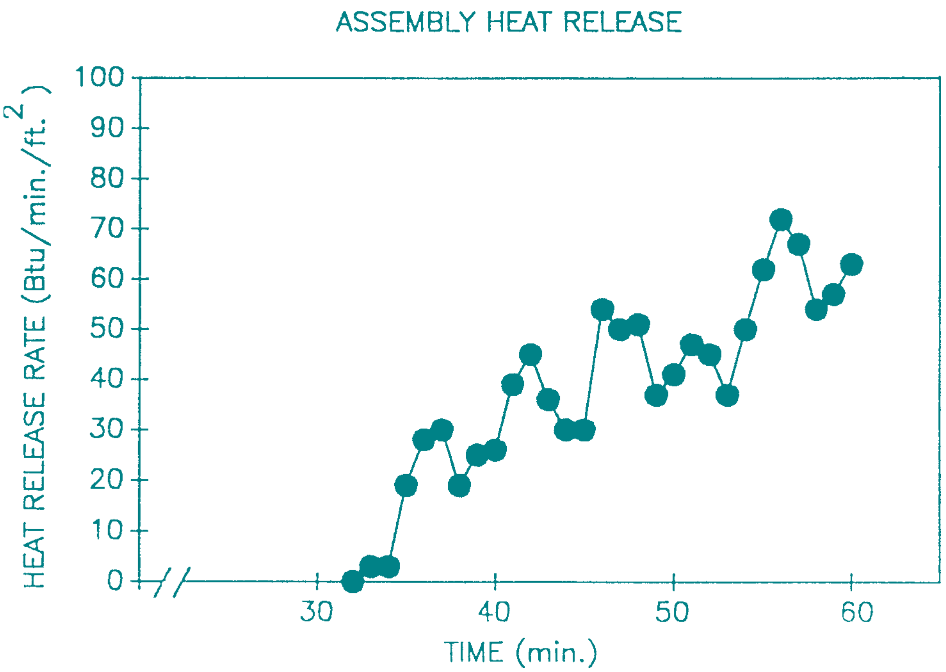
Heat Release Rates of Construction Assemblies



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INTRODUCTION***

Investigations of heat release rates of assemblies of wood and other construction materials complement studies of heat release rates of small samples of individual wood products.[1] Although small samples of a material (e.g. 0.2 to 2.0 sq. ft. in area) provide baseline heat release data for that material when exposed in a small-scale heat release rate calorimeter, the largest volume of wood products are used in assemblies containing materials of other types and in configurations different from those used in a small test. Thus consideration was given to possible methods of measuring heat release rates of full-scale construction assemblies, such as walls, floors and ceilings.

It was decided that the most informative approach to evaluating full-scale assemblies would be to use the substitution method for heat release measurements, as outlined in the Factory Mutual Construction Materials Calorimeter test procedure, in conjunction with the ASTM E119 standard fire endurance test.

The objective of the program was to extend heat-release-rate measurements to full-scale assemblies and, thereby, obtain improved evaluations of the fire performance of wood structural systems.

BACKGROUND

A procedure for measuring heat release rate based on the substitution method, the Factory Mutual Construction Materials Calorimeter, was described by Thompson and Cousins.[2] The test specimen used in this procedure is an interior finish material or model wall, roof or ceiling assembly of variable thickness having a surface area of 4.5 ft. by 5.0 ft. The specimen is mounted horizontally on the top of a furnace having a 4 ft. by 4 ft. opening and exposed for a specified time to the flames of a burner supplied with a liquid hydrocarbon fuel at a known and constant rate. A temperature/time (T/t) record is obtained for the test.

After the furnace has cooled to ambient temperature, an inert reference assembly is exposed to a fire from the same fuel. In the substitution run, the fuel is supplied at a rate which will duplicate the T/t curve for the previous test assembly. The rate of heat release of the latter assembly is calculated from the difference in fuel-flow rates of the reference and test assemblies and the heat of combustion of the fuel.

The foregoing substitution method of determining heat release rates was adapted to the fire exposure used in ASTM E119, Standard Method of Fire Tests of Building Construction and Materials.[3] In the E119 wall test, a 10 ft. by 10 ft. assembly is exposed in a furnace operated to maintain a prescribed standard T/t relationship. Therefore, the difference in the fuel rate required to maintain the standard T/t curve for a test assembly and that required to maintain the same curve for an inert or non-contributing reference assembly is the rate of heat contributed by the test assembly and detectable in the fire compartment. This methodology was employed to determine the heat released by wood-stud wall assemblies tested in this program. Steel-stud walls were used as the reference assembly. ****

The wall assemblies evaluated consisted of a number of preliminary steel-stud wall tests to establish the fuel measuring procedure and the range in fuel input rates required to maintain the standard T/t curve for successive runs of the same assembly; followed by matching tests of steel- and wood-stud walls to determine heat release rates for the latter. All wall assemblies were 10 ft. by 10 ft. made with one or two layers of gypsum board on both the fire exposed and unexposed sides, except that in one pair of steel and wood tests, gypsum board was applied only on the unexposed side. All fire tests were conducted without an external load on the assembly, as the purpose of the study was to evaluate fuel requirements rather than verify already established endurance ratings for standard assemblies.

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***The research described herein was conducted from 1976 to 1981 at the National Bureau of Standards under the direction of Dr. David Chamberlain, National Forest Products Association Research Associate.

**** A somewhat similar approach was used by Bletzacker, Lane and Denning [4] at Ohio State University in 1965-66 to compare the fire resistance of wood and steel floor-ceiling assemblies. In this work, the amount of fuel required to maintain the standard T/t curve was measured for a number of protected assemblies. However, it should be noted that excess oxygen was added during some tests. Heat release rates as such were not determined by the researchers.

Paired test and reference walls were carefully constructed so that they differed only in the material from which the framing was made. Construction and installation of these assemblies were carried out by the same personnel and according to a standard procedure. Elapsed time between the testing of paired test and reference walls was held constant and as short as possible to minimize environmental variables.

Fuel-Flow Measurement. A Technology, Inc., Model LFC-64 Mass Flow Meter was installed to measure fuel flow into the furnace. This meter was calibrated with a sample of natural gas over the range of 25 to 200 cubic feet per minute (cfm). Linear output voltage was recorded on a strip-chart recorder. Integration of the area under the flow-rate curve gave the total volume of gas consumed by the furnace for a particular time period. This type of mass-flow meter is sensitive to changes in the specific heat and density of the fuel gas.

During the course of this study, the gas supplier to the National Gypsum Research Corporation facility supplemented native natural gas with variable amounts of higher density imported middle-eastern gas and synthetic gas having a higher specific heat. To account for the effect of these gas mixtures, a Daniel Instrument Co. orifice meter was installed in series with the mass-flow meter. At regular intervals during each fire test, mass-flow and orifice meter readings were compared and the mass-flow meter strip-chart record was corrected by the average ratio of the two meter readings. The use of the orifice meter to measure fuel flow is discussed further under the **RESULTS AND DISCUSSION** section. A schematic of the furnace and fuel measuring devices used is shown in Figure 2.

Materials and Assembly Preparation. Preliminary fuel flow measurements were made on ten nominal reference wall assemblies. These assemblies, constructed and fire tested by the National Gypsum Research Corporation for product development purposes, were made of standard non-load bearing steel studs covered on both faces with two layers of ½ in. experimental gypsum board. Except for possible differences in the thermal properties of the proprietary gypsum board used, the materials and construction methods used in each of these ten tests were the same.

Five reference wall assemblies, two unpaired and three paired with wood test wall assemblies, were tested. These reference assemblies were made of non-load bearing nominal 2 in. by 4 in. by 10 ft. steel studs spaced 24 in. on center with one layer of $^{5}/_{8}$ in. Type X gypsum board on each side. The three wood test walls were made with nominal 2 in. by 4 in. by 10 ft. fire retardant treated southern pine studs spaced 16 in. on center with the same $^{5}/_{8}$ in. Type X gypsum board protection as used in the reference walls (similar to Underwriter's Laboratories approved Design No. U305 in layout only). Wood walls had mid-height blocking, and single top and double bottom plates made of the same treated 2 in. by 4 in. material as used for the studs. All lumber used was from the same production lot and was pressure treated and redried by the same treating chemical manufacturer. Treated wood framing and gypsum board was conditioned at 70°F and 50% relative humidity prior to assembly. All gypsum board used in the five reference and three wood test assemblies was from the same production lot.

One pair of unprotected wall assemblies was also tested to determine the sensitivity of the substitution method for measuring heat release rates. Each wall in this series was unprotected on the fire exposed side. The unexposed side of each assembly consisted of a double layer of $^{5}/_{8}$ in. Type X gypsum board with lapped joints. A horizontal steel bar support on the exterior of the wall was used to assure the integrity of these assemblies during fire test. Studs, plates and blocking in the wood wall test of this series were 2 in. by 4 in. untreated southern pine.

Reference and wood wall test assemblies were constructed according to standard recommended design, fastening, spackling and taping procedures appropriate for 1-hour rating performance. Completed assemblies were installed in the furnace specimen frame 16 to 20 hours before fire testing to allow sufficient time for the cement mortar seal to dry.

Fire Exposure. Fuel flow measurements were taken in addition to those required by ASTM E119. Special care was taken to maintain the actual temperature in the furnace at the level specified in the standard for each time period in the test. A comparison of actual with standard T/t curves showed that the fire exposure history of each test was well within E119 limits.

OTHER HEAT RELEASE CALCULATION METHODOLOGIES

Weight and Heat of Combustion Method of Estimating Heat Release. The total heat released by the burning of the wood framing in the assembly during the test can also be estimated from the initial and final weights and fuel values of the original and recovered wood and the recovered char residue. Prior to wall assembly, the weight and moisture content of the wood framing in each wall was measured. Following each fire test, the wall was disassembled and the wood and char were separated from nails, gypsum board and other residues. The char was scrapped from unburned wood and these two residues were weighed and sampled for moisture content. The heats of combustion of unburned wood and char were determined using a Parr oxygen bomb calorimeter. The heat released by the wood framing during the fire exposure was estimated as the difference between heat available at the beginning of the test and that remaining after the test had been terminated and the assembly disassembled.

Oxygen Consumption Method of Measuring Heat Release. Attempts were made to measure heat release by the oxygen consumption method.[5] The results were not satisfactory because of difficulties encountered in measuring flow rates of gaseous products in the furnace stack. These difficulties resulted from the very complex stack geometry at the National Gypsum facility and the irregular flow patterns that resulted from that geometry.

RESULTS AND DISCUSSION

Fuel Flow Measurement. As previously described, initial fuel measurements were made with a mass flow meter calibrated with 100% natural gas. As the mass flow rate is inversely proportional to the product of density and specific heat of the gas, the meter may be recalibrated for a different gas mixture if the specific heat and density of the calibration and new gas mixture at standard conditions of temperature and pressure are known.

After the mass flow meter was installed in 1975, discrepancies in flow-rate data led to the discovery that the chemical composition of the fuel was varying, often from day to day. Although attempts were made to adjust the meter calibration constant for each composition, this proved unreliable because composition data were available from the gas supplier only on an irregular basis.

As noted earlier, an orifice meter, which is much less sensitive to changes in specific heat and density than the mass flow meter, was installed in series with the later to obtain an on-line correction for any changes in gas composition that occurred during and between paired tests. Differential pressures were read at intervals throughout a fire test and the ratio of the orifice to mass flow meter rate was determined for each of these instantaneous readings. The average value of such ratios for a test was used as the correction factor for the continuous flow rate record of the mass flow meter.

As the project progressed, the uncertainty in the gas composition data served to emphasize uncertainty in the fuel flow-rate data. It was concluded that the orifice meter alone would provide the most reliable measurements and, therefore, all flow-rate data obtained after the orifice meter was installed were recalculated using an orifice meter equation recommended by the American Gas Association.[6] Use of this equation, described in Appendix A, permitted more accurate adjustment of flow rate measurements for daily variations in atmospheric pressure, upstream line pressure and specific gravity of the gas than that provided by the manufacturer's correction charts.

Furnace Temperature Measurement. It should be noted that the ASTM E119 standard does not prescribe specific construction details for test furnaces, but rather sets forth the operating and performance conditions that must be met. Therefore, although the general features of furnaces are common[7], specific design details do differ. The effect of furnace design on fire endurance test results has been considered by Siegel.[8] He concluded, among other things, that "the total intensity of fire exposure maintained in the ASTM Method E119 furnace is not affected seriously by furnace design so long as the thermocouples that control and indicate furnace temperature have approximately the same exposure as the specimen being tested".

One of the factors affecting furnace performance is the construction of the thermocouple itself. The E119 standard specifies thermocouples to be encased in ½ in. standard iron pipe. Siegel has estimated that the thermal lag (time constant) associated with this thermocouple assembly is 0.9 to 9 minutes, depending upon furnace temperature, rate of temperature rise, flow of gases around the thermocouple, and opacity of the flame surrounding the thermocouple. He concluded that the greatest thermocouple lag will occur during the first five minutes of a fire test and that the lag will be negligible after 30 minutes.

The foregoing assessments further support use of the substitution method to determine heat release rates of protected wood assemblies, particularly when reference and test assemblies are tested in the same furnace at approximately the same time. It should be noted that fuel consumption values in this report represent the heat released into the furnace by the primary fuel (natural gas) in order to maintain the standard T/t relationship. Additional fuel in the form of paper facing on the gypsum board protection was introduced during each wood and steel test. The heat released from this source is considered identical for both test and reference assemblies and therefore is not a factor in the determination of heat release by the substitution method.

Preliminary Wall Tests. Fuel consumption data for the ten experimental walls made of steel studs and two layers of ½ in. gypsum board on both sides are given in Table 1. Values shown for runs 1 through 5 are based on mass flow meter readings adjusted for gas composition. Values based on orifice meter readings adjusted using the American Gas Association equation are also shown for run 5 and for runs 6 through 10. Data tabulated include the average fuel input rate in Btu/min. for successive 15-minute intervals throughout the fire test; the total fuel consumed during each 15-minute period; and the cumulative fuel consumed at the end of each of these periods. Mean, standard deviation and coefficient of variation for each of these values are given for the mass flow meter and orifice meter data separately.

The general pattern of fuel consumption is the same in the ten tests. The initial 15-minute rate is exceeded during the second 15-minute period by 10 to 30 percent, which is to be expected from the nature of the standard T/t curve. From 30 minutes to the end of the exposure at 90 minutes, the rate decreases to a value similar to the initial rate.

It can be seen from Table 1 that fuel input values did not change appreciably from day to day. On the average, the orifice meter fuel input rates and cumulative totals are somewhat larger than those for the mass flow meter, and also less variable. At 60 minutes, the cumulative fuel input for five runs based on the mass flow meter ranged from 4,527,000 to 5,169,000 Btu, or -8 to +5 percent; and for six runs based on the orifice meter ranged from 5,026,000 to 5,418,000 Btu, or -3 to +4 percent. The lowest value in each set is for the assembly test common to both, run 5. As discussed previously, the orifice meter data are considered the most reliable.

The fuel consumption rate data for the 46 to 60 minute period show a similar trend. Values for the five mass flow meter runs ranged from 74,150 to 84,300 Btu/min. or -6 to +7 percent; whereas those for the six orifice meter runs ranged from 81,760 to 86,820 Btu/min. or -3 to +3 percent.

The possibility that temperature and/or relative humidity might account for the variation observed in fuel consumption was investigated. Total fuel used in the first 15 minutes and the first 60 minutes of test for runs 1 through 9 are shown in Table 2 with the outdoor temperature and relative humidity for the dates[9] these tests were run.

The wall test furnace at the National Gypsum Research Corporation facility is located in a large building that is maintained at about 70°F during cold weather. Thus, outdoor air temperature would not be expected to affect the fuel requirements of the furnace. Moderate changes in indoor relative humidity also are not expected to affect fuel consumption. Specific heats of air and water vapor are approximately, 0.25 and 0.45 Btu/lb/°F respectively. Assuming a maximum indoor relative humidity of 75%, and a vapor pressure of water at 70°F of 19 mm Hg, the total volumetric water concentration would be

$$\frac{\text{19mm v.p. } H_20}{\text{760 mm total pressure}} \times 0.75 = 0.0188$$

for a maximum of 1.9 percent. The additional heat requirement due to water vapor replacing air thus would be expected to be negligible.

The foregoing analyses are supported by the data in Table 2 which show no apparent correlation between outdoor temperature and relative humidity with fuel consumption.

Steel-Stud Reference Assemblies. Fuel consumption data for five standard steel-stud reference wall assemblies are given in Table 3. These assemblies were constructed with one layer of $^5/_8$ in. Type X gypsum board on each face. Two of the reference walls, not paired with wood assemblies, were tested two days apart to determine the variation that might be expected when a steel reference and paired wood test assembly were tested in the same time interval. The three remaining reference assemblies were paired with wood test walls and were tested two days before or after the latter. All assemblies were tested between 1978 and 1981.

As can be seen from Table 3, the five reference assemblies as a group exhibited substantially more variation in fuel consumption than was observed with the preliminary wall tests. For example, the coefficient of variation of the average fuel input rate of the five reference walls during the first 15 minutes of fire exposure was 15.1 percent compared to a value of 5.1 percent (orifice meter data) for the preliminary tests. The same trend is shown in cumulative fuel input values. The coefficient of variation in total fuel used at 60 minutes for the five reference walls was 11.2 percent compared to 2.1 percent (orifice meter data) for the preliminary test walls.

The greater variability in the fuel consumption data of the five standard reference assemblies is due in part to the high values obtained for the 1981 test relative to the values for the other tests that were run in 1978 and 1979. For example, values of total fuel consumed at 60 minutes for all five runs ranged from -0.8 to +17.2 percent of the average, whereas excluding the 1981 run reduced this range to -6.9 to +10.2 percent. No reason for the difference between the 1981 and earlier runs could be identified.

Fuel input values for the two reference assemblies that were tested two days apart were very similar. The cumulative fuel input values for these two runs at 60 minutes were 4,310,000 and 4,501,000 Btu, or a difference of 4.4 percent. Average fuel consumption rates for the 46 to 60 minute period were 75,570 and 79,100 Btu/min., or a difference of 4.7 percent.

The fuel consumption data for the five reference assemblies indicated that a wood wall test assembly should be paired with a steel reference assembly tested at about the same time to obtain maximum sensitivity from the substitution method of measuring heat release of protected assemblies.

Unprotected Wall Assemblies. Fuel consumption data for the steel-stud and wood-stud walls made without protection on the fire-exposed side and with two layers of $^{5}/_{8}$ in. Type X gypsum board on the unexposed side is given in Table 4. The two assemblies were tested two days apart. During the 60 minute test period, the unprotected wood framing was completely consumed while the steel framing was severely deformed.

Total fuel consumption at 60 minutes was 3,894,000 Btu for the wood assembly and 5,702,000 Btu for the steel assembly, a difference of 1,808,000 Btu or 31.7 percent. The percent differences in fuel consumed from 0 to 15, 16 to 30, 31 to 45 and 46 to 60 min. between the wood and steel assemblies were 28.5, 43.5, 26.3 and 27.7 percent, respectively. These differences reflect, at least in part, the heat contributed by the wood during the test.

The framing in the wood assembly weighed 144 lb. prior to test. Assuming a 10 percent moisture content and a net heat of combustion of dry wood of 8,500 Btu/lb., the total heat released by the wood consumed during the 60 minute test is calculated to be 144/1.10 x 8500 = 1,113,000 Btu. This is significantly less than the 1,808,000 Btu obtained by the substitution method, assuming that heat losses through the unexposed face of the two assemblies were the same. The fact that during the last 15 minutes of the test, when the wood would be expected to be already fully consumed, the fuel input to the steel assembly (1,528,000 Btu) was notably greater than that for the wood assembly (1,105,000 Btu) suggests that the assumption of equivalent heat loss may not be appropriate. Further, the fact that fuel consumption values for the unprotected steel assembly were higher than those observed for any of the five standard reference steel assemblies after the first 15 minutes of test, and that the total fuel consumed in 60 minutes for this test was 18 percent higher than the comparable average value for the five reference walls, also raises a question about heat loss differences between the two unprotected assemblies.

Relative to the average fuel consumption of the standard reference steel assemblies having one layer of gypsum board protection on both sides, the unprotected wood wall had a total heat release by the substitution method of 4,830,800 3,894,000, or 936,800 Btu. This is much closer to the heat release value of 1,113,000 Btu calculated by the weight and heat of combustion method.

Whether comparing the unprotected wood wall to its paired unprotected steel assembly or the average of the standard protected reference assemblies, it is evident that the substitution method can detect significant amounts of heat that are contributed to the furnace chamber by an assembly itself.

Wood-Stud Test Assemblies. Fuel consumption data for protected wood wall test assemblies made with fire-retardant treated southern pine framing are shown with comparable data for paired steel-stud reference assemblies in Table 5. It can be seen from this Table that fuel consumption rates for the wood walls follow the same trend as those for the reference walls, reaching a peak between 15 and 30 minutes and then decreasing during each of the two remaining 15-minute periods. It is in the 16-60 minute period that heat from pyrolysis of the wood framing is expected to be at a maximum. Observed behavior, in general, was consistent with this expectation, with the average rate of fuel consumption for the three wood wall tests in the 46-60 minute period being -6.8, -8.4 and +1.2 percent that of the paired reference steel assembly.

The summary data in Table 5 show that the mean fuel input values for the reference assemblies in each of the first three quarters of the test were slightly lower than those for the wood test assemblies, the reverse of what might be expected if the wood framing members were contributing heat to the furnace in these periods of the test. However, these differences were only 0.4, 1.8 and 0.1 percent, insignificant relative to the accuracy of the methodology. Also from the summary data of Table 6 it can be seen that the variability in average rate of fuel input for a period and in cumulative fuel input for the wood tests consistently exceeded that of the reference assemblies.

Net total heat released to the furnace from each wood assembly based on the substitution method and the paired steel reference assembly is shown in Table 6. These data show that the net heat released by the wood test assemblies during the 60 minute test period and measured in the furnace was 3.5, 1.3 and -2.8 percent of the paired reference assemblies for the 1978, 1979 and 1981 tests respectively. These values appear to be within the limits of reproducibility of the substitution method.

The data of Tables 3 and 5 are shown graphically in Figures 3 through 10. In these figures, the one minute average fuel input rate is plotted against time for each of the five steel reference wall tests and the three wood wall tests. Also shown in Figures 3 and 4 (paired steel reference tests) and Figures 7 through 10 (paired steel and wood tests) is a plot of the percent coincidence between the actual and the standard T/t curve. From these figures it can be seen that the deviation of the actual curves from the standard curve is negligible and does not represent a source of error in net heat release values of the wood assemblies. The deviation of T/t curves was obtained by graphic integration of the area under actual and standard curves. The method used to determine T/t curve areas is discussed in Appendix B.

Weight and Heat of Combustion Calculations for Wood Test Walls. Total heat released by combustion of the wood framing in the 1979 and 1981 wood assembly tests as determined by the initial weight of the wood and the weight of residual wood and char is given in Table 7. This methodology assumes that heat released by the wood in the assembly is a result of complete combustion into carbon dioxide and water vapor.

It can be seen from Table 7 that of 1,272,000 and 1,376,000 Btu of total heat available in the framing of the 1979 and 1981 test assemblies, 207,000 and 327,000 Btu respectively, or 16 and 24 percent, is calculated by the heat balance procedure to have been released during the test. This calculated total heat released represents 4.6 and 5.6 percent of the total external fuel required to maintain the standard T/t curve in these two tests and is greater than the heat contributed by these assemblies that was measured in the furnace by the substitution method (1.3 and -2.8 percent).

Several factors taken together would seem to account for a large part of the difference between the heat balance and substitution method results. First, although the fuel supply to the furnace was shut off at 60 minutes, glowing combustion of char in the fire retardant treated studs was not fully quenched until 10 to 15 minutes later. At the end of the exposure period, the test wall was removed from the furnace and the surface quenched with a minimum amount of water. Gypsum board on the exposed side was then removed and the studs further quenched with water. Because the char was essentially intact as a result of the fire-retardant treatment, extinguishment of glowing combustion took the extra time noted above. Thus, additional heat was released from the wood framing after the test that was accounted for by the weight of residual wood and char in the heat balance computation but which was not available to be measured in the substitution method.

Secondly, the assumption in the heat balance computation that all the weight loss of the wood framing during the test is a result of complete combustion of the treated wood to carbon dioxide and water vapor represents an error of unknown magnitude. The fact that recovered char represented approximately 42 percent of the weight of total recovered residue, and considering that char formation is endothermic and indicative of incomplete combustion, suggests the error could be significant.

Also, the heat released by combustion into carbon monoxide and water vapor is appreciably less than that from combustion into carbon dioxide and water vapor. A build-up of carbon monoxide in the cavity would be expected to occur if the oxygen supply is inadequate and the gypsum board effectively prevents or retards the gas from moving into the furnace where sufficient oxygen is present to convert it to carbon dioxide. Analyses of gas samples taken from the cavity of a protected wood assembly during an E119 test conducted in a separate study showed that an increase in carbon dioxide concentration from 14 to 20 percent occurred between 15 and 50 minutes of the test. The concentration of carbon monoxide increased from 1 to 6 percent over the same period; indicating that inadequate oxygen and the gypsum board barrier were preventing the complete combustion assumed in the heat balance computation.

Further, it should be noted that dehydration of cellulose to char can occur without the formation of either carbon dioxide or carbon monoxide and thus without any heat being released. Whether or not conditions in the cavity of the assembly during test are such as to permit this type of reaction at any point is unknown.

Thirdly, some of the heat released from the wood framing replaces heat from the furnace fuel required to vaporize the moisture in the wood members prior to combustion. Such heat loss is not part of the heat balance computation but is reflected in values obtained by the substitution method.

In view of these observations and considerations, the difference between the heat release values determined by the heat balance computation and those based on the substitution method do not appear unreasonable.

SUMMARY

Heat-release-rate measurements were extended to fire tests of full-scale wall assemblies using the substitution method. Through use of the methodology, which involved comparing fuel input rates required to maintain a standard fire exposure for a wood-stud wall assembly with those required to maintain the same exposure for a reference steel-stud wall assembly, information on the heat release performance of wood wall systems was obtained.

It was found that the heat released from protected wood wall assemblies, made of fire retardant treated framing and $^5/_8$ in. Type X gypsum board, and detectable during a 1-hour ASTM E119 fire test, was so low as to be within the limits of experimental error. Based on tests of three wood assemblies and three paired steel reference assemblies, heat released from the wood members and detectable in the fire compartment ranged from +3.5 to -2.8 percent of the total external fuel required to maintain the standard temperature/time fire exposure.

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Table 1. Fuel Input for Preliminary Steel-Stud Wall Assembly Tests

				Fuel supplied to furnace [1] Average rate for period, 1000 Btu./min. (Total for period, 1000 Btu) Cumulative, 1000 Btu					
Run Number	**Date**	**Meter Type**	**Gypsum Board Joints**	**0-15 min.**	**16-30 min.**	**31-35 min.**	**46-60 min.**	**61-75 min.**	**76-90 min.**
1	3/76	Mass Flow [2]	Sealed	76.46	81.79	79.17	74.59	70.10	70.10
				(1147)	(1227)	(1188)	(1119)	(1052)	(1052)
				1147	2374	3562	4681	5733	6785
2	3/76	Mass Flow	Unsealed	78.46	102.83	82.87	74.15	72.37	74.15
				(1177)	(1542)	(1243)	(1112)	(1086)	(1112)
				1177	2719	3962	5074	6160	7272
3	3/76	Mass Flow	Unsealed	85.90	92.54	84.59	81.51	83.75	89.92
				(1289)	(1388)	(1269)	(1223)	(1256)	(1349)
				1289	2677	3946	5169	6425	7774
4	4/76	Mass Flow	Unsealed	80.88	91.24	87.82	84.30	80.88	87.20
				(1213)	(1369)	(1317)	(1265)	(1213)	(1308)
				1213	2582	3899	5164	6377	7685
5	10/76	Mass Flow	Unsealed	68.54	77.11	78.06	78.06	74.26	72.35
				(1028)	(1157)	(1171)	(1171)	(1114)	(1085)
				1028	2185	3356	4527	5641	6726
5	10/76	Orifice [3]	Unsealed	75.68	85.78	86.82	86.82	86.82	80.73
				(1135)	(1287)	(1302)	(1302)	(1302)	(1211)
				1135	2422	3724	5026	6328	7539
6	11/76	Orifice	Unsealed	83.99	95.99	83.99	82.89	79.19	79.19
				(1260)	(1440)	(1260)	(1243)	(1188)	(1188)
				1260	2700	3960	5203	6391	7579
7	11/76	Orifice	Unsealed	80.72	100.90	92.79	86.76	83.74	79.68
				(1211)	(1514)	(1392)	(1301)	(1256)	(1195)
				1211	2725	4117	5418	6674	7869
8	11/76	Orifice	Sealed	80.47	96.47	83.31	82.74	79.43	75.64
				(1207)	(1447)	(1250)	(1241)	(1191)	(1135)
				1207	2654	3904	5145	6336	7471
9	11/76	Orifice	Sealed	73.54	86.32	100.03	81.76	81.96	78.11
				(1103)	(1295)	(1500)	(1226)	(1229)	(1172)
				1103	2398	3898	5124	6353	7525
10	10/78	Orifice	N.A.	81.63	93.09	86.80	85.42	85.42	85.42
				(1224)	(1396)	(1302)	(1281)	(1281)	(1281)
				1224	2620	3922	5203	6484	7765

Summary:							
Mass Flow Meter, 5 runs							
Rate:	Mean	78.05	89.10	82.50	78.52	76.27	78.74
	Std. deviation	6.38	10.03	3.99	4.39	5.8	9.13
	COV, percent [4]	8.2	11.3	4.8	5.6	7.6	11.6
15-min. period:	Mean	1170.8	1336.6	1237.6	1178.0	1144.2	1181.2
	Std. deviation	95.8	150.1	59.6	66.1	86.6	136.9
Cumulative:	Mean	1170.8	2507.4	3745.0	4923.0	6067.2	7248.4
	Std. deviation	95.8	224.1	272.0	298.7	362.6	488.6
	COV, percent	8.2	16.8	7.3	6.1	6.0	6.7
Orifice Meter, 6 runs							
Rate:	Mean	79.34	93.09	88.96	84.40	82.76	79.80
	Std. deviation	3.93	6.00	6.37	2.21	3.13	3.26
	COV, percent	5.0	6.4	7.2	2.6	3.8	4.1
15-min. period:	Mean	1190.0	1396.5	1334.3	1265.7	1241.2	1197.0
	Std. deviation	59.0	90.0	95.4	33.2	46.9	48.6
Cumulative:	Mean	1190.0	2586.2	3920.8	5186.5	6427.7	7624.7
	Std. deviation	59.0	142.2	126.1	130.8	133.5	156.4
	COV, percent	5.0	5.5	3.2	2.5	2.1	2.1

[1] Fuel supplied to maintain the ASTM E119 standard temperature/time relationship.

[2] Mass flow meter readings adjusted for gas composition.

[3] Orifice meter readings adjusted for pressures and gas specific gravity using American Gas Association equation.

[4] Coefficient of variation.

Table 2: Effect of Ambient Temperature and Relative Humidity on Furnace Fuel Consumption

Run Number	Date	Meter Type	Ambient (Outdoor) Conditions [1]		Total Fuel Used, 1000 Btu	
			Temp., F	R.H., %	1st 15 min.	60 min.
1	3/11/76	Mass Flow	29	63	1147	4681
2	3/17/76	Mass Flow	16	70	1177	5074
3	3/23/76	Mass Flow	40	62	1289	5169
4	4/5/76	Mass Flow	43	49	1213	5164
5	10/21/76	Mass Flow	41	82	1028	4527
5	10/21/76	Orifice	41	82	1135	5026
6	11/5/76	Orifice	37	82	1260	5203
7	11/10/76	Orifice	39	73	1211	5418
8	11/15/76	Orifice	38	73	1207	5145
9	11/19/76	Orifice	46	49	1103	5124

Table 3: Fuel Input for Steel-Stud Reference Wall Assembly Tests [1]

Date of Test	Fuel supplied to furnace [2,3] Average rate for period, 1000 BTU/min. (Total for period, 1000 BTU) Cumulative, 1000 BTU			
	0-15 min.	16-30 min.	31-45 min.	46-60 min.
6/6/78	62.82 (943) 943	75.57 (1134) 2077	73.25 (1099) 3176	75.57 (1134) 4310
6/8/78	66.99 (1005) 1005	76.72 (1151) 2156	77.20 (1158) 3314	79.10 (1187) 4501
10/17/78	77.38 (1161) 1161	90.07 (1351) 2512	87.53 (1313) 3825	84.90 (1274) 5099
1/18/79	68.38 (1026) 1026	79.65 (1195) 2221	77.59 (1164) 3385	80.97 (1215) 4600
1/13/81	90.53 (1358) 1358	99.88 (1498) 2856	95.82 (1437) 4293	91.38 (1371) 5664
SUMMARY				
Rate: Mean	72.23	84.38	82.28	82.38
Std. deviation	11.01	10.38	9.22	6.05
COV, percent [4]	15.1	12.3	11.2	7.3
Mean:	1098.6	1265.9	1234.2	1236.2
Std. deviation	165.4	155.5	138.2	90.7
Mean	1098.6	2364.4	3598.6	4830.8
Std. deviation	165.4	320.2	457.9	540.0
COV, percent	15.1	13.5	12.7	11.2

[1] One layer $^5/_8$ in. Type X gypsum board on each face of assembly.

[2] Fuel supplied to maintain the ASTM E119 standard temperature/time relationship.

[3] Fuel values based on the orifice meter.

[4] Coefficient of variation.

Table 4: Fuel Input for Unprotected Wood-Stud and Steel-Stud Wall Assembly Tests [1]

Framing	Date of Test	Fuel supplied to furnace [2] for period indicated, 1000 Btu.				
		0-15 min.	16-30 min.	31-45 min.	46-60 min.	0-60 min.
Steel Studs	10/7/77	1183	1521	1470	1528	5702
Wood Studs [3]	10/5/77	846	859	1084	1105	3894

[1] Assemblies made with two layers of $^5/_8$ in. Type X gypsum board on face away from furnace and no protection on furnace side.

[2] Fuel supplied to maintain the ASTM E119 standard temperature/time relationship.

[3] Wood studs, plates and blocking were untreated southern pine. Studs were spaced 16 in. on center.

Table 5. Fuel Input for Paired Wood-Stud and Steel-Stud Protected Wall Assembly Tests [1]

Date of Wood Assembly Test [3]	Fuel supplied to furnace [2]							
	Average rate for period, 1000 Btu/min. (Total for period, 1000 Btu) Cumulative, 1000 Btu							
	0-15 min.		16-30 min.		31-45 min.		46-60 min.	
	Wood	Steel	Wood	Steel	Wood	Steel	Wood	Steel
10/19/78	76.10	77.38	88.71	90.07	84.16	87.53	79.13	84.90
	(1142)	(1161)	(1331)	(1351)	(1262)	(1313)	(1187)	(1274)
	1142	1161	2473	2512	3735	3825	4922	5079
1/16/79	68.61	68.38	81.13	79.65	78.87	77.59	74.17	80.97
	(1029)	(1026)	(1217)	(1195)	(1183)	(1164)	(1113)	(1215)
	1029	1026	2246	2221	3429	3385	4542	4600
1/15/81	92.53	90.53	104.73	99.88	98.25	95.82	92.45	91.38
	(1388)	(1358)	(1571)	(1498)	(1474)	(1437)	(1387)	(1371)
	1388	1358	2959	2856	4433	4293	5820	5664
SUMMARY								
Rate: Mean	79.08	78.76	91.52	89.87	87.09	86.98	81.92	85.75
Std. deviation	12.24	11.14	12.05	10.12	10.02	9.13	9.45	5.26
COV, percent [4]	15.5	14.1	13.2	11.3	11.3	10.5	11.5	6.1
Mean	1186.3	1181.7	1373.0	1348.0	1306.3	1304.6	1229.0	1286.7
Std. deviation	183.6	167.0	180.7	151.5	150.5	136.7	141.7	78.7
Mean	1186.3	1181.7	2559.3	2529.7	3865.6	3834.3	5094.6	5121.0
Std. deviation	183.6	167.0	364.3	317.9	514.6	454.1	656.3	532.3
COV, percent	15.5	14.1	14.2	12.6	13.3	11.8	12.9	10.4

[1] One layer $^5/_8$ in. Type X gypsum board on each face of assembly. Wood studs, plates and blocking were fire retardant treated southern pine. Studs were spaced 16 in. on center.

[2] Fuel supplied to maintain the ASTM E119 standard temperature/time relationship.

[3] Steel reference assembly tested two days before wood assembly.

[4] Coefficient of variation.

Table 6. Heat Released by Protected Wood Wall Assemblies

Date	Total fuel consumed in 60 min. test [1], 1000 Btu		Net heat released from wood assembly	
	Steel Assembly [2]	Wood Assembly [2,3]	1000 Btu	Percent of Steel Assembly
10/78	5099	4922	177	3.5
1/79	4600	4542	58	1.3
1/81	5664	5820	−156	−2.8
Mean	5121	5095	26	0.5

[1] Total fuel supplied to furnace to maintain the ASTM E119 standard temperature/time relationship.

[2] Assemblies made with one layer of $^5/_8$ in. Type X gypsum board on each face.

[3] Wood framing was fire retardant treated southern pine. Studs were spaced 16 in. on center.

Table 7. Heat Released by Wood Assemblies Based on Weight and Heat of Combustion

Material Property	Date of Wood Assembly Test	
	1/16/79	1/15/81
Wood in assembly		
Weight, lbs. [1]	170	184
Total Heat Available, 1000 Btu [2]	1272	1376
Recovered Wood		
Weight, lbs. [1]	67.0	62.2
Heat Available, 1000 Btu [2]	501	465
Recovered char		
Weight, lbs. [1]	47.0	48.7
Heat Available, 1000 Btu [3]	564	584
Heat Released, 1000 Btu	207	327

[1] Weight of wood and char are on a dry-weight basis.

[2] Net heat of combustion of fire retardant treated southern pine lumber assumed to be 7480 Btu/lb. (dry weight basis). This value based on gross heat of combustion obtained from a Parr oxygen-bomb calorimeter test and corrected to a net value from carbon, hydrogen, and oxygen ash analysis.

[3] Net heat of combustion of char from fire retardant treated southern pine assumed to be 1200 Btu./lb. based on a Parr oxygen bomb calometer test.

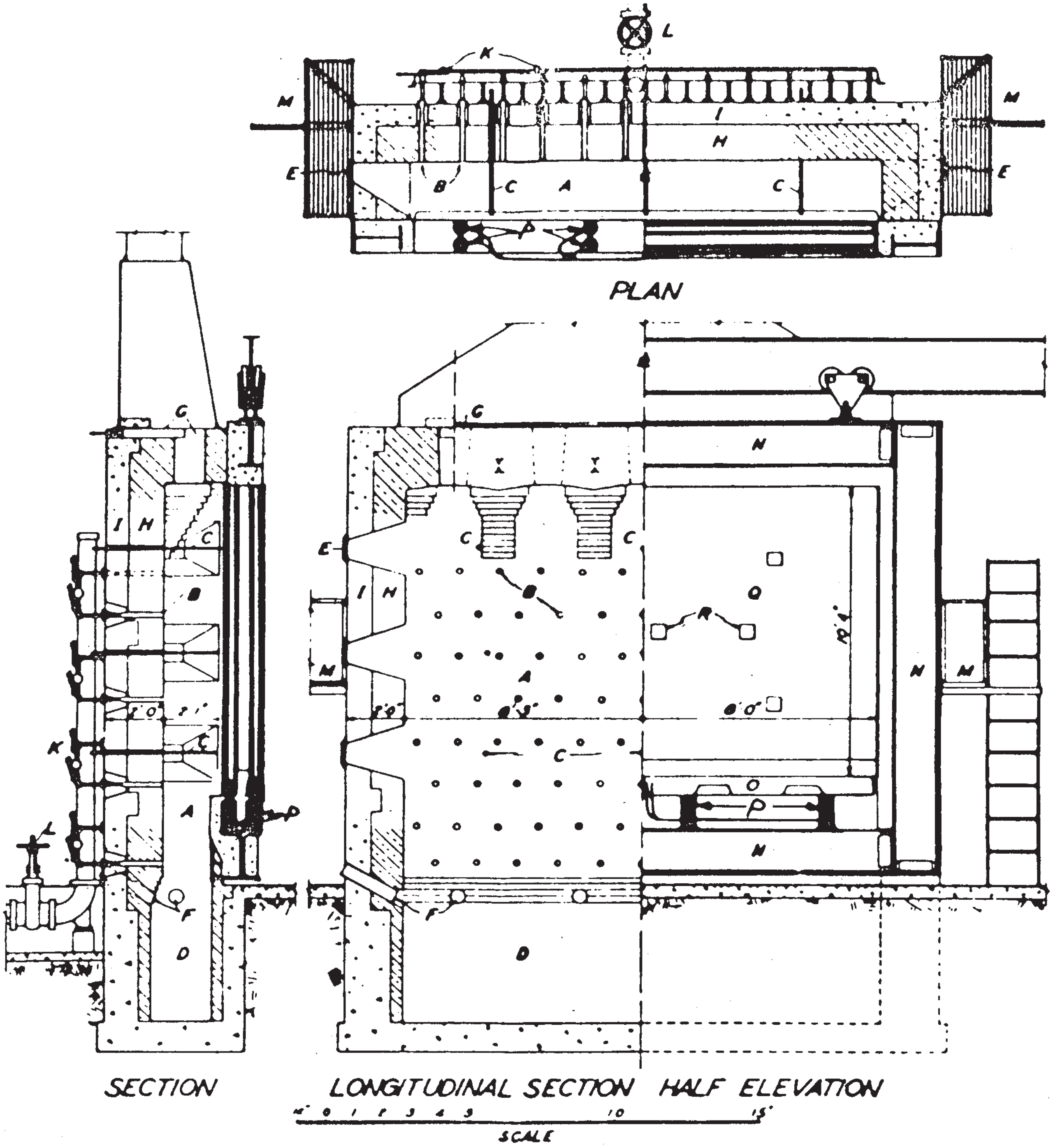
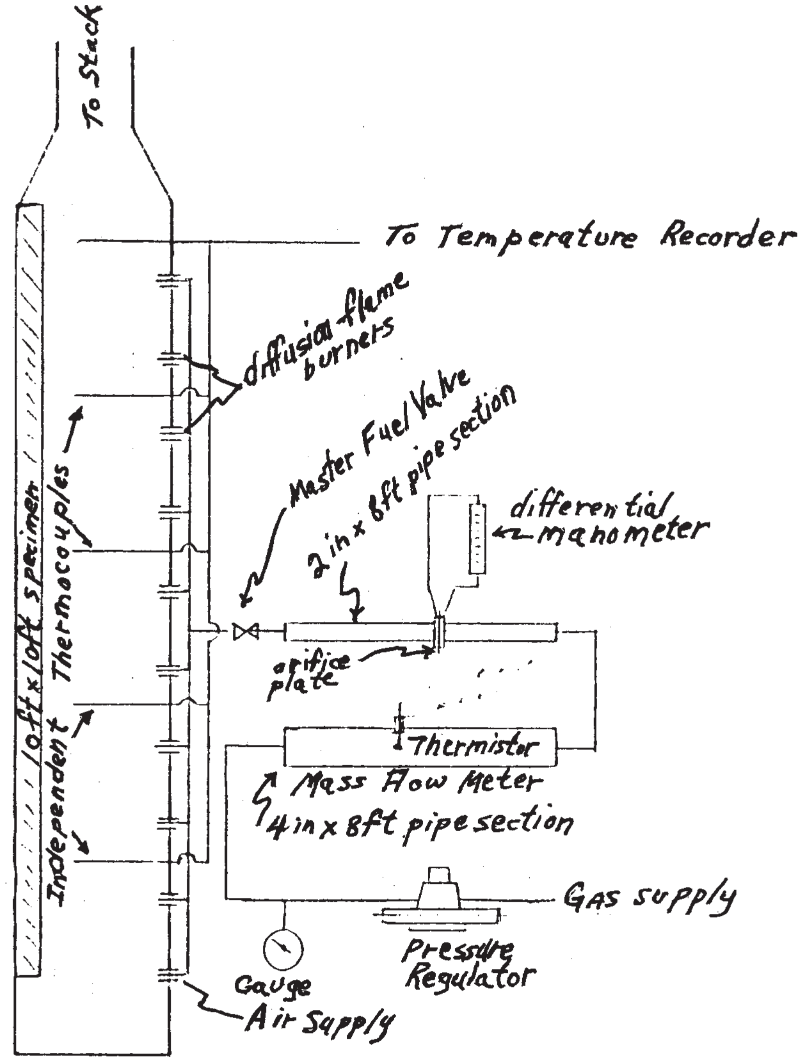


FIGURE 1. Details of Wall-Testing Furnace

A, Furnace Chamber; B, Burners; C, Thermocouple Protection Tubes; D, MT for Debris; E, Observation Windows; F, Air Inlets; G, Flue Outlets and Dampers; H, Firebrick Furnace-Lining; I, Reinforced Concrete Furnace-Shell; K, Gas Cocks; L, Control Valve; M, Ladders and Platforms To Observation Windows; N, Moveable Fireproofed Test Frame; O, Loading Beam; P, Hydraulic Jacks; Q, Test Wall; R, Asbestos Felted Pads Covering Thermocouples on Exposed Surface of Test Wall.

FIG. 2

A SIMPLIFIED SCHEMATIC OF THE ASTM E119 FIRE TEST FURNACE AT NATIONAL GYSUM



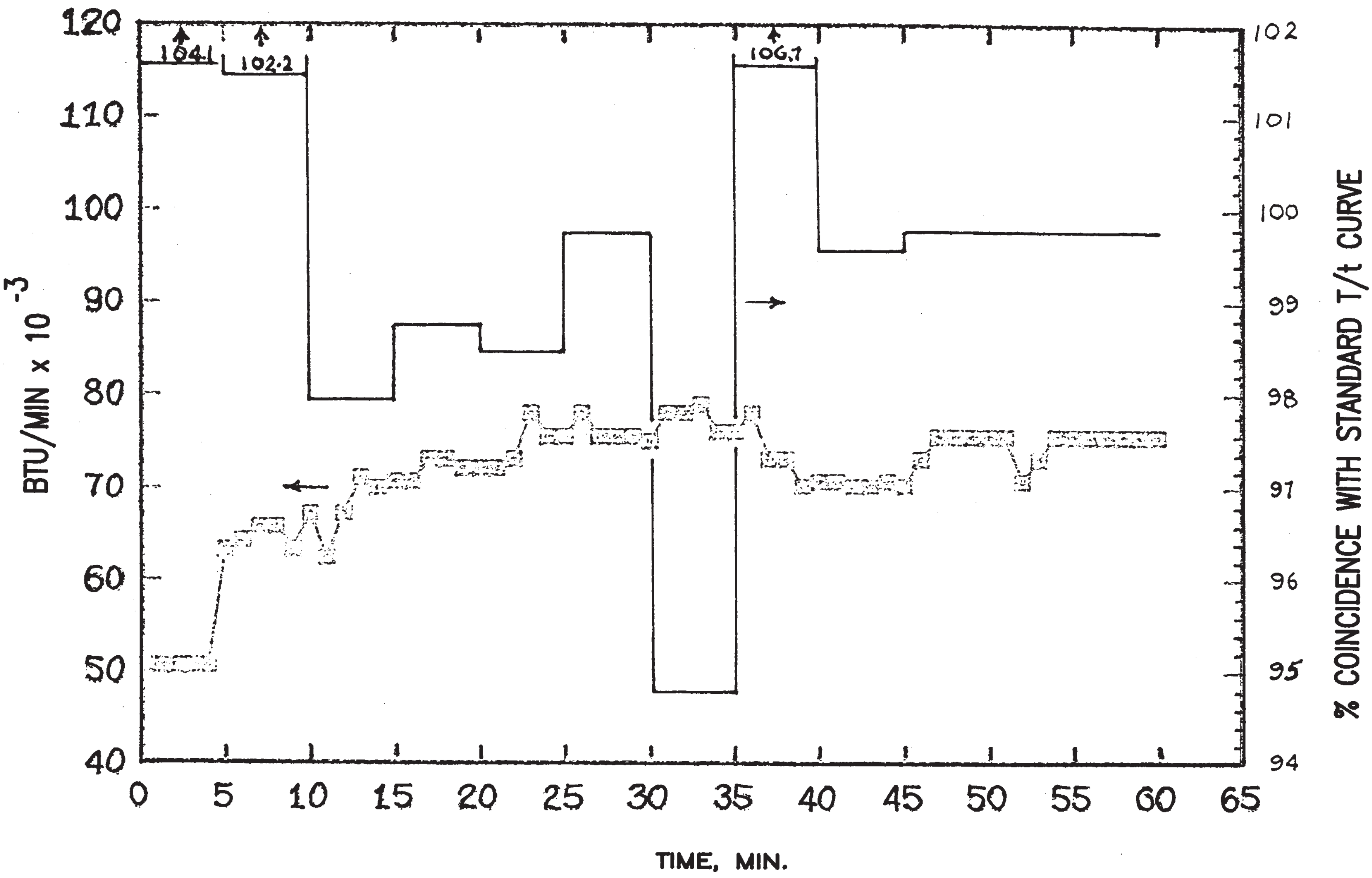


FIG. 3
FUEL CONSUMPTION RATE, STEEL STUD TEST, 6 JUNE 1978

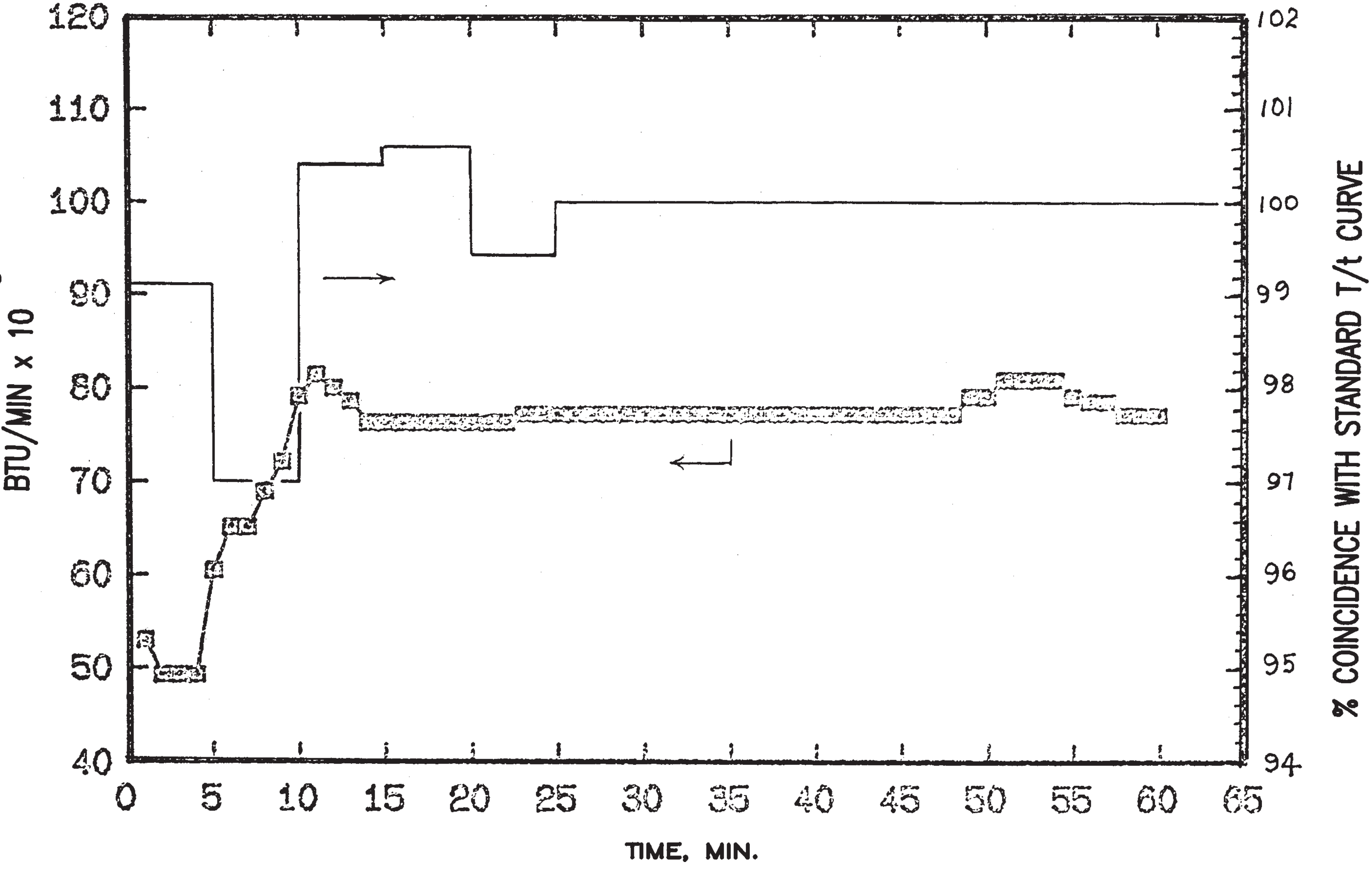


FIG. 4
FUEL CONSUMPTION RATE, STEEL STUD TEST, 8 JUNE 1978

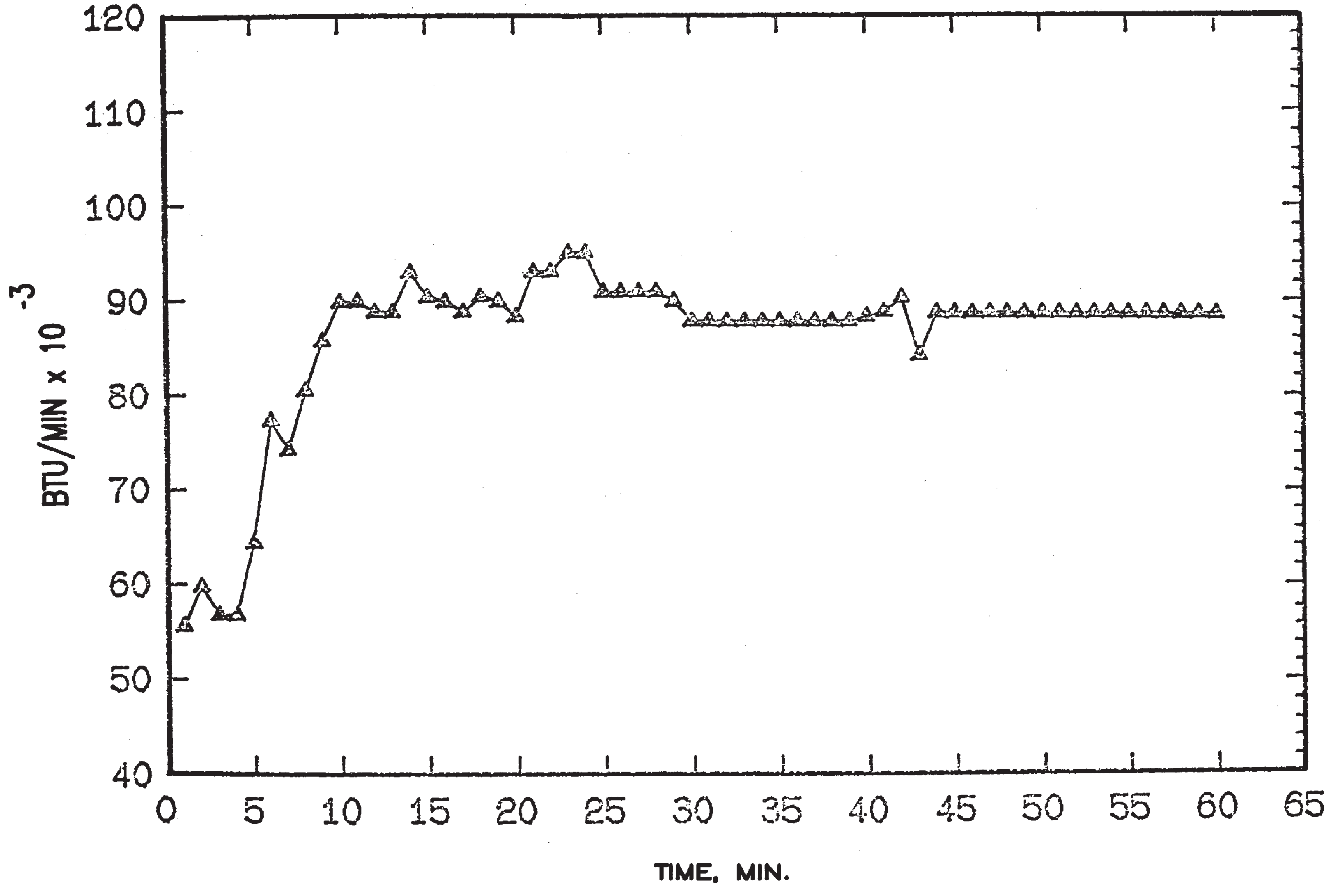


FIG. 5
FUEL CONSUMPTION RATE, STEEL STUD TEST, 17 OCT. 1978

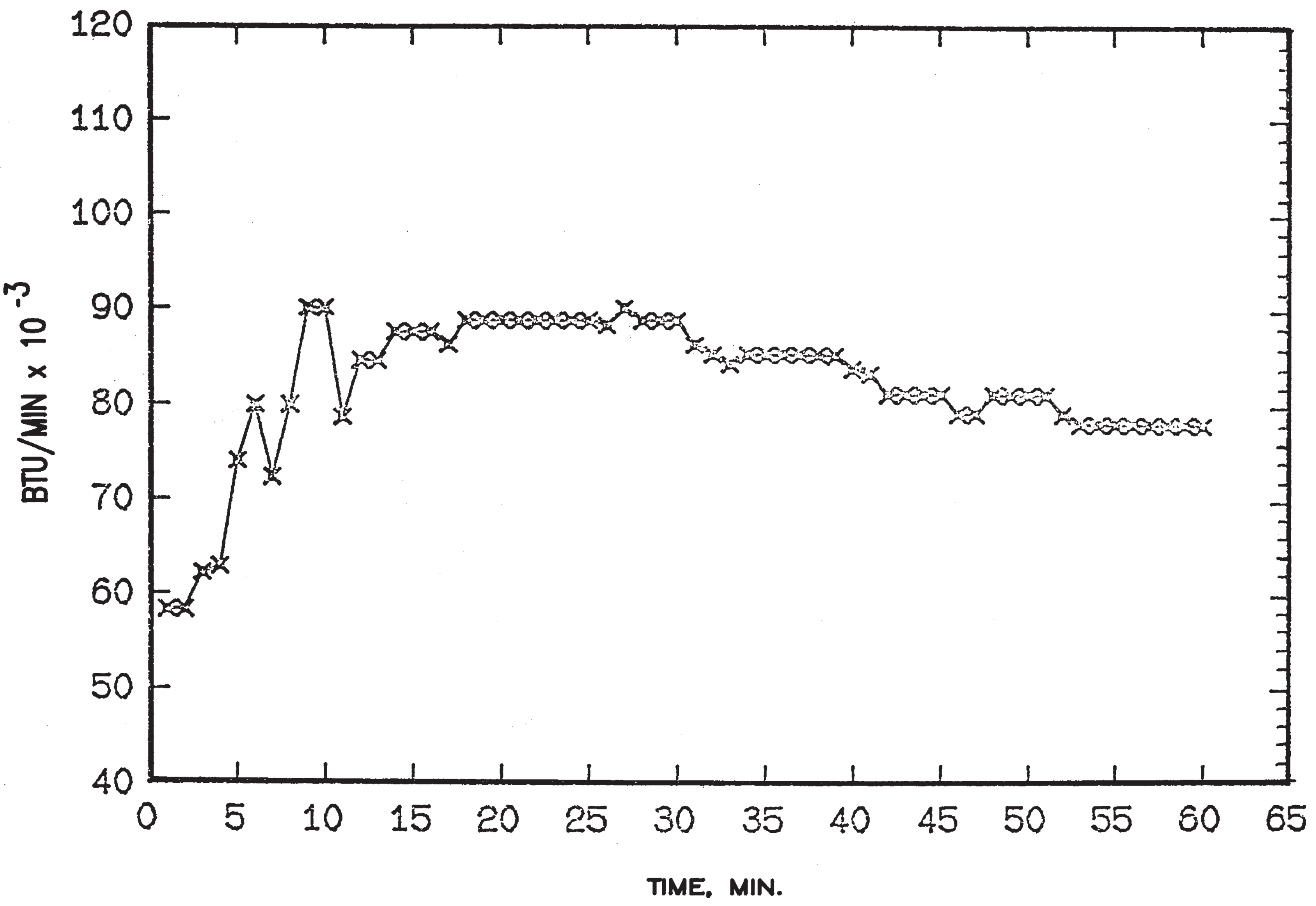


FIG. 6
FUEL CONSUMPTION RATE, WOOD STUD TEST, 19 OCT. 1978

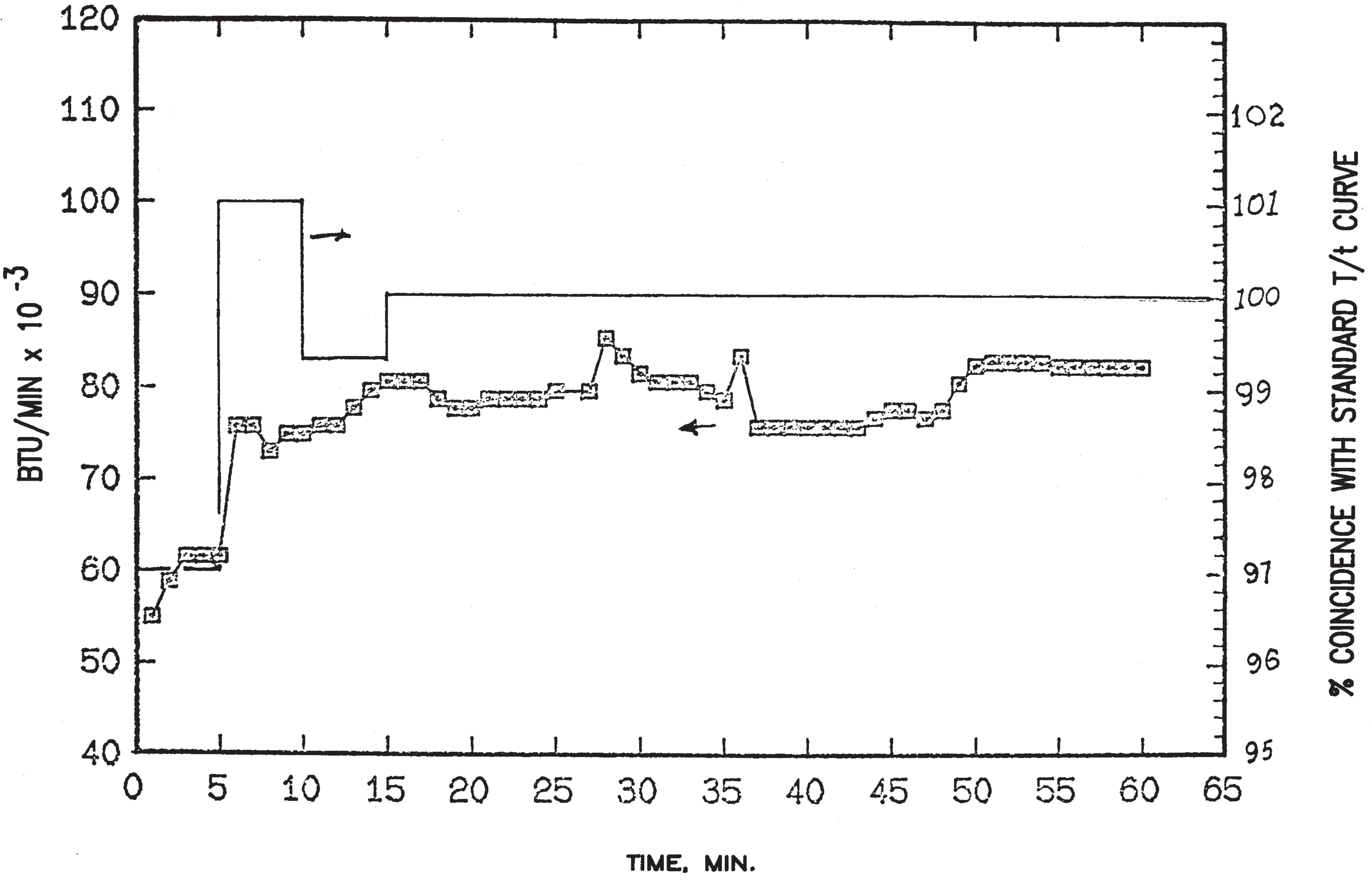


FIG. 7
FUEL CONSUMPTION RATE, STEEL STUD TEST, 18 JUNE 1979

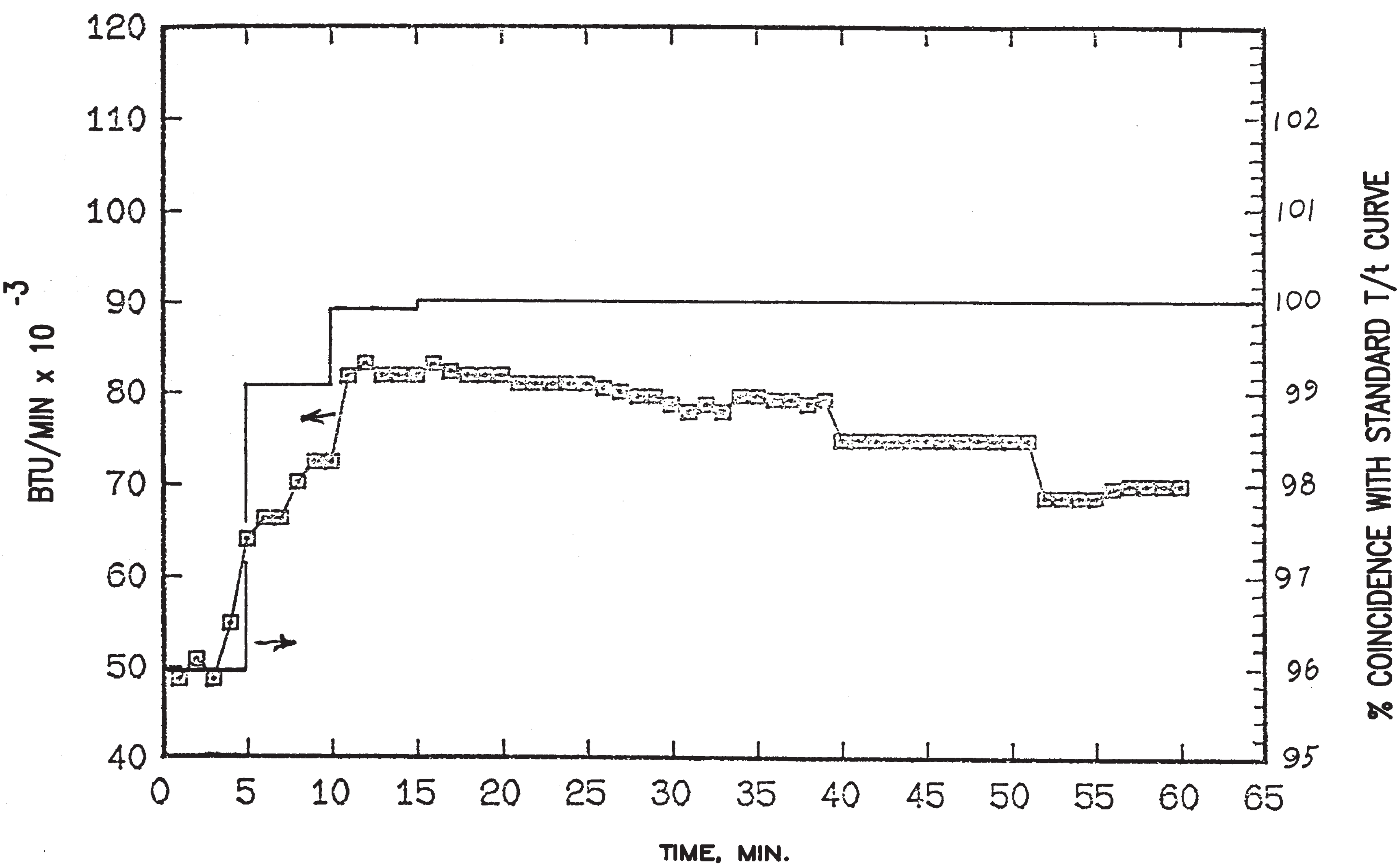


FIG. 8
FUEL CONSUMPTION RATE, WOOD STUD TEST, 16 JAN. 1979

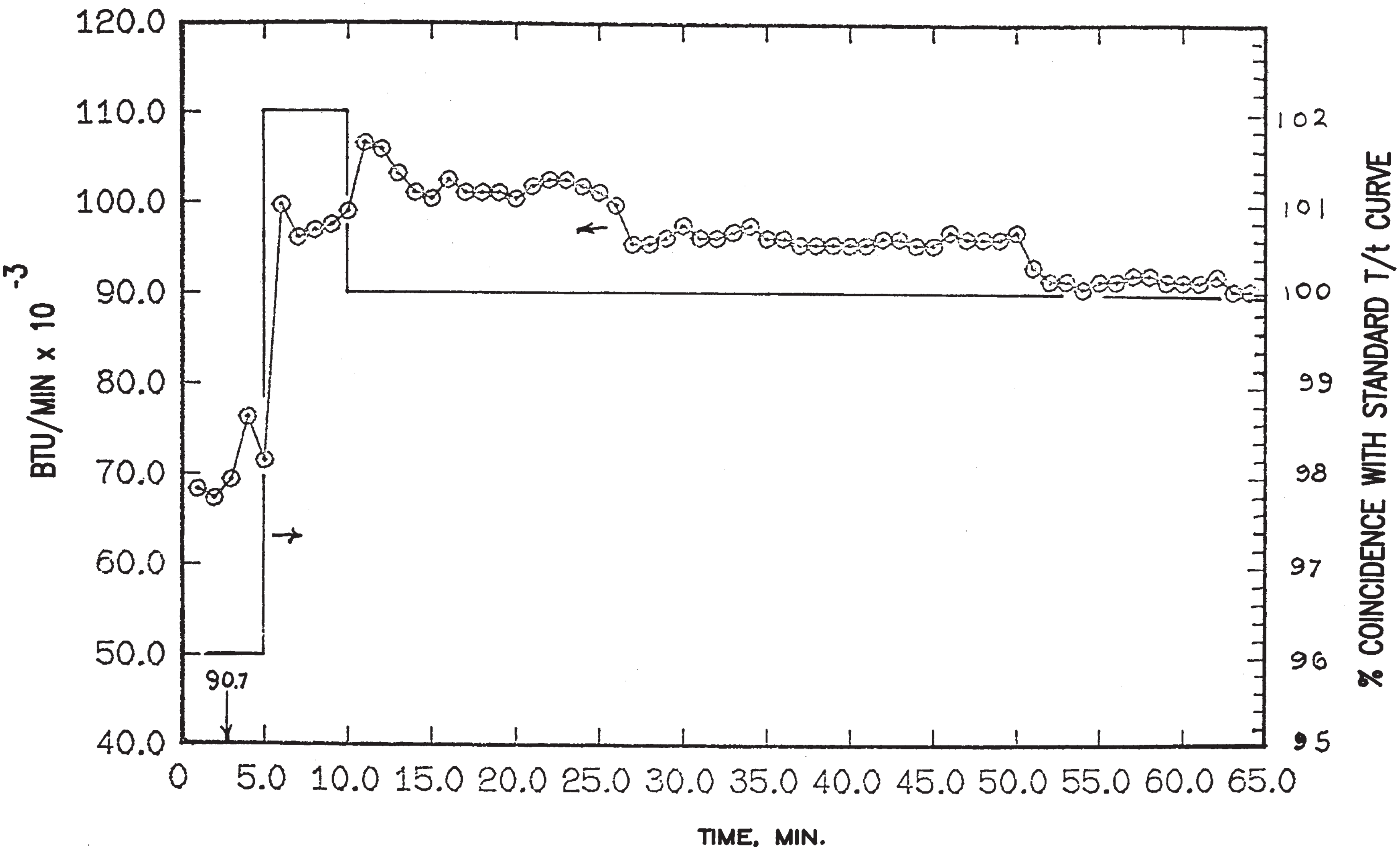


FIG. 9
FUEL CONSUMPTION RATE, STEEL STUD TEST, 13 JAN. 1981

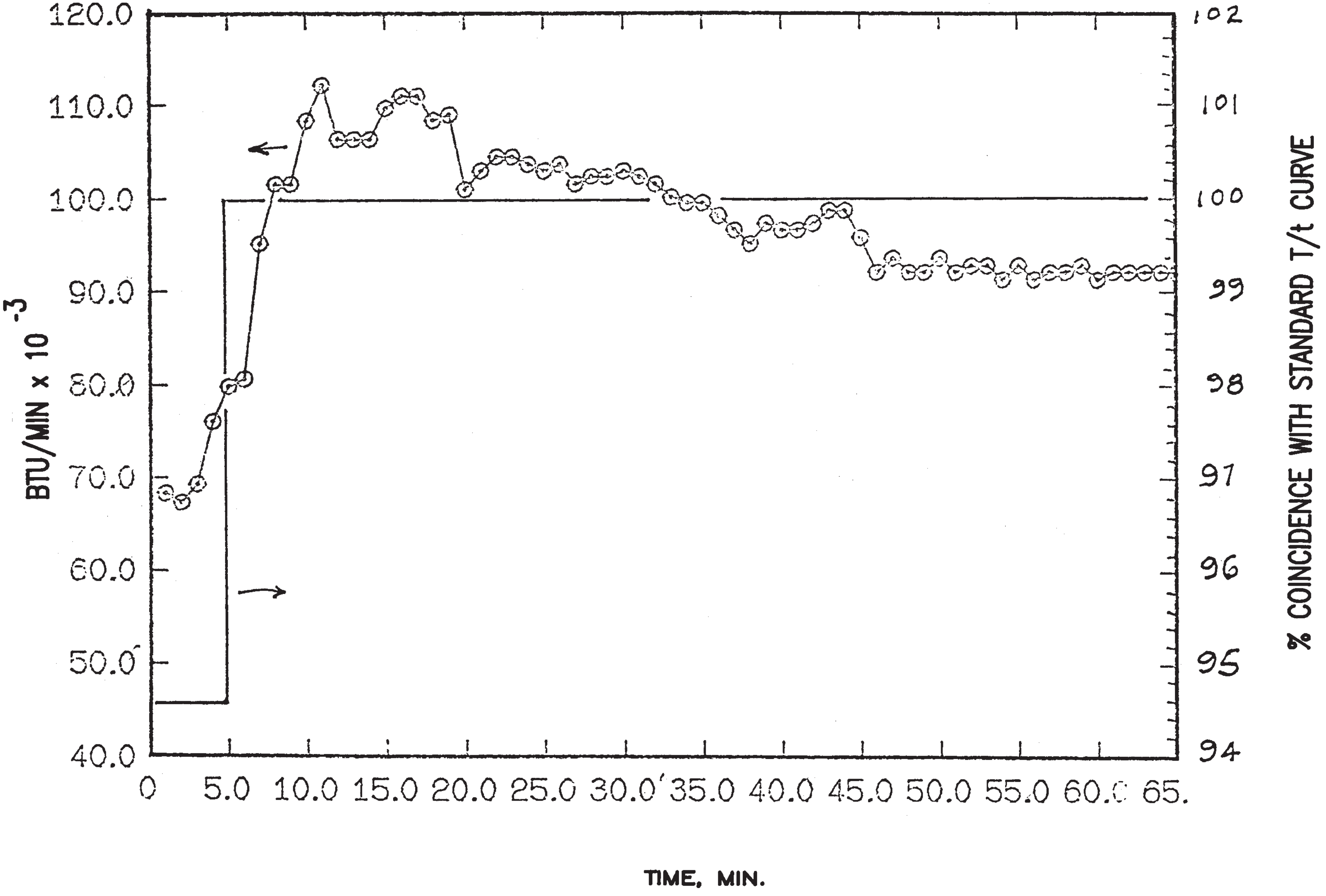


FIG. 10
FUEL CONSUMPTION RATE, WOOD STUD TEST, 15 JAN. 1981

APPENDIX A

Calibration of the Daniels Instrument Company Orifice Meter at the National Gypsum Research Corporation

This Appendix describes the derivation of the orifice flow constant, C, in the basic orifice flow equation

$Q = C' (h_w P_f)^{1/2}$

where: Q = flow, standard cubic feet per hour
C' = orifice flow constant
h_w = differential pressure across the flanged-topped orifice plate, in. of $H_2 0$
and P_f = absolute static pressure, psi at the up-stream side of the orifice plate

The derivation and use of the foregoing equation are discussed in detail in the American Gas Association's 1969 Revised Edition of "Orifice Metering of Natural Gas," the Gas Measurement Committee Report No. 3.

The orifice flow constant, C', may be expressed as the product of several terms each of which represents the influence of the important factors of orifice meter geometry and placement, properties of the gas, and environmental factors such as temperature and barometric pressure. Thus,

$$C' = F_b \bullet F_r \bullet Y \bullet F_{pb} \bullet F_{tb} \bullet F_{tf} \bullet F_g \bullet F_{pv} \bullet F_m \bullet F_a \bullet F_l$$

where:

F_b = basic orifice factor
F_r = Reynolds' number factor
Y = expansion factor
F_{pb} = pressure base factor
F_{tb} = temperature base factor
F_{tf} = flowing temperature base factor
F_g = specific gravity factor
F_{pv} = super compressibility factor
F_m = manometer factor (for mercury manometers only)
F_a = orifice thermal expansion factor
and F_l = gauge location factor

Tables are available for caculating each of the foregoing factors. These tables are based on a base temperature of 60°F (520R), a flowing temperature of 60°F, a base pressure of 14.73 psia, and a gas specific gravity of 1.0.

The orifice plate is of the sharp-edge type, with an inside diameter of 1.375 in., and is installed in a normal 2 in. pipe that has an actual inside diameter of 2.067 in. The pressure drop through the orifice is measured with a water-filled differential manometer, and the average pressure drop, h_w, is 6.0 in. An up-stream static pressure of 28 in. of water is maintained by a pressure regulator. Under these conditions existing at the National Gypsum furnace, the following factors are obtained:

F_b = 464.8
F_r = 1.0075
Y = 0.9946
F_b = 1.002
F_{tb} = 1.0
$F_{tf} = (520° / (460° + T_f °F))^{1/2}$
$F_g = (1/G)^{1/2}$
F_{pv} = 1.0
F_m = 1.0
F_a = 1.0
F_l = 1.0

Therefore,

$$Q = 466.7\ (520/(460+T_f))^{1/2} \bullet (l/G)^{1/2} \bullet (h_w P_f)^{1/2}\ \text{CFH}$$
$$= 177.4\ (l/T_f\ (°R))^{1/2} \bullet (l/G)^{1/2} \bullet (h_w P_f)^{1/2}\ \text{CPM}$$

where: T_f = gas temperature, degrees Rankine (T°F + 460)
G = specific gravity of gas (air = 1.0)
and P_f = absolute up-stream static pressure

APPENDIX B

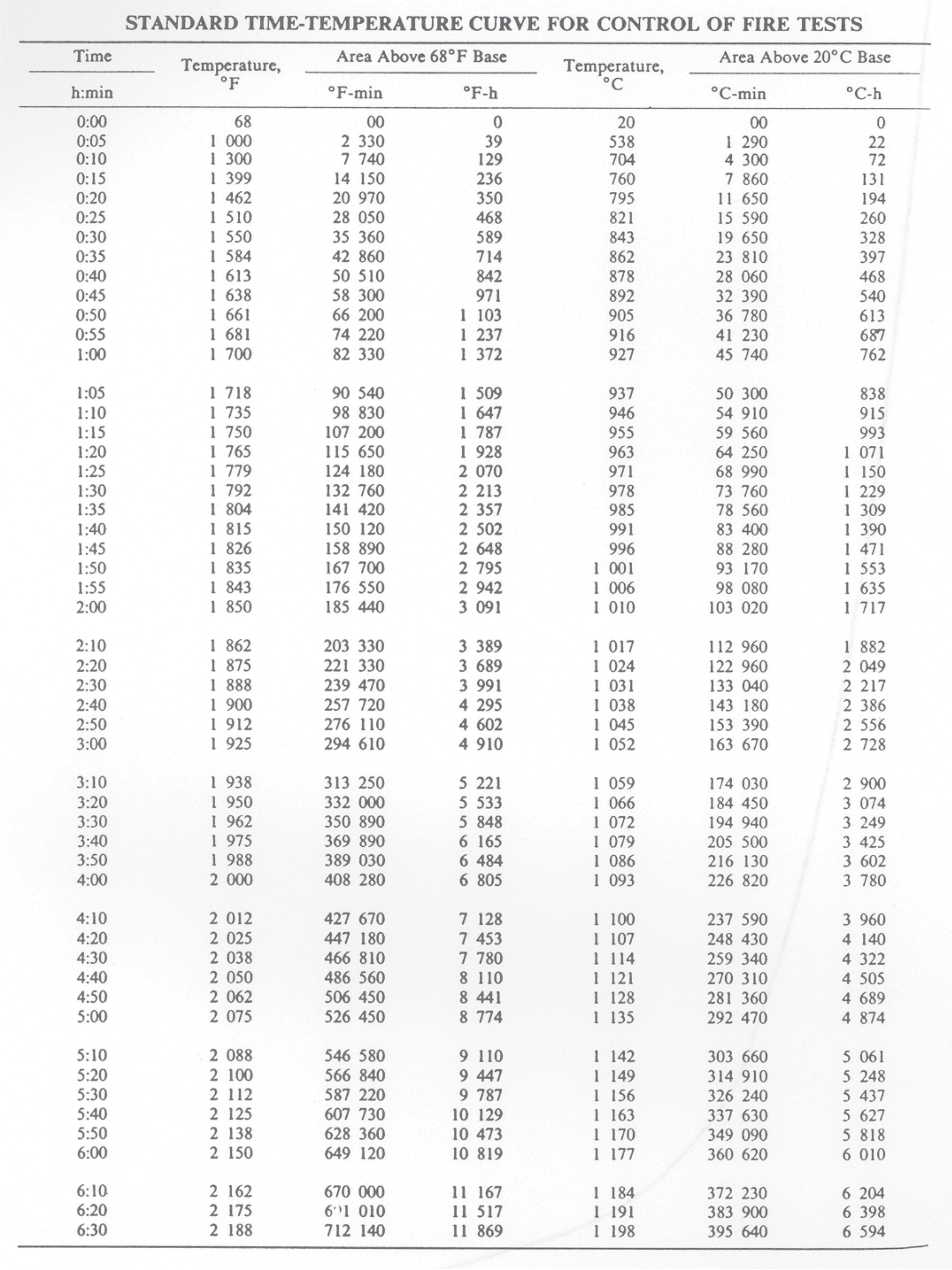
ASTM E119 Temperature-Time Relationship

The ASTM E119 fire test[3] is a method of determining the standard fire endurance of full-scale wall and floor/ceiling assemblies. The test assembly is included as one wall or the ceiling of a large furnace. Fuel is fed to this furnace such that the temperatures measured at selected sites in the fire chamber follow a standard temperature/time (T/t) relationship. This standard T/t relationship is given in Table B-l.

Also given in Table B-l is the area under the standard T/t curve above a 68°F (room temperature) baseline for five-minute intervals. The T/t curve and related areas are shown in Figure B-l for a time of 60 minutes.

The area under the standard T/t curve for each five minute interval was determined by a straight-line approximation of the standard curve. This approximation, which is used in the standard, is adequate for time periods greater than 10 minutes. The difference between the smooth curve and the straight-line approximation as shown in Figure B-l is 16.3 percent for the first five-minute period and 2.8 percent for the second five-minute period. The overall ten-minute difference is 6.9 percent. A discrepancy of this magnitude could be important in fire endurance tests of less than twenty minutes. However, in tests of longer duration, the discrepancy is probably negligible.

Table B-1



STANDARD TIME-TEMPERATURE CURVE FOR CONTROL OF FIRE TESTS

Time	Temperature, °F	Area Above 68°F Base		Temperature, °C	Area Above 20°C Base	
h:min		°F-min	°F-h		°C-min	°C-h
0:00	68	00	0	20	00	0
0:05	1 000	2 330	39	538	1 290	22
0:10	1 300	7 740	129	704	4 300	72
0:15	1 399	14 150	236	760	7 860	131
0:20	1 462	20 970	350	795	11 650	194
0:25	1 510	28 050	468	821	15 590	260
0:30	1 550	35 360	589	843	19 650	328
0:35	1 584	42 860	714	862	23 810	397
0:40	1 613	50 510	842	878	28 060	468
0:45	1 638	58 300	971	892	32 390	540
0:50	1 661	66 200	1 103	905	36 780	613
0:55	1 681	74 220	1 237	916	41 230	687
1:00	1 700	82 330	1 372	927	45 740	762
1:05	1 718	90 540	1 509	937	50 300	838
1:10	1 735	98 830	1 647	946	54 910	915
1:15	1 750	107 200	1 787	955	59 560	993
1:20	1 765	115 650	1 928	963	64 250	1 071
1:25	1 779	124 180	2 070	971	68 990	1 150
1:30	1 792	132 760	2 213	978	73 760	1 229
1:35	1 804	141 420	2 357	985	78 560	1 309
1:40	1 815	150 120	2 502	991	83 400	1 390
1:45	1 826	158 890	2 648	996	88 280	1 471
1:50	1 835	167 700	2 795	1 001	93 170	1 553
1:55	1 843	176 550	2 942	1 006	98 080	1 635
2:00	1 850	185 440	3 091	1 010	103 020	1 717
2:10	1 862	203 330	3 389	1 017	112 960	1 882
2:20	1 875	221 330	3 689	1 024	122 960	2 049
2:30	1 888	239 470	3 991	1 031	133 040	2 217
2:40	1 900	257 720	4 295	1 038	143 180	2 386
2:50	1 912	276 110	4 602	1 045	153 390	2 556
3:00	1 925	294 610	4 910	1 052	163 670	2 728
3:10	1 938	313 250	5 221	1 059	174 030	2 900
3:20	1 950	332 000	5 533	1 066	184 450	3 074
3:30	1 962	350 890	5 848	1 072	194 940	3 249
3:40	1 975	369 890	6 165	1 079	205 500	3 425
3:50	1 988	389 030	6 484	1 086	216 130	3 602
4:00	2 000	408 280	6 805	1 093	226 820	3 780
4:10	2 012	427 670	7 128	1 100	237 590	3 960
4:20	2 025	447 180	7 453	1 107	248 430	4 140
4:30	2 038	466 810	7 780	1 114	259 340	4 322
4:40	2 050	486 560	8 110	1 121	270 310	4 505
4:50	2 062	506 450	8 441	1 128	281 360	4 689
5:00	2 075	526 450	8 774	1 135	292 470	4 874
5:10	2 088	546 580	9 110	1 142	303 660	5 061
5:20	2 100	566 840	9 447	1 149	314 910	5 248
5:30	2 112	587 220	9 787	1 156	326 240	5 437
5:40	2 125	607 730	10 129	1 163	337 630	5 627
5:50	2 138	628 360	10 473	1 170	349 090	5 818
6:00	2 150	649 120	10 819	1 177	360 620	6 010
6:10	2 162	670 000	11 167	1 184	372 230	6 204
6:20	2 175	691 010	11 517	1 191	383 900	6 398
6:30	2 188	712 140	11 869	1 198	395 640	6 594

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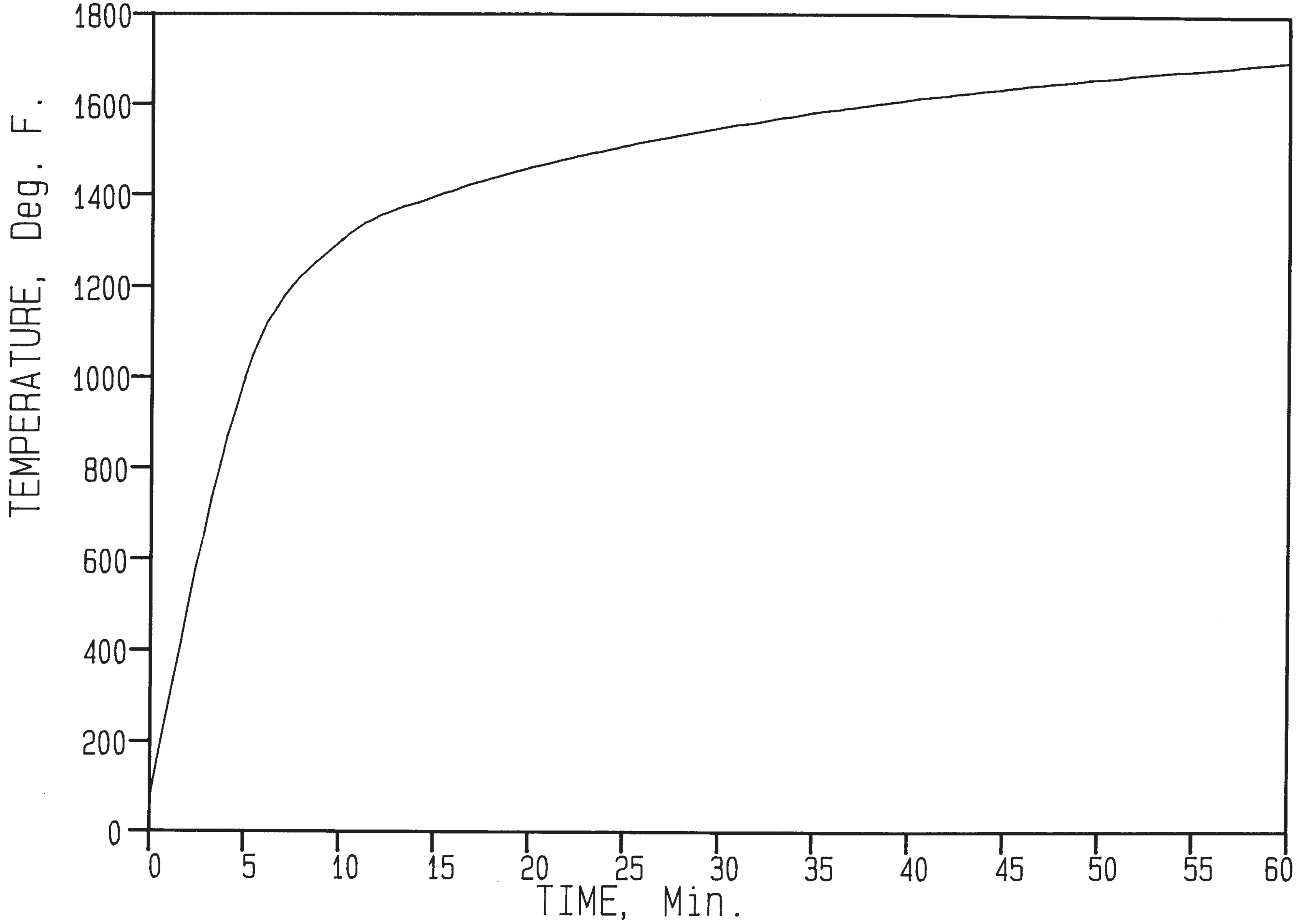
Fig. B-1 ASTM STANDARD TEMPERATURE-TIME CURVE



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