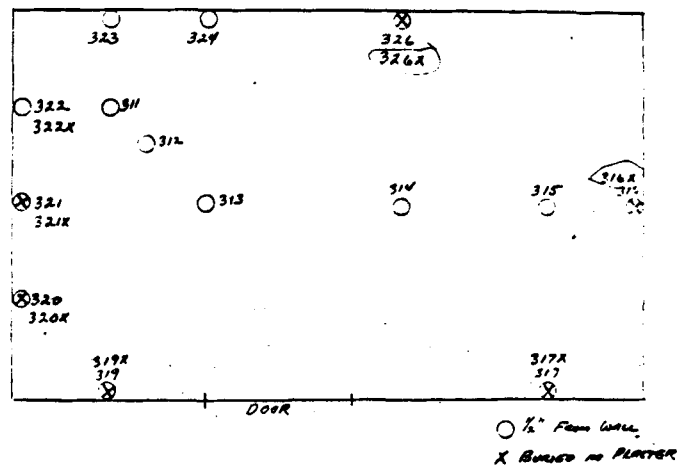


FIGURE 4. Thermocouple Locations.

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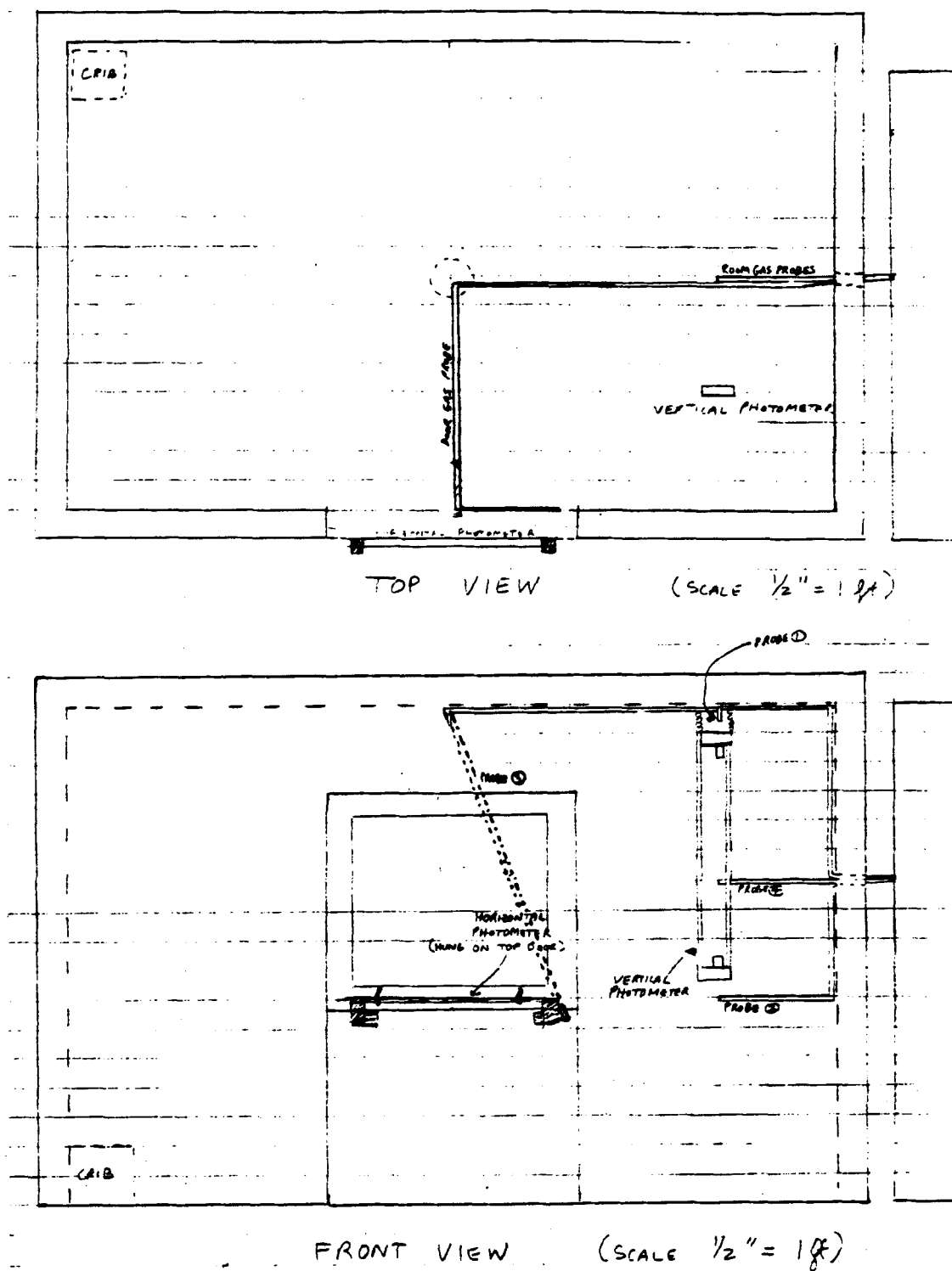


FIGURE 5. Location of gas sampling probes and smoke measuring photometers in burn room.

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Smoke Detectors -- Two smoke measuring systems were used during these tests. A 121 cm (4') path length vertical photometer was used inside the room to measure the total accumulated smoke in the room. A vertical path is necessary to account properly for stratification of the smoke. The smoke exiting the room with the hot combustion gases was measured by a horizontal photometer mounted at the bottom of the top portion of the dutch door. The pathlength of the horizontal photometer was 61 cm (2'). Locations of both photometers are shown in Figure 5.

Construction of both photometers were rugged with the collimated light source and photo-darlington light sensor sealed in water-cooled tubes supported by 3.8 cm (1½") angle-iron. An acid-resistant, high temperature epoxy paint was used for the final exterior coat. The photo-darlington light sensors (Motorola MRD 300) read out directly in terms of optical density instead of light intensity and were calibrated before each run with neutral density filters to an optical density of 7.0. It is important to use high quality neutral density filters if more than one is used at a time in the calibration process. Cheap filters have built-in optical axes and when stacked to achieve different neutral densities they gave different results depending on the relative orientation of each filter used in the stack.

Heat Flux Measurement -- Medtherm (Huntsville, Ala.) heat flux transducers were used for all surface heat flux measurements. Several versions are possible depending on the heat flux desired. If the transducers are run with the sensing surface exposed, then a combined radiative and convective heat transfer measurement is made. If the special made Irtran 2 covers are attached then only the radiative heat transfer is measured. If the environment is sooting a special gas-purging of the Irtran 2 window is also available. Basic operating principles for the Medtherm transducers are similar to that employed in Gardon foil(17) radiometers. The Medtherm transducers are factory calibrated and the calibration supplied as a plot of heat flux (Btu/ft² sec) versus millivolt output. These plots are very linear and can be reduced to a least-square line of the form

$$\text{Heat flux (Btu/ft}^2 \text{ sec)} = A (\text{millivolt output}) + B$$

Results for the gauges used in our study are listed below (all had ranges from 0-10 Btu/ft² sec):

<u>Serial No.</u>	<u>Flux Measured</u>	<u>Model No.</u>	<u>Slope A</u>	<u>Intercept B</u>
820615	radiative + convective	64-10-20T	1.16233	0.02872
820615W*	radiative	"	1.81141	0.03935
82063	radiative + convective	"	1.18559	0.04914
82063W*	radiative	"	1.88726	-0.00434
82065	radiative (gas purge)	64-10-24T	1.18675	0.05781
820616	radiative (gas purge)	"	0.98528	0.05234

*with Irtran 2 window in place

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For conversion purposes $1 \text{ Btu/ft}^2 \text{ sec} = 1.1349 \text{ watt/cm}^2$. Since the output of the heat flux transducers are in millivolts, a standard millivolt strip chart recorder was used for recording data.

Gas Velocity Measurements -- Because our tests showed that a substantial amount of material (smoke, toxic gases) was flowing out of the test room an independent measurement of the gas velocity and temperature was important. A bi-directional probe designed by G. Heskestad of FMRC(18) and discussed by B. J. McCaffrey of NBS(19) was used for the measurement. The probe was connected to a 0 to 1 torr differential pressure cell which in turn was read out through an electronics manometer. The probe is made of stainless steel tubing and is very rugged. Connection to the differential pressure cell is remote using vacuum tubing. Details are given later in this report concerning this measurement technique.

Data Logging -- During the period in which the facility was brought into readiness for this test sequence (it had been used in other tests earlier and required extensive rebuilding), we purchased and attempted to bring on-line a Gould Model 6000 high speed data logging system. After considerable effort on the part of BFG personnel and Gould personnel it became clear that the system had fundamental, unsolved problems in recording and playing back data fed into it. The unit was returned to Gould. Since there were no suitable alternatives for the environment we were working in, all data were stored on suitable charts by a combination of high speed and slow speed multipoint recorders. Data from the charts will be manually transferred to computer sheets on a "as-needed" basis and therefore the amount of data reduction and future analysis will be decreased substantially.

Conditions Used in Testing -- Because our facility is exposed to the weather, tests run in it are subject to criticisms concerning effects of humidity, wind velocity, etc. on the results obtained. In an attempt to minimize these criticisms, we restricted our testing days to those which had (a) a relative humidity less than 70%, and (b) calm winds, avoiding wind directions from the north. This reduced the number of days available for testing to ~1 to 2 days/week. Comparative burns (8750 vs. 87265, etc.) were made on the same day, usually about two hours apart. The relative humidity restriction was made to avoid HCl aerosols forming during the PVC burn tests. The wind restriction was made to avoid distortion of the crib's plume from the corner and to avoid distortion of the neutral plane and flow out the facility through the smoke measuring system on the upper half of the door. Outside air temperatures ranged from 2° to 25°C and had no apparent effect on the tests. However, outside air temperature did have an effect on operation of the facility, etc., with bitterly cold days being avoided.

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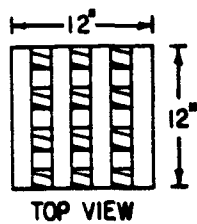
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II. Control Crib Burns

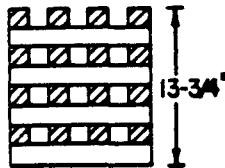
Before exposing any of the PVC sheet materials to our fire environment, we first carried out a number of measurements on wooden cribs burning by themselves in the burn room.

W. Fitzgerald(16) of Monsanto has introduced the idea of turning the room burn test into a large-scale rate-of-heat-release calorimeter by properly accounting for all of the heat generated during the fire test. To do this one must know the air flow and air temperature going in and out of the room as well as the heat release rate from the ignition source. The thermocouple placement employed will allow us to calculate the thermal balance in the room. Burning cribs, while measuring the weight loss, allows us to account for the ignition source contribution.

The wooden cribs used in our tests were either 6.4 kg (14 lb.) or 9.1 kg (20 lb.) in weight and were made of fir 2 x 2 strips as illustrated in Figure 6.

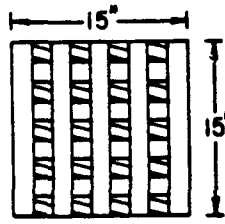


TOP VIEW

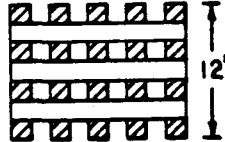


SIDE VIEW

14 LB. CRIB
(4 Sticks per Layer,
8 Layers)



TOP VIEW



SIDE VIEW

20 LB. CRIB
(5 Sticks per Layer,
7 Layers)

Figure 6.
WOODEN CRIBS
STICKS-2 X 2 FIR
(Actual Size-1 3/4" X 1 3/4")

Crib geometry(20,21) is important. The constructions shown in Figure 6 were chosen after conversations with investigators at Underwriters Lab, FMRC, and NBS. Changes to other crib geometries don't change the total heat released but do change the rate of heat release and hence also the length of fire exposure. A 6.3 kg (14 lb.) crib of the geometry of Figure 6 has a rate-of-heat-release versus time curve very similar to that seen from stuffed chairs. (22) The 6.3 kg (14 lb.) crib was used in a number of corner burn(13), room burn(3,13), and mobile home fire tests(23-25). The 9.1 kg (20 lb.) crib is a standard ignition source(13) for foam insulation corner burn tests.

The cribs were prepared by nailing the sticks together. The cribs were then dried in an air circulating oven for 48 hrs. at ~100°C to drive the moisture content very low. The cribs were then stored on a 50% relative humidity room and allowed to equilibrate. This required usually a week and was checked by the weight gain of the crib. Final adjustments in the cribs weight were then made to bring its weight in the desired range. This usually required adding one or two additional sticks to the top of the crib. Each testing day cribs were transported and stored at the burn building in sealed polyethylene bags.

The mounting assembly used in burning cribs is shown in Figure 7. A Marinite® board was used as a platform above the load cell. The load cell was a Tyco Model JP200. The cribs were placed on the platform using bricks to elevate the crib above the surface of the platform. The ignition sequence was (a) place one pound of wood excelsior between the supporting bricks on the platform, (b) place the crib over the excelsior and on the bricks, (c) pour 100 cc of ethanol over the crib leaving one corner of the excelsior free of ethanol, and (d) using a propane torch and some care, ignite the untreated corner of the excelsior. Total crib involvement in burning is rather swift using this ignition sequence. The effect of the igniting fluid has basically disappeared before the heat contribution from the crib approaches its maximum.

Spacing of the crib with respect to the wall surfaces in the corner is critical in terms of the heat flux seen by materials tested on the wall surfaces. We used a spacing of 2.5 cm (1") from both walls in the corner.

Heat contribution from a crib is normally estimated from a knowledge of the weight loss rate of the crib while burning. Assuming a constant heat of combustion for wood we estimate the heat released per unit time during combustion, I_C ($\frac{\text{kcal}}{\text{hr}}$), by

$$I_C = R \cdot W \quad \text{kcal/hr.} \quad (1)$$

where R is the rate of combustion in kg of wood per hour and W is the heat value of burning wood in kcal per kg of wood. Values assumed for W are less than oxygen bomb calorimeter values (~4000 cal/gm) and more in the range of 2500 cal/g. So by measuring the

weight loss from the crib during burning one can estimate the total heat contributed to the fire room by the crib. For a lot of fire modeling this is sufficient(26-28).

However, we are interested in the role played by the interior surface finish. And particularly we would like to relate other fire test ratings on the interior surface finish to the performance seen in the room burn test. For this reason⁽²⁹⁾ we need a better characterization of the ignition source than its burning rate. What we want is the surface heat flux seen by the interior finish as a function of crib burning time, crib geometry, and crib placement with respect to the wall supporting the interior finish. To measure some of these quantities we flush mounted two of the heat flux transducers described earlier in one of the walls making up the corner. Their location is noted in Figure 7. The transducers could measure either total heat flux (radiative and convective) or just radiative heat flux. The locations of the transducers were chosen for peak heat flux to the wall (bottom transducer) and heat flux transferred via the fire plume (top transducer). By varying the operation mode of the transducers, both total and radiative heat fluxes were measured for the 6.3 kg (14 lb.), and 9.1 kg (20 lb.) cribs as a function of time. These data are shown in Figures 8 and 9 respectively. There are a great deal of useful information in these figures:

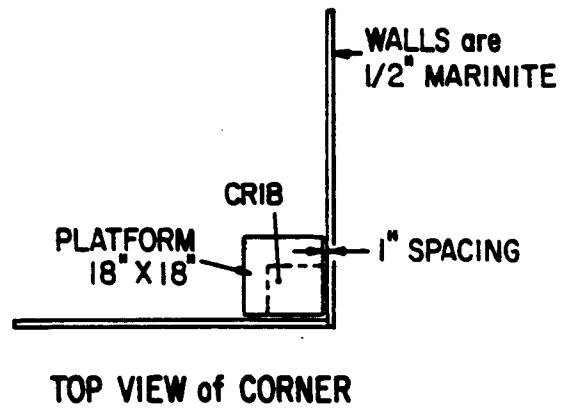
(1) The wall adjacent to the crib (bottom transducer) sees very high heat fluxes from the burning crib that increase as the burn progresses. Peak total fluxes for the 14 lb. crib are ~7 Btu/ft² sec (~8 watt/cm²) and 9.5 Btu/ft² sec (10.8 watt/cm²) for the 20 lb. crib. Most of this heat flux is radiative (70-85%) with the convective heat contribution being somewhat constant around 1.0 to 1.5 Btu/ft² sec (1.1 to 1.7 watt/cm²).

(2) Ignition of most wall surface samples is normally seen in the 4-5 minute elapsed time period which corresponds to surface fluxes of 3-4 Btu/ft² sec (3.4 to 4.5 watt/cm²), not out of line with our experience.

(3) Heat flux in the upper part of the corner from the fire plume to the wall surfaces is also very high. But is much more sensitive to the crib size because that governs the turbulent plume due to the crib. Here the dominant mode of heat transfer is radiative and the convective heat transfer is actually cooling due to entrainment of fresh air in the plume^(29,30). Heat transfer from the plume to the wall quickly rises to a certain value (3-4 minutes) and remains almost constant during the course of the burn.

(4) Remember that the heat fluxes recorded in Figures 8 and 9 are in the absence of any heat contribution from the wall itself. These tests were run against walls having no fuel content. If the ignition of a combustible wall yields fuel (which it will as excess pyrolyzate) then we have a "thermal run-away" possibility leading to total involvement of the corner area. And further, if enough fuel is consumed we have a total "flashover" of the room, the most serious fire safety situation⁽³²⁾.

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(NO SCALE)

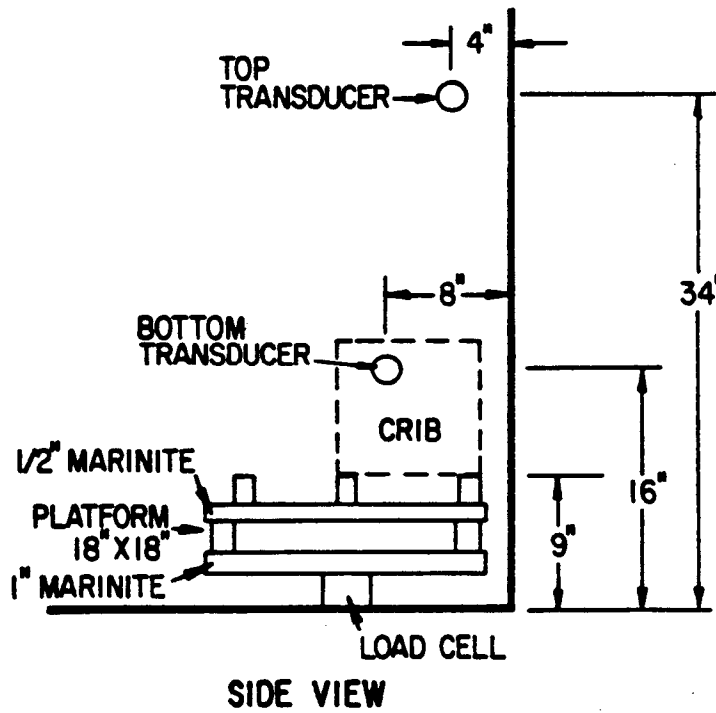


Figure 7. CRIB SUPPORT ASSEMBLY and LOCATION of
HEAT FLUX TRANSDUCERS

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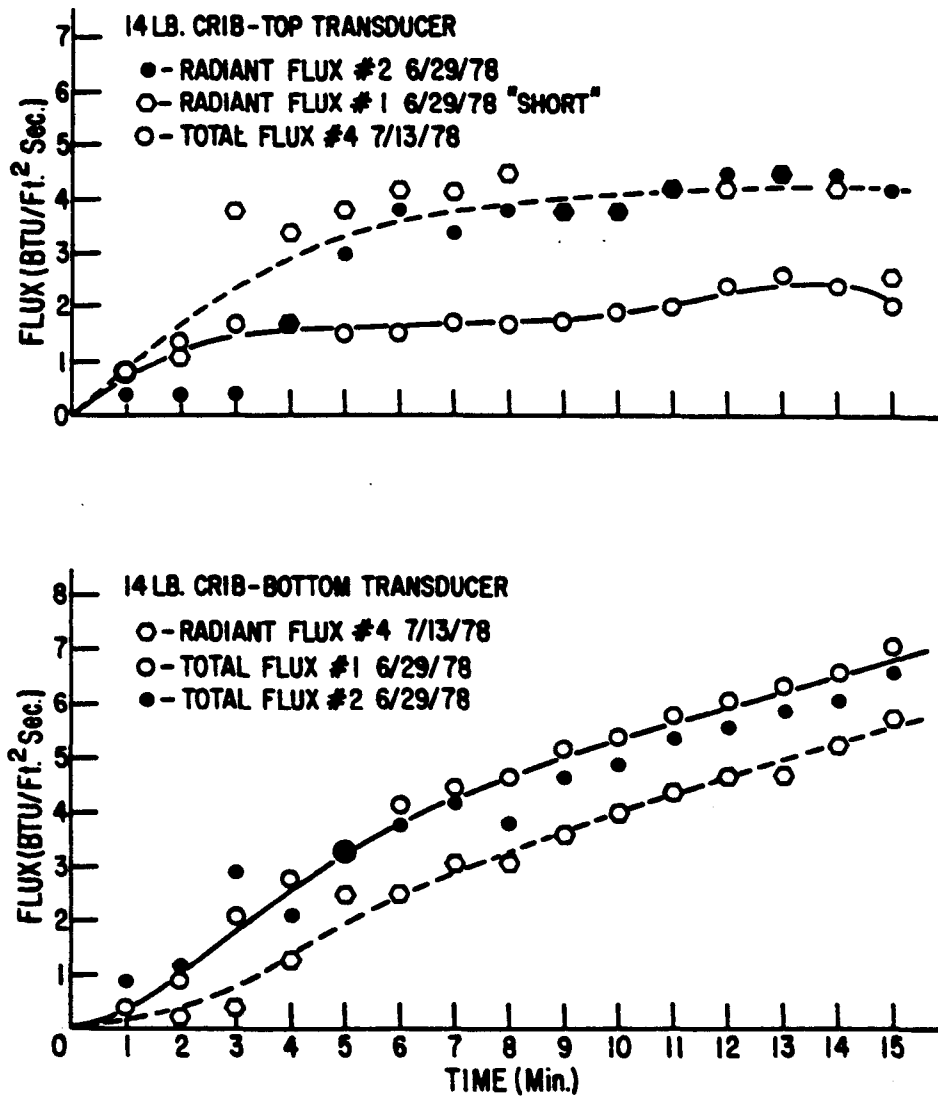


Figure 8. HEAT FLUX MEASUREMENTS for 14 LB. CRIB in CORNER TEST

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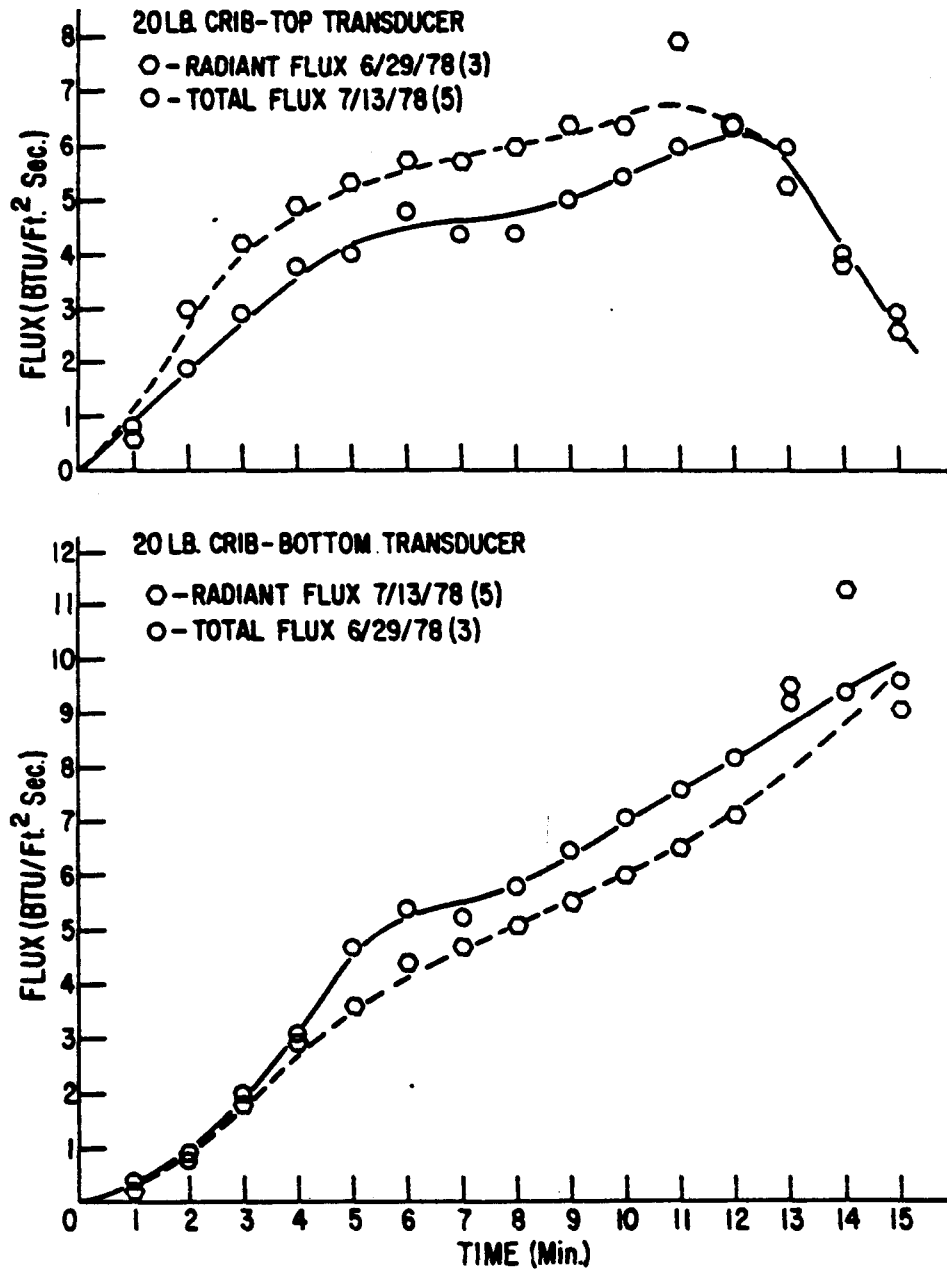


Figure 9. HEAT FLUX MEASUREMENTS for 20 LB. CRIB in CORNER TEST

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(5) In addition, we also ran a 13.6 kg (30 lb.) crib. This is shown as Figure 10. It was much slower in getting started, however, it sustained its flux level for much longer. Because of the fuel loading, this crib by itself almost took the empty fire room to flashover. This can be seen by the top transducer's radiative flux reading reaching exceptionally high values (~ 17 Btu/ft² sec or 19 watts/cm²).

(6) Compare these conditions with those used in our standard small-scale tests. For instance the NBS Smoke Chamber uses a heat flux of 2.5 watt/cm² and the OSU Rate-of-heat-release calorimeter usually operates under ~ 3 watt/cm². It is not hard to visualize how small-scale tests could be misleading in predicting performance(33). An example of this is seen in this work in the case of the polycarbonate sheet tested. This will be discussed later in this report.

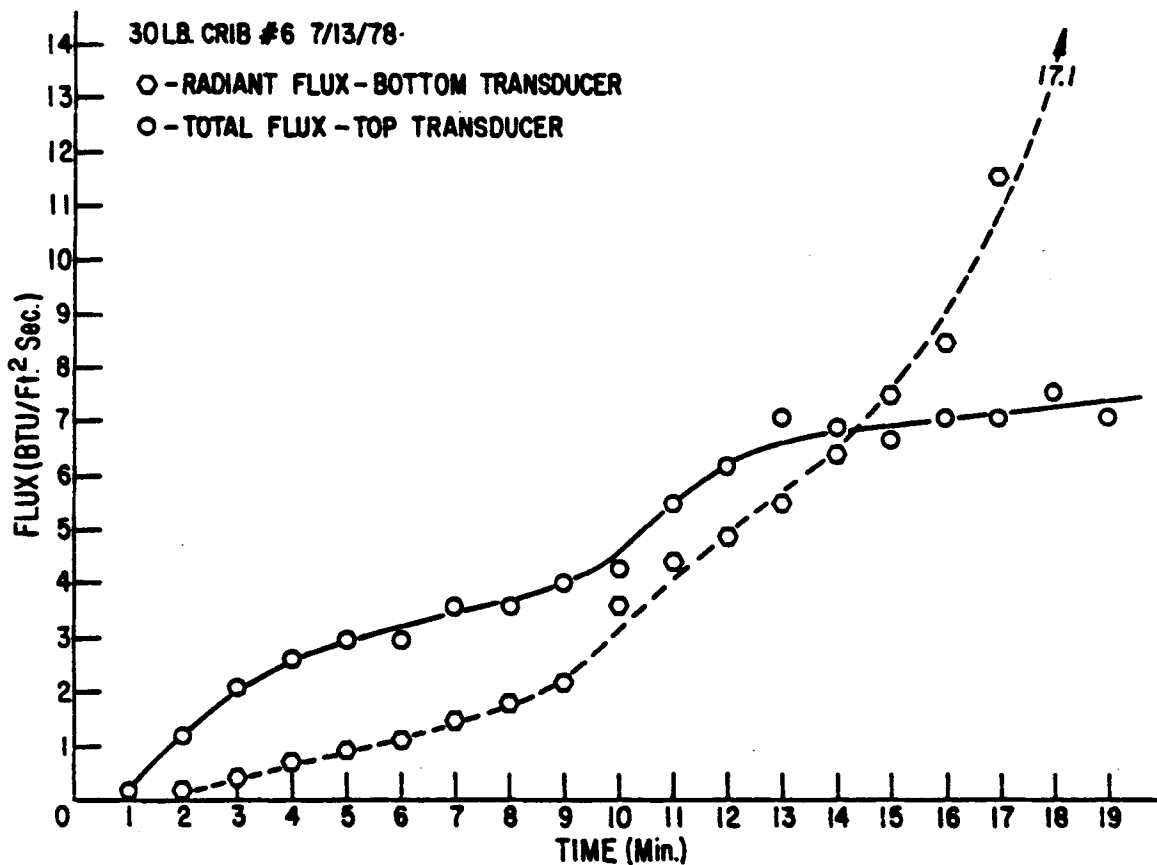


Figure 10. HEAT FLUX MEASUREMENTS for 30LB CRIB in CORNER TEST

CRIB GEOMETRY- STICKS- $1\frac{3}{4}'' \times 1\frac{3}{4}'' \times 15''$
- 5 STICKS PER LAYER, 11 LAYERS TOTAL
- OVERALL $15'' \times 15'' \times 16''$ HIGH

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Smoke from the burning cribs was very light. Toxic gas and temperature data taken in the crib burns will be discussed in a later section. Weight loss curves from the load cell were nearly linear with average slopes of 362 g/min. (0.80 lb/min.) for the 6.3 kg (14 lb.) crib, 629 g/min. (1.39 lb/min.) for the 9.1 kg (20 lb.) crib, and 685 g/min. (1.51 lb/min.) for the one 13.6 kg (30 lb.) crib tested. Using equation (1) these slopes translate into the following rate-of-heat-release values: 923 kcal/min. for the 6.3 kg (14 lb.) crib, 1604 kcal/min. for the 9.1 kg (20 lb.) cribs, and 1750 kcal/min. for the one 13.6 kg (30 lb.) crib tested.

III. PVC Sheet Burns

After several trial burns, we found a method of mounting the rigid PVC sheet samples that seemed to be a good compromise for the problems seen. The rigid PVC sheets were trimmed to give a fairly straight edge and were butt-joined to make up panels around 100 cm (40") wide. These in turn were glued to a 122 cm x 244 cm (4 ft. x 3 ft.) panel of 1 cm (3/8" Gypsum® wallboard using 3M Adhesive No. 2226, a latex contact adhesive based on Neoprene which is UL®-rated for E-84 tests of plastic laminates. Two wallboard mounted panels were used for each test (one attached to each wall making up the corner). This allowed rapid assembly and disassembly of the test corner. All tests run in our program are listed in Table I. As a precaution to avoid adhesive failure high in the corner, thereby allowing the entire PVC panel to fall into the crib fire, we used a band of glass fiber based "glass tape" around the top of each panel about 2.5 cm (1") down from the top. This worked well and contributed no fuel to the fire. Metal fasteners (nails, tacks, etc.) fail because a hole "melts" around the fastener in the heated upper part of the corner. All panels were 230 cm (90.5") high. The ceiling of the corner in all cases was Gypsum® wallboard, replaced on a "as needed" basis.

All fire tests were started using the excelsior/ethanol method described earlier. Tests were terminated by a small water hose. Scott Air-pacs® were used by personnel near the burn building. The tests were all run with the upper part of the door closed and the ventilating fan off during the test.

In all tests involving PVC, the pungent odor of HCl was apparent. Tests involving Geon 8750G, a commercial extrusion grade compound, had high levels of very black smoke. Tests involving Geon 87265, 87266, 87234, and 87235 had little visible smoke. The Tuffak® polycarbonate sheet showed little activity until about half-way through the test then it almost flashed over, billowing huge clouds of intense black smoke under the door. Figures 11, 12, and 13 are representative photos of what was seen visually by us and others present for the tests. Analyses of the data obtained from these tests are carried out in the next section.

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TABLE I

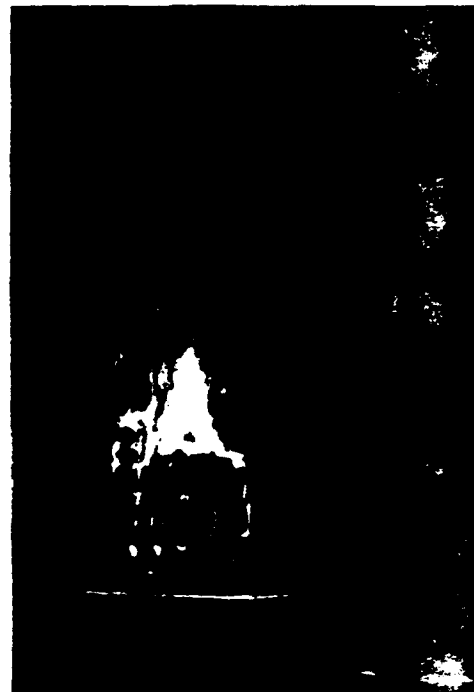
No.	Material Tested	Crib Size (lb)	PVC Width Supplied (in)	PVC* Width Tested (in)	PVC Sheet Thickness (in)	Total Weight PVC Tested (lb)	Relative Humidity (%)	Outside Temperature °F	Barometer (in Hg)	Sample Color
1	none	14.0	---	---	---	---	42	90	29.5	---
2	none	14.1	---	---	---	---	42	90	29.5	---
3	none	20.1	---	---	---	---	42	90	29.5	---
4	none	13.9	---	---	---	---	61	70	29.2	---
5	none	19.5	---	---	---	---	61	70	29.2	---
6	none	30.0	---	---	---	---	61	70	29.2	---
10**	8750G	14.0	12	39	.040	18	62	74	29.9	grey
11	87565	14.0	15/30	39	.030	12	50	83	30.0	off-white
12	8750G	14.0	12	39	.040	18	65	87	30.0	grey
13	87265	14.0	15/30	39	.030	12	60	90	30.0	off-white
14	87265	20.0	15/30	39	.030	12	67	84	30.0	off-white
15	87265	14.0	11.5	40	.125	46	64	63	29.9	off-white
16	8750G	14.0	12.5	38	.100	36	57	67	29.9	grey
17	87265	14.0	11.5	40	.125	46	59	68	29.9	off-white
18	8750G	14.0	12.5	38	.100	36	54	72	29.8	grey
19	87266	14.0	30	40	.030	12.4	65	49	29.8	off-white
20	8750G	14.0	12	39	.040	18	53	59	30.2	grey
21	87234	14.0	13	40	.125	44.6	69	47	30.2	white
22	87235	14.0	13	40	.125	42.9	56	60	30.2	beige
23	87265	14.0	28	42	.070	26.8	58	53	30.4	off-white
24	Tuffak® Polycarbonate	14.0	48	48	.030	20.8	59	58	30.3	transparent

*Several pieces of PVC sheet were butt-joined to make up the full width panel. Dimension given refers to just one wall common to the corner, total amount of PVC is twice this amount.

**Tests 7, 8, and 9 were used to line out the sample mounting techniques and instrumentation and are not reported here.

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Figure 11. Test No. 18, Geon 8750G (0.100")

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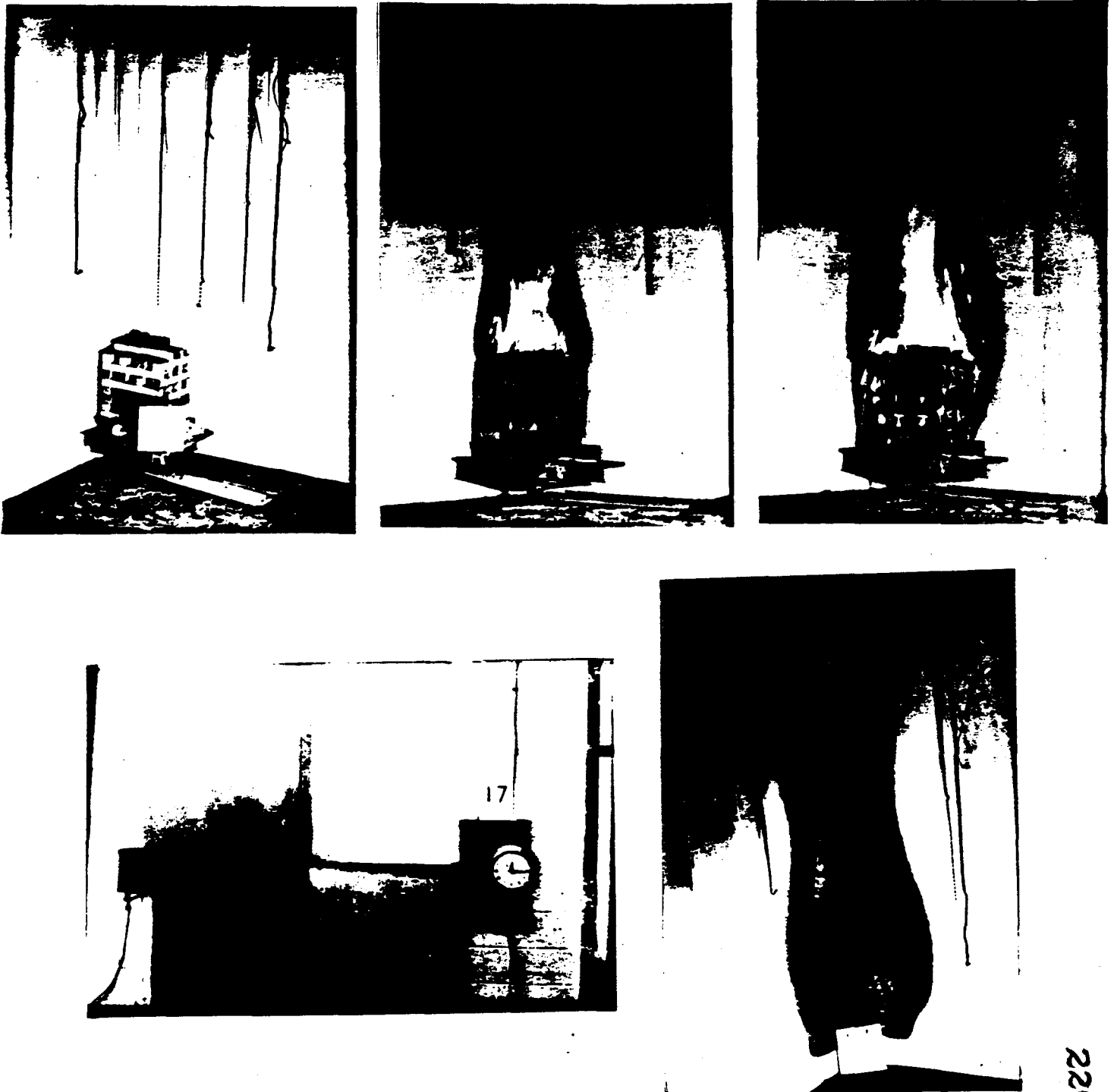


Figure 12. Test No. 17, Geon 87265 (0.125'').

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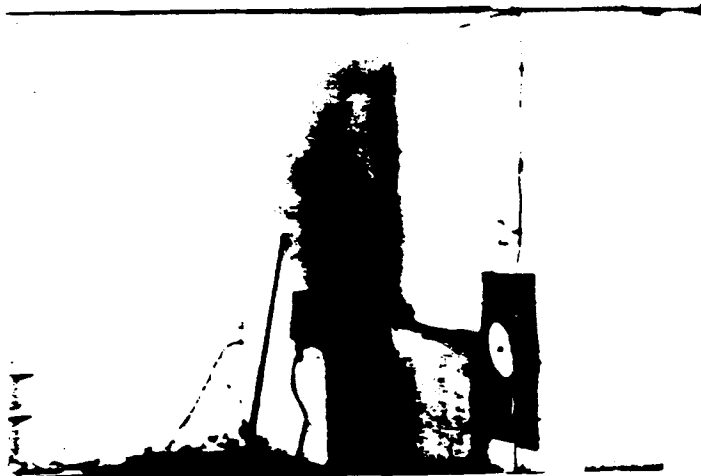


Figure 13. Test No. 24, Tuffak® Polycarbonate (0.030")

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IV. Data Analysis and Modeling of the Room Burn

In analyzing the data taken from the crib burns and the PVC sheet burns we have chosen a specific model of the room burn test to work from. The model is a two-fluid hydraulic flow model developed by H. Emmons and Factory Mutual Research^(4,5). It allows us to keep track of all of the heat, smoke, and combustion gases generated during the test. If enough data were available, it would also allow us to do a total heat and mass balance on the fire test.

A. Smoke -- Smoke is generated by the PVC exposed to the crib fire. The amount of PVC consumed during the fire test can be estimated from photos taken of the corner after the test was halted. The amount of smoke generated by the PVC during the fire test is calculated using the following equation:

$$W_{\text{smoke}} = W_{\text{flow}} + W_{\text{residual}}$$

where W_{smoke} is the total weight of smoke (in grams) generated during the fire test, W_{flow} is the weight of smoke that escaped the burn building by flowing under the top part of the dutch door during the fire test, and W_{residual} is the weight of smoke left in the burn room at the end of the fire test. W_{flow} is calculated from a knowledge of two parameters, (a) the instantaneous smoke per unit volume as measured by the horizontal photometer mounted on the dutch door (which "samples" the smoke in the gas flow going out of the room) and (b) the instantaneous volumetric flow rate out the door. W_{residual} is also calculated from two parameters, (a) the residual smoke per unit volume in the room at the end of the test, and (b) the volume of gas containing smoke in the room at the end of the test. A key technical point in these calculations is that the volume of the burn room is not the volume used in these calculations. A close examination of the photos in Figures 11 to 13 will show the presence of a "boundary" above which the smoke is contained and below which the air appears clear. This "boundary", called the neutral buoyancy plane, separates the cold (in a relative sense) incoming air from the hot exiting gases. Its position with respect to the height of the room is dynamic and can be calculated using a variety of fluid mechanical models^(34,35). It can also be measured by thermocouple measurements or by bidirectional flow meters if they are closed spaced in a vertical manner.

The Home Fire Project^(4,5,34) jointly sponsored by Factory Mutual Research and Harvard University has developed a very reasonable model for this flow using Emmons⁽³⁴⁾ two fluid buoyancy driven hydraulic flow model and has experimentally documented it in detail. We elected to use this model because of its mathematical simplicity. Using a bidirectional low velocity flow meter (described in more detail in a later section) we verified that the values obtained from the model are in the correct range. However, because of electronic problems with the instrumentation, we were unable to obtain actual flow data for all experiments and we

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relied upon the model to calculate flow curves for those experiments. The Emmons⁽³⁴⁾ two fluid model gives the mass flow rate of air out the door as

$$\frac{W_o}{\phi} = C \frac{\sqrt{g}}{3} [R(1-R)]^{\frac{1}{2}} \left[\frac{h_o}{H} \right]^{\frac{3}{2}} \quad (2)$$

where W_o = mass flow rate of air out the door (g/sec)

$\phi = g^{\frac{1}{2}} \rho_a A H^{\frac{3}{2}}$ = buoyancy flow (g/sec)

C = doorway flow coefficient = 0.68

$R = \frac{\rho}{\rho_a} = \frac{T_a}{T}$

ρ = density of gas at temperature, T

ρ_a = density of air at temperature, T_a

H = doorway height

A = doorway opening area

h_o = depth of outflow at the door

g = gravitational constant

Putting in values appropriate for our experimental set-up and converting Equation (2) to a volume flow rate gives

$$V_o = 1.757 [R(1-R)]^{\frac{1}{2}} \left[\frac{h_o}{H} \right]^{\frac{3}{2}} \quad (3)$$

where V_o has units of m^3/sec . Using Emmon's analysis of flow under "choked" conditions as a guide we make the following ansaltz

$$\frac{h_o}{H} \sim \frac{1}{1 + \chi^{\frac{1}{3}}} ; \chi = \frac{R}{1-R} = \frac{T_a}{T - T_a} \quad (4)$$

which satisfies all the boundary conditions and correctly predicts the form of the curve of h_o versus temperature in the room. Using this we simplify Equation (3) to obtain

$$V_o = 1.757 \left[\frac{1}{\chi^{\frac{1}{3}}(1 + \chi^{\frac{1}{3}})} \right]^{\frac{3}{2}} (m^3/sec) \quad (5)$$

where the value of T used to calculate χ is the temperature in the doorway where the smoke measurement is made. Using this model (Equations (4) and (5)) we can calculate the location of the neutral boundary plane and the volume of gas flowing out of the burn room during the test.

Going back then to the desired smoke values, W_{flow} and $W_{residual}$, we calculate these values using the following equations:

$$W_{flow} = C'' \int_0^{t_{end}} I_H(t) V_o(t) dt \quad (6)$$

$$W_{residual} = C'' I_v A R h_e \quad (7)$$

where $I_H(t)$ = properly averaged optical density of smoke from horizontal photometer at elapsed time, t .
 V_o = volumetric flow out doorway at elapsed time, t , calculated by Equation (5).
 I_v = optical density of smoke remaining in room at end of test, taken from vertical photometer.
 A_R = cross-sectional floor area of room.
 h_e = height of neutral boundary at end of test (calculated from Equation (4)).

and where C'' is a constant converting the optical density per unit length pathlength measurement of smoke to a weight per unit volume measurement of smoke (mg/m^3). Fortunately King⁽³⁶⁾ measured C'' for rigid PVC and several other plastics and found it to be a constant over a reasonable range of optical density per meter values. We assume this to hold for our measurements and of all the assumptions made in this calculation this is the most important one. For our experimental system C'' has units of $(\text{mg}/\text{m}^3)/\text{OD}$ and has the numerical value

$$C'' = 218 \frac{(\text{mg}/\text{m}^3)}{\text{OD}}$$

where OD stands for optical density.

The procedure for calculating W_{flow} is a point by point multiplication of the optical density versus time plot and volumetric flow rate out the door versus time plot and then a summing over the elapsed time in the test. To reduce the work involved, we averaged the optical density and air velocity profiles over one minute intervals before multiplying and summing. The data for smoke from the tests ran are in Table II. Examples of the volumetric flow rate plots for tests run are given in Figure 14.

Table II also contains other smoke data that relates well with our visual observations and impressions. Column D lists the peak smoke optical density measured during the test on the vertical photometer. Column E gives an integrated average optical density per meter (OD/m) pathlength for each of the tests. Past studies have shown that OD/m values much over 0.2 pose visual hazards. Values of OD/m seen for 8750 Grey and the Tuffak® polycarbonate (1.0-1.5) represent impenetrable blackness and would make vision impossible. (Note that these smoke values apply to the top layer of hot gases in the room, the floor was generally clear). Column F gives the corresponding average optical density per meter value for the horizontal photometer on the door. Columns G, H, I give the weight of smoke values corresponding to Equations (6) and (7) and the total weight of smoke produced, respectively.

For comparison purposes in Column J we give NBS Smoke Chamber flaming mode smoke values for the actual samples tested in the burn room. For the PVC based materials we see a good correlation between the values from the NBS Smoke Chamber and the smoke values in Columns E and I. This is shown in Table III.

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RESULTS FROM LARGE SCALE TESTS

TABLE II

Column	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
Material Tested	Crib Size (in)	Thickness PVC(in)	Sample Weight (lb)	Vertical Smoke Peak CO	Vertical Smoke Avg./m	Horizontal Smoke Avg./m	Weight Smoke Wt (lb)	Weight Smoke Wt (lb)	Total Weight Smoke Wt (lb)	NBS Smoke < 100 >	Peak CO (ppm) (Probe #2)	Peak CO (ppm) (Probe #3)	Total Weight CO (lb)	Total Weight CO (lb)	Peak Temp. Location (1131°C)	CO as % of Sample Wt.	Station in Pylon Ending Up As Smoke	Yield %	
1	14	---	---	neg.	<0.05	<0.05	---	---	---	---	MA	MA	MA	MA	230	MA	---	---	---
2	14	---	---	neg.	<0.05	<0.05	---	---	---	---	MA	MA	MA	MA	232	MA	---	---	---
3	20	---	---	neg.	<0.05	<0.05	---	---	---	---	MA	MA	MA	MA	225	(est) 2.7	---	---	---
4	20	---	---	neg.	<0.05	<0.05	---	---	---	---	MA	MA	MA	MA	370	MA	---	---	---
5	20	---	---	neg.	<0.05	<0.05	---	---	---	---	640	680	232	---	302	2.6	---	---	---
6	30	---	---	neg.	<0.05	<0.05	---	---	---	---	(est) 841850	(est) 2250	(est) 377	---	415	3.8	---	---	---
10	14	.040	18	>7	1.71	1.20	192	6	198	571 ± 85	MA	MA	MA	MA	1097	MA	---	---	---
12	14	.040	18	>7	1.45	0.60	110	6	116	"	MA	MA	MA	MA	705	MA	---	---	---
14	14	.040	18	>7	1.33	0.36	MC	MC	MC	"	2,300	4,600	628	1176	260	MA	---	---	---
16	14	.100	36	>7	1.88	0.80	155	26	181	863	4,300	9,000	1,565	3553	312	5.6	---	---	---
18	14	.100	36	>7	1.78	0.58	92	26	118	"	11,000	10,000	2,140	4114	285	8.5	---	---	---
19	14	.030	12	2	0.47	0.28	41	5	46	140	MA	MA	MA	MA	260	12.2	---	---	---
21	14	.030	12	2	0.32	0.35	75	3	78	"	MA	MA	MA	MA	255	MA	---	---	---
22	20	.030	12	2.5	0.56	0.36	MC	MC	MC	"	MA	MA	MA	MA	322	MA	---	---	---
23	14	.070	26.8	2	0.44	0.61	35	2	37	245	3,200	3,700	616	625	312	3.7	---	---	---
24	14	.125	46	3.5	0.49	0.62	61	8	69	244	1,200	6,000	976	2100	285	3.8	---	---	---
25	14	.125	46	3	0.38	0.30	36	11	49	"	6,000	6,400	829	1818	285	3.2	---	---	---
26	14	.030	12.4	3.5	0.55	0.55	37	1	38	237	2,000	3,000	359	423	270	3.4	---	---	---
27	14	.125	42.6	3.8	0.86	0.08	3	8	11	487 ± 88	1,400	3,200	470	416	270	1.6	---	---	---
28	14	.125	42.6	3	0.70	0.25	16	8	22	327 ± 92	1,500	2,500	303	536	262	0.7	---	---	---
29	14	.030	20.8	>7	1.15	0.98	304	14	318	68	18,000	19,000	1,888	neg.	540	18.2	---	---	---

*This value was estimated from the 20 and 30 pound crib data.
 †Values for the 30 pound crib are minimum values due to a base line shift in the CO system that occurred during the test.

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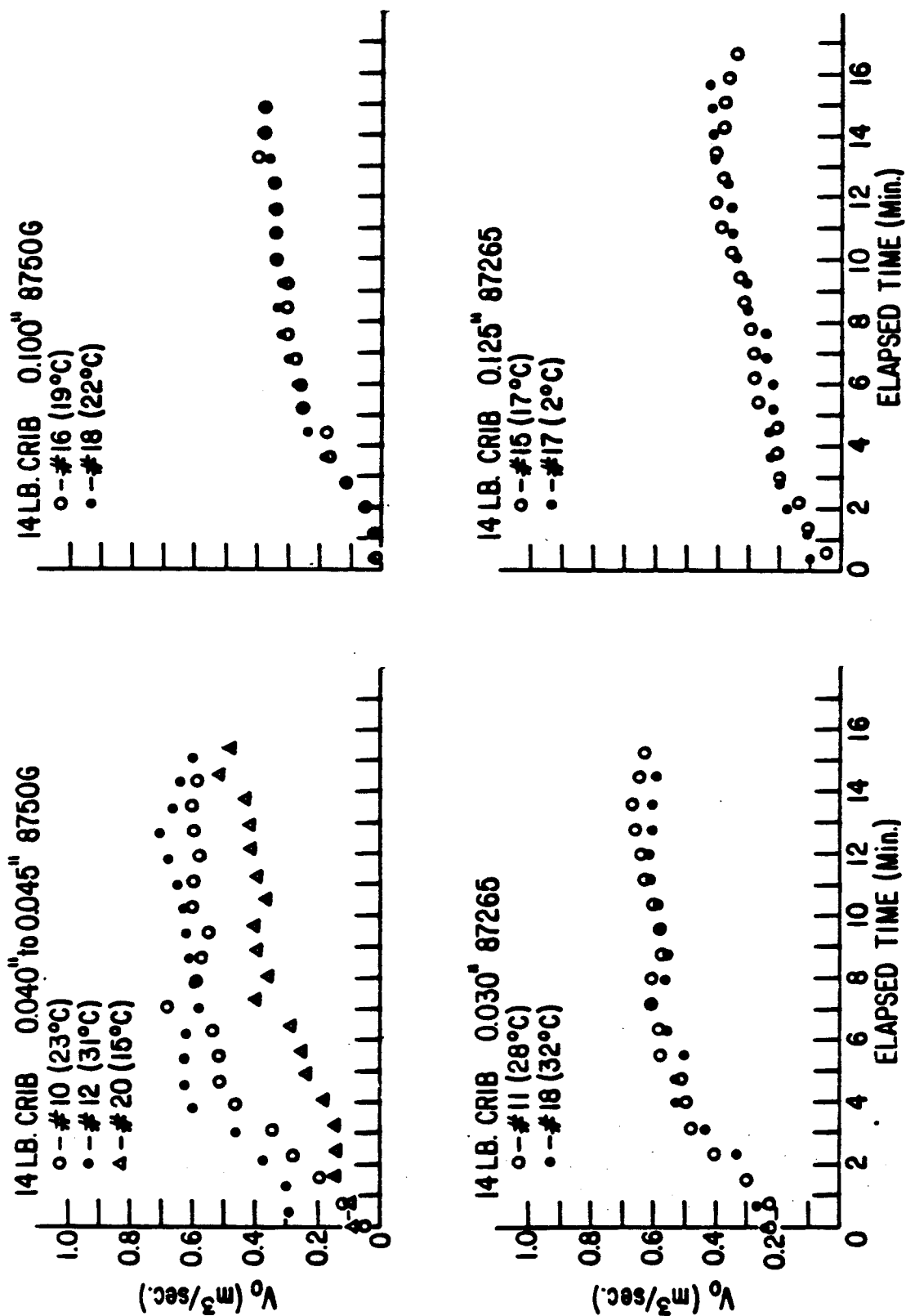


Figure 14. CALCULATED DOOR OUTFLOW RATES

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TABLE III

<u>Material</u>	<u>Thickness(in)</u>	<u>%Reduction in Smoke</u>	<u>%Reduction In NBS Smoke</u>
8750G	.040	--	--
87265	.030	61	67
87266	.030	76	45
8750G	.100	--	--
87265	.125	61	72
87234	.125	93	44
87235	.125	85	62

The outstanding difference is the Tuffak® polycarbonate which is remarkably low in smoke in the small-scale NBS smoke test but produced enormous quantities of smoke in the large scale test. This is a classic illustration of the problem of small scale-large scale lack of correlation. We believe the difference to be explained by the difference in heat flux experienced by the polycarbonate sample.

Column R gives a final smoke measurement by relating the total smoke measured (Column I) to the weight of sample tested, adjusting for the carbon content of the sample. On this basis, 8750 Grey and the polycarbonate sample give about the same yield of smoke per weight of sample tested. Both smoke retardants and increased sample thickness (slowing down the heat conduction) reduced the yield of smoke and were consistent with our past information.

Air Flow Measurement -- Since we are using a calculated volumetric flow rate as the basis of our smoke calculation, we felt it important to get experimental conformation under our test conditions of the reasonableness of the values calculated by Equation (7) and shown in Figure 14.

The technique we used was a rugged bidirectional velocity meter developed by Factory Mutual Research⁽¹⁸⁾ and calibrated by the National Bureau of Standards⁽¹⁹⁾. A drawing of the probe is given in Figure 15 along with a block diagram of how the probe instrumentation is set-up.

The probes we used were made from stainless steel and had a diameter of 1.2 cm ($\frac{1}{2}$ "). The probe works by sensing the pressure difference across the steel diaphragm and then using the NBS calibration curve to convert the pressure difference into the velocity of the gas stream probed. Because of its symmetry, the probe is bidirectional and because of its construction it is extremely rugged and capable of remote mounting. The differential manometer cell used was a Model 570D-IT-2AI-VI cell made by Datametrics. A Datametrics electronic manometer readout unit was already available at Brecksville and was used with this cell. Unfortunately, the readout unit had not been used in several years and when activated was

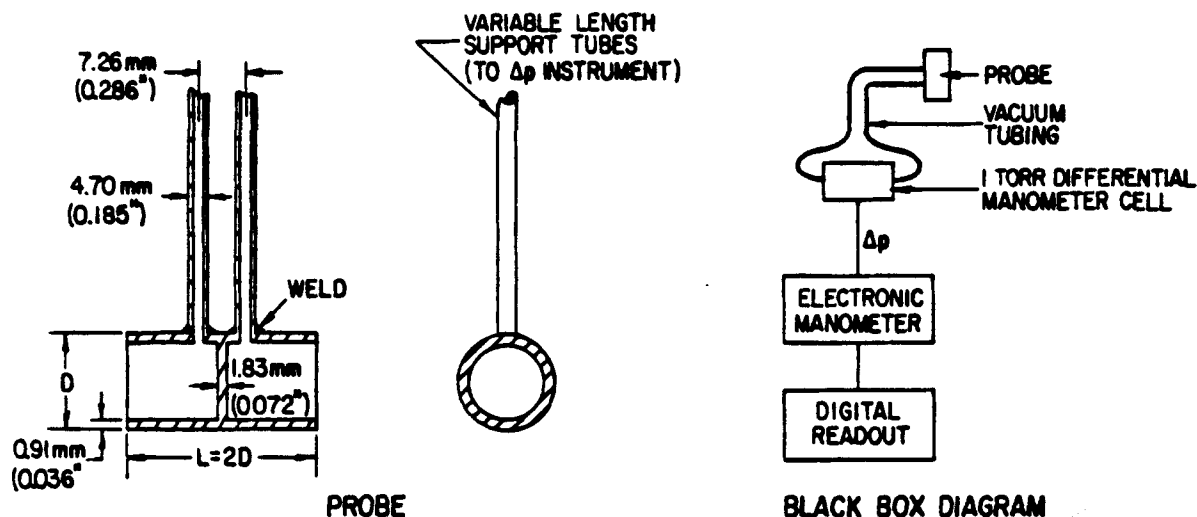


Figure 15. BIDIRECTIONAL FLOW METER

found to have enough problems that it was returned to the factory for repair which required several months.

The calibration supplied by NBS for the probe is of the form of a fifth order regression equation in the Reynolds number,

$$\frac{(2\Delta p/\rho)^{1/2}}{V} = A + B(Re) + C(Re)^2 + D(Re)^3 + E(Re)^4 + F(Re)^5 \quad (8)$$

where Re is the Reynolds number and A to F are constants that can be found in Reference 19. Because of the wide range of temperatures involved in our work, we solved Equation (8) for the velocity, V , as a function of the pressure differential, Δp taking into account the temperature variations of the density and gas viscosity. The net result of this is shown in Figure 16 which shows that temperature differences come into play only at the higher flow rates. Using a 14# crib burn we found that Δp varied from 0.01 to a peak of 0.03 torr and that this translated into a volumetric flow rate of from 0.45 to a peak of 0.82 m³/sec respectively, in excellent agreement with the calculated values per Equation (5).

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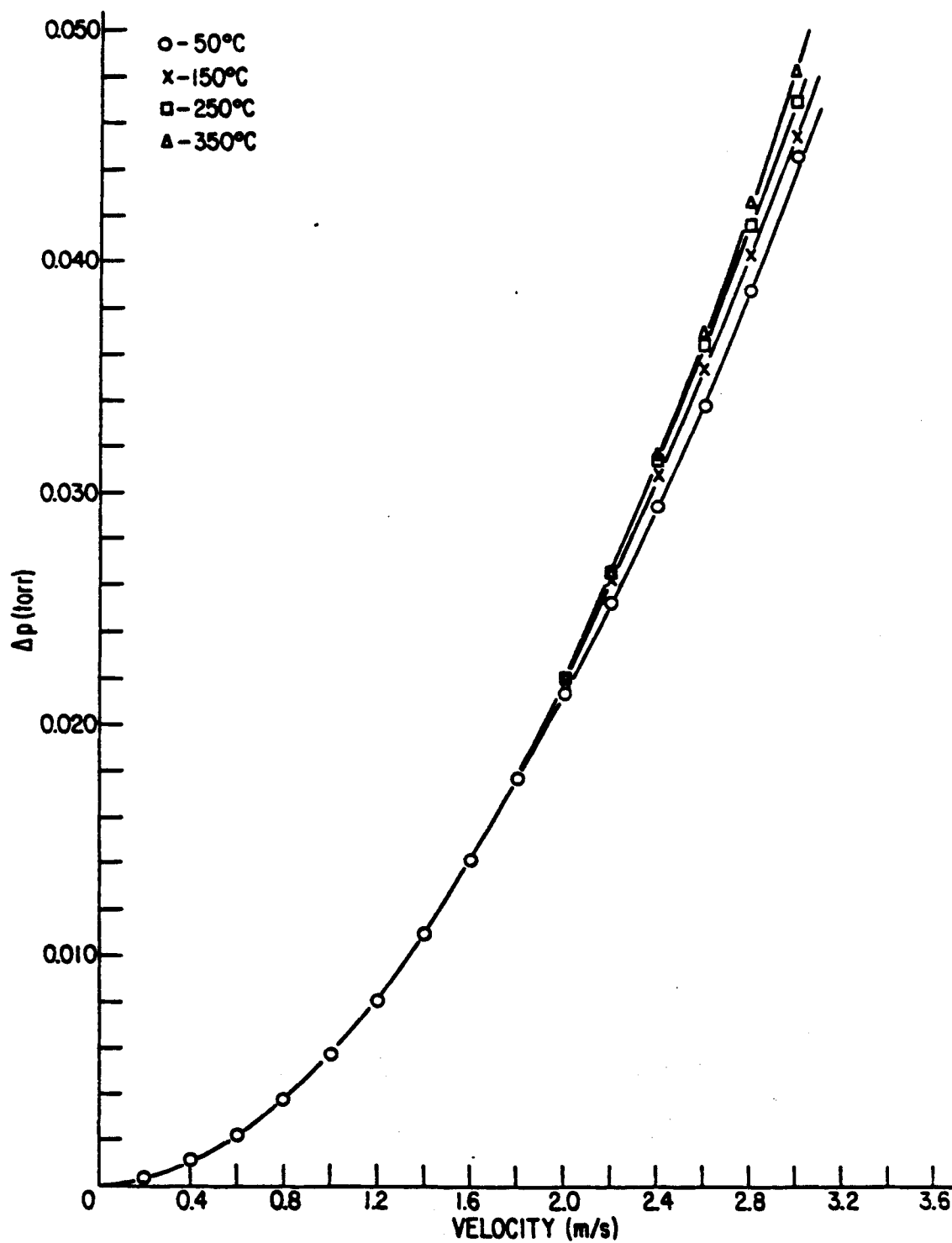


Figure 16. Response Curve for FMRC Velocity Probe.

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B. Toxic Gas -- The toxic gas data generated during our tests are also given in Table II. Columns K and L in Table II give peak CO levels recorded for probe locations #2 and #3 as shown in Figure 5. Figure 17 plots out the CO data for some typical runs from all four probe points. Examining the data in Column K and L we find that the peak CO levels seen for PVC samples increase as the amount of PVC exposed increases. The peak CO concentrations seen for the thick 8750G material (Tests 16 and 18) and for the polycarbonate (Test 24) are in the range of 1-2% which are dangerously high.

Using the same methodology as outlined earlier for the total weight of smoke calculation, R. Yount (ALTC) computed the total measured yield of CO for our tests. His values are given in Column M of Table II. Subtracting out the CO due to the cribs, we calculated the CO yield as a percentage of the total carbon available in the test (gCO/gC in sample). Again the 8750 and polycarbonate samples show the highest values. Comparing the smoke retarded PVC's (87265, 87234, 87235) to the control PVC (8750G) we see a dramatic decrease in the weight of CO generated at equivalent thicknesses. This is illustrated in Table IV.

TABLE IV

<u>Material</u>	<u>Thickness(in)</u>	<u>%Reduction in CO Generated*</u>	<u>%Reduction in HCl Generated*</u>
8750G	.040	--	--
87265	.030	NA	12
87266	.030	59	43
8750G	.100	--	--
87265	.125	59	59
87234	.125	85	91
87235	.125	93	89

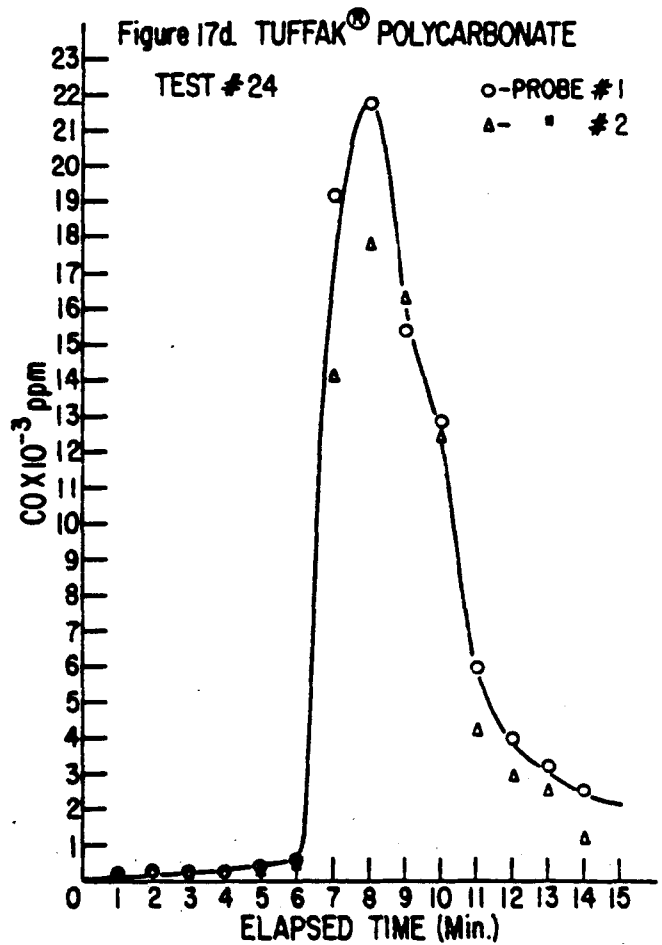
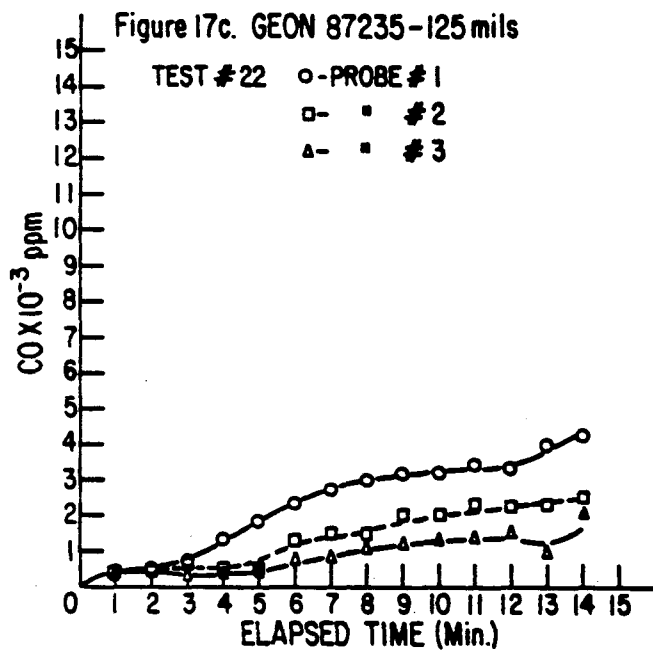
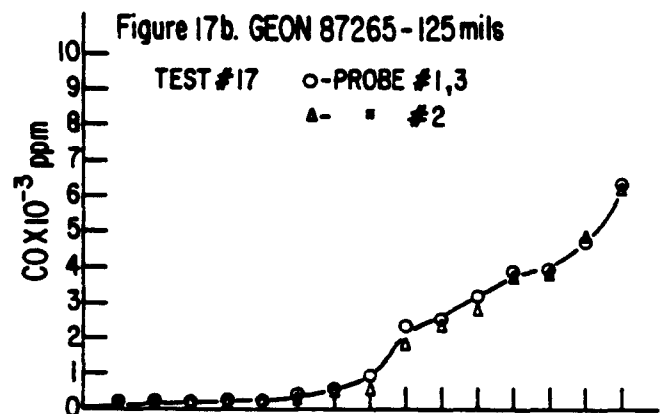
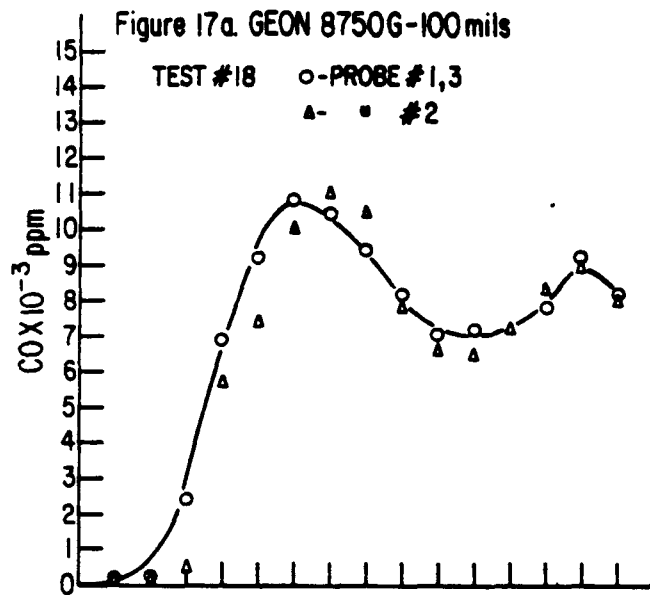
*Based on average of two burns in most cases.

For the thin gauge samples, we do not see much difference in the HCl generation while for the heavy gauge PVC samples we see large reductions in both CO and HCl yields. This is very consistent with the char formation mechanism established for the smoke retarded PVC materials. At thin gauges the char is not sufficient in depth to protect virgin polymer underneath the surface. But at thermally thick gauges the char is functioning well in removing fuel from the surface layer. Visual observation and photographs easily confirm the large intumescent chars formed by the smoke retarded PVC compounds which once formed remained virtually intact during the test and limited the area of PVC exposed to the fire source.

The HCl data in Columns N and S as well as Table IV are also consistent with our char formation model.

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C. Heat Buildup -- Because of the problems encountered with our electronic data logging system, all of our temperature data was put on strip-chart recorders and has to be transcribed to a computer format by hand. At this writing we have not completed this phase of the work and the associated heat and mass balance phase to follow it. Column P in Table II gives peak temperatures seen at one of the key thermocouple locations during the tests. Table V compares the materials tested in terms of heat contributed to the fire.

TABLE V

<u>Material</u>	<u>Thickness(in)</u>	<u>%Temperature Increase Over Crib*</u>
8750G	.040	20
87265	.030	9
87266	.030	14
Tuffak® polycarbonate	.030	129
8750G	.100	31
87265	.125	21
87234	.125	14
87235	.125	11
87265 (20# crib)	.030	negligible

*Based on average of two burns in most cases.

In line with our general expectations, rigid PVC does not contribute significantly to the fire buildup and the char-forming smoke retarded PVC samples contributed less than the regular PVC. The Tuffak® polycarbonate sheet made a significant contribution to the fire and the temperature reached, 500°-600°C, is in the range seen for flashover under these conditions. Figure 18 shows temperature-time profiles for some of the tests run.

V. Technical Conclusions

By all the measures we could apply under a room corner burn environment, the smoke-retarded, char-forming PVC compounds gave superior performance to a comparative commercial PVC compound. The smoke-retarded PVC compounds generated lower smoke, lower CO, lower HCl, and contributed somewhat less heat to the fire. Compared to flammable plastics and natural products such as wood and plywoods the rigid PVC control compound performed well in the sense that it did not tend towards flashover even at high loadings in the corner.

Because of the condensed phase mechanism of our smoke retardants, we expected, and we found, that the improved PVC materials (87265, 87266, 87234, and 87235) demonstrated their superiority

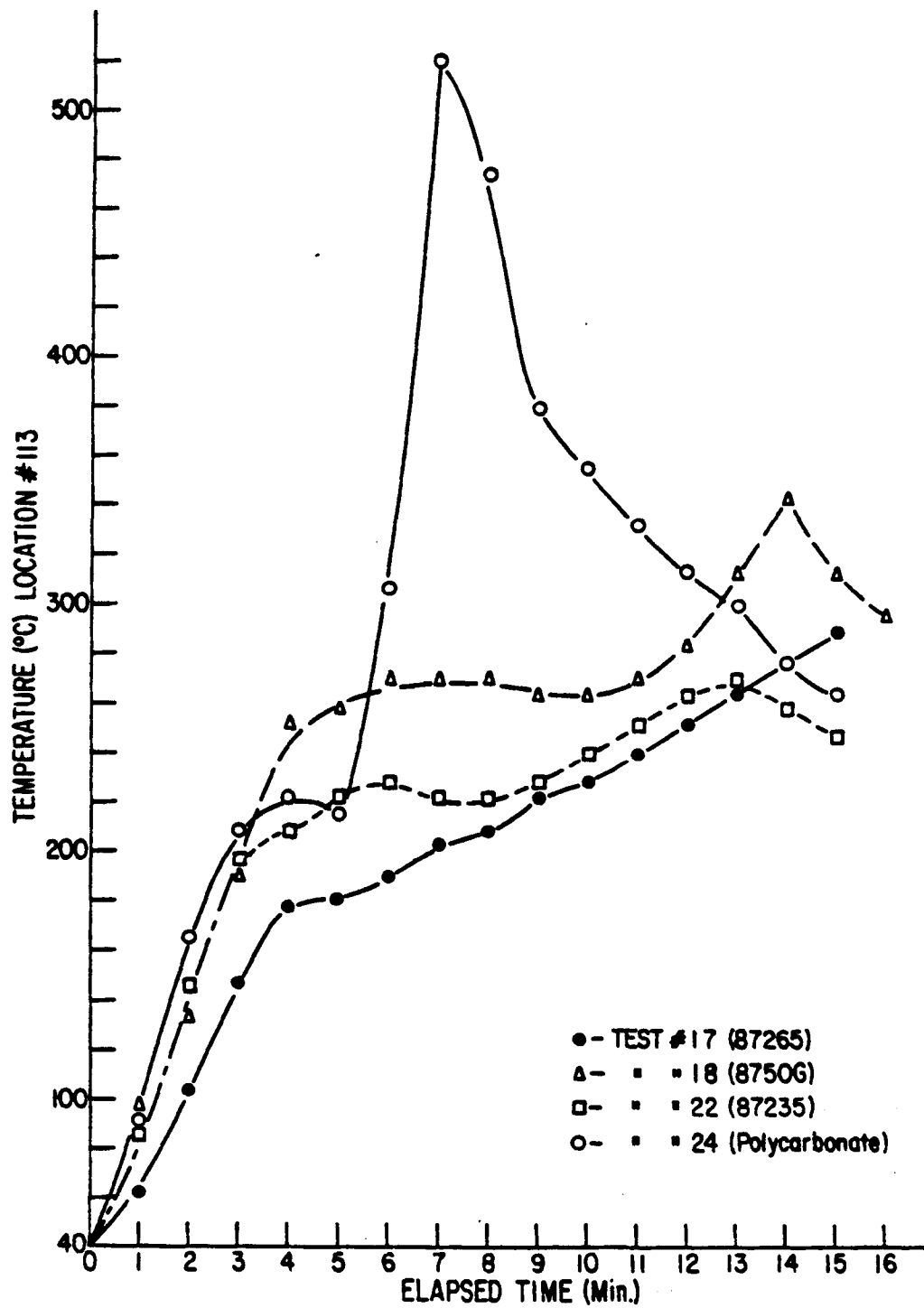


Figure 18.

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under these more rigorous and more realistic testing conditions. Other flame retardant mechanisms have been shown to not have this test insensitivity.

Insights into the problems with small-scale test protocols were illustrated in three different performance categories in this study. (A) The first case involved the relationship between small-scale NBS Smoke Chamber ratings and the smoke generated under our room burn test conditions. The PVC samples related well but the polycarbonate sample, which has exceptionally good NBS Smoke Chamber ratings, had the highest (worst) smoke ratings under our conditions. (B) The second case involved the relationship between small-scale toxic gas protocols and the amount of CO and HCl generated under our test conditions. There are a bewildering number of toxic gas protocols. However, a general consensus of results generated on our smoke-retarded PVC compounds was that under these protocols they were perhaps equal to but not superior to regular PVC in terms of CO generation (exceptions to this comment are 87234 and 87234⁽³⁷⁾) and that HCl generation would be at least equal to and perhaps occur at a faster rate than the control PVC compounds.⁽³⁸⁾ Our test results argue that intumescent char, particularly in the thicker samples, significantly impedes the fire growth and even if the small-scale test results are correct on a per unit area burnt basis, this char formation substantially reduces the total yield of toxic gases to be transported away from the fire region. (C) The third case involves the choice of crib size (and hence the heat flux on the surface of the sample) and shows how this choice can lead to very misleading results. General Electric in its publication⁽³⁹⁾ and advertisements claims that polycarbonate sheet performs very well in both corner tests and small-scale tests. Their comparison is to acrylic sheet that is easily ignited by 6-10 lb. cribs (or practically a match). Photos in their advertisements show very small cribs, canted in the corner to minimize the flux seen by the sample. Under our more "standard" arrangement and a 14 lb. crib, we virtually had flashover. Studies⁽⁴⁰⁾ have shown that surface heat flux is critical to ignition and for many materials you find that above some critical heat flux value the sample ignites and below it sustained ignition is not possible.

Whether a larger crib would lead to flashover for the smoke-retarded or regular PVC is not clear. The one test made with a 20 lb. crib and 87265 (0.030 in) did not flashover. And at some crib size, the crib itself will take the room to flashover.

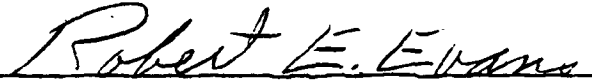
From a practical point-of-view, there are few if any plastic materials (even "space-age" plastics) that have documented large scale performance as good as the smoke-retarded PVC compounds tested here. Properly used, we feel that these compounds could lead to improved safety and help change the "image" surrounding the use of PVC in many applications.

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