NATIONAL BUREAU OF STANDARDS REPORT

7058

ESTIMATION OF THE FIRE ENDURANCE OF STEEL PROTECTED BY SPRAYED INSULATION THROUGH USE OF AN ANALOG COMPUTER

by

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and
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NBS

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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*Participating in Junior Scientist and Engineer Program 1959

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ABSTRACT

Electrical analog computer solutions are presented for estimating the fire endurance of steel protected by sprayed insulation upon exposure to a "standard" fire. Resistors and capacitors comprising the electrical model were selected to represent the measured or estimated thermal properties. Comparisons with experimental results are given and possible explanations for the causes of differences are suggested.

1. INTRODUCTION

In connection with investigations of the effectiveness of fire-retardant insulating materials sprayed directly on structural steel members, it was considered desirable to compare the predictions of an electrical analog computer with experimental results on one type of sprayed insulation. Based upon estimates of its thermal properties, comparisons were made for the following constructions: (a) sprayed insulation in 1/2-in., 1-in., and 2-in. thicknesses on two-foot square, No. 16 U.S.G. steel plates, (b) sprayed insulation of nominal 1/2-in. thickness on a 6- by 6-in. by 13 ft high, wide flange stanchion steel column and (c) a 6-in dia by 24-in. long cylinder of this insulation material. This report presents and discusses the results of the analog computations, and compares the results with experimental data. Details concerning the thermal and fire-retardant properties of eight sprayed insulations, including the one selected for this study, are given in NBS Report Nos. 5821, 5943, and 6558.

2. MATERIAL

The spray insulation for this study was selected on the basis of its performance in the preliminary fire endurance tests. It was a proprietary fibrous material (about 75% glass and 25% asbestos) plus binders, fillers, etc.*

* Material used was the fifth listed on page 2 of NBS Report No.5821

3. EXPERIMENTAL DETAILS

(a) Two-foot Slabs. The sprayed insulation was applied to a two-foot square section of No. 16 U.S.G. steel plate. Specimens of three thicknesses, 1/2 in., 1 in., and 2 in. were prepared by spraying into enclosures whose side walls were of welded angle of the the desired height. Each specimen, after drying, was placed insulation side down to form the top surface of a gas-fired furnace. Above the steel plate of the specimen were, in order, a 3/4-in. air space, a 1-in. thick refractory board, an air space and a large steel pan containing circulating water at nearly constant temperature. The results are shown in Figures 1, 2, and 3.

(b) Stanchion Column. The column was a 6-in. by 6-in. by 13 ft wide flange stanchion steel column onto which was sprayed a nominal 1/2-in. coating of the insulation. The spraying was done by a commercial contractor using commercial equipment. Prior to test, a survey of the actual thickness of insulation was made by measuring the penetrations of a fine needle at four elevations on the column corresponding to the elevations at which thermocouples were installed. As shown in Figure 4, the actual thickness varied from about 1/8 in. to 1-1/8 in. with an estimated mean thickness possibly slightly greater than 1/2 in. The column was tested under load in a standard fire test [1]. The results are shown in Figure 5.

(c) Solid Cylinder. A sprayed solid cylinder of the same insulation was prepared at the same time as the column. The insulation was sprayed into a cardboard concrete form 6 in. I.D. by 24 in. long, which, when removed, provided a simple solid cylinder of the same insulation as was applied to the column. The cylinder was dried and weighed prior to test and found to have a density of 0.33 gm/cc for the two-foot slabs. The latter density was also assumed for the column, since no "tamping" or compression was done on the column or slabs insulation as was the case for the cylinder. The cylinder was tested at the same time and in the same furnace as the column. The results are shown in Figure 6.

In all cases, slabs, column and cylinder, thermocouples were placed on the test specimens for indicating temperatures within the specimen. The unusual temperature record of the first cylinder test prompted a repeat test on the same cylinder with the same thermocouples. The results are also shown in Figure 6 and are discussed later.

4. ANALOG COMPUTATIONS

The similarity between heat flow through thermal circuits and current flow in resistance-capacitance electrical circuits provides the basis for the electrical analog method [2]. The properties assumed for the sprayed insulation are listed in Table 1. The estimation of thermal conductivity with temperature is based upon available handbook values for similar materials in combination with an accurate determination for the actual sprayed insulation at room temperature. In each case, the resistors and capacitors comprising the electrical model were selected to represent the thermal resistance and heat capacity for the mean temperature expected at each section. The magnitude of these components for each test depends upon scale factors chosen to maintain the proper electrical and thermal time relationship.

(a) Two-foot Slabs. In Figures 1, 2 and 3, the analog solutions for the three different slab thicknesses have been drawn for direct comparison with the experimental curves. Also shown are the electrical networks used. The following assumptions or approximations were made:

(1) Because of its high thermal conductivity, the steel plate was represented by a single capacitor only. The temperature variation of specific heat for iron was taken from the Handbook of Chemical Engineering and the capacitor was selected to represent the heat capacity for the mean temperature at the plate.

(2) Because of the low heat capacity of air, the 3/4 in. air gap was represented by a single resistor only. The use of a simple resistor is an approximation inasmuch as heat transfer across an air gap is a combination of radiation, convection and conduction. To properly represent this type of heat transfer would require the appropriate non-linear resistor sensitive to the absolute voltage applied. A slight change in the "effective conductance" of the air gap for the 2-in. test was made as an approximate allowance for the change in heat transfer with change in mean temperature level.

(3) The assumed properties of the refractory board were as follows: $K = 0.0005$,* $\rho = 0.812$ and $s = 0.19$ cgs units and were assumed temperature-independent. This is not too severe an assumption since the temperature gradient across the board is

*subsequently measured as .00067 at 118°F on pentane hot plate not too large and the effect of refractory board property changes upon the steel plate temperature were not of the same order of magnitude as those of the sprayed insulation.

(4) The upper air space was simulated by a non-linear, voltage-sensitive resistor arranged to represent heat transfer by radiation and free convection from a horizontal plate facing upward. Due to the proximity of the steel pan, the assumption of a free convection coefficient is somewhat questionable.

(b) Stanchion Column. Figure 5 is a comparison between the analog and experimental curves on the steel column protected with 1/2-in. of sprayed plaster insulation. The electrical network employed is also shown.

(c) Solid Cylinder. Figure 6 is a comparison between the analog and experimental curves for a 6-in. diameter solid cylinder of sprayed insulation. Because the initial test yielded unusual temperature curves, the results of the repeat test are considered useful for comparison. Radial heat flow is reduced to the one-dimensional case by selecting values of 1/R and C proportional to the (mean) radius of the section. The density used for this case was 0.5g/cc, as measured.

5. Discussion

In comparing the analog results from the three slab tests with the corresponding experimental data, it is seen that (a) good agreement was obtained for the 1-in. thick insulation, (b) the analog solution was slightly higher for the 1/2-in. thick insulation and (c) the analog solution was considerably lower for the 2-in. thick insulation. Since the good agreement for the 1-in. thick insulation involved the arbitrary selection of an effective conductance for the air gap, several determinations were subsequently made to evaluate the validity of this assumption. It was found that when one or two sheets of asbestos millboard (ρ = .86, k = .00029 c = 0.20) were used in place of the steel plate and insulation, the temperature curves in Figure 7 were obtained. The good agreement between the analog and experimental results for these tests gives added confidence to the selection and representation of the air gap by a single linear resistor for approximate analyses.

The differences in the 1/2-in thick insulation results may be due to a number of factors, of which the following are immediately suggested:

1. Over-rating of the temperature effect upon the thermal conductivity of the sprayed plaster.

2. An exothermic reaction which would tend to increase the experimental temperature curve particularly for the thicker specimens.

3. General lack of knowledge of the physical, chemical and thermal transformations during rapid heating of sprayed insulation.

The analog temperature curves for the insulated steel column in Figure 5 and the solid cylinder in Figure 6 compare favorably with the experimental curves. Since there were no complex heat flow paths or external heat losses in these two cases, the closer agreement is reasonable.

The criterion generally employed for determining the fire endurance of an insulated steel member is the time period during which the steel temperature remains below 1000°F (538°C). This corresponds to the point at which the steel starts to lose strength rapidly and consequently can no longer act as an effective structural member or fire barrier. The fire endurance times as determined by means of the analog computer are compared in Table 2 with the experimentally measured values.

The anomolous temperature record, see Figure 6, of the first cylinder test led to some qualitative investigations of the behavior of thermocouples imbedded in this type of sprayed insulation. A discussion of the results obtained may be useful in the interpretation of this as well as future experimental data.

Following the second cylinder test, one of the thermocouples located along the center line of the cylinder was removed and checked for calibration. At a temperature of 91°C within a heated oven, the test thermocouple reading was within one degree of a mercury-in-glass thermometer reading and identical to that from another thermocouple which had not been fire-exposed. At this temperature, at least, the calibration of this thermocouple was not seriously in error.

The effect of the sprayed insulation on the temperature readings during a fire test was examined in a series of tests employing an electrically heated furnace set at about 700°C, a porcelain crucible or stainless steel wire basket, some sprayed insulation and several thermocouples. The following conclusions were indicated from the results obtained:

1. Sprayed insulation was not incombustile, but generated heat when exposed to high temperatures; there was a significant temperature rise (greater than 50 degrees C) above the furnace temperature when a small sample was placed in a furnace at about 700°C. This occurred when bare or insulated thermocouples were used for the measurements.

2. The reading of a thermocouple which passes through the sprayed insulation without an electrically impermeable covering will be affected by the surrounding insulation at high temperatures. This was determined using No. 24 B&S (.020 in. dia) insulated chromel-alumel thermocouple wire, the type generally used in National Bureau of Standards fire tests. The same effect does not occur during the burning of the thermocouple insulation in air at these temperatures.

3. This effect results from electrical conductance (a partial short circuit) through the sprayed insulation. It was determined that the electrical resistance between two separate and bare chromel and alumel wires placed in close proximity within the sprayed insulation may decrease to 10K ohms or less during exposure to high temperatures. The same result was obtained with insulated chromel and alumel wires inasmuch as the thermocouple insulation also breaks down at these temperatures. After a period of time at these temperatures, the resistance was found to increase and approach the initial open circuit resistances.

A possible explanation for the anomolous temperature behavior of the first cylinder test may therefore be formulated as follows:

The thermocouple located along the vertical center line of the cylinder passed up through the sprayed insulation and passed through a fairly sharp temperature gradient. At a time when the center was still cool, the surface layers experienced a rapid temperature rise corresponding to the application of the standard fire exposure. At the high temperatures, there was a breakdown of the thermocouple insulation and also a decrease in the electrical resistance of the surrounding spray insulation. The emf output of the thermocouple circuit represented a combination of (a) the low temperature at the thermocouple junction along the cylinder centerline and (b) the high temperature at the location of the (partial) short near the cylinder surface. Consequently an erroneously high reading was obtained. This may have been due, in part, to heat generated by combustible material in the sprayed insulation. After a period of time, the electrical resistance of the sprayed insulation increased and the partially shorted condition disappeared. The readings then decreased and approached the true temperatures at the thermocouple junctions. The fact that the temperature record for the second cylinder test did not show this unusual effect means that the sprayed insulation had undergone an irreversible physical, chemical or electrical transformation during the high temperature exposure of the first test.

This effect was not observed in the fire tests of the sprayed column and two-foot slabs inasmuch as the thermocouple leads were not brought out through sharp temperature gradients within the sprayed insulation.

6. References

[1] American Society for Testing Materials. "Standard Methods of Fire Tests of Building Construction and Materials," ASTM Designation E 119-59 T.

[2] Robertson, A. F. and Gross, D.,"An Electrical-Analog Method for Transient Heat-Flow Analysis," J. Res NBS, 61, 105-115, Aug 1958.

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Table 1. Assumed Thermal Properties of Sprayed Plaster

Temperature	Density	Specific Heat	Thermal Conductivity	Remarks
°C	gm/cm3	cal/gm °C	cal/gm °C	
23	0.334		0.000117	Measured
100		0.22	.00015	
200		0.25	.00018	
400		0.28	.00026	
600		0.29	.00036	
800		0.29	.00048	

Table 2. Fire Endurance of Steel and Sprayed Insulation Assemblies

Comparison of Experimental and Analog Results

	Fire Endurance Time (1000°F), min	
	Experiment	Analog
1/2-in. Sprayed Insulation on Steel Plate	68	37
1-in. Sprayed Insulation on Steel Plate	140	125
2-in. Sprayed Insulation on Steel Plate	>300	>300
1/2-in. Sprayed Insulation on Steel Column	36	44

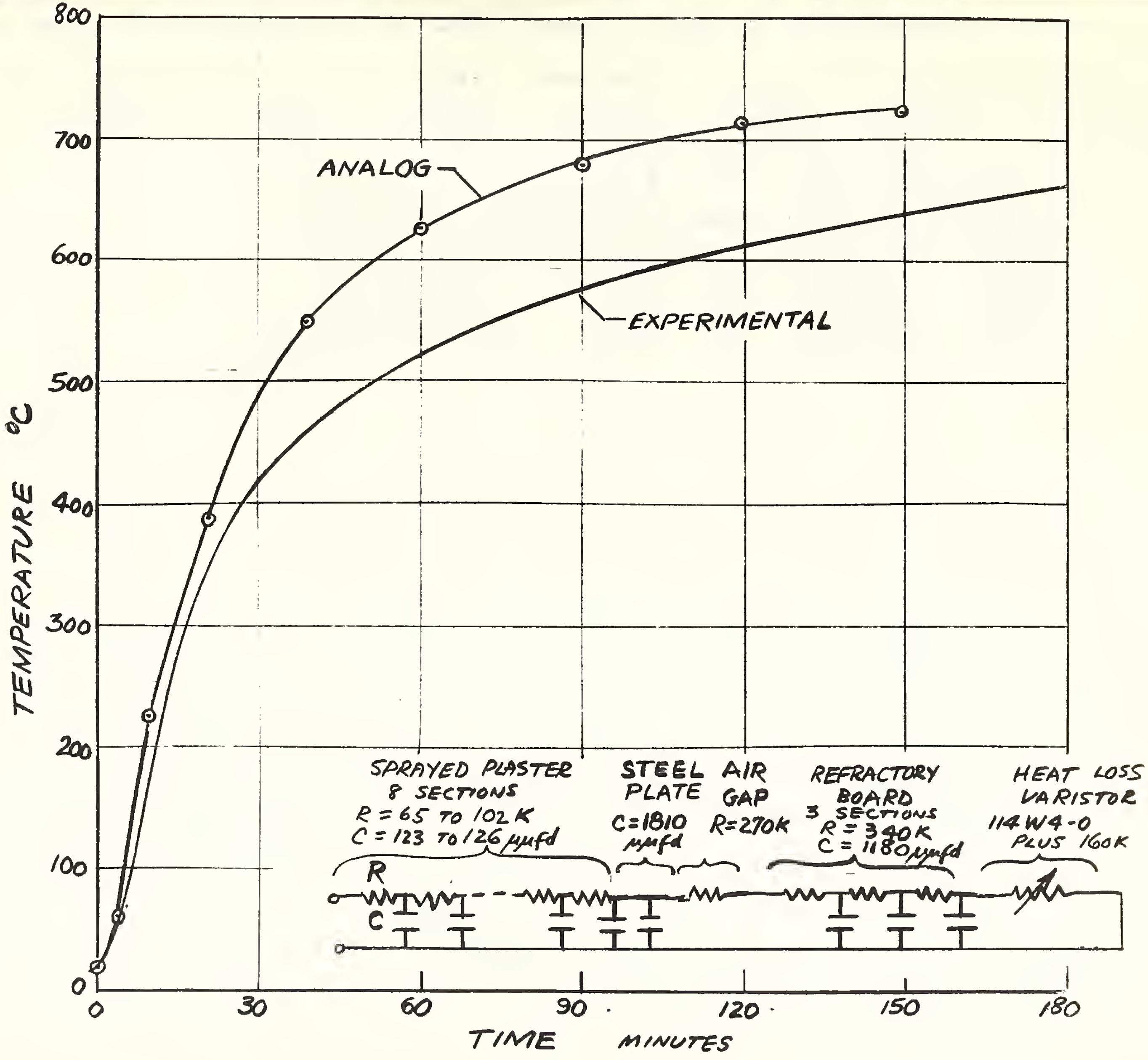

FIG. 1 TEMPERATURE OF A STEEL PLATE WITH 1/2 IN. SPRAYED INSULATION SUBJECTED TO STANDARD FIRE EXPOSURE

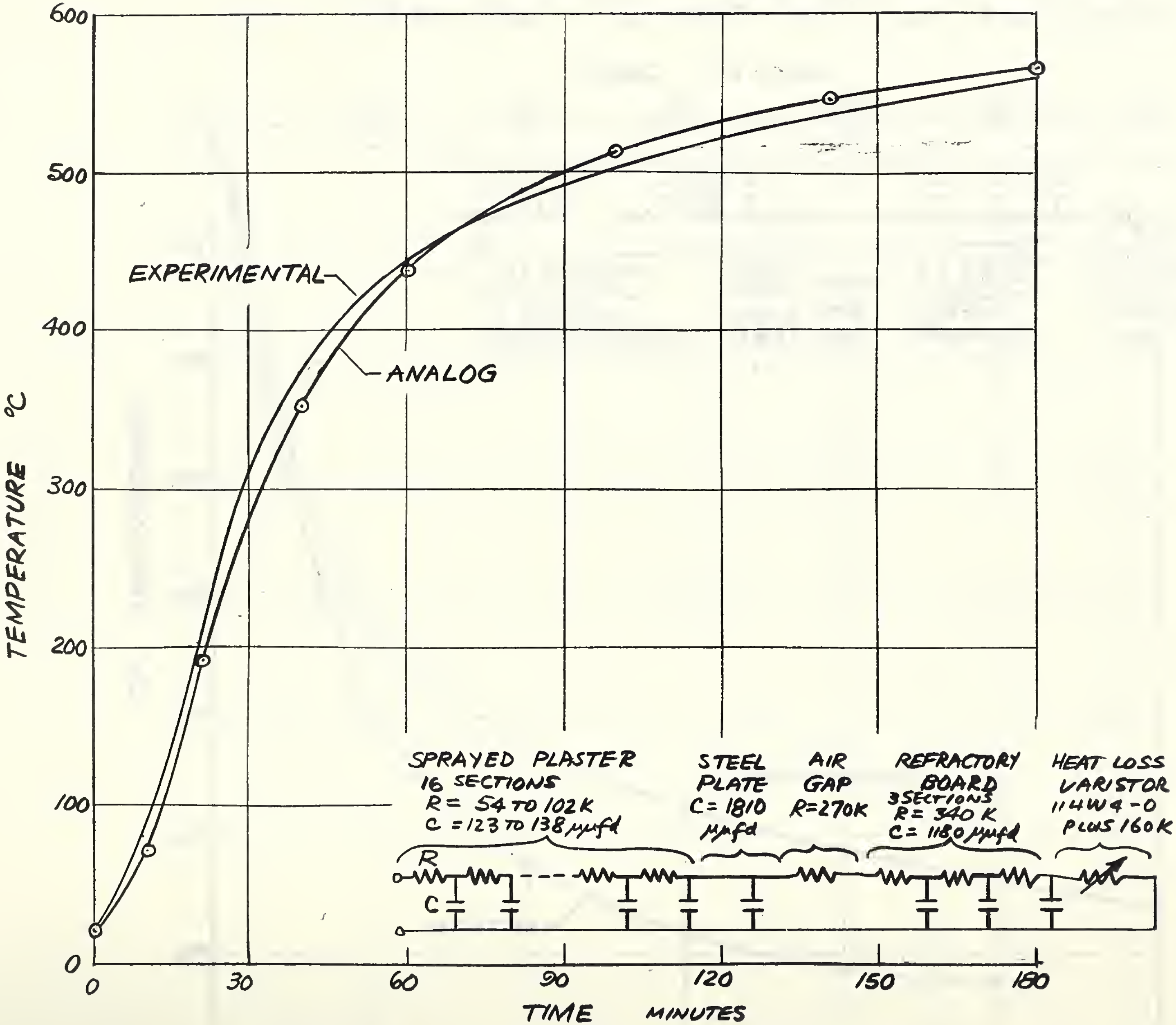

FIG. 2 TEMPERATURE OF A STEEL PLATE WITH 1 IN. SPRAYED INSULATION SUBJECTED TO STANDARD FIRE EXPOSURE

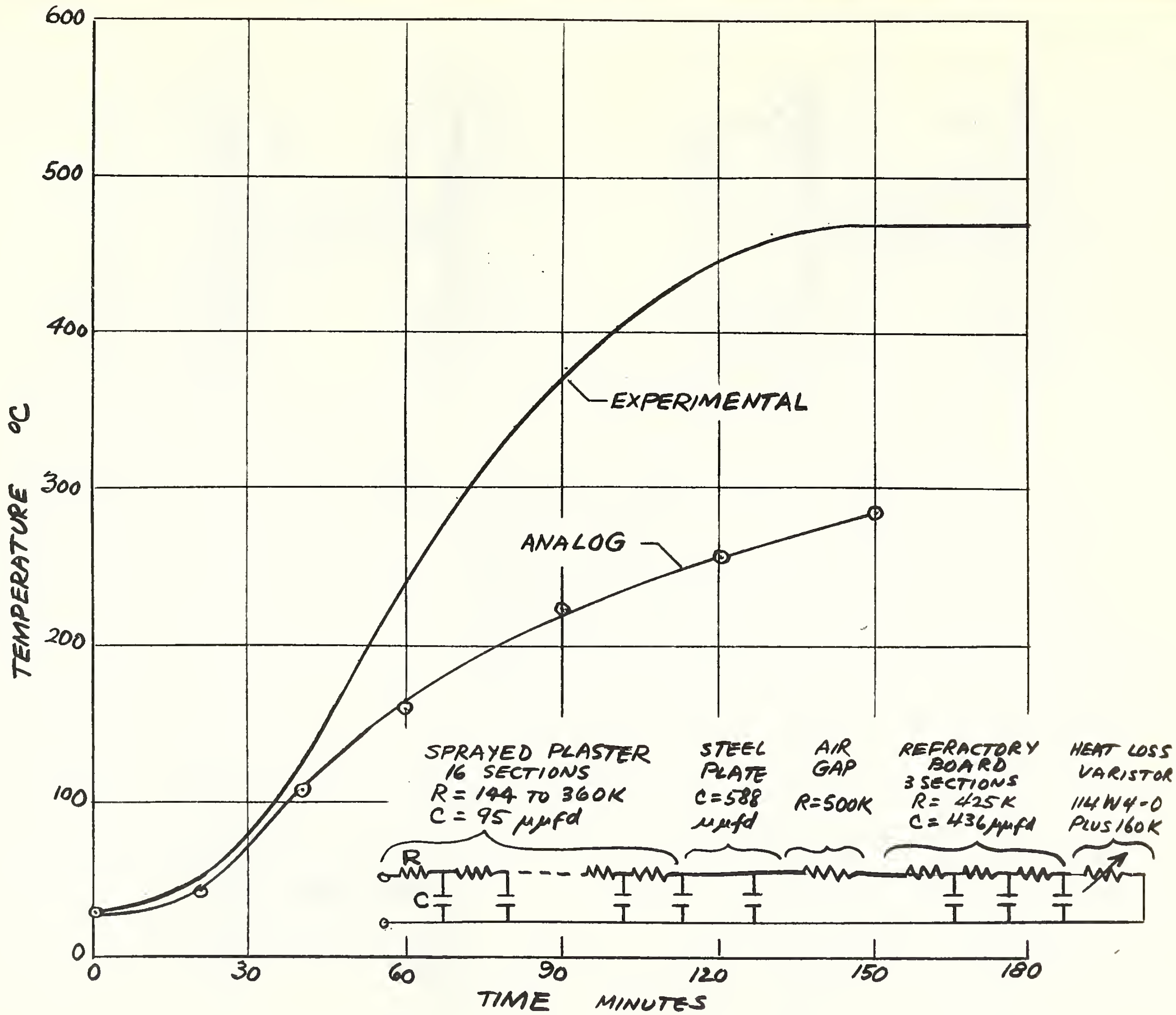

FIG. 3 TEMPERATURE OF A STEEL PLATE WITH 2 IN. SPRAYED INSULATION SUBJECTED TO STANDARD FIRE EXPOSURE

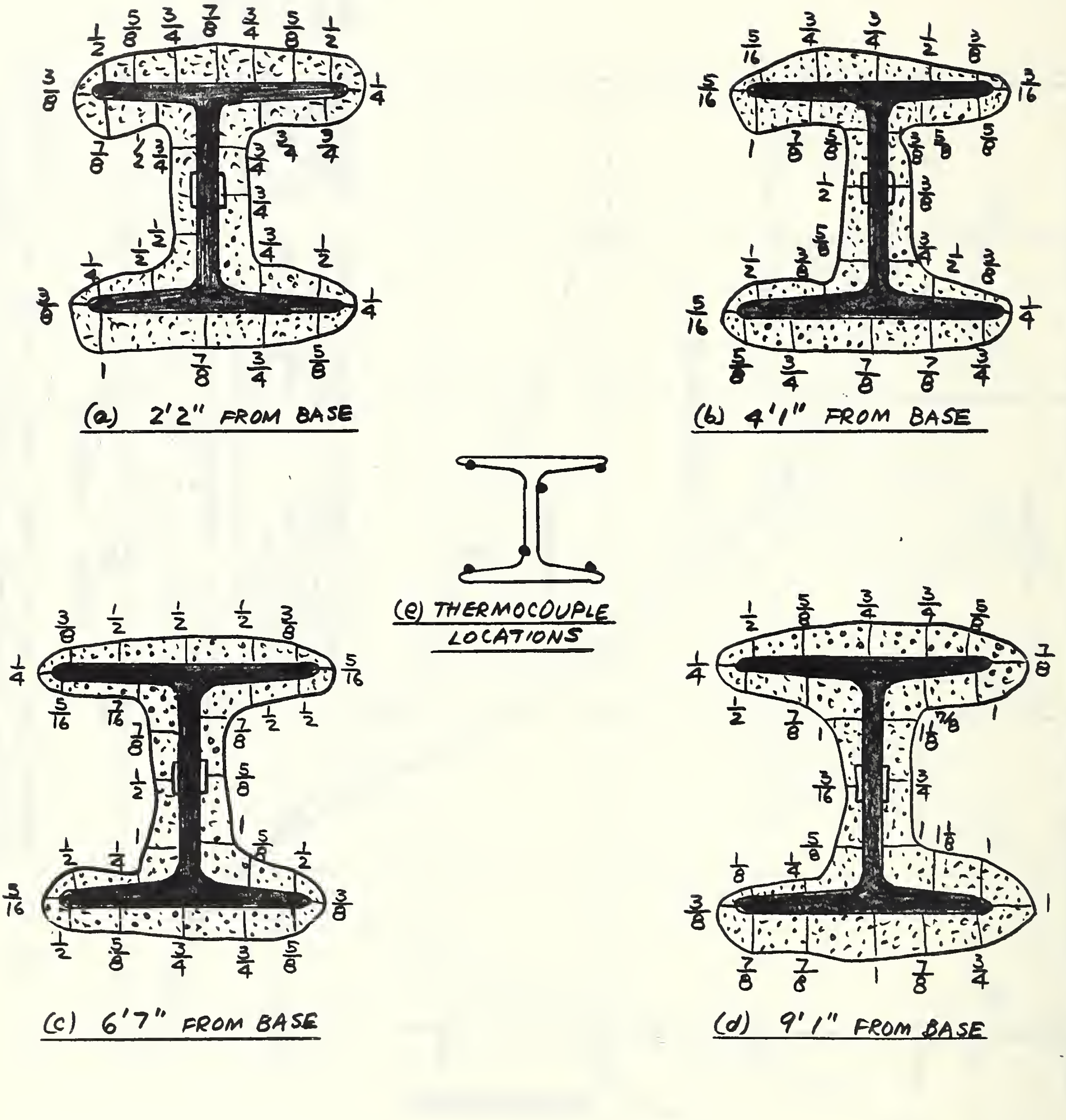

FIG. 4 MEASURED THICKNESS OF SPRAYED INSULATION ON 6 BY 6 IN. STANCHION COLUMN

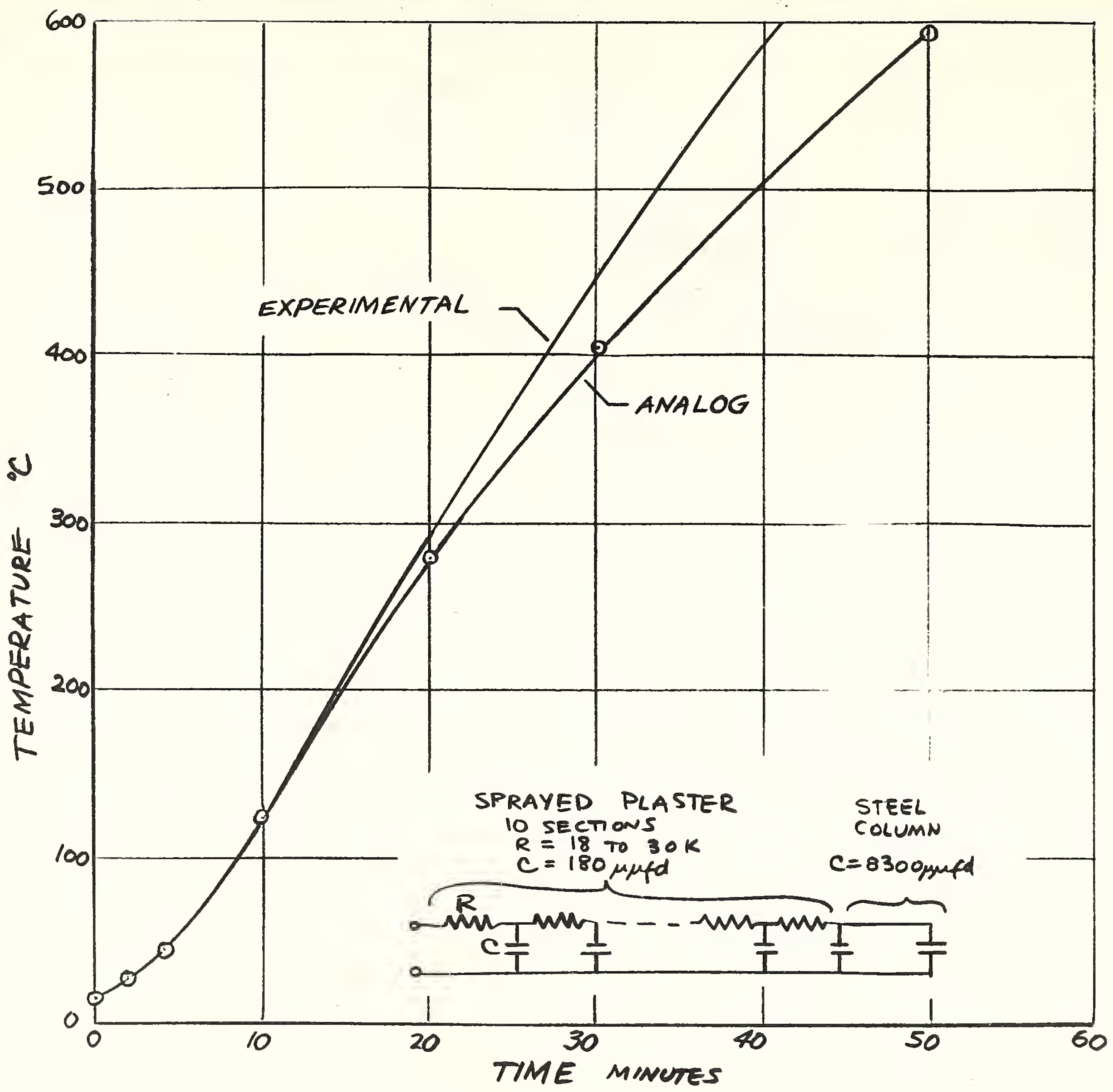

FIG. 5 TEMPERATURE OF A STEEL COLUMN WITH 1/2 IN. SPRAYED INSULATION SUBJECTED TO STANDARD FIRE EXPOSURE

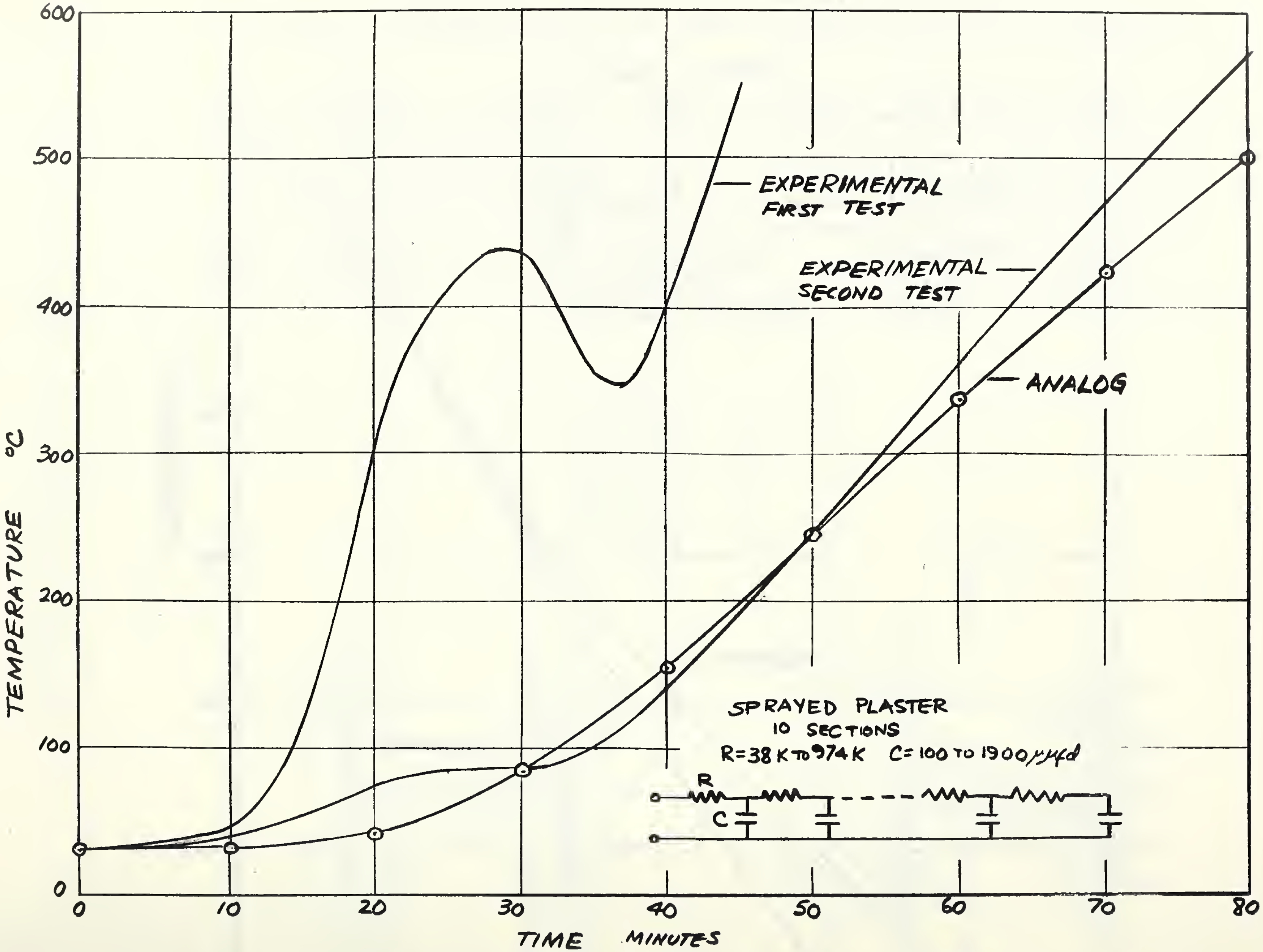

FIG. 6 TEMPERATURE AT CENTER OF 6 IN. DIA. CYLINDER OF SPRAYED INSULATION SUBJECTED TO STANDARD FIRE EXPOSURE

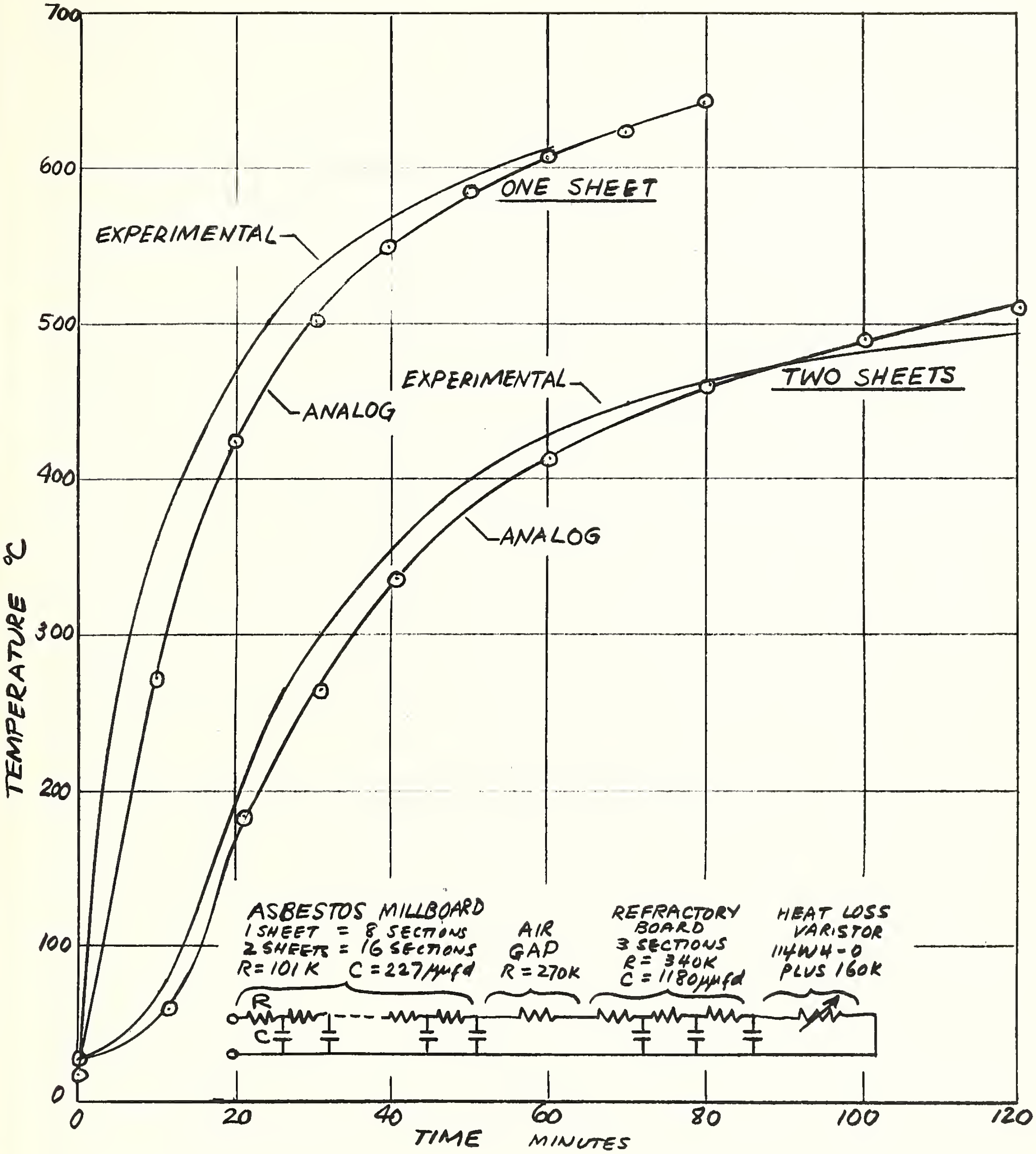

FIG. 7 TEMPERATURE ON UNEXPOSED SURFACE OF ASBESTOS MILLBOARD SHEETS SUBJECTED TO STANDARD FIRE EXPOSURE

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