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# Fire Endurance of Mine Stoppings

By D. Ng, C. P. Lazzara, K. E. Mura, and C. Luster

BUREAU OF MINES

U.S. DEPARTMENT OF THE INTERIOR

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UNITED STATES DEPARTMENT OF THE INTERIOR
Donald Paul Hodel, Secretary

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T S Ary, Director

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# CONTENTS

Page

Abstract . . . 1
Introduction . . . 2
Experimental facility and test procedures . . . 2
  Experimental facility . . . 2
  Test procedures . . . 5
Results and discussion . . . 7
  Preliminary tray fire tests . . . 7
  Concrete block stopping tests . . . 8
  Metal stopping tests . . . 9
    Uncoated metal stopping . . . 9
    Coated metal stopping . . . 15
Summary . . . 17
References . . . 18
Appendix.–Heat flux calculation . . . 19

# ILLUSTRATIONS

1. Schematic of Bureau of Mines Bruceton Experimental Mine, multiple entry section . . . 3
2. Schematic of test area . . . 3
3. Installation of fireproof material at test site . . . 4
4. Fuel supply system . . . 4
5. Concrete and metal stoppings used in test . . . 5
6. Location of thermocouples and flux gauge on stopping . . . 6
7. Locations of thermocouples flux gauges, infrared camera, and gas sampling line used in test 15 in the region behind the stopping . . . 6
8. Average temperature of five roof thermocouples above fire tray . . . 7
9. Temperatures of thermocouples located on top and under ceramic insulation blanket above tray fire . . . 7
10. Tray fire . . . 8
11. Variation of temperatures of thermocouples at locations A through J along the ventilation flow . . . 9
12. Total heat flux measurement on front surface of concrete block stopping . . . 9
13. Temperatures of top, middle, and bottom row thermocouples on front surface of concrete block stopping 9
14. Temperatures of top row of thermocouples on back surface of concrete block stopping . . . 10
15. Crack in concrete block of stopping . . . 10
16. Temperatures of top, middle, and bottom row thermocouples on front surface of metal stopping . . . 11
17. Temperatures of top, middle, and bottom row thermocouples on back surface of metal stopping . . . 11
18. Temperatures of air thermocouples at various distances from back surface of metal stopping . . . 12
19. Temperatures of air thermocouples 3 ft from roof along centerline of entry, at various distances from the back surface of metal stopping . . . 14
20. Least square fitted data of air temperature thermocouple located 1 ft from back surface of metal stopping . . . 14
21. Reading of heat flux gauges behind metal stopping . . . 15
22. Calculated and measured heat flux at flux gauge located 2 ft from back surface of metal stopping . . . 15
23. Temperatures of top, middle, and bottom thermocouples at plaster metal interface of plaster-coated metal stopping . . . 16
24. Temperatures of top, middle, and bottom back surface thermocouples of plaster-coated metal stopping . 16
25. Temperatures of air thermocouples 1 ft from back surface of plaster-coated metal stopping . . . 17

## UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

| | | | |
|---|---|---|---|
| Btu/lb | British thermal unit per pound | $ft^3$/min | cubic foot per minute |
| Btu/min | British thermal unit per minute | gal | gallon |
| °C | degree Celsius | gal/min | gallon per minute |
| $cal/cm^2 \cdot s$ | calorie per square centimeter per second | h | hour |
| ft | foot | in | inch |
| ft/min | foot per minute | psig | pound per square inch, gauge |
| $ft^3$ | cubic foot | | |

## UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

### With Factors for Conversion to Units of the International System of Units (SI)

| Unit of measure | To convert to– | Multiply by– |
|---|---|---|
| Btu/lb | joule per kilogram | 2,324 |
| Btu/min | watt | 17.57 |
| $cal/cm^2 \cdot s$ | watt per square meter | 41,840 |
| ft | meter | .3048 |
| ft/min | meter per second | .005080 |
| $ft^3$ | cubic meter | .02832 |
| $ft^3$/min | cubic meter per second | $4.72 \times 10^{-4}$ |
| gal | liter | 3.785412 |
| in | centimeter | 2.54 |
| psig | kilopascal | 6.894757 |

# FIRE ENDURANCE OF MINE STOPPINGS

By D. Ng,[1] C. P. Lazzara,[2] K. E. Mura,[3] and C. Luster[4]

## ABSTRACT

A facility to evaluate the fire endurance of mine stoppings was constructed by the Bureau of Mines in the multiple entry section of the Bruceton (PA) Experimental Mine. Stoppings up to 6 by 18 ft can be tested in a manner simulating mine conditions. The stopping is subjected to a 70-min liquid fuel tray fire with an energy output of 75,000 Btu/min. The stopping and adjacent areas are instrumented with thermocouples and heat flux gauges. Data acquisition is by an automatic data logger capable of continuously recording over 100 channels of information.

Two 8-in-thick concrete block stoppings and a galvanized steel stopping were tested. A crack developed on the fire side surface of the block stoppings where the flames were most intense. However, the temperatures of the unexposed surfaces of the stoppings never exceeded 80° C and the surfaces were undamaged. The steel stopping retained its structural integrity during the test. The temperature of the unexposed steel surface reached 500° C, but combustible materials located 1 ft from the surface did not ignite. A 3/4-in-thick coating of construction plaster was applied to the fire side of the previously tested uncoated steel stopping. The quantity of heat energy transmitted across this coated metal stopping was reduced approximately 50%. All stoppings prevented the passage of flame and smoke.

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# INTRODUCTION

Permanent stoppings or partitions are used in mines to separate ventilation airways. The ability of stoppings to retain their structural integrity for a minimum length of time under fire conditions and prevent the spread of flame and toxic combustion products to an adjacent airway is critical. The success of miners to reach safety during a fire emergency depends largely on the presence of uncontaminated airways.

Traditionally, permanent stoppings for coal mines are constructed of concrete or other masonry blocks and possess satisfactory structural and fire-resistant qualities. Recently, metal stoppings have been introduced. While metal stoppings obviously satisfy many of the statutory requirements (*1*)[5] demanded of the materials used for permanent stopping construction (requirements such as incombustibility, strength, ability to withstand transverse loading, etc.), their use also introduces concerns.

The ability of a stopping to maintain its ventilation control function when exposed to a fire and the potential that the fire could transmit enough heat energy through the stopping to ignite combustible materials on the unexposed side are of greater concern for metallic than for concrete block stoppings. These concerns became more urgent after a mine fire accident with fatalities in Utah in which early failure of an aluminum overcast contributed to the severity of the accident (*2*).

The Mine Safety and Health Administration (MSHA) Industrial Safety Division at its Bruceton (PA) Safety Technology Center has been conducting small-scale experiments and tests in its fire gallery to investigate the potential problems associated with metal stoppings (*3-5*). Certain preliminary recommendations were proposed concerning their use in underground coal mines (*6*). However, because of the physical size of the MSHA fire gallery, the size of the test stopping (6 by 6 ft) was not representative of actual mine installations. At the request of MSHA, the Bureau of Mines initiated a program to establish a full-scale test facility in its Bruceton Experimental Mine to investigate the fire endurance of mine stoppings. This report describes the facility and the results obtained for concrete block stoppings and a galvanized steel stopping.

# EXPERIMENTAL FACILITY AND TEST PROCEDURES

## EXPERIMENTAL FACILITY

The test stopping site is located in room 7 of the multiple entry section of the Experimental Mine, 15 ft from a crosscut connecting rooms 6, 7, and 8 (fig. 1). A permanent concrete block stopping with access door and observation windows, was constructed 35 ft from the test stopping (fig. 2). The viewing windows are made of heat-tempered, infrared reflecting glass. A TV camera is located at one of the observation windows for monitoring and recording the tests.

Concrete block stoppings were erected at the indicated locations in figure 2 to route the ventilation flow by the test area. With the mine ventilation fan on high, delivering an airflow volume of 34,000 $ft^3$/min, the ventilation velocity 15 ft from the test stopping is about 340 ft/min; it is about 60 ft/min in the reverse direction at the stopping. This velocity is obtainable only when all the ventilation control doors directing air to other areas of the Experimental Mine are closed and is comparable to that reported by Luzik (*5*) in his fire gallery test. The airflow is necessary to sweep away the combustion products and permit visual observation of the tests. There was no measurable pressure differential across the stopping.

The ribs (wall) and roof of the Experimental Mine are coated with gunite. There was concern that the intense heat from repeated test fires would destroy this coating and inadvertently ignite the underlying coal. The mine ribs and roof immediately in front of and behind the test stopping and in the crosscut were therefore protected with fireproof ceramic fiber blankets. The ceramic blankets were installed by impaling them on stainless steel studs that were cemented in holes drilled into the roof and ribs of the test area at spacings varying from 1.2 to 1.5 ft (fig. 3). Additionally, a layer of sand, about 2 in thick, was used to protect the concrete floor in front of the stopping from potential spalling because of the extreme heat.

A noncombustible rectangular frame was constructed to hold the test stopping. This frame was necessary because of the irregular shape of the mine ribs and roof. The two sides of the frame were constructed from solid concrete blocks. A C-shaped steel beam spanned the two concrete structures to form the top of the frame. The beam was supported by steel roof bolts and boxed in with 2-in-thick fireproof (calcium silicate) boards. The rectangular frame can accommodate 6- by 18-ft stoppings.

A 12,000-$ft^3$ region behind the test stopping, measuring approximately 7 ft high by 20 ft wide by 85 ft long, is isolated from downstream smoke and combustion products by stoppings equipped with access doors (fig. 1). In this region a TV camera is installed to monitor the unexposed side of the stopping for physical integrity and smoke and flame penetration. In addition, in the test of the metal stopping, an infrared imaging video system was also installed to monitor the surface temperature of the stopping as the test progressed. The unique feature of this imaging system was that the temperatures of the (stopping) surface area under observation were represented by different colors. Images from the TV

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[5] Italic numbers in parentheses refer to items in the list of references preceding the appendix.

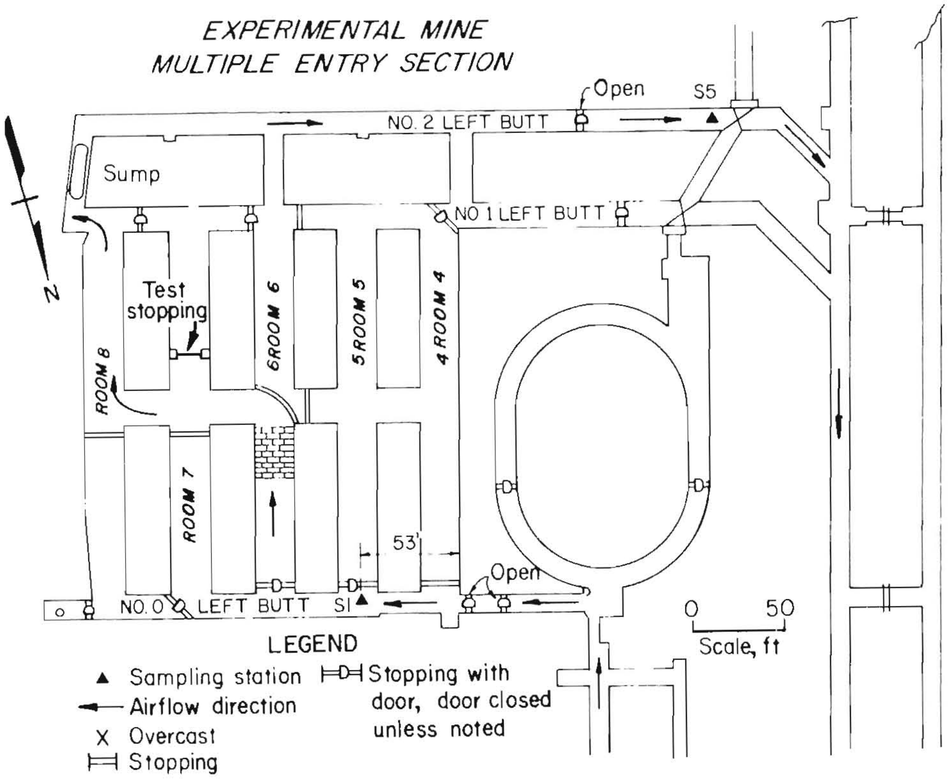

Figure 1.—Schematic of Bureau of Mines Bruceton Experimental Mine, multiple entry section.

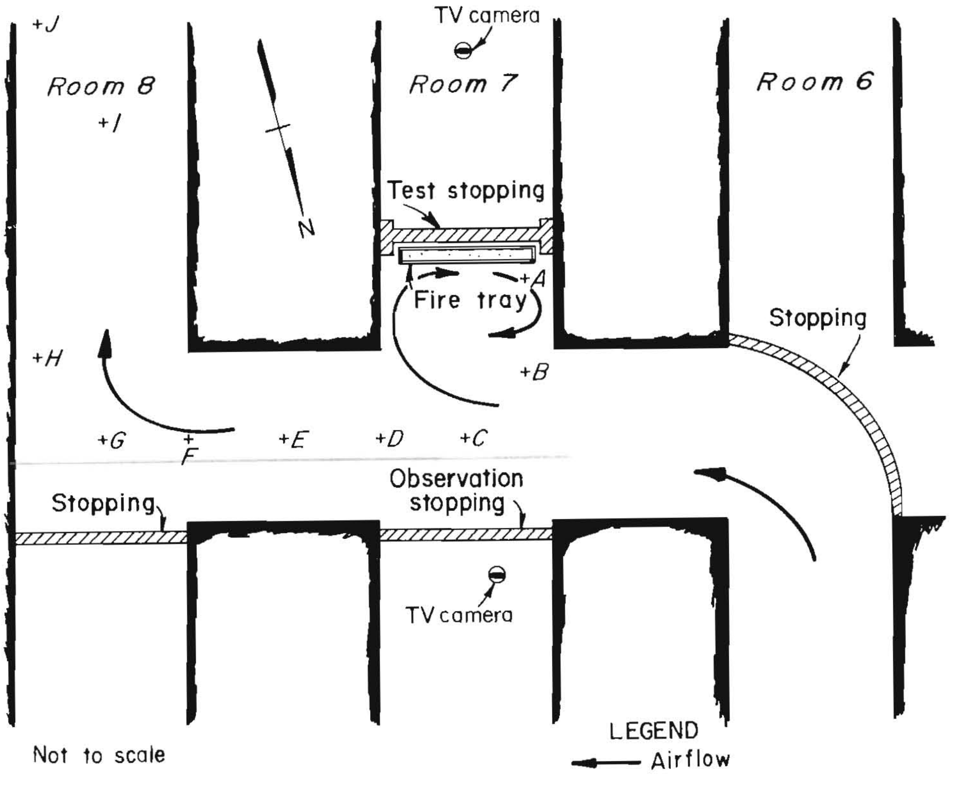

Figure 2.—Schematic of test area. *A* through *J* designate roof thermocouple locations.

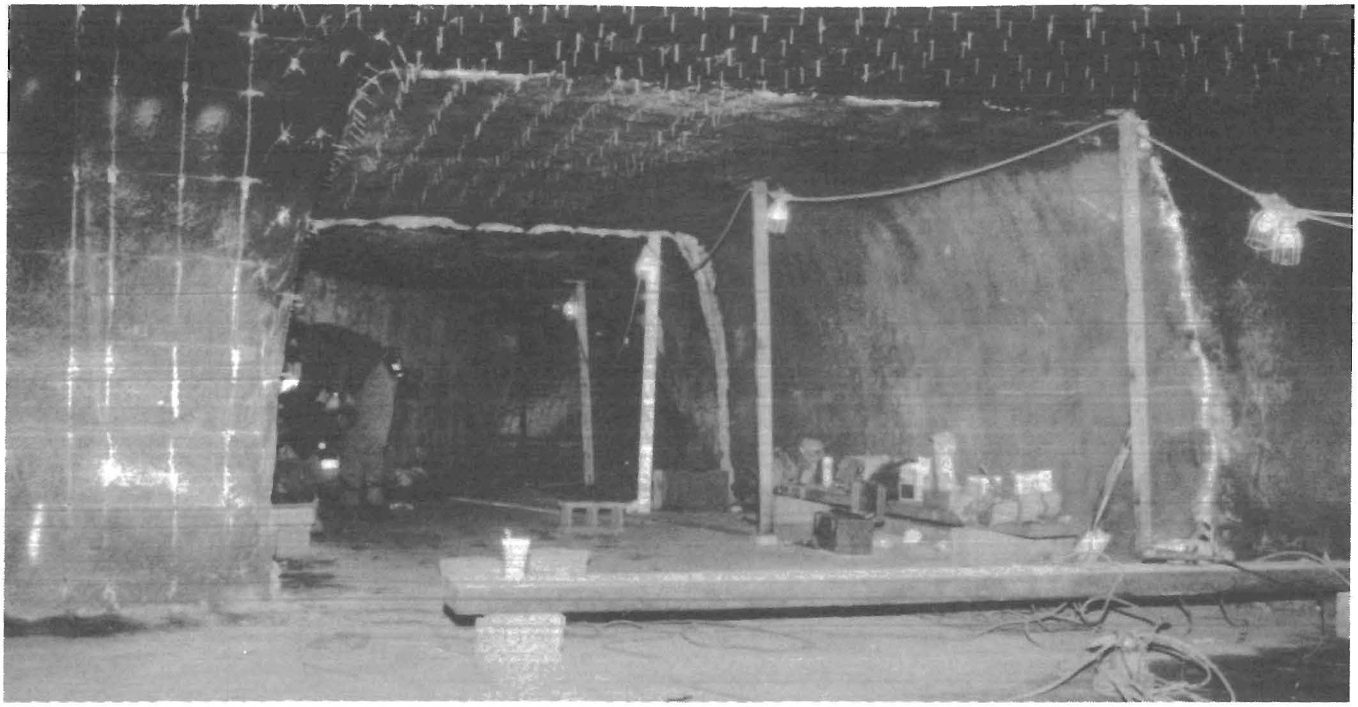

Figure 3.—Installation of fireproof material at test site.

cameras and the infrared imaging camera were recorded on tape. The digital thermal images were also recorded on computer disks.

The heat source for the tests is a liquid fuel tray fire. The 10-in by 10-in by 16-ft tray was constructed from a piece of square structural steel tubing by removing one of the 10-in by 16-ft surfaces and welding two 10-in square pieces to close the ends. Liquid fuel for sustaining the fire is fed into the tray near the bottom, beneath a 5-in layer of water, through a check valve from a fuel delivery system via steel pipe and fire-resistant hydraulic hose. The piping and hose are protected with ceramic blankets in the immediate test area where intense heat is present.

The fuel is a commercially by available solvent containing 90% paraffins and 10% naphthene. The fuel was selected because of its clean burning characteristics and low cost. It also has about the same heat content (20,000 Btu/lb) as diesel fuel, a fuel used in some coal mines.

The fuel is obtained in 30-gal drums. Delivery from the drums to the tray is by pressurizing (5 psig) the drums with nitrogen gas. Such a low pressure poses no danger to the structural integrity of the drums. A discharge tube is immersed in the liquid close to the bottom of the drum to allow most of the liquid to be withdrawn. After exiting the discharge tube, the liquid flows through a metering valve and flowmeter that can measure flow rates of up to 1 gal/min. For tests lasting about 70 min, about 50 gal of fuel is required. This requirement is easily met by connecting two fuel drums together. By opening and closing valves, fuel flow can quickly be switched from an emptying container to a full one with no interruption. Figure 4 shows the fuel delivery system.

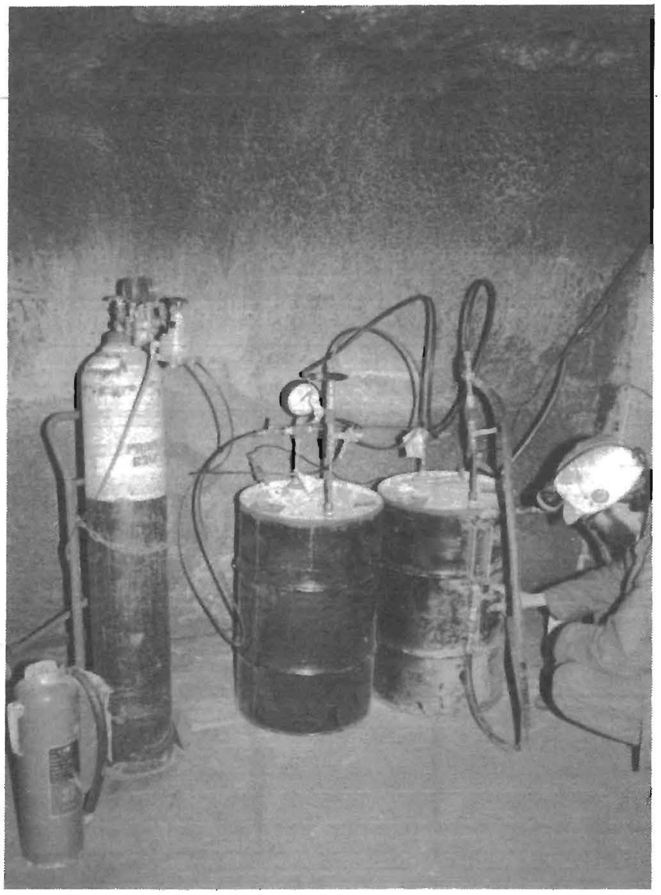

Figure 4.—Fuel supply system.

A data acquisition system previously used for sealed coal mine fire tests (*7*) was adapted to acquire the experimental data from thermocouples and heat flux gauges that were installed on the test stopping and at locations adjacent to the test site. It has the capacity of recording more than 100 channels of data on printed hard copy and magnetic tape for subsequent analysis by a mainframe computer. The data acquisition system records data sequentially from the first channel until the last channel and then repeats the process. In all the tests, the system was configured such that it took approximately a minute to complete a 100-channel cycle. It is, however, capable of cycling much faster. The data are also displayed, recorded, and analyzed using a personal computer. In addition to data safety resulting from redundancy, the personal computer allows real-time display of the most important data and initiation of the data analysis as soon as a test is over. This is an improvement over the previous data analysis procedure where data had to be transferred from the magnetic tape to the main computer before the analysis could begin.

## TEST PROCEDURES

Concrete or metal stoppings, 6 ft high by 18 ft wide were constructed in the test frame. The concrete stoppings were built using 8-in-thick, hollow, two-cell concrete blocks laid with wet mortar joints. The commercial metal stopping was erected from 1-ft-wide 18-gauge telescopic galvanized steel panels. It was installed with assistance from the manufacturer, adhering to recommended procedures (*8*). The small gaps that existed between adjacent panels and at the perimeter of the stopping were sealed using a water-glass-based paste to make the stopping airtight. Figure 5 shows the completed stoppings.

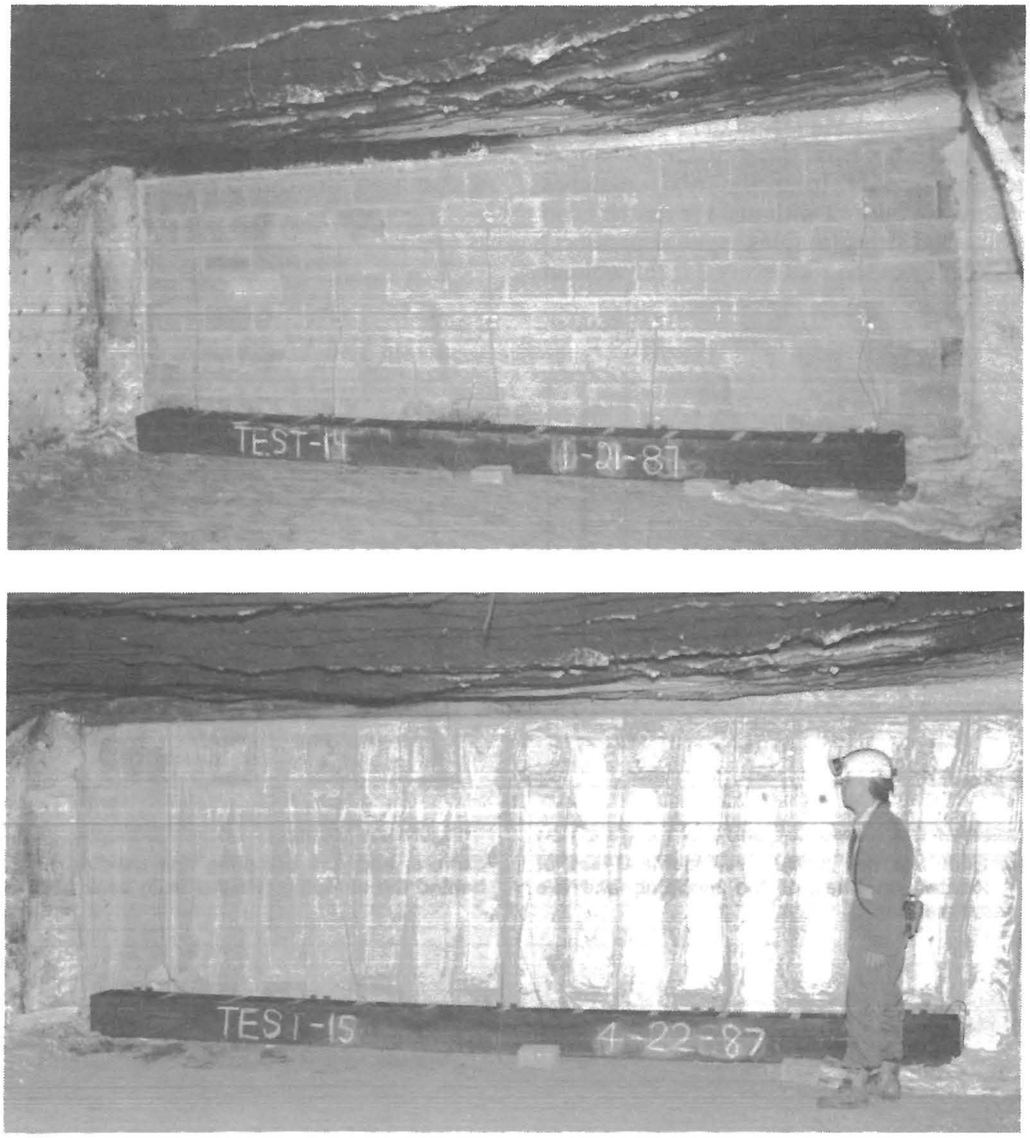

Figure 5.—Concrete (top) and metal (bottom) stoppings used in test.

In all the stopping tests, 15 type K thermocouples, in a 3 by 5 array (fig. 6), were installed on the exposed and unexposed sides of the stopping to measure the surface temperatures. The bare thermocouple beads were in contact with the stopping surface. The type K thermocouples were constructed from ceramic insulated, Inconel braid shielded 20-gauge wires. The location of the water-cooled total heat flux gauge (F) is also shown in figure 6. The output of all these sensors were recorded by the data acquisition system.

In the preliminary tray fire tests and tests of the concrete block stoppings, the data collected were thermocouple readings of stopping surfaces and areas immediately adjacent to it. In the test of the metal stopping, in addition to monitoring the temperatures at the same locations, extra thermocouples were installed in the region behind the stopping (fig. 7) at distances 1, 2, 5, 7, 10, 20, 38, and 75-ft from it to measure the air temperatures near the ribs, roof, and midpoint from the floor.

Combustible materials were positioned on shelves behind the stopping. They consisted of a 1/4-in-deep, 10- by 12-in layer of Pittsburgh seam coal dust at a distance of 21 in from the stopping and 34 in from the floor, chunks of Pittsburgh seam coal 39 in from the stopping and about 25 in from the floor, 34 in from the rib; matches imbedded in the ceramic blanket with just the match head exposed; and small wood strips (maple tongue depressors) suspended 6 and 36 in from the roof every 2 ft throughout the entry for a distance 30 ft from the stopping. Additional heat flux gauges were installed at the roof at distances of 2, 5, 7, and 11 ft from the stopping to measure the heat energy radiated by the metal stopping. Furthermore, a gas sampling line was installed about 5 ft from the stopping at the roof to monitor the CO concentration as another indication as to combustion product leakage across the stopping.

At the beginning of each test, the fire tray contains a 5-in-layer of water. Fuel is neither present in the tray nor in the hose and the connections between it and the supply. Fuel is then metered from the supply drums into the tray. At first, air in the fuel line is forced out as bubbles; when bubbling stops, fuel begins to appear as a layer on top of the water. At that point, the fuel is manually ignited and the test begins.

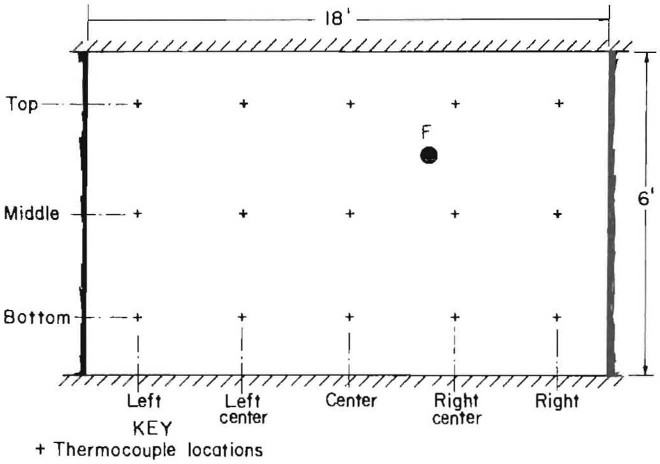

Figure 6.—Location of thermocouples and flux gauge (*F*) on stopping (viewed from the fire side). An identical set of thermocouples is located on back of the stopping and are identified in the same manner.

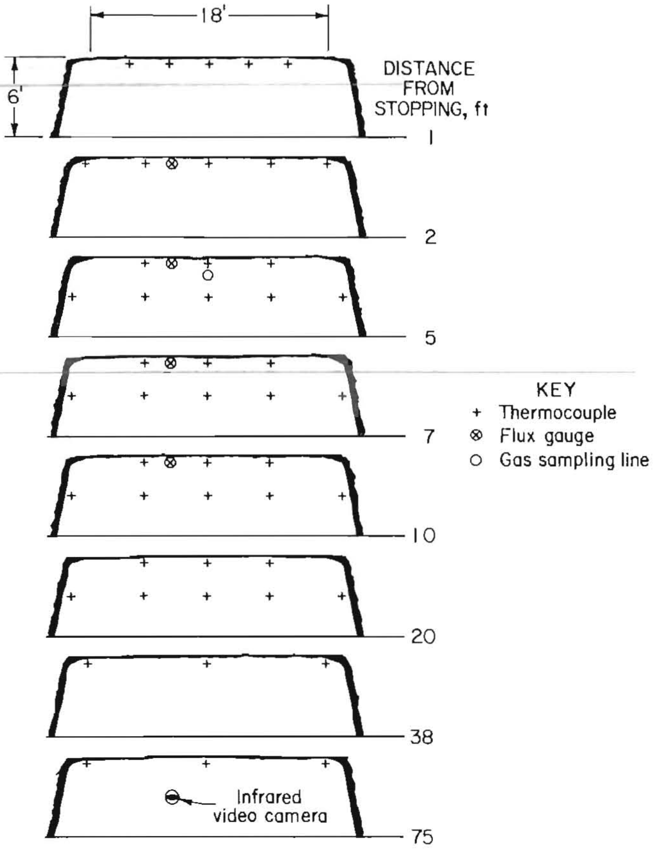

Figure 7.—Locations of thermocouples, flux gauges, infrared camera, and gas sampling line used in test 15 in the region behind the stopping (viewed from back of stopping).

# RESULTS AND DISCUSSION

## PRELIMINARY TRAY FIRE TESTS

Initial tests of the tray fire were performed aboveground to gain experience with the fuel delivery system and fire characteristics, such as burning rate. The tray was then moved underground to the test site and 12 preliminary tests were conducted, with tray fires lasting 5 min to over an hour. For these tests, the tray was positioned at the base of a concrete block stopping and the stopping was covered with ceramic blanket insulation to protect it from the fire. The purpose of the tests was to determine the optimal fuel delivery rate to produce a fire over the entire tray surface without the generation of excessive smoke. Also, thermocouple temperatures beneath the ceramic blankets on the ribs and roof were monitored, as well as air temperatures immediately downstream of the test site for a distance of 150 ft.

Figure 8 shows the average temperature of five thermocouples located near the roof above the tray. It indicates that the fire intensity attained a steady level within 10 min after ignition of the tray fire. Temperatures near the roof in the region where the flames were most intense reached 1,000° C; however, the mine roof protected by the ceramic blanket insulation experienced a temperature rise of only about 10° C (fig. 9). In both figures 8 and 9 one can see the sharp drop in temperatures that occurred with the termination of fuel into the tray.

It was also discovered during these tests that the fuel must be introduced into the tray from the left side (facing the stopping) in the same direction as the ventilation flow over the tray (the ventilation flow in the crosscut over the tray is opposite that of the mine ventilation flow, see figure 2). As a consequence of the recirculation pattern above the fire tray, the flames are most intense over the right side of the stopping (facing the stopping).

A fuel delivery rate of 0.7 gal/min was found to produce the desired fire characteristics–a fire over the entire tray without excessive smoke (fig. 10). The heat output of the fire was about 75,000 Btu/min. It took about 10 min for the flames to spread over the surface of the tray and the fire to "burn in." A tray fire with these characteristics and a 70-min duration was selected as the standard fire for the stopping tests.

As a result of these initial tests, it was decided that air temperatures 150 ft downstream from the tray fire were insufficient to ignite mine timbers located there. Figure 11 shows air temperatures near the roof at several downstream locations (A to J in figure 2) during a 70-min

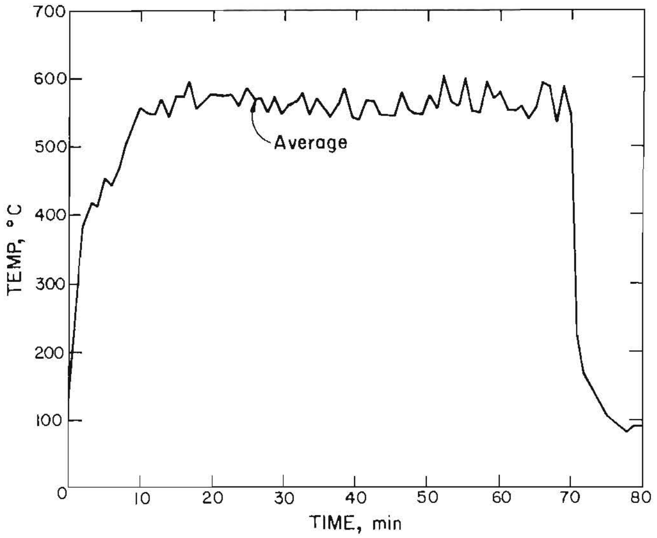

Figure 8.—Average temperature of five roof thermocouples above fire tray.

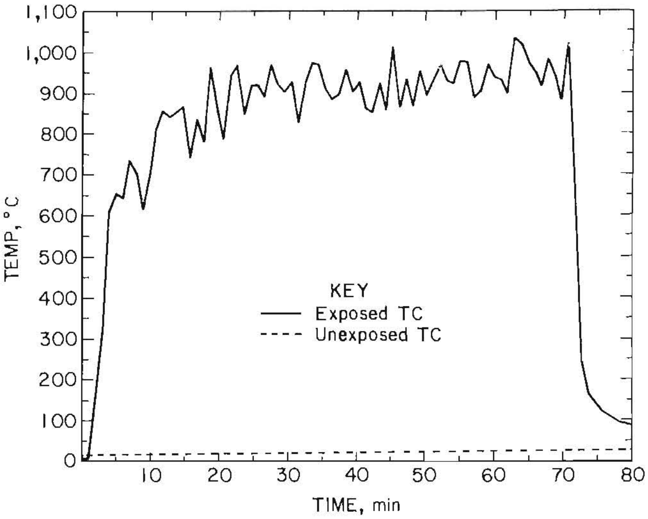

Figure 9.—Temperatures of thermocouples (TC's) located on top (exposed) and under (unexposed) ceramic insulation blanket above tray fire.

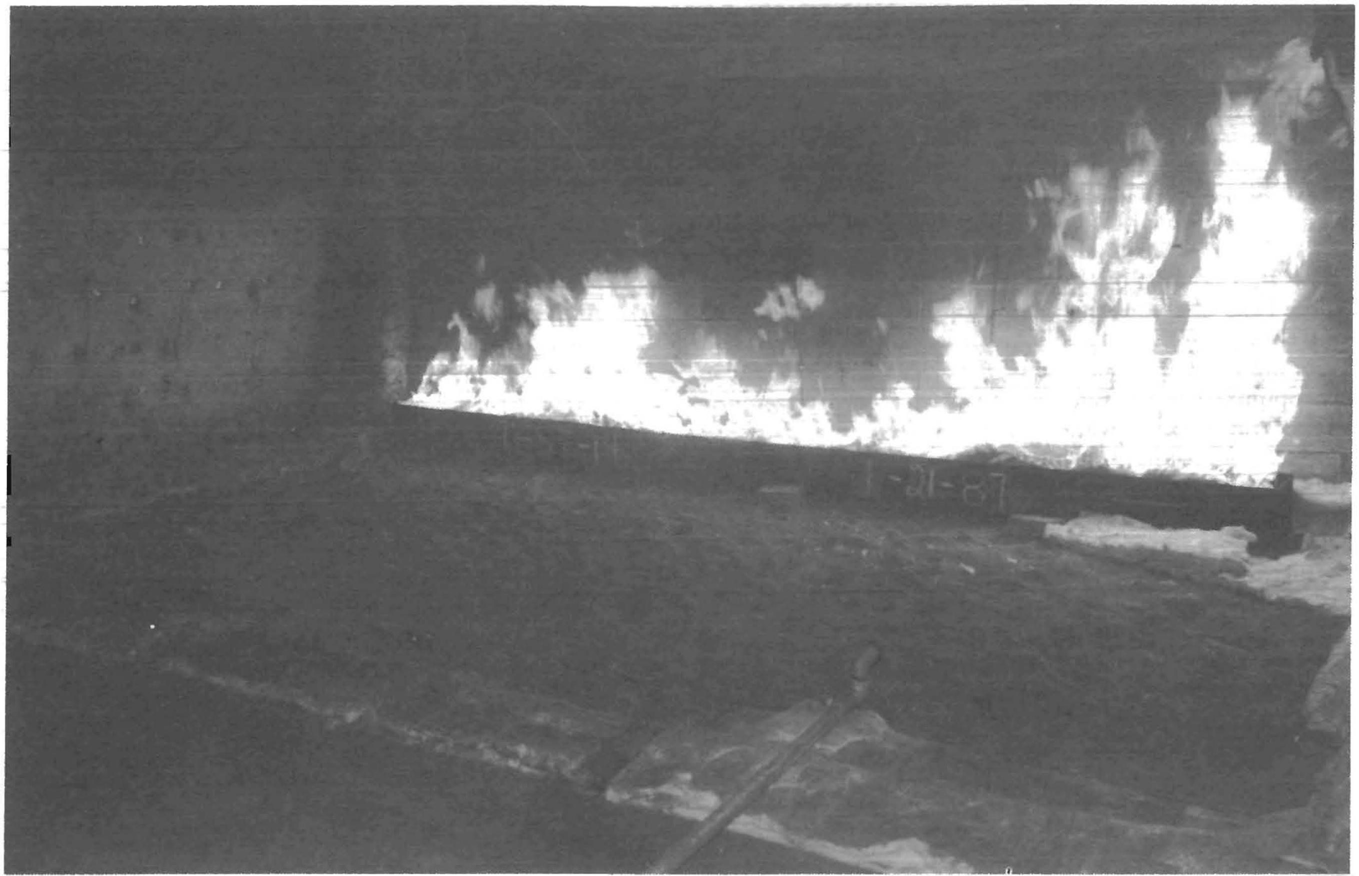

Figure 10—Tray fire.

tray fire. The temperatures fall off with distance because of mixing of the combustion gases with the mine ventilation flow and heat losses to the mine walls. The air temperature at location J, 150 ft from the tray, never exceeded 90° C.

## CONCRETE BLOCK STOPPING TESTS

Two concrete block stoppings of identical construction were subjected to the 70-min, 75,000-Btu/min tray fire. About 49 gal of fuel was consumed in each test. The results of both tests were similar and the data presented in this report are principally from only one of the tests. The total heat flux on the stopping surface, as measured by a water-cooled heat flux gauge (F in figure 7), is shown in figure 12. The average flux was about 2 $\mathrm{cal/cm^2 \cdot s}$ where the flames were most intense.

The temperature versus time histories of the 15 thermocouples on the front surface (fire side) of the stopping are shown in figure 13. The locations and labeling of the thermocouples are referred to in figure 6. The top and middle row temperatures (figure 13*A* and 13*B*, respectively) ranged from about 200° to over 800° C, increasing from left to right, because of the influence of the ventilation flow on the tray fire. Slightly lower temperatures (200° to 600° C) were measured by the bottom row thermocouples (fig. 13*C*).

All 15 thermocouples positioned on the back surface of the stopping recorded temperature rises above ambient. However, none of the temperatures were higher than about 80° C. The temperature-time histories of the top row of these thermocouples are shown in figure 14. The left-right designations correspond to those of the front surface of the stopping.

The video pictures of the back of the block stoppings showed that flames and smoke did not penetrate the barriers during the tests. When the tests were over, visual inspection indicated that there was a 1/4-in-wide vertical crack on the front surface of a block in the stopping, about a fifth to a quarter of the distance from the right (fig. 15). This region was where the fire was most intense. Thermal expansion resulting from heating one surface of the concrete blocks had introduced local stress and fractured the blocks and mortar joints. At the point of fracture, the front surfaces of cracked blocks crept forward about 5 in from the original position, in spite of this, the back (unexposed side) of the stopping was undamaged with no sign of soot from smoke penetration.

A smoke test was conducted after the test fire by setting off a smoke candle in front of the stopping while viewing

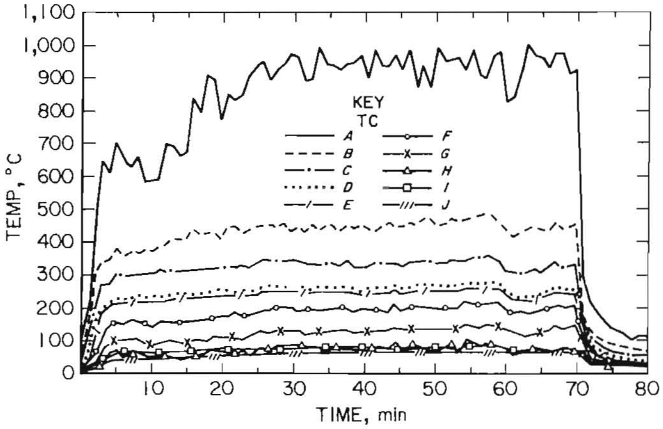

**Figure 11.—Variation of temperatures of thermocouples at locations A through J (fig. 2) along the ventilation flow.**

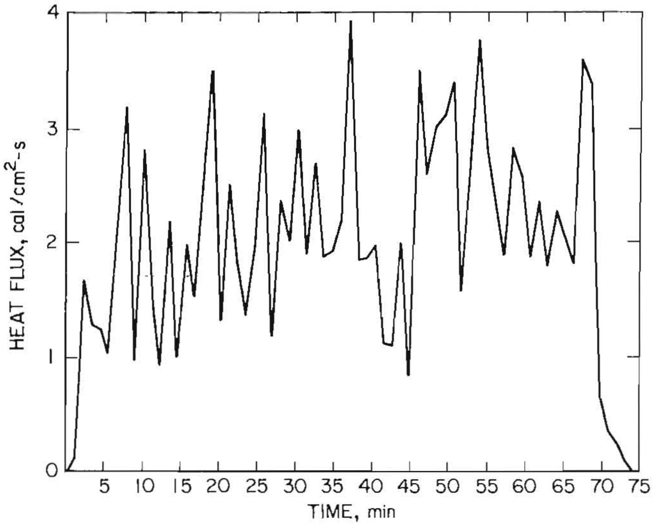

**Figure 12.—Total heat flux measurement (F in figure 6) on front surface of concrete block stopping.**

the back side via the TV camera behind the stopping. There was no smoke infiltration through the concrete blocks.

A temperature of 80° C on the unexposed surface of the concrete stopping is not high enough to ignite combustibles such as coal dust or wood in contact with it (*9*). The thermocouples monitoring the air temperatures behind the stopping did not register temperatures higher than 35° C. In view of the absence of flame and smoke penetration across the stopping, and the low surface temperatures on the unexposed side, it was concluded that the concrete block stoppings successfully withstood the 70-min fire.

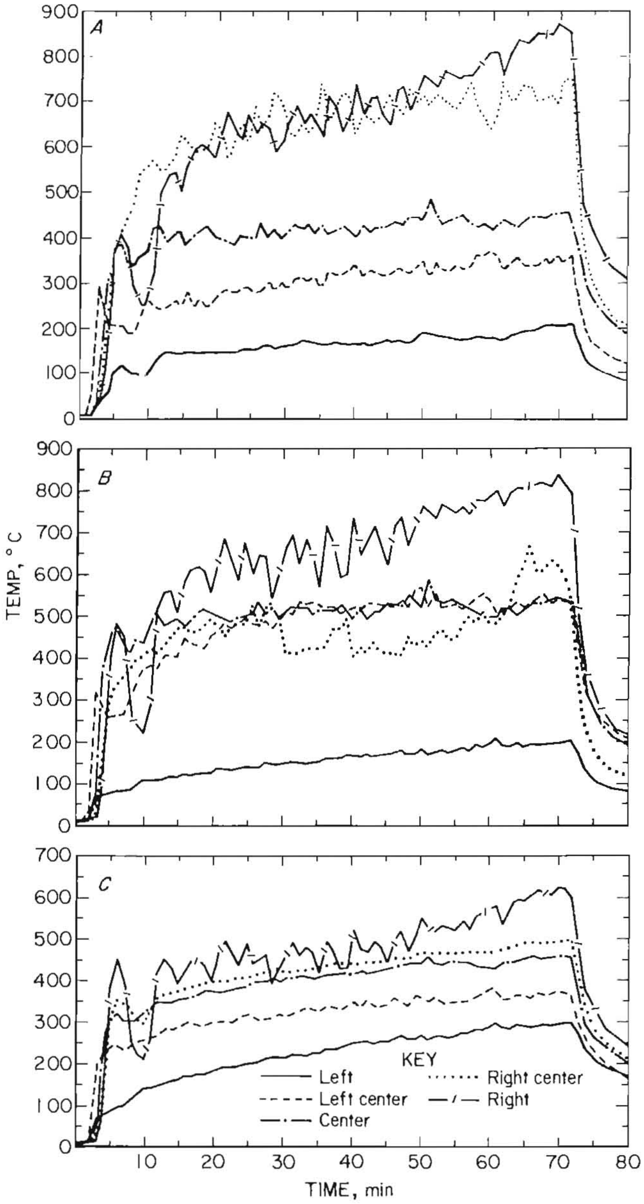

**Figure 13.—Temperatures of top row (*A*), middle row (*B*), and bottom row (*C*) thermocouples on front surface of concrete block stopping.**

## METAL STOPPING TESTS

### Uncoated Metal Stopping

The galvanized steel stopping was subjected to the same 70-min tray fire as the concrete block stoppings. The temperatures recorded by the thermocouples on the front

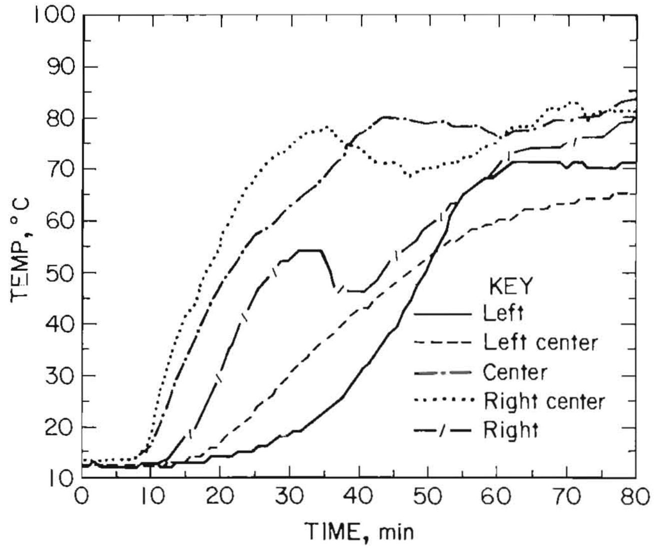

**Figure 14.—Temperatures of top row of thermocouples on back surface of concrete block stopping.**

surface of the metal stopping (fig. 16) are similar to those obtained for the concrete block stopping test. They display the similar variation in temperatures from left to right due to the influence of the ventilation recirculation on the tray fire. The temperatures on the back surface of the metal (fig. 17) are considerably higher than the corresponding temperatures in the block stopping tests. A temperature maximum of 490° C was recorded by the right, top row thermocouple and occurred toward the end of the test. The left-right designations correspond to those of the front surface of the stopping.

Assuming each thermocouple on the stopping monitors an equal size area on the stopping surface, from figure 17 it can roughly be estimated that at about 20 min into the test, at least 80% of the metal stopping back surface experienced temperatures higher than 100° C, at least 53% higher than 200° C, and at least 20% higher 300° C. These percentages remain about the same until the end of the test, at which time at least 13% of the back surface experienced temperatures of at least 400° C.

The infrared thermal video system recorded temperatures as high as 600° to 700° C on the back surface of the stopping. It must be borne in mind that the temperature measured by this system is sensitive to the emissivity of the hot surface. For this test, the emissivity used was that for galvanized steel, 0.21. However, as the stopping is subjected to heat and temperatures rise above the melting point of zinc (419.6° C), which is used in making galvanized steel, the surface emissivity of the steel stopping increases by an unknown amount. As a result, the temperatures measured by the infrared system are somewhat uncertain. It is, however, unequivocal that the surface temperature had exceeded the melting point of zinc (419.6° C) as evidenced by the discoloration on the metal surface resulting from its melting.

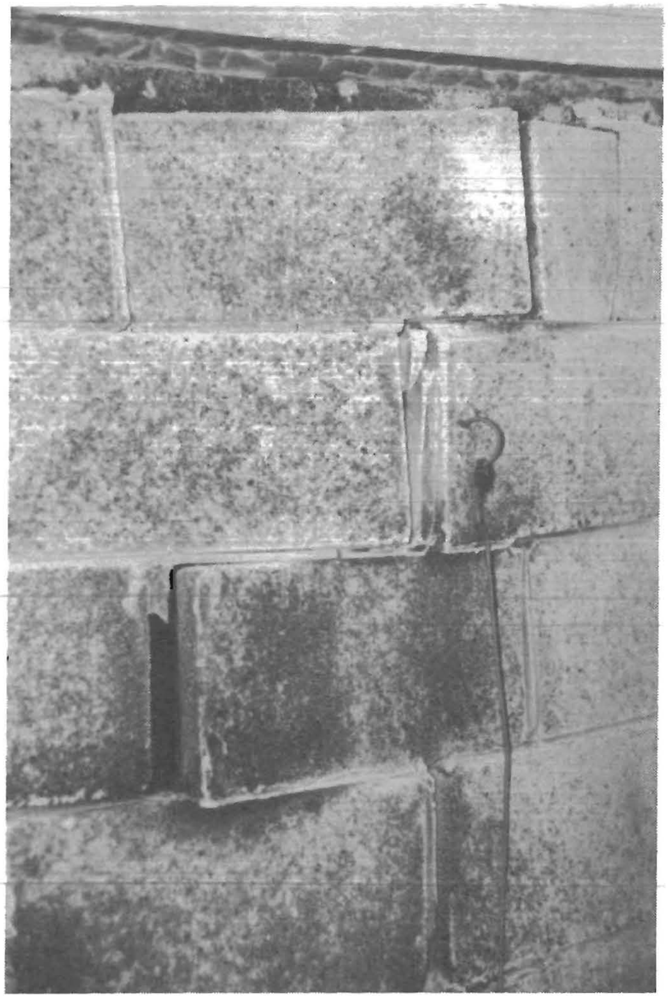

**Figure 15.—Crack in concrete block of stopping (upper right).**

The air thermocouples located at distances from 1 to 75 ft from the back surface of the stopping (fig. 7) all registered temperature rises as shown in figures 18 and 19. The highest air temperature recorded by thermocouples located at 1 ft from the back surface of the stopping was about 150° C; this compares to only about 35° C for the concrete block stopping tests. It is obvious that the effect of the fire was felt at the roof (fig. 18*H*) where temperatures approached 40° C as far away as 75 ft.

Characteristically, the temperatures rose exponentially reaching an asymptotic value, $T_{asym}$. When the tray fire was extinguished at time $t_1$, $T_1$ was the temperature that decayed exponentially to the ambient temperature, $T_0$. The temperature versus time curves at different locations behind the stopping are of the mathematical forms

$$T = T_0 + (\dot{q}/h)\,[\,1 - \exp(-ht/ms)], \qquad (1)$$

for increasing temperature, and

$$T = T_0 + (T_1 - T_0)\,\exp(-h(t-t_1)/ms), \qquad (2)$$

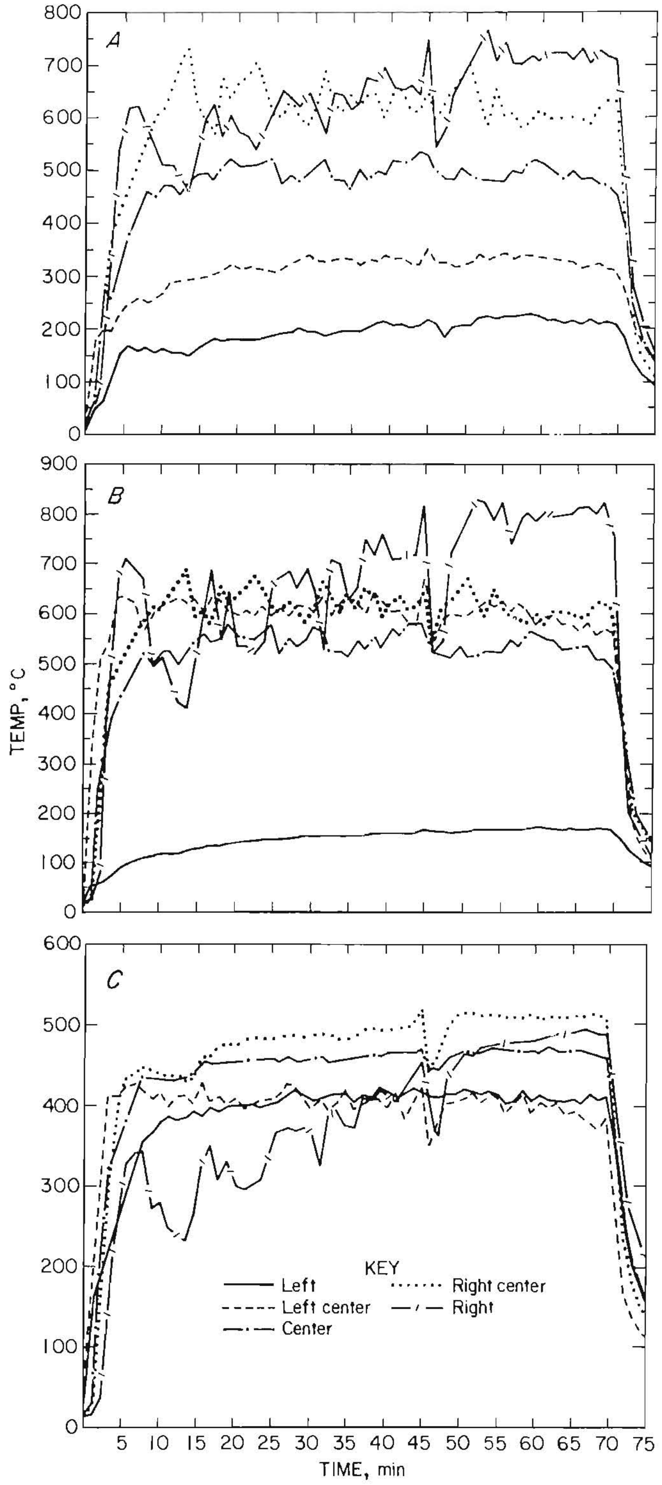

Figure 16.—Temperatures of top row (*A*), middle row (*B*), and bottom row (*C*) thermocouple front surface of metal stopping.

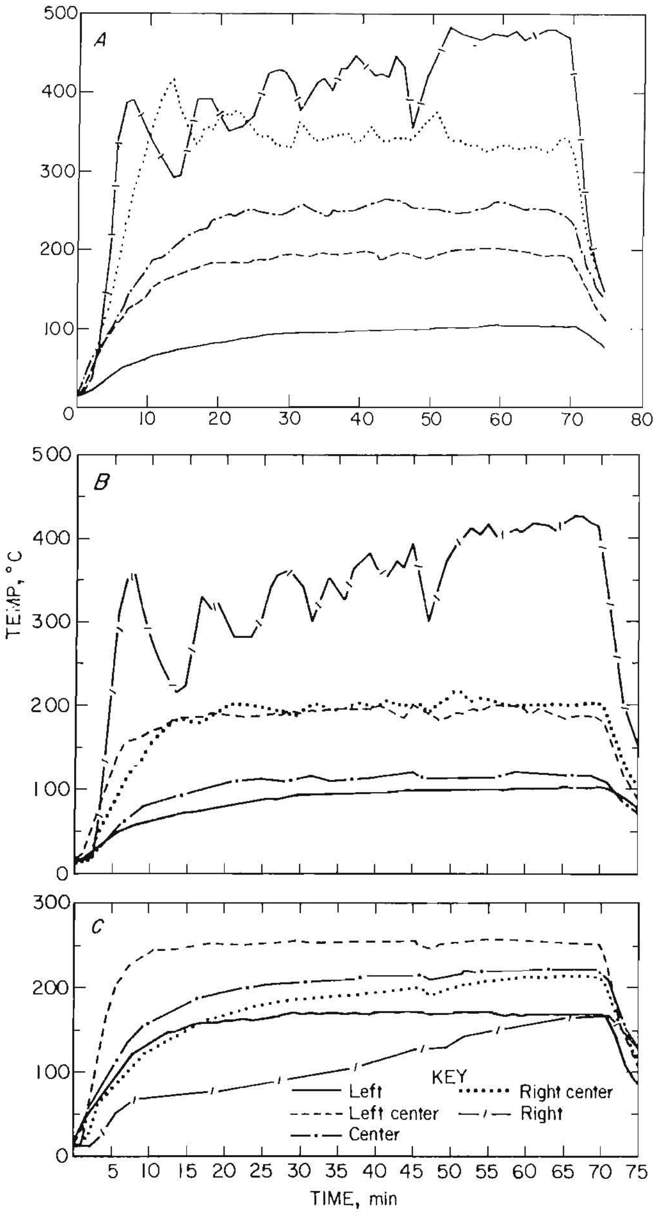

Figure 17.—Temperatures of top row (*A*), middle row (*B*), and bottom row (*C*) thermocouples on back surface of metal stopping.

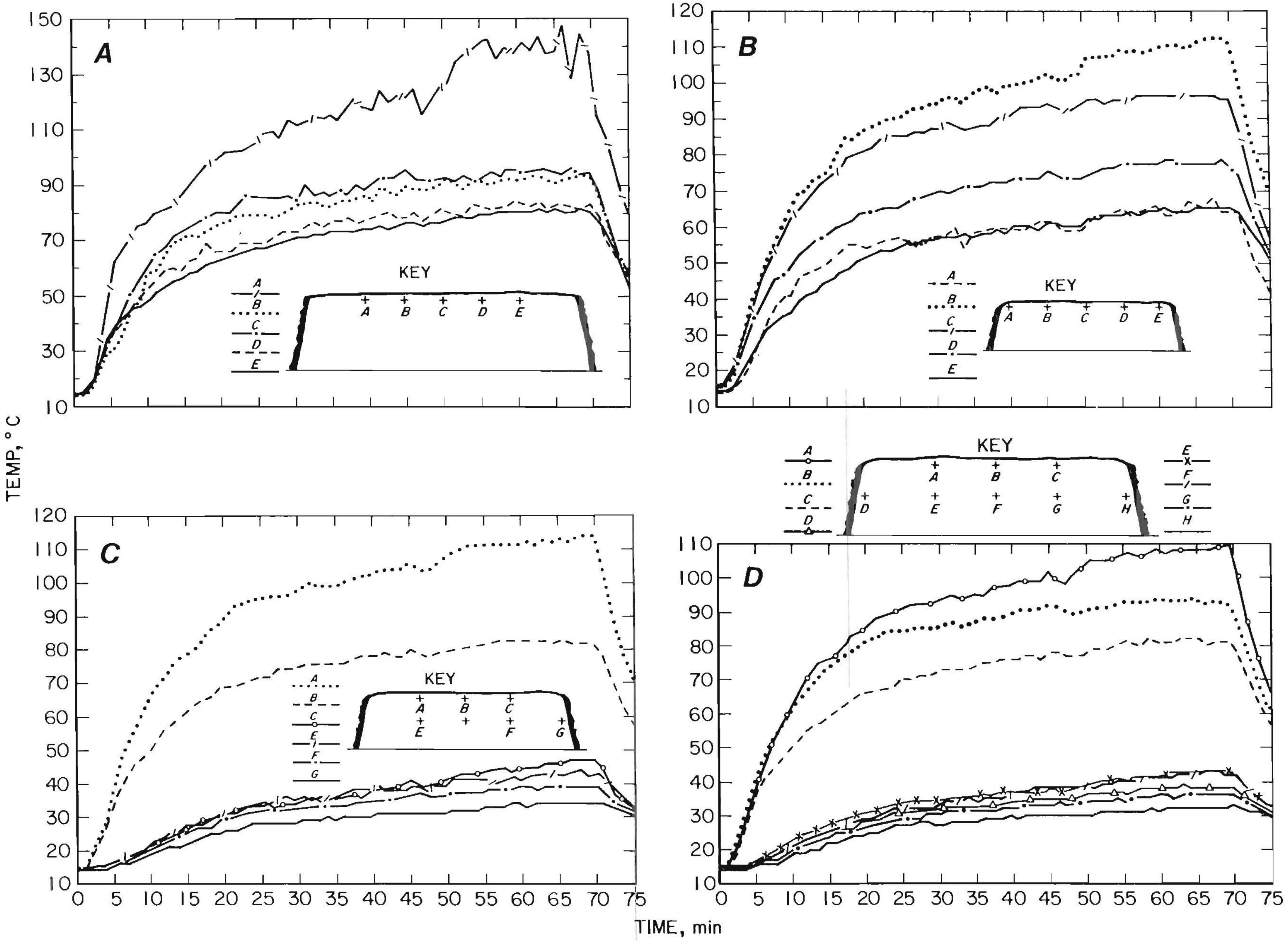

Figure 18.—Temperatures of air thermocouples at various distances from back surface of metal stopping. *A*, 1 ft; *B*, 2 ft; *C*, 5 ft; *D*, 7 ft.

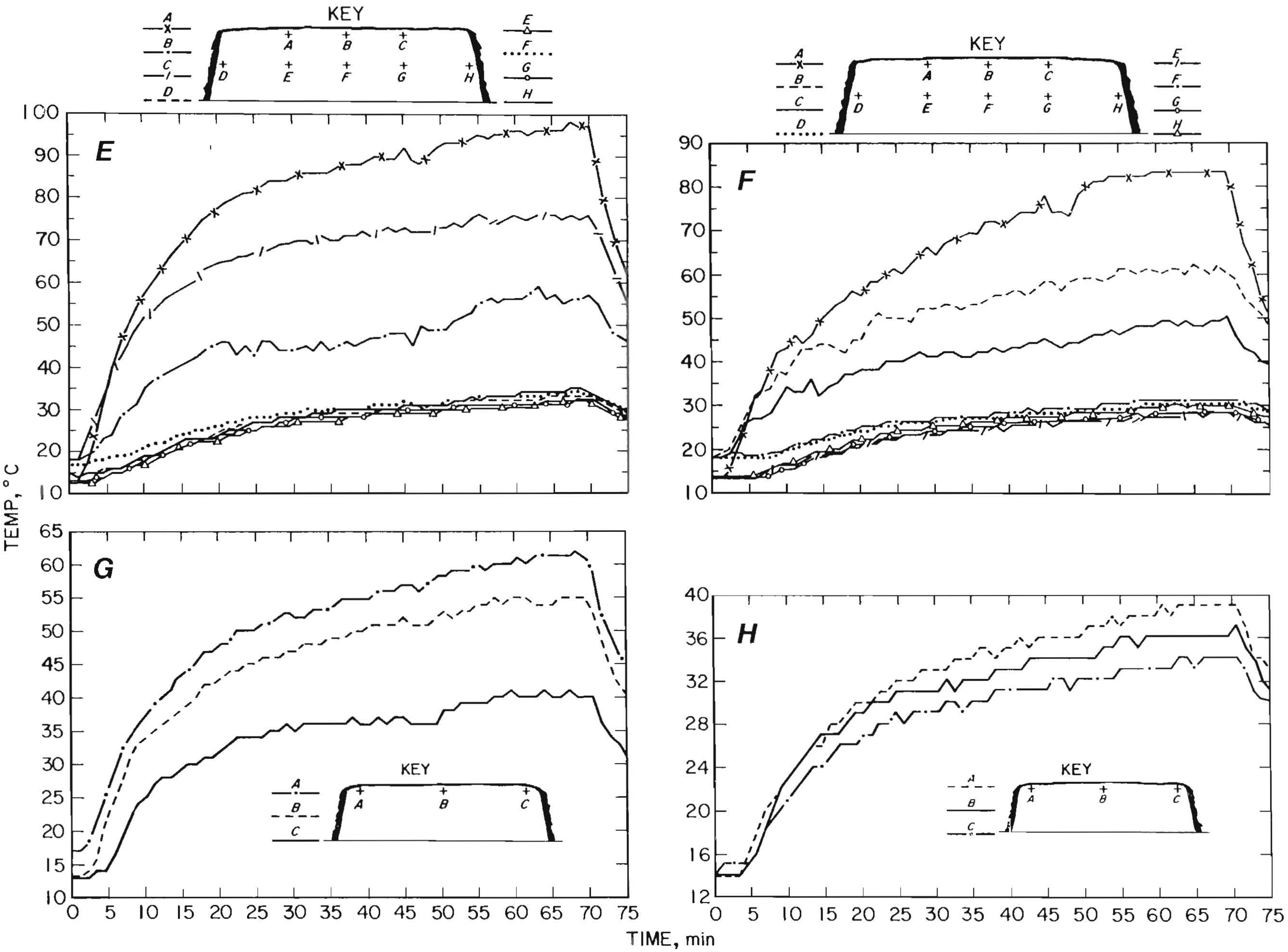

Figure 18.—Temperatures of air thermocouples at various distances from back surface of metal stopping.—Con. *E*, 10 ft; *F*, 20 ft; *G*, 38 ft; *H*, 75 ft.

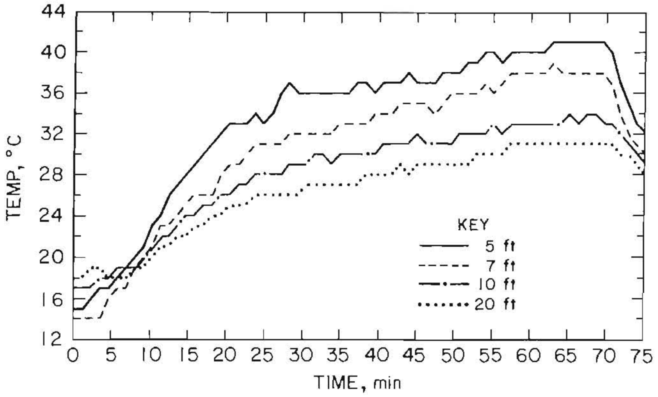

**Figure 19.—Temperatures of air thermocouples 3 ft from roof along centerline of entry, at various distances from the back surface of metal stopping.**

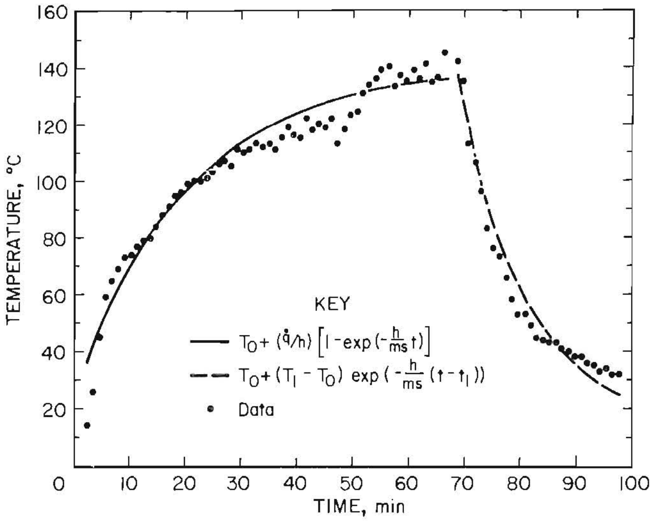

**Figure 20.—Least square fitted data of air temperature thermocouple located 1 ft from back surface of metal stopping.**

for decreasing temperature. These expressions are in fact the solutions of temperature, T, for the heat transfer equation

$$ms\, dT/dt = \dot{q} - h(T-T_0), \qquad (3)$$

describing a body with mass (m), specific heat(s), heat loss coefficient (h), in an ambient temperature ($T_0$), receiving a constant heat flux $\dot{q}$. In general, $\dot{q}$ is the total contribution from radiation and convection.

For the metal stopping test, it is shown later that the contribution is due almost entirely to radiation. Equation 1 is the solution of equation 3 for the case $\dot{q}$ = constant > 0. As t increases, T approaches an asymptotic value, $T_{asym} = T_0 + \dot{q}/h$. This solution applies for time between 0 and $t_1$. Also, equation 2 is the solution for the case $\dot{q} = 0$, corresponding to the case $t_1 < t < \infty$, when the fire was out. As t increases, T approaches the ambient temperature, $T_0$. In figure 20, the data (represented by symbols) of the air thermocouple located 1 ft from the stopping are least square fitted to the solutions represented by equations 1 and 2 for $T_0 = 14.0$ and the others constants as adjustable. In spite of the simple assumption, the data fit the theoretical solutions quite well.

As can be seen from the figure, equation 1 overestimated the temperature rise because it assumed a constant heat flux beginning from t = 0, whereas experimentally, it took the tray fire some 10 min to reach a steady state. Similarly equation 2 overestimated the temperature drop because the heat flux was taken to be zero whereas in fact it was nonzero though rapidly decreasing. No doubt better agreement would result if numerical integration was performed.

TV monitoring during the test did not reveal any flame and smoke penetration across the stopping. None of the target materials (coal, coal dust layer, matches, and wood pieces) were ignited and the wood was not charred or discolored. Also during the test, CO was not detected via the gas sampling line, indicating that combustion products had not infiltrated through the stopping.

Immediately after the test, close visual observation of the stopping showed no signs that the stopping had buckled under the intensity of the fire nor that the sealant had cracked at the joints between panels. However, as the stopping cooled, some of the water glass paste that sealed the gaps between panels debonded and separated from the metal stopping. The paste, which originally was pliable, had became a hard ceramiclike mass after being cured by the high temperature of the fire. The spalling is presumably due to differences in the thermal expansion coefficients of the metal and the ceramiclike material.

The results of the metal stopping test were quite different from those obtained by Luzik (*4*) who tested a metal stopping of a different design. He observed flame penetration through gaps in the metal stopping at about 30 min from the beginning of test followed by eventual ignition of combustible materials. The stopping he investigated was constructed of thinner (28 gauge) metal panels mounted horizontally. The seams between panels and the stopping perimeter were not sealed. Even though the back surface temperatures of the stoppings in both studies are comparable; it is believed that the flame penetration accompanied by hot combustion gases resulted in the ignition of the combustible materials.

The heat fluxes recorded by the total flux gauges located at distances of 2, 7, and 11 ft from the back surface of the metal stopping (fig. 7) are shown in figure 21. Similar to the heat flux reading shown in figure 12 for the flux gauge mounted on the stopping, these figures show a lot of scatter. It is not clear whether this is because of the localized fluctuation in the intensity of the tray fire, whose flickering was quite noticeable, or to the manner in which data were recorded by the data logger. There was a time

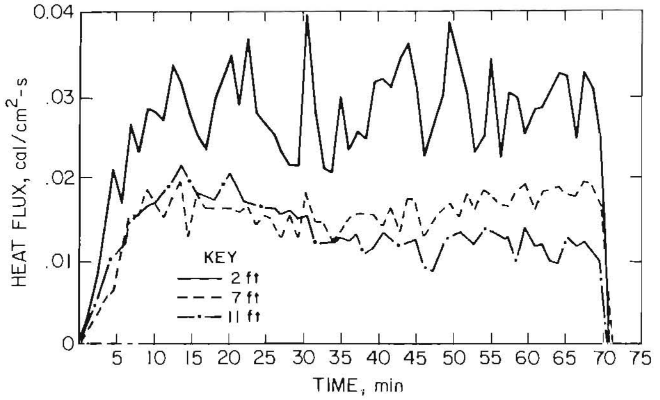

Figure 21.—Reading of heat flux gauges behind metal stopping.

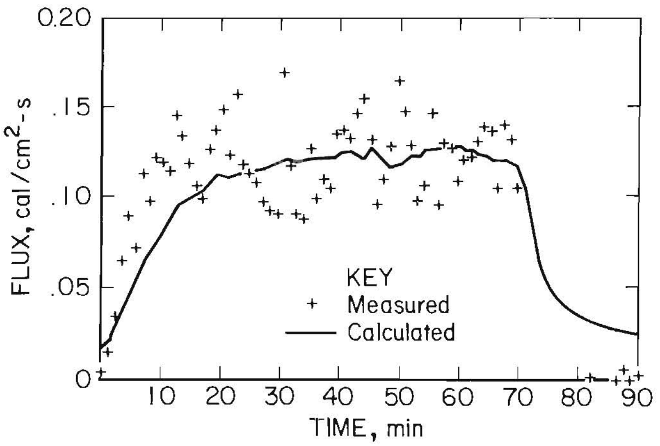

Figure 22.—Calculated and measured heat flux at flux gauge located 2 ft from back surface of metal stopping.

separation of about 1 min between the recording of each data point, and they were joined by a straight line.

An analysis was done to correlate the temperatures of the back surface of the stopping and the measured fluxes. It is obvious that the thermal coupling between the fire and the region behind the stopping is through the stopping. The tray fire heated the stopping and heat energy was transported across it by conduction. The signal detected by the heat flux gauge 2 ft from the stopping is assumed to be from radiation alone. The radiant flux $F_u$ (x,y,z,t) reaching the flux gauge located at x,y,z from the stopping surface located at x', y', z' was calculated from the expression

$$F_u(x,y,z,t) = \int \epsilon \sigma \frac{T^4(x', y', z', t)}{|R|^4} (z-z')^2 \, dA, \quad (4)$$

where $\epsilon$ is the emissivity of galvanized steel, $\sigma$ is the Stefan-Boltzmann constant, $|R| = |R(x,y,z,x',y',z')|$ is the distance between the measuring surface and the surface whose temperature is T(x', y', z', t) at the time instant t, dA is a surface element on the radiating surface. The derivation of this equation is presented in the appendix.

The calculation is for the flux detected by a flux gauge directed at the stopping. The x,y coordinates in the formula in the appendix are taken along the horizontal and vertical direction of the stopping, the z direction is the direction perpendicular to this surface. In this case, the calculated and the measured values are shown in figure 22. In this calculation, the only adjustable parameter is the emissivity, which is taken to be 0.21. The agreement is quite good indicating that heat transfer to points remote from the unexposed surface of the metal stopping is predominately by radiation.

In comparison with the concrete block stopping, the galvanized steel stopping performed well in terms of structural integrity and resistance to flame and smoke penetration when installed according to the manufacturer's instructions. Based on the same consideration given to the concrete block stoppings, the metal stopping withstood the 70-min fire. However, in view of the considerably higher back surface temperatures resulting in the metal stopping test, even though combustible materials positioned as close as 1 ft from the metal surface were not ignited, location of such materials at distances closer than 1 ft should be avoided. It would be prudent in fact to exclude such materials at even greater distances as a further precaution against fires larger than the standard 70-min test fire used in this investigation.

## Coated Metal Stopping

The metal stopping that withstood the 70-min test was prepared for another test by covering its front surface with a 3/4-in-thick layer of building plaster in two applications. The plaster is a commercial perlited gypsum product reported (*10*) to have satisfactory fire endurance characteristics. Basically the same experimental condition and instrumentations were employed as in the previous test with the exception that an infrared camera was not available. Furthermore, additional wood strips were placed touching the metal surface of the stopping on the unexposed side. The thermocouple arrays that previously measured the front surface temperatures of the stopping now measured the interface temperatures between the plaster coating and the metal stopping.

The plaster coated metal stopping was subject to the standard 70-min fire used for the previous stopping tests. None of the wood strips in contact with the back surface were ignited or charred. The plaster coating adhered to the front surface in spite of some cracks that appeared in the region where the fire was most intense. The temperatures of the interface as well as those of the back surface are shown in figures 23 and 24. It can be seen

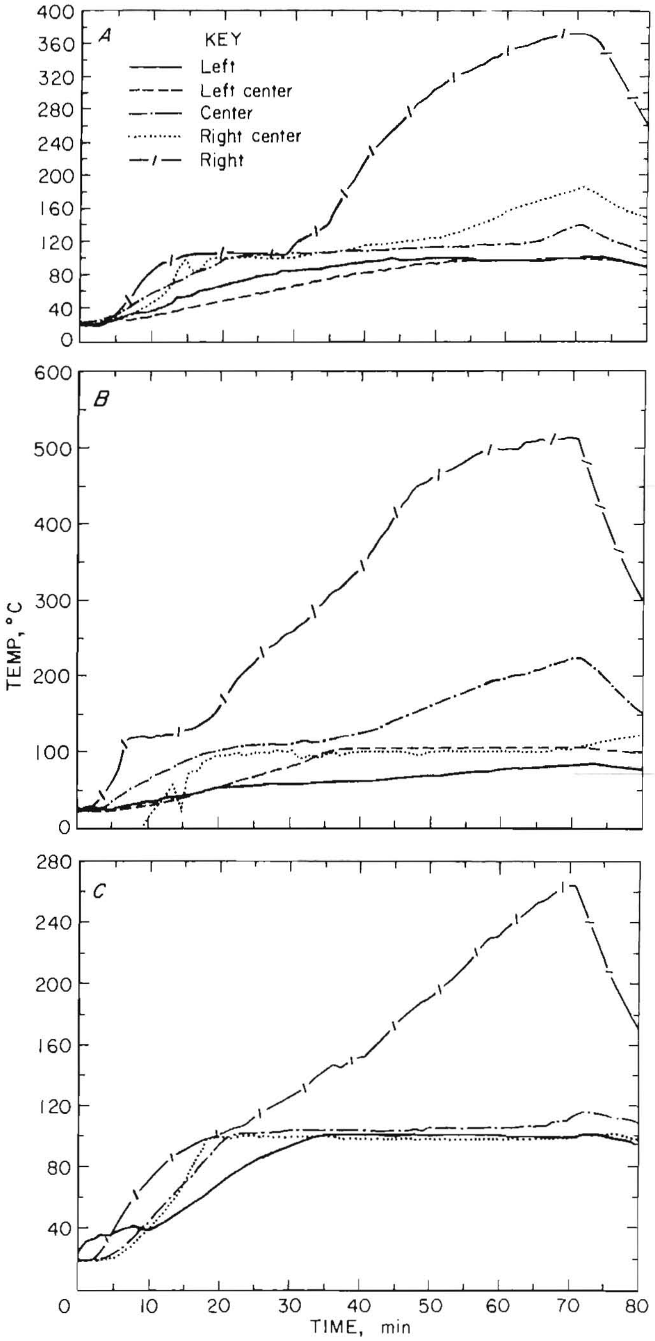

**Figure 23.—Temperatures of top (*A*), middle (*B*), and bottom (*C*) thermocouples at plaster-metal interface of plaster-coated metal stopping.**

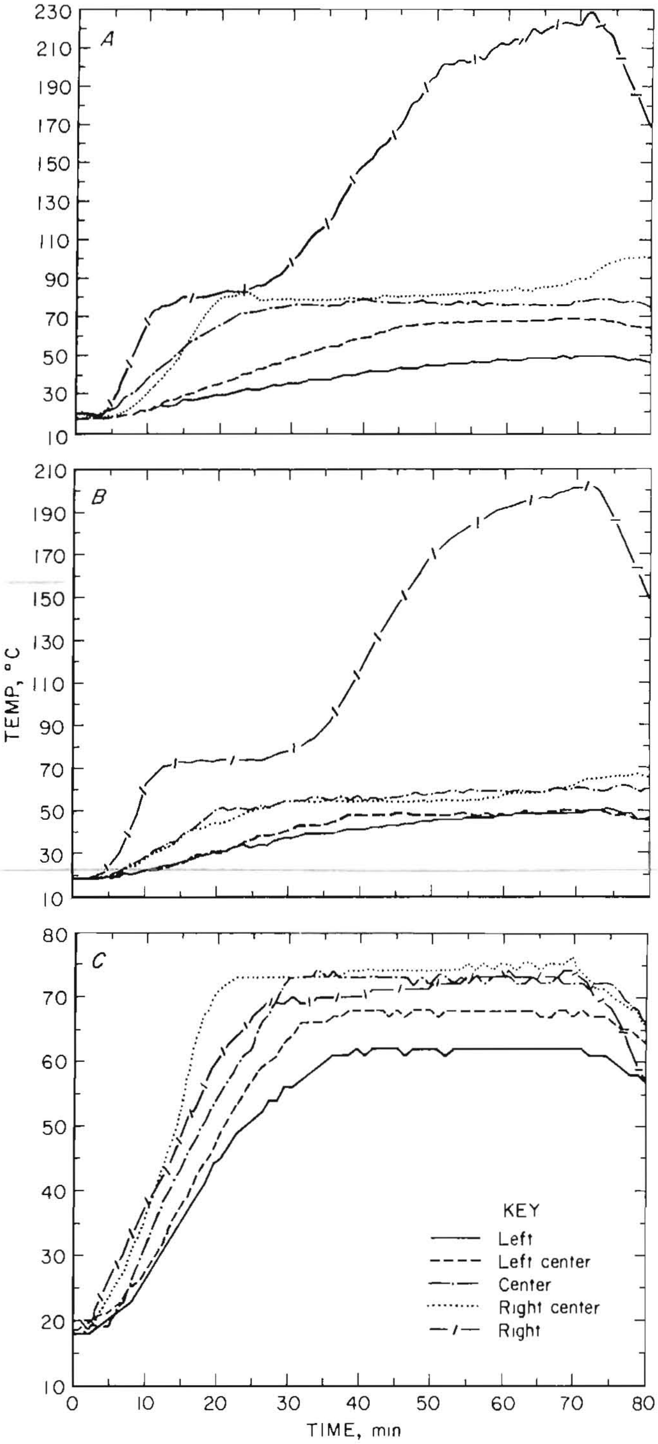

**Figure 24.—Temperatures of top (*A*), middle (*B*), and bottom (*C*) back surface thermocouples of plaster-coated metal stopping.**

from figure 23, that at almost all the thermocouple locations the interface temperatures were in the 100° to 120° C range with the exception of the ones on the right where the fire is most intense. In those regions, the plaster coating began to crack about 30 min into the test. After the crack developed, the interface temperature began to rise to about 400° to 500° C. These temperatures are still some 400° C less than those recorded on the front surface of the uncoated metal stopping.

The stopping back surface temperatures for this test are shown in figure 24. The temperatures are generally below 80° C, similar to those of the concrete block stopping. The exceptions were at locations on the right where the intense heat had cracked the surface plaster coating and increased heat transfer in that area. The coating definitely was effective in decreasing the overall heat transfer across the stopping. This was further indicated by the row of thermocouples measuring the air temperatures near the roof at a distance of 1 ft from the back surface of the stopping (fig. 25). The highest reading recorded there was about 70° C, which again is about half of what it was in the case of the uncoated metal stopping (150° C).

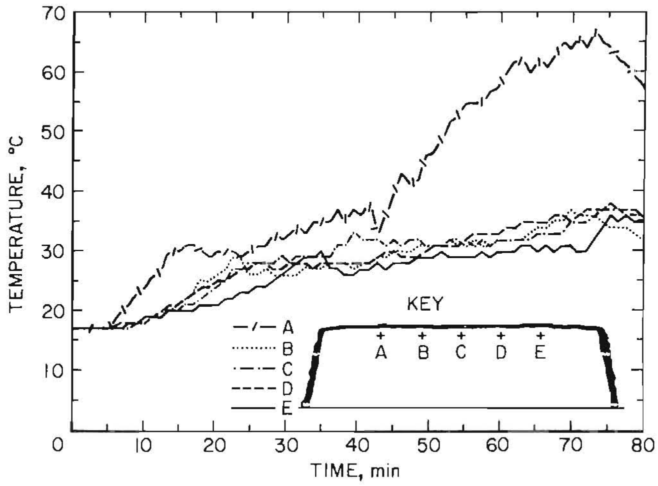

**Figure 25.—Temperatures of air thermocouples 1 ft from back surface of plaster-coated metal stopping.**

## SUMMARY

A facility was constructed in the Bruceton (PA) Experimental Mine to conduct fire endurance tests of stoppings. This facility is capable of testing mine-size structures and recording up to 100 channels of temperature and voltage data. A series of preliminary tests resulted in the selection of a standard 70-min liquid fuel tray fire for the stopping tests. The optimal fuel delivery rate was 0.7 gal/min, producing a fire with an output of 75,000 Btu/min.

Concrete block stoppings and a galvanized steel stopping were subjected to the fire and the findings summarized below.

### Concrete Block Stoppings

- The concrete blocks stoppings withstood the intensity of the fire for the duration of the tests and prevented the penetration of flame and smoke. In spite of the appearance of a vertical crack (width about 1/4 in) on the fire side of the stopping, the unexposed side was not damaged.

- The hottest temperature measured on the fire side of the stopping was as high as 800° C, while temperatures on the unexposed side of the block stoppings never exceeded 80° C (70° C above ambient); such a temperature rise would not ignite combustible material in contact with the surface.

### Metal Stopping

- The metal stopping was undamaged by the fire and prevented the passage of flame and smoke. The maximum temperature on the unexposed surface of the metal stopping was 490° C.

- The hottest air temperature near the roof and 1 ft from the unexposed surface was 150° C. Materials such as coal, coal dust, matches, and wood did not ignite when placed about 1 ft from the metal stopping.

- Because of the high surface temperatures generated in the event of a fire , combustible materials should not be placed in contact with the stopping surface.

Plaster-Coated Stopping

o A 3/4-in-thick gypsum plaster coating on the fire side of the metal stopping was able to keep the back surface temperature to the same level as that of the concrete blocks until the plaster developed a crack at the hottest region produced by the fire. Even when that occurred (toward the end of the 1-h test) the highest temperatures on the back surface of the stopping and at a location 1 ft from the stopping were about half those for the uncoated metal stopping. The coating clearly reduced the heat energy conducted across the metal stopping.

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## APPENDIX.–HEAT FLUX CALCULATION

An x, y, z coordinate system is used. Unit vectors along the coordinates are represented by i, j, k. The coordinates of the radiating surface are represented by (x',y',z') and those of the detector are represented by (x,y,z). u is a unit vector in an arbitrary direction. S is a surface vector on the radiating surface and dS(x',y',z') is a surface element on it. R = R(x,y,z,x',y',z') = (x-x')i + (y-y')j + (z-z')k is the vector from the surface element to the detector and the square of its length is given by $|R|^2 = (x-x')^2 + (y-y')^2 + (z-z')^2$ and a unit vector in this direction is given by $R/|R|$.

The component of heat flux in a direction u arriving at the detector is given by

$$dF_u = \sigma \epsilon \ dS \bullet \frac{R}{|R|} \frac{T^4(x',y',z',t)}{|R|^2} u \bullet \frac{R}{|R|}$$

where $\sigma$ the Stefan-Boltzmann constant and $\epsilon$ is the emissivity.

The total flux arriving at the detector is the integral of this expression over the total radiating surface and is given by

$$F_u = \int \epsilon \sigma \ dS \bullet \frac{R}{|R|} \frac{T^4(x',y',z',t)}{|R|^2} u \bullet \frac{R}{|R|}$$

When dS = dA k and u = k, corresponding to the case when the radiating surface and the detector are facing each other as in the case of the metal stopping and the heat flux gauge,

$F_u = F_k$ = Flux at the detector looking at the stopping

$$= \int \epsilon \sigma \frac{T^4(x',y',z',t)}{|R|^4} (z-z')^2 \ dA.$$

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