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A TRANSIENT HEAT TRANSFER ANALYSIS OF THE MTR MOCK-UP

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REACTOR TECHNOLOGY DIVISION

A TRANSIENT HEAT TRANSFER ANALYSIS OF THE MTR MOCK-UP

H. F. Poppendiek
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SUMMARY

The Project Department of the Reactor Technology Division requested that a prediction of the transient thermal behavior of the MTR Mock-up be made for the hypothetical condition that all cooling water is suddenly removed from the system.

The differential equations involved were solved by a numerical method for the pessimistic case of instantaneous and complete removal of cooling water. Analyses for two power levels of operation before shut-down were investigated.

It was found that for an initial power level of 500 KW the melting temperature of the aluminum fuel assembly was reached in 135 minutes at a point 16.8 inches from the top of the fuel assembly. For an initial power level of 1300 KW, melting occurred at 22.6 inches from the top in 26 minutes.

[redacted]

NOMENCLATURE

a,	thermal diffusivity of heat ($k/\gamma\ c_p$), ft^2/hr
A,	heat transfer area, ft^2
A_s,	cross sectional area of flow tube, ft^2
C,	thermal capacitance, Btu/°F
c_p,	heat capacity, Btu/lb °F
$G(\theta,x)$,	heat generated per foot of flow tube length, Btu/hr ft
k,	thermal conductivity, Btu/hr ft^2 (°F/ft)
P,	power level before shut-down, KW
q,	heat transfer rate, Btu/hr
Q,	average cumulative heat generated for the whole lattice, Btu
Q_m,	maximum heat generated for the whole lattice, Btu
R,	thermal resistance, hr °F/Btu
t,	temperature, °F
W,	weight of solid, lb
x,	distance along flow tube (origin at top of fuel assembly), ft
γ,	density, lb/ft^3
Δ,	a finite increment
θ,	time after shut-down, hr

<u>Subscripts</u>:

c	refers to capacitance
g	refers to air gap
k	refers to the kth time increment
l	refers to the left of a capacitance
n	refers to the nth distance increment
r	refers to the right of a capacitance
t	refers to total

[redacted]

INTRODUCTION

The writers of this report have been asked to predict the transient temperature behavior of the MTR Mock-up under the hypothetical conditions that all the cooling water for this reactor is suddenly removed from the system without the addition of replacement water.

This problem has arisen in connection with some safety considerations regarding the MTR Mock-up. In the event that the lower portion of the Mock-up is seriously damaged so that all of the cooling water would suddenly leave the system, the reactor would cease operating but the fission products would continue to decay and emit energy in the form of beta and gamma particles. The resulting heat generated, which can be represented by a decreasing power function, would be partially stored within the fuel plates and partially conducted to and stored within surrounding reactor components. However, for the hypothetical problem under consideration, no heat is lost from the fuel plates and surrounding components by convection to water because it has been postulated to be non-existent. Large transient fuel plate temperature rises can occur in the absence of cooling water. In particular it is desired to discover how much time will elapse before these plates will reach the melting temperature.

[redacted]

ACTUAL SYSTEM

A detailed description of the fuel assembly and surrounding reactor components that comprise the thermal circuit can be obtained from the numerous design drawings of the Mock-up.*

The fuel assemblies, which weigh about 14 lb. each, are supported in an aluminum grid. Each assembly (see drawing TD-1472 and DRP-291) is composed of 18 parallel aluminum-uranium fuel plates joined by end plates of aluminum and spaced 0.177 inches center to center. Each fuel plate is 24 5/8 inches long and 2.62 inches wide. It is composed of a sandwich of an aluminum-uranium alloy between two plates of aluminum; each layer is 0.020 inches thick making the total fuel plate thickness equal to 0.060 inches.

The aluminum grids contain 45 spaces for fuel assemblies and beryllium reflectors (see drawing TD-601). The Mock-up loading considered for the analysis under consideration was 15 fuel assemblies and 20 beryllium reflectors. These reflectors weigh about 25 lb. apiece.

The lower grid (weight about 40 lb) is supported by a 2000 lb. aluminum casting by means of two aluminum skirt plates each weighing about 10 lb. (see drawing TD-597). An aluminum plate, 1/4 inch thick and weighing about 35 lb., lies upon the aluminum casting and supports the external reflector. The external reflector consists of stacked beryllium bricks with a total weight of about 2000 lb.

---

* Messrs K. C. Baczewski and S. E. Beall supplied valuable data concerning the reactor.

[redacted]

There are structural members below the aluminum casting which support it and also a superstructure surrounding the fuel assemblies and reflector. These structural members are enclosed in an outer aluminum shell which is lagged by concrete blocks and sand. The thermal resistances between 1) the aluminum casting and the supporting structural members and 2) the upper grid and structural members are estimated to be very large compared to the other thermal resistances in the circuit.

[redacted]

IDEAL SYSTEM

Heat flow within the fuel assembly is essentially unidirectional because the dimensions of the heat transfer cross sectional area of the fuel assembly are small compared to the fuel assembly length. Thus, it is possible to trace a heat flow tube through the thermal system under consideration. This tube consists of prorated portions of the following reactor elements: 1) the fuel assembly, 2) the grid, 3) the inner beryllium reflector, 4) the skirt plate, 5) the aluminum casting, 6) the aluminum plate, 7) the beryllium bricks, and 8) the air gaps (contact resistances) which lie between these elements. An ideal heat flow tube which represents the actual one is schematically represented in Figure 1. This tube is composed of distributed and lumped circuits. The lumped circuit was used for convenience because the thermal elements in that part of the circuit consisted of 1) relatively large thermal resistances (air gaps) with negligible thermal capacitances and 2) relatively large thermal capacitances (grid, casting, etc.) with negligible thermal resistances.

The contact resistance between the grid and the inner beryllium reflector has been removed from that portion of the circuit and inserted, in part, in series with the other thermal resistances. This modification was effected to facilitate the calculation procedure*.

---

* It is felt that this modification is valid because the grid-inner beryllium reflector contact resistance is small compared to the other adjacent thermal resistances in the circuit such as the grid-skirt plate contact resistance.

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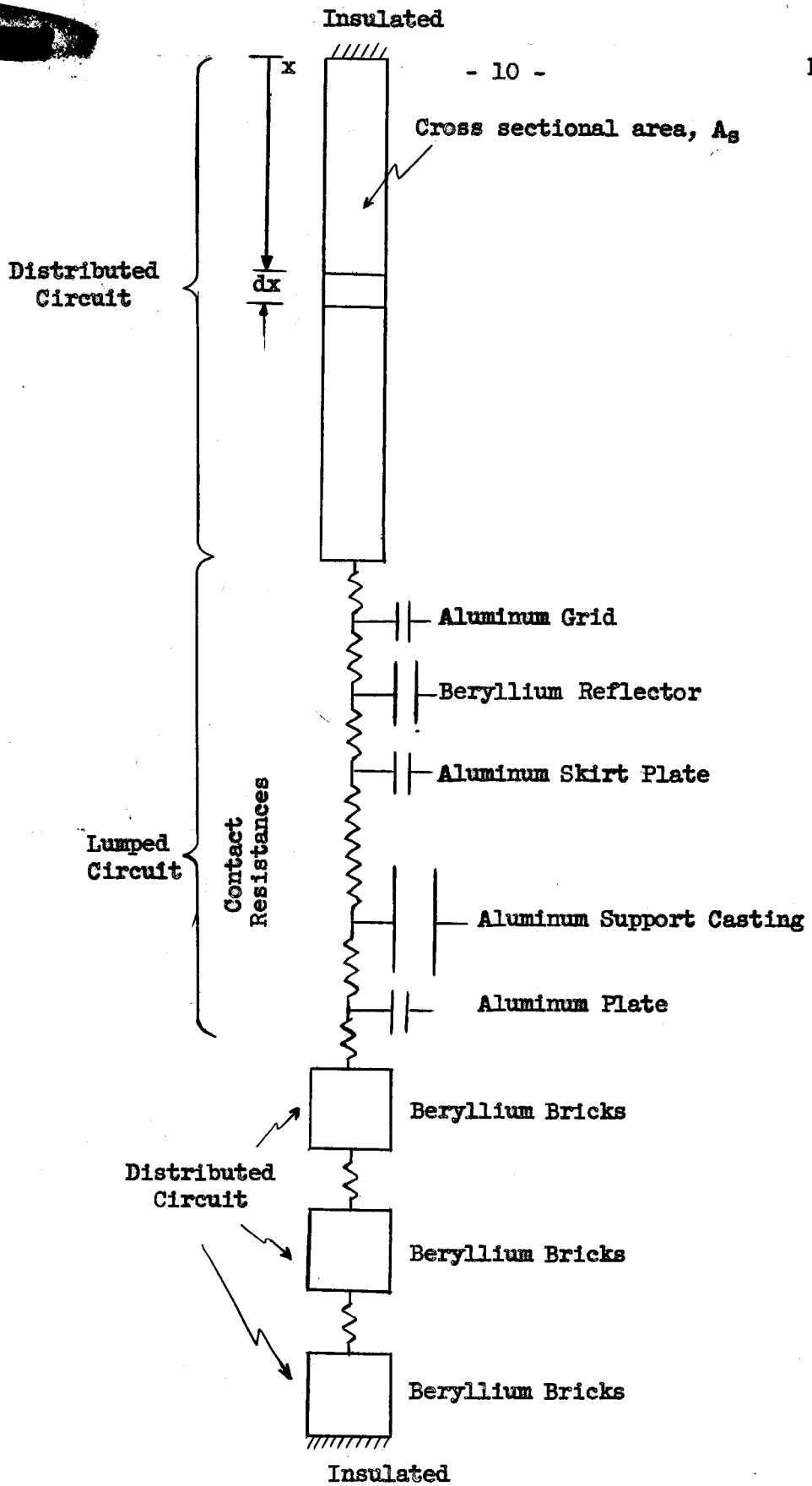

FIGURE 1

IDEAL HEAT FLOW CIRCUIT

[redacted]

In the ideal system the many beryllium bricks and corresponding contact resistances in the actual system were represented by three beryllium slabs separated by two lumped contact resistances. This modification, which was effected to facilitate the calculation procedure, was justified because this substitute circuit (containing the same total resistance and capacitance as before modification) is located far from the fuel assembly.

It is postulated that no heat is transferred from the flow tube via radiation because the tube is surrounded by other flow tubes of the same temperature. Of course, those flow tubes near the boundary of the bundle of tubes will lose heat by radiation and will consequently be at a lower temperature; thus only the inner flow tubes need be considered.

The thermal circuit shown in Figure 1 has been postulated to be insulated from the outer structural members of the reactor because of the high thermal resistance between this circuit and the outer structural members and the surroundings. Therefore, all heat generated within the fuel assemblies is conducted and stored within the elements shown in Figure 1. Actually, heat would flow very slowly to the surroundings after a long period of time had elapsed. However, this heat flow would only influence the later part of the temperature history (beyond the region where the temperature-time curve has become very flat) which is of no particular consequence because only maximum temperature rises and the time of their occurrence are of interest here.

The contact resistances* in the thermal circuit were estimated with the aid of S. E. Beall, who supervised the construction of the MTR Mock-up. Some experiments to determine regions of good contact between the fuel assemblies and the grid, using Prussian blue dye, were conducted. Table I, which follows, presents the results of an evaluation of the contact resistances for the heat flow tube. Thermal resistance is defined as

$$R_t = \frac{\Delta x_g}{k_g A_g} = \frac{\Delta t_g}{q} \qquad (1)$$

Δx_g, gap thickness, ft.

k_g, thermal conductivity of air gap, Btu/hr ft^2 ($^\circ$F/ft)

A_g, heat transfer area, ft^2

Δt_g, temperature drop across gap, $^\circ$F

q, heat flow, Btu/hr

---

* These resistances consist of air gaps for the particular problem under consideration.

[redacted]

TABLE I

Contact Resistances Along Flow Tube

Location	Mean area, ft^2	Mean gap thickness, inches	Thermal resistance, °F hr/Btu
Fuel Assembly to grid	0.000453	0.001	10.2
Grid to Be reflector	0.000604	0.001	7.70
Grid to skirt plate	0.0000773	0.0005	30.0
Skirt plate to aluminum casting	0.000590	0.0005	3.92
Aluminum casting to aluminum plate	0.0238	0.015	2.92
Aluminum plate to beryllium brick	0.0150	0.01	3.09
Between beryllium bricks	6.01	0.003	0.926

The resistances in Table I were computed for air at 200 °F; in the solution itself, the variation of thermal conductivity with temperature was considered, (see Appendix for physical properties). Note that the major thermal contact resistance is located between the grid and the skirt plate.

It was felt that the control rods need not be included in this analysis for the following reason. Although the control rods, which contain fuel, will also release heat after shut-down, they are massive (130 lb each) and project into the superstructure which is open to the air and thus should be able to satisfactorily conduct away and store the generated heat.

[redacted]

EQUATIONS OF HEAT TRANSFER

A. Distributed Circuit

A heat balance on a differential flow tube volume dx units long with a cross sectional area A_s is

heat generated = net heat conducted out + heat stored

$$G(\theta,x)dx = -\frac{\partial}{\partial x}\left[k A_s \left(\frac{\partial t}{\partial x}\right)\right] dx + c_p \gamma A_s dx \frac{\partial t}{\partial \theta} \qquad (2)$$

where

$G(\theta,x)$, heat generated per foot of flow tube length, Btu/hr ft

k, thermal conductivity of solid, Btu/hr ft^2 (^oF/ft)

A_s, cross sectional area of flow tube, ft^2

t, temperature of flow tube, ^oF

θ, time after shut-down, hr

x, distance along flow tube (origin at top of fuel assembly), ft

c_p, heat capacity of solid, Btu/lb ^oF

γ, density of solid, lb/ft^3

Upon rearranging equation (2) and noting that k and A_s are very insensitive functions of x in the fuel assembly region, there results

$$\frac{\partial t}{\partial \theta} = \left(\frac{k}{\gamma c_p}\right) \frac{\partial^2 t}{\partial x^2} + \frac{G(\theta,x)}{\gamma c_p A_s} \qquad (3)$$

This equation can be transformed to the following finite difference equation:

$$t_{n,k+1} = t_{n,k} + \frac{2a \Delta \theta}{\Delta x^2}\left[\frac{t_{n+1,k} + t_{n-1,k}}{2} - t_{n,k}\right] + \frac{G(\theta,x) \Delta \theta}{c_p \gamma A_s} \qquad (4)$$

where,

n, refers to the nth distance increment

k, refers to the kth time increment

$a = \dfrac{k}{\gamma\, c_p}$, thermal diffusivity of the solid, ft^2/hr

$\Delta\theta$, time increment, hr

Δx, distance increment, ft

If Δx and $\Delta\theta$ are chosen* such that $\dfrac{2a\,\Delta\,\theta}{\Delta\bar{x}^2} = 1$, equation (4) reduces to

$$t_{n,k+1} = \frac{t_{n+1,k} + t_{n-1,k}}{2} + \frac{G(\theta,x)\,\Delta\,\theta}{c_p\,\gamma\,A_s} \tag{5}$$

This equation can be used to determine the transient thermal structure in the distributed circuit.

B. Lumped Circuit

A heat balance on a typical R-C unit of a lumped circuit (see Figure 2) is

$$q_l = q_r + q_c \tag{6}$$

or

$$\frac{t_l - t_c}{R_l} = \frac{t_c - t_r}{R_r} + C\,\frac{\partial t}{\partial \theta} \tag{7}$$

where

q_l, heat flow through left resistance, Btu/hr

q_r, heat flow through right resistance, Btu/hr

q_c, heat flow into the capacitance, Btu/hr

t_l, t_r, t_c, the temperatures in the thermal circuit shown in Figure 2, °F

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*Further remarks on the selection of these increments are to follow.

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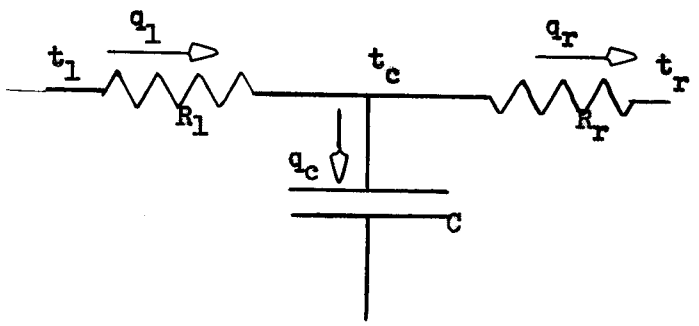

FIGURE 2

TYPICAL RESISTANCE-CAPACITANCE UNIT

[redacted]

R_l, R_r, the left and right thermal resistances, ^oF hr/Btu

$C = Wc_p$, thermal capacitance, Btu/^oF

W, weight of the lumped capacitance, lb

c_p, heat capacity of the lumped capacitance, Btu/lb ^oF

Equation (7) can be expressed in finite difference form as follows:

$$\frac{t_{l,k} - t_{c,k}}{R_l} = \frac{t_{c,k} - t_{r,k}}{R_r} + C \left[\frac{t_{c,k+1} - t_{c,k}}{\Delta \theta} \right] \tag{8}$$

or

$$t_{c,k+1} = t_{c,k} + \frac{\Delta \theta}{C} \left[\frac{t_{l,k} - t_{c,k}}{R_l} - \frac{t_{c,k} - t_{r,k}}{R_r} \right] \tag{9}$$

This equation can be used to determine the transient thermal structure in the lumped circuit.

HEAT SOURCE TERM

The following equation* gives the average cumulative heat generation for eighteen active units (fifteen fuel assemblies and three shim-safety rods) in the lattice.

$$Q = 60.2\ P\theta^{0.85} \tag{10}$$

where

Q, average cumulative heat generated for the whole lattice, Btu

P, power level before shut-down, KW

θ, time after shut-down, hr

The thermal flux distribution within the Mock-up is not uniform. Thus, the coefficient 60.2 in equation (10) has been increased to account for the maximum flux that exists in the lattice, or

$$Q_m = 103\ P\theta^{0.85} \tag{11}$$

Upon differentiating equation (11) and prorating to an individual heat flow tube there results

$$G(\theta,x) = \frac{87.5\ P\theta^{-0.15}}{18x18x2x2.05} = 0.0659\ P\theta^{-0.15} \tag{12}$$

where $G(\theta,x)$ is the heat generated in Btu/hr per foot of flow tube length. The data indicate that this equation is valid for $\theta \geq 0.0000278$ hr (or 0.1 second). A simple linear source expression for the interval $0 \leq \theta \leq 0.0000278$ hr, based on the premise that the heat generation at $\theta = 0$ is 9 percent of the original power level, is

$$G(\theta,x) = (0.395 - 2650\ \theta)P \tag{13}$$

---

*This equation was derived by K. C. Baczewski from results of J. A. Lane's work (memo CF 48-10-263).

NUMERICAL SOLUTION PROCEDURE

The numerical solution procedure used to solve the problem under consideration follows:

1) Select a time increment, $\Delta\theta$, sufficiently small that the transient temperature profiles do not exhibit abrupt changes.
2) Calculate the distance increments, Δx, for the distributed circuits.
3) Divide the distributed circuits into increments.
4) Starting with some given initial temperature distribution, begin the numerical procedure utilizing the finite difference equations (5) and (9).
5) Transient temperatures at the interface between distributed and lumped circuits are obtained by 1) making heat balances at the left and right sides of the interface in terms of known temperatures and thermal resistances on the two sides and the unknown temperature at the interface, 2) solving for the heat flow through the interface, and 3) solving for the temperature at the interface from one of the two heat flow expressions which now contains a known heat flow.
6) Account for physical property changes with temperature as the solution progresses by changing time increments and in some cases the distance increments.

RESULTS

A numerical solution for the problem under consideration was obtained for the following specific conditions. At the time of shut-down, the fuel assembly temperature was stipulated to be 200 °F while the casting and the succeeding components were at 100 °F. The initial power level was 500 KW. The time-temperature history of a point 16.8 inches from the top of the fuel assembly (point of maximum temperature) is shown in Figure 3. The temperature at that point reaches 1220 °F (the melting point of aluminum) in 135 minutes. The time increments used in this computation were $\Delta\theta = 0.0066543$ hr for the first 27.1 minutes and $\Delta\theta = 0.012979$ hr for the remaining time. Figure 4 shows longitudinal temperature distributions of the fuel assembly for two different times, namely, $\theta = 68$ minutes and $\theta = 135$ minutes.

For the sake of comparison, a time-temperature history of a point 22.6 inches from the top of the fuel assembly for a 1300 KW (rather than 500 KW) power level condition has been presented in Figure 5. The melting time in this case was 26 minutes.

The solutions for both cases indicated that at the time the melting temperature had been reached, only a small amount of heat had yet started to flow into the later part of the thermal circuit.

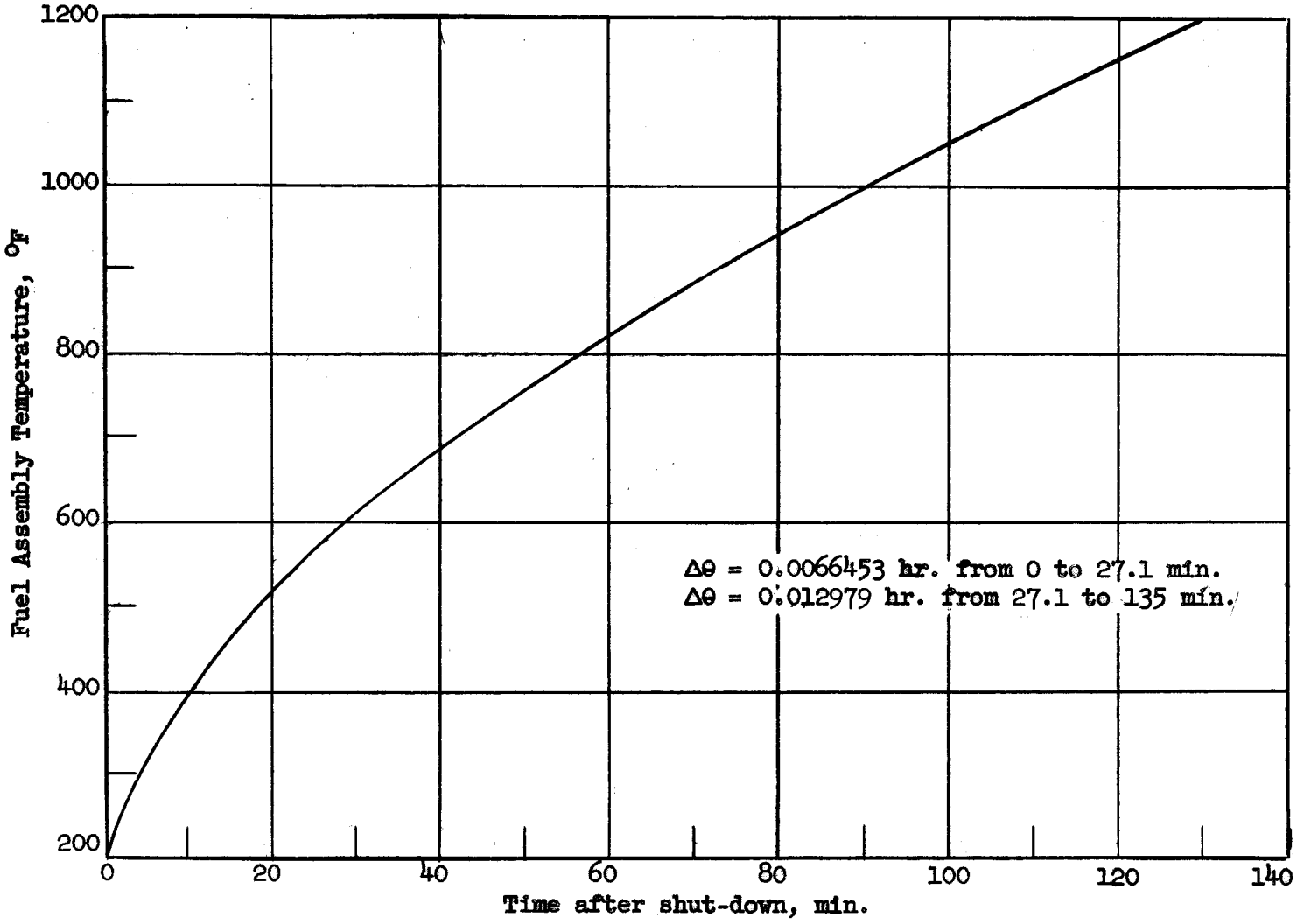

FIGURE 3
TIME-TEMPERATURE HISTORY OF A POINT WITHIN
THE FUEL ASSEMBLY (16.8 IN. FROM TOP) FOR AN INITIAL
500 KW POWER LEVEL

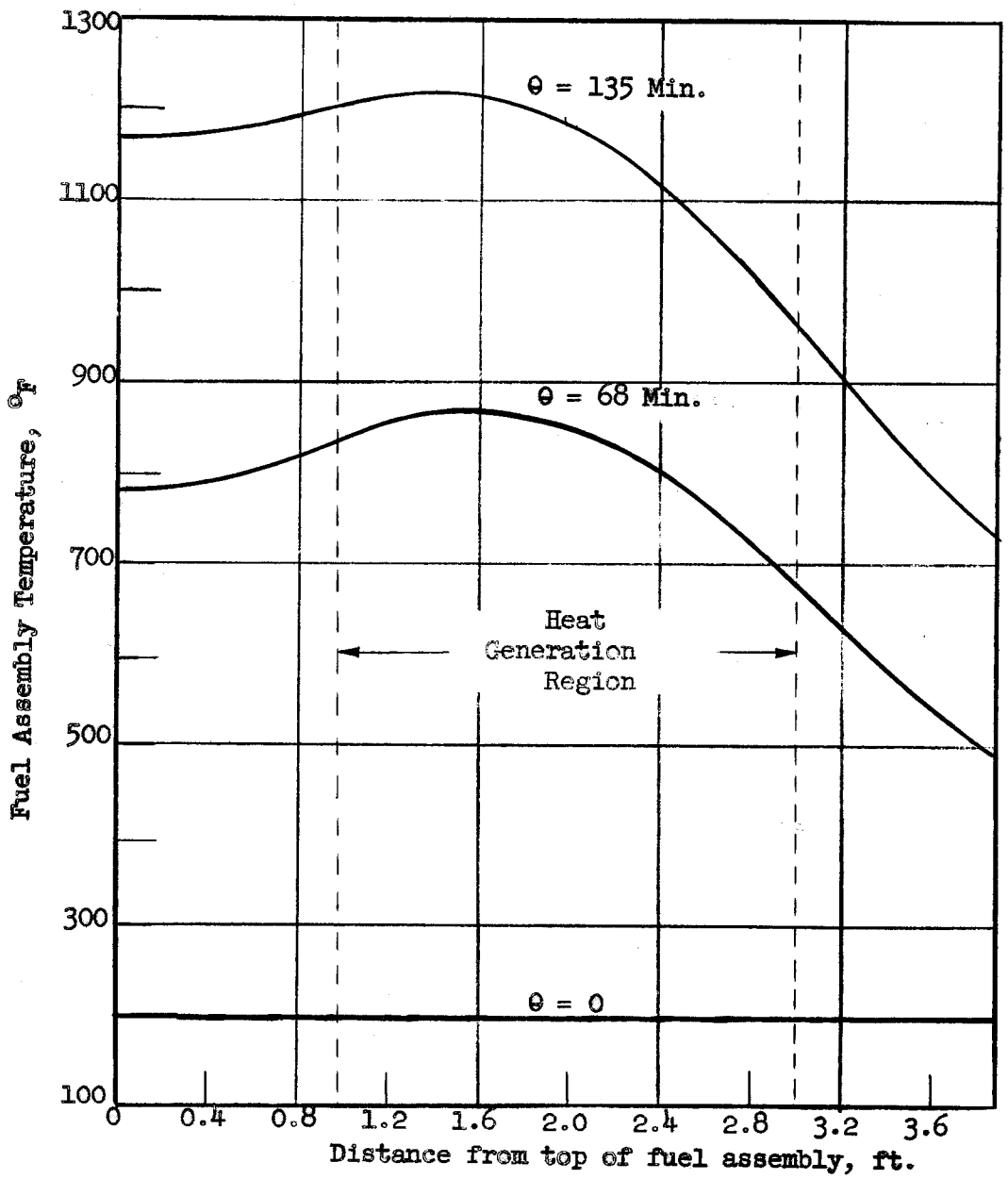

FIGURE 4

LONGITUDINAL TEMPERATURE DISTRIBUTION OF FUEL ASSEMBLY
FOR AN INITIAL 500KW POWER LEVEL

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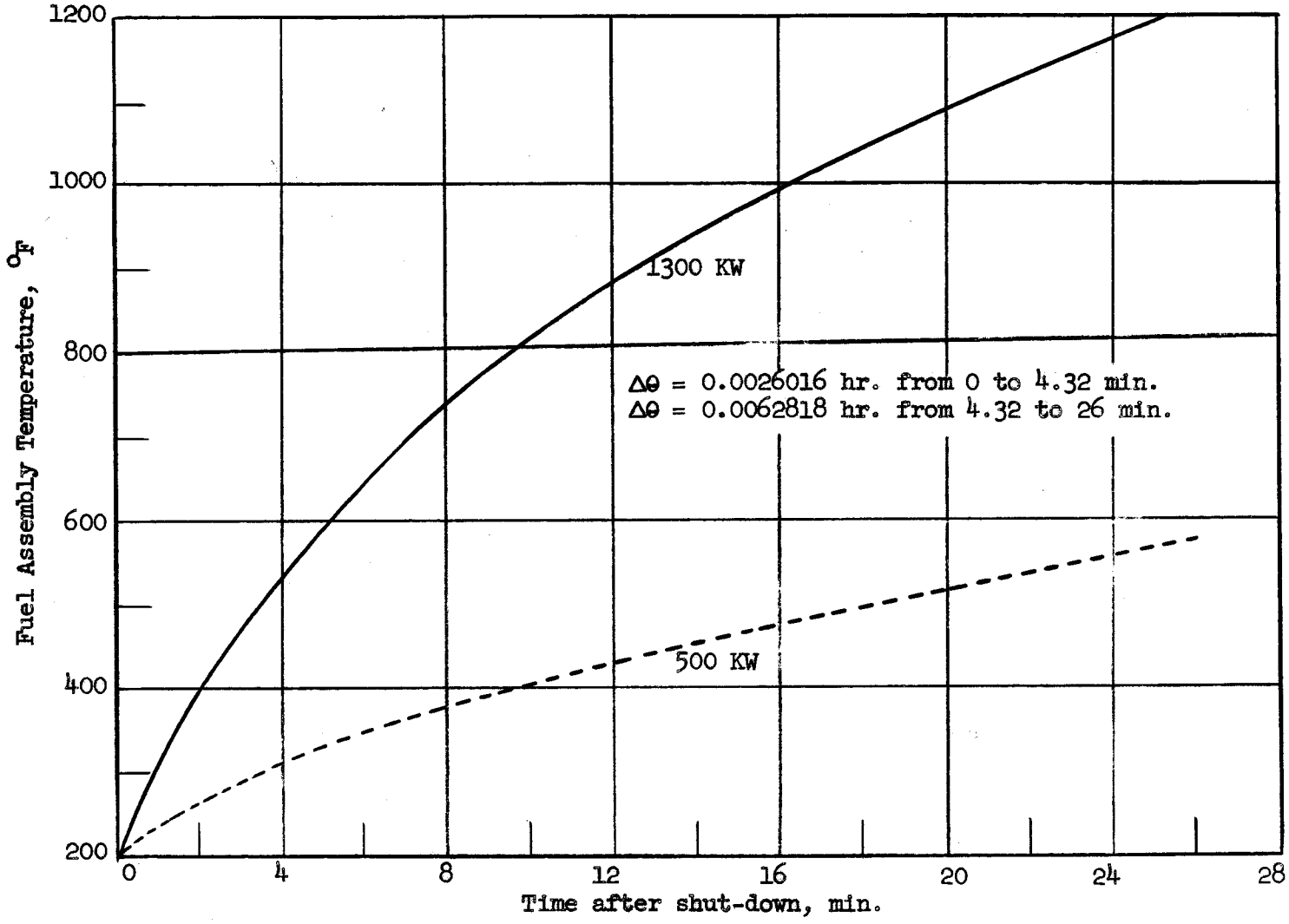

FIGURE 5

TIME-TEMPERATURE HISTORY OF A POINT WITHIN THE FUEL ASSEMBLY (22.6 In. FROM TOP) FOR AN INITIAL 1300KW POWER LEVEL

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DISCUSSION

It is again emphasized that the problem which has been studied here is a hypothetical one whose solution may be considered as a limit. Actually it is not physically possible for water to be removed from the reactor in zero time. As a matter of fact, during the finite time interval of water cooling a significant portion of the heat generated can be removed by the water because of the character of the heat source function. Also, the controlling thermal resistances in the thermal circuit (the air gaps) would be reduced by a factor of about twenty for the initial portion of the heat transfer process because the gaps would be filled with water instead of air. In addition, after the water has finally dropped through the fuel assemblies in the actual system, some water films and droplets will adhere to the fuel plates thus providing considerable evaporative cooling.

Some free convection air cooling would occur during the transient heat transfer process but this heat flow would be relatively small because 1) no draft would exist for the convection as the top of the reactor is sealed and 2) the air flow rates in the narrow gaps between fuel plates would be quite low.

It would have been and is still possible for the writers of this report to include the effects of 1) partial convective cooling by water, 2) increased heat transfer due to water contact resistances, and 3) evaporative cooling for some specific prescribed set of conditions. However, it was felt that only an analysis for a limiting case was justified at this time.

APPENDIX

THERMAL PROPERTIES

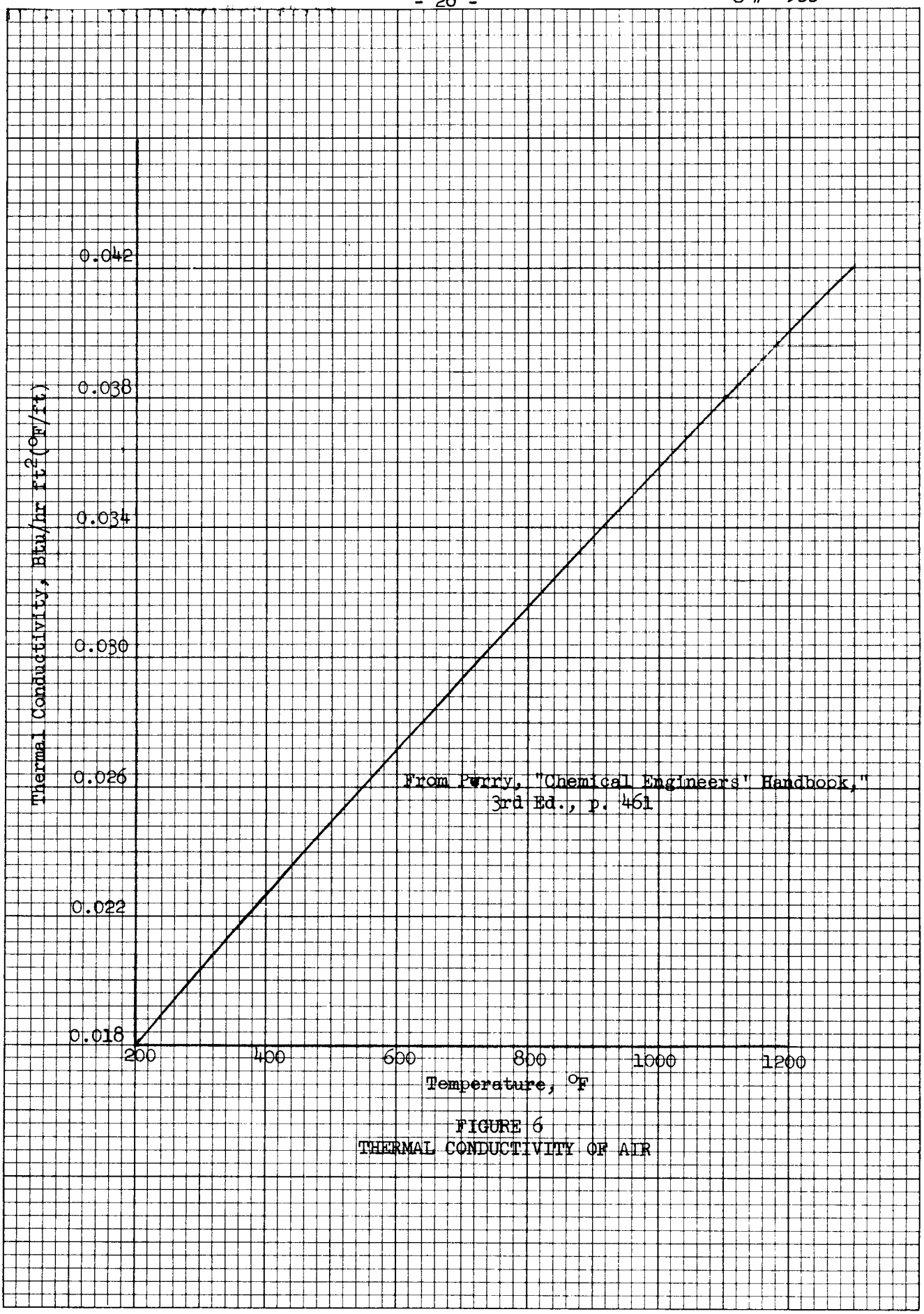

FIGURE 6
THERMAL CONDUCTIVITY OF AIR

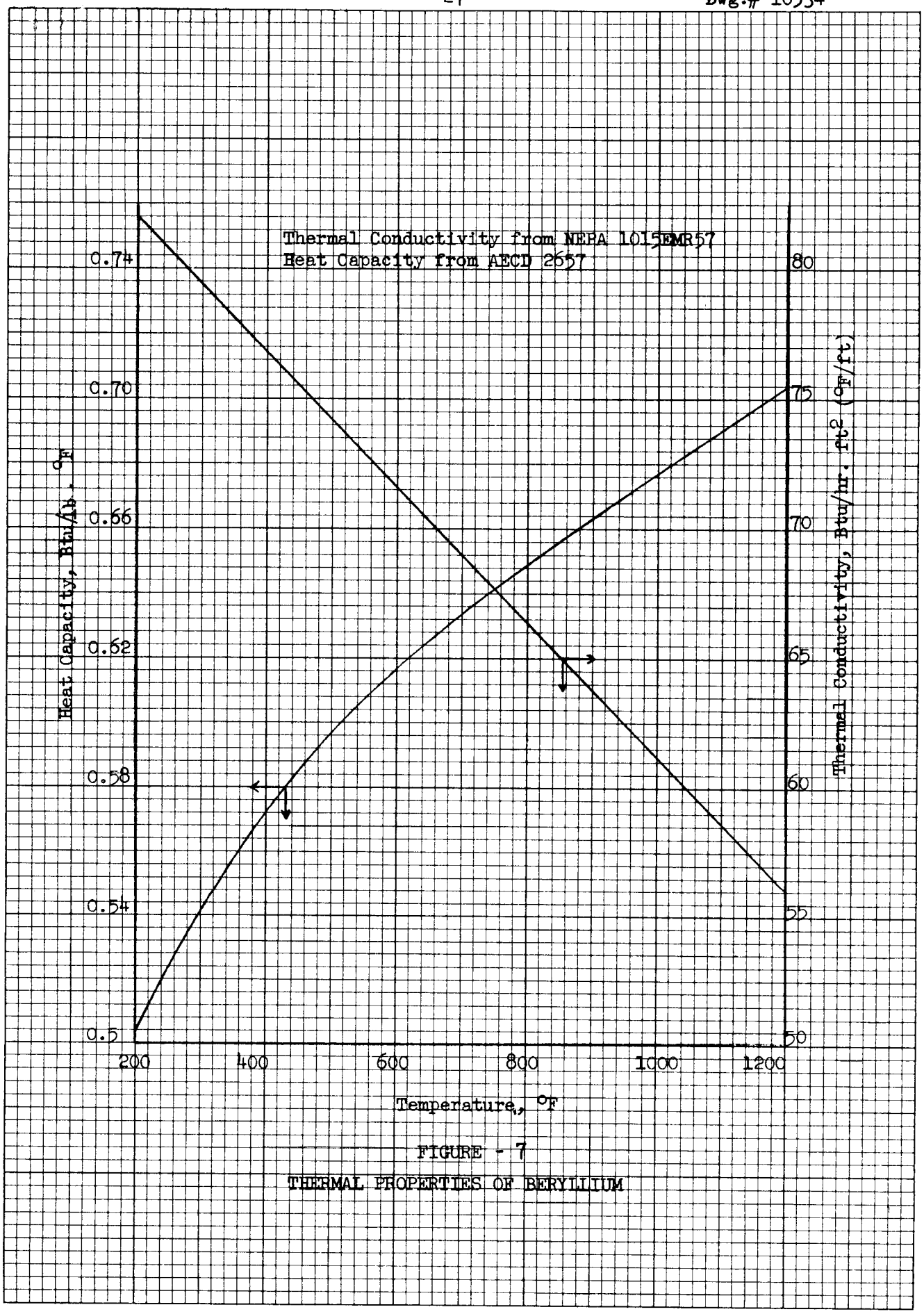

FIGURE - 7

THERMAL PROPERTIES OF BERYLLIUM

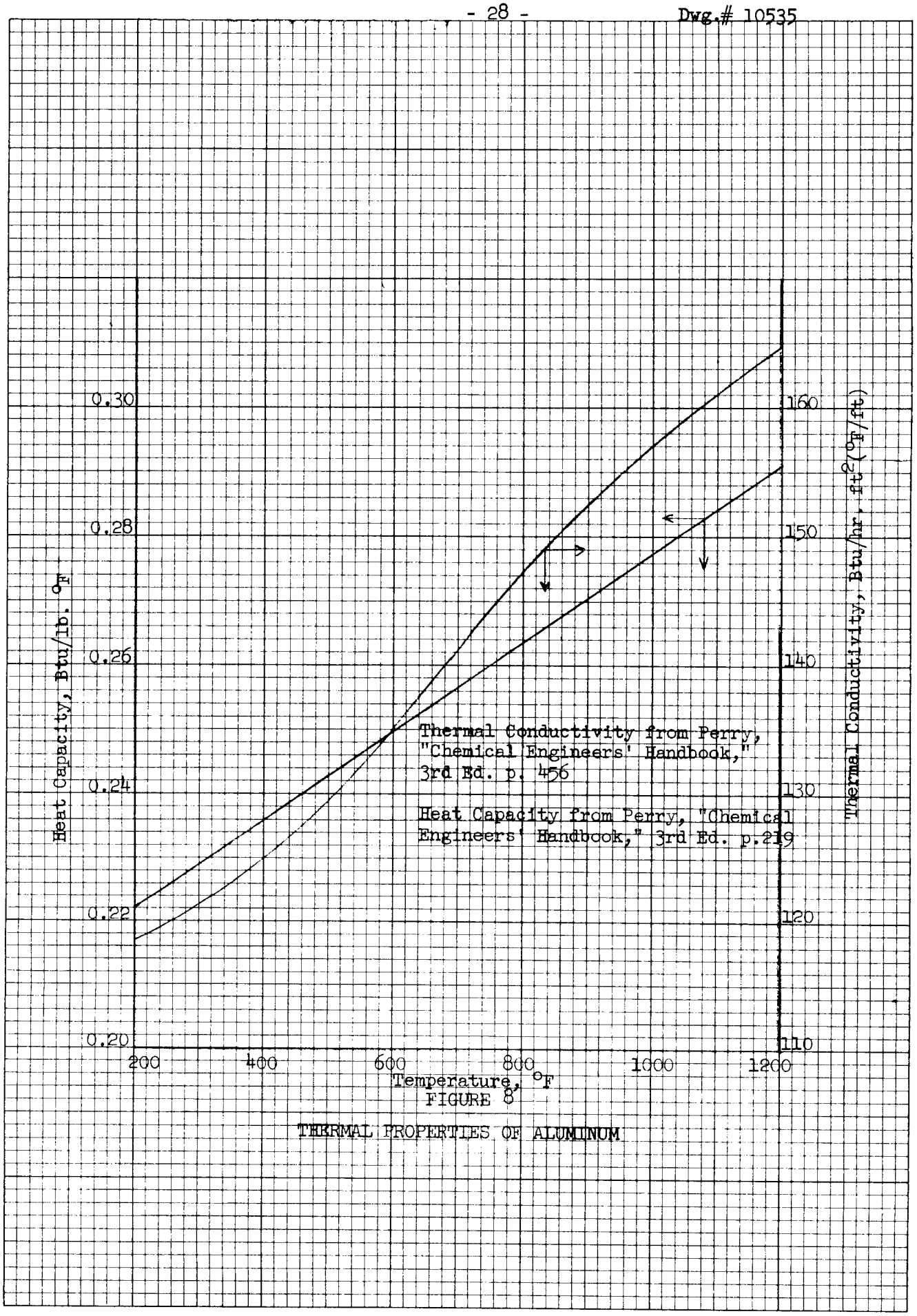

FIGURE 8

THERMAL PROPERTIES OF ALUMINUM