Fire Performance Characteristics of Protected Wood and Steel Floor-Ceiling Assemblies

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FIRE PERFORMANCE CHARACTERISTICS OF PROTECTED WOOD AND STEEL FLOOR-CEILING ASSEMBLIES

AS REPORTED IN

“FIRE RESISTANCE OF CONSTRUCTION ASSEMBLIES”
BY BLETZACKER, LANE, AND DENNING
OHIO STATE UNIVERSITY, 1969

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Introduction

During 1965 and 1966, a series of fire tests were conducted at the Engineering Experiment Station at Ohio State University with the purpose, “To develop comparative performance data from fire resistance tests of typical building assemblies of steel, wood, and heavy timber connections; to assess the effect of the use of fire retardant treated wood in similar assembles; and to study the effect of varying control parameters on the fire exposure severity.” A report on the study by R.W. Bletzacker, W.W. Lane, and D.W. Denning was issued in 1969.

The Ohio State University report contains significant information on the fire performance characteristics of protected wood and steel floor-ceiling assemblies, particularly the heat release properties of wood construction as shown by relative fuel consumption data. This discussion evaluates those findings in the report related to the magnitude of, and the effects of construction variables on, detectable fuel contribution from protected wood assemblies.

Study Plan

The Ohio State University study consisted of three separate series of tests: pilot ceiling tests to determine if each of a number of ceiling membrane systems provided equal protection to structural assemblies made with wood and steel joists; pilot deck tests to determine the thermal transmission resistance of various concrete decks on steel joists and of wood decks on wood joists; and full-scale fire endurance tests to develop comparative data on the performance of protected steel joists with concrete deck, protected joists with wood decks, and unprotected timber beams with wood decks. Results from each series pertaining to the performance of protected assemblies are discussed below.

Ceiling Membrane Pilot Tests

Thirty-three specimens, approximately 5' by 7' in size, were exposed to the ASTM E119 standard temperature-time relationship to determine the protection provided by one layer of ½" regular, one and two layers of ½" Type X, one layer of ½" Type XX (improved), and one and two layers of $^5/_8$" Type X gypsum board. All test assemblies had a metal deck covered with 3" of dry silica sand. Steel joist assemblies were made with 8" open web joists spaced 16" on center with the gypsum board screwed to furring channels wired directly (in contact) to the joists. Two types of wood assemblies were used: one having nominal 2" by 8" joists spaced 16" on center, with gypsum board screwed to furring channels and attached directly to the joists; the other having actual 2" by 9" joists spaced 16" on center, with gypsum board nailed directly to the joists.

Ceiling tests were terminated when the gypsum board membrane dropped off. Because inadequate fastener spacing and edge distance caused premature fall-off of the membrane in the first eight tests, results from these runs are excluded from discussion.

Plenum temperatures of assemblies made with wood joists were found to be slightly higher than those made with steel joists. However, because the maximum temperature difference was only 30°F, the researchers combined the data for both joist types to develop curves of average plenum temperature and total gypsum board thickness (see Figure 1). Further, the researchers concluded that plenum temperature was governed by the thickness of the protective membrane and was relatively independent of the formulation of the gypsum board used as long as the ceiling remained in place.

A comparison of ceiling fall-off times is shown in Table 1. It can be seen that the fall-off times for the ½" gypsum board system were five to eight minutes longer for wood joists than for steel joist assemblies. Only in the case of the $^5/_8$" ceiling membrane were the times for the wood and steel joists approximately the same. The thermal expansion properties of the steel joists may have been a factor in reducing the protection time provided by the particular ceiling membrane support system used, namely furring channels wired directly to joists. In the full-scale fire tests, a suspended rather than direct tie protective membrane system was used.

Deck Ceiling Pilot Tests

Sixteen wood and concrete decks, also approximately 5' by 7' in size, were subject to the ASTM E119 standard temperature-time exposure to determine the effect of deck material, deck thickness, and deck construction on resistance to thermal transmission. All test assemblies were made with 10" steel joists spaced 24" on center and were protected with a $^5/_8$" suspended mineral acoustical lay-in panel system. Concrete decks evaluated range from 1½" to $^3/_4$" thick. Four wood decks were evaluated: Nominal 2" and 4" thick T&G southern pine planks; 25/32" T&G hardwood flooring over $^5/_8$" Douglas Fir plywood (1$^3/_8$" total thickness); and 25/32" hardwood flooring over ¾" Douglas fir plywood (1½" total thickness).

Temperatures in the plenum were measured during all deck tests. Each test was terminated when either the average temperature rise on the unexposed surface exceeded 250°F, or the temperature rise at one thermocouple location on the unexposed surface exceeded 350°F, or cotton waste was ignited.

Plenum temperatures were found to be relatively unaffected by differences in deck thickness for a given deck material. However, a large difference was observed in the plenum temperatures for the wood decks and the concrete decks. Mid-depth plenum temperatures average about 650°F for the wood decks and 475°F for the concrete decks after one hour of fire exposure. The difference was attributed by the researchers to the greater (four times) thermal diffusivity of concrete relative to that of wood and to possible exothermic reaction in the wood assemblies at the plenum temperatures exceeding 350°F.

Unexposed surface temperatures of concrete decks were found to be related to deck thickness, with about a 100°F difference occurring between 1½" and 3½" thick decks after one hour of fire exposure.

The fire endurance times of the various deck systems are summarized in Table 2. It can be seen from this table that the fire endurance times of the $1^3/_8$" thick and 1½" thick plywood-hardwood flooring decks averaged 35 minutes and 52 minutes longer, respectively, than the 1½" concrete decks. The relationship between concrete thickness and endurance time indicates a $2^3/_8$" thick concrete deck is required to provide endurance equivalent to that of a 1½" thick plywood-hardwood deck. This thickness difference was attributed to the thermal insulation characteristics of the two materials.

Alternatively, wood decks made with T&G planks had a lower fire endurance than an equivalent thickness of concrete. As shown in Table 2, the average endurance times of the 1½" and 3½" wood plank decks were 1 hour 56 minutes and 3 hours 48 minutes, respectively, compared to 2 hours 2 minutes and 4 hours and 14 minutes for the equivalent thickness concrete decks. This difference in behavior was attributed to local hot spots on the wood decks, (assumed to be at T&G joints), causing "premature" end-points on the basis of either ignition of cotton waste or high thermocouple reading; whereas the concrete decks failed by average temperature rise.

On the basis of the combined results of the ceiling and the deck pilot tests, it was determined that a suspended ceiling membrane system should be used as the protection for steel and wood joist full-scale floor test assemblies, and that a 2" concrete deck and a 1½" plywood-hardwood flooring deck should be used to provide comparable resistance to thermal transmission in the two constructions.

Full-Scale Floor-Ceiling Fire Endurance Tests

Assemblies Tested. A total of eleven full-scale fire tests were conducted on protected steel joist or wood joist assemblies in general accordance with ASTM E119 test procedures except with regard to control of fire exposure severity and the introduction of secondary air into the furnace after fall-off of the protective membrane on a number of the wood assembly tests.

Steel assemblies consisted of 10" open web joists spaced 24" on center supporting a 2" concrete slab placed over $^3/_8$" by 3.4 lb. ribbed metal lath. The slab was reinforced with 6" by 6" No. 10 welded wire mesh at mid-depth. Suspended ceiling protection was supported in a fire-rated exposed tee system.

Wood assemblies consisted of nominal 2" by 10" joists spaced 16" on center, with 1" by 3" mid-span bridging and solid end blocking, supporting a 1½" deck consisting of ¾" plywood subfloor, 15 lb. building paper, and 25/32" T&G hardwood flooring. Ceiling protection was either direct nailed with 6d cement-coated nails 6 in. on center to the bottom of the joists, or suspended in the same fire-rated exposed tee system used with the steel assemblies. Fire retardant treated joists and plywood subfloor were used in two of the wood assembly tests. Construction details of typical steel and wood assemblies are shown in Figures 2 and 3, as reproduced from the report.

Specific protected assemblies tested were:

Type	Assembly No.	Protection
Steel joist with 2" concrete deck	F1, F2, F3	5/8" Type X gypsum panels-suspended
	F4	5/8" acoustical panels-suspended
Untreated 2x10 wood joists with 1-1/2" deck (untreated 3/4" plywood and 25/32" hardwood flooring)	F5, F7	5/8" Type X - direct nailed
	F6	5/8" acoustical-suspended
	F8, F9	5/8" Type X -suspended
Fire retardant treated 2x10 wood joists and 1-1/2" deck (fire retardant treated 3/4" T&G plywood and untreated 25/32" T&G hardwood flooring)	F10, F11	5/8" Type X -suspended

Fire Exposure. The furnace chamber exposed a 13' by 15' area of the test assembly to the flames from natural gas burners. Except with assemblies F9 and F11, fire tests were conducted using the ASTM E119 standard temperature-time relationship to control the fire exposure. In test F9 and F11, a cumulative time-fuel input curve based on steel tests was used to control fire exposure. The temperature-time curves resulting from these fuel controlled exposures were similar to the standard temperature-time curve indicating a general equivalence between temperature and fuel controlled fire severity for the protected assemblies involved.

A significant part of the full-scale testing program was the measuring of the fuel required to maintain the standard fire exposure. This enabled fuel consumption rates for wood and steel test assemblies to be compared. The difference in fuel consumption provides a relative indication of the amount of heat being released by the wood elements during the test and detectable in the fire compartment. However, because of the difference in the thermal diffusivity properties of the wood and concrete deck materials, a portion of the difference in fuel consumption between the wood joist-wood deck assemblies and steel joist-concrete deck assemblies is not a result of heat released by the wood materials, but is fuel required to offset the greater loss of heat from the plenum through the concrete deck.

Full-Scale Test Results. Data from the fire tests of protected steel and wood assemblies are summarized in Table 3. Included in the table are time to tile or protective membrane fall-off or joint failure, time to estimated load failure (excessive rate of deflection), time to burn through, hot spot or average temperature rise, and the difference (area variation) between the actual and ASTM E119 standard temperature-time curve.

The basis used to determine time to load failure was not described by the researchers. Analysis of the deflection-time curves for each of the full-scale tests indicates that the slope or rate of deflection which was judged to constitute failure was not necessarily uniform. For example, in one case the slope of the deflection-time curve was near 50° at the designated failure time while in another this slope exceeded 70°. This apparent non-uniformity, when coupled with the early failure of the protective membrane in a number of the tests, prevents making any meaningful comparisons of time to load failure for the different assemblies.

Relatively early ceiling fall-off or joint failure occurred with three of the wood assemblies. In assemblies F5 and F7, where $^5/_8$" gypsum board was nailed directly to the joists, ceiling fall-off began at 36 and 30 minutes, 15 to 40 minutes less than the fall-off times observed in the ceiling pilot tests for the same type of assemblies (see 17C, 18C, and 31C in Table 1). It also should be noted that the plenum temperatures in F5 and F7 were lower prior to ceiling fall-off than the plenum temperatures in those wood assemblies which had suspended ceiling protection and longer times to ceiling fall-off. In wood assembly F6, an expansion joint in the suspended rated tee system failed to perform early in the test, allowing flame to enter the plenum after only 10 minutes. Because of the early failures in the protective membrane system, comparisons of the performance of assemblies F5, F6, and F7 with the protected steel assemblies do not appear appropriate.

In tests of wood assemblies F8, F9, and F10, large quantities of secondary air were introduced into the furnace when ceiling tile fall-off began to occur (56, 50, and 53 minutes respectively). This was apparently done to assure full combustion of any gases released by the wood joists and deck. Addition of secondary air is not part of the ASTM E119 test, where it is assumed that as long as furnace temperatures are reasonably close to the standard temperature-time curve (±5% area variation), a standard fire exposure exists.

Basis for Fuel Consumption Comparisons. For initial evaluation purposes, comparison of 60-minute fuel consumption rates for the four steel-concrete deck assemblies (Fl, F2, F3, and F4) and four of the wood assemblies (F8, F9, F10, and F11) was considered appropriate for obtaining estimates of the amount of heat the wood assemblies might be contributing to the severity of the fire. These constructions were selected on the basis that the effects on fuel consumption of introducing secondary air in the test of assemblies F8, F9, and F10 could be neglected; the use of fuel-time rather than temperature-time as the basis of controlling fire severity could be assumed to have an insignificant effect on fuel consumption; the effects of early ceiling protection fall-off in assemblies F1, F8, F9, and F10 that occurred at 46, 56, 50, and 53 minutes, respectively, could be assumed not to have unduly confounded fuel consumption rates; and that the fire testing of assembly F4 without an externally applied load could be assumed to have no effect on the fuel consumption performance of this assembly.

Fuel consumption rates for the four steel and four wood assemblies being compared are shown in Figures 4a through 4h. Total fuel consumed at 45 and 60 min., and the differences in areas between actual and standard temperature-time curves for each assembly are given in Table 4. Plots of cumulative fuel consumption versus 10-minute time intervals are shown for each assembly in Figure 5. All fuel consumption values tabulated and illustrated are based on graphical integration of the areas under the fuel-time curves in Figures 4a through 4h.

It can be seen from both Table 4 and Figure 5 that the cumulative fuel consumption at 60 minutes for the four wood assemblies fell within the range of the consumption values for the steel assemblies (6251 cu. ft. for F3 and 8763 cu. ft. for F2). Consumption values for the two wood assemblies made with fire retardant treated joists and plywood were very similar to the value for steel assembly F4 and only slightly lower than that for steel assembly F2. Fuel consumption values for wood assemblies F8 and F9 were similar to those for steel assemblies Fl and F3.

Fuel Consumption Adjusted for Temperature-Time Differences. The observed low value of 6251 cu. ft. for steel assembly F3 was obtained with a fire exposure that was significantly less severe than that associated with the standard temperature-time curve (the result of a thermocouple malfunction). This is shown by the area variation factor of -7.31 percent for this particular test. Conversely, the high value of 8763 cu. ft. for assembly F2 was obtained with a slightly more severe exposure than that associated with the standard curve (area variation factor of +0.864 percent). Inspection of the fuel consumption and area factors for the eight assemblies as a group indicated that a general correlation existed between the two variables. Linear regressions of 60-minute fuel consumption and area variation factors were fitted to the data for all eight assemblies and for the four steel assemblies alone. These regressions are shown in Figure 6. It can be seen from this Figure that the correlation of the two variables is significant and that both the slope and intercept terms for the eight combined assembly group and the four steel assembly group are very similar.

Fuel consumption values at 60 minutes for the four steel assemblies were adjusted to a 0.00 percent area variation factor, using the steel only regression, to determine the range in values that could be expected for the same exposure. These adjusted values are shown below.

Assembly	Area factor, percent	60-minute fuel consumption, cu. ft.	
		Actual	Adjusted for T/t area
F1	−0.154	7270	7310
F2	+0.864	8763	8537
F3	−7.31	6251	8155
F4	+0.08	8346	8325
Mean		8082	
Standard deviation		537.7	
Coefficient of variation, %		6.7	

The mean and standard deviation of the adjusted values for the four steel assemblies were used as a more sensitive measure of the heat released by the wood assemblies and measured in the fire compartment. The mean fuel consumption value was adjusted to the area variation factor associated with each of the wood assemblies using the steel only regression. This adjusted steel assembly value then was compared with the observed fuel consumption value of the wood assembly, as shown below.

Assembly	Area factor, percent	60-minute fuel consumption, cu. ft.			
		Wood, actual	Steel, adjusted for area		
			Mean	16% E.V.*	2.5% E.V.*
F8	−3.71	6765	7116	6669	
F9	−3.81	6272	7090	6645	6267
F10	−1.07	8137	7803	7313	
F11	+1.82	8193	8556	8019	

* E.V.= exclusion value: 16%=mean (1-1.00cov)
2.5%=mean (1-1.96cov)

The foregoing comparison of fuel consumption values indicates that the fuel used in three of the four wood assembly tests is well within the range of values that would be expected of steel-concrete assemblies having the same fire severity as measured by area variation factor. Only in the case of assembly F9 does it appear that the fuel consumed may be outside the expected range of the steel-concrete assembly. The fact that the F9 assembly had the most erratic fuel-time curve of any of the eight assemblies being compared (see Figure 4f) and had ceiling fall-off at 50 minutes with subsequent introduction of secondary air may have been influencing factors in this lower fuel consumption behavior.

As further verification of the relatively small amount of heat being released by the wood assemblies and detected in the fire compartment, the fuel consumed between 45 and 60 minutes of each of the four wood and four steel assemblies was compared. The wood assemblies would be expected to release the maximum amount of heat at this time in the test, particularly in the case of the three assemblies in which secondary air was used after ceiling fall-off. The comparison of final 15-minute fuel input values is shown below.

Assembly No.	Assembly Type	Fuel consumed between 46 and 60 min., cu. ft.
F1	Steel	1920
F2	"	1805
F3	"	1526
F4	"	1961
F8	Untreated Wood	1515
F9	"	1394
F10	F.R.T. Wood	1968
F11	"	1978

These 15-minute data are generally consistent with the trends shown by the total fuel consumed values. The two fire retardant treated wood assemblies especially show no indication of releasing measurable heat into the furnace.

Summation

When the greater loss in heat from the plenum of protected steel joist-concrete deck assemblies is taken into account, the Ohio State University tests indicate that the difference in the fuel required to maintain standard fire conditions in fire tests of protected wood joist-wood deck assemblies and steel joist-concrete deck assemblies is within the range of experimental variation. This suggests that the wood elements in a 1-hour rated floor-ceiling assembly contribute negligible amounts of heat to the fire compartment during the fire exposure period.

Of particular note, rated floor-ceiling assemblies made with fire retardant treated joists and plywood subfloor appear to be equivalent to rated steel joist-concrete deck assemblies in terms of contributing to the severity of a one-hour compartment fire.

Table 1. Length of Time to Ceiling Fall-Off for Steel and Wood Pilot Assemblies

Gypsum Ceiling	Joist Type	Method of Ceiling Attachment	Test No.	Length of Time to Ceiling Fall-off, min. Test	Avg. for Assembly
½" Type X	Steel	Furring Channels	25C	38	
			26C	41	39.5
	Wood	Furring Channels	27C	49	
			28C	46	47.5
	Wood	Direct	9C	48	
			10C	45	47.5
½" Type XX	Steel	Furring Channels	11C	48	
			12C	55	57
			29C	68	
	Wood	Furring Channels	13C	55	
			14C	70	62
			30C	61	
⅝" Type X	Steel	Furring Channels	15C	68	
			16C	67	67.5
	Wood	Direct	17C	63	
			18C	74	68.5
			31C	43	
2 Layers ½" Type X	Steel	Furring Channels	23C	61	
			24C	67	62.3
			32C	59	
	Wood	Direct	19C	63	
			20C	78	70.5

Table 2. Average Endurance Times of Protected Steel Joist Assemblies Made with Various Deck Materials

Deck System	Type of Failure (ASTM E119 Criteria)	Average Exposure Times, Hrs. :Min. [1]
1½" Concrete	Average Temperature	2:02
3½" Concrete	Average Temperature	4:14
5/8" Plywood and 25/32" Hardwood Flooring	High Thermocouple	2:38
2" x 6" nominal T & G Planking	High Thermocouple	1:56
¾" Plywood and 25/32" Hardwood Flooring	Average Temperature	2:55
4" x 6" nominal T & G Planking	Cotton Waste	3:48

[1] Based on tests of two assemblies

Table 3. Data from Fire Endurance Tests of Protected Steel and Wood Floor-Ceiling Assemblies

Ceiling Protection and Joist Type	Assembly No.	Date of Test	Furnace Control	Time, min. Tile Fall-off or Joint Failure	Load Failure	Burn Through	Hot Spot or Avg. Temp. Rise	Area Variation (Difference between Actual and Standard T/t curves), percent
⅝" Gypsum - Direct Nail								
Untreated Wood	F5	5/11/65	Temp.	36 (tile)	45	—	—	−0.685
Untreated Wood	F7	6/14/65	Temp.	30 (tile)	45	—	—	−0.007
⅝" Accoustical - suspended								
Untreated Wood	F6	5/21/65	Temp.	10 (joint)	32	72	—	+0.034
Steel	F4	7/1/65	Temp.	60 (joint)	no load	—	60	+0.080
⅝" Gypsum - suspended								
Untreated Wood	F8	12/10/65	Temp.	56	57	—	—	−3.71
Untreated Wood	F9	2/11/66	Fuel	50	54	—	—	−3.81
Treated Wood	F10	2/24/66	Temp.	53	54	67	—	−1.07
Treated Wood	F11	3/4/66	Fuel	66	51	60	—	+1.82
Steel	F1	12/6/65	Temp.	46	58	—	—	−0.154
Steel	F2	12/16/65	Temp.	76	82	74	—	+0.864
Steel	F3	2/4/66	Temp.	—	—	—	123	−7.31

Table 4. Total Fuel Consumption of Protected Steel and Wood Floor-Ceiling Assemblies After 45 and 60 Minutes of Fire Test

Assembly Type	Assembly No.	Temperature-time Area Factor, percent	Fuel Consumption, cu. ft. 45 min.	60 min.
Steel Joists - Concrete Deck	F1	−0.154	5350	7270
	F2	+0.864	6958	8763
	F3	−7.31	4725	6251
	F4	+0.08	6385	8346
Wood Joists - Wood Deck	F8*	−3.71	5250	6765
	F9*	−3.81	4878	6272
	F10	−1.07	6169	8137
	F11	+1.82	6215	8193

* Untreated Wood Joists

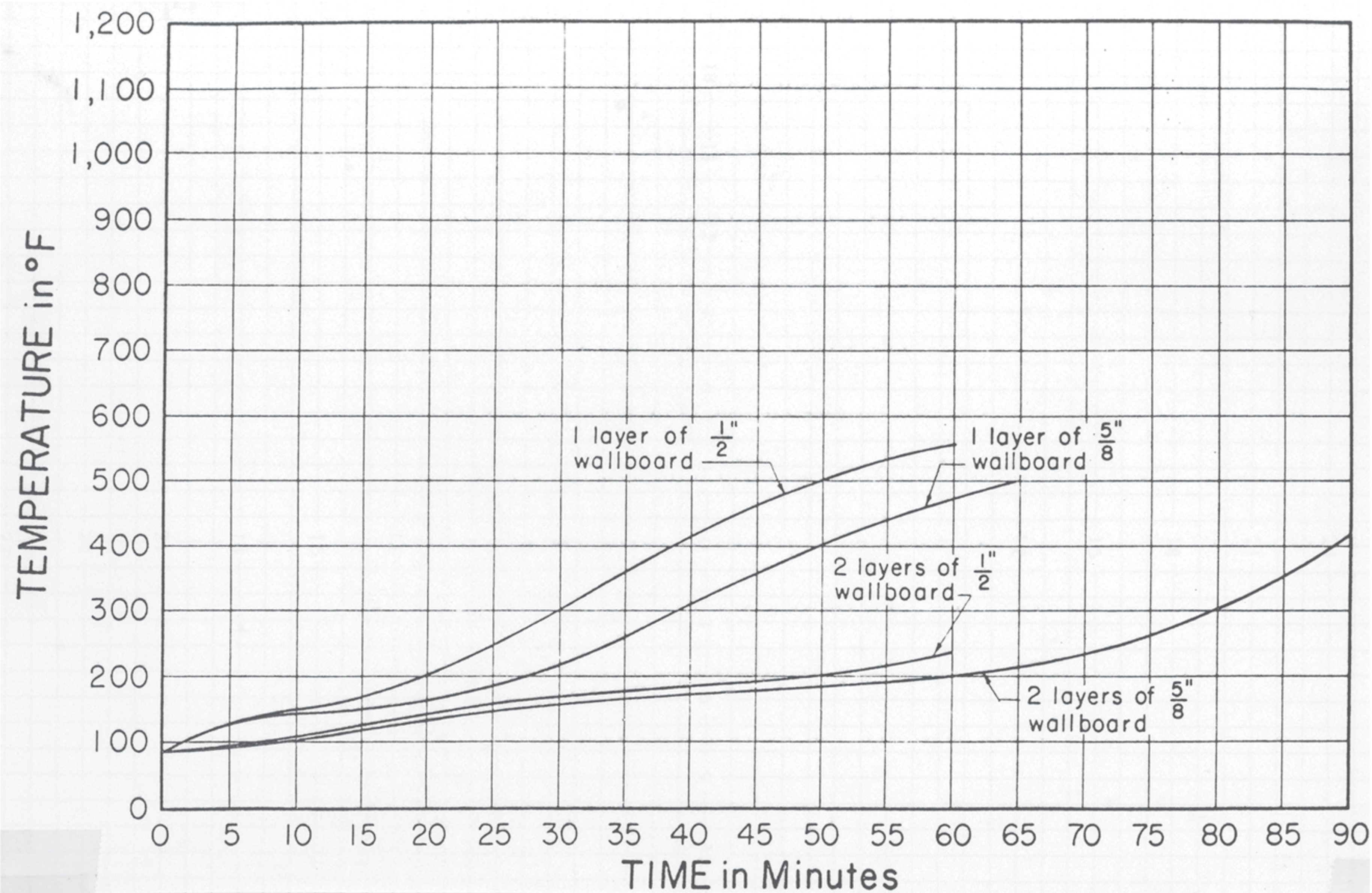


Figure 1 Indicated Composite Plenum Temperature at Underside of Floor Deck For Various Thicknesses of Ceiling Membrane

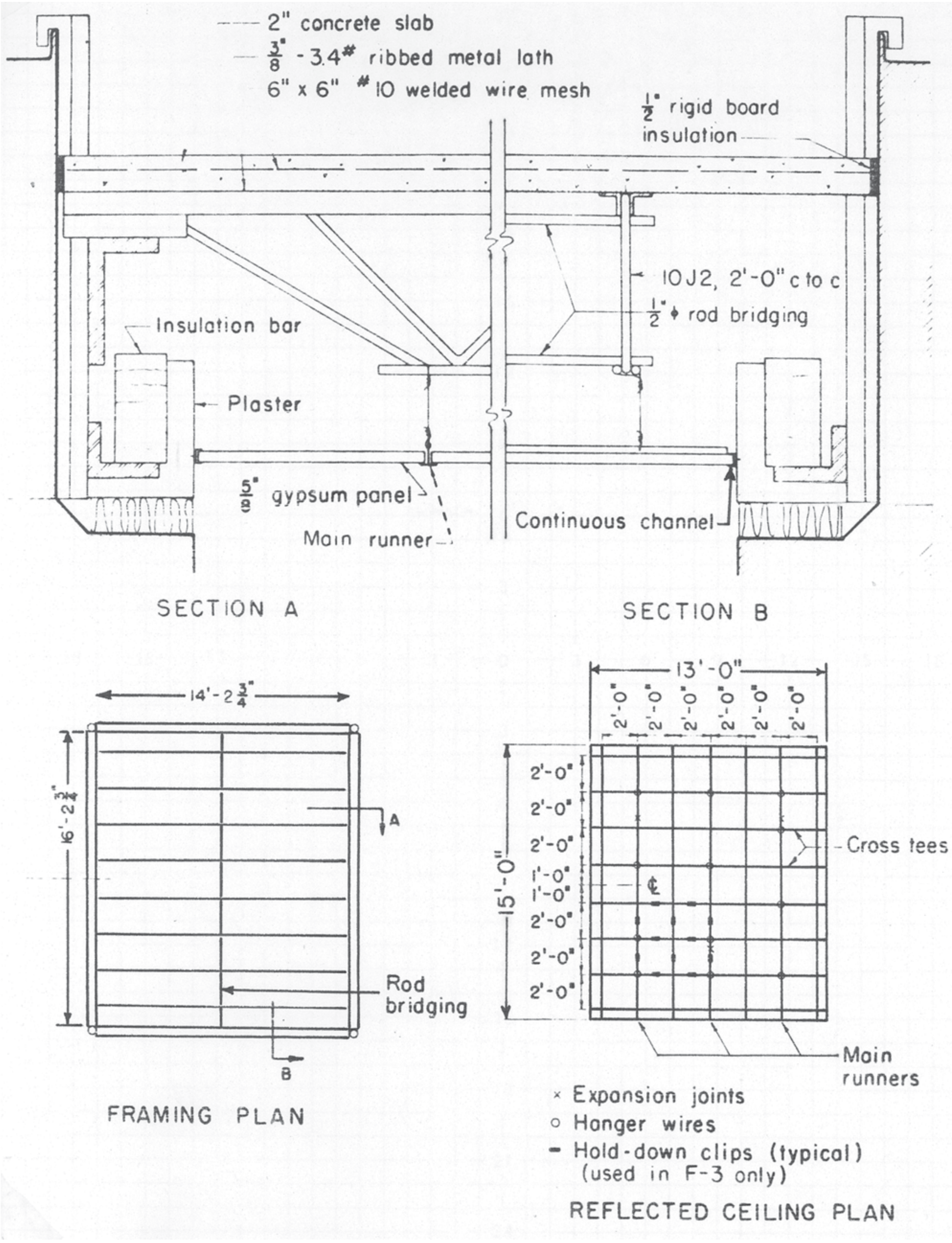


Figure 2 Construction Details for Assemblies F-1, F-2, and F-3

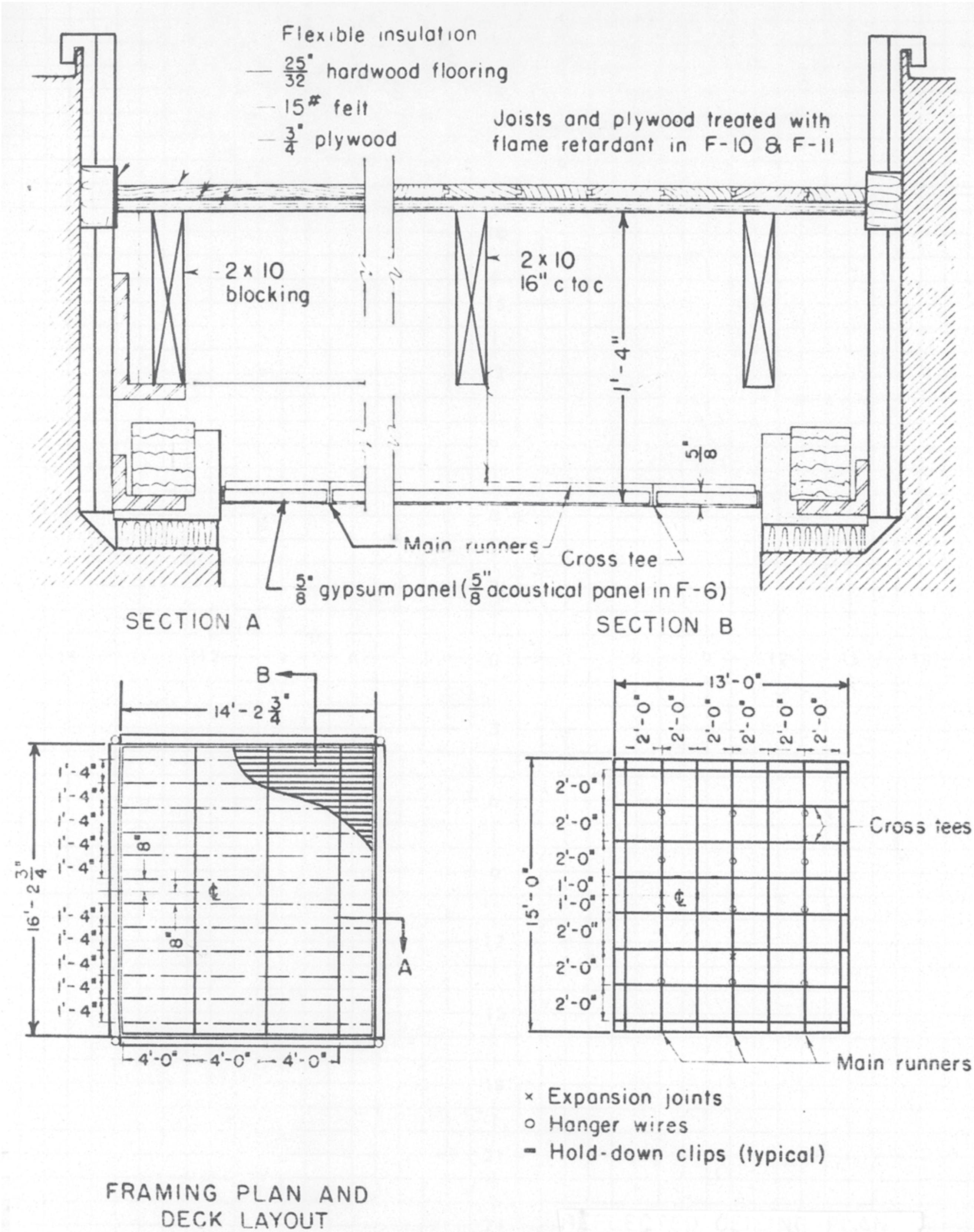


Figure 3 Construction Details for Assemblies F-8, F-9, F-10, and F-11

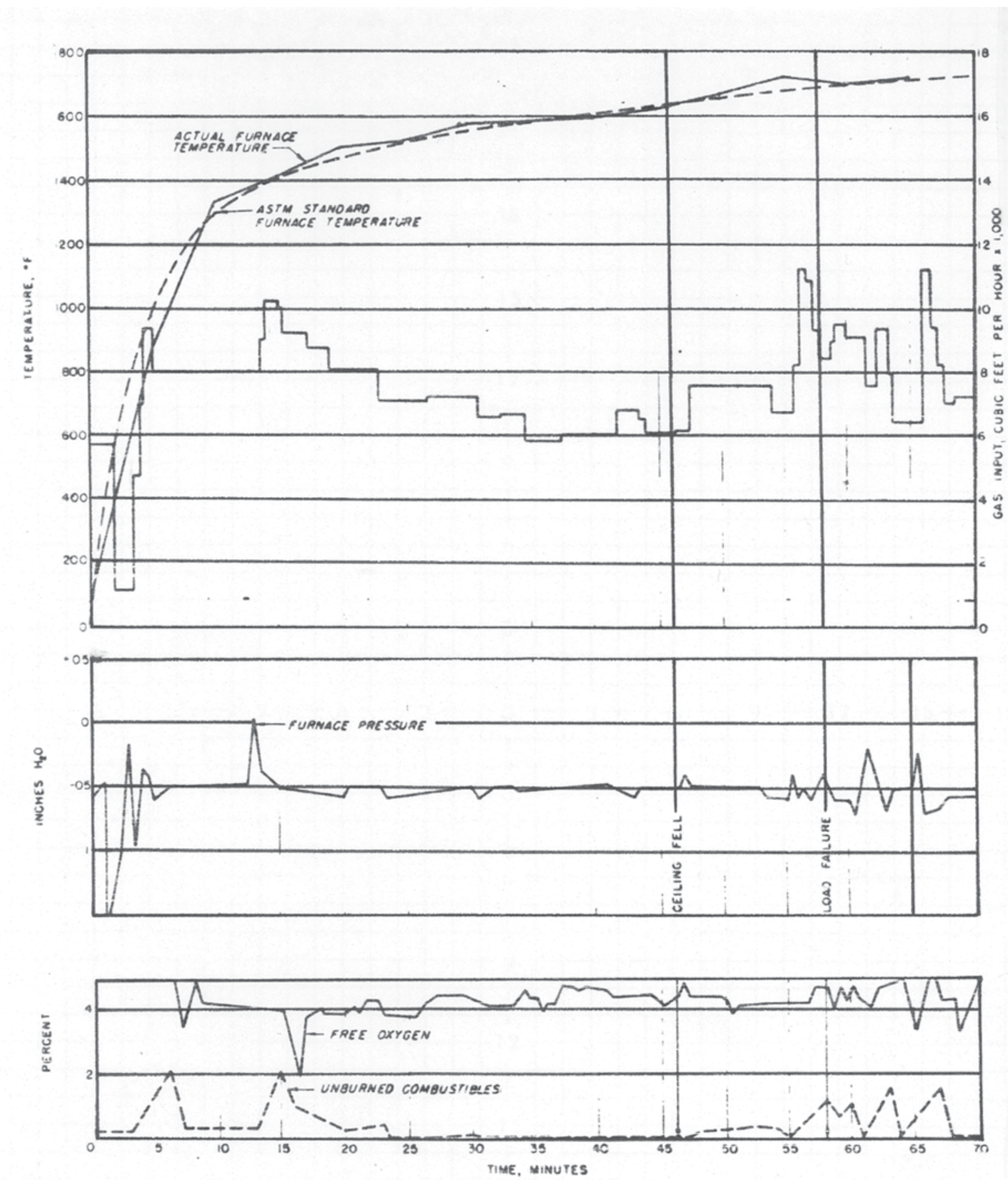


Figure 4a Furnace Test Data on Assembly F-1

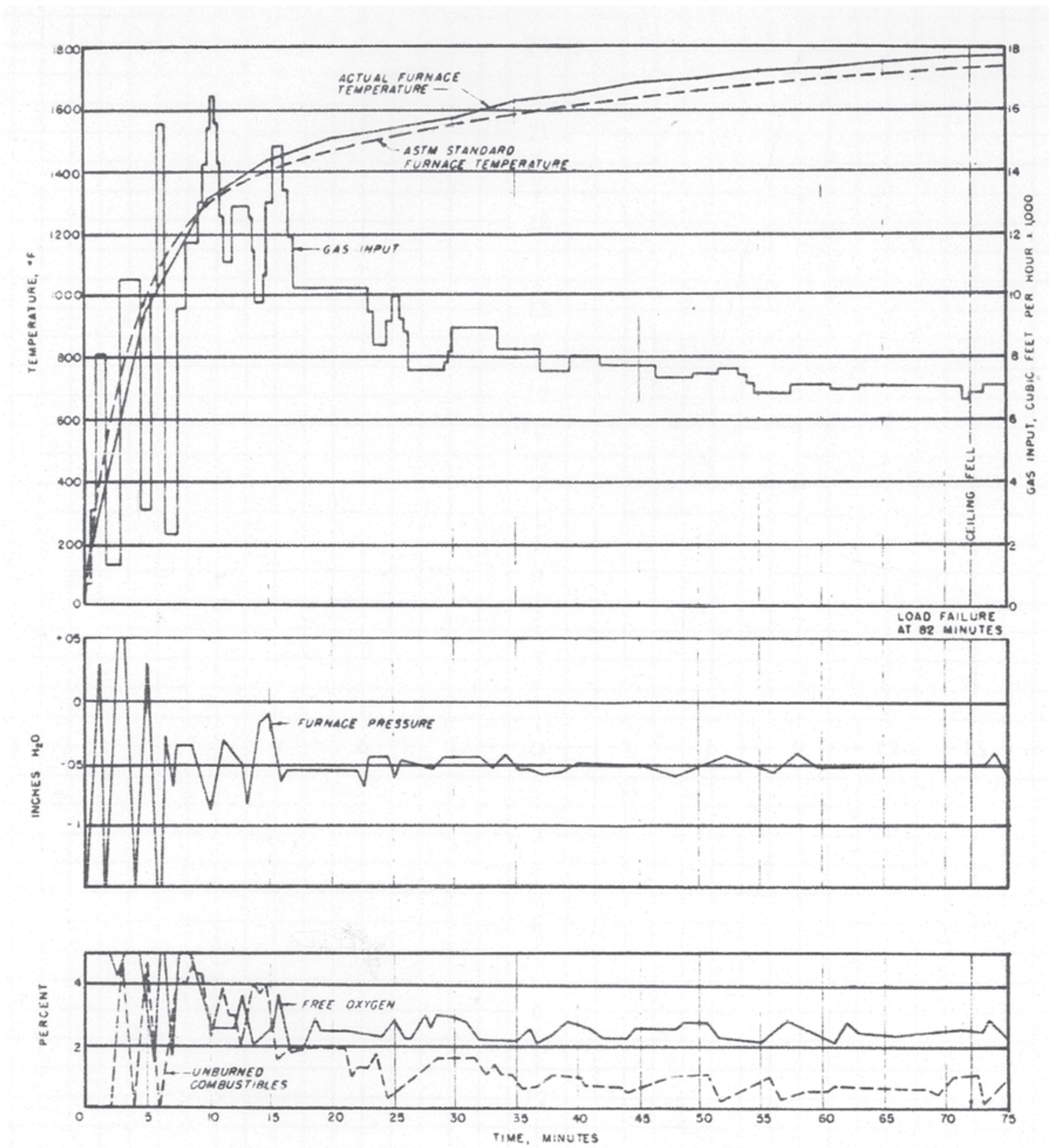


Figure 4b Furnace Test Data on Assembly F-2

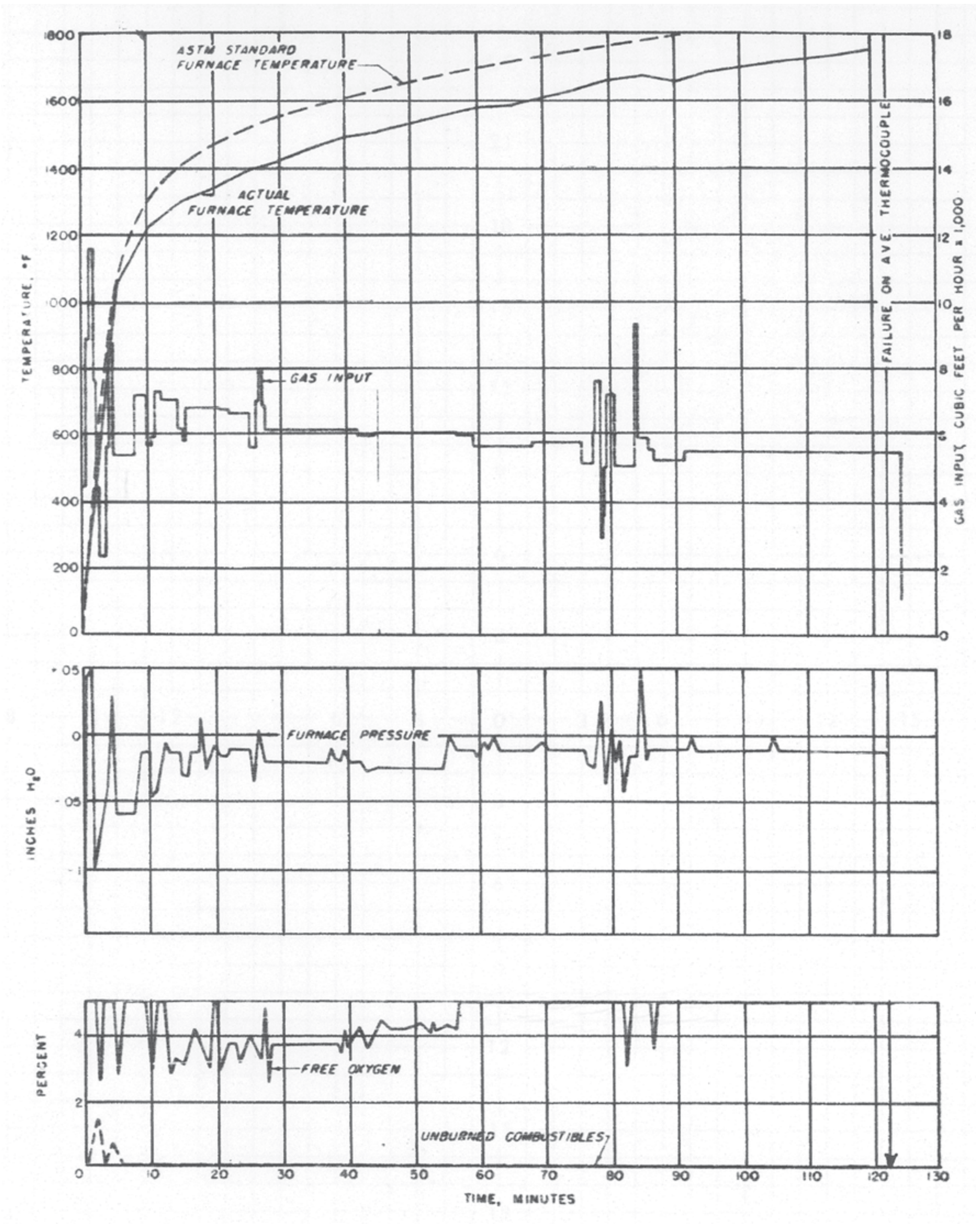


Figure 4c Furnace Test Data on Assembly F-3

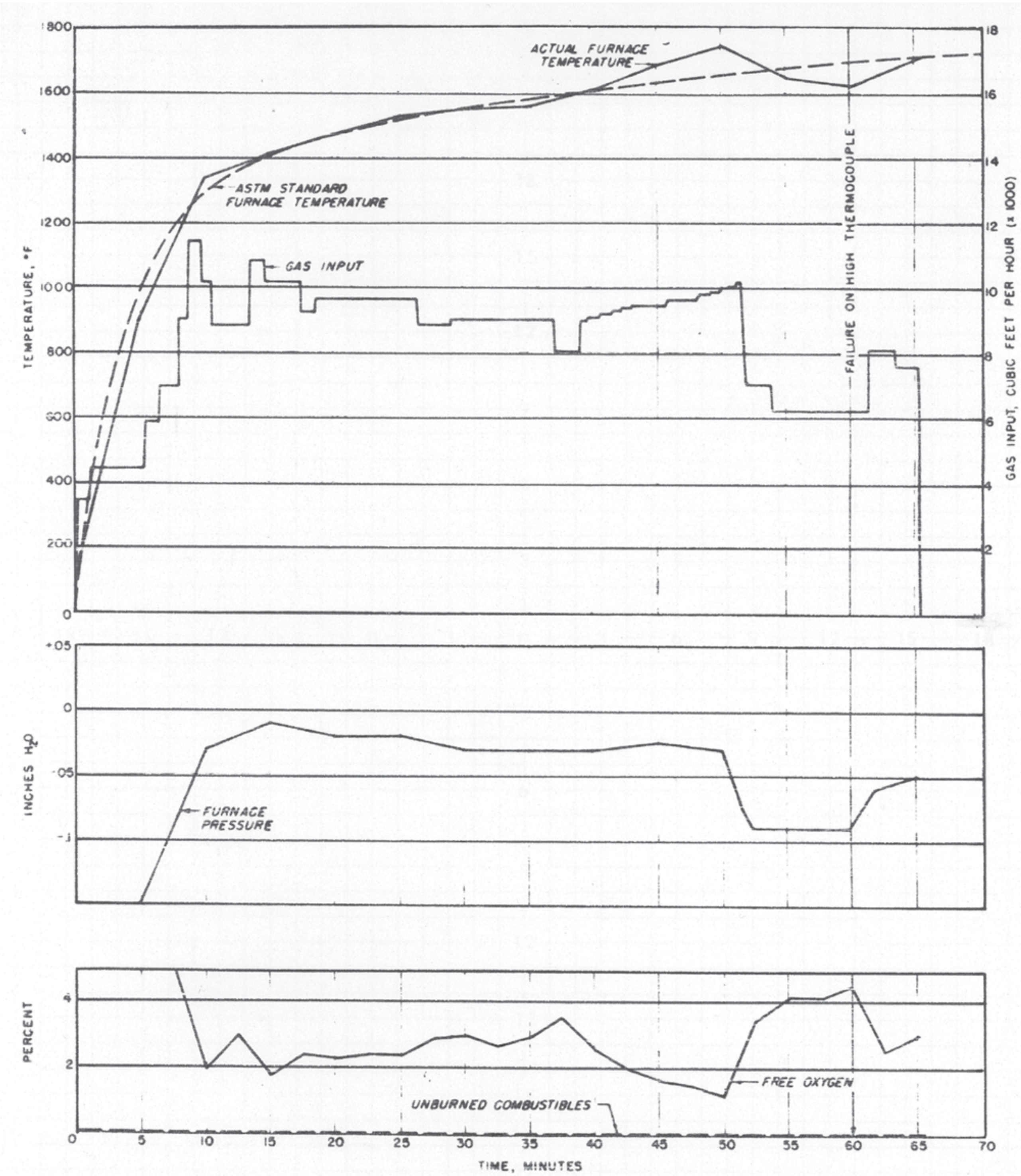


Figure 4d Furnace Test Data on Assembly F-4

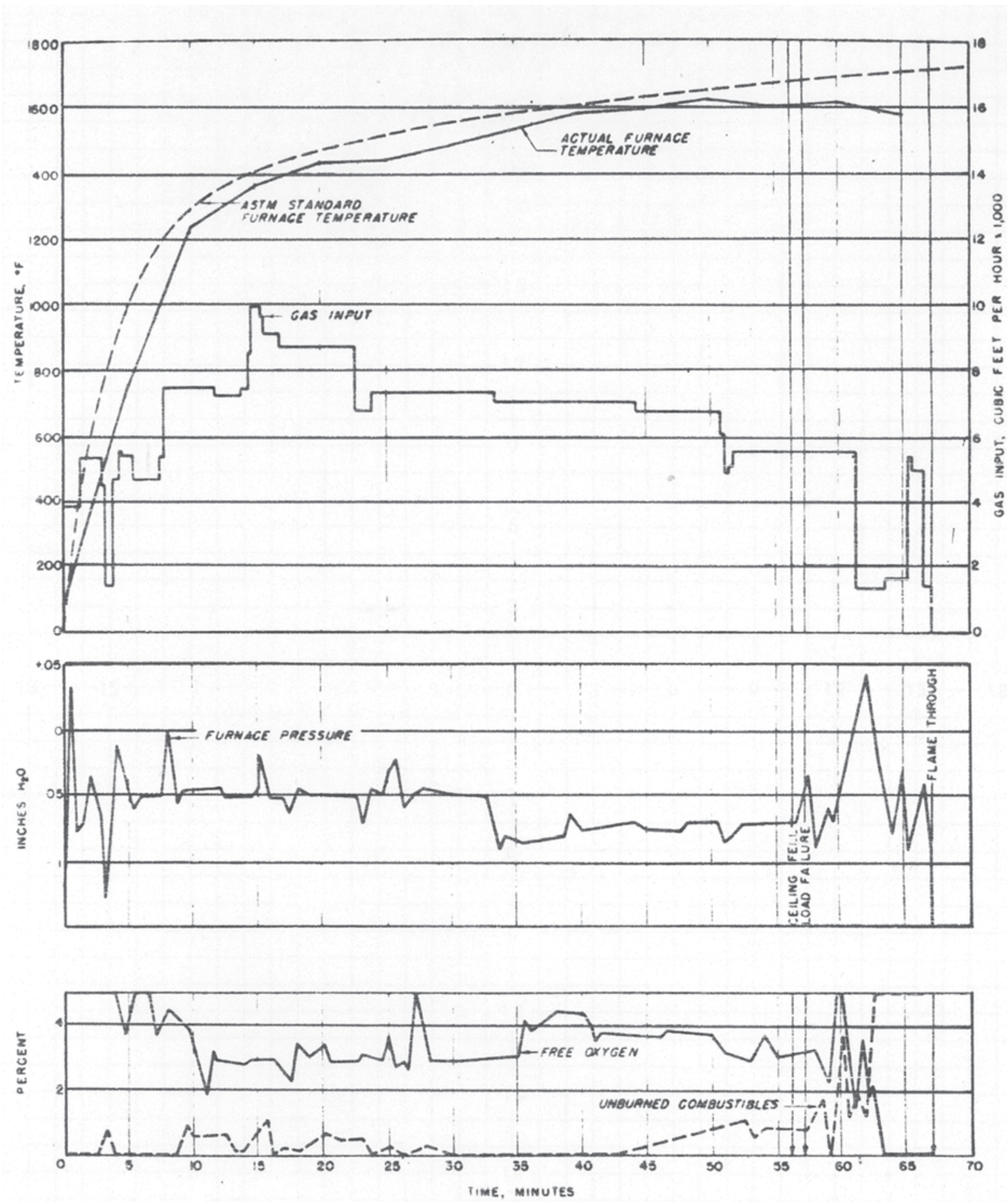


Figure 4e Furnace Test Data on Assembly F-8

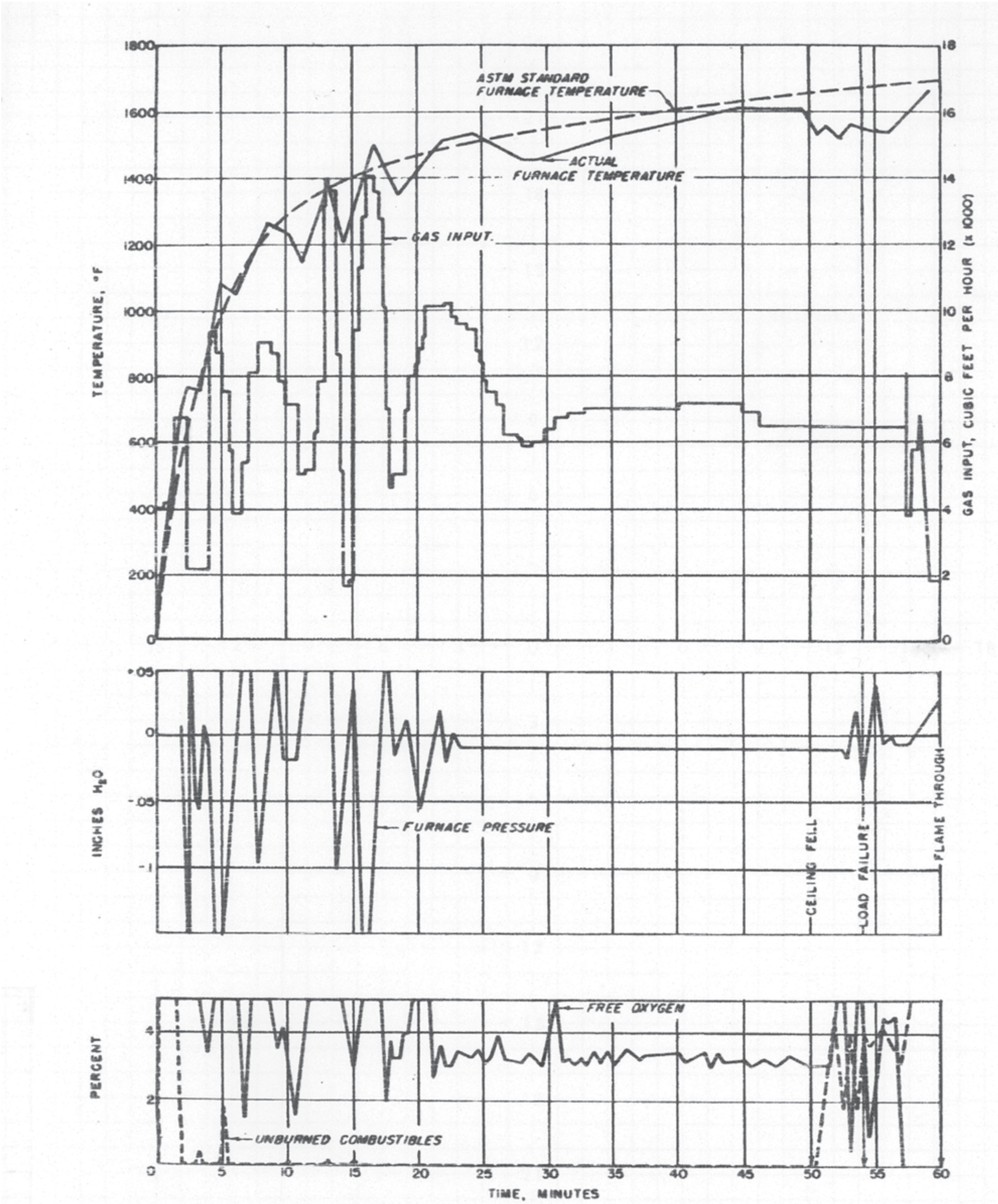


Figure 4f Furnace Test Data on Assembly F-9

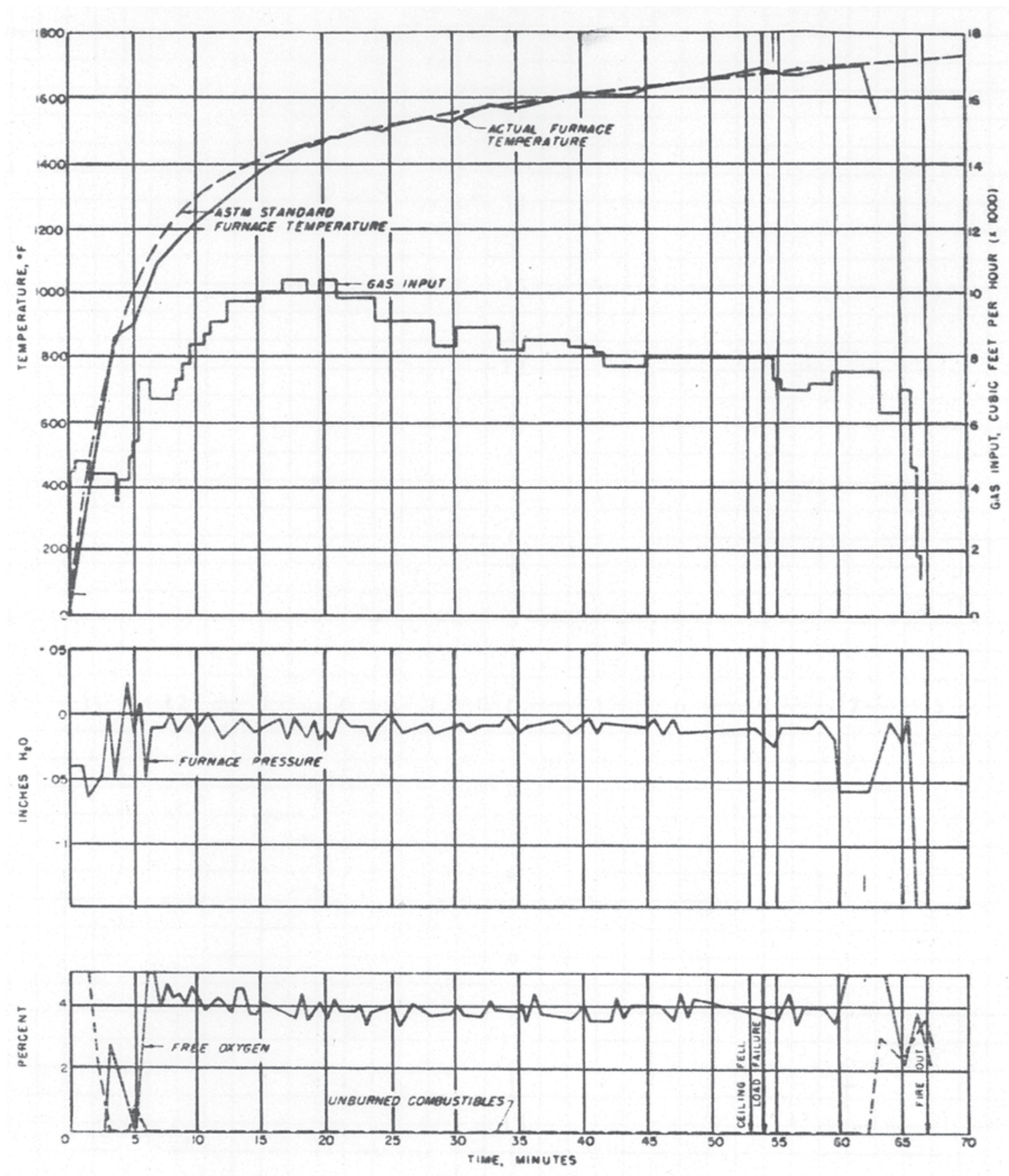


Figure 4g Furnace Test Data on Assembly F-10

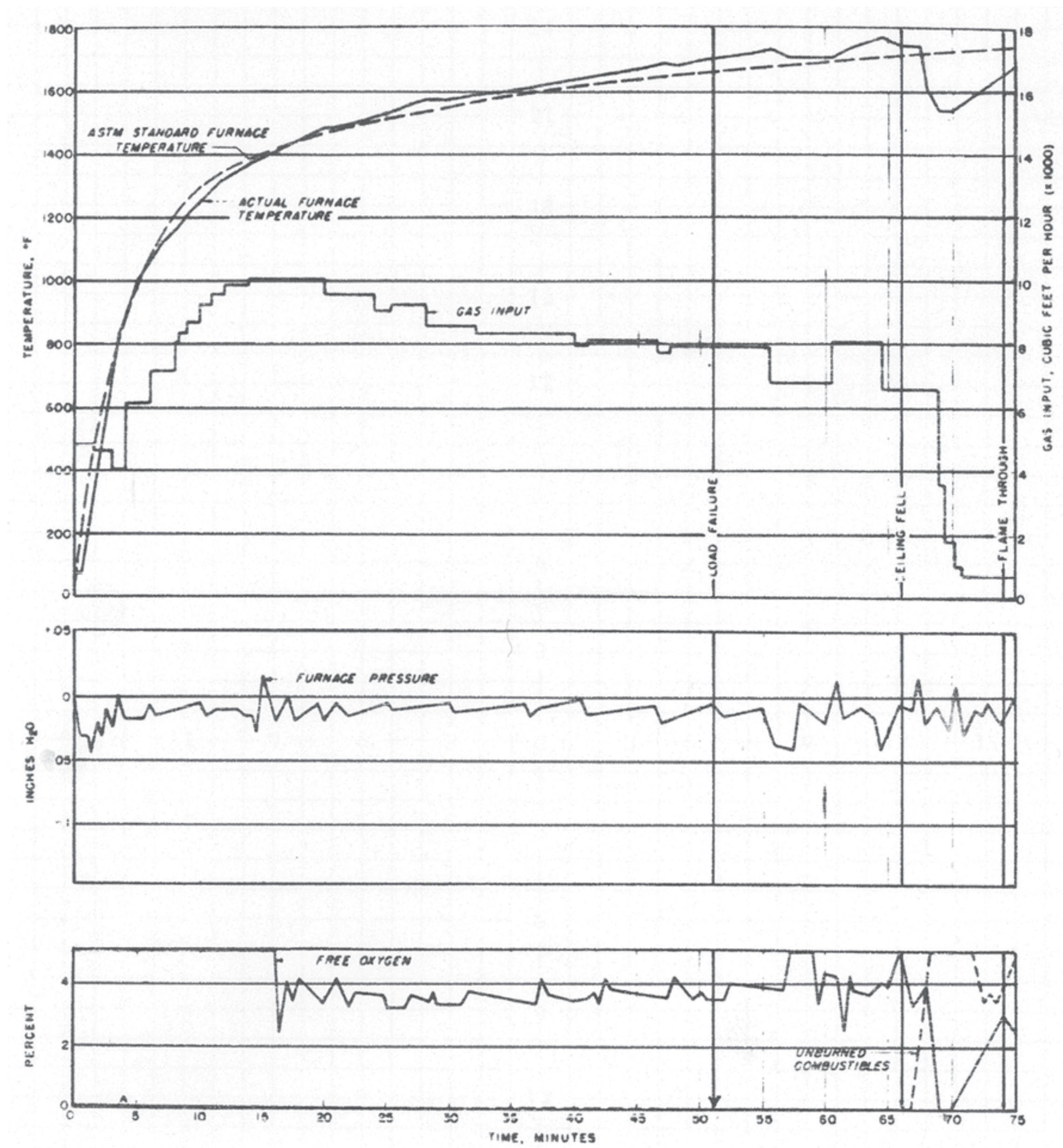


Figure 4h Furnace Test Data on Assembly F-11

FIG. 5

CUMULATIVE FUEL CONSUMPTION OF PROTECTED STEEL AND WOOD ASSEMBLIES

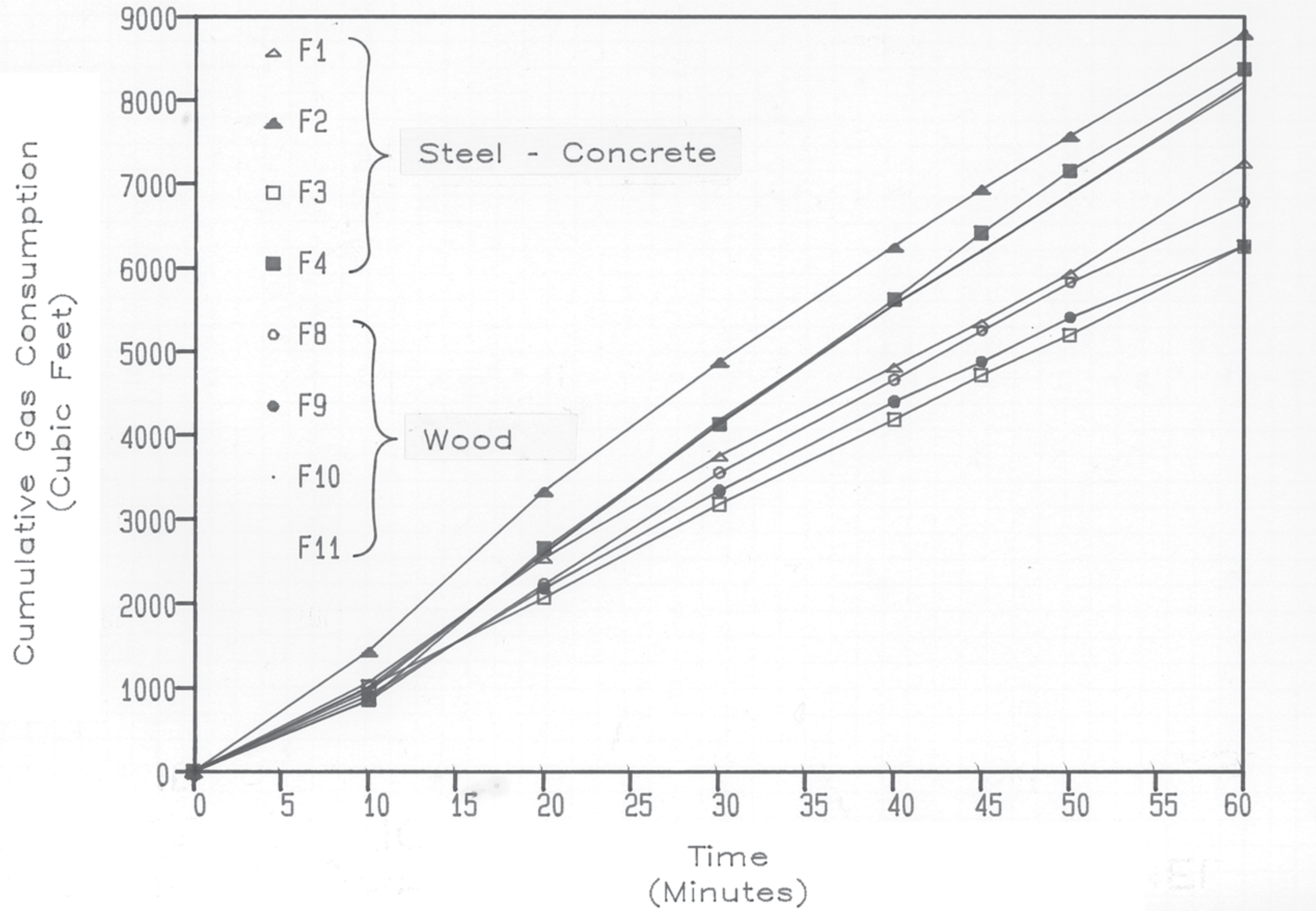
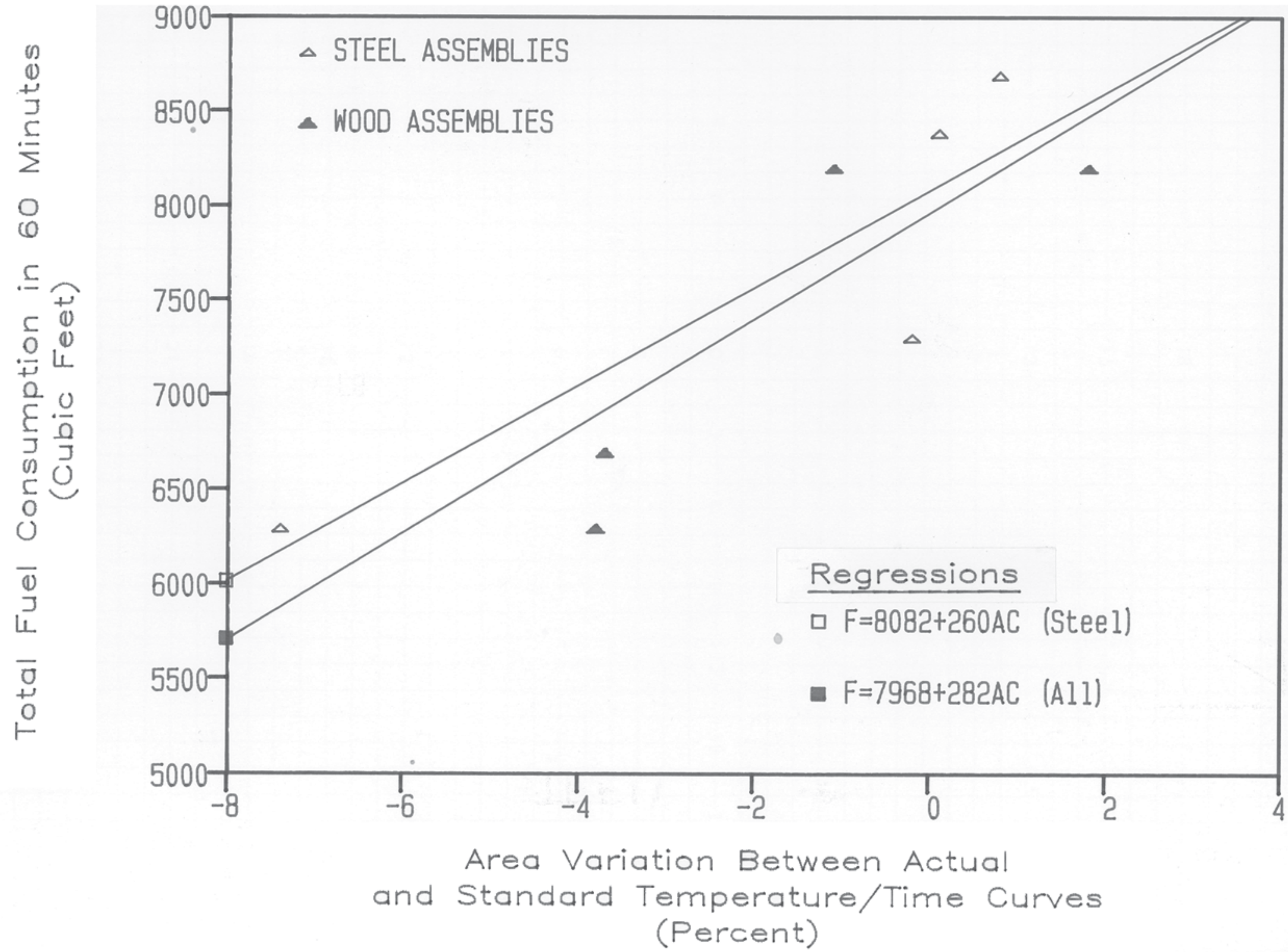


FIG. 6

RELATIONSHIP BETWEEN 60 MINUTE FUEL CONSUMPTION AND DIFFERENCE IN ACTUAL AND STANDARD TEMPERATURE/TIME AREAS



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