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Sprinklers in Combustible Concealed Spaces

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SUMMARY

NFPA 13 - Standard for the Installation of Sprinkler Systems requires that all combustible concealed spaces be protected with sprinklers, with certain exceptions. One exception is for combustible wood joist assemblies where the ceiling membrane is within 6 inches (152 mm) of the joists. Two tests were carried out to examine fire spread in such an assembly. Automatic sprinkler protection was included in the tests to determine its effectiveness in containing fire spread in spaces permitted to be unsprinklered by the exception.

The present tests indicate that unsprinklered 6 inches (152 mm) concealed spaces between the ceiling membrane and joists represent a major path for fire spread throughout a building. Omitting sprinklers in such a space should only be considered if such spaces are limited in areal extent by fire stopping or some other means is used for limiting fire spread. These tests also show that sprinkler protection has limited effectiveness

INTRODUCTION

Concealed spaces in buildings are an inevitable aspect of some types of construction with crawl spaces created by construction of floors over uneven ground, dropped ceilings installed to conceal piping or ductwork, or ceilings lowered in rooms modified to suit changing needs. Whatever the reason for their presence, combustible concealed spaces create special problems for those concerned with fire protection in buildings. A fire established in a concealed space containing combustibles may be completely out of reach of hose streams and other fire fighting efforts and can thereby spread to other parts of the building. If the fire subsequently emerges in several sprinklered areas, many sprinklers may be activated and the water supply may be over-taxed. As a result, even buildings equipped with automatic sprinklers may be lost if a fire becomes established in an unsprinklered combustible concealed space.

There has been long standing recognition of the need to sprinkler concealed spaces. The National Fire Protection Association Standard on the Installation of Sprinkler Systems, NFPA-13,[1] requires in Subsection 4-4.4 that all combustible concealed spaces be protected by sprinklers. It has been recognized, however, that sprinkler installation is not always practical, and several exceptions have been incorporated into the standard to eliminate the need to make an "experienced judgement" each time a situation is encountered. Most of these exceptions appear to have been incorporated in NFPA 13 on the basis of their reasonableness in the context of specific situations. Unfortunately, the specific conditions that justified the exception may not be present in all the situations to which it is applied.

Prior to 1985, the Standard permitted sprinklers to be omitted from combustible concealed spaces formed between a ceiling and the joists above if the ceiling membrane was attached directly to the underside of the joists. An exception was added in 1985 to include concealed spaces created by suspending a ceiling membrane within 6 in. (152 mm) of the underside of combustible wood joists. This exception was included in recognition of the difficulty of installing sprinklers in spaces less than 6 in. (152 mm) deep – a recognition that had been traditionally extended to pitched roof spaces at the eaves. The exception does not require the installation of fire stopping or other fire protection.

EXPERIMENTS

Two tests were carried out to determine the

Table 1. Material and Equipment Specifications

Item	Specifications
Joists	2 in x 10 in x 24 ft (50.8 mm x 254 mm x 8.7 m) spruce with 9% moisture content.
Floor	5/8 in. (16 mm) waferboard with flame spread rating# of 232.
Ceiling	
Test 1	1/4 in (6 mm) plywood with a flame spread rating# of 211 mounted in an aluminum T-bar assembly with 4 ft x 4 ft (1.2 m x 1.2 m) spacing.
Test 2	3/8 in. (9.5 mm) gypsum board with a flame spread rating# of 17 on the concealed space side of the ceiling assembly, and mounted in an aluminum T-bar assembly with 4 ft x 4 ft (1.2 m x 1.2 m) and 2 ft x 4 ft (0.6 m x 1.2 m) spacings.
Sprinklers	165°F (74°C) Grinnell Duraspeed upright sprinklers with a 1/2 in. (12.5 mm) orifice on a light hazard "above and below" wet pipe schedule (no sprinklers were mounted below the ceiling assembly).

The flame spread ratings were measured using the standard tunnel test. Samples were tested on the side which was exposed to the concealed space.

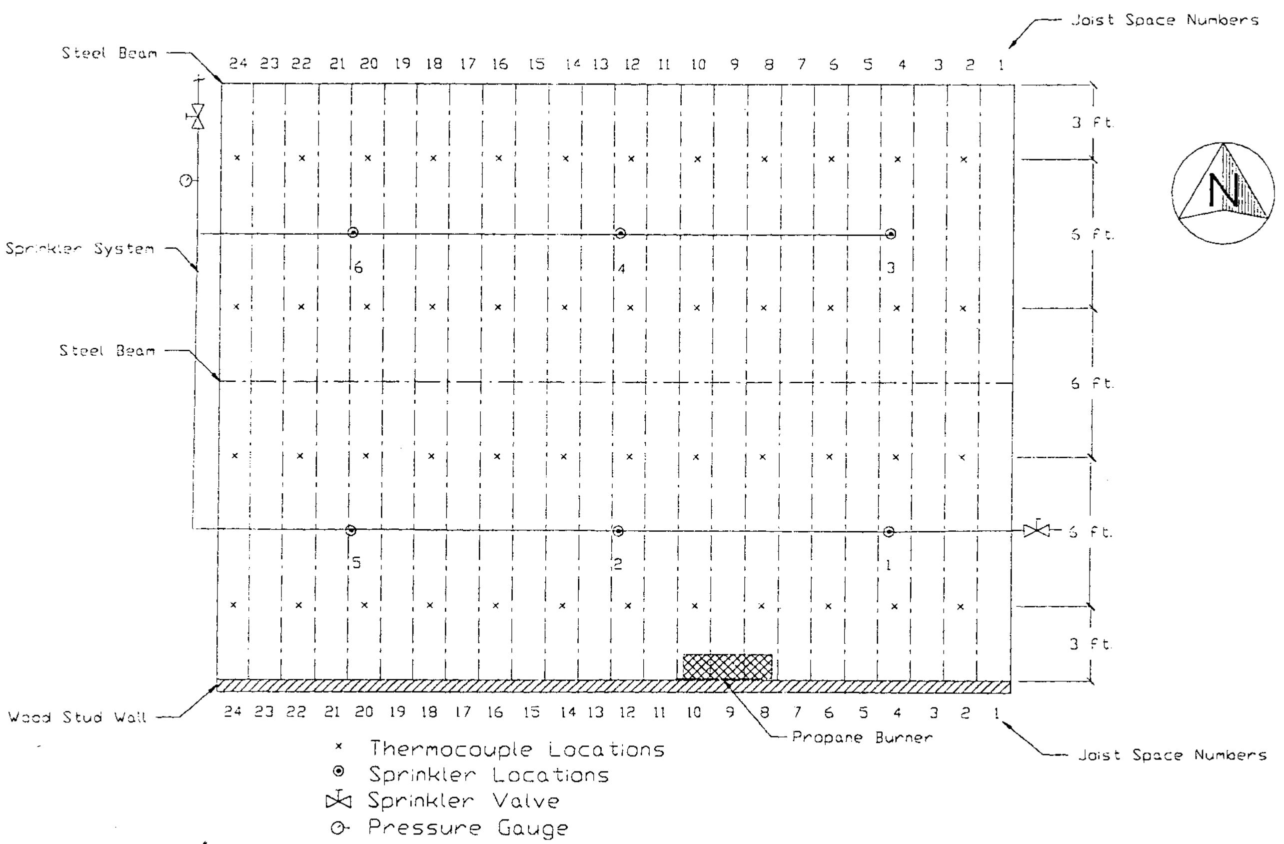

Figure 1. Plan view of the ceiling assembly showing the location of the propane burner, sprinklers and thermocouples for Test 1.

nature of fire spread in a concealed space created by a ceiling assembly suspended 6 in. (152 mm) below the wood joists. The space was protected by sprinklers even though not required by NFPA 13. The automatic sprinkler protection was included in order to determine its effectiveness in containing fire spread in the confined space produced when the ceiling is suspended within the limits permitted by the Standard.

Test Facility

A 24 ft long by 32 ft wide (7.3 m x 9.8 m) ceiling assembly was constructed with nominal 2 in. by 10 in. (51 mm by 254 mm) spruce joists spaced 16 in. (406 mm) on centres and a 5/8 in. (16 mm) thick waferboard subfloor. An aluminum T-bar ceiling was suspended below the joists using wires with a 6 in. (152 mm) space created between the bottom of the joists and the top of the ceiling panels. The specifications for the materials used in the test assembly are given in Table 1.

The plan view of the assembly used for the test is shown in Figure 1. The relative positions of the sprinklers and the thermocouples are also indicated. The joists at the south end of the assembly were supported by a gypsumboard on wood stud wall which enclosed that end of the joist spaces. The remaining three sides of the concealed space between the joists and the ceiling were open. The joists were also supported along the center and the open (north) side of the assembly by 6 in. (152 mm) deep steel beams mounted on concrete block columns.

The sprinkler piping layout and relative sprinkler locations are shown in Figures 1, 2 and 3. A light hazard "above and below" pipe schedule (no sprinklers were installed below the ceiling) was used with a 130 ft^2 (12.1 m^2) spacing in the concealed space using Grinnell Duraspeed upright sprinklers on a wet system. The sprinkler deflectors were located 1 in. (25 mm) below the bottom of the joist.

Ignition Source

Ignition was provided through a 1 ft x 3.5 ft (0.3 m x 1.1 m) opening in the ceiling membrane by a 3.4 x 10^5 Btu/hr (100 kW) propane sand burner with dimensions of 6 in. x 30 in. (150 mm x 760 mm). This source approximates the 3.1 x 10^5 Btu/hr (90 kW) ignition source intensity used in the Steiner tunnel test.[2] The top of the burner was located 28.5 in. (720 mm) below the bottom surface of the waferboard flooring with the flame just able to reach that surface at full propane flow. The burner was centered on a joist space with some overlap into the two adjacent spaces. The location of the ignition source relative to the sprinklers for the first test is shown in Figure 1 and in Figure 9 for the second test.

Instrumentation

Temperatures were measured using 26 gauge

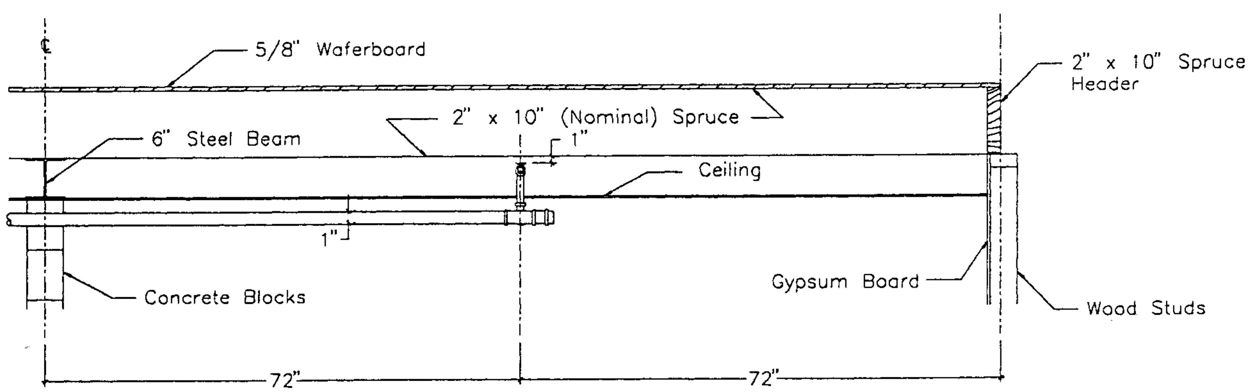

Figure 2. Cross-section of the ceiling assembly viewing normal to the joists showing the relatiave position of the sprinkler.

chromel-alumel thermocouples installed 2 in. (51 mm) below the bottom surface of the flooring. In the first test, the thermocouples were mounted in alternate joist spaces at distances of 3, 9, 15 and 21 ft (0.9, 2.7, 4.6, and 6.4 m) from the support wall. In the second test, further thermocouples were included in the joist space on which the ignition source was centered as well as at the sprinklers.

Other instrumentation included a closed circuit event timer to record sprinkler activation times, a paddle-wheel flowmeter (Signet Accum-U-Flow) to monitor water flow and a digital pressure gauge to measure the water pressure. Video records were made with two cameras located to view the ceiling assembly parallel and normal to the line of the joists.

Test Procedure

The sprinkler piping was precharged with water by using the inspector's test connection at the hydraulically most remote point.

The propane sand burner was ignited and the flame was allowed to develop fully (approximately 10 s) before the commencement of timing for the test. The burner was set to deliver 3.4×10^5 Btu/hr (100 kW) output. The burner was turned off after 3.5 minutes of fire exposure.

The sprinkler control valve was adjusted to maintain 12 psi (87 kPa) pressure at the valve after the operation of the first sprinkler and as additional sprinklers opened. The minimum allowable residual pressure at that location for 4 sprinklers operating in this configuration is 10.5 psi (76 kPa). This minimum allowable pressure is based on the NFPA 13 criterion that 7 psi (kPa) pressure be maintained at the most remote sprinkler. At the minimum operating pressure, the calculated total flow with four sprinklers operating is approximately 62 US gpm (235 L/min).

Results

Test 1

Both the floor membrane and the ceiling panels (plywood) had high flame spread ratings. The flame spread ratings of 232 for the waferboard subfloor and 211 for the ceiling panels were measured in the standard tunnel test. The flame front moved rapidly along the ignited joist space with fire visible out of the open end, 24 ft (7.3 m) from the burner position, within 97 s and flames extending 3 m outside the assembly after 176 s.

As noted previously, thermocouples were mounted in alternate joist spaces to monitor temperatures. In Test 1, the ignition source was centered on Joist Space 9 (with no thermocouples) and extended partially into Joist Spaces 8 and 10. After sprinkler activation, the maximum temperatures decreased rapidly in the direction normal to the joists. This is illustrated in Figure 4 by the temperature profiles measured by the thermocouples mounted in the

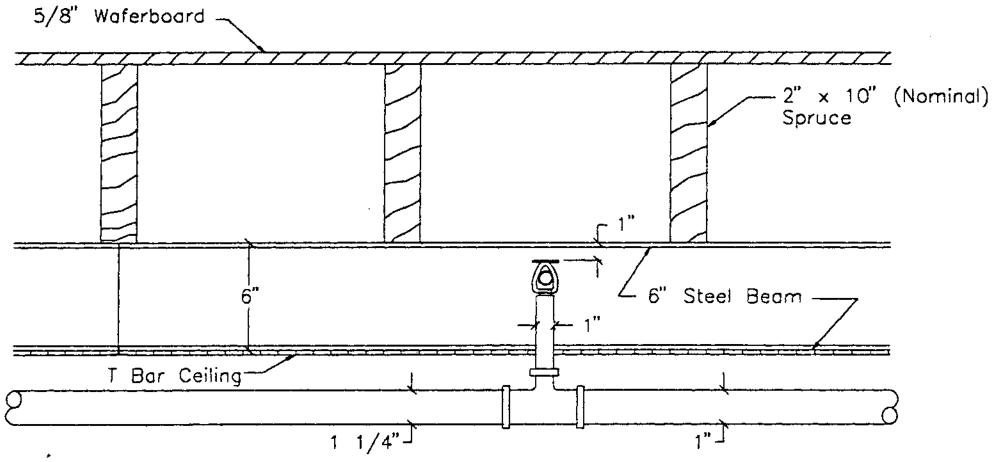

Figure 3. Cross-section of the ceiling assembly viewing parallel to the joists showing the relative positions of the sprinklers.

first, third and fifth joist spaces on either side of the ignition source and 3 ft (0.9 m) from the support wall. Temperatures did not exceed 600°F (315°C) by the fifth joist space.

Figures 5-7 show the temperatures measured at 9,15 and 21 ft (2.7, 4.6, 6.4 m) from the south wall in the first and third joist spaces on either side of the ignition source. These profiles indicate that a high temperature jet moved rapidly along the channel formed by the joists. At 75 s, the flame was observed at the open end of Joist Space 8, and by 3 min, fire was emerging from Joist Spaces 7-12 with flames reaching approximately 10 ft (3 m) above the assembly. The sprinkler activation times are noted in Table 2, and are indicated by an * on the abscissas in Figures 4-7.

The flame front temperature of 980°F (527°C) shown in Figures 4-7 is that occasionally employed for flame front determination in the Steiner tunnel.[2] This definition for the flame front has been used to determine the approximate extent of the flame propagation at several times during the test (Figure 8). The rapid development of the flame front along the channels formed by the joists is illustrated. On the other hand, the flame spread across the joists was much slower.

Four sprinklers were eventually activated in Test 1. An activated sprinkler is indicated by the large circles in Figure 8 with the radius, R, representing the maximum distance the droplets would attain under ideal conditions. Assuming the droplets fall a distance y (in this

Table 2. Sprinkler Activation Times

Sprinkler	Test 1 (s)	Test 2 (s)
1	111.6	146.0
2	112.3	153.0
3	168.2	N.A.
4	207.9	N.A.
5	N.A.	N.A.
6	N.A.	N.A.

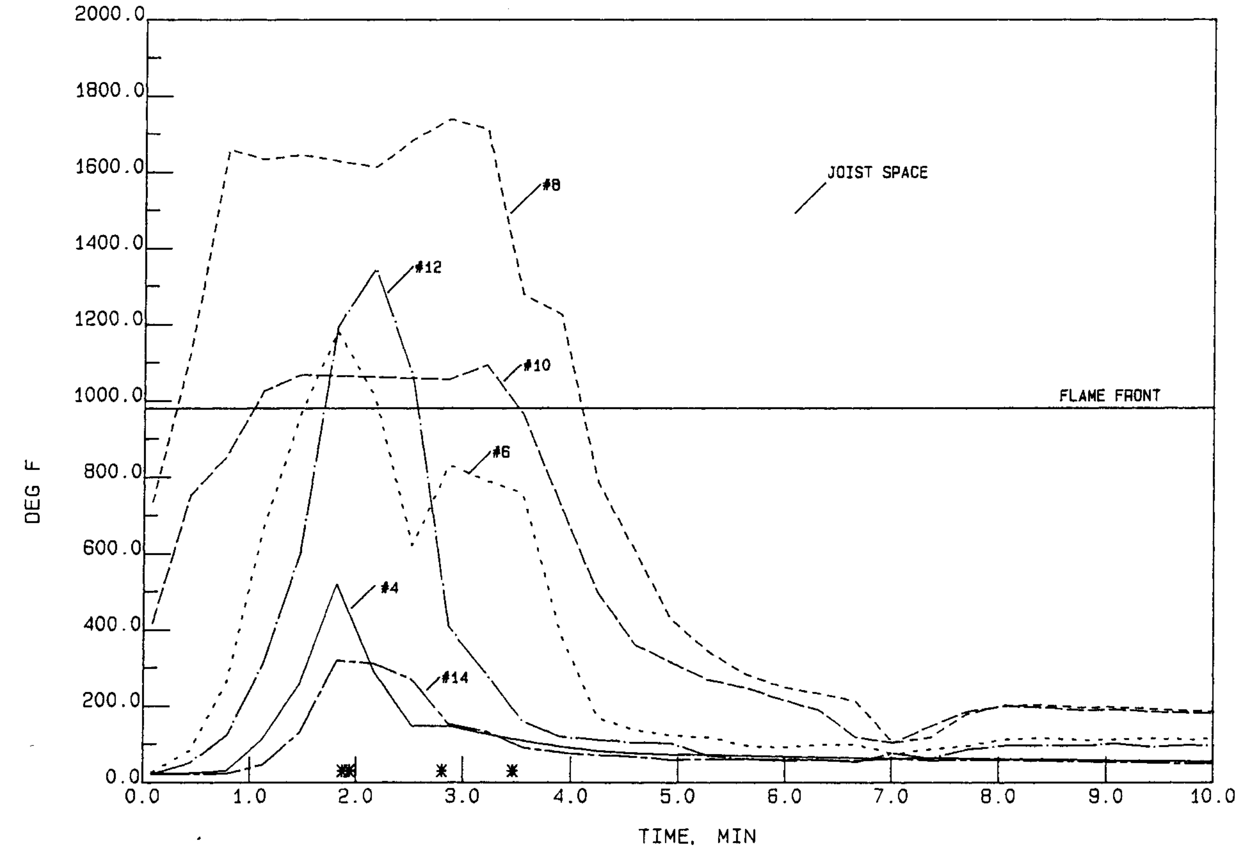

Figure 4. Temperature profiles for Test 1 measured 3 ft (0.9 m) from the south end.

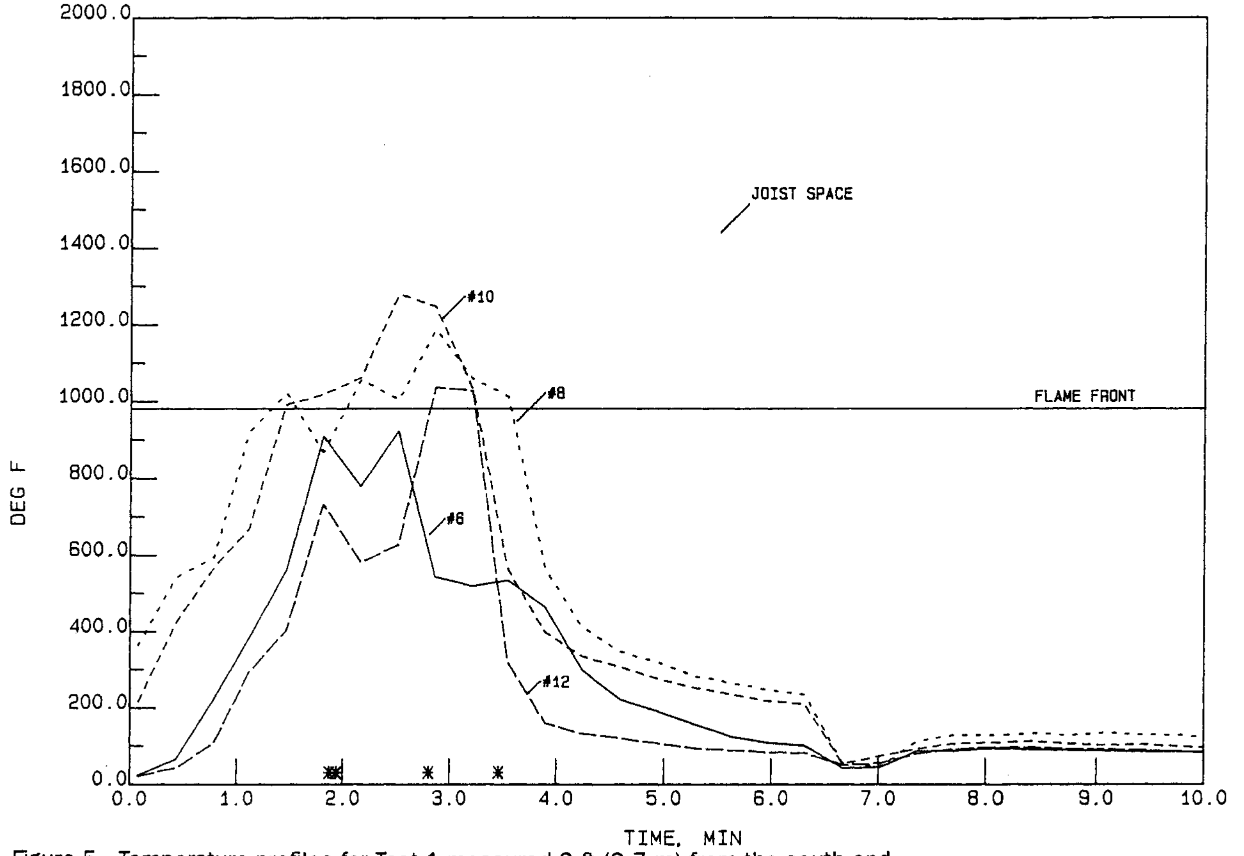

Figure 5. Temperature profiles for Test 1 measured 9 ft (2.7 m) from the south end.

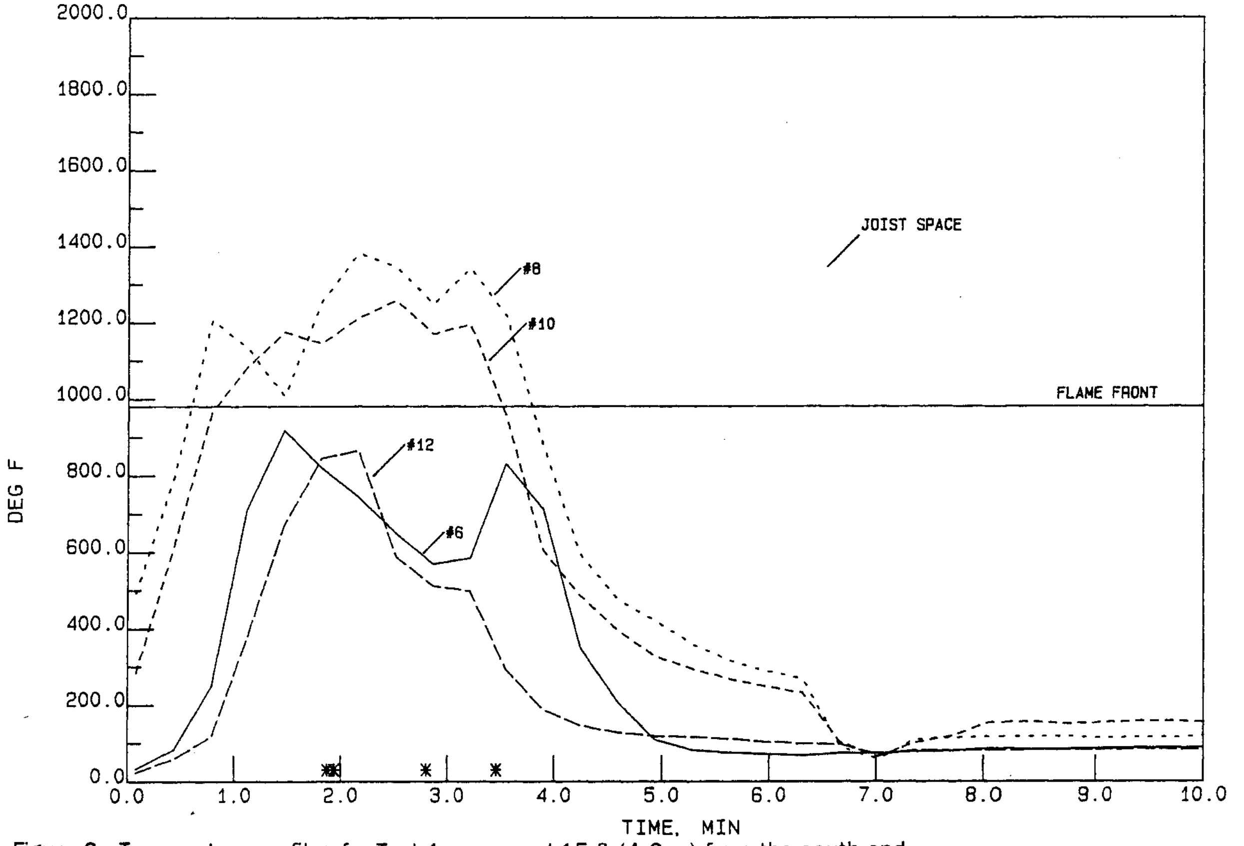

Figure 6. Temperature profiles for Test 1 measured 15 ft (4.6 m) from the south end.

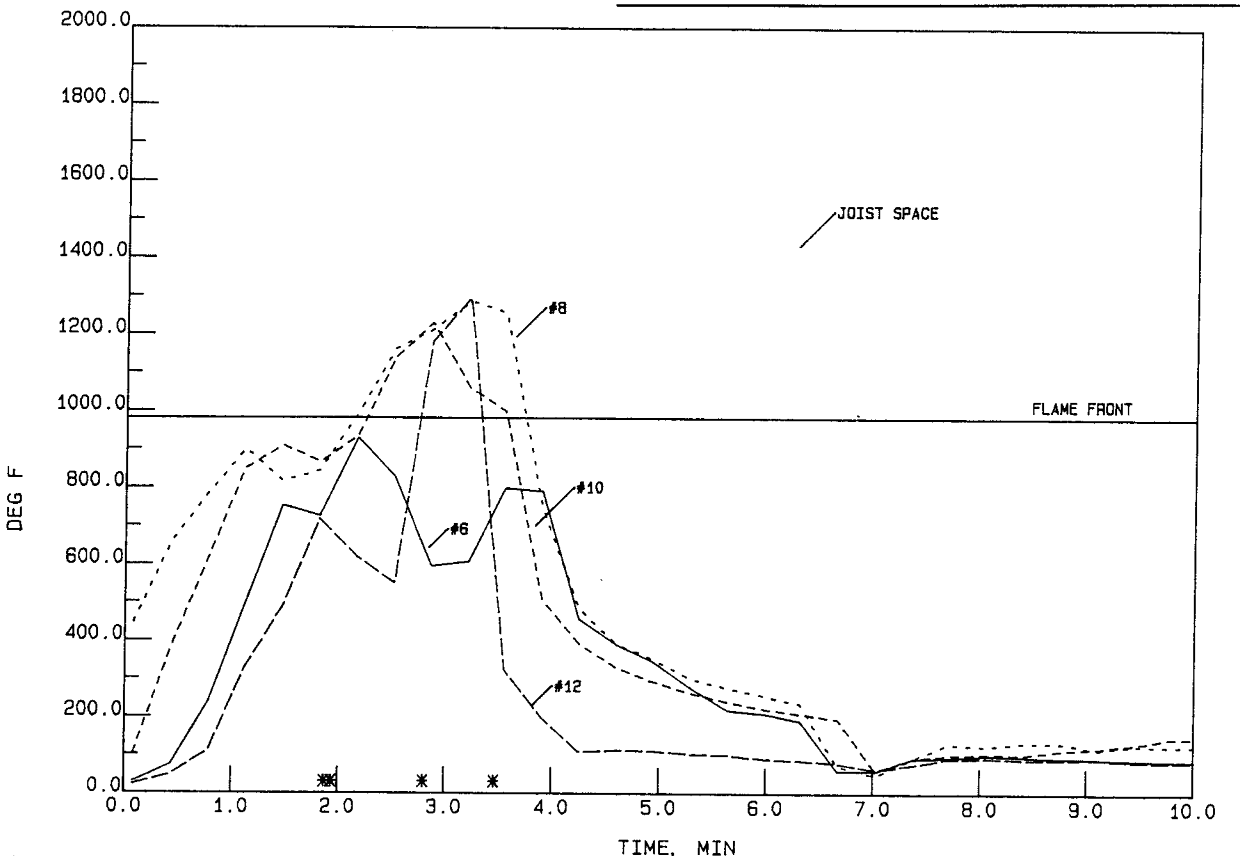

Figure 7. Temperature profiles for Test 1 measured 21 ft (6.4 m) from the south end.

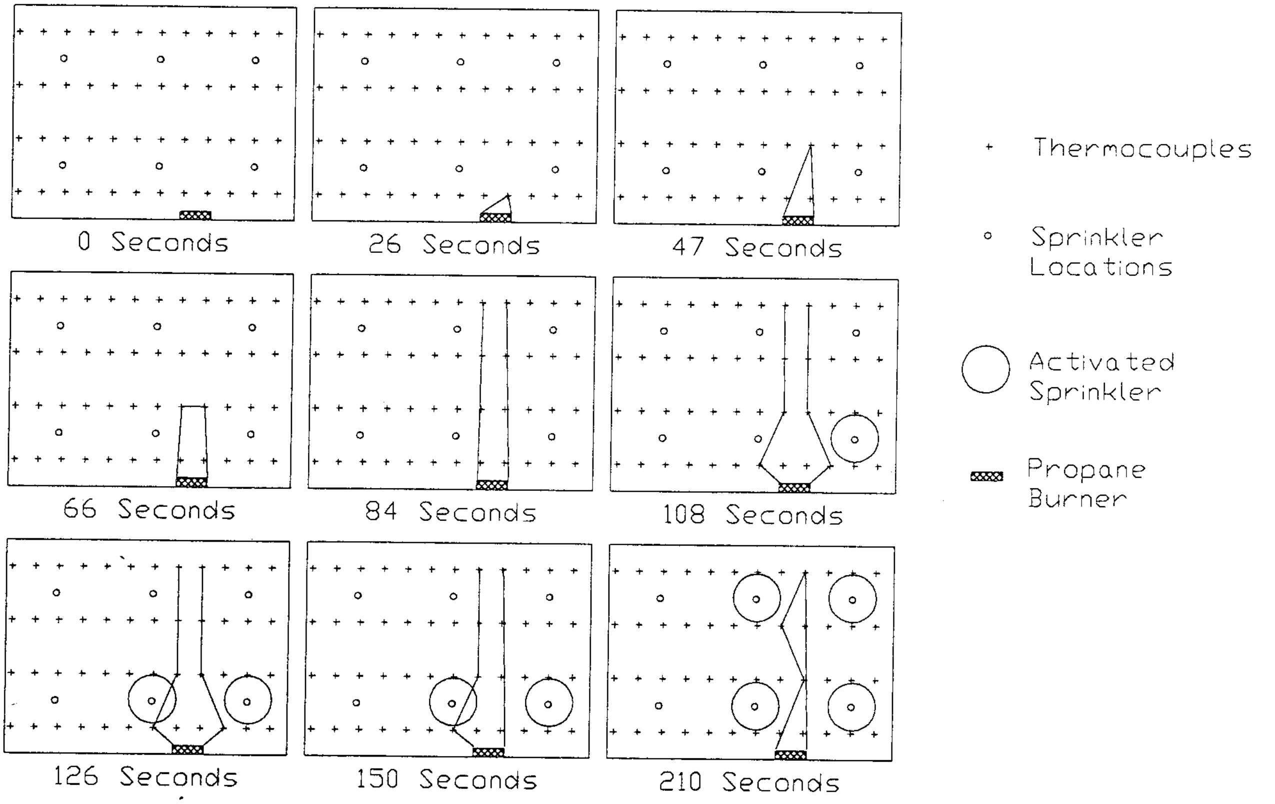

Figure 8. Flame extent at various times for Test 1.

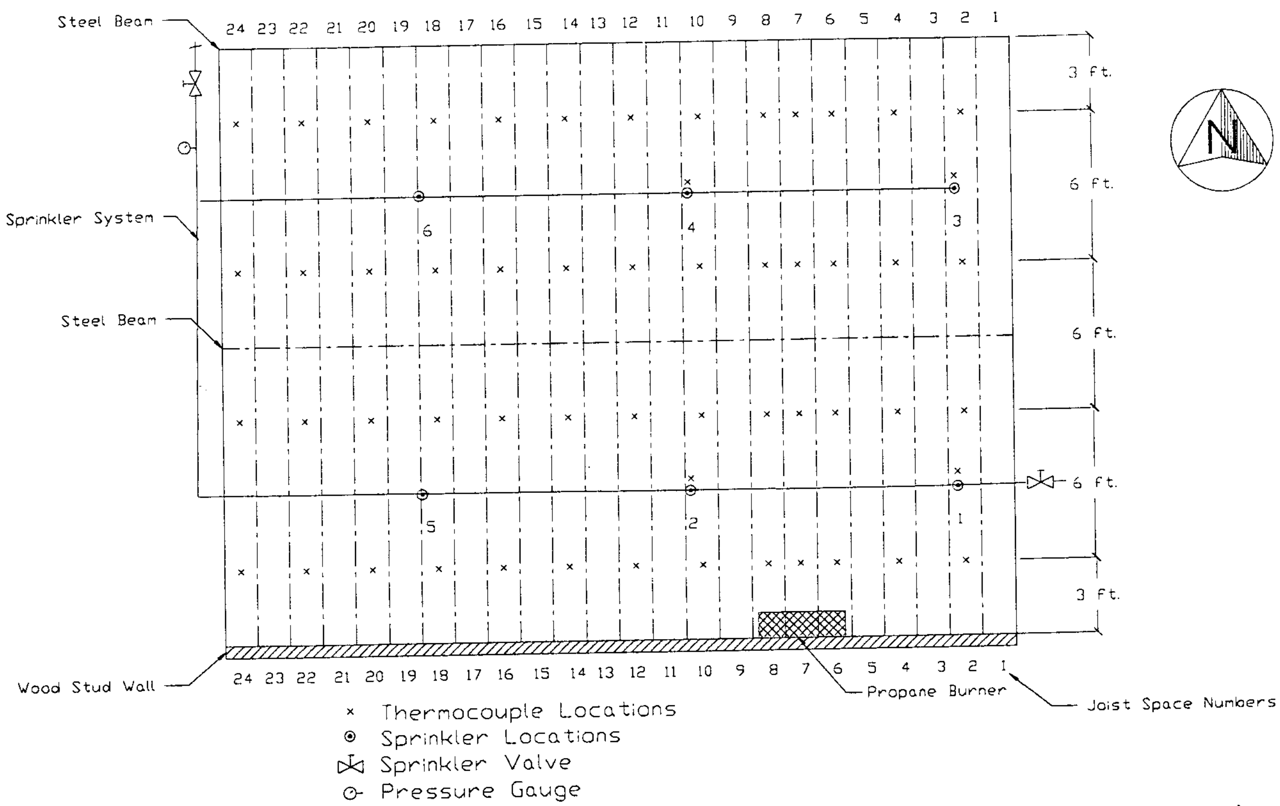

Figure 9. Plan view of the ceiling assembly showing the location of the propane burner, sprinklers and thermocouples for Test 2.

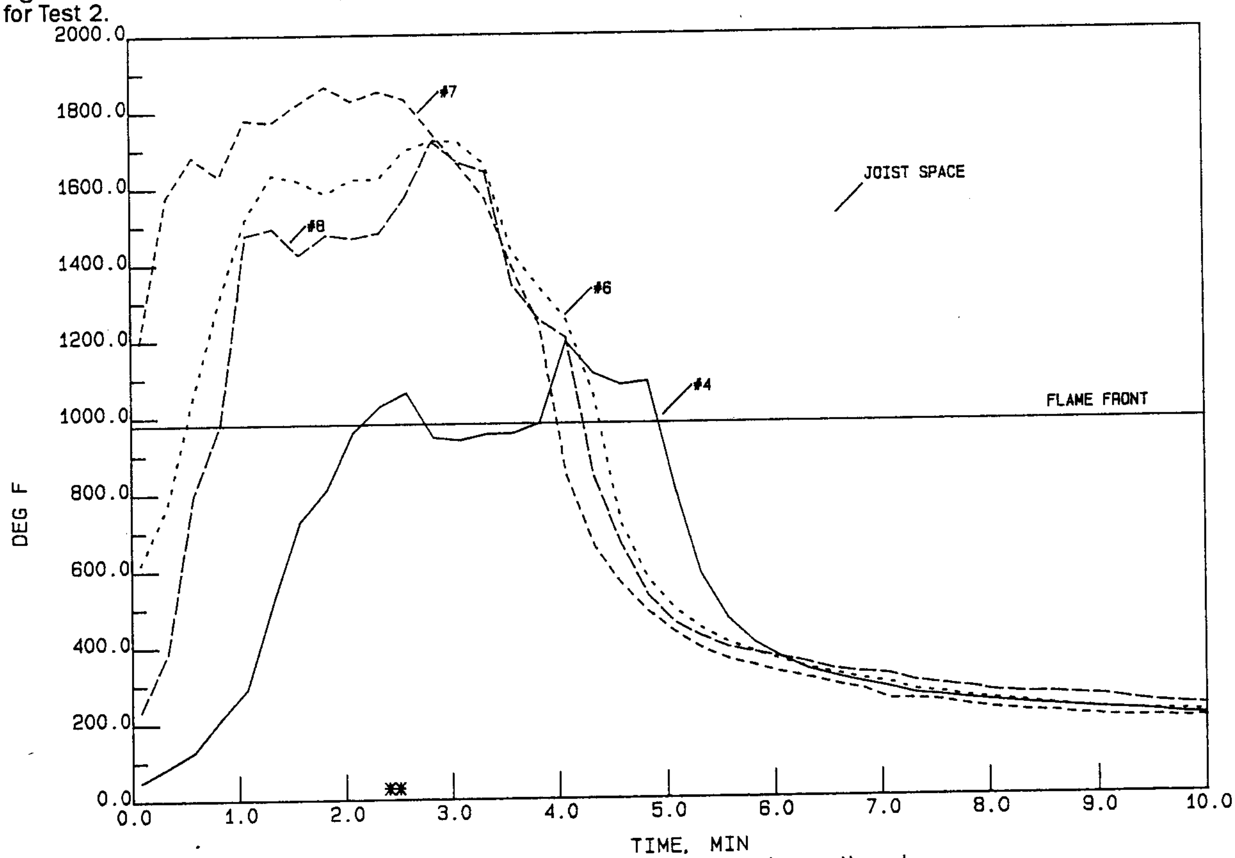

Figure 10. Temperature profiles for Test 2 measured 3 ft (0.9 m) from the south end.

case 5 in. (127 mm)) acted on only by gravity, the maximum distance attained is given by

$$R = \left(\frac{2y}{g}\right)^{1/2} \frac{Q}{0.25\ \pi D^2}$$

where g is the acceleration due to gravity, Q is the nozzle volume flow, and D is the nozzle diameter.[3] (The maximum distance measured experimentally is usually only 75-80% of the idealized estimate.) For the present ceiling configuration, the direct sprinkler coverage is limited to a 64 in. (1.6 m) diameter area. Deflected droplets, hot gas turbulence and steam generation in the confined space will extend the effective coverage of the sprinklers.

The sprinkler activation was not sufficiently fast to limit the flame spread along the joist channel. The two sprinklers nearest the fire source did not operate until after the fire had reached the open end of the assembly. The sprinklers did, however, limit the flame spread across the joists and eventually reduced the extent of the fire.

Test 2

In the second test, a low flame spread material (gypsumboard) was substituted for the plywood as the ceiling panels. The propane burner was centered on Joist Space 7. The sprinklers were also moved to maintain the same relative distance from the burner as the first test. Thermocouples were added in the Joist Space on which the burner was centered, and at the sprinkler locations. The remainder of the test arrangement was identical to that in the first test. The plan view for the assembly used for Test 2 is shown in Figure 9.

Figures 10-13 show the temperatures measured in the joist spaces (4,6,7,8 and 10) on which the burner was centered. Some thermocouples were damaged during the test, and thus the temperature is not shown for all joist spaces in some figures. The flame front moved along the joist spaces ahead of sprinkler activation. However, the movement was much slower than in the first test with only minor burning at the open end of the structure. A comparison of the flame extent at several times during Test 2 shown in Figure 14 with the results shown in Figure 8 for Test 1 further illustrates the slower flame spread in the second test. For the joist spaces partially exposed to the propane burner, the flame front required 140 s to reach the thermocouples located at 21 ft (6.4 m) compared with 84 s for the first test. Some fire was observed at the north end of these spaces after 155 s. The fastest flame spread, as would be expected, was along Joist Space 7 on which the burner was centered with only 65 s required for the temperature measured at the end thermocouple to reach 950°F (527°C). The fire was observed at the north end of this joist space at 98 s with flames approximately 3 ft (0.9 m) above the assembly by 110 s.

The flame also spread across the joists with sufficiently high temperatures for the two sprinklers nearest the burner to operate with the activation times noted in Table 2 and indicated by an * on the abscissas of Figures 10-13. No other sprinklers were activated during the test. The horizontal flame spread was halted by the two sprinklers which did activate. However, up to 150 s after sprinkler activation was required before cooling was observed in some areas of the test assembly (see Figure 10 Joist Space 4). The temperature at the north end of the assembly did decrease rapidly after sprinkler activation with no flame observed out the open joist channels after 225 s.

Discussion

Flame spread along the joist channels can be compared to a situation reported in the literature: flame spread along corridor ceilings.[4,5,6] In these tests carried out at the Fire Research Station in the U.K., a flame from a porous bed gas burner was allowed to impinge on the closed end of an inverted channel with a variety of noncombustible and combustible ceiling linings tested.

The 1.7 x 10^5 Btu/hr (50 kW) ignition source used in the tests documented by Hinkley *et.al.*[6] with combustible ceiling materials is comparable to the 3.4 x 10^5 Btu/hr (100 kW) obtained with the

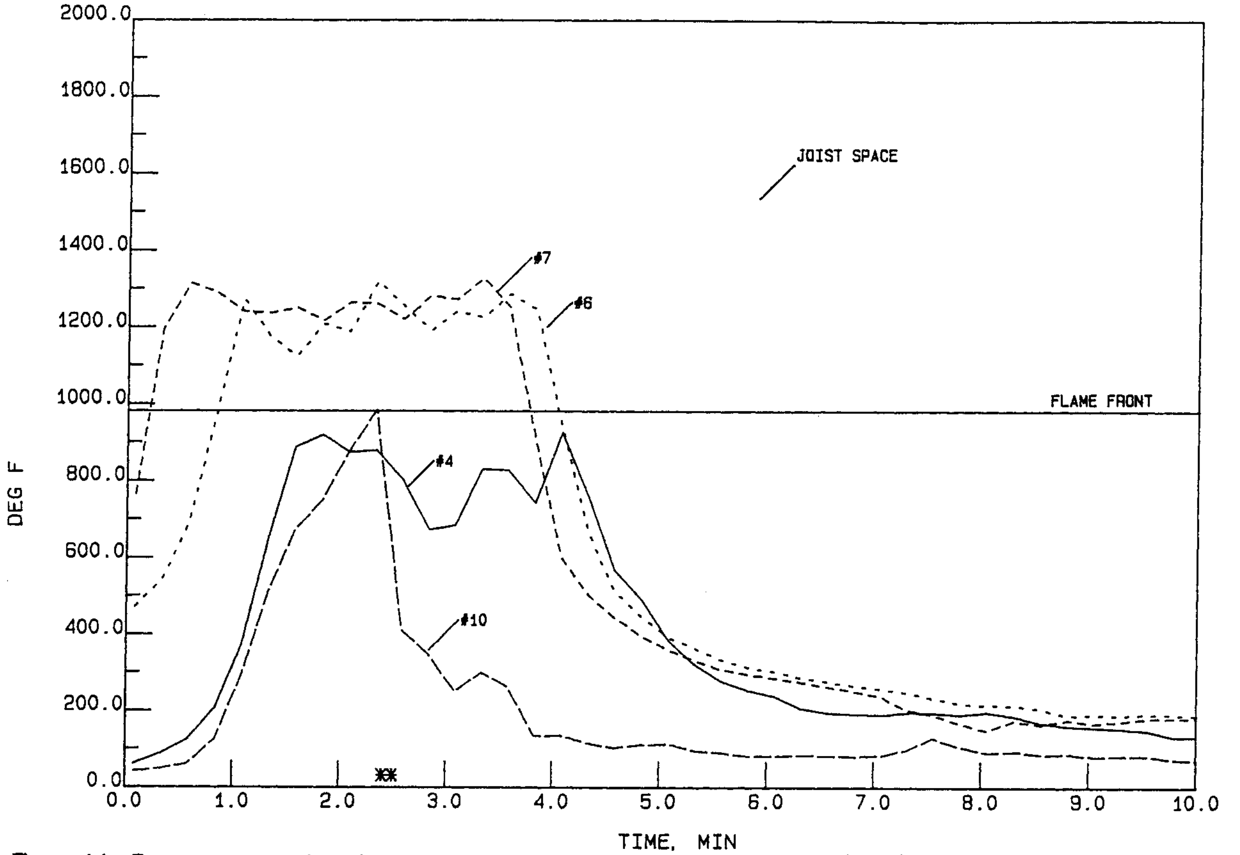

Figure 11. Temperature profiles for Test 2 measured 9 ft (2.6 m) from the south end.

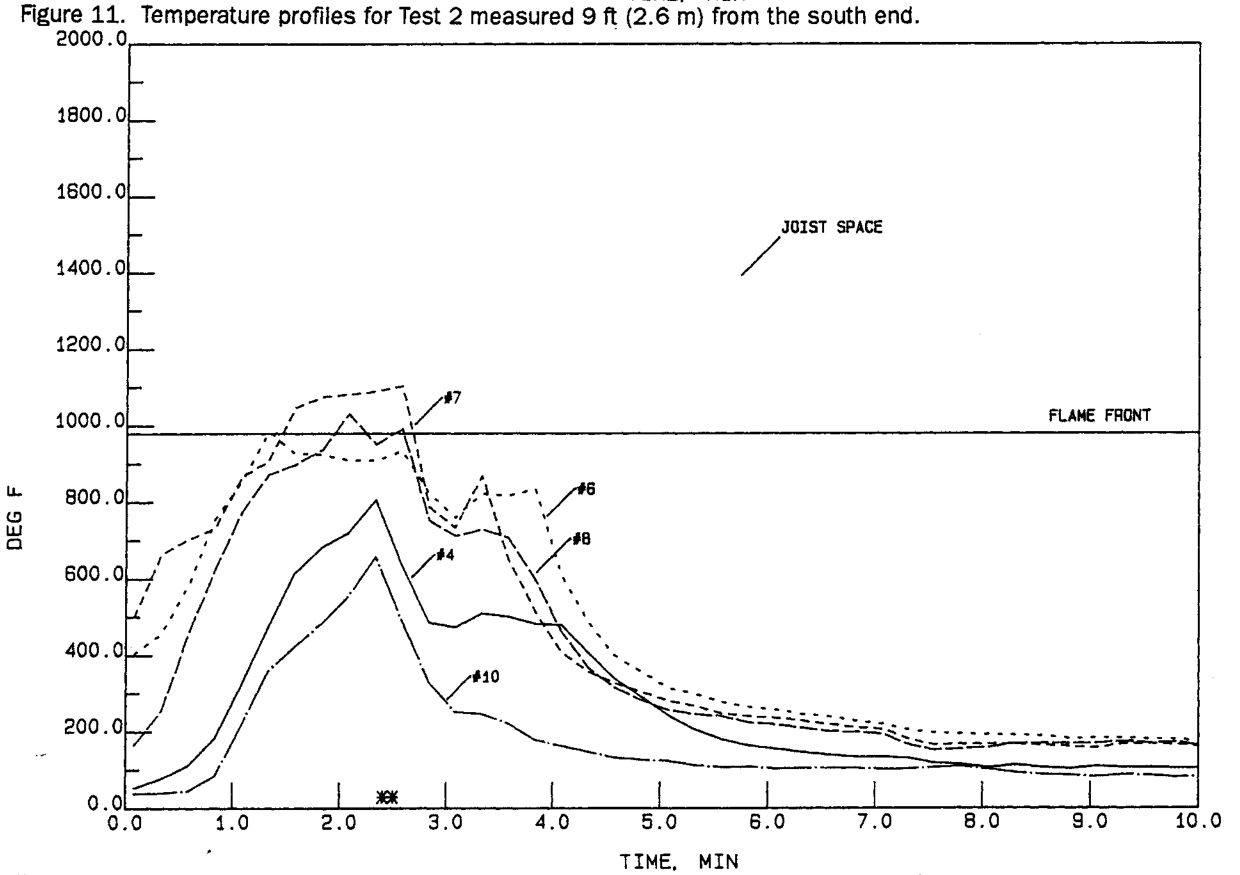

Figure 12. Temperature profiles for Test 2 measured 15 ft (4.6 m) from the south end.

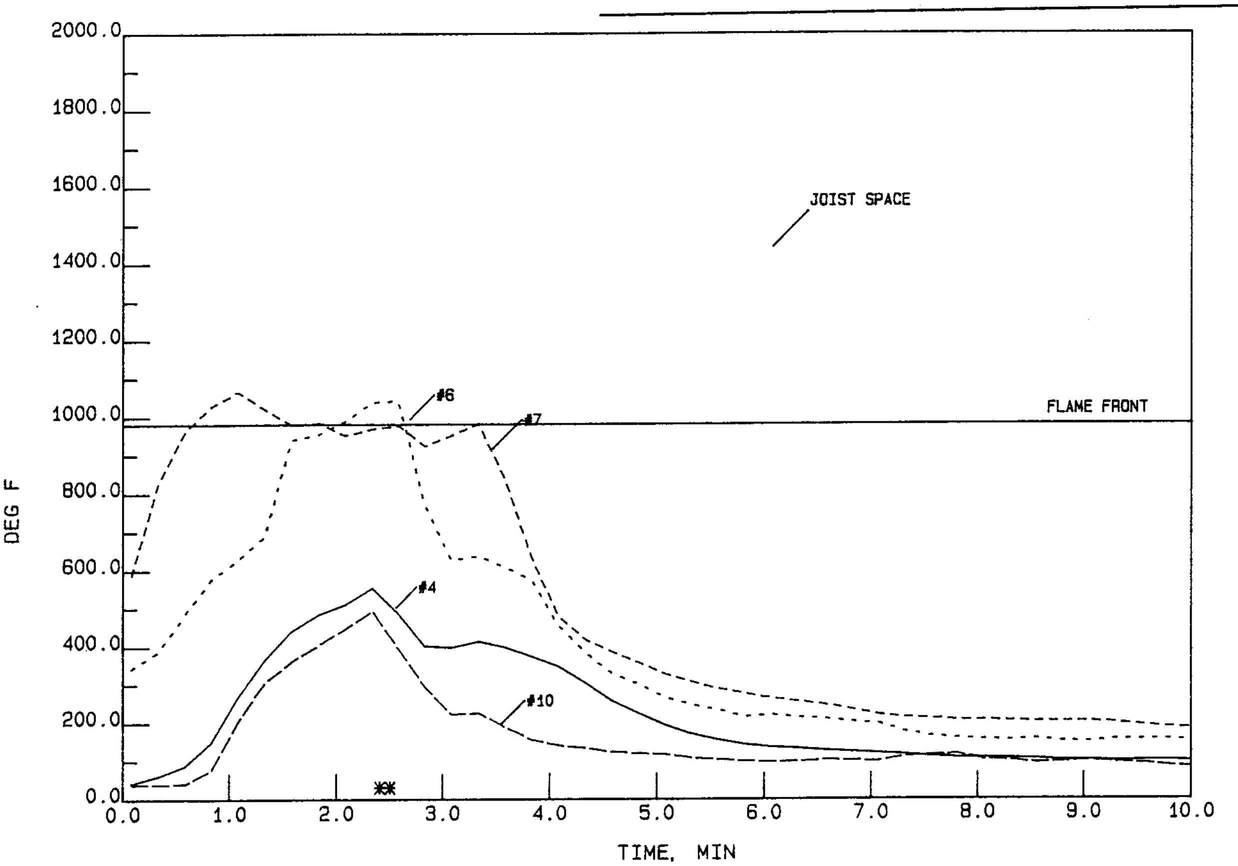

Figure 13. Temperature profiles for Test 2 measured 21 ft (6.4 m) from the south end.

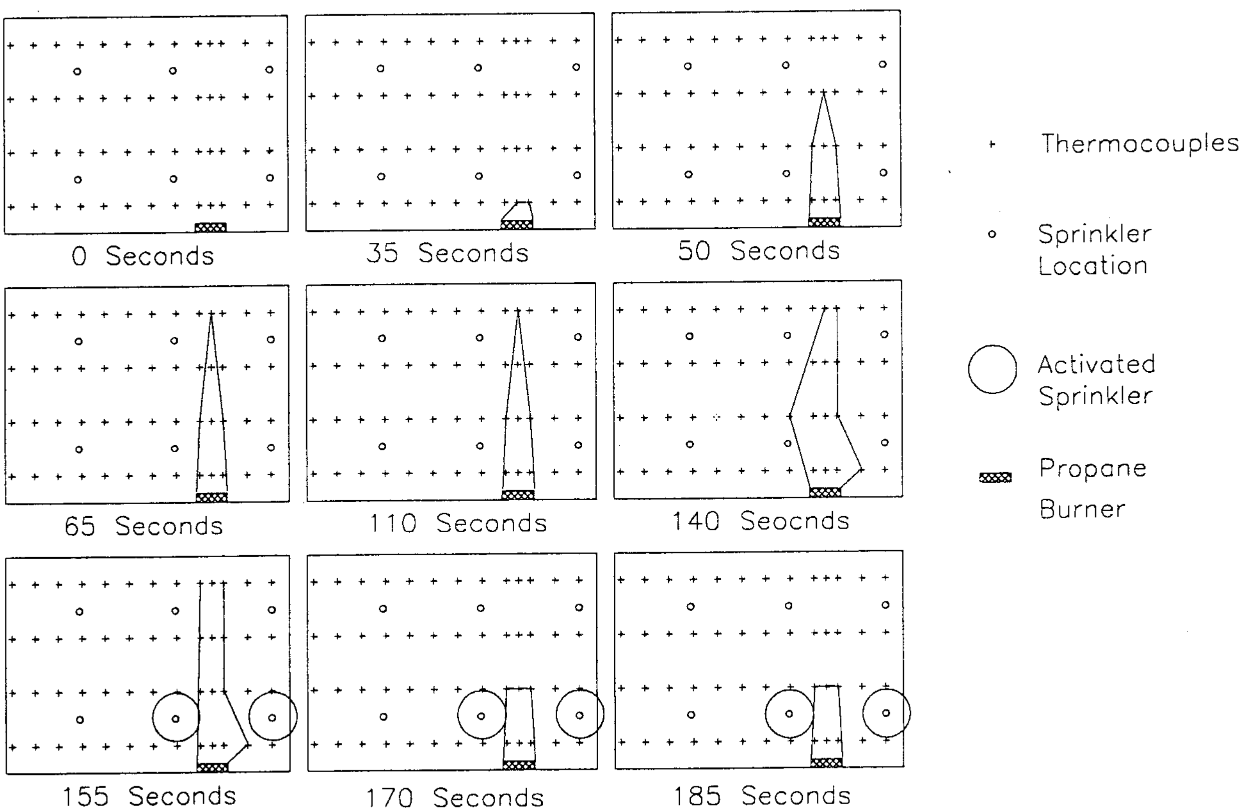

Figure 14. Flame extent at various times for Test 2.

propane sand burner. The flame in those tests very quickly (approximately 60 s for a 14.8 ft (4.5 m) length) reached the end of the channel assembly and extended 16.5-23 ft (5-7 m) beyond the end of the channel. In Test 1 (reported previously) with the sprinklered ceiling assembly, flames extended up to 10 ft (3 m) beyond the end of the joist channel (24 ft (9 m) length) at 167 s. The peak temperatures 1470°F (800°C) in the joist channels are comparable to the combustible ceiling tests, and considerably higher than the 1110°F (600°C) obtained with noncombustible linings.[5] The channel tests also indicated a fast rise, high intensity radiation exposure (>6.3 x 10^3 Btu/hr/ft^2 (20 kW/m^2)) to a wood floor with a resulting high flame spread. This is similar to the first test where a rapid flame spread is observed along the combustible ceiling material.

A major difference with the tests reported in this paper compared with the corridor situation is the close proximity of the ceiling to the joist channel which may further limit the air flow to the fire located in the joist spaces. There were indications with the relatively open channel structures that fuel rich combustion dominated with the hot gas layer extending 6-8 in. (150-200 mm) below the ceiling. Ventilation-limited combustion could account for the slow flame spread in the second test with a noncombustible ceiling material even though the flooring material above the ceiling had a high flame spread rating.

The sprinklers did halt the fire spread across the joists, but were ineffective in slowing the fire spread along the joist channels. In fact in Test 1, the fire had already spread beyond the end of the structure by the time the nearest sprinklers opened. The use of a low flame spread material for the ceiling tiles did alleviate the problem to some extent, but did not prevent the fire from spreading to the end of the assembly. The steam generated by the contact of the water droplets with the hot fire gases had a significant effect in the confined spaces and would be expected to suffocate the fire even beyond the direct penetration of the sprinkler droplets.

Conclusions

These tests were run primarily to examine the exception for sprinkler protection in concealed spaces formed by ceiling membranes suspended within 6 in. (152 mm) of the joists of a combustible ceiling assembly as permitted by NFPA 13. The tests conducted indicate that sprinkler protection does not afford adequate protection against fire spread along the joist channels, especially if a combustible material is used for the ceiling panels. However, once the sprinklers are activated, the resulting steam cloud does limit lateral spread of the fire and does suffocate the fire beyond the limits of direct sprinkler spray penetration.

The characteristics for flame spread in the concealed ceiling assembly are similar to that found for corridors with combustible ceilings. The joist spaces act as a channel for the rapid transport of the fire gases to the open (north) end of the assembly. For the first test, there was rapid flame spread along the joist channel enhanced by the burning of the combustible ceiling membrane. The extended flame observed in the second test was due to ventilation limited combustion in the ceiling assembly. The decrease in the extent of the flame once the two sprinklers near the burner were activated was due to suffocation of the fire by steam even though these sprinklers should have had minimal or no direct effect on a fire situated near the open end of the assembly.

Further tests are required to determine the spacing at which adequate control of the fire spread can be obtained. Variations in the sprinkler system such as the use of quick response sprinklers or staggered sprinkler layouts should also be considered.

There is a definite need for further protection in ceiling assemblies with concealed spaces. For example, the use of fire stops to minimize flame spread along the joists or filling the space between the suspended ceiling and the joists with noncombustible insulation should be considered. Exception 4 of Subsection 4-4.4.1 does allow for no sprinkler protection for composite wood construction if the joist channels are firestopped into volumes not exceeding 160 cu ft (4.53 m^3) or do not exceed 300 sq ft (27.9 m^2) channel area. However, this exception stipulates that the ceilings should be attached directly to the composite wood joist construction, and would have to be modified before it could be applied to a suspended ceiling with wood joist construction. Tests are required with combustible ceiling assemblies to determine the effectiveness of fire stopping in controlling flame spread along the joist space for ceilings suspended below the joists.

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