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EXPERIMENTAL INVESTIGATIONS OF
STEEL-SUPPORTED CONSTRUCTION

by

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OPENINGS IN FIRE PROTECTIVE CEILINGS: EXPERIMENTAL INVESTIGATIONS OF STEEL-SUPPORTED CONSTRUCTION

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W.W. Stanzak

Membrane ceiling fire protection has been under study for over a decade. This Note summarizes the available experimental information and from a practical point of view draws conclusions concerning a technically complex subject.

A protective membrane is a continuous layer separating the member or members to be protected from fire without coming into direct thermal contact with them. At high temperatures, therefore, it can be shown that the bulk of the heat transfer between the unexposed side of the membrane and the under side of the superstructure is due to radiation (1) and is thus dependent only on the temperature of the bounding surfaces. Harmathy (2) has provided the following information relevant to membrane protection:

> "Rule 3: The fire endurance of constructions containing continuous air gaps or cavities is greater than the fire endurance of similar constructions of the same weight, but containing no air gaps or cavities.
>
> "The validity of this rule rests on the fact that by the insertion of voids, additional resistances are produced in the path of heat flow. Numerical heat flow analyses indicated that a 10 to 15 per cent increase in fire endurance can be achieved by creating an air gap at the midplane of a brick wall [2].
>
> "Since the gross volume of constructions is also increased by the presence of voids, the air gaps and cavities have a beneficial effect on the stability as well.
>
> "Constructions containing combustible materials along an air gap may be regarded as exceptions to this rule, because of the possible development of burning in the gap.
>
> "Rule 4: The farther an air gap or cavity is located from the exposed surface, the more beneficial is its effect on the fire endurance.

"In the heat transfer through an air gap or cavity, radiation is the predominant mechanism. Since the heat transfer by radiation increases markedly with the average level of temperature in the void, an air gap or cavity is a very poor insulator if it is located in a region which attains high temperatures during fire exposure.

"Rule 5: The fire endurance of a construction cannot be increased by increasing the thickness of a completely enclosed air layer.

"There is evidence [2] that if the thickness of the air layer is larger than about ½ in., the heat transfer through the air layer depends only on the temperature of the bounding surfaces, but is practically independent of the distance between them.

"Rule 6: Layers of materials of low thermal conductivity are better utilized on that side of the construction on which fire is more likely to happen.

"The validity of this rule has been demonstrated [2]. The rule may not be applicable to materials undergoing physicochemical changes accompanied by significant heat absorption or heat evolution."

This information indicates that as long as no significant gas flow is permitted into the plenum space, fire resistance of floor-ceiling assemblies should not be greatly affected by suitably shielded (against radiative heat transfer) service openings.

Because of the lack of technical information on this topic it has been customary to conduct standard fire tests (3, 4) on floor-ceiling assemblies incorporating such openings. These as-tested designs are published (5, 6) along with alternate methods of protection acceptable to the major North American commercial testing laboratories. It is worth emphasizing, however, that the tests were conducted under static plenum conditions with a slightly negative furnace pressure. For this condition to be realistic, air flow must be stopped in the event of fire by such devices as fire dampers, flaps, or an automatic shut-down of the air handling system.

In this context the first published test data (7) indicated, as surmised, that service openings in a membrane protective system under steel construction may be incorporated provided duct protection methods described in References 5 to 7 are used. This research, however, is subject to the following limitations:

- As a 'split-frame' type assembly was used, the mechanical performance of the construction elements as well as the heat transfer process may not be completely accurate as an indication of performance in a full-scale test.

- None of the tests explored the effectiveness of protecting openings and ductwork against the effects of vertical radiation only (i.e., the sides of ductwork were protected, adding considerably to the expense of the construction).

- The maximum size of duct opening incorporated in the tests was less than that required to achieve good mechanical efficiency of air handling in certain types of occupancy.

- One of the methods involved use of a 'fire-stop flap' or so-called 'ceiling damper'; this device is expensive, usually field manufactured, and does not provide an effective means of stopping air and smoke flow.

Additional full-scale tests were therefore designed to demonstrate the following:

- The presence of ductwork does not significantly affect the mechanical performance of construction elements or the heat transfer process in the full-scale test.

- Protection of the opening and ductwork against vertical radiation is adequate; this is known as 'partial protection' and is most conveniently accomplished by using the ceiling material as the radiation barrier.

- The maximum size of duct opening into the ceiling membrane need not be limited to very small areas.

In demonstrating this, it is assumed that suitable provision is made to stop air flow in the ductwork without use of a fire-stop flap or ceiling damper. This is accomplished either by fire dampers where the ductwork passes through fire separations, or by a shut-down of the mechanical system.

Five fire tests on floor-ceiling assemblies with and without openings were performed. Two preliminary tests were conducted at the DBR/NRC Fire Research Section under a cooperative program known as the Steel Industries Fellowship. The other three were carried out at Underwriters' Laboratories of Canada under the sponsorship of the Canadian Steel Industries Construction Council. These tests will be described in some detail.

PRELIMINARY TESTS AT DBR/NRC

Variables in the investigation were kept to a minimum. One assembly incorporated an unpenetrated gypsum board ceiling, the other an identical ceiling with a nominal 3- by 3-ft duct opening at ceiling level and suspended ductwork above. Details of the assemblies and their construction will be described.

Description of Test Assemblies

Figure 1 is an isometric view of assembly No. 2. The following item numbers correspond to the part numbers shown:

Part No. 1. Steel joists: 6 in. deep, spaced 3 ft either side of furnace centreline (6 ft o.c.), clear span 15 ft 0 in., effective span 15 ft 4 in. The two joists in assembly No. 1 were provided with 1- by 1- by 1/8-in. angle X-bridging at mid-span and had cold-formed chords. The joists of assembly No. 2 were unbridged because the duct was located between them and had hot rolled steel chords. All joists were supported on W10X21 beams at the east and west ends of the test frame and were attached to the beams with a tack weld about 1 in. long.

Part No. 2. Steel deck: 16-ga (0.060-in.) wiped-zinc galvanized steel, $1\frac{1}{2}$ in. deep, fluted, supplied in 6-ft and 3-ft 2-in. spans. The deck was plug welded to the joists at approximately 8 in. o.c. with a 5/8-in. steel washer and was simply supported on unit masonry at the perimeter of the test frame.

Part No. 3. Concrete fill: placed $2\frac{1}{2}$ in. deep over the steel deck, average compressive strength 3670 psi (73 days), maximum aggregate 5/8 in., average slump 2 3/8 in.

Part No. 4. Sheet steel duct: 26-ga (0.024-in.) galvanized steel 14 ft long by $35\frac{1}{2}$ in. wide and 12 in. deep, with a 4-in. riser measuring $35\frac{1}{2}$ in. sq (area 8.63 ft^2), duct ends closed.

Part No. 5. Grill: 26-ga (0.024-in.) galvanized sheet steel $35\frac{1}{2}$ in. sq inserted in riser and attached with four sheet metal screws. The grill was provided with ten diffuser blades and a 1-in. lip round the perimeter.

Part No. 6. Duct hanger straps: 1 by 1/16 in., screwed to threaded steel studs embedded in steel deck and concrete. Four hangers were provided on each side of the duct and screwed to it with two sheet metal screws at each hanger.

Part No. 7. Steel stud: standard 1 5/8-in. drywall stud, cold-formed from wiped-zinc galvanized steel approximately 0.019 in. thick, supplied in 9-ft lengths and spaced at 4 ft o.c. The studs were nested in the installation to provide a sliding joint to accommodate thermal expansion. Four lines of studs were spaced at 4 ft o.c.

Part No. 8. Hanger wire: 12-ga (0.164-in.) galvanized steel rod was welded to the steel deck and used to suspend the studs from the deck at 4 ft o.c.

Part No. 9. Furring channel: standard $2\frac{3}{4}$ in. wide by 7/8 in. deep wiped-zinc galvanized steel approximately 0.020 in. thick, supplied in 12-ft lengths and placed at right angles to the steel studs at 2 ft o.c.

Part No. 10. Tie wire: 19-ga (0.048-in.) soft steel galvanized wire was used to single-loop tie the furring channels to the studs.

Part No. 11. Gypsum board: 5/8 in. thick, paper laminated, listed by Underwriters' Laboratories of Canada (5), supplied in 4- by 8-ft sheets. Joints were treated with tape and premixed joint compound.

Part No. 12. Duct protection (i.e., the radiation barrier also referred to as 'partial protection'): gypsum board as in No. 11, overhanging duct by 3 in. round the centre perimeter. The protection was edge-notched where necessary to allow passage of the duct hangers.

Figure 2 shows details of the ceiling system and duct layout and Figures 3 to 7 indicate other essential details of construction and instrumentation. Figures 8 to 17 are photographs relevant to the investigation.

Specimen No. 1 was identical to specimen No. 2 except that ductwork and ceiling penetration were absent. It should be noted that in assembly No. 1 the small ribs of the steel deck were turned upward, whereas the orientation was reversed for assembly No. 2. All construction was carried out by members of the staff of DBR/NRC and the ductwork was manufactured in NRC's Plant Engineering Division. The workmanship was good and generally in accordance with normal commercial practice.

Test Method

The specimens were subjected to fire test in accordance with the provisions of ASTM E119-71 (3), with the following exceptions in procedure:

- Assembly No. 2 was not loaded in order to minimize any chance of premature ceiling failure.

- Because unexposed surface temperatures were not of prime concern, they were measured at only five points on assembly No. 1.

- Moisture content of the concrete topping, approximately 10 months old, was not measured.

Gas flow into the furnace was controlled automatically so as to follow closely the temperature-time curve prescribed by the standard. Furnace temperature was measured by nine symmetrically distributed thermocouples enclosed in 13/16-in. o.d. inconel tubes having a wall thickness of 0.035 in. and equipped with a carbon steel cap at the tip. The hot junction of the thermocouples was placed 12 in. from the exposed face of the specimen. Both the individual temperatures at the nine points and the average of the nine were recorded during the test.

The temperature of the unexposed surface of specimen No. 1 was measured by five thermocouples located at the centre and quarter points of the assembly. On specimen No. 2 temperatures in the plenum and on the unexposed surface were measured by thermocouples located as shown in Figures 6 and 7. All unexposed surface thermocouples were covered with standard asbestos pads 6 in. square and 0.4 in. thick.

Joist temperatures were measured at 24 points at the centre and quarter spans. Location of the thermocouples on the cross-section is shown in Figure 5.

During the test a live load of 125 lb/sq ft was applied to assembly No. 1; assembly No. 2 was not loaded.

Numerous thermocouples were distributed throughout the plenum space to measure temperatures of the unexposed ceiling face, air, ductwork and under side of the steel deck, etc.

Observations

Significant observations on the exposed surface were recorded during the fire tests; they were fairly similar for both tests. At about ½ min the exposed surface had already darkened and was beginning to flame; after about 2 min the flames were diminishing. By 6 min the joint compound and tape were peeling, and by about 15 min the joints were completely bare and were opening owing to shrinkage of the gypsum board. Both ceilings remained relatively intact for about 2 hr: in assembly No. 1 a panel dropped at 2 hr 24 min; in assembly No. 2 a large portion of a panel dropped at 119 min. Following this, other panels fell successively for about 10 min until the tests were terminated.

The unexposed surfaces of the test specimens developed numerous cracks ranging from hairline to ¼ in.

Results

Temperatures that developed in the furnace and tested assemblies are illustrated in Figures 18 to 28, which are labelled so as to be self-explanatory. Imminent structural failure of the assemblies was judged by use of critical temperature criteria, as described in ASTM E119. Because the joists are spaced at more than 4 ft o.c. beam criteria apply, and the critical temperatures are an average of 1100°F (593°C) at any cross-section and 1300°F (704°C) at any individual point. According to these criteria, the fire resistance of the unrestrained assemblies was 2 hr, with failure of assembly No. 1 at 145 min and failure of assembly No. 2 imminent at 132 min.

Comments

It may be seen from Figures 20 and 21 that temperatures of the structural steel in the assembly incorporating the duct opening (assembly No. 2) were consistently about 100 F deg (56 C deg) higher than those for the other specimen, as were other plenum temperatures. On the other hand, temperatures above the duct protection and on the unexposed surface above the duct were somewhat lower. This indicates that inclusion of a partially protected duct system poses only a minor threat to the structural support system and does not significantly affect the fire performance of the entire assembly.

TESTS AT ULC

Three tests (8) were designed and conducted on the basis of the earlier investigation at DBR/NRC. Again, the variables were kept to a minimum. One joist-supported steel floor assembly incorporated a continuous suspended-tee, lay-in mineral board ceiling. The others were identical except for inclusion of ductwork and openings. To be representative of normal fire test practice, all assemblies were loaded to develop the theoretical working stresses in the significant structural elements.

Description of Test Assemblies

Figure 29 is an isometric view of a typical test assembly. The numbers below correspond to the part numbers shown.

Part No. 1. Open web steel joist (OWSJ): Depth 16 in., span 13 ft 8 in., resisting moment 24.87 ft-kips, spacing 6 ft o.c.

Part No. 2. Steel floor deck: non-composite, 16-ga (0.060 in.) galvanized, 1½ in. deep, 6-ft span, 2-ft width, total allowable load 176 lb/ft^2.

Part No. 3. Concrete topping: 2½ in. over top of flutes in steel deck, sand-gravel aggregate, average density 151 lb/ft^3, average compressive strength 3400 psi.

Part No. 4. Main-tee: 1½ in. deep by 1 in. wide, roll formed of 0.018-in. thick galvanized steel and provided with a rolled-on prepainted steel cap (0.010 in.) on the exposed face; supplied in 12-ft lengths with one expansion point per length, spaced 4 ft o.c., listed by ULC (5).

Part No. 5. Cross-tee: as above, but supplied in 4-ft lengths without expansion point, spaced 2 ft o.c., listed by ULC (5).

Part No. 6. Hanger wire: No. 12 SWG (0.164 in.), spaced 4 ft o.c.

Part No. 7. Ceiling panels: mineral fibre, 47-$\frac{3}{4}$ × 23-$\frac{3}{4}$ × 9/16 in. thick, listed by ULC (5).

Parts No. 8 to 10. Simulated air ducts (present only in Tests No. 2 and 3):

Test No. 2, Parts 8 and 10. 24-ga (0.027-in.) galvanized sheet steel, 12 in. deep by 18 in. wide by 8 ft long, closed ends, 12-in. diam header 6 in. long located 3 ft from one end of duct.

Test No. 2, Part 9. 24-ga (0.027-in.) galvanized sheet steel, 12 in. deep by 22 in. wide by 8 ft long, closed ends, 18-in. diam header 6 in. long located 3 ft from one end of duct.

Test No. 3, Parts 8, 9. Same as 8 and 10 above.

Test No. 3, Part 10. 24-ga (0.027 in.) galvanized sheet steel 12 in. square by 8 ft long, closed ends, 6-in. diam header 6 in. long located 3 ft from one end of duct.

Part No. 11. Ceiling panels (used as top of duct protection): centred over the header as follows

Test No. 2 - 2 by 4 ft for ducts 8 and 10
- 2 pieces, 2 by 4 ft for duct 9.

Test No. 3 - 2 by 4 ft for ducts 8 and 9
- 2 by 2 ft for duct 10.

Part No. 12. Air diffuser: standard units of sheet steel without fire stop flaps, area of opening* in ceiling above the diffusers as follows

Test No. 2 - ducts 8 and 10:	451 in.^{2} (25"ø)
duct 9 :	1074 in.^{2} (37"ø)
total ceiling opening:	2056 in.^{2} (7.4 per cent of ceiling area)
Test No. 3 - ducts 8 and 9 :	453 in.^{2} (24"ø)
duct 10 :	113 in.^{2} (12"ø)
total ceiling opening:	1019 in.^{2} (3.7 per cent of ceiling area)

The assemblies for Tests No. 1 and 2 were constructed on the same date by workmen in the employ of Underwriters' Laboratories of Canada; the assembly for Test No. 3 was built some months later. The ductwork and ceilings were installed by representatives of the sponsor and manufacturers of ceiling materials. The ceiling was installed approximately 28 in. below the under side of the steel deck.

* As air flow is assumed to be stopped during a fire and is not possible during the fire test because of the closed ends, the area of opening in the protective membrane is considered rather than the area of header.

Figures 29 and 30 show construction features and a typical reflected ceiling plan for the specimens and indicate important mechanical details. Figures 31 to 38 are photographs relevant to the investigation.

Test Method

The specimens were subjected to fire test in accordance with the provisions of ULC S101-75 (4). Gas flow into the furnace was controlled manually so as to follow closely the temperature-time curve prescribed by the standard. Furnace temperature was measured by 12 symmetrically distributed thermocouples enclosed in black iron pipes with a carbon steel tip. The hot junction of the thermocouple was placed 12 in. from the exposed face of the specimen. Both individual and average temperatures at the 12 points were recorded during the tests.

The unexposed surface was provided with 11 thermocouples under standard asbestos pads at the mandatory locations and at points expected to develop information regarding extra heat transmission caused by ducts and openings. The locations are shown in Figure 39 and are identical for the three specimens.

Joist temperatures were measured at 24 points at the centre and on the spans, as identified in Figure 40. Steel deck temperatures were measured at significant locations identified in Figure 41. Temperatures on the top of the tile and in the air of the plenum were measured at numerous locations that need not be detailed in this report. Deflections were measured at the centre of the assembly and over the mid-span of each joist.

At the time of test, moisture contents of the concrete topping were as follow:

Test No. 1	69.5 per cent RH
Test No. 2	67.7 per cent RH
Test No. 3	82.1 per cent RH

Observations

Significant observations are on file for all tests. Only Test No. 2 was terminated because a portion of tile dropped out (ceiling failure) at about 160 min; the others were terminated shortly after 3 h because this was the maximum time of interest in the investigation.

The condition of the exposed surface of specimens just after the fire test is shown in Figures 42 to 44. A typical view of the superstructure following fire test, cooling, and removal of the ceiling is shown in Figure 45.

Results

Centre deflections of the assemblies are compared in Figure 46. Temperatures that developed in the tested assemblies with the furnace temperatures closely following the prescribed function are illustrated in Figures 47 to 52. The figures are labelled and are self-explanatory.

Structural failure due to deflection was not imminent in any of the tested assemblies at the time each test was terminated. (Assembly No. 2 would have collapsed within about 10 min because of ceiling failure, but this was not of interest in the present investigation.)

A structural end-point during a fire test for an unrestrained rating is defined by ASTM E119 and ULC S101 for members spaced more than 4 ft o.c. as being the time to reach an average of 1100°F (593°C) at any measured cross-section, and 1300°F (704°C) at any individual measured point. According to these criteria only the joist near the ceiling failure in Assembly No. 2, exceeding 1100°F (593°C) at about 152 min, obtained an unrestrained beam classification of less than 3 h. The joists of the other assemblies had not exceeded the classification criteria when the tests were terminated.

According to unexposed surface temperature rise criteria, which for these restrained assemblies determined the end-point, the assemblies failed at the following times:

Test No. 1	190 min (average unexposed)
Test No. 2	158 min (average unexposed)
Test No. 3	186 min (maximum individual)

Assemblies 1 and 3 obtained a 3-h fire resistance classification; assembly 2 obtained a 2-h fire resistance classification.

Comments

It may be seen that temperatures of the steel joists in the assemblies incorporating duct openings (assemblies 2 and 3) were consistently as much as 200 F deg (111 C deg) higher than the reference specimen without openings. Temperatures measured at the back of the ceiling tile, in the air space, on the steel deck, and on the unexposed surface were also higher in specimens with openings, as would be expected.

The main objective of the research work was to obtain a simple rule by which the fire endurance of an assembly tested without openings may be assessed once openings have been incorporated in that assembly. Because of the expense of fire tests and the crudeness of the entire approach, which ignores the possibility of positive fire pressures and air flow in the ducts, the author considers it appropriate to attempt to obtain definite, though conservative, conclusions from these data.

DISCUSSION

The simplest relation between reduction of fire endurance and size of opening that might be obtained is a linear reduction of fire endurance time with size of opening. Inherent in this approach is the thought that at some point the ceiling makes no contribution to the fire resistance of the assembly because the openings are too large or too numerous. At this point either a double ceiling, the upper one serving a purely fire protective function, or an alternate form of fire protection is required.

Examination of data from both test series indicates that where openings are partially protected (i.e., radiation barrier equivalent to ceiling material) both the total area of opening and the size of an individual large opening influence the reduction of fire endurance time. Unfortunately, the data are not sufficiently definite to assign an area that will designate an opening as "large" with respect to what might be considered "small, evenly dispersed" openings. An arbitrary value based on the experience of these tests can be chosen, however. The ULC tests indicate that an opening of up to 450 $in.^2$ (Test No. 3) does not promote premature ceiling failure or extremely high local temperatures. Both the NRC and ULC tests show, however, that much larger openings as well as adjacent high temperatures do cause ceilings to fail earlier, although the temperatures directly above the opening, with its radiation barrier, may be relatively cool.

The method must therefore provide for two situations; for "dispersed openings" and for "large openings." Both terms require definition on the basis of the assemblies tested, and it is recognized that such definitions are crude and rather arbitrary.

A <u>large opening</u> is defined as one that has an area of 450 $in.^2$ or more, or a dimension greater than 24 in. in any direction, located 10 ft or more from any other opening. (No large opening shall have an area greater than 1000 $in.^2$ because this approximately represents the limit of the test data.)

<u>Dispersed openings</u> are defined as openings having an area of less than 450 $in.^2$ and no dimension greater than 24 in. in any direction. (No individual opening shall be located closer than 7 ft to any other opening and no closer than 10 ft from any large opening.)

The data show that large openings have the most significant effect on unrestrained steel assemblies, which are liable to collapse with structural steel temperatures in the neighbourhood of 1100 to 1300°F (593 to 704°C). Dispersed openings hasten failure by unexposed surface temperature rise - the usual mode of failure for restrained steel assemblies. The method developed, therefore, should also distinguish between the effects on restrained and unrestrained ratings where these differ for a particular assembly (usually they do not).

Finally, the present information considers only penetrations of assemblies that were tested without openings. The method will therefore not necessarily apply to additional penetrations of assemblies tested with openings.

Based on examination of the data and the preceding discussion the following method is proposed:

$$t = t_i\ (1 - cO),$$

where

t = fire endurance time of assembly with openings

t_i = fire endurance time of tested assembly without openings

c = constant

O = opening fraction.

The value c, based on the available fire test data, is assigned as follows:

Restrained Assembly

dispersed openings	$c = 2$
large opening	$c = 3$

Unrestrained Assembly

dispersed openings	$c = 3$
large opening	$c = 4$

Because of the fire endurance times involved in the tests, this method can be considered applicable only if the reference assembly has a fire resistance classification of 2 or 3 h. Table I compares the fire endurance time of the tested assemblies with those computed by the proposed method. As may be seen, the results are in all cases conservative (see also Appendix A).

CONCLUSIONS

1. Provided that air flow is stopped, partial protection of duct openings against vertical radiation to the assembly above provides a satisfactory method for retaining the fire resistive qualities of membrane-protected floor systems with ceiling penetrations.

2. A 'fire-stop flap' or 'ceiling damper' is redundant when other means of stopping air flow in mechanical systems are provided and when the duct opening is appropriately shielded to block vertical radiative heat transfer.

3. Until better information becomes available the method proposed for computing the fire endurance times of assemblies to be penetrated by openings, but tested without, should be applied.

4. For almost all assemblies with some safety margin over the required fire resistance classification the openings permitted by the National Building Code 1975, Section 3.1.5.6, can be incorporated by application of the proposed method without reducing the fire resistance classification.

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8. Private communication. Fire test data on file at Underwriters' Laboratories of Canada provided by permission of the Canadian Steel Industries Construction Council.

TABLE I. COMPARISON OF ACTUAL AND COMPUTED FIRE ENDURANCE TIMES FOR ASSEMBLIES TESTED

0	t_i	t (test)	t (computed)	Test
0.048	145	132	117[1]	(NRC) Unrestrained assembly
0.037	190	186	176	(ULC)
0.074	190	158	148[2]	restrained assembly

[1] The actual opening incorporated in the test assembly exceeded 1000 $in.^2$ in area and would not be permitted by the proposed method.

[2] According to the proposed method, the large opening in the assembly would not be permitted because it is less than 10 ft from another opening.

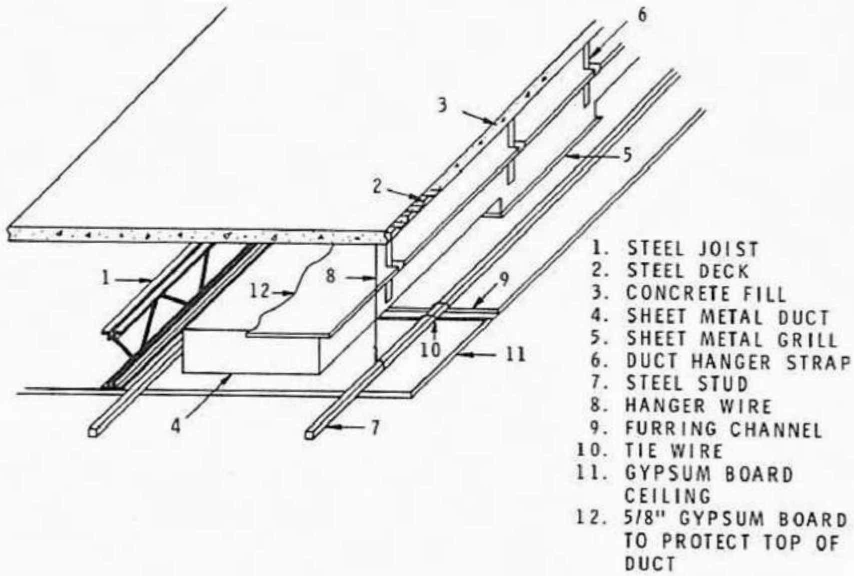


FIGURE 1
CONSTRUCTION DETAILS

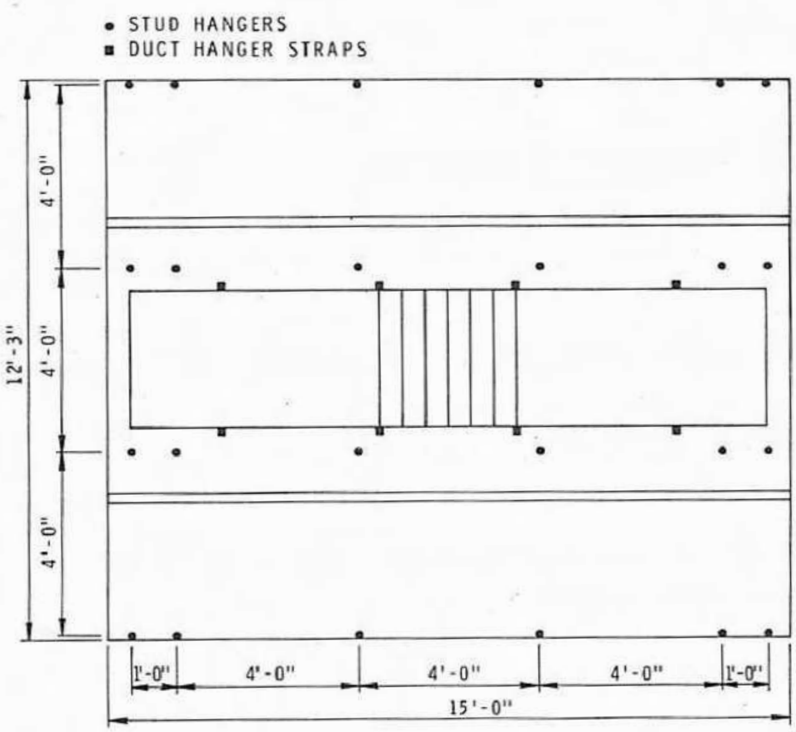


FIGURE 2
REFLECTED VIEW OF CEILING SHOWING POSITIONS OF HANGERS

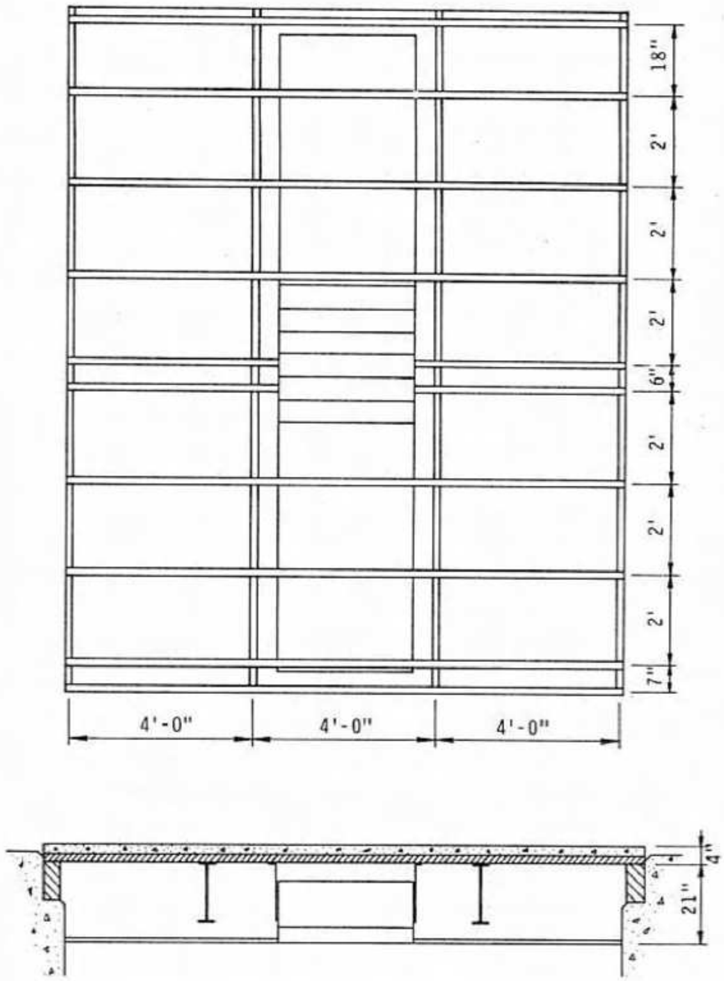


FIGURE 3
LOCATION OF FURRING STRIPS

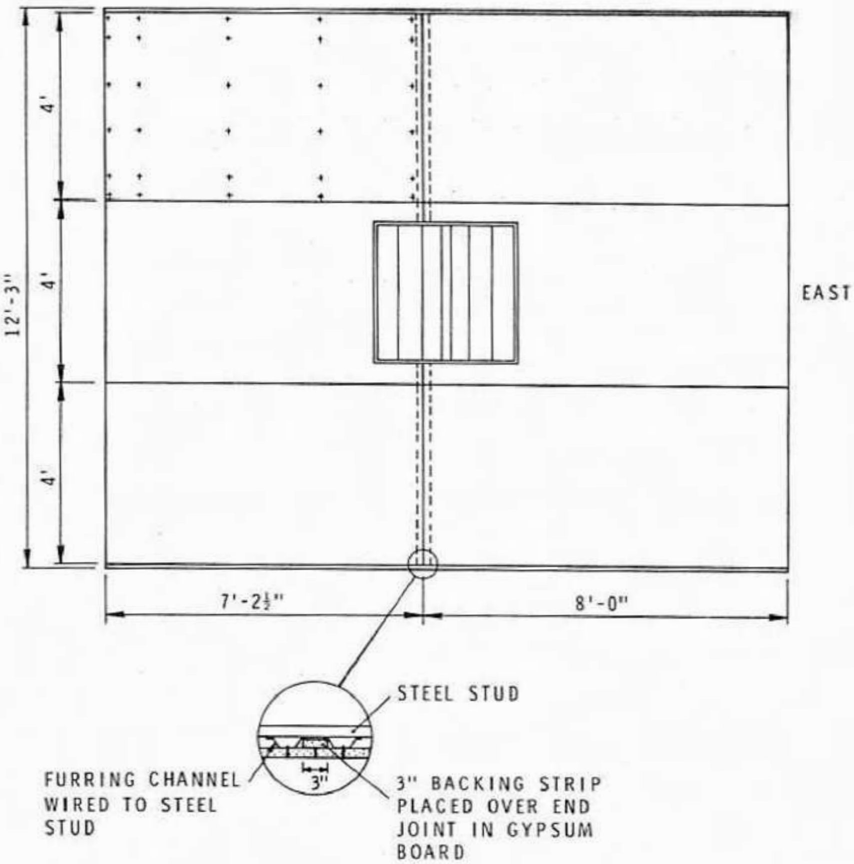
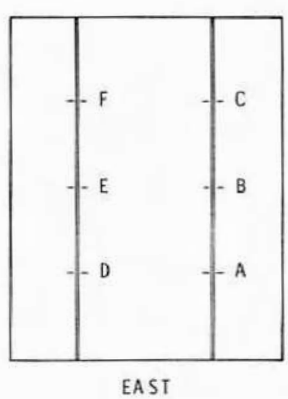


FIGURE 4

REFLECTED VIEW OF CEILING SHOWING GYPSUM BOARD LAYOUT AND SCREW LOCATIONS



	1	2	3	4
A	1	2	3	4
B	5	6	7	8
C	9	10	11	12
D	13	14	15	16
E	17	18	19	20
F	21	22	23	24

FIGURE 5

LOCATION AND NUMBERING OF THERMOCOUPLES ON STEEL JOISTS

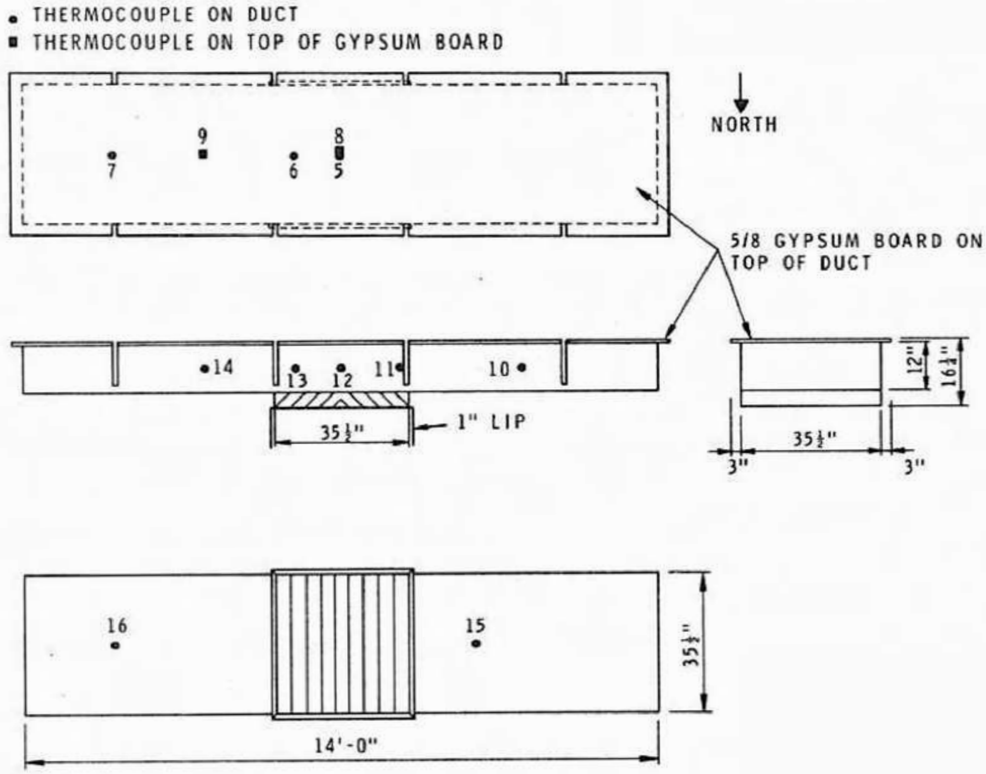


FIGURE 6
DETAIL OF DUCT AND LOCATION OF THERMOCOUPLES

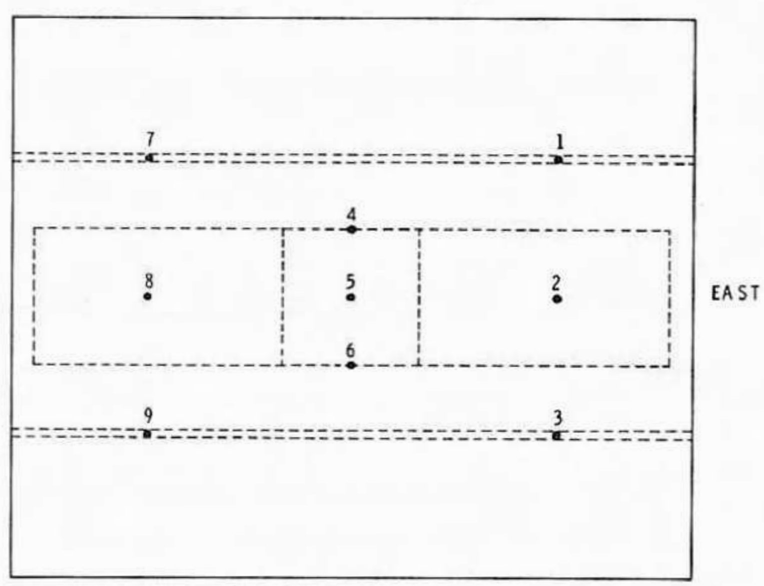


FIGURE 7
LOCATION OF THERMOCOUPLES ON UNEXPOSED SURFACE

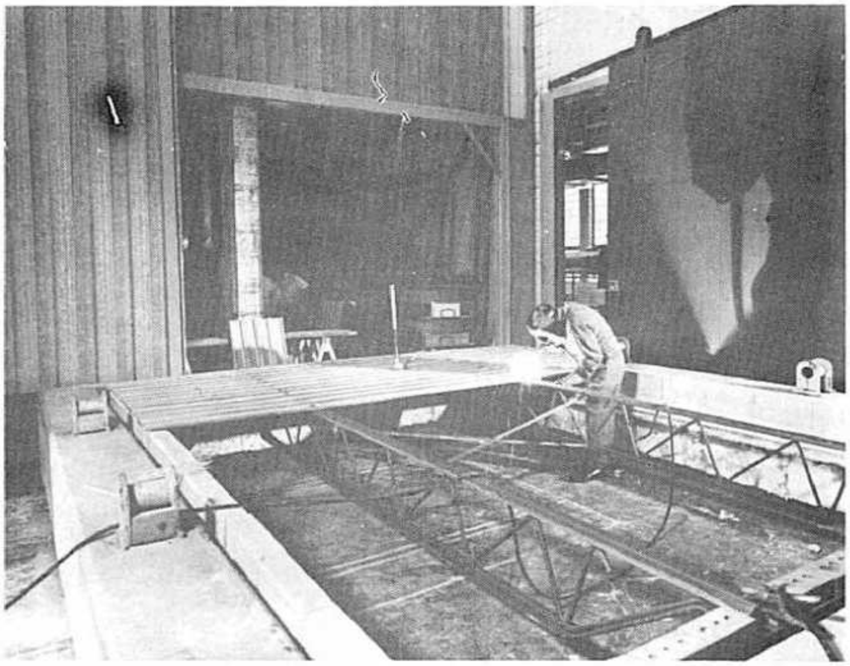


FIGURE 8 DECK INSTALLATION

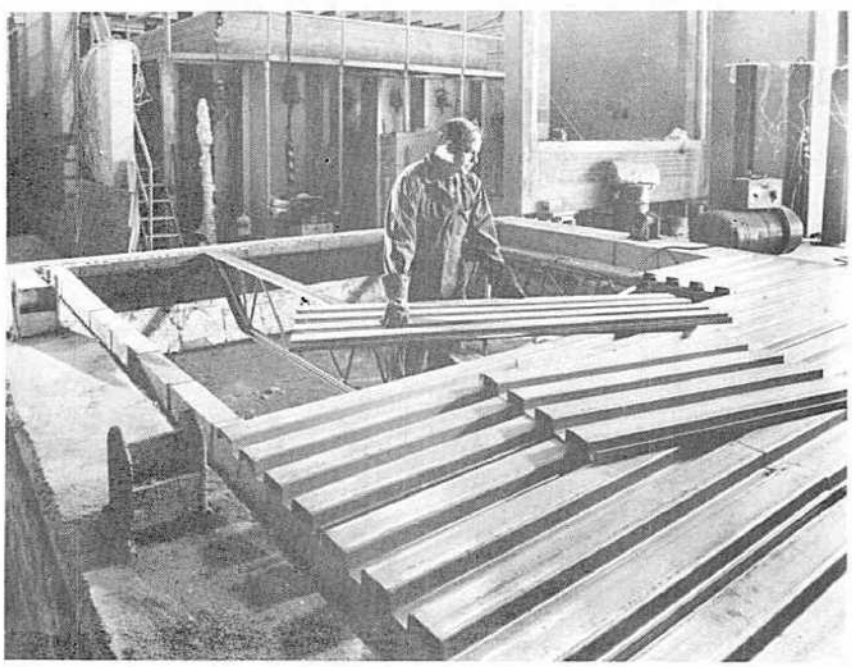


FIGURE 9 DECK INSTALLATION

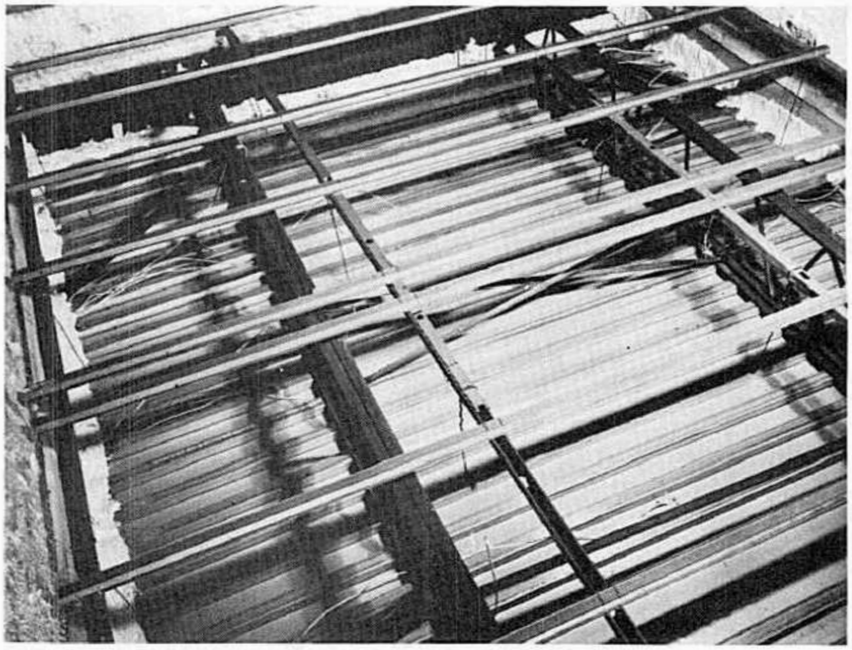


FIGURE 10 SUSPENSION AND FURRING

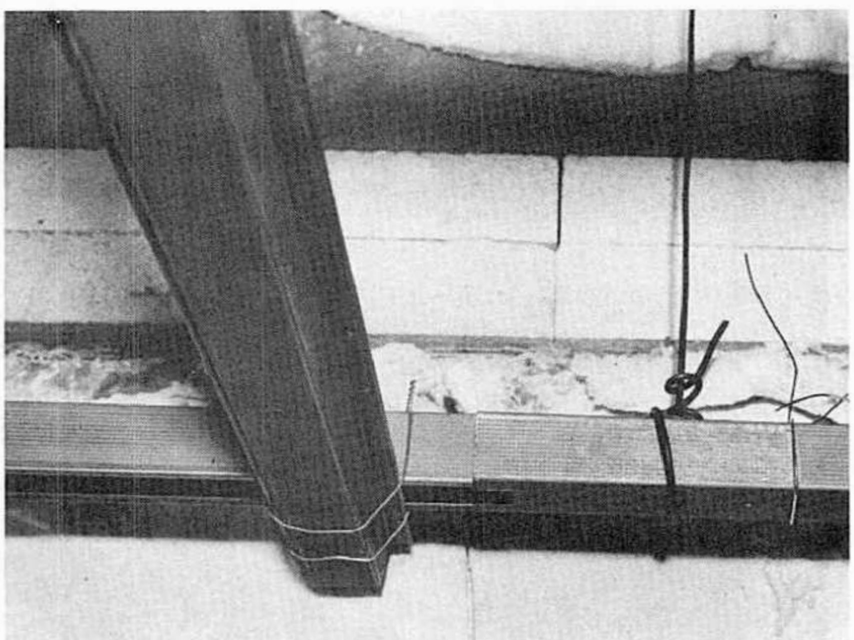


FIGURE 11 CLOSE-UP OF SUSPENSION AND FURRING

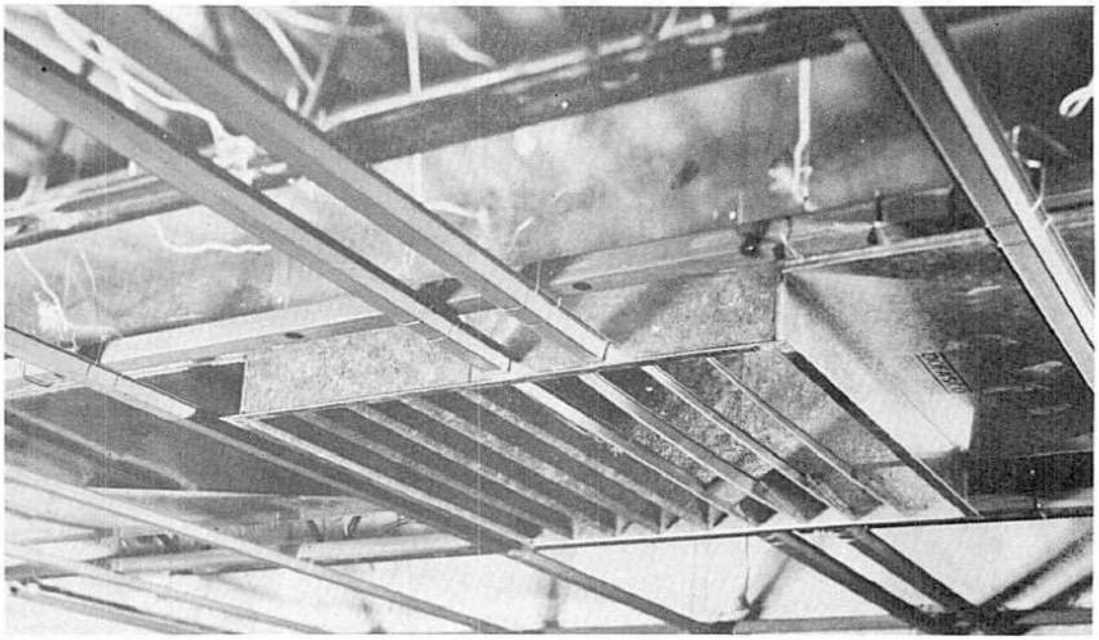


FIGURE 12 SUSPENSION AND DUCTWORK (ASSEMBLY NO. 2)

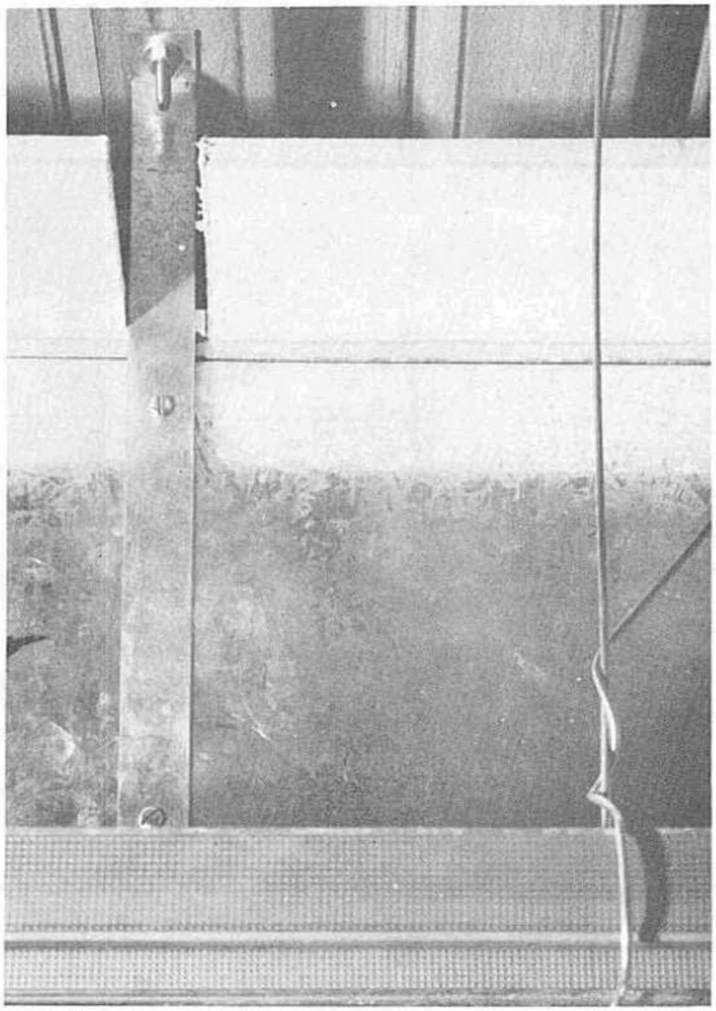


FIGURE 13 DUCT STRAP HANGER (ASSEMBLY NO. 2)

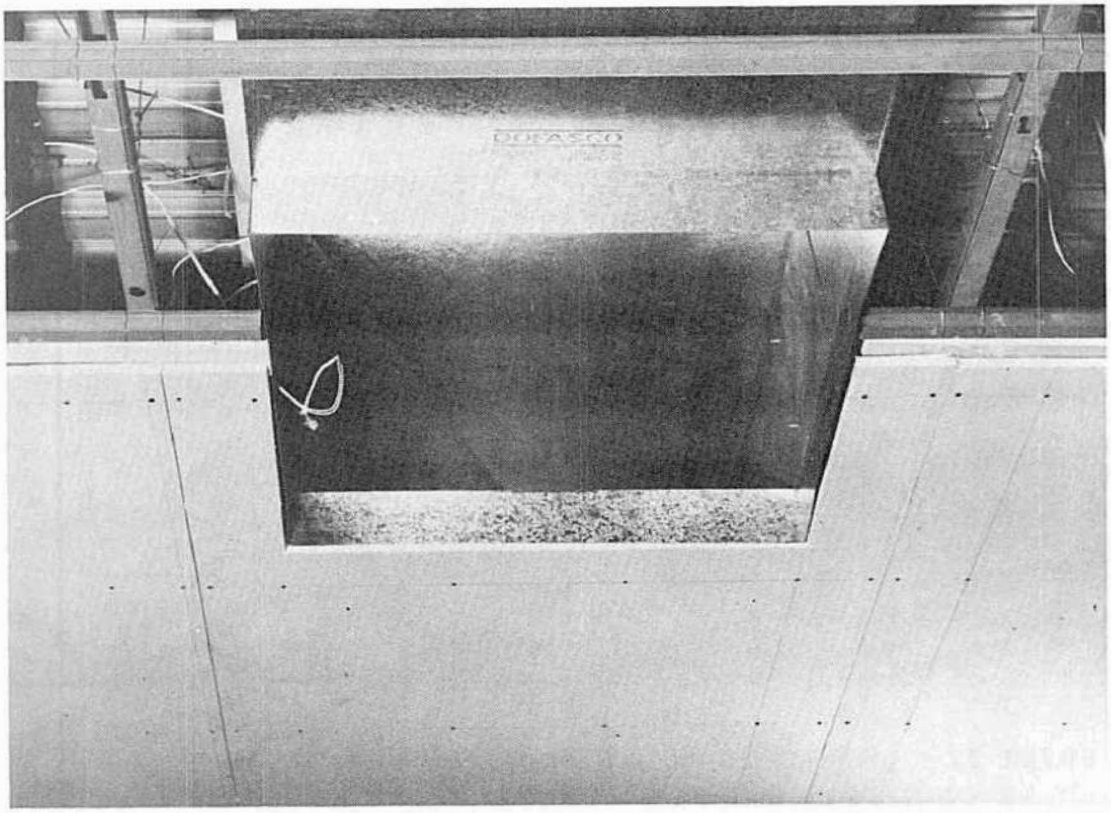


FIGURE 14 APPLICATION OF GYPSUM BOARD (ASSEMBLY NO. 2)

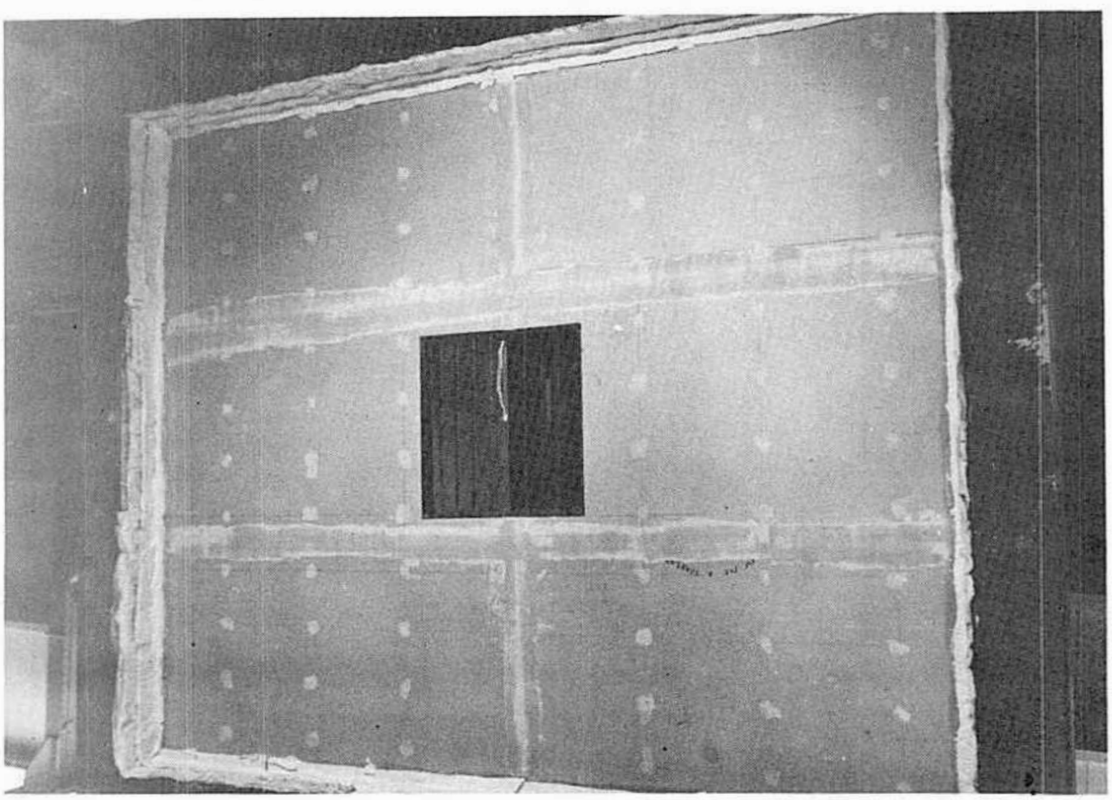


FIGURE 15 COMPLETED CEILING (ASSEMBLY NO. 2)

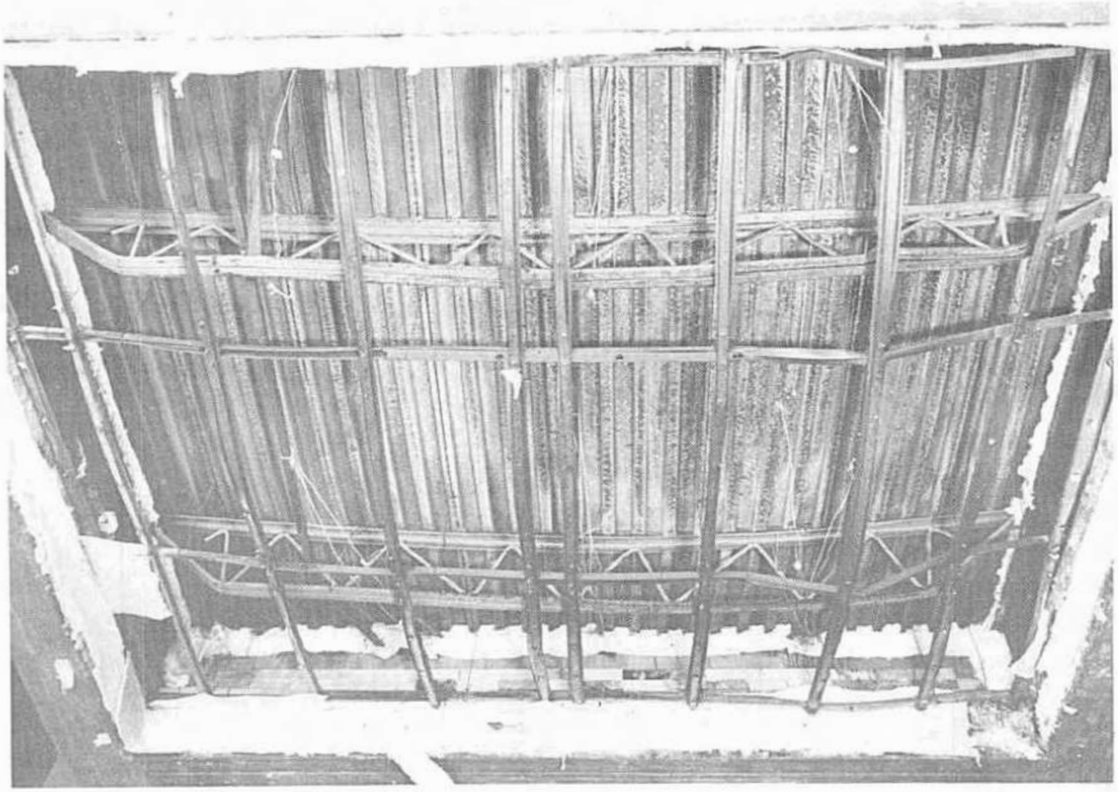


FIGURE 16   ASSEMBLY NO. 1 AFTER FIRE TEST

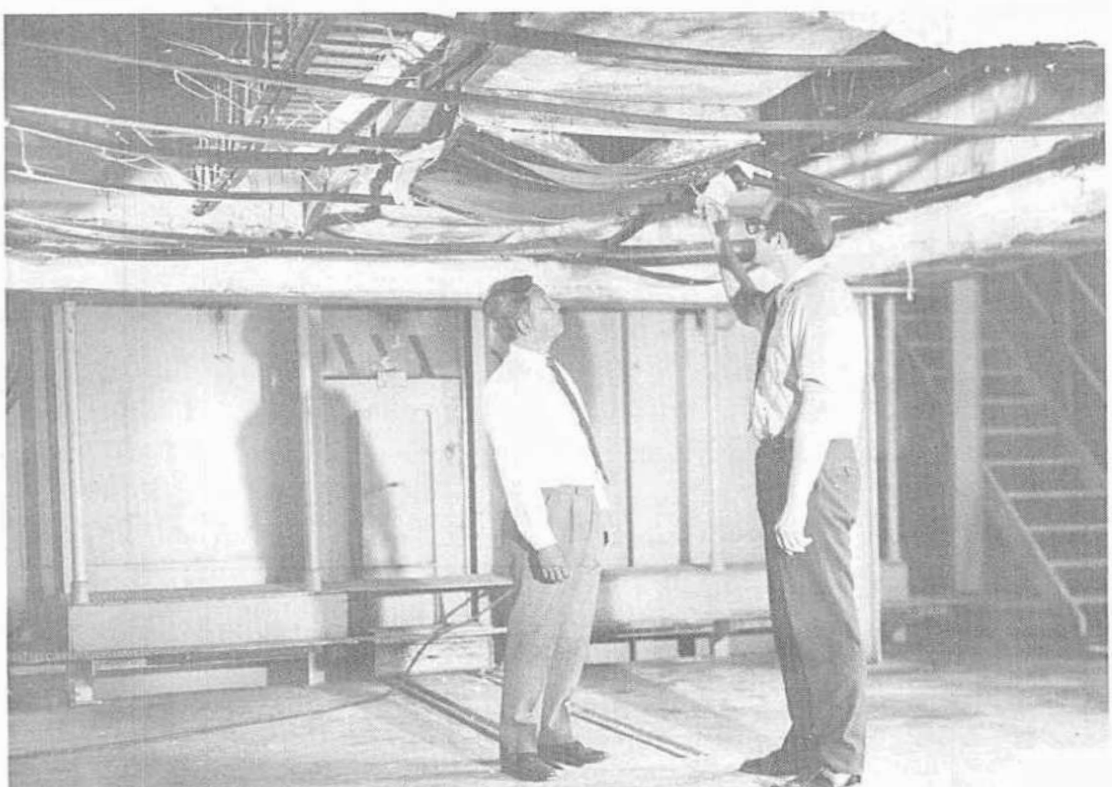


FIGURE 17   ASSEMBLY NO. 2 AFTER FIRE TEST

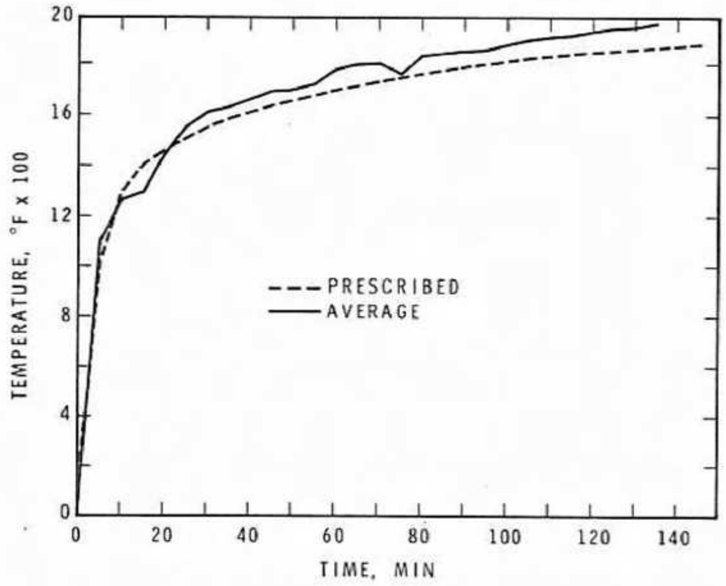


FIGURE 18

FURNACE TEMPERATURE, TEST NO. 1

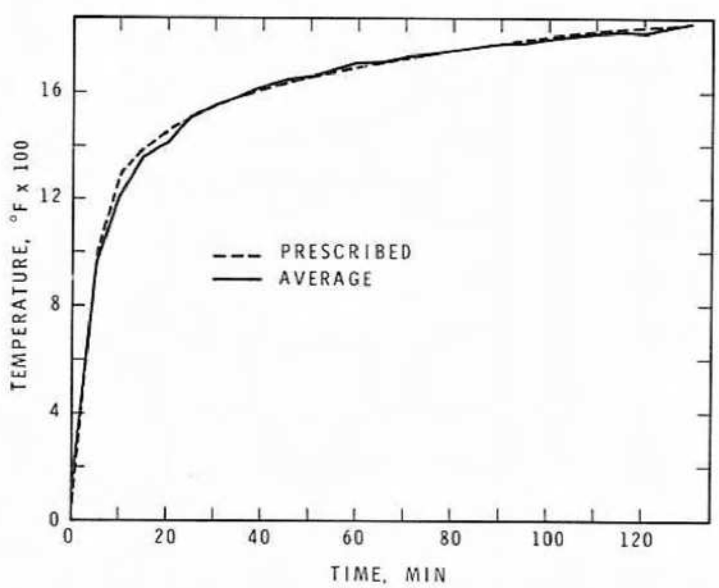


FIGURE 19

FURNACE TEMPERATURE, TEST NO. 2

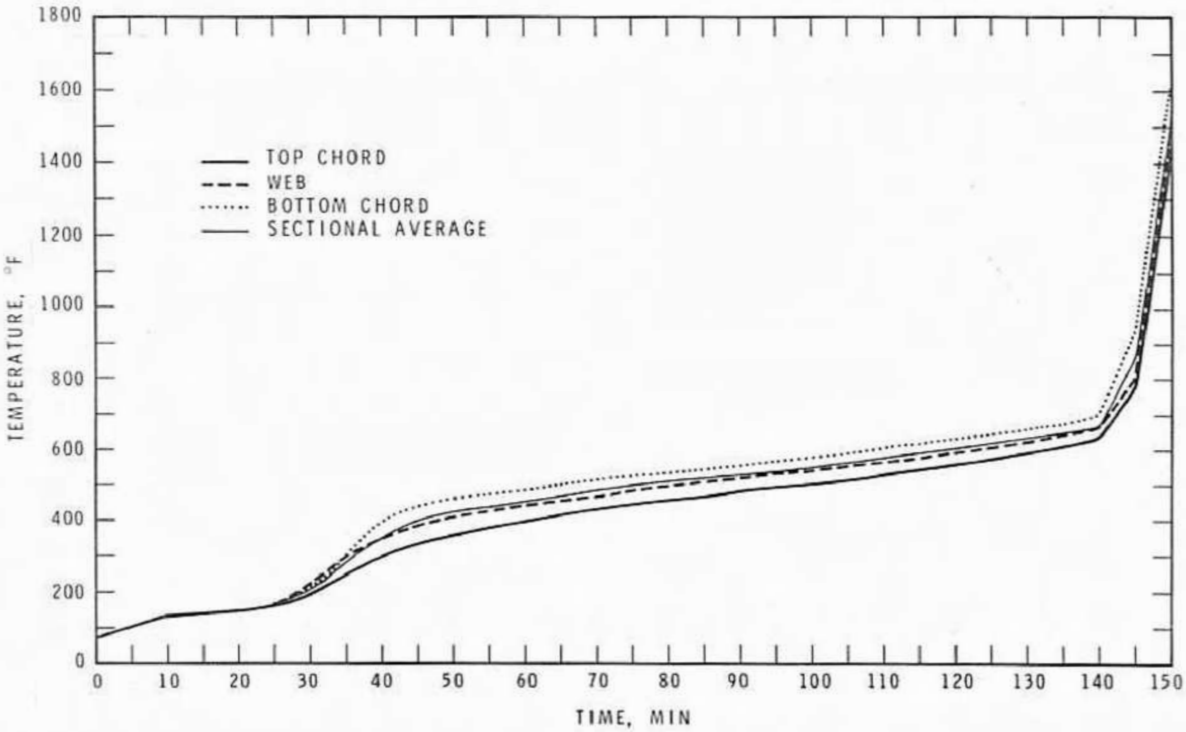


FIGURE 20

TEMPERATURE OF STEEL JOISTS, TEST NO. 1 (NO DUCT)

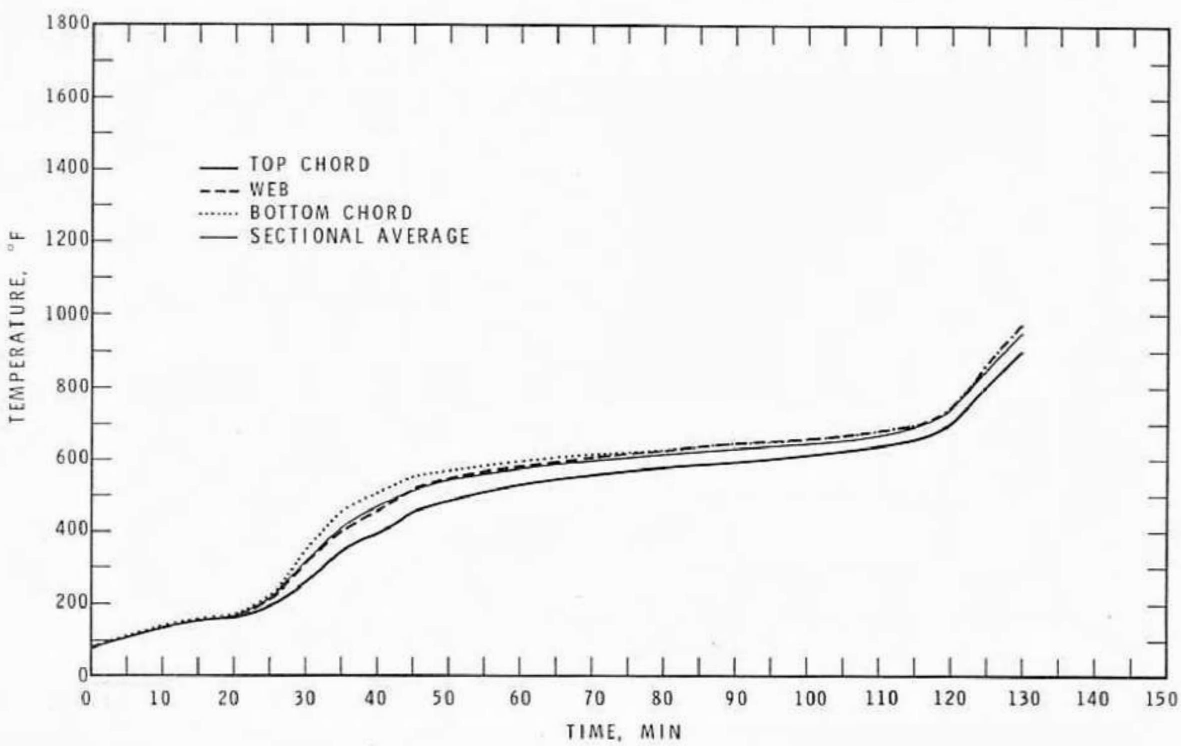


FIGURE 21

TEMPERATURE OF STEEL JOISTS, TEST NO. 2 (WITH DUCT)

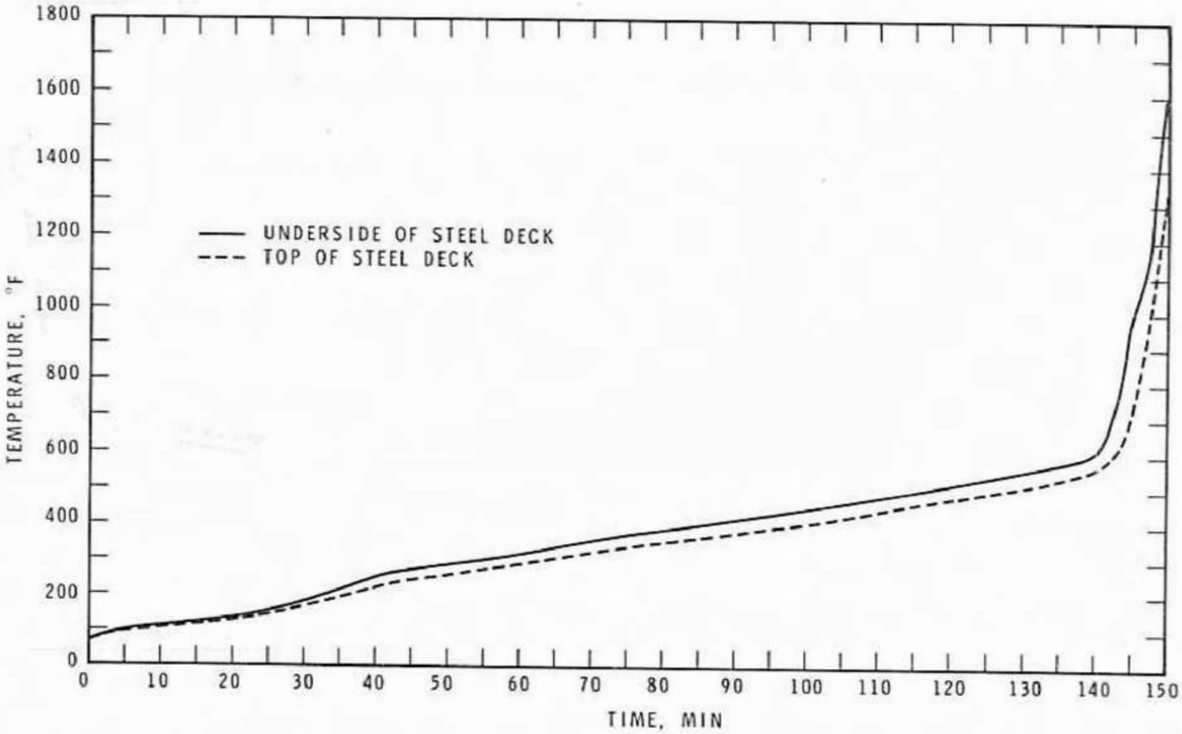


FIGURE 22

TEMPERATURES OF STEEL DECK, TEST NO. 1

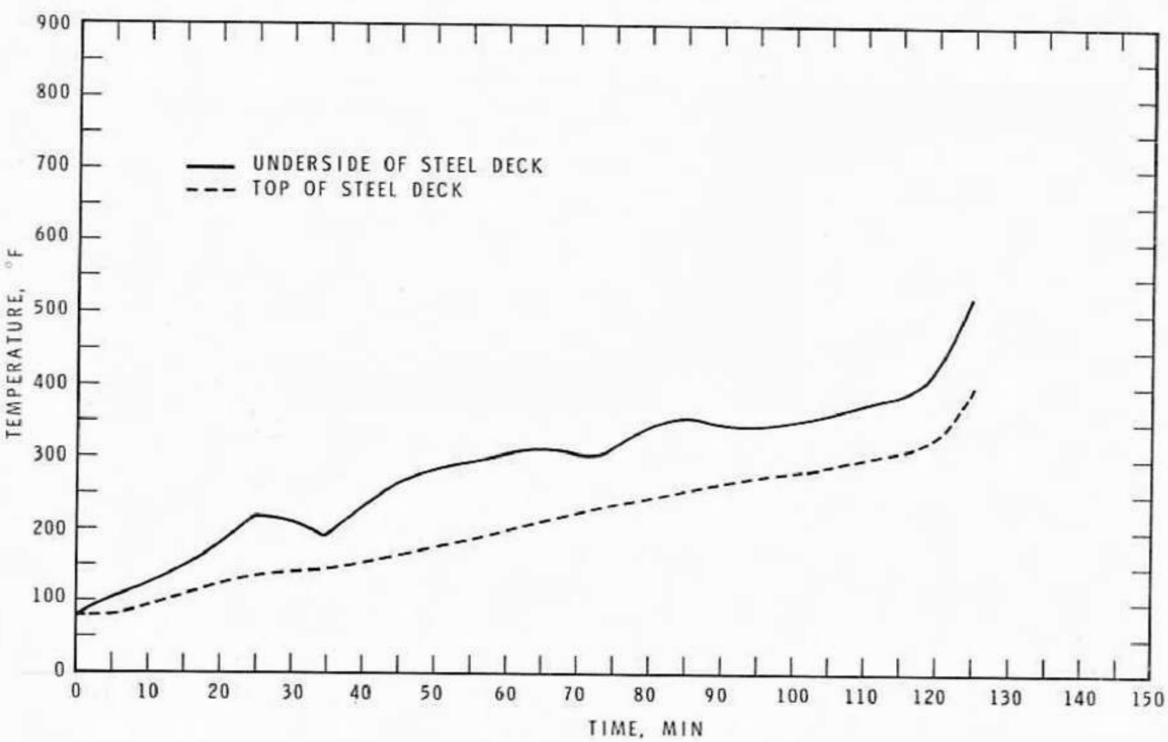


FIGURE 23

TEMPERATURES OF STEEL DECK, TEST NO. 2

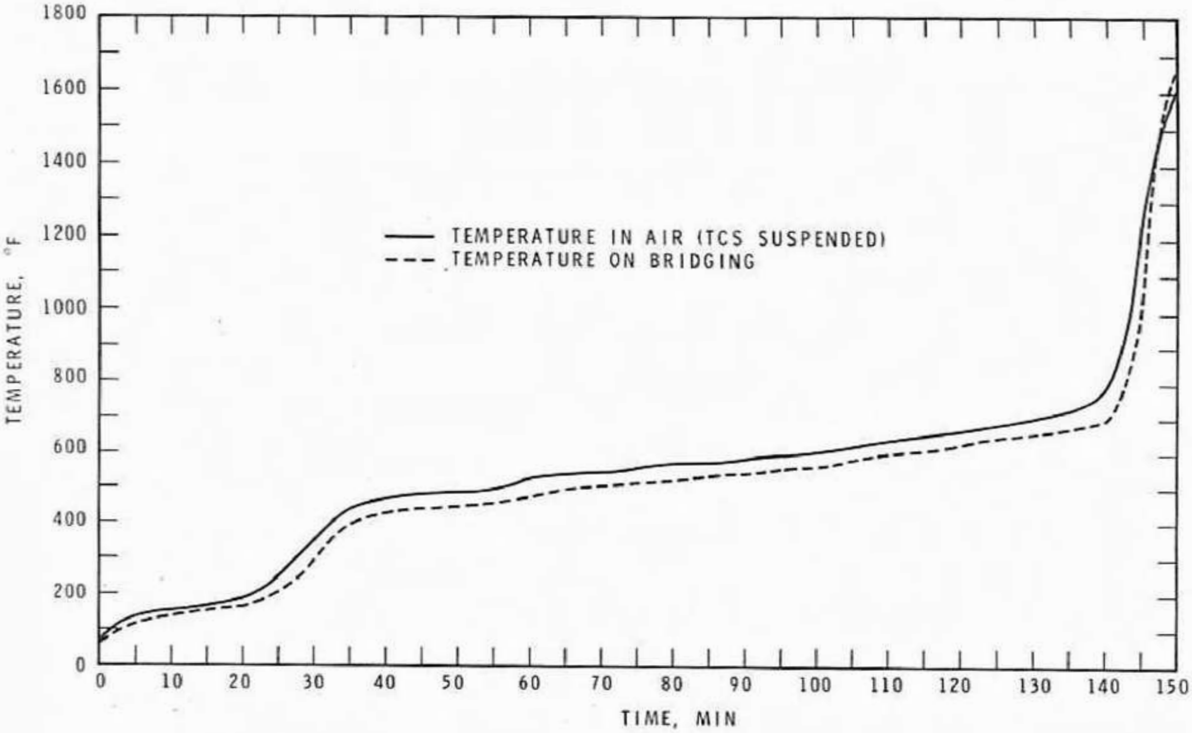


FIGURE 24

PLENUM TEMPERATURES, TEST NO. 1

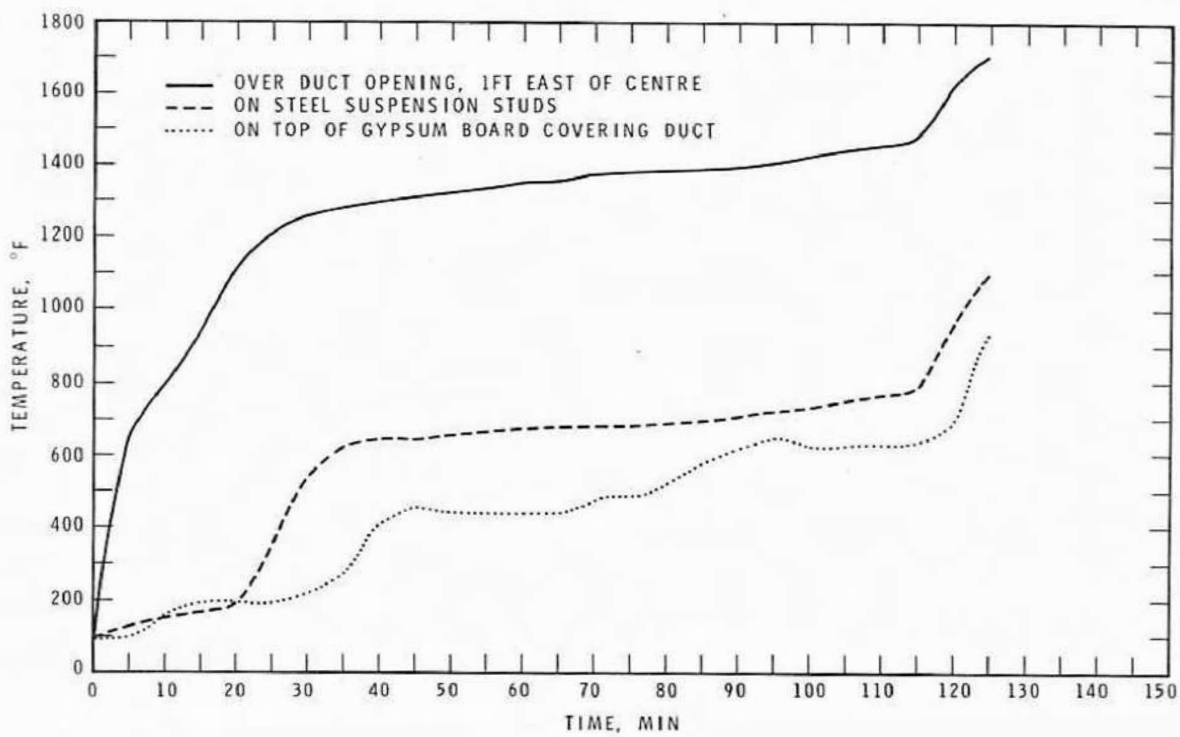


FIGURE 25

PLENUM AND DUCT TEMPERATURES, TEST NO. 2

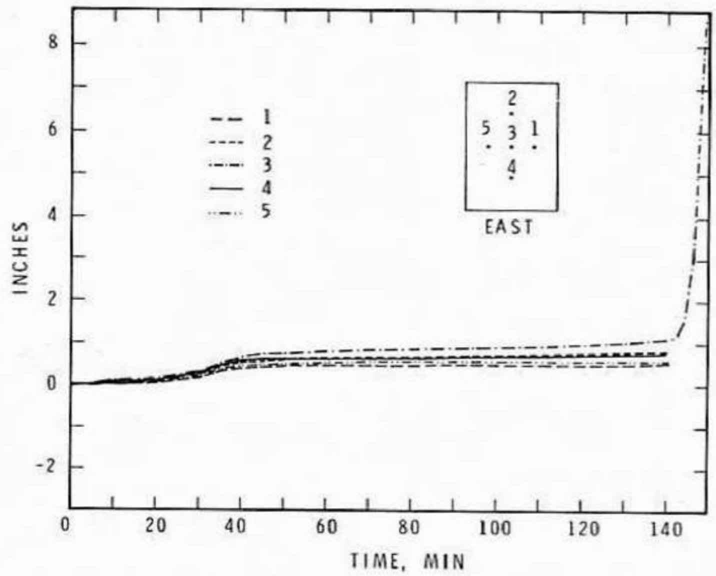


FIGURE 26

DEFLECTIONS, TEST NO. 1

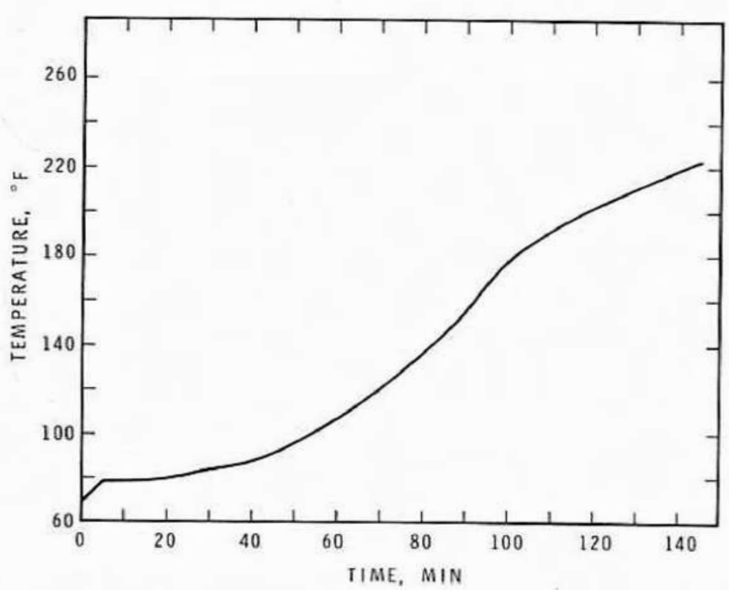


FIGURE 27

AVERAGE UNEXPOSED SURFACE TEMPERATURE, TEST NO. 1

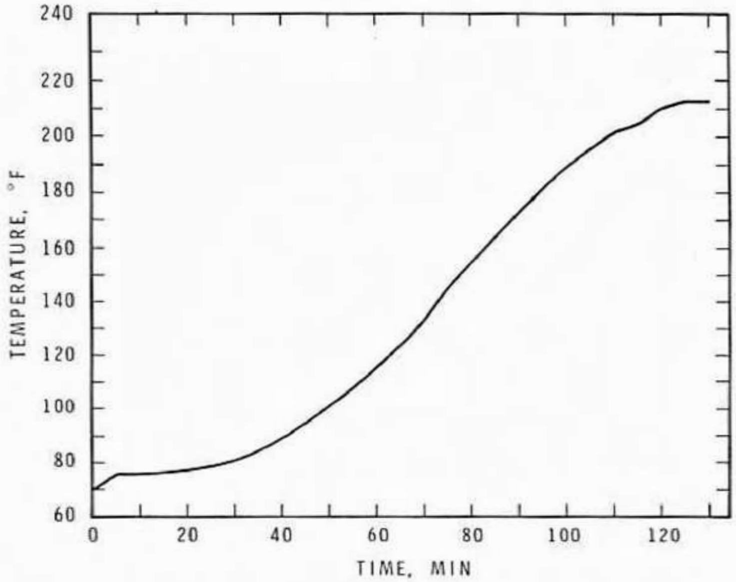


FIGURE 28

AVERAGE UNEXPOSED SURFACE TEMPERATURE, TEST NO. 2

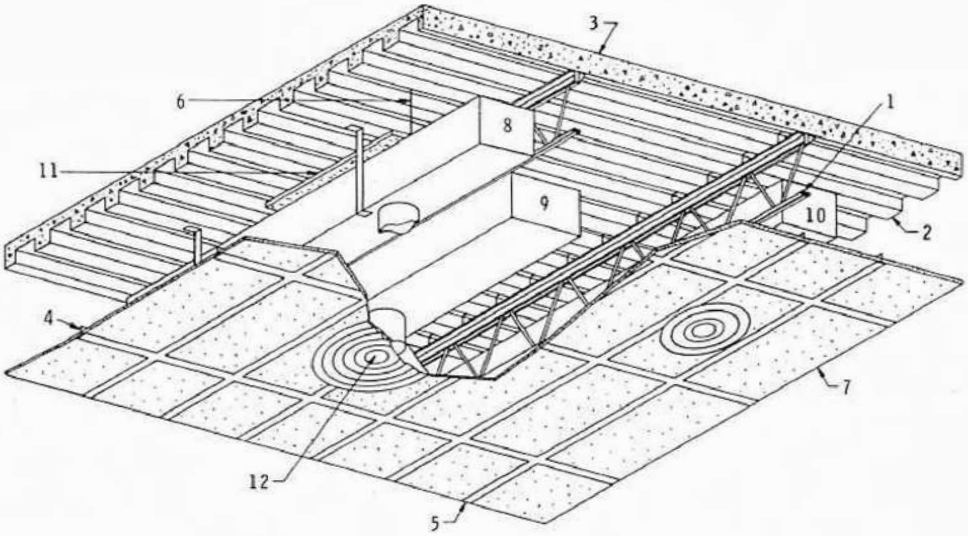
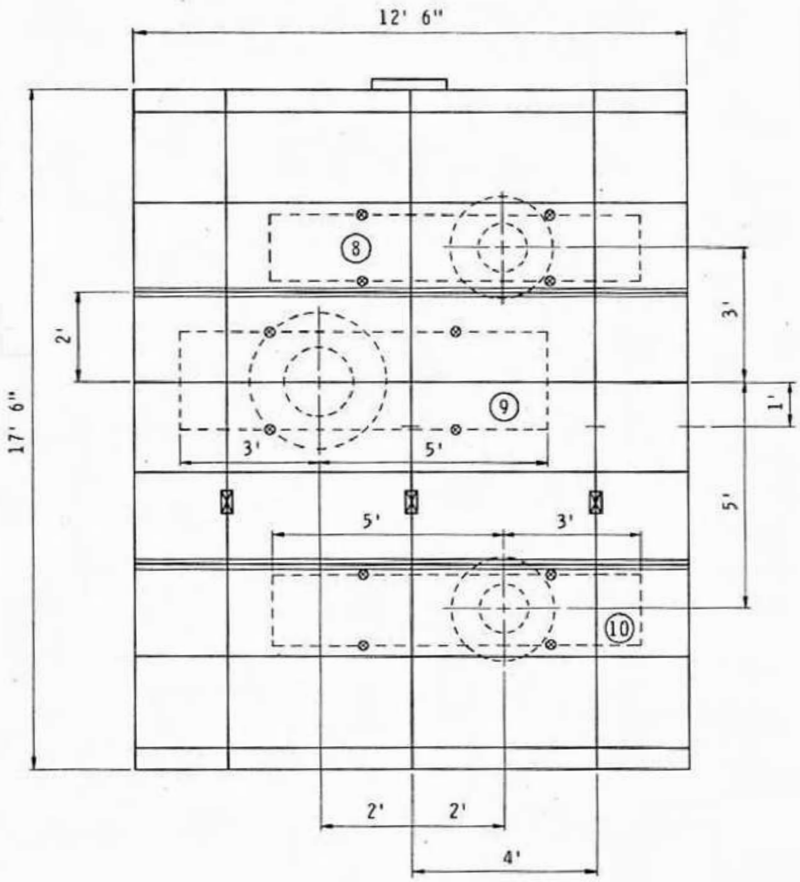


FIGURE 29

CONSTRUCTION DETAILS



⊗ DUCT HANGER

■ TEE-BAR SUSPENSION POINT

⊠ MAIN TEE EXPANSION POINT

FIGURE 30
REFLECTED CEILING PLAN

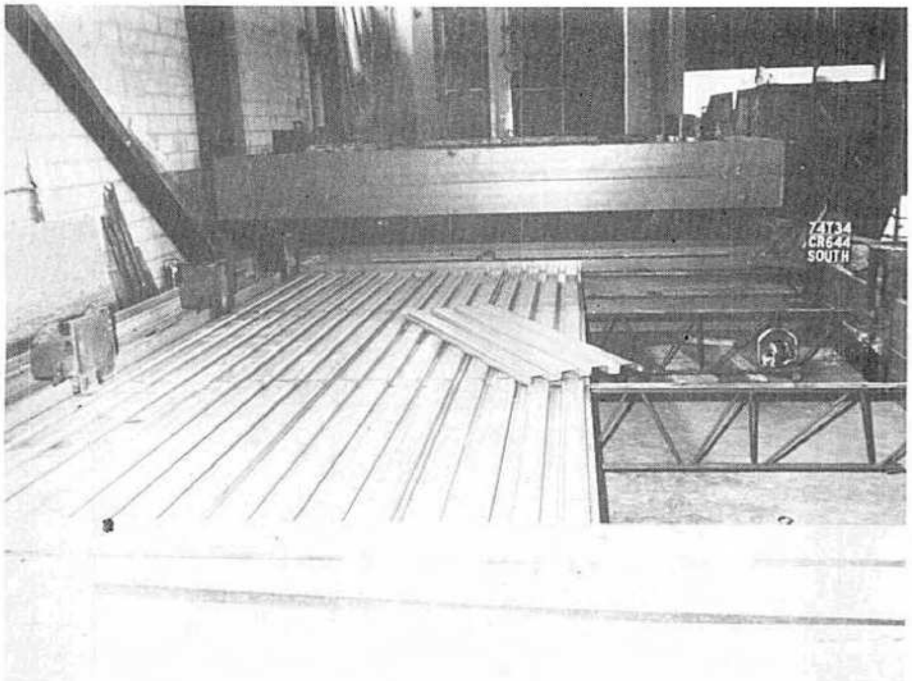


FIGURE 31 STEEL ERECTION OF TYPICAL ASSEMBLY

(COURTESY UNDERWRITERS' LABORATORIES CANADA)

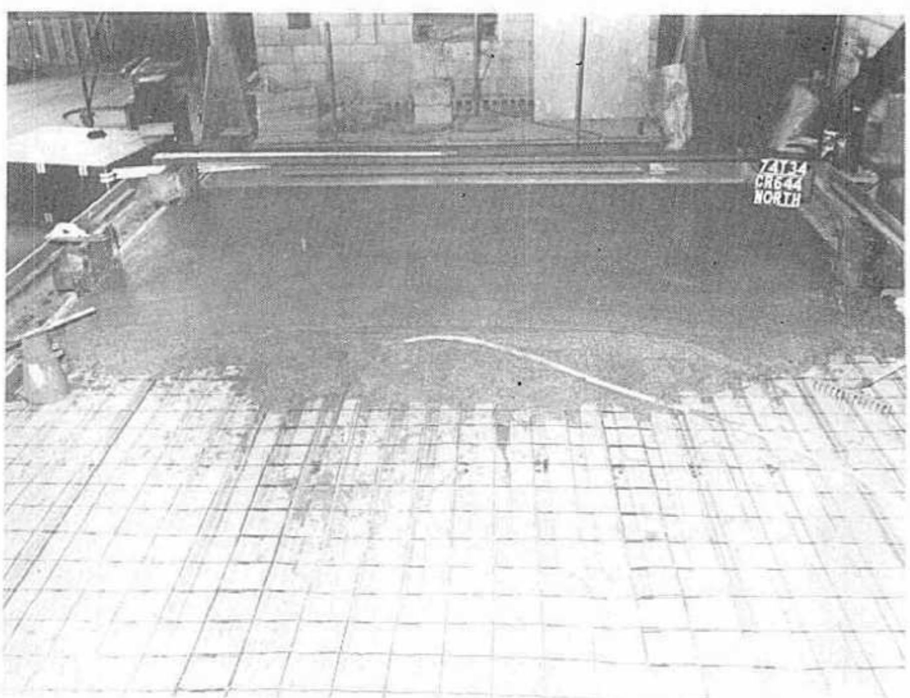


FIGURE 32 CONCRETE TOPPING BEING PLACED ON TYPICAL ASSEMBLY

(COURTESY UNDERWRITERS' LABORATORIES

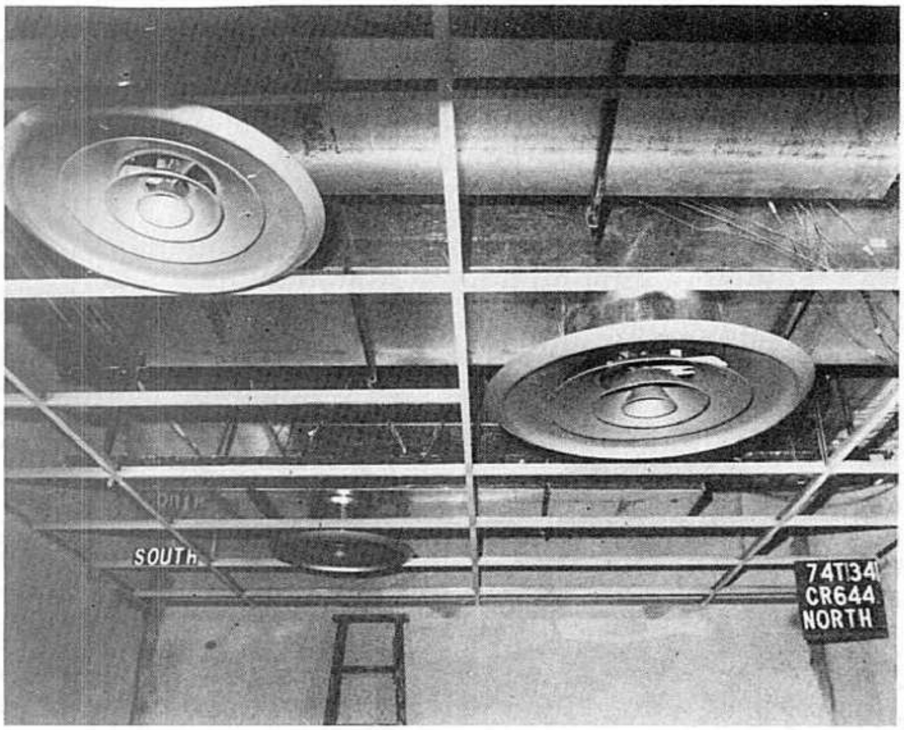


FIGURE 33 DUCT AND GRIDWORK CONSTRUCTION OF ASSEMBLY NO.

(COURTESY UNDERWRITERS' LABORATORIES CANADA)

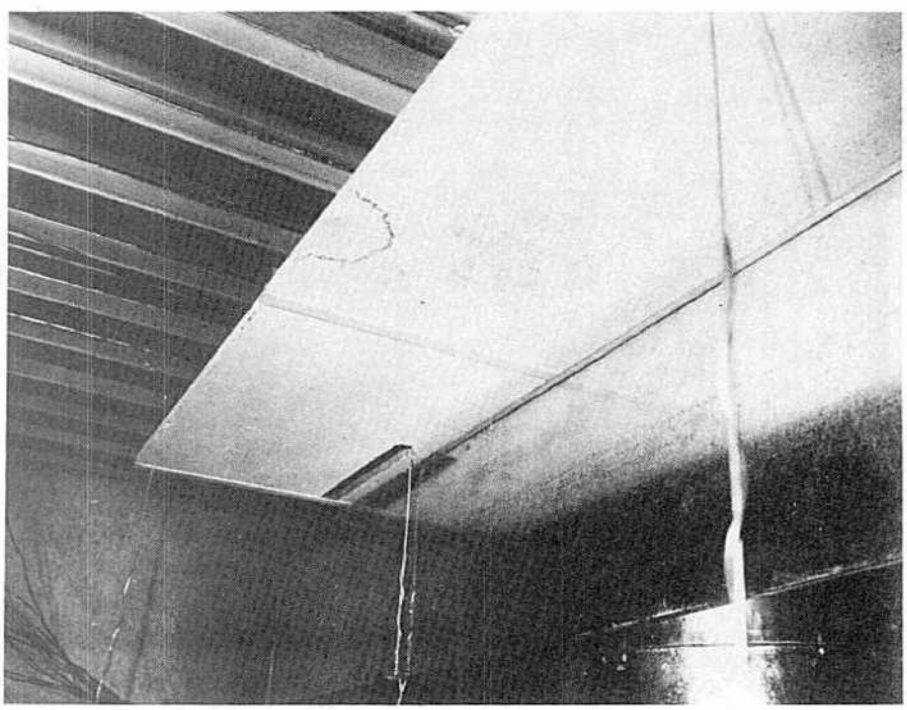


FIGURE 34 PROTECTION OF DUCT NO. 9, ASSEMBLY NO. 2 - PARTIAL PROTECTION

(COURTESY UNDERWRITERS' LABORATORIES CANADA)

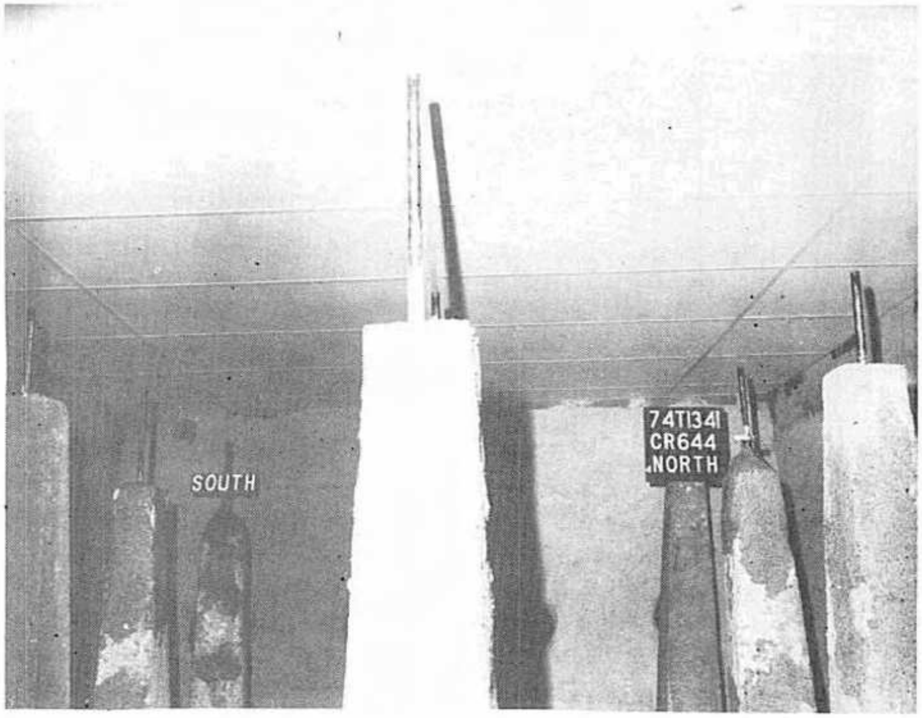


FIGURE 35 EXPOSED SURFACE BEFORE FIRE TEST, ASSEMBLY NO. 1
(COURTESY UNDERWRITERS' LABORATORIES CANADA)

FIGURE 36 EXPOSED SURFACE BEFORE FIRE TEST, ASSEMBLY NO. 2
(COURTESY UNDERWRITERS' LABORATORIES CANADA)

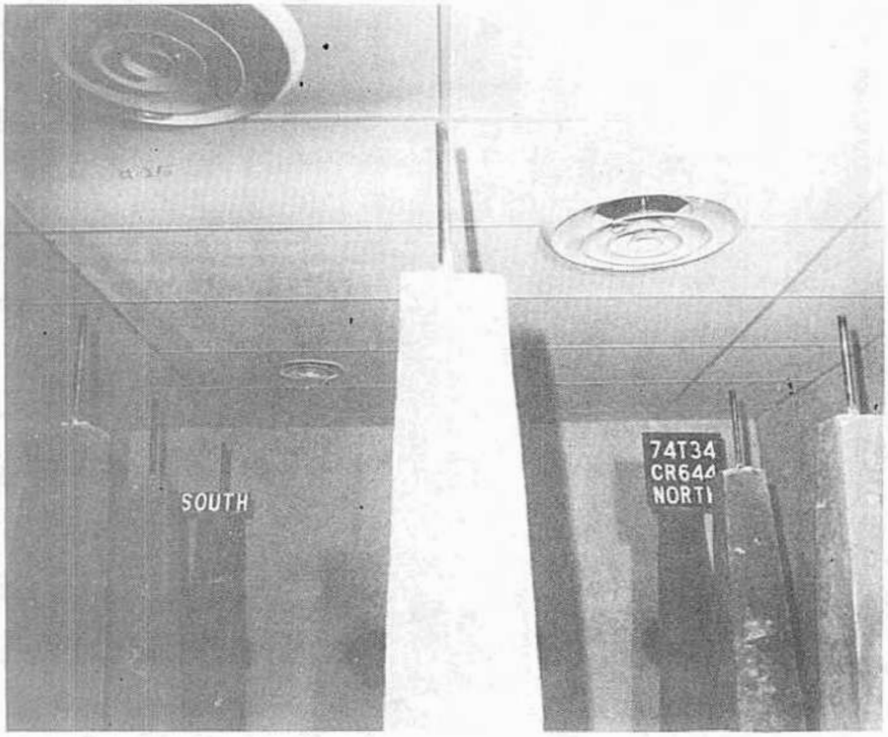
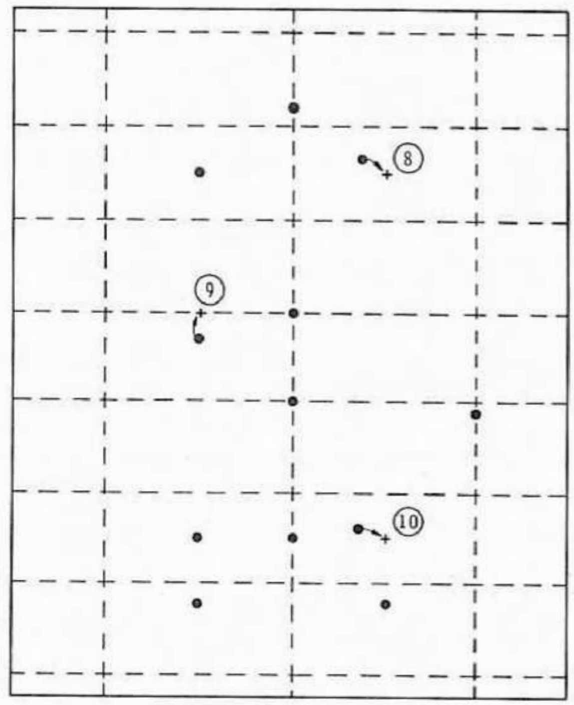


FIGURE 37 EXPOSED SURFACE BEFORE FIRE TEST, ASSEMBLY NO. 3

(COURTESY UNDERWRITERS' LABORATORIES CANADA)

FIGURE 38 UNEXPOSED SURFACE WITH LIVE LOAD APPLIED, TYPICAL ASSEMBLY

(COURTESY UNDERWRITERS' LABORATORIES CANADA)



+ CENTRE OF CEILING OPENING
● UNEXPOSED SURFACE THERMOCOUPLES

FIGURE 39

LOCATION OF THERMOCOUPLES ON UNEXPOSED SURFACE

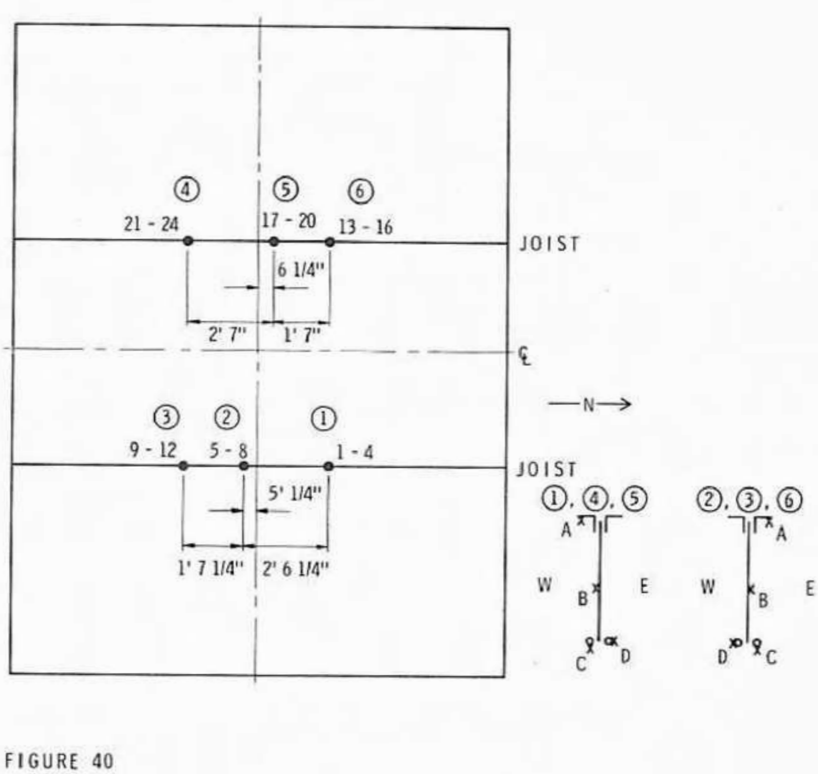


FIGURE 40

LOCATION OF THERMOCOUPLES ON STEEL JOISTS

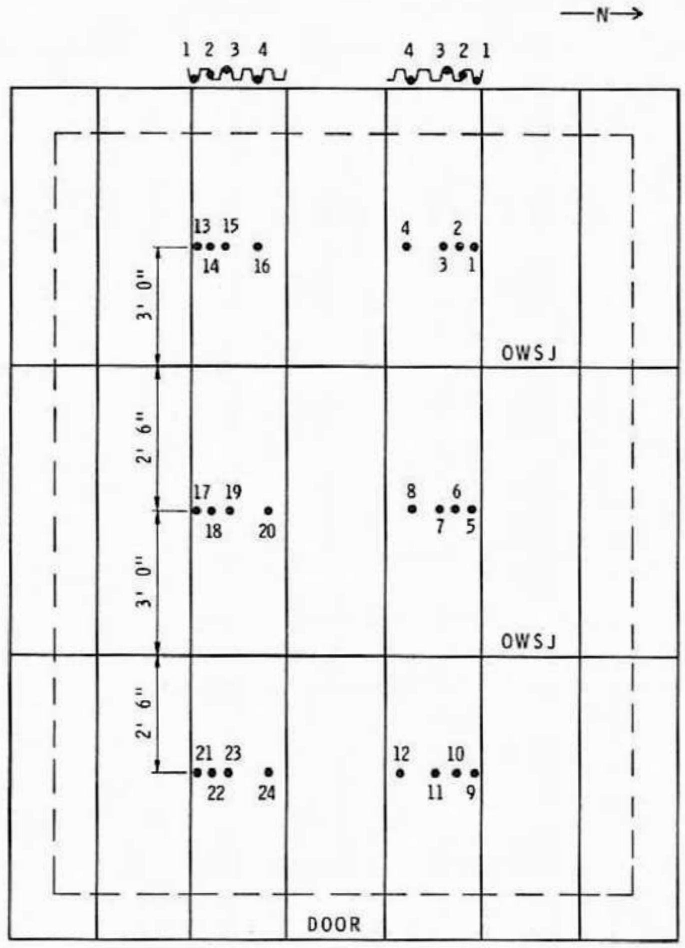


FIGURE 41

LOCATION OF THERMOCOUPLES ON STEEL FLOOR UNITS

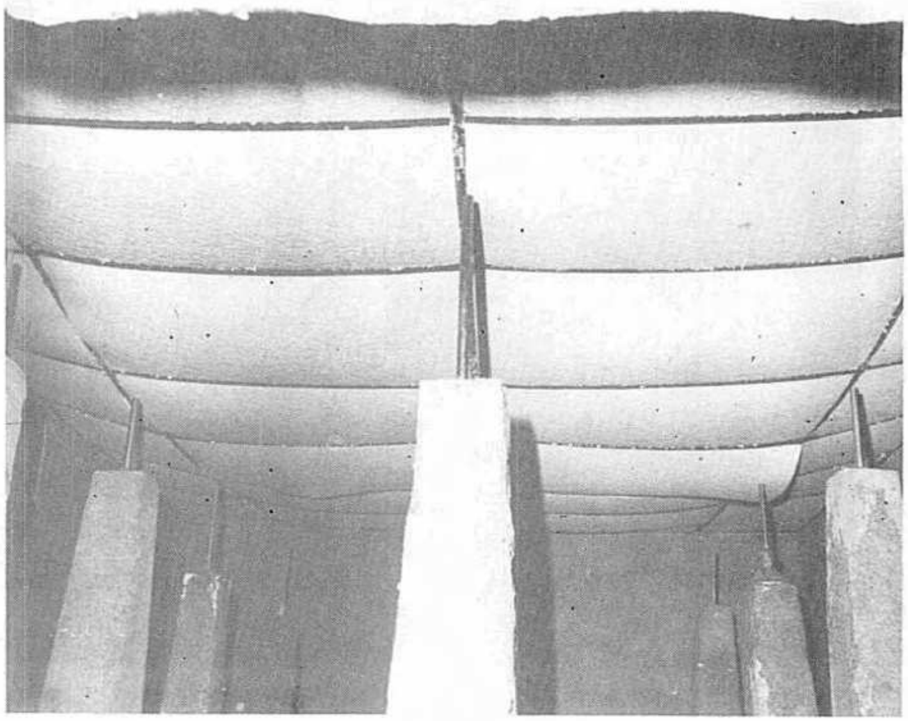


FIGURE 42 EXPOSED SURFACE IMMEDIATELY AFTER FIRE TEST, ASSEMBLY NO. 1

(COURTESY UNDERWRITERS' LABORATORIES CANADA)

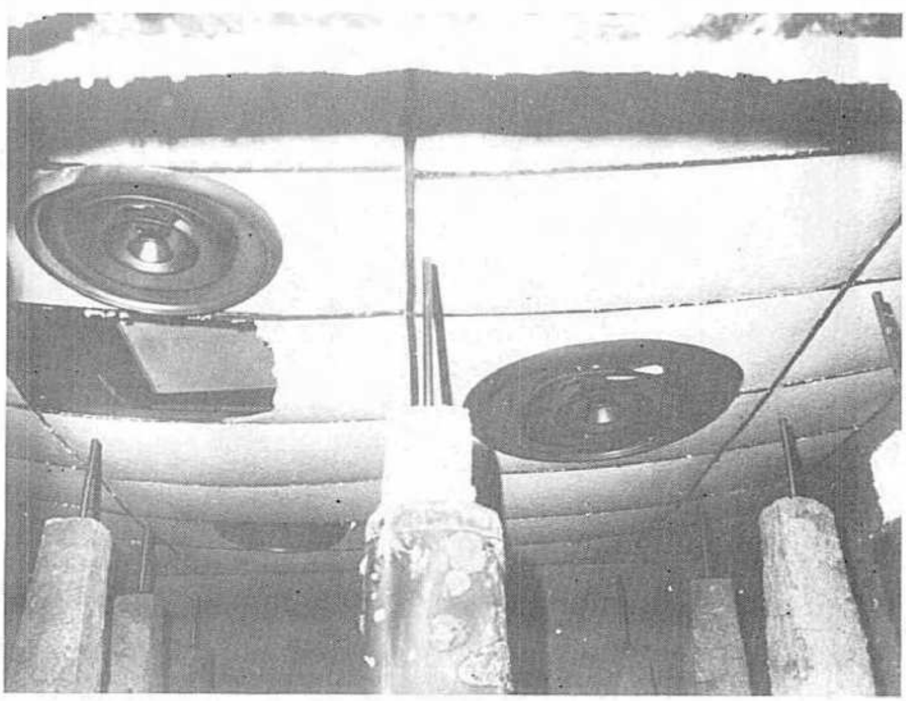


FIGURE 43 EXPOSED SURFACE IMMEDIATELY AFTER FIRE TEST, ASSEMBLY NO. 2

(COURTESY UNDERWRITERS' LABORATORIES CANADA)

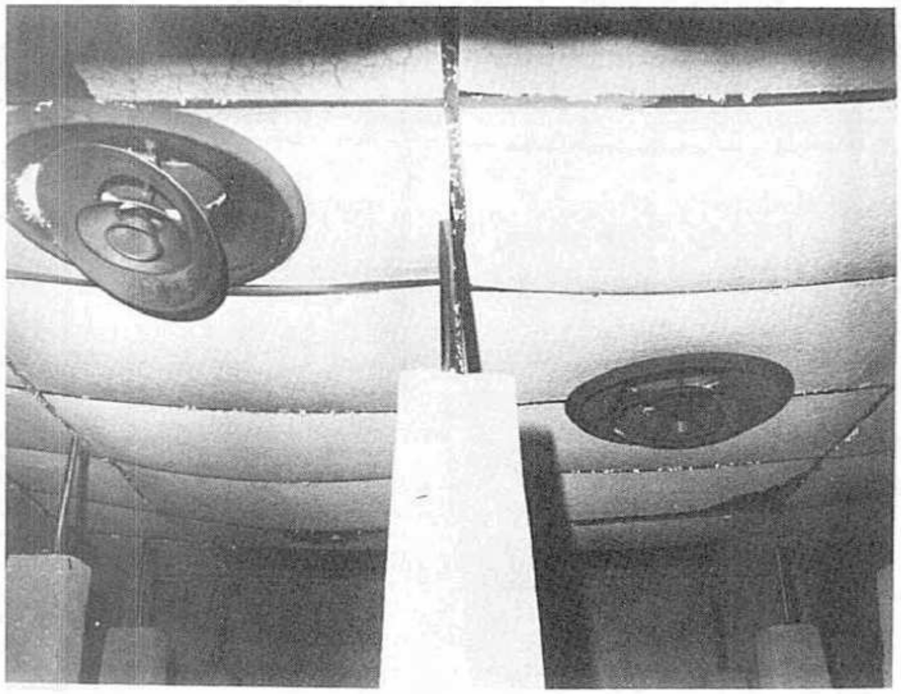


FIGURE 44 EXPOSED SURFACE IMMEDIATELY AFTER FIRE TEST, ASSEMBLY NO. 3

(COURTESY UNDERWRITERS' LABORATORIES CANADA)

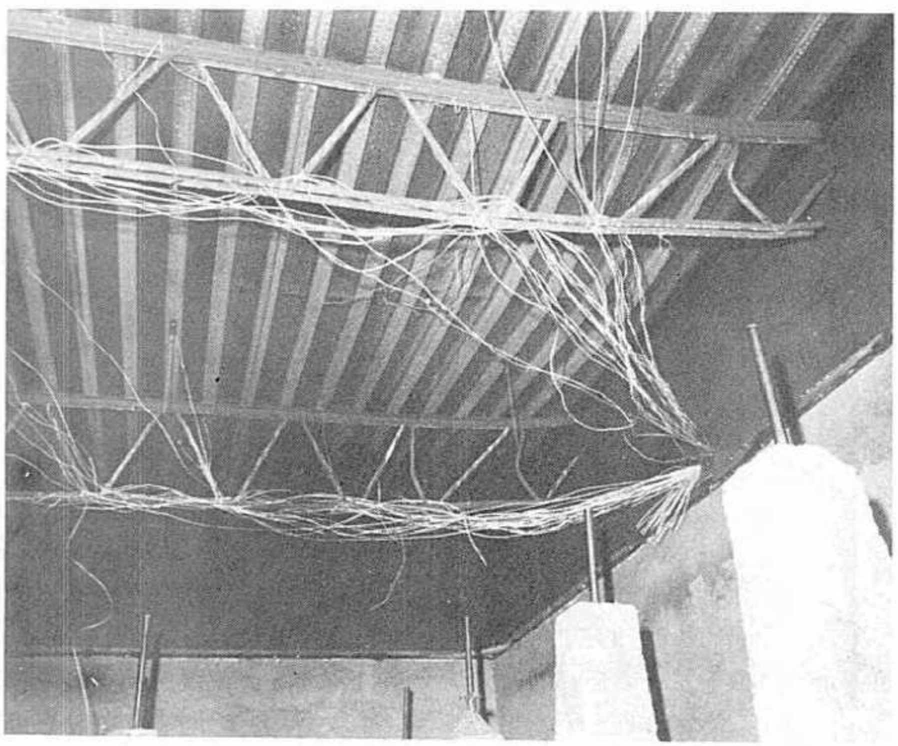


FIGURE 45 TYPICAL SUPERSTRUCTURE AFTER FIRE TEST AND REMOVAL OF CEILING

(COURTESY UNDERWRITERS' LABORATORIES CANADA)

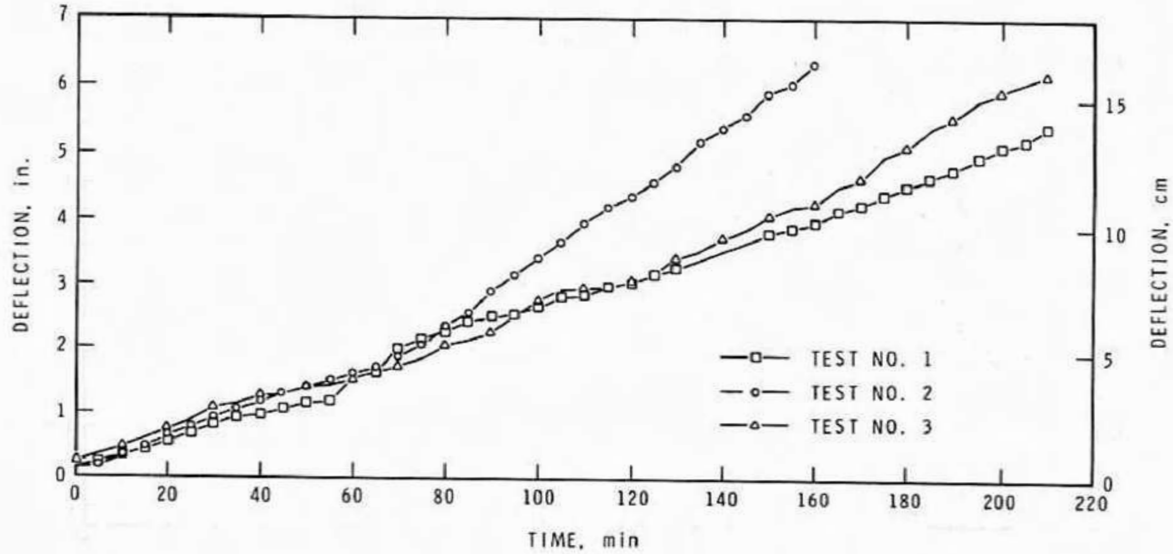


FIGURE 46

DEFLECTIONS AT CENTRE OF ASSEMBLY

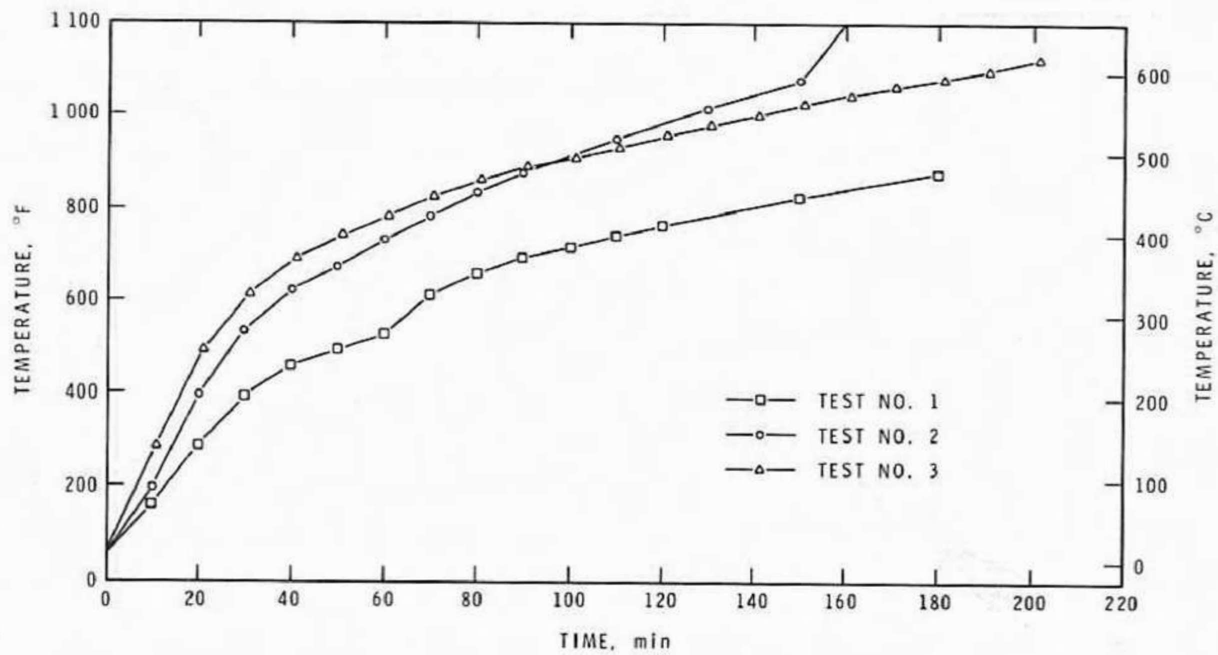


FIGURE 47

MAXIMUM SECTIONAL AVERAGE JOIST TEMPERATURES

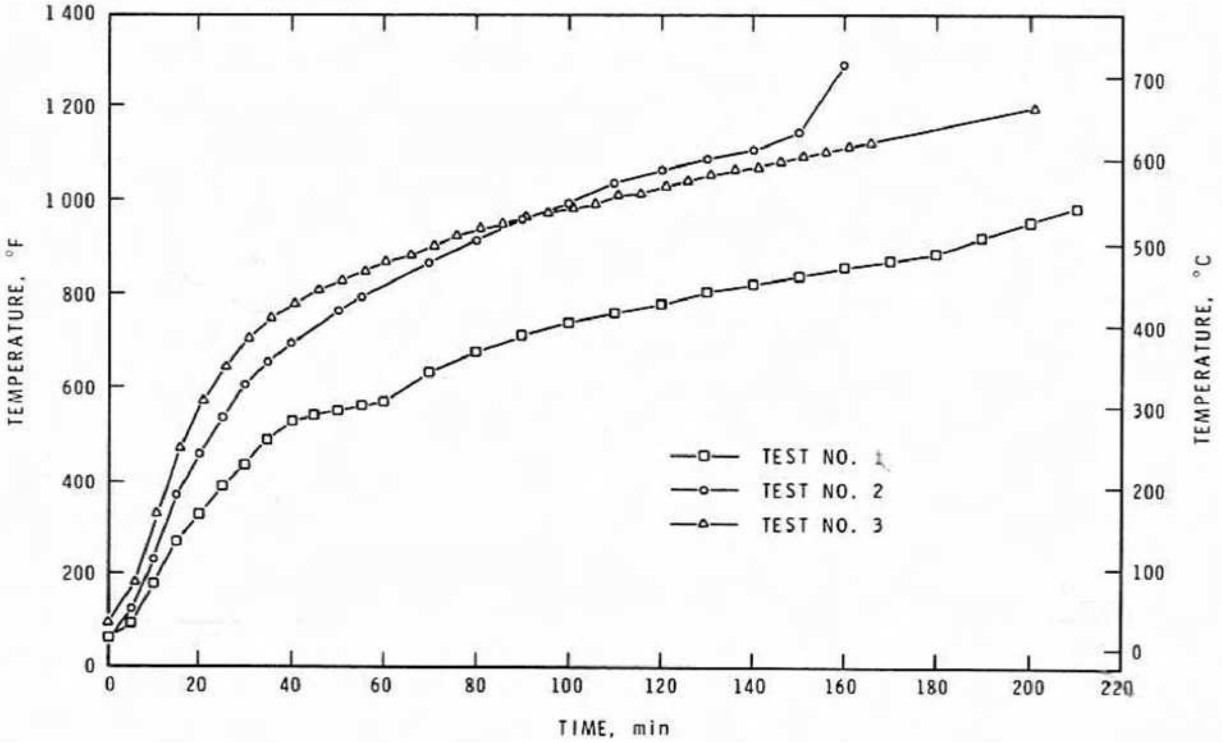


FIGURE 48
MAXIMUM INDIVIDUAL JOIST TEMPERATURES

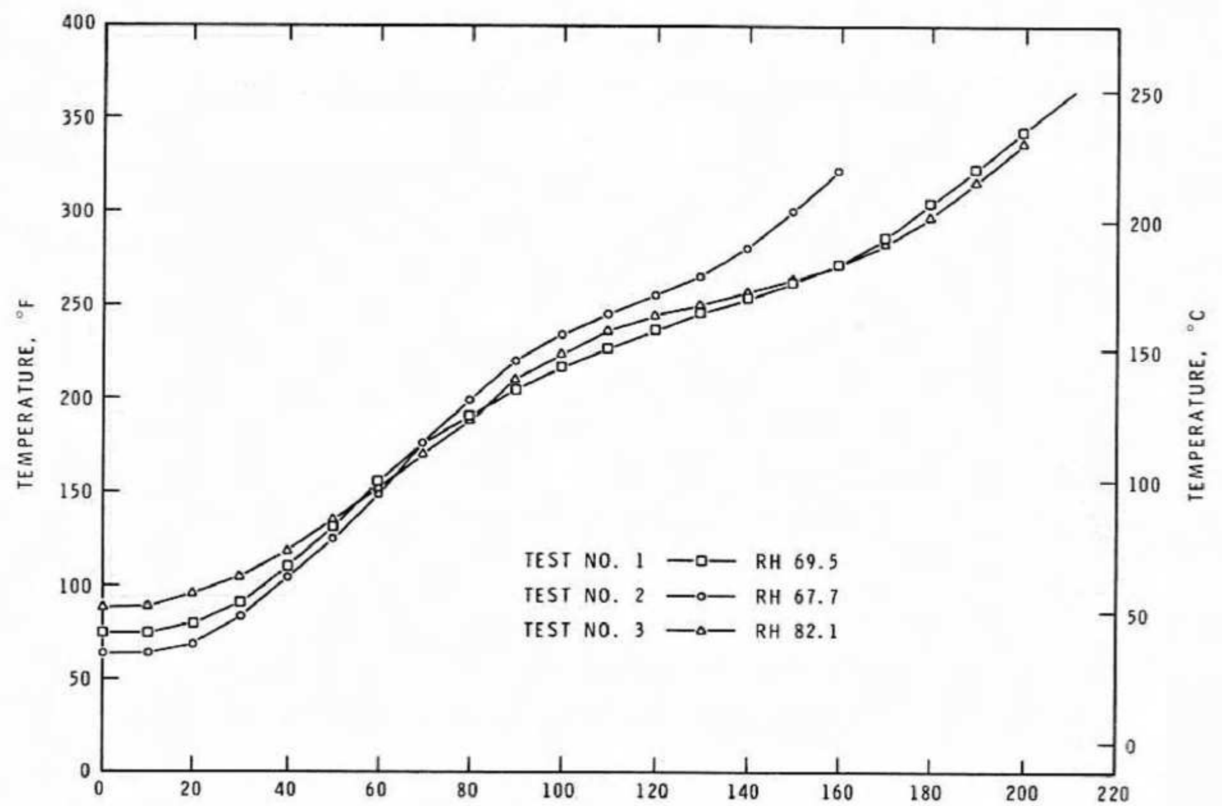


FIGURE 49
AVERAGE UNEXPOSED SURFACE TEMPERATURES

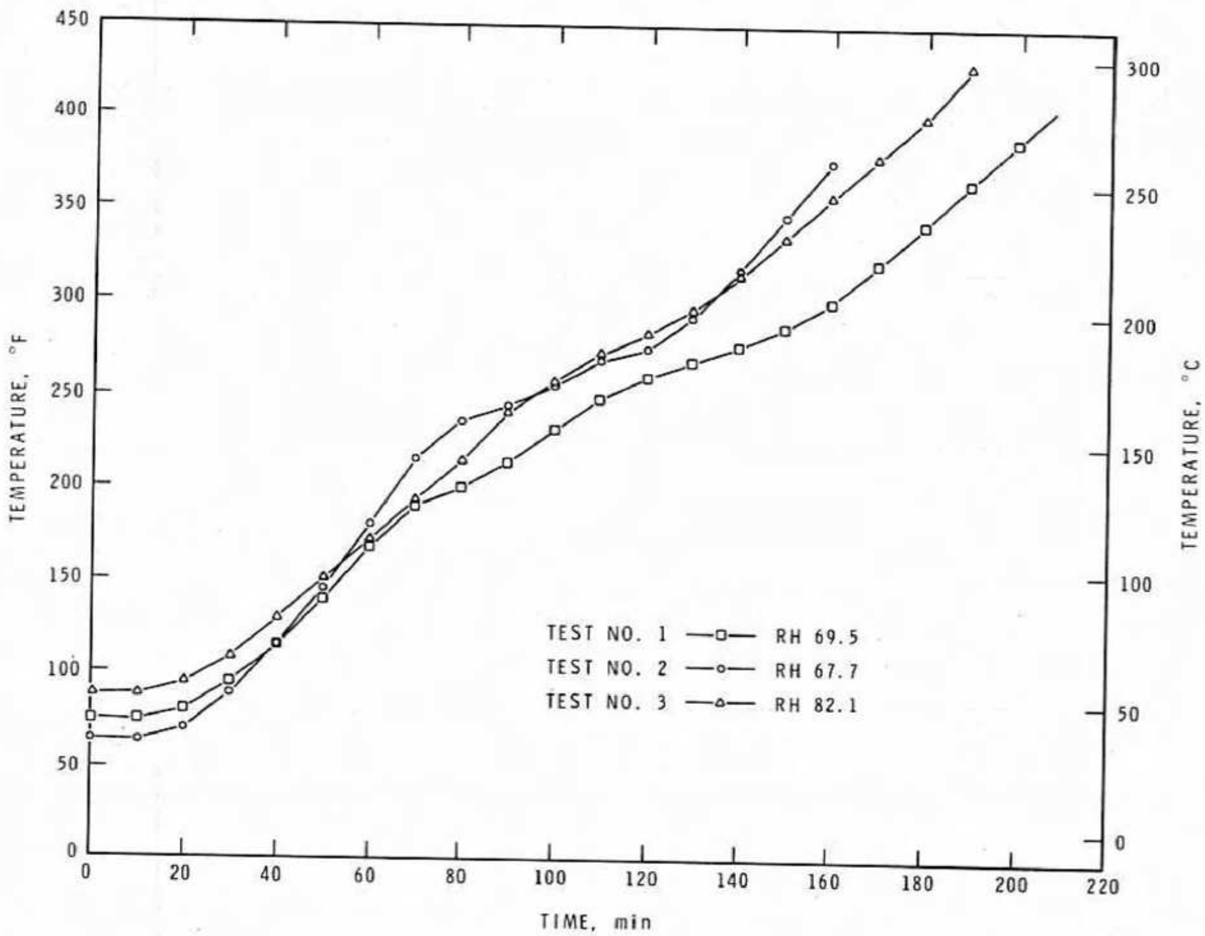


FIGURE 50

MAXIMUM INDIVIDUAL UNEXPOSED SURFACE TEMPERATURES

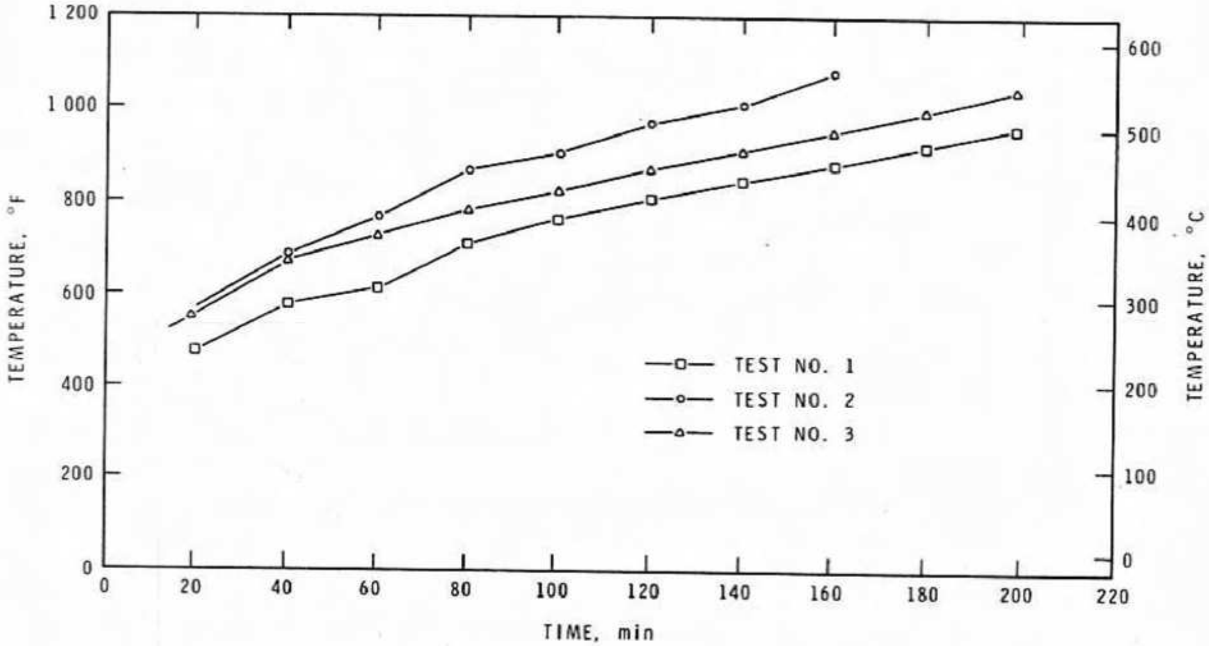


FIGURE 51
AVERAGE PLENUM TEMPERATURES (3" ABOVE MEMBRANE)

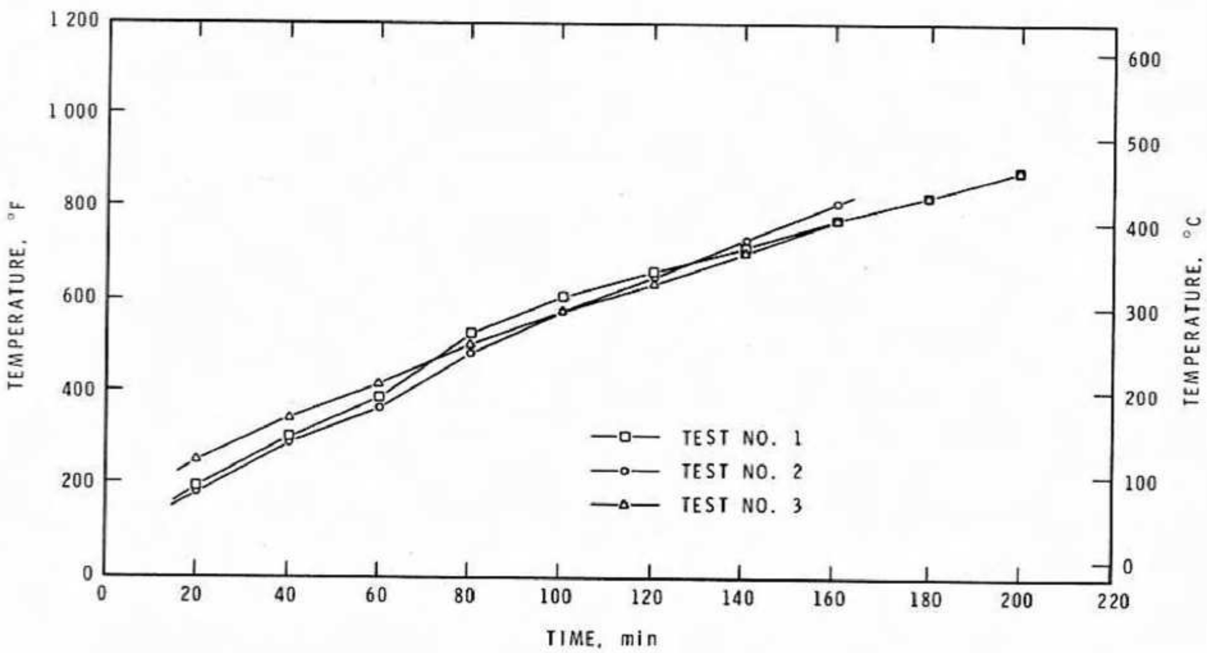


FIGURE 52
AVERAGE STEEL DECK TEMPERATURES

APPENDIX A

Two fire tests on very similar assemblies, one without and one with ceiling openings, were carried out at DBR/NRC on a commercial basis. The unpenetrated assembly was unrestrained while the other was restrained; both failed by temperature rise on the unexposed surface. Because the assemblies are of a proprietary nature they are not described in detail. The results do, however, indicate that small openings result in very little reduction in fire endurance, as is predicted by the methods proposed in this report.

The assemblies incorporated $2\frac{1}{2}$-in. concrete slabs supported by patented composite steel joists. They were protected by a ceiling of $\frac{1}{2}$-in. gypsum wallboard (the product was from the same manufacturer for both assemblies and is listed by Underwriters' Laboratories of Canada) attached to steel furring channels. The assembly with openings incorporated two closed-end ducts, one with a 12-in. square dampered ceiling penetration, the other with a 5-in. diameter undampered ceiling penetration, for an opening fraction of 0.0063.

The unpenetrated assembly failed at 126 min by average temperature rise on the unexposed surface. The other failed at 122 min by temperature rise at an individual point; failure by average unexposed surface temperature rise occurred at 124.5 min. Using $c = 2$ for a restrained assembly, the method proposed in this report predicts a reduction in fire endurance time of 2 min.