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CENTRAL FILES NUMBER
60-9-55

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COPY NO. 54

DATE: September 19, 1960

SUBJECT: MSRE Drain Tank - Heat Removal Studies

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ABSTRACT

The problem of removing after-heat from fuel stored in the MSRE drain tanks is considered. It is shown that a system capable of removing 100 kw is considered adequate for 80 hr after the reactor is shut down. A cooling system of 50 kw capability is adequate for 80 - 500 hr.

Several alternative cooling schemes are considered. A system using concentric thimbles projecting into the mass of salt, with boiling water in the inner thimble, is recommended on the basis of relative simplicity. Methods of calculating the heat transfer performance of such a system are presented. It is shown that the emissivity of the oxidized metal surfaces is the most serious uncertainty in the calculated cooling performance.

INTRODUCTION

Among other requirements, drain tanks for the Molten Salt Reactor Experiment must be capable of dissipating the after-heat remaining in the fuel at a sufficient rate so that neither fuel nor tank wall temperatures become excessive. This memorandum summarizes investigations which have been made of the cooling requirements and possible means of accomplishing the desired cooling.

COOLING REQUIREMENTS

Since the rate of after-heat release decays fairly rapidly with time, a cooling system having a cooling capability somewhat less than the heat generation rate at the time the irradiated fuel enters the drain tank is adequate to control the tank temperature. Data on after-heat generation in natural uranium and in uranium-235 have been published.[1] Figure 1 shows these data replotted using a time scale in hours.

Any cooling process will be temperature-dependent. The currently-favored cooling arrangement is shown in Figure 2. A number of INOR-8 thimbles are installed through the top head of the drain tank, extending almost to the bottom of the tank. Stainless steel thimbles of somewhat smaller diameter are mounted concentrically in each and are supplied with feedwater by means of small tubes connected to a head tank. Heat is transferred from the salt to the INOR-8 tubes by conduction and natural convection; from the INOR-8 tube to the stainless tube by radiation and conduction through the air gap, and is ultimately dissipated by boiling the water. The cooling capability of such a system is quite temperature-dependent. Figure 3 presents data for a possible configuration: a 1.5-in. OD tube inside a 2-in. OD x 0.072-in. wall tube.

The outer surface temperature of the inner tube was assumed to be at 250°; this may be slightly too high but will not introduce a significant error in the calculated heat transfer rate. The outer tube temperature is that at its inner wall; its outer wall temperature is never more than 5°F

1. S. Untermeyer and J. T. Weills, Heat Generation in Irradiated Uranium, ANL 4790.

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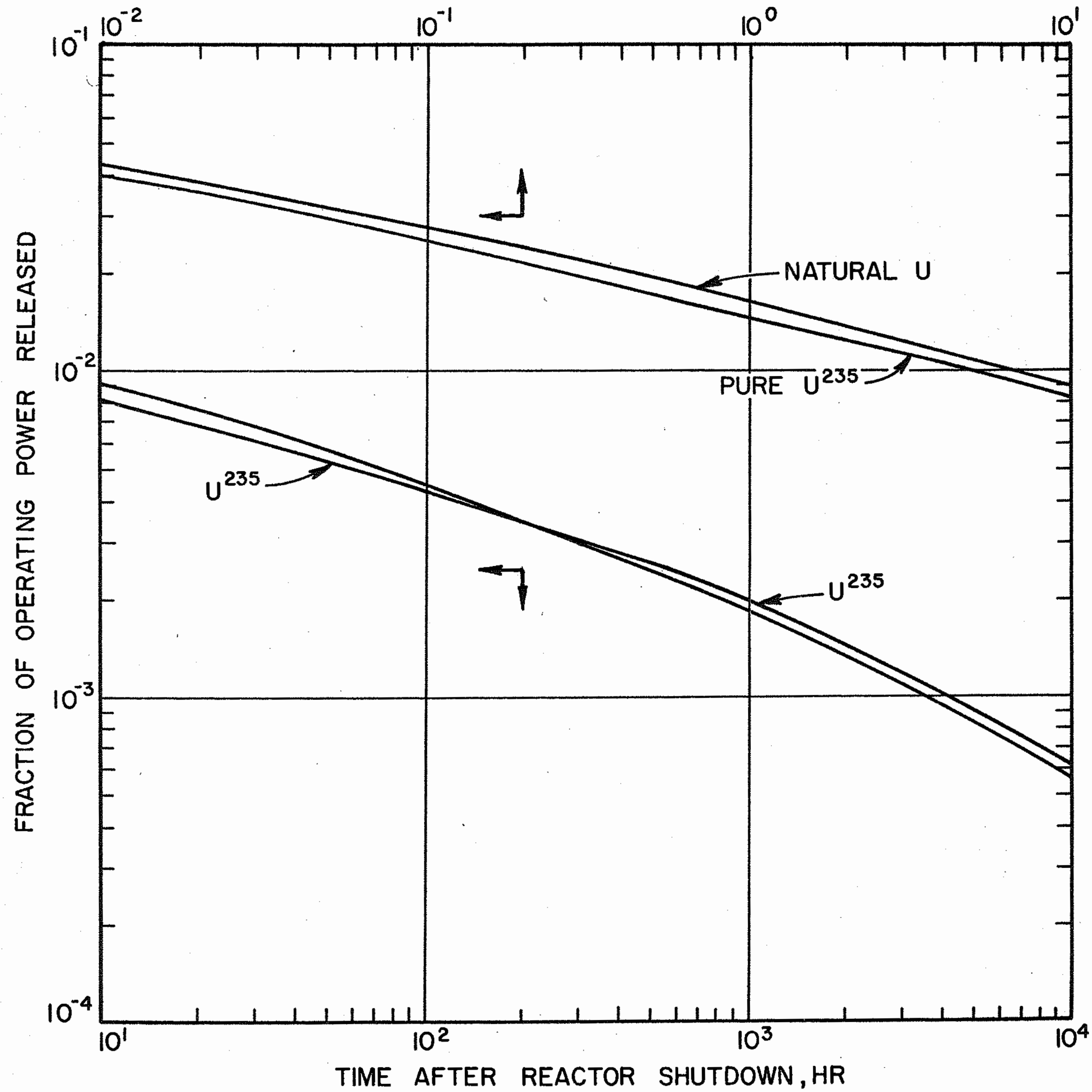

FIG. I. AFTER-HEAT RELEASE FROM NATURAL URANIUM AND U^{235} vs TIME FOR INFINITE IRRADIATION PERIOD. REPLOTTED FROM ANL 4790

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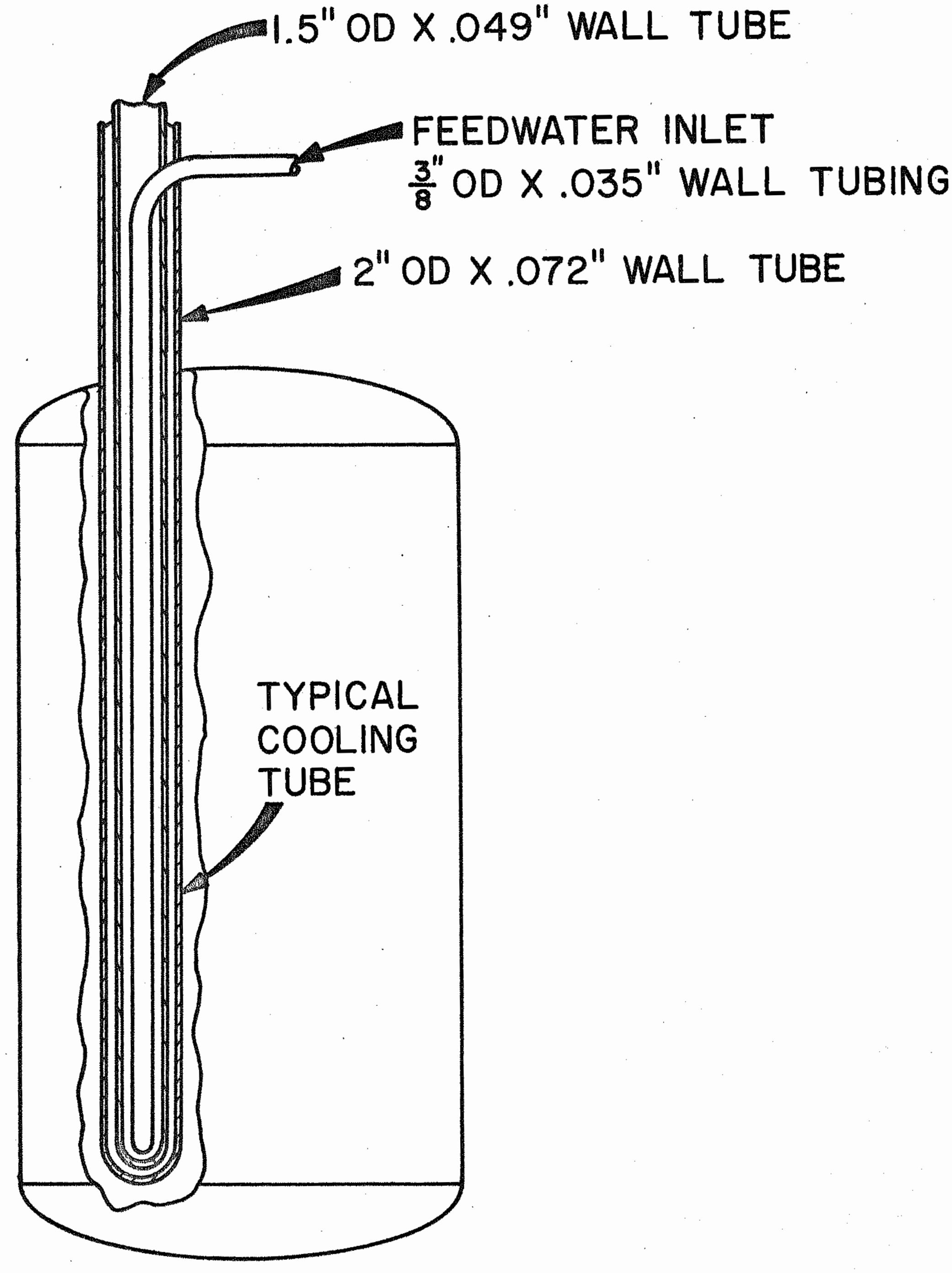

FIG. 2. COOLING TUBE ARRANGEMENT IN DRAIN TANK

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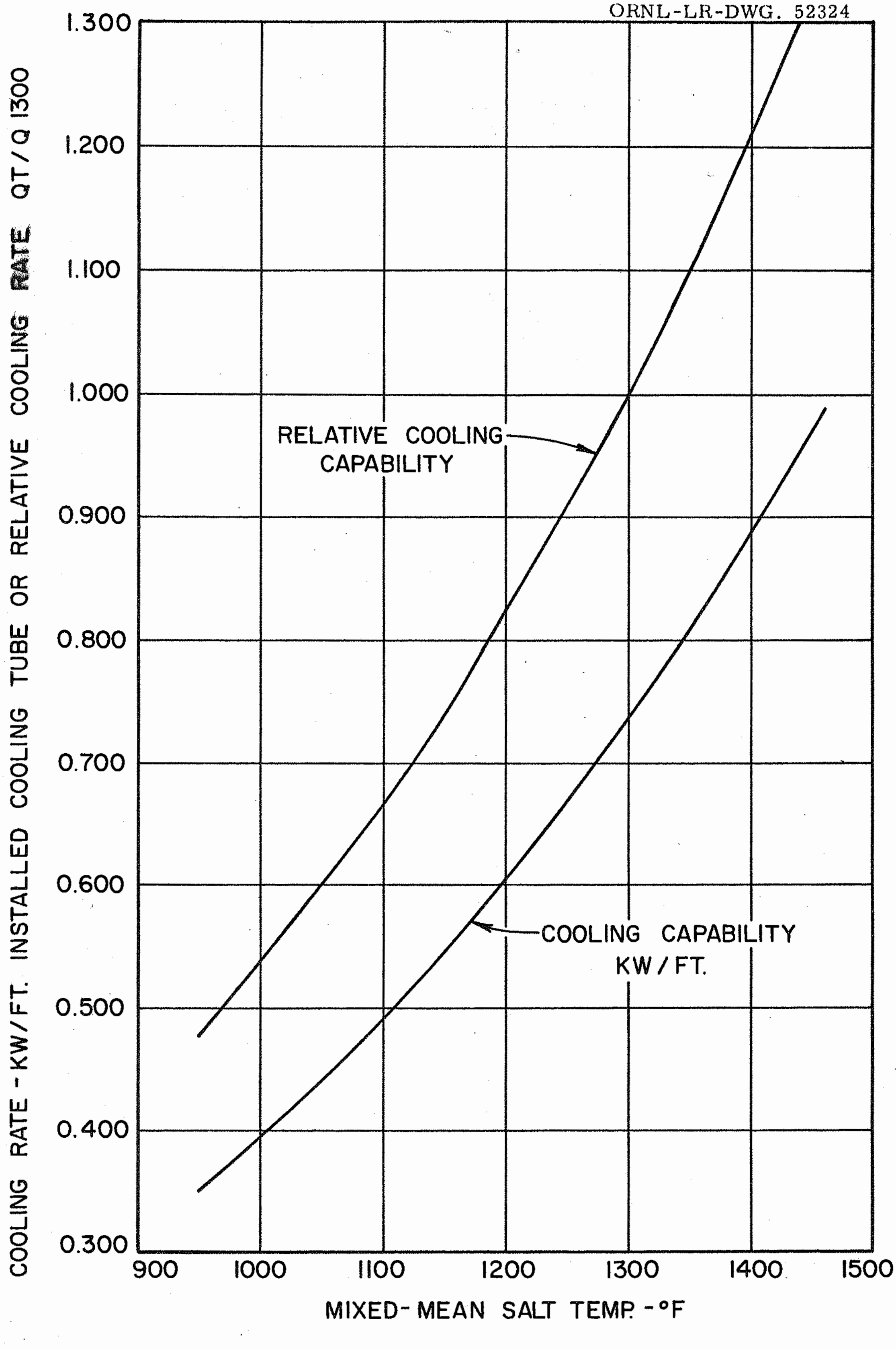

FIG. 3. COOLING CAPABILITY vs TEMPERATURE FOR CONCENTRIC TUBE DRAIN TANK COOLER USING 1.5" O.D. X 0.049" WALL STAINLESS TUBE INSIDE 2.0" O.D. X 0.072" WALL INOR-8 TUBE.

higher so that the inner wall temperature may be used without significant error.

An analysis of the time-temperature behavior of the drain tank is presented in Figure 4. The following assumptions were made for purposes of this analysis:

(1) The fuel is transferred to the drain tank 0.25 hr after reactor shutdown and is at 1250°F at the time of transfer.

(2) The fuel-INOR-8 interface temperature at the cooling tubes is 25°F below the mixed-mean fuel temperature.

(3) The initial cooling rate for any time interval may be used as the average rate during the time interval.

This analysis shows that if a cooling system having a capability of 100 kw at 1300°F is installed in the tank, a maximum mixed-mean temperature of approximately 1405°F will occur at 4 hr after shutdown. If the cooling system capability is 125 kw at 1300°F, the temperature peak would be about 1340°F, 3 hr after reactor shutdown. The temperature drops gradually once the maximum is passed and would be 985°F at 80 hr.

Beyond this point, if freezing of the salt is not desired, two alternatives are possible. One is simply to operate the cooling system intermittently; the other is to shut off half the cooling system. If the latter is done, there would be a second temperature peak and decay cycle with the temperature again dropping to 985°F at about 500 hr. Past this time, intermittent cooling would probably be required until the after-heat dropped to the level of the tank heat loss, which might occur at some time between 800 and 3000 hr after reactor shutdown, depending on how effective the tank insulation turns out to be.

Insulation losses were not considered in the computations leading to the above estimates of the time-temperature behavior. They would, of course, have the effect of additional cooling capability and thus shorten the time to maximum temperature and the magnitude of the maximum.

A cooling installation rated for 100-125 kw at 1300°F appears adequate to remove after-heat without producing excessive mean fuel temperature.

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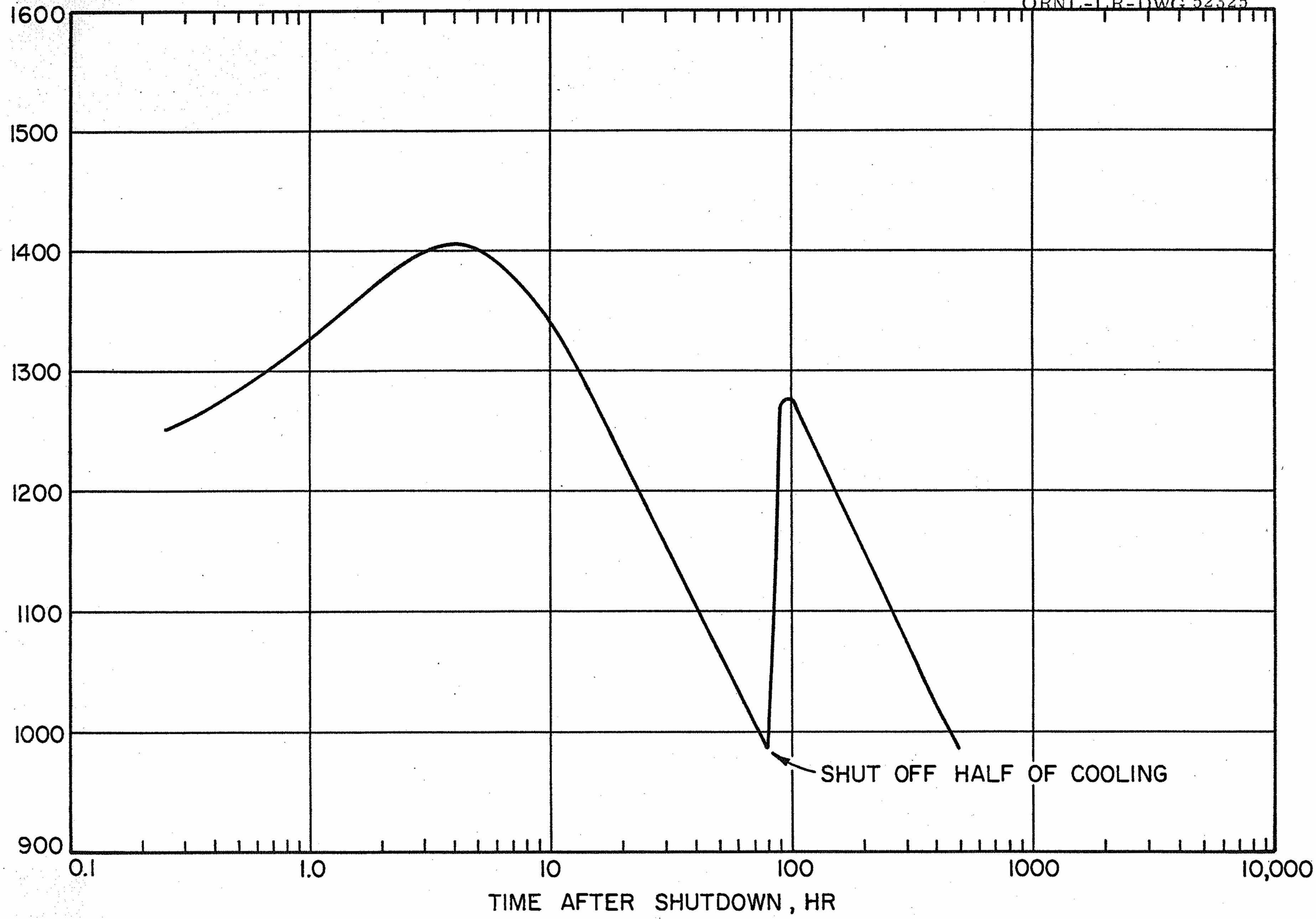

FIG. 4. TIME - TEMPERATURE BEHAVIOR OF MSRE DRAIN TANK HAVING COOLING CAPACITY RATED 100 KW AT 1300°F.

COOLING SYSTEMS CONSIDERED

Preliminary consideration was given to a number of alternative schemes for heat removal. Cooling by means of a fluid circulating in a jacket surrounding the tank was considered and appears to be feasible using either a gas or barren salt as the cooling medium. The maximum temperature of the salt is almost impossible to predict for this case, because no procedure for calculating the thermal convection flow in a vessel of small ℓ/d ratio is available. However, it appeared improbable that an excessive maximum salt temperature would be developed. The highest salt temperature must occur on the free surface near the center of the vessel, and if the salt here becomes appreciably hotter than the vessel wall, considerable cooling by radiation to the top head would occur.

The principal objection to a peripheral cooling scheme appeared to be the complexity of the coolant system. Coolants considered included air, barren salt in natural convection and barren salt with forced convection. For air, it appeared that a rather large radiator would be required. Barren salt in natural convection required excessively large piping. Barren salt in forced convection requires a pump and radiator; in effect, a cooling system just as complex as that for the reactor proper but of smaller size.

The boiling water cooling system selected has the advantage of minimum dependence on mechanical components. On-site storage of sufficient feedwater for at least 6 hours can easily be provided. This system was selected on the basis of simplicity and reliability.

CALCULATION OF PERFORMANCE OF BOILING WATER COOLING SYSTEM

Heat transfer in the boiling water cooling system occurs by a combination of radiation and conduction between the concentric tubes. For design purposes assume a system as follows:

Outer tube - 2-in. OD x 0.072-in. wall. Inner tube 1-1/2 in. OD x 0.049-in. wall type 347 stainless steel tubing. The tubing surfaces are assumed to be oxidized. For computation purposes, the following assumptions will be made:

1. The inner surface of the outer tube is at the same temperature as the salt in contact with the outer tube surface.
2. The salt in contact with the outer tube surface is 25°F below the mixed-mean salt temperature.

3. The outer surface of the inner tube is at 250°F.

With the above assumptions, it becomes easy to compute the heat transfer between the two tubes and to evaluate the errors introduced by assumptions 1 and 3. As noted above, convection effects in this tank geometry cannot be calculated and assumption 2 cannot therefore be checked.

The heat transfer between the tubes occurs by two effects: radiation between the concentric tube surfaces and conduction.

For radiation, the applicable equation is:[2]

$$\frac{Q}{A_1} = \frac{F_A \sigma}{\frac{1}{\epsilon_1} + \frac{A_1}{A_2}\left(\frac{1}{\epsilon_2} - 1\right)} \left(\frac{T_1}{100}^4 - \frac{T_2}{100}^4 \right)$$

A	=	surface of tube
F_A	=	geometric factor ≡ 1 for concentric cylinders
σ	=	Stefan-Boltzmann constant = 0.173 for Q in Btu, A in ft^2 and T in °R
ε	=	emissivity of tube surfaces
T	=	temperature in °R
1		refers to outer tube
2		refers to inner tube

Based on data for monel metal and 18-8 stainless steel given in Table 4.1[2] ε is taken as 0.4 for both surfaces. This is one of the least certain assumptions in the computation; the ε might be as high as 0.9.

Substituting appropriate constants we find

$$\frac{Q}{\ell} = .0193 \left[\left(\frac{T_1}{100} \right)^4 - 2500 \right] \quad \text{Btu/hr(ft tubing)}$$

For conduction, using an air conductivity of 0.0265 Btu/hr(ft^2)(°F/ft) (300°C value), we find

$$\frac{Q}{\ell} = .785 \quad (t_1 - 250) \text{ Btu/hr(ft)}$$

2. D. Q. Kern, chap. 4 in Process Heat Transfer, McGraw-Hill, New York, 1950.

Results for cooling tubes of the configuration assumed are tabulated in Table 1 and plotted in Figure 3.

Table 1. Cooling Capability vs Salt Temperature - 1.5-in. OD x 0.049-in. Wall Inner Tube with Water Boiling Inside, 2.0-in. OD x 0.072-in. Wall Outer Tube with Hot Salt Outside

Temp. of Salt in Contact with Tube	Radiant Heat Transfer Rate	Conductive Heat Transfer Rate	Total Heat Transfer Rates	
°F	Btu/hr (ft tubing)	Btu/hr (ft tubing)	Btu/hr(ft)	kw/ft
950	661	530	1191	.349
1000	771	570	1341	.394
1050	890	605	1495	.438
1100	1022	648	1670	.490
1150	1170	687	1857	.544
1200	1331	727	2058	.603
1250	1510	765	2275	.667
1300	1695	805	2500	.732
1350	1908	845	2753	.806
1400	2140	885	3025	.886
1450	2380	925	3305	.970

A brief analysis of the errors introduced by the various assumptions has been made. At 1300°F, the actual boiling water film Δt is about 7°F and the tube wall drop is 3° so that the outside surface of the inner tube would be at 222°F. The drop across the outer tube wall is 2.25°F. Using these instead of the assumed values, the heat flux is increased by about 2% and the error introduced by the assumptions is insignificant. A far more serious error is introduced by the uncertainty in the proper value of emissivity. If the maximum value of 0.9 is assumed for both surfaces, the radiant heat transfer becomes 3.5 times and the overall heat transfer 2.7 times that based on the assumed emissivity of 0.4.

CONCLUSIONS

A cooling system capable of removing 100 kw at a salt temperature of 1300°F is adequate to control the temperature of the salt in the drain tank at a reasonable level. Such a system might comprise 136 lineal ft of 2-in. OD x 0.072-in. wall tubing with 1.5-in. OD x 0.049-in. wall tubing containing boiling water mounted concentrically inside. (The required length is that submerged in the molten salt.) A considerable uncertainty exists in the performance calculation due to the uncertainty in the value of emissivity chosen; the results quoted are based on what is believed to be a conservative value. Excessive cooling capability does not appear to be harmful. It would merely result in reduced maximum salt temperature. Figure 5 compares permissible radial heat fluxes with calculated fluxes as a function of outer tube temperature.