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COOLING OF THE HFIR BERYLLIUM REFLECTOR FOLLOWING A REACTOR SCRAM OR AN ELECTRICAL POWER OUTAGE

H. A. McLain

ABSTRACT

Thermal stresses in the HFIR beryllium reflector were computed for the unlikely case where the reactor is scrammed with a simultaneous loss of coolant flow and for the case following an electrical power outage where the reactor power level and the coolant flow rate are reduced simultaneously. For the case where the reactor is scrammed with a sudden loss of the coolant flow, the resulting maximum tensile thermal stress following the scram is 22,500 psi. In case of an electrical power outage, the maximum tensile thermal stress following a reduction of the fission power level from 100 Mw to 10 Mw with the lowering of the coolant flow rate to 10% of the normal value is 12,800 psi.

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Introduction

Previous calculations which ignored the heat capacity of the beryllium indicated that the HFIR reflector possibly may be damaged following a reactor scram or an electrical power outage.[1] Further calculations which consider the relatively large volume to surface ratio of the beryllium, therefore, are required for the cooling of the reflector during these periods of time.

The geometry of this reflector has been described previously by Hilvety.[2] The inner region of the beryllium, called the removable reflector, has the following dimensions:[2,3]

Cylinder No.	Material	Inside Radius, in.	Thickness, in.
1	Al	9.374	0.0625
2	Be	9.4365	0.3765
3	H_2O	9.813	0.027
4	Be	9.840	0.903
5	H_2O	10.743	0.027
6	Be	10.770	1.1095
7	H_2O	11.8795	0.0625
Semi-permanent	Be	11.942	1.183

The semi-permanent reflector has an outside radius of 13 1/8 in. and is in contact with the outer region of the beryllium. This outer region, called the permanent reflector, has an inside diameter of 26 1/4 in. and an outside diameter of 43 in.[2] For thermal stress considerations, Hilvety assumed that the permanent reflector consists of the following cylindrical elements:[3]

Cylindrical Element No.	Distance of Element From Reactor Centerline	Radius of the Element
1	13.080 in.	0.58 in.
2	14.124	0.66
3	15.306	0.75
4	16.662	0.86
5	18.219	0.99
6	20.013	1.14

It is assumed that all of the heat generated in these elements is removed through 1/8-in.-diameter holes located along the centerline of the cylindrical elements. The length of the beryllium reflector is 2 ft.

For computation purposes, the following physical properties were assumed for beryllium:[2]

Density	1.84 gm/cc
Thermal conductivity	5.83 Btu/hr in.°F
Specific heat	0.50 Btu/lb°F
Coefficient of thermal expansion	9×10^{-6} in./in.°F
Modulus of elasticity	40×10^{6} psi
Poisson's ratio	0.024

Cooling of the Reflector Following a Reactor Scram

Postulated Model and Analysis

For this situation, it is assumed that the reactor is suddenly scrammed and that the coolant flow is suddenly stopped at the same time. It is assumed further that the heat generated in the reflector during the time following the scram is removed by natural convection heat transfer. For calculation purposes, it is assumed that the heat generation rate Q, the metal temperature t, the coolant temperature T, and the heat transfer coefficient h, are uniform at any given instant of time. A simple heat balance for a cylinder with an inside diameter of D_1, an outside diameter of D_2, and a length L where the heat is removed only from the inner surface states that

$$\frac{\pi}{4}(D_2^2 - D_1^2)LQ - \pi D_1 Lh(t-T) = \frac{\pi}{4}(D_2^2 - D_1^2)L\rho c\frac{dt}{d\theta}$$

where ρ = density of the metal

c = specific heat of the metal

θ = time

If it is assumed that the coolant temperature T, and the heat transfer coefficient h remain constant with respect to time, the above relation can be modified to

$$\frac{dt'}{d\theta} + At' = \frac{Q}{\rho c}$$

where $t' = t - T$

$$A = \frac{4D_1 h}{\rho c(D_2^2 - D_1^2)}$$

Q = a function of θ

Solving this equation with the boundary condition that $t' = t'_o$ at $\theta = 0$,

$$t' = e^{-A\theta}\left[\frac{1}{\rho c}\int_o^{\theta} Qe^{A\theta'}d\theta' + t'_o\right]$$

Heat Generation Rates

The after shutdown heating rates in the beryllium reflector at the reactor midplane have been calculated previously,[1] and they are shown in Figure 1 for three positions in the permanent reflector.

Heat Transfer Coefficient

To calculate the natural convection heat transfer coefficient h in the above relations, the flow rate which is a function of the coolant temperature rise in the channel must first be determined. Assuming steady state natural convection with a constant inlet temperature, the coolant velocity V through a D diameter cylindrical channel of the length L can be found by the relation

$$f\frac{L}{D}\frac{V^2}{2g_c} = \frac{(\rho_i - \rho_{ave})L}{\rho_{ave}}$$

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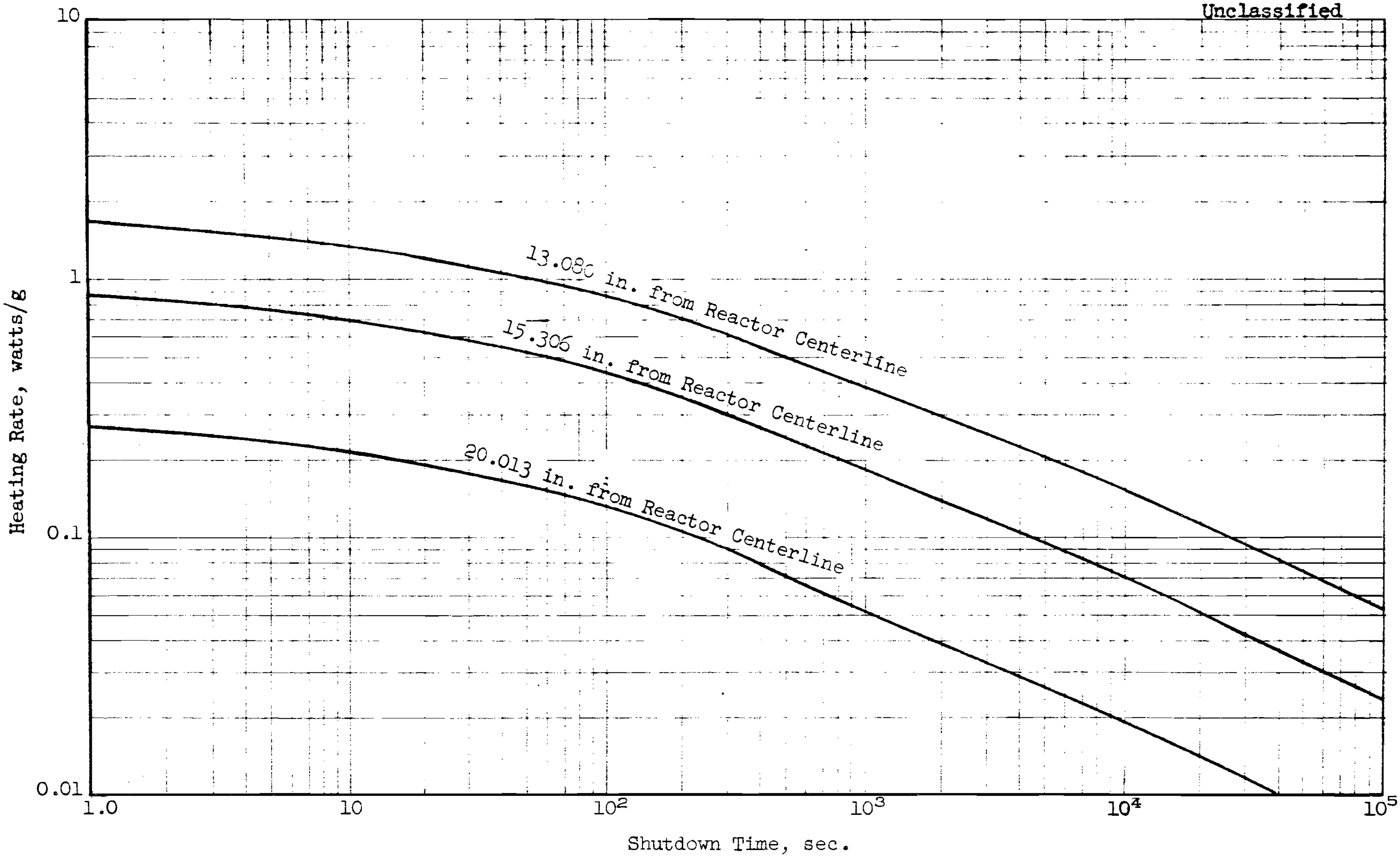

Fig. 1. After Shutdown Heat Generation Rates in the HFIR Beryllium Reflector

where f = Moody friction factor

ρ_i = density of the inlet water

ρ_{ave} = average density of the coolant in the channel.

For laminar flow

$$f = \frac{64}{\frac{DV\rho}{\mu}}$$

where μ = coolant viscosity.

Combining the last two relations and rearranging

$$V = \frac{g_c D^2(\rho_i - \rho_{ave})}{32\ \mu}$$

Assuming an inlet temperature of 120°F, the velocities through the permanent reflector's cooling channels were calculated as a function of the outlet temperatures. The results are shown in Figure 2.

The heat transfer coefficient h then may be calculated by the relation

$$\frac{h\ D}{k} = \frac{2}{\pi}\frac{wc}{kL}$$

where k = thermal conductivity of the coolant

c = specific heat of the coolant

w = mass flow rate of the coolant.

This is the relation for predicting the heat transfer coefficient for a fluid flowing in a vertical tube with streamline flow and having an outlet temperature equal to that of the tube surface.[4] For the low Graetz numbers wc/kL found here, the coefficients predicted by this relation should be somewhat conservative. The coefficients computed for this specific case are shown in Figure 2.

In calculating the permanent beryllium reflector temperatures, it was assumed that the heat transfer coefficient is constant at 50 Btu/hr ft^2°F. A coefficient of 100 Btu/hr ft^2°F was assumed for one position in the permanent reflector for comparison purposes.

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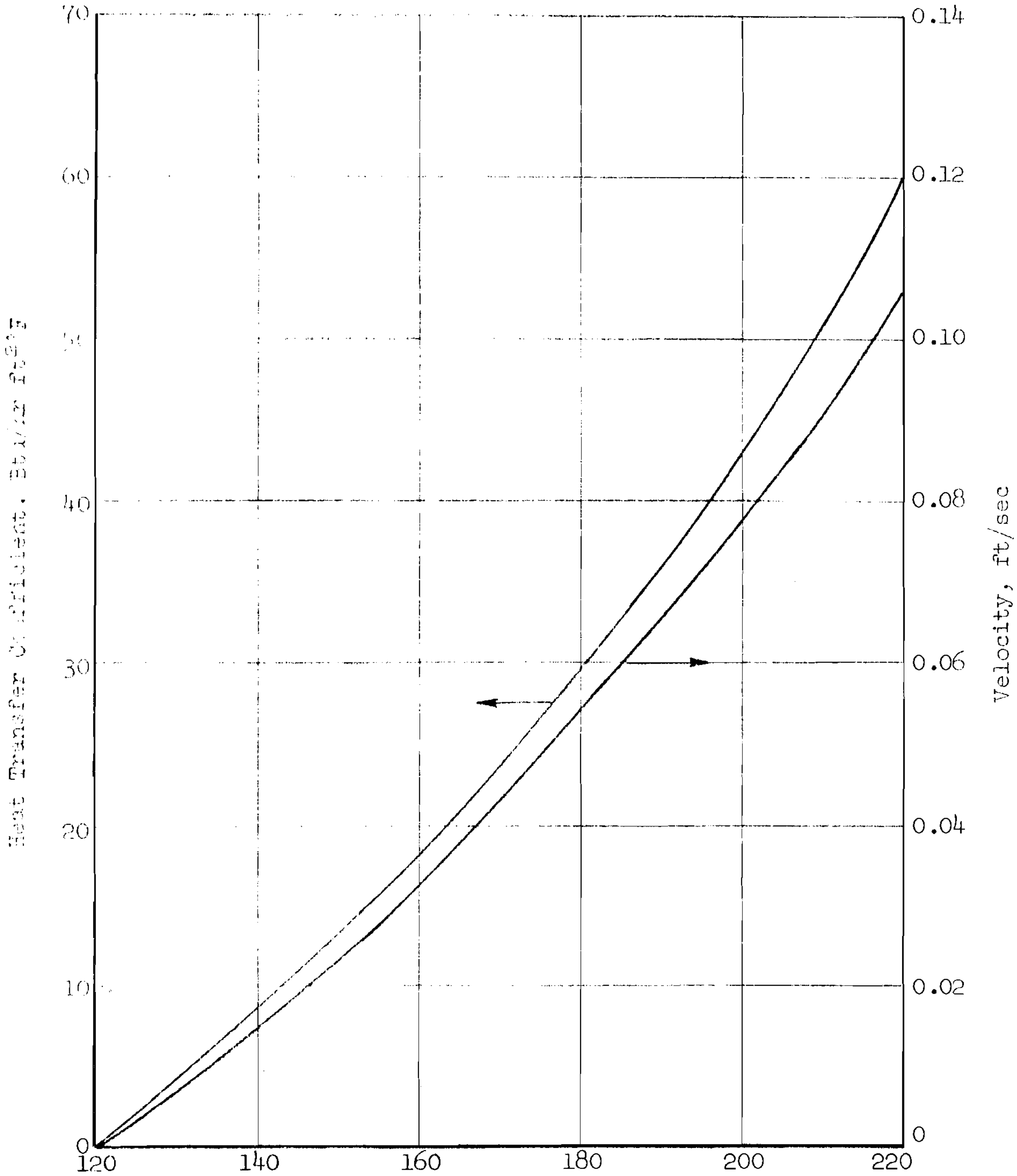

Fig. 2. Velocity and Heat Transfer Coefficient for Water Flowing Through Permanent Reflector Cooling Channels as a Function of the Outlet Temperature (Inlet Water Temperature = 120°F)

The correct method of computing the heat transfer coefficient is to calculate the flow rate at each instant of time from the fluid flow equation and heat balances. As shown by Gambill and Bundy,[5] this requires a trial and error solution technique, which for transient cases probably would require a large number of iterations. This could be accomplished by making use of the computing machines, but such amount of effort does not appear to be warranted here.

Temperatures in the Permanent Reflector

Figure 3 shows the temperatures at three positions in the HFIR permanent beryllium reflector assuming that the initial beryllium temperature is 35°F above the average coolant temperature. The latter assumption is somewhat arbitrary, being about one-half of the temperature difference between the beryllium and the water under normal operating conditions.[3]

Inspection of Figure 3 shows that for a constant heat transfer coefficient of 50 Btu/hr $ft^2{}^\circ F$, the maximum temperature difference exists at 1075 sec after shutdown. At this time, the inside surface is 284°F above the water temperature, the outside surface is 88°F above the water temperature, and by graphical integration, the average temperature is 149°F above the water temperature.

Resulting Thermal Stresses in the Permanent Reflector

Using the standard relation for the thermal stress in a thick-walled, hollow, infinite cylinder,

$$\sigma = \frac{E\alpha(t_{ave} - t_{surface})}{1 - \nu}$$

where σ = thermal stress
E = modulus of elasticity
α = coefficient of thermal expansion
ν = Poisson's ratio

the tensile thermal stress at the outside surface of the permanent beryllium reflector is found to be 22,500 psi. This is below the minimum value of 28,200 psi measured for failure of hot pressed beryllium.[6]

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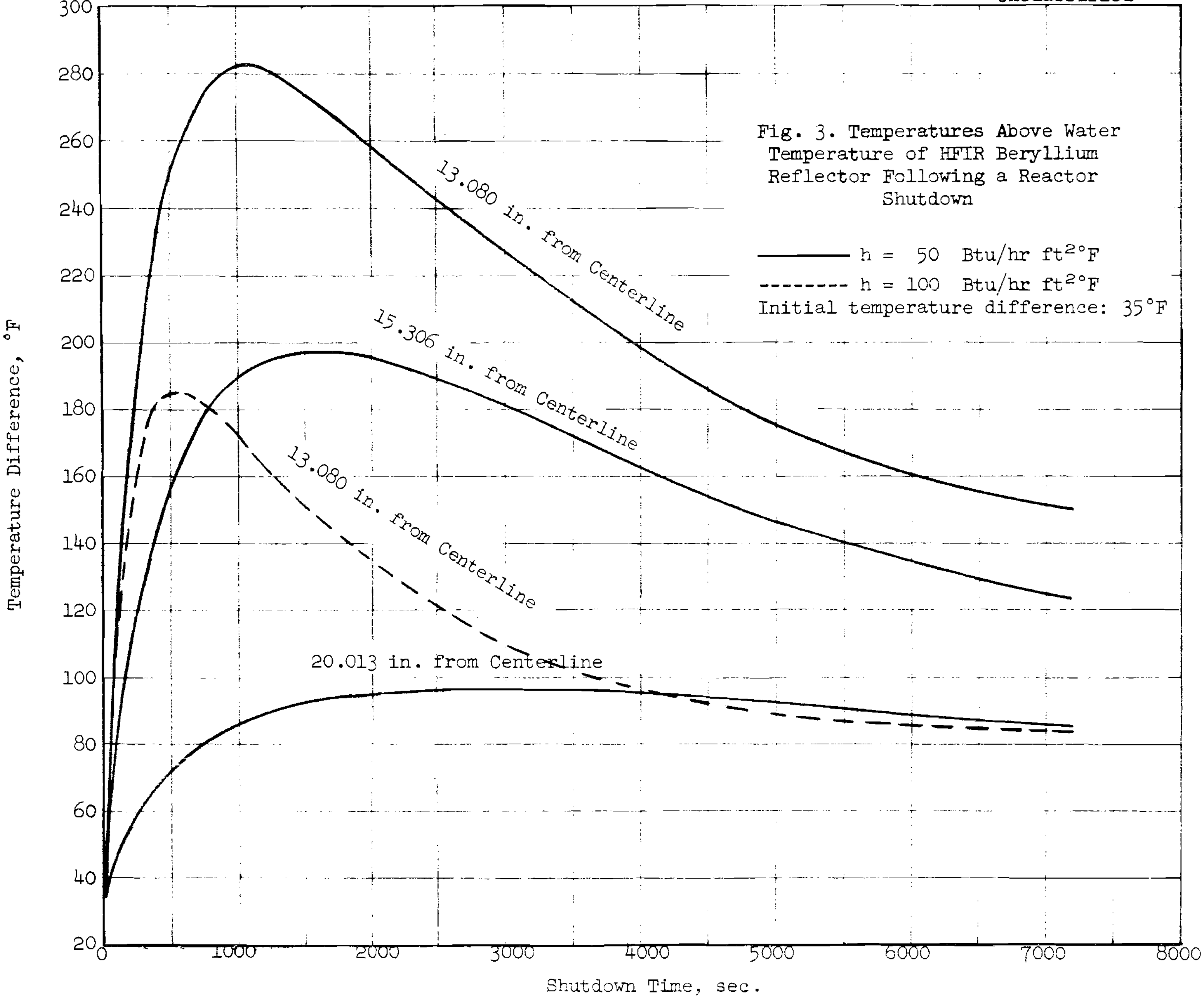

Fig. 3. Temperatures Above Water Temperature of HFIR Beryllium Reflector Following a Reactor Shutdown

Discussion of Reflector Cooling Following a Reactor Scram

The thermal stress calculated here for the permanent reflector is for an idealized situation in which many assumptions were made. It has been assumed that the reactor has been suddenly scrammed, that flow reversal has taken place, and that the cooling is by natural convection heat transfer with the cooler fluid flowing down through a downcomer such as the island region. A constant heat transfer coefficient has been assumed.

Normally, at least 10% flow is assured at all times by means of battery powered pony motors attached to the main coolant circulating pumps. The batteries have sufficient capacity to permit the operation of the pumps at 10% of the normal flow rate for about an hour to prevent a possible meltdown of the fuel element within the reactor.[7]

If the electrical power to the pumps is cut off altogether at the time the reactor is scrammed, time still would be required for the coolant to coastdown and to reverse during which heat would be removed from the beryllium reflector. This would tend to lower the temperature difference between the inside and outside surfaces of the beryllium reflector which will lower the thermal stress.

The temperature history at the inside edge of the permanent reflector was calculated using heat transfer coefficients of 50 Btu/hr ft^2°F and 100 Btu/hr ft^2°F. The larger coefficient of course results in a lower peaking of the temperature in the beryllium reflector. As the temperature of the beryllium increases, the heat transfer coefficient increases. Thus the temperature differences are inclined to be lower than indicated in Figure 3 which would again result in lower thermal stresses.

Although the model assumed for these calculations is very idealized, it appears that thermal stress cracking of the beryllium will not be a problem following a reactor scram. A more accurate analysis of this problem would require an extensive amount of calculations which does not appear to be warranted here.

Cooling of the Reflector Following an Electrical Power Outage

Postulated Model and Analysis

For this situation, it is assumed that the reactor fission power level suddenly is reduced from 100 Mw to 10 Mw and that the flow rate is reduced to

10% of its normal value. The assumption that the fission power level is reduced to 10 Mw is conservative since the total reactor power would be lowered to 10 Mw.[8] This implies that the fission power level of the reactor would be between 3 and 7 1/2 Mw during an electrical power outage.

The analytical model, assumptions, and equations used for calculating the temperatures in the beryllium following a reactor scram are assumed to be valid here.

Heat Generation Rates

After shutdown heating rates for the beryllium reflector have been calculated previously and are reported in CF 60-12-118.[1] These calculations assumed that the reactor had operated at 100 Mw for 15 days and that the beryllium heating results from the fission product and Al^{28} gammas present in the fuel element. Heating rates in the beryllium during the normal operation of the reactor have been calculated by Vondy,[9] and they include the contributions from the prompt and capture gammas and the fast neutron slowing down in addition to the contributions from the delayed gammas.

To calculate the heating rates in the reflector at 10 Mw fission power level, the sum of heat contributions from the following sources are used:

a. 90% of the decay heat values reported in CF 60-12-118.

b. 10% of the decay heat values reported in CF 60-12-118 for 1.0 sec shutdown time which are assumed to be constant for all times following an electrical power outage.

c. 10% of the prompt and capture gamma values reported by Vondy.

d. 10% of the fast neutron slowing down values reported by Vondy.

A summary of these results is shown in Table 1 and Figure 4 for six different times following an electrical power outage. A cross plot of these results shown in Figure 5 gives the heat generation rates at the various locations of interest in the beryllium reflector as a function of the time after an electrical power outage.

Heat Transfer Coefficient

For the normal operation of the reactor, Hilvety[2] assumed that the heat transfer coefficient in the permanent reflector is 5000 Btu/hr ft^2°F. Using

Table 1

Heat Generation Rates in the Beryllium Reflector
Following an Electrical Power Outage

Time After Power Outage sec →	1.0	10	10^2	10^3	10^4	10^5
Source and Position	Heating Rate, watts/g Be					
Decay Heat						
23.274 cm	6.62	5.43	3.54	1.642	0.727	0.265
27.084	3.58	2.92	1.880	0.853	0.382	0.1292
30.894	2.16	1.769	1.130	0.482	0.1920	0.0709
38.514	0.813	0.665	0.419	0.1670	0.0669	0.0225
53.754	0.1863	0.1510	0.0926	0.0354	0.01380	0.00449
Fission Product and Al^{28} Gammas						
23.274 cm	0.736					
27.084	0.398					
30.894	0.240					
38.514	0.0903					
53.754	0.0207					
Prompt and Capture Gammas						
23.274 cm	1.302					
27.084	0.795					
30.894	0.525					
38.514	0.257					
53.754	0.0743					
Fast Neutron Slowing Down						
23.274 cm	0.992					
27.084	0.460					
30.894	0.192					
38.514	0.026					
53.754	0.00026					
Total						
23.274 cm	9.65	8.46	6.57	4.67	3.76	3.30
27.084	5.24	4.58	3.53	2.51	2.035	1.782
30.894	3.12	2.726	2.087	1.439	1.149	1.028
38.514	1.186	1.038	0.792	0.540	0.440	0.396
53.754	0.282	0.246	0.1879	0.1307	0.1091	0.0998

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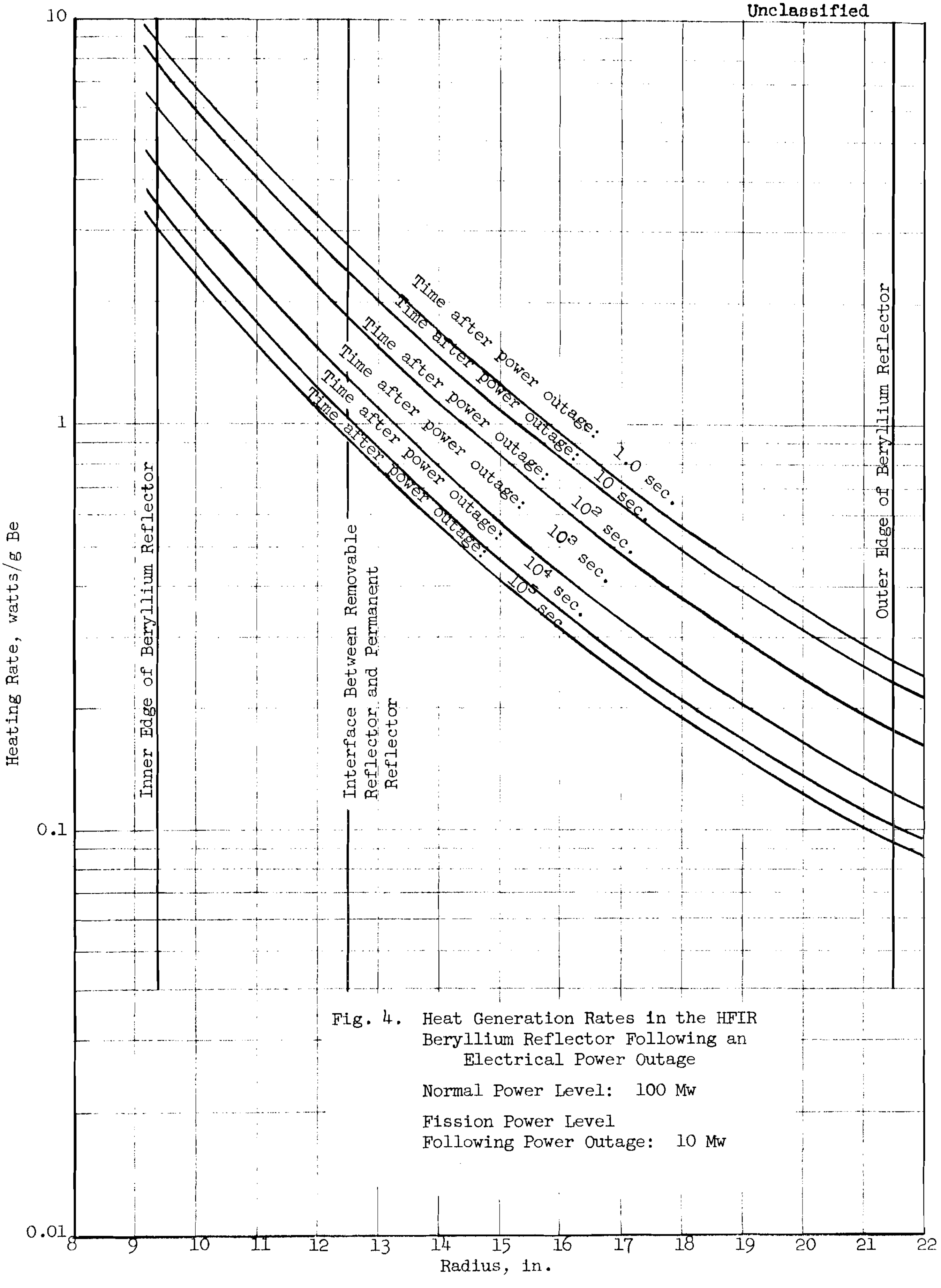

Fig. 4. Heat Generation Rates in the HFIR Beryllium Reflector Following an Electrical Power Outage

Normal Power Level: 100 Mw

Fission Power Level
Following Power Outage: 10 Mw

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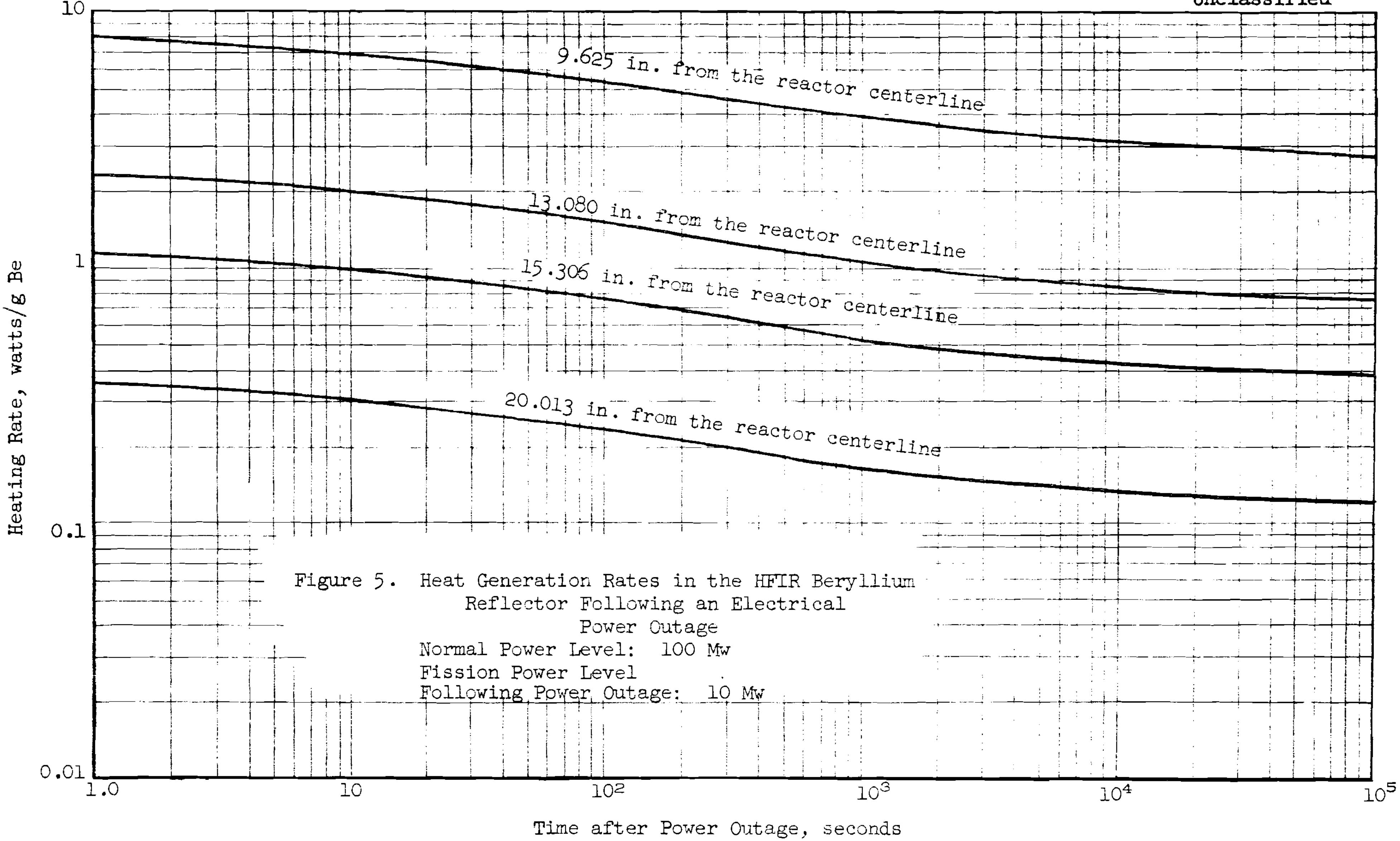

Figure 5. Heat Generation Rates in the HFIR Beryllium Reflector Following an Electrical Power Outage
Normal Power Level: 100 Mw
Fission Power Level
Following Power Outage: 10 Mw

the Dittus-Boelter relation and assuming 1/8 in. diameter cooling channels, this is equivalent to a Reynold's number of 2.814×10^4. At 10% flow (assuming constant physical properties of the water), the Reynold's number is 2.814×10^3 which indicates that the coolant flow is in the transition region.

For heat transfer in the transition range for small diameter tubes with small film temperature drops, McAdams[4] recommends the relation

$$\frac{hD}{k} = 1.86 \left[\left(\frac{DV\rho}{\mu}\right)\left(\frac{c\mu}{k}\right)\left(\frac{D}{L}\right)\right]^{1/3}$$

The buoyant forces which are small and difficult to estimate are neglected in this case. This relation predicts that the heat transfer coefficient in the permanent reflector for 10% flow is 250 Btu/hr ft^2°F.

Another relation for predicting the heat transfer coefficient for flow in the transition range is the Hausen equation[4] which is

$$\left(\frac{h}{cpV}\right)\left(\frac{c\mu}{k}\right) = 0.116 \left[\frac{\left(\frac{DV\rho}{\mu}\right)^{2/3} - 125}{\frac{DV\rho}{\mu}}\right]\left[1 + \left(\frac{D}{L}\right)^{2/3}\right]$$

This equation predicts the heat transfer coefficient in the permanent reflector for 10% flow to be 320 Btu/hr ft^2°F. For the purposes of the calculations here, however, the 250 Btu/hr ft^{2}hr value is assumed. This should be a conservative assumption.

In the case of the removable beryllium reflector, Hilvety assumed that the heat transfer coefficient is 7500 Btu/hr ft^2°F during the normal operation of the reactor. Assuming that the Sieder-Tate equation

$$\frac{hD}{k} = 0.027 \left(\frac{DV\rho}{\mu}\right)^{0.8} \left(\frac{c\mu}{k}\right)^{1/3}$$

is valid for this region with 0.027 in. thick cooling channels, this coefficient is equivalent to a Reynold's number of 1.49×10^4. At 10% flow (assuming constant physical properties of the water), the Reynold's number is 1490 which indicates that the coolant is flowing in the laminar range.

To compute the heat transfer coefficient for a coolant flowing in the laminar range in rectangular passages, McAdams[4] recommends a graphical correlation of the form:

$$\frac{hD_e}{k} = \text{fn}\left[\left(\frac{D_e V\rho}{\mu}\right)\left(\frac{c\mu}{k}\right)\left(\frac{D_e}{L}\right)\right]$$

Using this correlation, the heat transfer coefficient in the removable reflector for 10% flow is estimated to be 422 Btu/hr ft^2°F.

Temperatures in the Permanent Reflector

Temperatures at three positions in the HFIR permanent beryllium reflector are shown in Figure 6. In this case, it is assumed that the initial beryllium temperature is 70°F above the average coolant temperature.[3] For this situation, the maximum temperature difference exists 350 sec after the electrical power outage. At this time, the inside surface is 194°F above the water temperature, the outside surface is 95°F above the water temperature, and by graphical integration, the average temperature is 126.5°F above the water temperature.

To check the assumption of the uniform temperature distribution in the individual cylindrical elements used for computational purposes, the temperature distributions in the element 20.013 in. from the centerline were calculated for various times after an electrical power outage. These temperatures were computed using the Generalized Heat Conduction Code,[10,11] and the results of this calculation are shown in Figure 7. These results indicate that the temperature distribution in this element is quite uniform within 10 sec after the power outage.

Temperatures in the Removable Reflector

The temperatures in the inner ring of the removable beryllium reflector during the first few seconds following an electrical power outage were calculated using the Generalized Heat Conduction Code. As mentioned above, this beryllium piece has an inside radius of 9.4365 in. and an outside radius of 9.813 in. Using the heat generation rates 9.625 in. from the reactor centerline shown in Figure 5, the temperature distributions shown in Figure 8 were computed.

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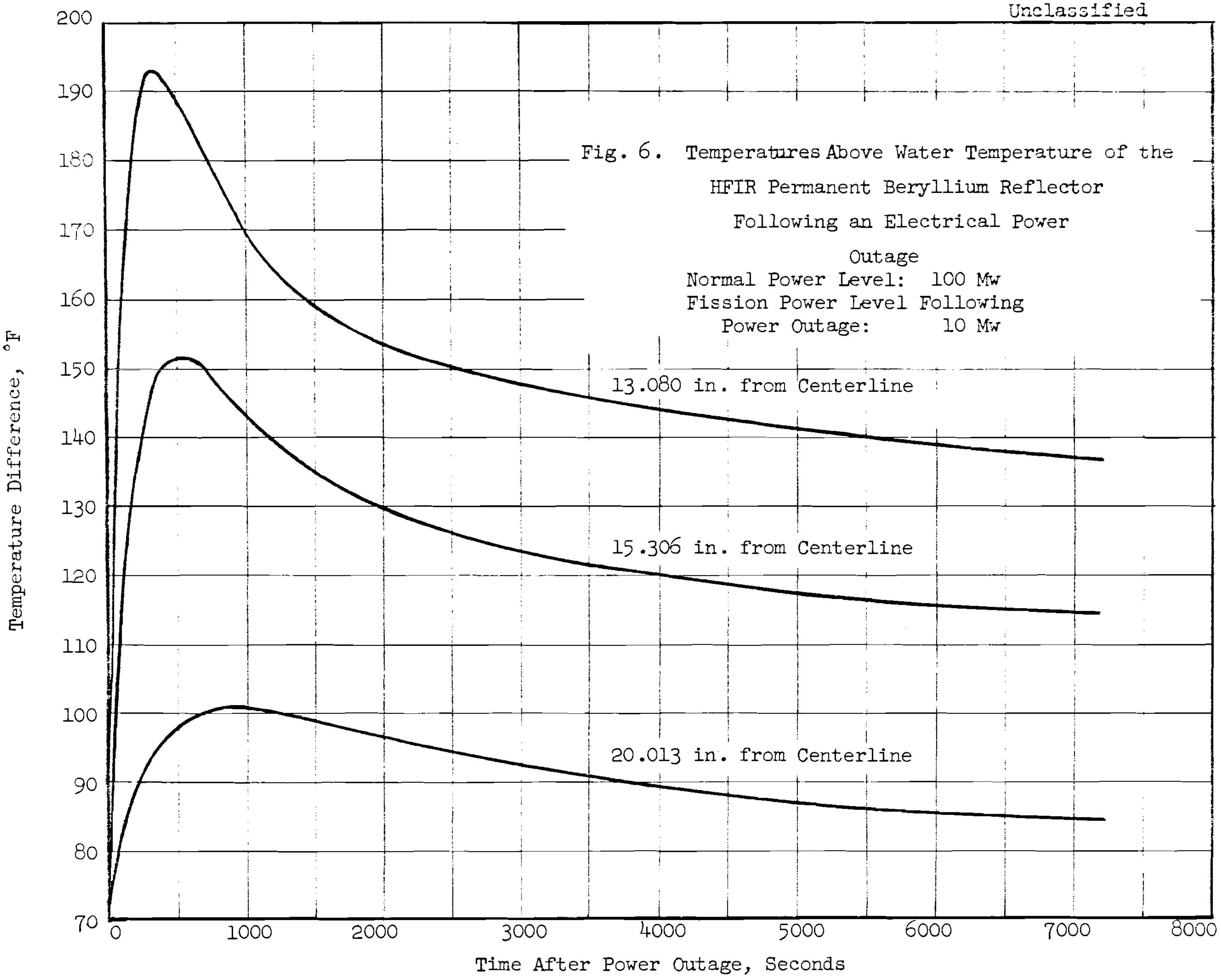

Fig. 6. Temperatures Above Water Temperature of the HFIR Permanent Beryllium Reflector Following an Electrical Power Outage

Normal Power Level: 100 Mw
Fission Power Level Following
Power Outage: 10 Mw

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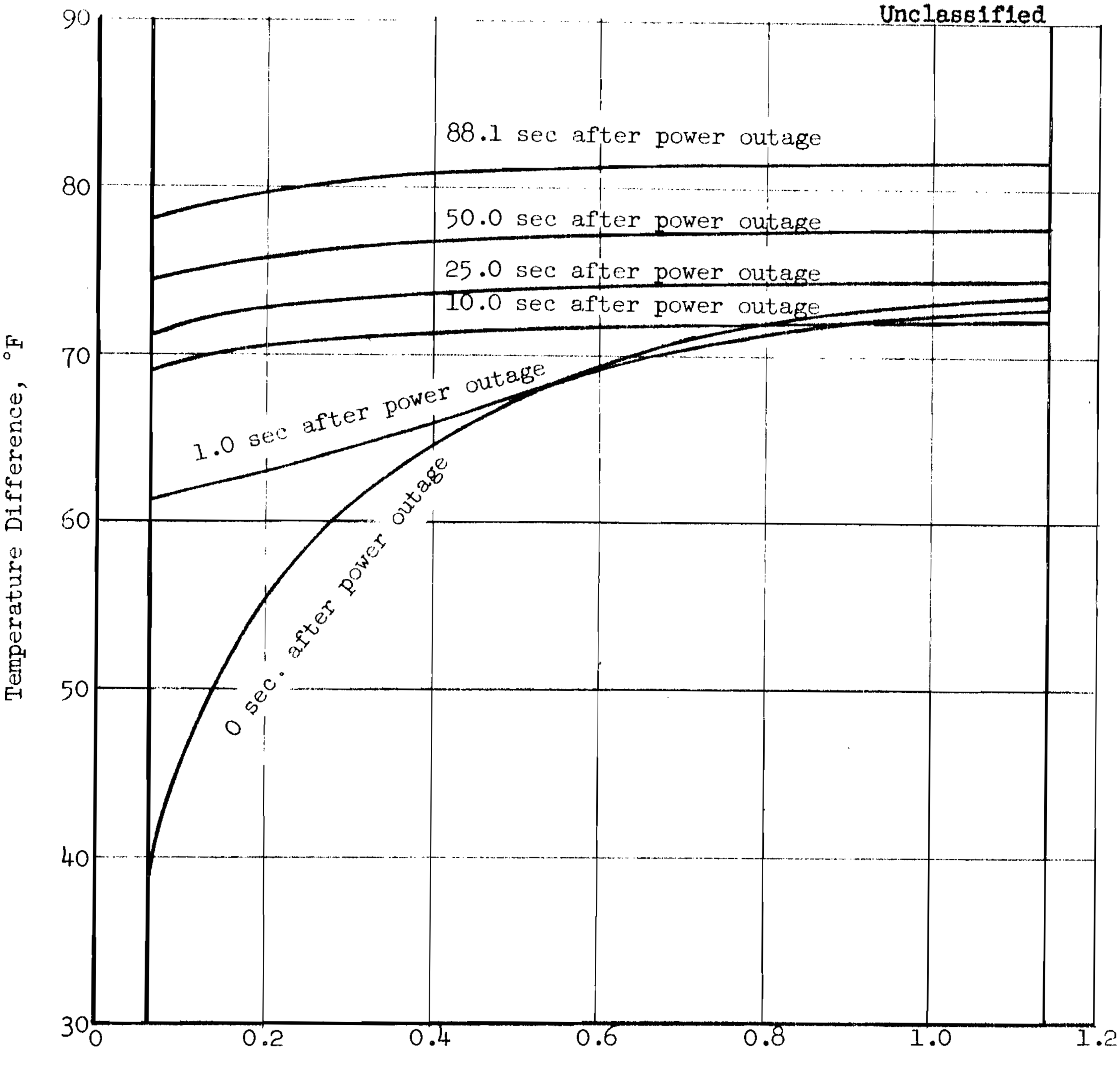

Fig. 7. Temperatures Above Water Temperatures in the Cylindrical Element 20.013 inches from the Reactor Centerline Following an Electrical Power Outage

Normal Power Level: 100 Mw
Fission Power Level Following Power Outage: 10 Mw

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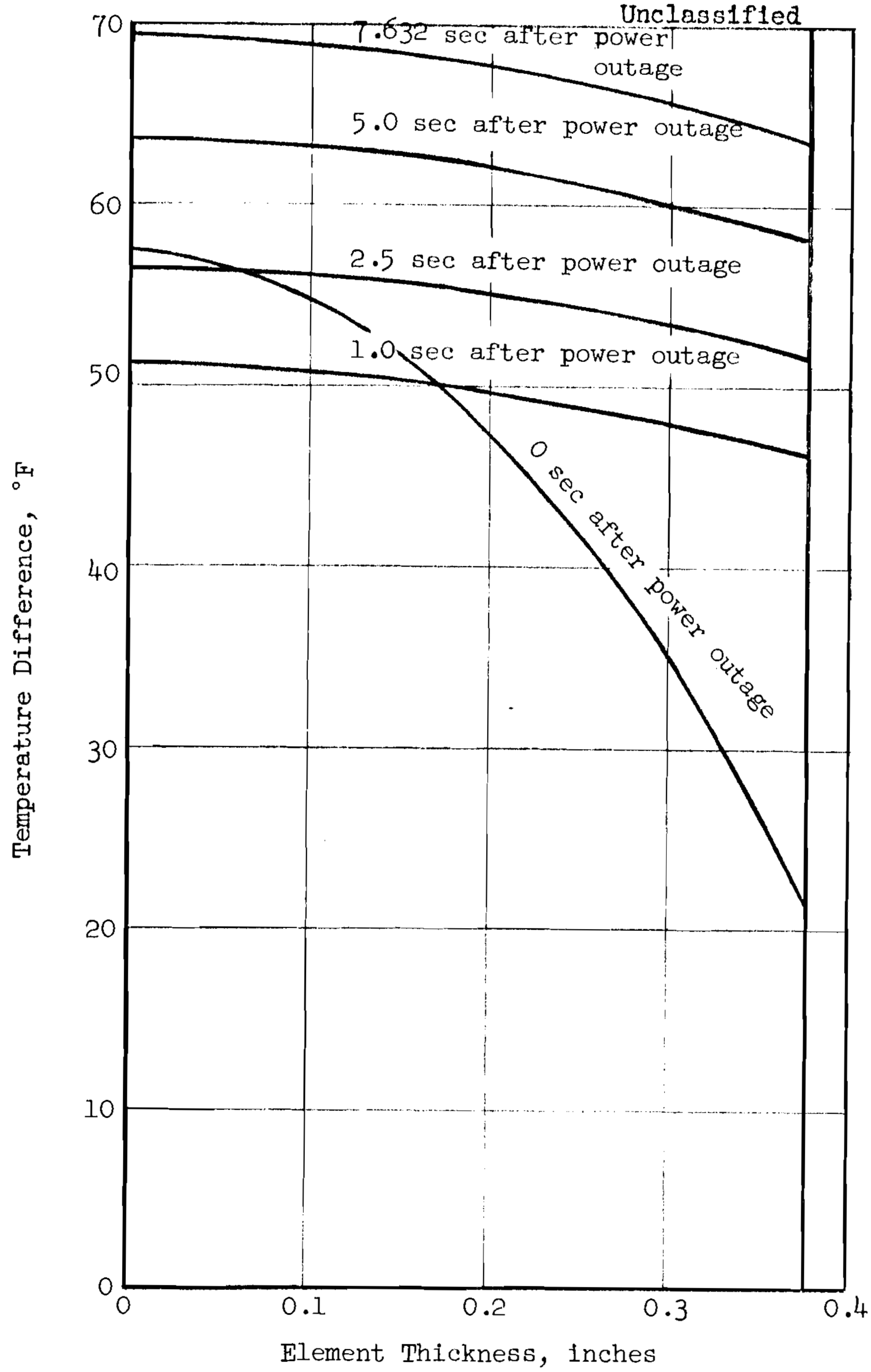

Figure 8. Temperatures Above Water Temperatures in the Inner Removable Reflector Following an Electrical Power Outage

Normal Power Level: 100 Mw
Fission Power Level
Following Power Outage: 10 Mw

These results show that the temperature distributions in the inner removable reflector is fairly uniform even for times as low as 1.0 sec after an electrical power outage.

Resulting Thermal Stresses in the Beryllium Reflector

As for the case following a reactor scram, the thermal stress in the permanent beryllium reflector may be calculated using the relation,

$$\sigma = \frac{E\alpha(t_{ave} - t_{surface})}{1 - \nu}$$

The tensile thermal stress at the outside surface of the permanent beryllium reflector is 11,600 psi, which is below the 12,000 psi value used by Hilvety[2] in the design of the beryllium reflector. The compressive thermal stress at the inside surface of the permanent reflector is 24,900 psi, which is well below the 70,000 psi limiting value reported by Savage.[6]

The addition of any thermal stresses due to the uniform temperature distribution assumption in each of the cylindrical elements used for computing the transient temperature distribution over the entire beryllium reflector is small. At 88.1 sec, the maximum temperature difference for the element at the outer edge of the beryllium reflector is 3.3°F, which is equivalent to a thermal stress of 1220 psi.

In the case of the removable reflector, the temperature profiles appear to be quite uniform for the time following an electrical power outage. For instance, the difference between the average and the outside surface temperature 7.6 sec after a power outage is about 4°F, which is equivalent to a tensile thermal stress of 1480 psi.

Discussion of Reflector Cooling Following an Electrical Power Outage

As for the previous situation, the thermal stresses calculated here are for somewhat an idealized case. It had been assumed that the reactor suddenly is reduced from 100 Mw fission power level to 10 Mw fission power level and that the flow suddenly is reduced to 10% of its normal value. Both of these assumptions are conservative since the reactor fission power level will be reduced to a value less than 10 Mw and a finite length of time is required to reduce the flow to 10% of its normal value.

The assumption of an uniform temperature distribution in the cylindrical elements used for computing the temperature distribution in the permanent reflector appears to be valid. Superimposing the tensile thermal stress at the cooling surface of the outer element on that at the outer surface of the permanent reflector, a value of 12,800 psi is obtained. This is not regarded as a problem since it is only slightly over the conservative 12,000 psi design value, and well below the 28,200 psi experimental required for thermal stress cracking.

Thermal stresses in the removable beryllium reflector appear to be quite low and do not present a problem. Although the thermal stress was calculated for only the inner beryllium piece of the removable reflector, those in the other pieces should be of the same order of magnitude since the heat generation rates are the greatest for the inner piece.

Conclusions

By allowing the temperature of the beryllium metal in the HFIR reflector to rise, it appears that the reactor may be scrammed or operated at reduced powers with reduced flow rates without damage to this component. The thermal stresses calculated for the case following a reactor scram are for a very conservative situation since forced circulation of the coolant must be maintained for about one hour after the scram to prevent damage to the fuel element.[12] Those calculated for the operation of the reactor following an electrical power outage are close to or below the 12,000 psi design value and should not present a problem.

Table of Nomenclature

$A = \frac{4D_1 h}{\rho c(D_2^2 - D_1^2)}$
c = specific heat
D = diameter
D_e = equivalent diameter
D_1 = inside diameter of cylinder
D_2 = outside diameter of cylinder
E = modulus of elasticity
f = Moody friction factor
h = heat transfer coefficient
k = thermal conductivity
L = length
Q = heat generation rate
T = coolant temperature
t = metal temperature
t' = $t-T$
V = velocity
w = mass flow rate
α = coefficient of thermal expansion
θ = time
μ = viscosity
ν = Poisson's ratio
ρ = density
ρ_i = density of inlet water
ρ_{ave} = average density of water
σ = thermal stress
fn = function

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