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COST STUDY OF A POWER INCREASE FOR THE BULK SHIELDING REACTOR

J. R. Bohannon

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COST STUDY OF A POWER INCREASE FOR THE BULK SHIELDING REACTOR

J. R. Bohannon*

* Captain, USAF.

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ABSTRACT

It is known that the Bulk Shielding Reactor can be operated at higher powers than the present 100-kw level since the similar Materials Testing Reactor and Low Intensity Test Reactor are operated at 30 and 3 megawatts, respectively. The fuel elements, coolant, and moderator of all three reactors are fundamentally the same; therefore, only the type of cooling system to be employed for a higher power level of the BSR must be decided upon. This report presents a cost study of three cooling systems: (1) a free convection cooling system, the system now used; (2) a pump forced convection cooling system with a one-pass-flow of water through the elements, and (3) a pump forced convection cooling system with a three-pass-flow of water through the elements. The third system is effected by passing water successively through three parallel regions of the element. The range of power levels considered is 1 to 10 megawatts. On the basis of this study it was found that a 2.5- to 2.8-megawatt power level with free convection cooling would be possible for $15,200 while the cost of the one-pass-flow pump forced convection system for 10 megawatts would be $180,000. Costs of the free convection and one-pass-flow pump forced convection systems for various power levels are quoted with a recommendation that the strongest consideration be given to the free convection cooling system.

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INTRODUCTION

It has recently been proposed that the Bulk Shielding Reactor (BSR) be converted to a higher powered reactor which could be used for a more extensive research program. In view of this proposal, a preliminary investigation of the engineering and economical aspects of an increased power level for the BSR above its present 100-kw maximum has been made. Preliminary studies of several possible power levels and associated cost analyses are presented for two commonly recognized reactor cooling systems along with a brief consideration given to a third method.

It is evident that higher power levels are attainable in the BSR when it is noted that the present operational levels of the similar Materials Testing Reactor (MTR) and the Low Intensity Test Reactor (LITR) are 30 and 3 megawatts, respectively. Since the fuel elements, coolant and moderator for the BSR are fundamentally the same as those of the above reactors, the only remaining concern is the type of cooling system to be employed for the new power level and the problems associated with the particular system selected.

In the analysis of this problem, three basic methods of cooling were considered:

1. Free convection cooling system in which the fuel elements would be cooled by water forced through the elements by a pressure differential set up by the difference between the water density within the reactor and that outside the reactor.

2. One-pass-flow pump forced convection cooling system in which the fuel elements would be cooled by water drawn into the top of the elements and out the bottom by centrifugal pumps, circulated through the heat exchanger, and returned to the pool (open system) or to a surge tank (closed system).

3. Three-pass-flow pump forced convection cooling system in which the fuel elements would be cooled by water drawn into the top of the elements and passed successively through three parallel regions of the element before being discharged by centrifugal pumps to the heat exchanger.

This report presents a discussion on each of the above cooling systems along with the calculations necessary for determining the heat transfer properties, total coolant flow rates, pressure losses in fuel plate channels, maximum surface temperature of fuel plates, radiation hazards, and other related subjects. On the basis of these calculations as well as related experimental data from the LITR and MTR, the minimum flow design requirements for specific power levels were established. The range of power levels considered was 1 to 10 megawatts. In analyzing this problems, strong consideration was given to the desirability of retaining, as far as possible, the versatility and maneuverability of the reactor as it now exists.

The cost analyses were based on the f.o.b. quotations for materials, assemblies, units, or fabrications along with the cost of installation on the construction site. No consideration was given to the engineering design costs, engineering or consultant fees, freight charges, major excavation, amortization, operational cost, miscellaneous labor requirements, or overhead.

The specification for individual units of equipment were determined through the use of:

1. Perry, J. H., Chemical Engineers' Handbook, 3rd ed., McGraw-Hill Publishing Co., New York, 1950.

2. Recommendations of manufacturers based on the requirements established in Table 2 (p. 27).

3. Consultation with members of various divisions at ORNL.

The cost estimates for various power levels were based upon the assumption that the particular level concerned would be the regular operating power level. If a lower operating power level were desired, the equipment would be flexible enough to allow such a variation but the lower level would not necessarily be the most economical operating point.

The cost of miscellaneous materials (piping, small pumps, cabling and the like) was based upon tables and graphs from Chemical Engineering Cost by O. T. Zimmerman and I. Lavine (Industrial Research Service, Inc., Dover, New Hampshire, 1954) corrected by current cost index or upon the latest Chemical Engineering Cost Data Quarterly (Industrial Research Service, 1954).

The entire study was based on BSR loading No. 22A, modified by using 27 whole elements and three partial elements. The loading consists of 30 elements in 5 by 6 rectangular loading. The two safety rods and one regulating rod are located in the three partial elements; however, a third safety rod and partial element may be added for power levels above three megawatts.

I. FREE CONVECTION COOLING SYSTEM

Description of System

The free convection cooling system, the system now used for the BSR, offers the most versatile and flexible reactor and would allow the retention of all advantages of ease of operating and handling of the present facility. This system would afford capabilities for both basic and development research, which is conducive to maximum utilization of a reactor. The main shortcomings of the system as designed are its operation time limit due to the heating of the water surrounding the reactor and the accumulation of activity in the pool.

One major alteration of the present BSR facility would be necessary: The reactor carriage would have to be redesigned to permit vertical adjustment of the reactor core from a depth of 16.5 to 24.0 ft below the water surface (Fig. 1).

The reactor would be cooled by process water flowing through the core lattice as a result of a differential pressure established by the difference of water density within the core as compared to that around the core.

Degassing or boiling within the core lattice would limit the upper power level, and this condition would cause the power level of the reactor to oscillate.[1] In this unstable condition, the reactor would be automatically shut down by the safety trips in the linear level or pile period circuits.

Problems related to this type of system are:

1. Time limit of operation as a function of maximum allowable temperature of the water in the pool.

2. The radiation hazard resulting from direct reactor gamma rays.

3. The radiation hazard resulting from neutron activation of O^{16} in the cooling water and its subsequent flow to the top of the pool where the decay process yields 6.2- and 7.0-Mev gamma rays:

$$O^{16}(n,p)N^{16*} \longrightarrow N^{16} + \begin{array}{l} 6.2 \text{ Mev} \\ 7.0 \text{ Mev} \end{array}$$

4. The radiation hazard resulting from neutron activation of sodium chromate and the accumulation of this activity within the pool.

---

1 W. M. Breazeale, T. E. Cole, J. A. Cox, "Preliminary Boiling Experiment in the LITR," Reactor Sci. Tech. 2, No. 2, p. 173 (TID-2002) (1952); "Further Boiling Experiments in the LITR," Reactor Sci. Tech. 2, No. 4, p. 186 (1952).

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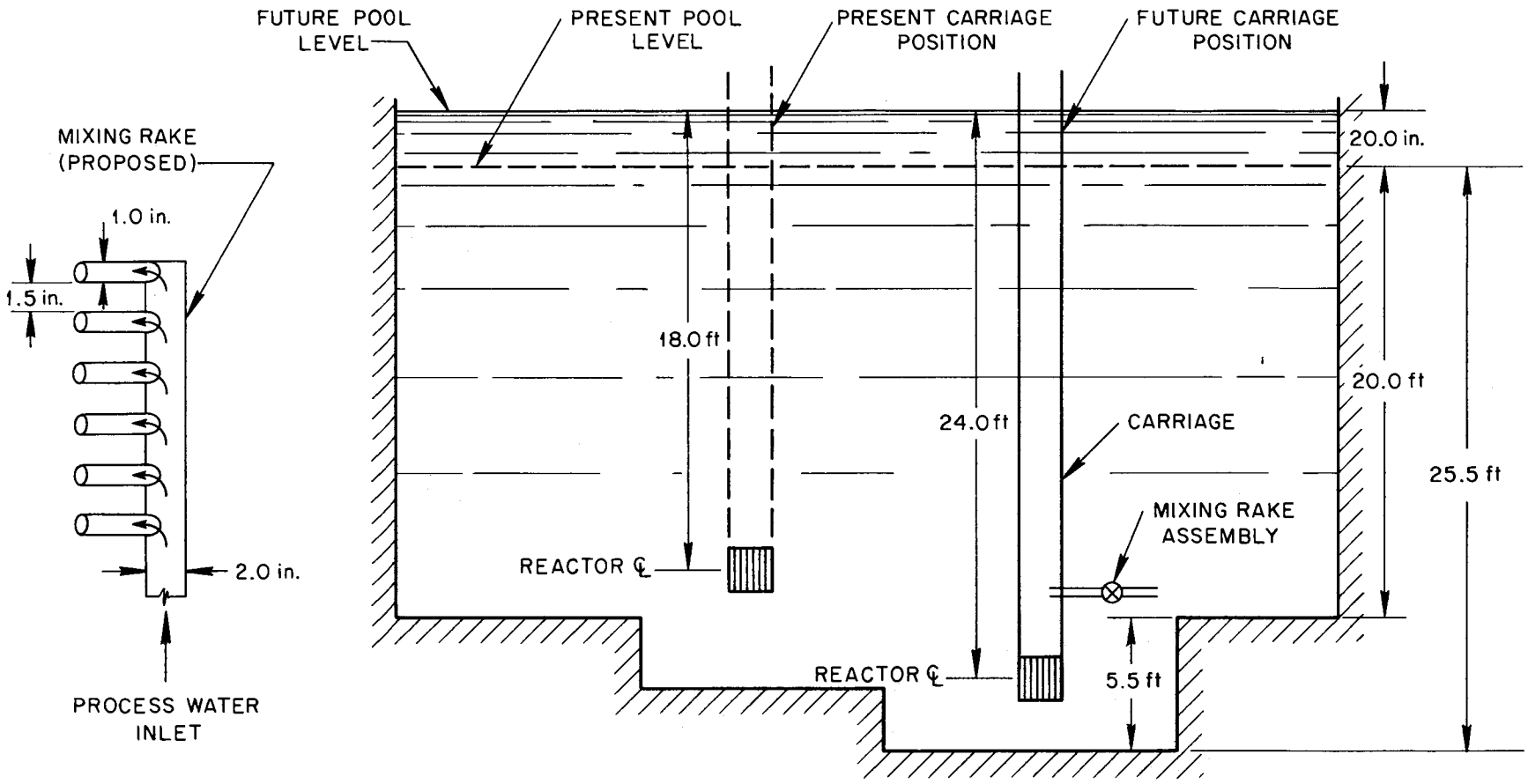

Fig. 1. Free Convection Cooling System.

5. Possible need for control rod modification or blackening as well as additional safety features for control and warnings at higher power levels. This includes the relocation of chambers to facilitate loading.

6. Amercoating of pool to prevent contamination of the demineralized water if such should be used in place of process water.

7. Sewage modification for dumping activated water into a hot disposal system in the event demineralized water is not used.

Discussion

Heat Transfer

Boiling experiments[1] were conducted at the LITR for the purpose of determining the maximum nonboiling, transferable, heat flux for MTR-type fuel elements cooled by free convection. This maximum condition was identifiable by the existence of boiling or degassing within the core lattice that caused oscillations on the power level recorder. The maximum transferable heat flux value was approximately 15,000 Btu ft^{-2} hr^{-1} at about 1.8 megawatts. The loading for these tests was a slab geometry of (3 x 8) + 1 elements reflected with beryllium, and the ratio of maximum thermal-neutron flux to over-all average thermal-neutron flux was 1.35.[2] The maximum power level attained was approximately 1.8 megawatts.

In evaluating the results of these tests, the rather poor circulating conditions that existed in the LITR for free convection cooling must be considered. The construction of the LITR is such that the pump-circulated coolant water normally flows through the core lattice from the top to an outlet in the bottom of the tank. In these tests this forced circulation was stopped and the reactor was cooled by free convection only. Because of the physical arrangement of the core the circulation by free convection consisted of water rising in the center portion of the core lattice while flowing down in the outer perimeter of the lattice. This means that the inlet temperature of the water flowing through the center of the reactor was gradually increased by the re-use of the coolant water. It is evident that the maximum transferable heat flux is directly related to the inlet water temperature and hence determines the upper power limit of the cooling system.

In the BSR, the ratio of maximum thermal-neutron flux to average thermal-neutron flux is 1.95 for loading No. 22A;[3] the MTR, with a slab geometry of 3 x 9 elements, has a flux ratio of 1.64.[4]

---

2 C. D. Cagle, ORNL, private communication concerning LITR flux curves from stainless steel poisoning experiment.

3 R. G. Cochran, J. L. Meem, T. E. Cole, and E. B. Johnson, "Reactivity Measurements with the Bulk Shielding Reactor," ORNL-1682 (Nov. 9, 1952).

4 R. B. Briggs, ORNL, to J. P. Sanders, ORNL, private communication.

The reliability of the LITR ratio, 1.35, is questionable in that the foil work was a secondary result of another experiment in which the poisoning effects of stainless steel within the fuel element channels were studied. From this work the activated stainless steel strips were cut into small segments and the gamma activity was measured in a 4π ionization chamber. The results were normalized and plotted for the flux curve, integrated by a planimeter, and used in obtaining the 1.35 ratio. It is believed that the experimental work on the MTR[5] is more indicative of the true LITR ratio; therefore, the value 1.64 will be used for all LITR ratios. The ratio of the relative fluxes of the BSR to the LITR is:

$$\frac{\text{BSR}}{\text{LITR}} = \frac{1.95}{1.64} = 1.19$$

The respective heat source areas or fuel plate surface areas of the LITR and BSR are now considered. The LITR had 25 elements (20 whole elements with 18 fuel plates, 2 partial elements with 9 fuel plates, and 3 shims with 80% normal fuel loadings) with a total surface area of 410 ft^2, while the BSR loading would have 30 elements (27 whole, and 3 partial)* with an approximate total surface area of 488 ft^2. The ratio of the surface areas is:

$$\frac{\text{BSR}}{\text{LITR}} = \frac{488.0}{410.0} = 1.19$$

If it is assumed that the effects of the flux ratios as compared to the area ratios is compensative, then the effect of a high specific heat flux in the BSR would be compensated by the increased surface area for the heat load. This means that the maximum free convection power level that could be expected in the BSR would be at least 1.8 megawatts. This leaves one remaining parameter, the inlet temperature of the cooling water, which would influence the maximum heat flux transfer value and thus the upper power limit.

It is a certainty that the inlet water temperature in the LITR tests was much higher (86 to 125°F) than the normal water temperature at the BSR (50 to 65°F). Thus the power limit of the BSR should certainly be above 1.8 megawatts.

As a first estimate of the upper power limit, reference is made to Fig. 2 in which the temperature rise in the hottest BSR fuel element (No. 25) in loading 22A[3] is plotted as a function of power level (see also Table 1). If it is assumed that the point of boiling is at the top of the fuel element and that for an 18-ft head of water the boiling point of water is 233°F, then with an inlet temperature of 100°F the rise necessary for boiling is 133°F. The inlet water temperature was taken as 100°F because this is the highest temperature the pool water will be allowed to reach.

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* This would be a modification of loading 22A.

5 J. P. Sanders, "Operating Conditions of the ORR Cooling System," CF-54-3-169 (Mar. 19, 1954).

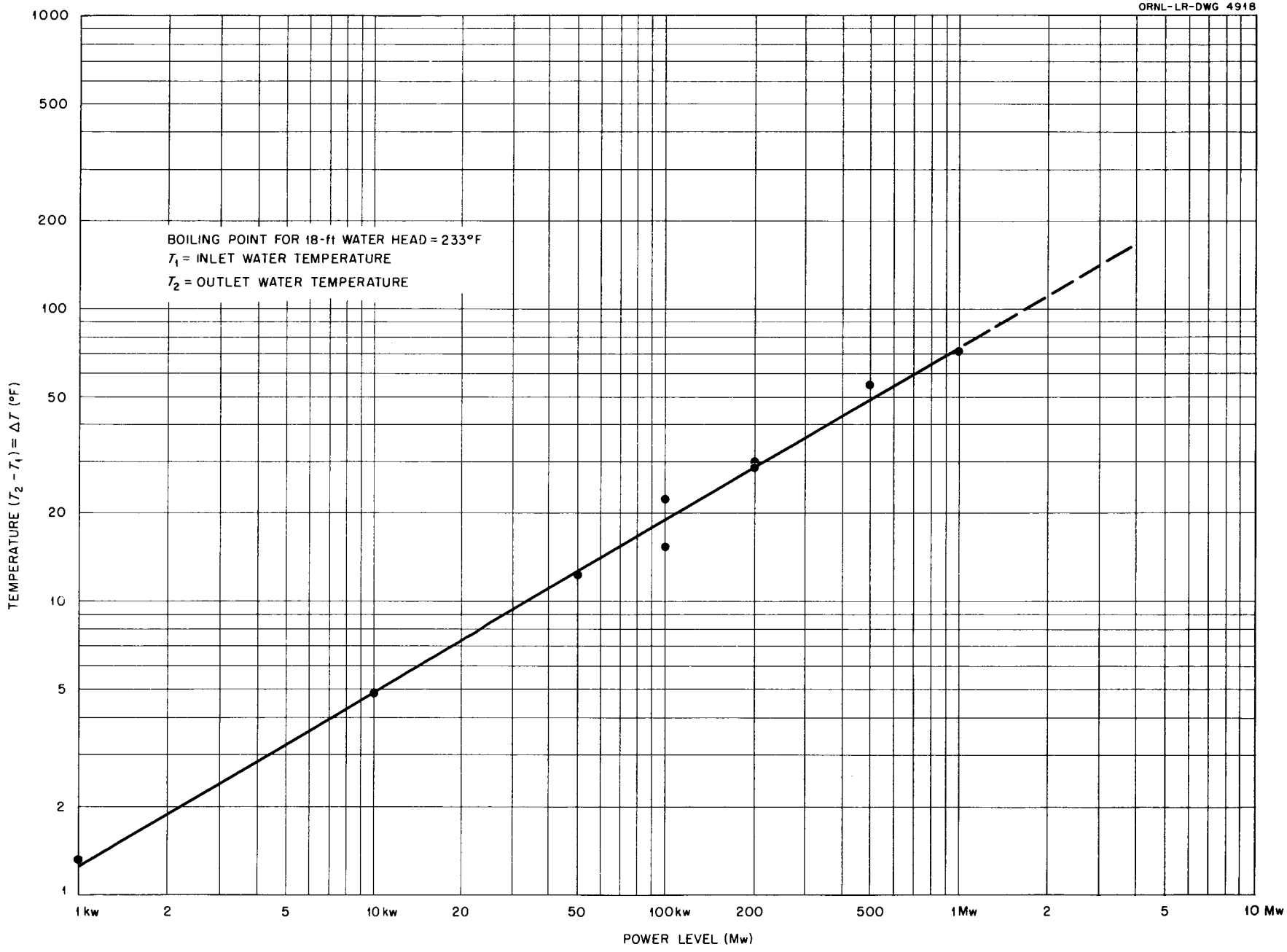

Fig. 2. Change of Cooling Water Temperature Across Fuel Element No. 25 vs. Reactor Power Level, Free Convection.

Table 1

Change of Cooling Water Temperatures Across BSR Element No. 25,[a] Free Convection Cooling

Power Level (kw)	ΔT^a (°F)	
	Element No. 15	Element No. 25[b]
1	0.9	1.1
10	4.1	4.8
50	10.8	12.6
100	13.1	15.4
100	19.1	22.4
200	23.9	28.0
200	25.2	29.5
500	46.8	54.8
1000	61.2	71.5

a ΔT = cooling water outlet temperature, T_2, minus inlet water temperature, T_1.

b Ratio of specific power for element 25 to element 15 = 1.17, as reported in ORNL-1682, R. G. Cochran et al., "Reactivity Measurements with the Bulk Shielding Reactor," (Nov. 9, 1954).

This fixes the maximum nonboiling power at between 2.5 and 2.8 megawatts. This power estimate is based on the assumption that the heat distribution along the fuel plates is a constant. Also precluded is the possibility of nuclear boiling which would increase the transferable heat flux.

A theoretical study of the upper power limit for free convection cooling has been initiated by H. F. Poppendiek, ORNL; however, since both the LITR and MTR are well proven systems and in the light of the results from the "Borax" experiments[6] it is felt that the most expedient and conclusive method of determining the upper power limit for a free convection system is to run the BSR up to the point of boiling or oscillation of the power level.

Shielding

The increase in direct gamma rays from the reactor at higher powers could be controlled by either of two ways: (1) using Tower Shielding Reactor (TSR) type fuel elements which have a sectionalized lead shield built into the top of each element, or (2) modifying the reactor carriage so that the reactor core could be lowered into the deepest part of the pool. With the latter method, the reactor horizontal centerline would be at a water depth of 22 to 24 ft, and calculations[7] indicate that the reactor direct gamma rays would not render a dose above laboratory tolerance on the surface of the pool at a 2.5- to 2.8-megawatt power level. As an additional shield, the water level of the pool may be raised another 20 in.

With the additional water shielding it will not be necessary to use TSR fuel elements. They would only effect a reduction of about a factor of 5 in any case because of the circumvention of the top lead shield by gammas from the reactor sides.[8]

The gamma rays from the reaction

$$O^{16}(n,p)N^{16*} \xrightarrow[T_{1/2} = 7 \text{ sec}]{} N^{16} + 6.2 \text{ Mev} \quad 7.0 \text{ Mev}$$

become predominant in the BSR as the megawatt range of power is approached. With a higher flux and a higher temperature rise across the elements, the N^{16}-laden water would rise to the surface of the pool more rapidly and thus constitute the primary external radiation hazard to operation. The activity on the surface of the pool would be somewhat accumulative since the warm water from the reactor rises to the surface and remains there. This radiation is controlled by delaying the arrival of the N^{16}-laden water at the surface of the pool by baffles or forced reversed flow until the activity is reduced by decay (half-life of N^{16} is 7.0 sec).

6 J. R. Dietrich and D. C. Layman, "Transient and Steady State Characteristics of a Boiling Reactor--The Borax Experiments, 1953," ANL-5211 (Feb., 1954); J. R. Dietrich, "Experimental Investigation of the Self-Limitation of Power During Reactivity Transients in a Subcooled, Water-Moderated Reactor. Borax-I Experiments," ANL-5323 (1954).

7 H. E. Hungerford, "Bulk Shielding Facility Water Data Work Sheet," ORNL-CF-52-2-37; also published in ORNL-CF-51-1-70, Part II Revised, p. 87.

8 C. E. Clifford et al., "Effectiveness of Lead Gamma Shielding in the Fuel Elements of the Tower Shielding Reactor," ORNL-CF-54-7-14 (July 8, 1954).

A second and more appealing method of preventing the N^{16}-laden water from immediately reaching the surface and a method by which the reactor could remain unobstructed is that of mixing the warm water leaving the reactor with the cooler water of the pool. This could be accomplished by a jet mixing system or pump assembly as indicated in Fig. 1. Since the resultant mixture of reactor water and pool water would have such a small density difference as compared to surrounding water, the convection rise to the surface of the pool would be considerably reduced. It is anticipated that jet mixing tests will be run on the BSR in the near future to determine the amount of pumping desirable to effect proper mixing and subsequent reduction of surface activity.[9] It is believed that a jet of water equivalent to the flow through the reactor will satisfy this condition.

If sodium chromate is to continue as a corrosion inhibitor, consideration must be given to the activation of this material as it passes through the reactor. Figure 3 gives the accumulated activity in the pool as a function of the kilowatt hours of reactor operation. Since the activated constituents of sodium chromate have relatively long half-lives (15 hr), the accumulation of activity in the pool may become a prohibitive factor for any extended operation at the megawatt level. Without external cooling, however, the pool temperature rise would be the limiting factor before the activity level. As a possible control for this activity, the pool water could be diluted with process water so as to maintain a low level of activity. If the dilution method is used, provisions may have to be made for diverting the overflow to the hot disposal lines southeast of Building 3010 rather than through the present sewage system. If the activity is to be allowed to accumulate until shutdown is required, then the draining of the pool into the hot disposal lines must be considered. The Health Physics group agrees with the general provisions for this, but they have stated that if the bulk of the sodium chromate activity is due to Na^{24}, which it would be, then consideration would be given to the disposal of the water through the regular cold lines if the holding time in the pool and drainage time are sufficiently large. A possible alternative to the problem might be that of running the high power levels with an initial charge of process water without sodium chromate, and then adding the inhibitor. This alternate would require considerable thought from the standpoint of corrosion as well as reactor utilization planning.

It should be mentioned that if sodium chromate is used, the leaks in the pool must be stopped in order to prevent the leakage of activated materials into the surrounding area.

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9 Subsequent to the writing of this report these tests were made and reported in ORNL-1682, R. G. Cochran *et al.*, *op. cit.*

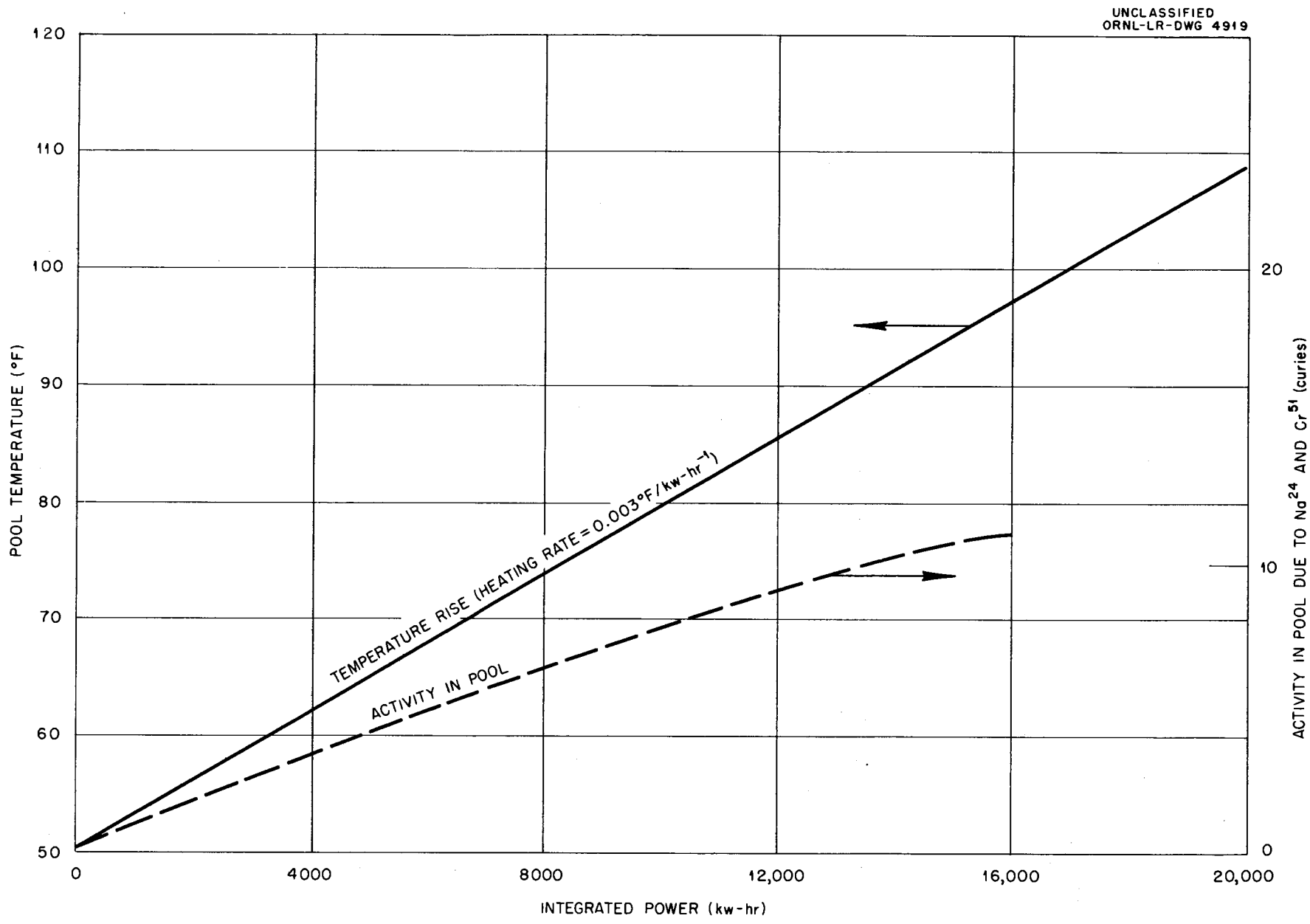

Fig. 3. Pool Activity (from Sodium Chromate) and Temperature vs. Integrated Power.

Temperature Limitation

The operation time of the free convection cooling system would be further limited by the heating of the pool water. Figure 3 gives the pool temperature as a function of the integrated power of operation. This is based on the assumption that very little surface cooling takes place during operation. The amount of heat released by surface cooling with the pool temperature at 100°F is approximately 2.8% of the heat produced in the reactor. The limit on operation time appears to be around 17,000 kw.hr. This was based upon an upper pool temperature limit of 100°F, which is considered to be the maximum temperature compatible with satisfactory working conditions in the building.

Controls

Sufficient reactivity would be required to handle the xenon poisoning at higher power levels and it might become necessary, for example, when using a modified loading No. 22A to increase the $\Delta k/k$ worth of the safety rods or to use an additional safety rod. At present, the safety rods are filled with a cadmium-lead mixture containing 17 1/2% cadmium, with a total of 3 to 4% worth for the full 24 in. of travel of both rods. The $\Delta k/k$ values for control and safety rods for loading No. 22A will be covered in another report.[3]

It is anticipated that certain additions and modifications may be required by the Advisory Committee on Reactor Safeguards, the ORNL Reactor Controls Group, and the BSF staff. This would include instrumentation, recorders, safety circuits, etc.

Corrosion

The use of 50 ppm (grams of sodium chromate to million grams water) of sodium chromate in the cooling water should be continued as a corrosion inhibitor for short-time operation shcedules. Actually, much lower concentrations have proved satisfactory in work at ANL on aluminum corrosion studies.

Cost Analysis

The cost analysis for this system has been divided into the following categories:

a. Shielding
b. Controls, instrumentation, and general modifications of equipment
c. Cooling systems (free convection)
d. Corrosion

The cost analysis is presented in Appendix C.

The final system used in obtaining the cost versus power curves shown in Fig. 13 consists of a modified BSR that has an adjustable carriage and a pool that has wall and floor surfaces water-proofed against contamination and outward leakage. The system includes (1) a group of mixing jets (rake) for minimizing the N^{16} activity on the surface of the pool and (2) provisions for purging the initial charge of demineralized water within the pool.

It should be mentioned that the use of demineralized water would best minimize the corrosion of the fuel elements; however, the ability of maintain the proper pH and resistivity as well as to prevent contamination of the water by foreign matter, atmospheric carbon dioxide and nitrogen, and/or fungus formations such as algae is not well known for a large open surface system such as exists at the BSR.

The present lifetime of LITR fuel elements when operating at 3 megawatts is one year. This is primarily determined by fuel burnup rather than corrosion damage. The lifetime of BSR fuel elements may be limited by corrosion damage rather than burnup depending upon the average power level.

II. ONE-PASS-FLOW PUMP FORCED CONVECTION COOLING SYSTEM

Description of System

The pump forced convection cooling system would utilize the same facilities as described in the free convection system with the following additions and modifications (refer to Figs. 4, 5, and 6):

1. An aluminum housing placed under the bottom of the reactor to channel the reactor cooling water to the circulation pump.

2. Amercoating of all water exposed surfaces within the pool, exclusive of the reactor, carriage, chambers, etc. to minimize contamination of the demineralized water.

3. A demineralizer to purge and maintain the proper pH and resistivity of the cooling water.

4. One of three types of heat exchangers to maintain the cooling water at the proper inlet temperature.

    a. Fixed-tube sheet, or tube and shell type of water-to-water exchanger using process water as the secondary coolant.

    b. Water cooling towers with coil banks or plate coils mounted in the tower basin or above the basin in the drip region.

    c. Air coolers or radiators (dry type) utilizing atmospheric air as the cooling medium.

For reactor cooling, demineralized water would be drawn from the pool into the top of the reactor core and circulated through the core by a circulation pump. From the pump, the water would be forced through a heat exchanger and bypass type purge demineralizer and then back to the diffusion pipes on the floor of the pool.

Problems related to this type of system are:

1. The radiation hazard resulting from direct reactor gamma rays.

2. The radiation hazard resulting from neutron activation of O^{16} in the cooling water.

3. The difficulty of maintaining the proper acidity and resistivity of the demineralized water in order to minimize the corrosion on the fuel plates.

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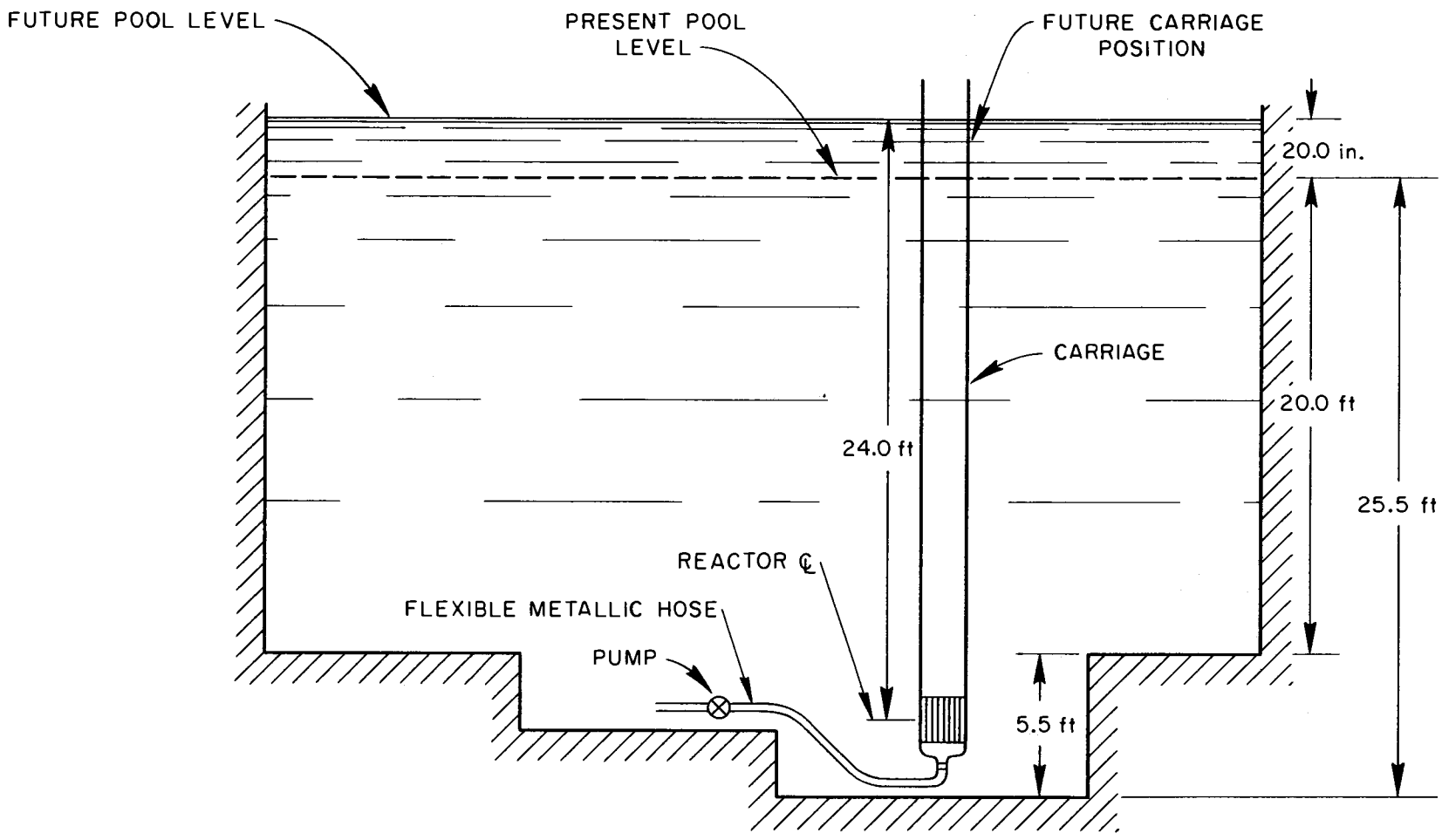

Fig. 4. Pump Forced Convection Cooling System.

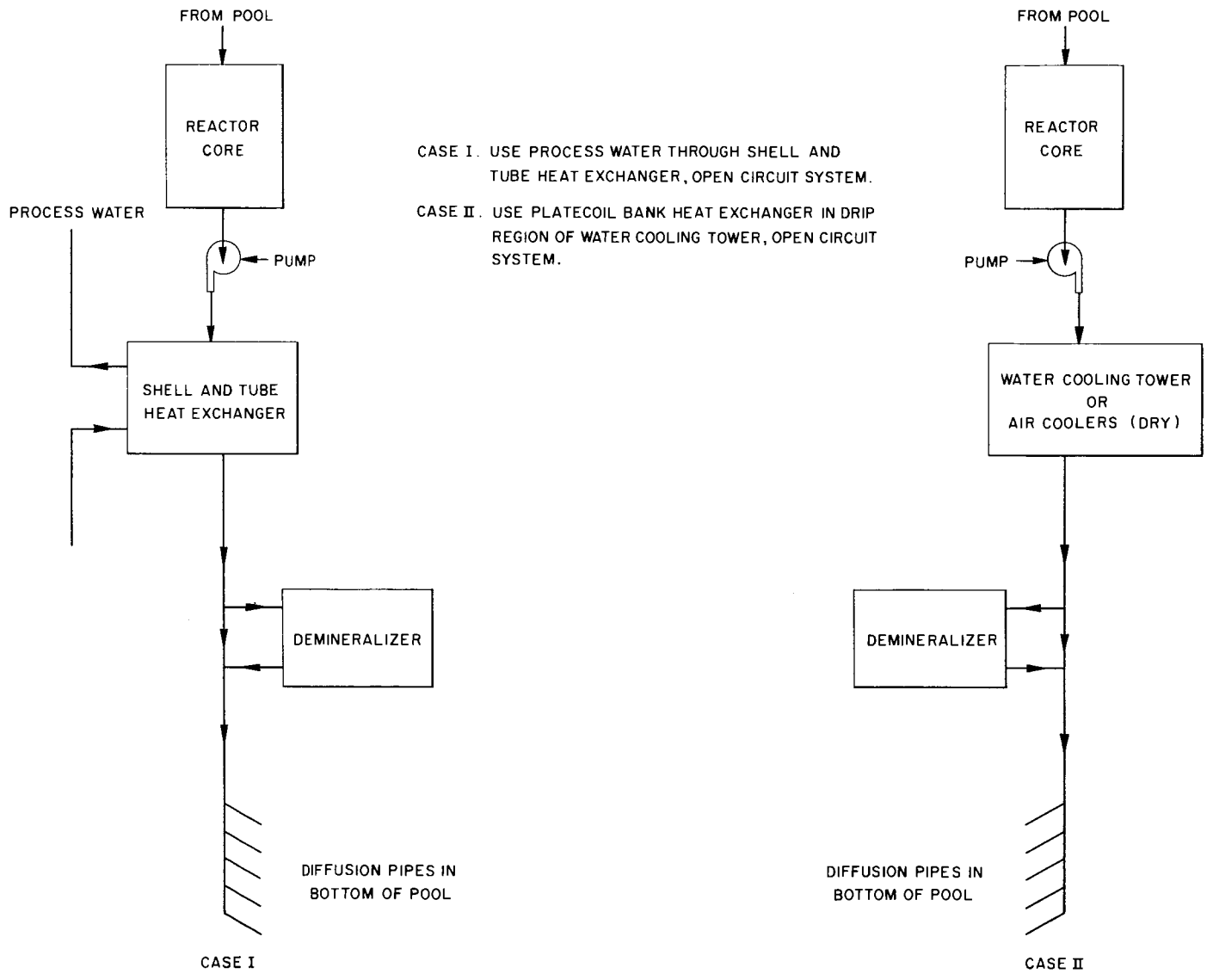

Fig. 5. Pump Forced Convection Cooling System, Cases I and II.

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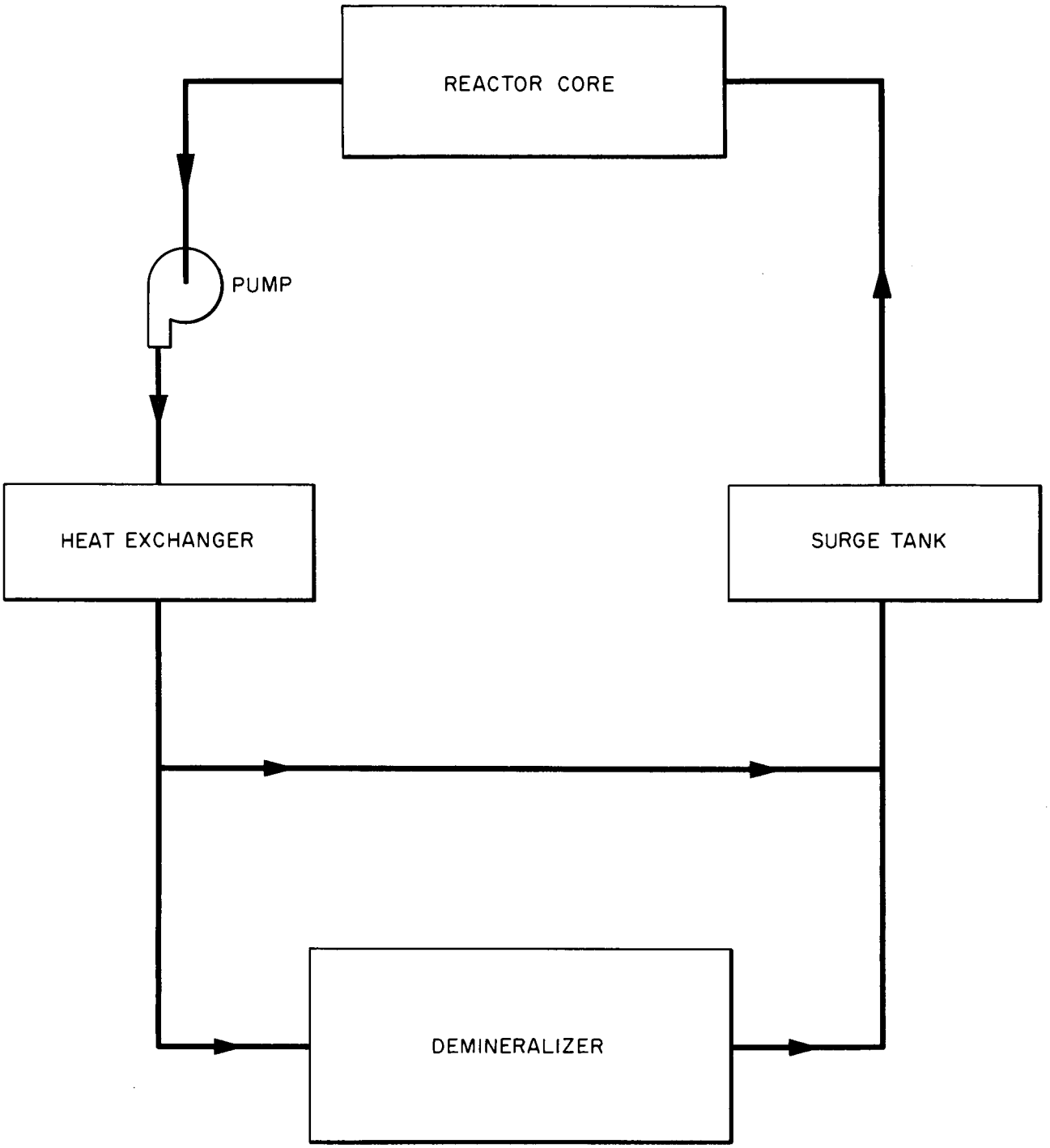

CASE III. USES AIR (DRY TYPE) COOLERS IN A CLOSED SYSTEM

Fig. 6. Pump Forced Convection Cooling System, Case III.

4. The possible need for safety rod modification or blackening and additional safety features for control and warning at higher power levels. This includes the relocation of chambers to facilitate loading of fuel elements.

5. Physical accommodations needed for experiments other than for shielding, such as fuel loop studies.

6. Possibly serious increased structural strains on the system.

These difficulties do not appear to be serious but overcoming each will add to the cost of the system.

Some consideration has been given to a closed cycle pump forced convection cooling system as a means of controlling the excess activity from N^{16}. In addition, this system would use higher inlet and outlet cooling water temperatures which would improve the heat transfer in the heat exchanger as compared to the open system. This is especially true of air coolers if T_2 (reactor coolant water outlet temperature) can approach 160 to 170°F.

Discussion

Heat Transfer

Experiments[10] were performed at the LITR to determine the minimum flow rate of cooling water through the core lattice which would preclude boiling or degassing at various power levels. The results (Fig. 7) indicate that for 1.5 megawatts and above, the transferable heat flux increased linearly with the flow rate and power level. From this linearity it might be inferred that turbulent flow exists in the fuel plate channels. Heat transfer coefficients are proportional to $V^{0.8}$ for turbulent flow and $V^{0.33}$ for laminar flow, where V is velocity in feet per second.[11] Figure 7 gives an indication of the water flow conditions existing in the LITR fuel elements and may be applied to the BSR flow design studies.

In consideration of this flow data, the differences of flux ratios (1.64 to 1.95), loading geometry, and total heat source area are as applicable as they were in the comparison of free convection in the LITR and BSR. All the water flowing through the LITR does not pass through the core lattice since some will bypass the lattice by flowing through the beryllium reflector. This condition would lead to a higher LITR flow requirement as compared to the BSR under similar conditions.

10 Review of LITR daily performance logs for 1953 and 1954.
11 W. H. McAdams, Heat Transmission, 2nd rev. ed., p. 183, McGraw-Hill Book Co., New York, 1942.

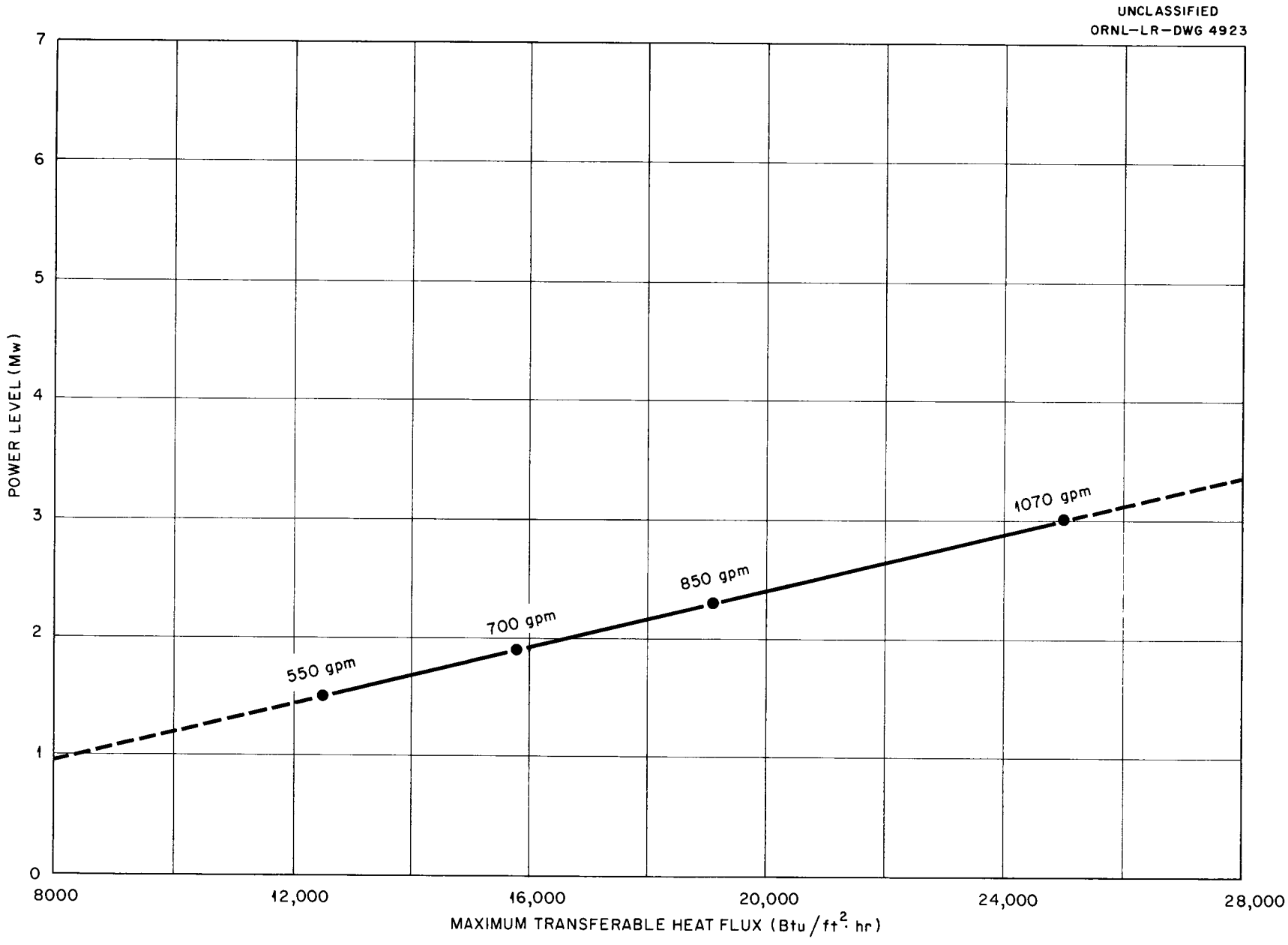

Fig. 7. Maximum Transferable Heat Flux vs. Power Level (LITR)

In order to obtain a correlation of flow rates as a function of power level, it is essential that the maximum surface temperature of fuel plate (T_m), as related to the inlet cooling water temperature, flow rate of inlet water, and power level be determined. Appendix A gives the details for determining this relationship and Figs. 8, 9, and 10 illustrate the results for 1 to 10 megawatts with the inlet water temperature taken at 100, 120, and 140°F, respectively. It should be noted that these curves were developed on the basis of turbulent flow in the fuel plate channels. The design flow rates (see Table 2) for power levels under 1.5 megawatts are therefore low since the Reynold's numbers for these levels are within the transition region of flow conditions where $N_R < 2100$. The requirements for this region must be considered above those indicated; if the pump requirement for a power level of 1.5 megawatts is used the proper turbulent condition will be furnished within the fuel plate channels for the lower power levels.

Flow Rates

The minimum flow rates for this system were based on Figs. 8, 9, and 10, using 200°F as the maximum allowable fuel plate surface temperature. Figure 11 gives the flow rate for the open system as a function of power, where 100°F was chosen as the maximum allowable pool temperature (T_1) compatible with working conditions in the reactor room.

A temperature of 120°F was chosen as the maximum inlet temperature (T_1) for the closed system because of the temperature effects upon the Amercoating in the surge tank and elsewhere. This temperature limit could be raised to 140 to 150°F if an aluminum or stainless steel surge tank were used.

The pressure drops across BSR-type fuel elements as a function of flow rates are shown in Fig. 12. These values were obtained from Vennard[12] and Sanders.[13]

Shielding

The direct gamma-ray radiation from the reactor can be handled by methods described for the free convection system. The gamma rays from the neutron activation of O^{16} would be handled somewhat differently. In this case the coolant water and hence the activated O^{16} (N^{16}) would be pumped through the entire cooling system before being discharged into the bottom of the pool through diffusion pipes, so that most of the activity would have had sufficient time to decay before discharge.

In the closed system the activity would be retained within the cooling circuit and thus prevented from reaching the surface of the pool. The problem then would be limited to the shielding of cooling water lines outside the reactor pool.

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12 J. K. Vennard, Elementary Fluid Mechanics, 2nd ed., John Wiley and Sons, Inc., New York, 1940.

13 J. P. Sanders, "Heat Transfer and Pressure Loss in Proposed ORR Fuel Assemblies," ORNL-CF-54-3-57 (Mar. 11, 1954).

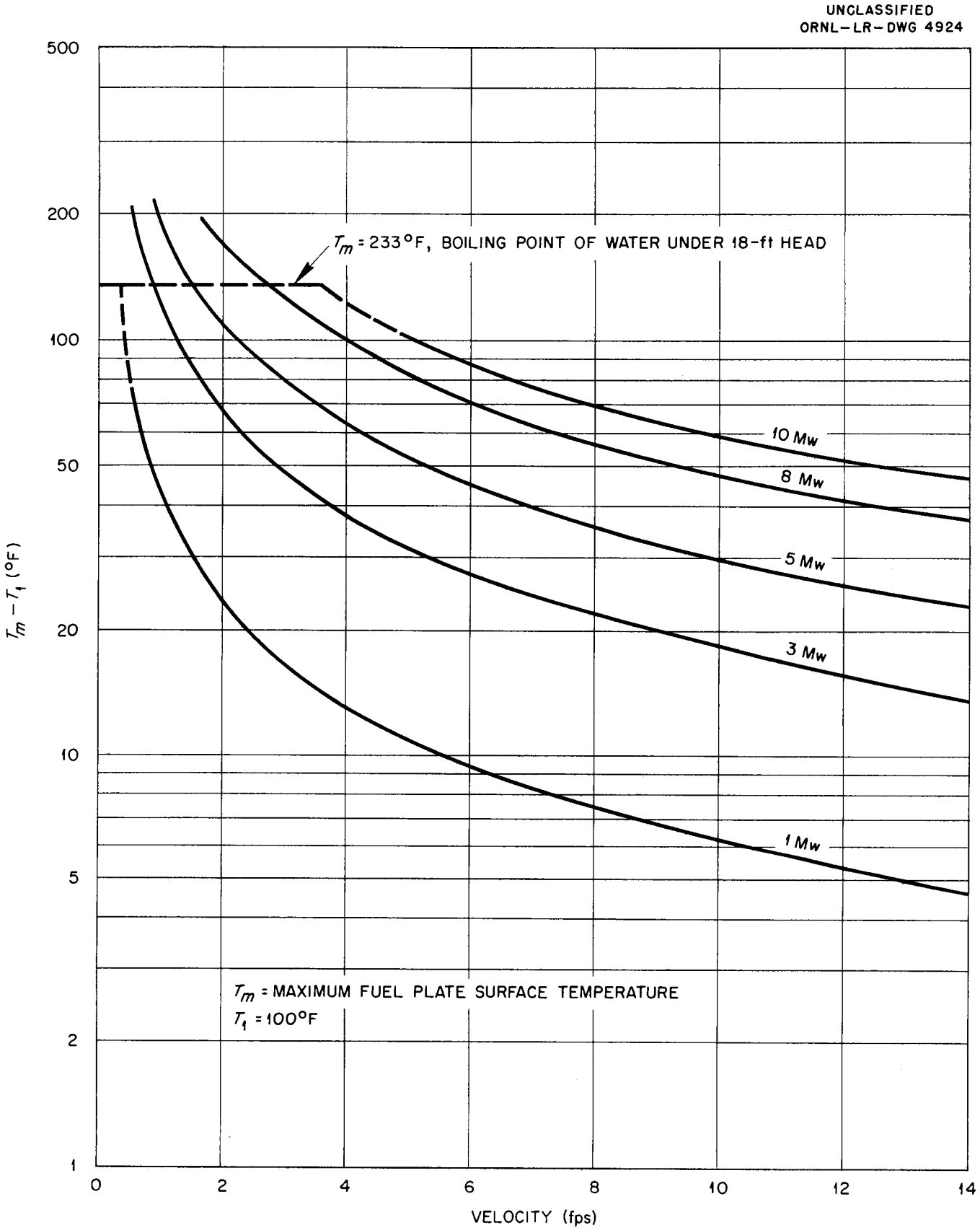


Fig. 8. Interrelation of Fuel Plate Temperature, Reactor Power, and Flow Velocity for 100°F Inlet Water Temperature.

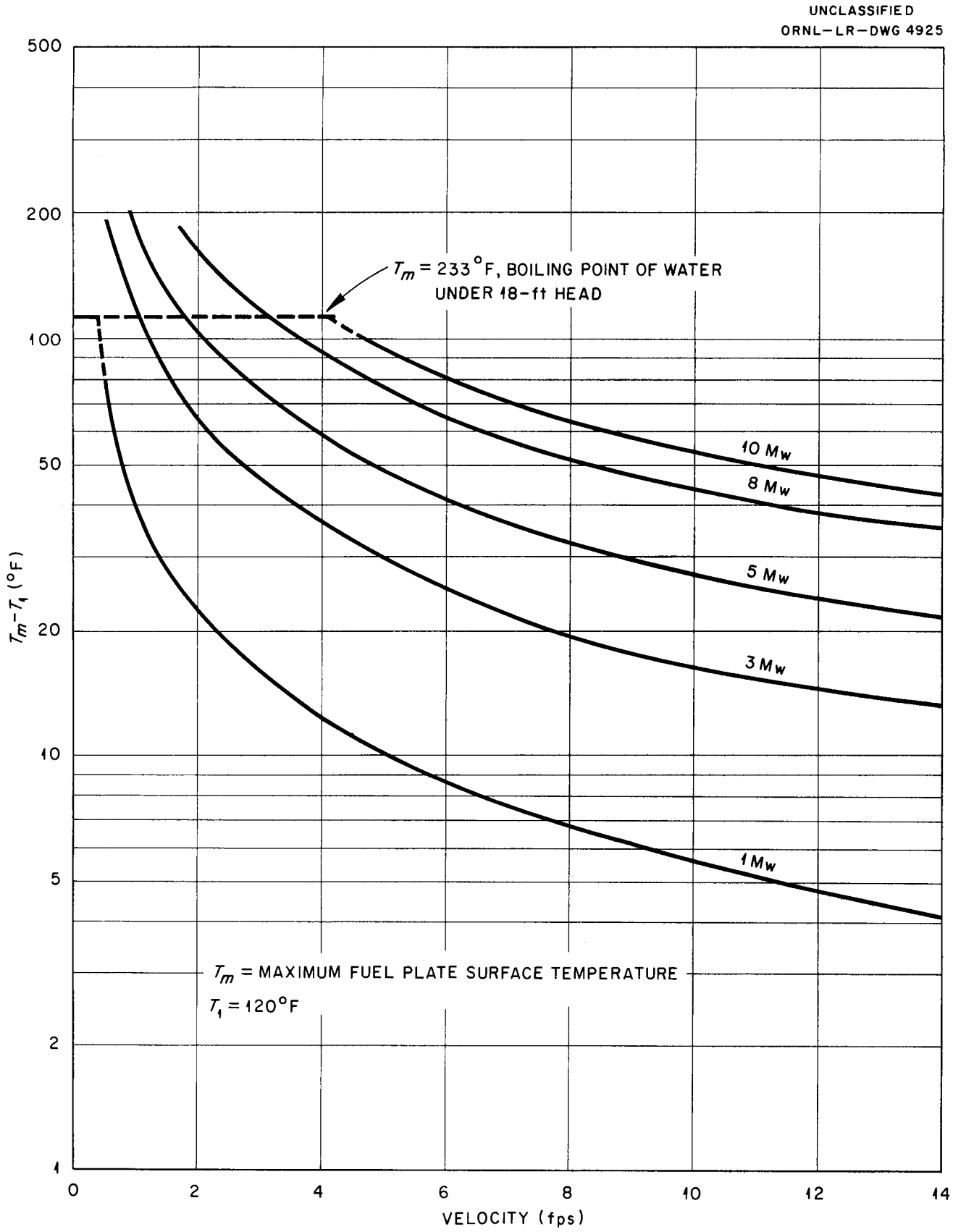


Fig. 9. Interrelation of Fuel Plate Temperature, Reactor Power, and Flow Velocity for 120°F Inlet Water Temperature.

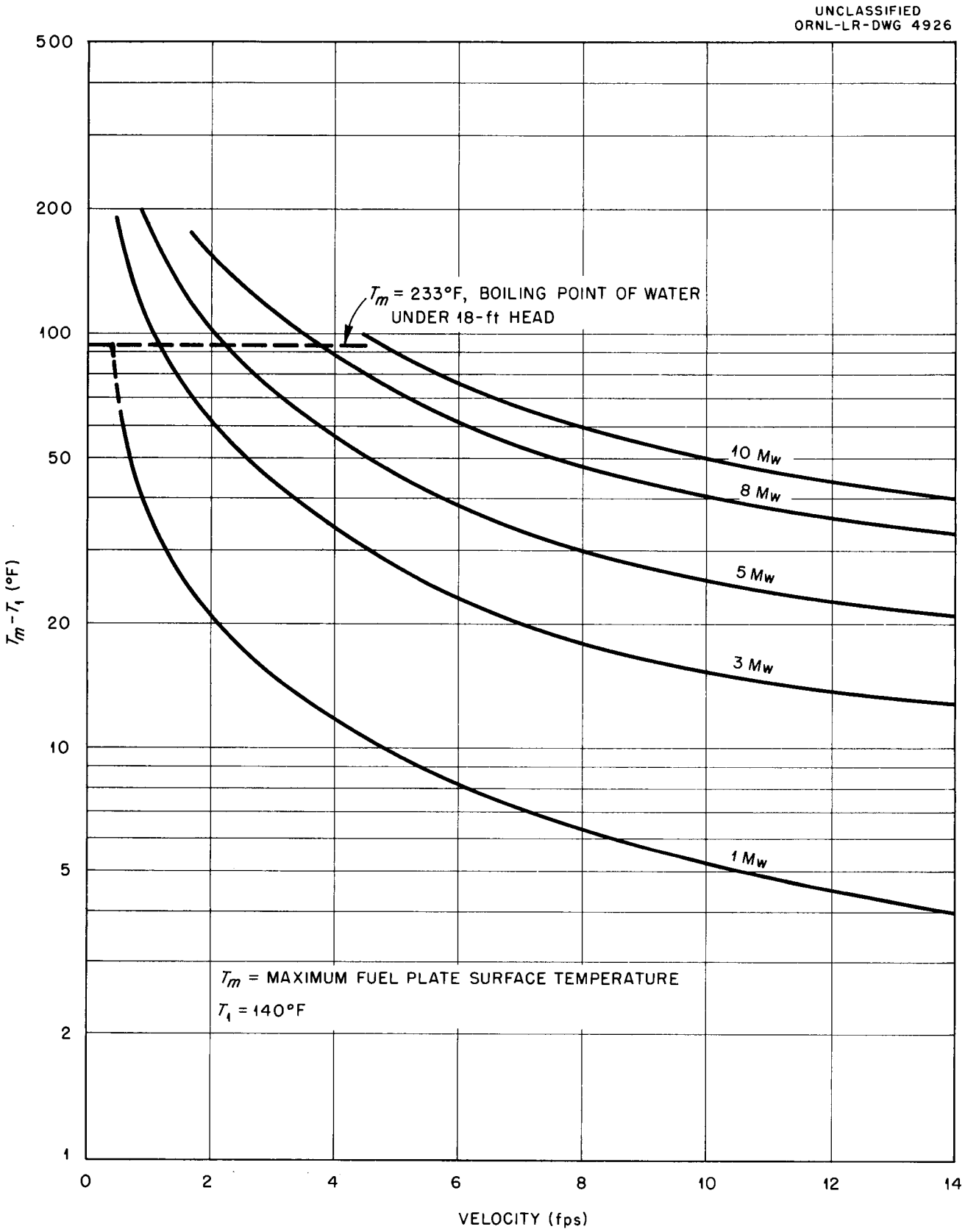


Fig. 10. Interrelation of Fuel Plate Temperature, Reactor Power, and Flow Velocity for 140°F Inlet Water Temperature.

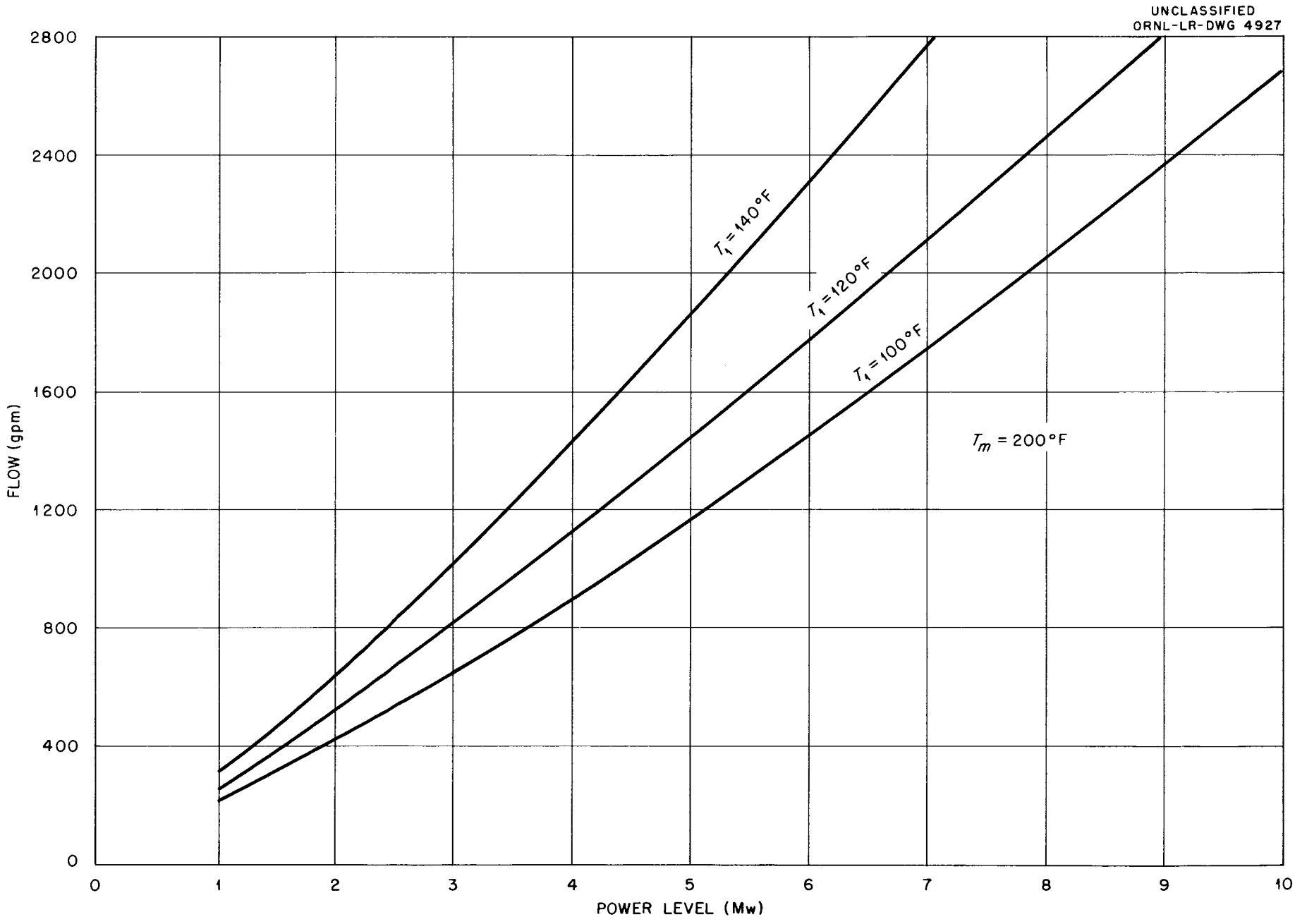


Fig. 11. Design Flow Requirements vs. Power Level for Inlet Water Temperatures of 100, 120, and 140°F.

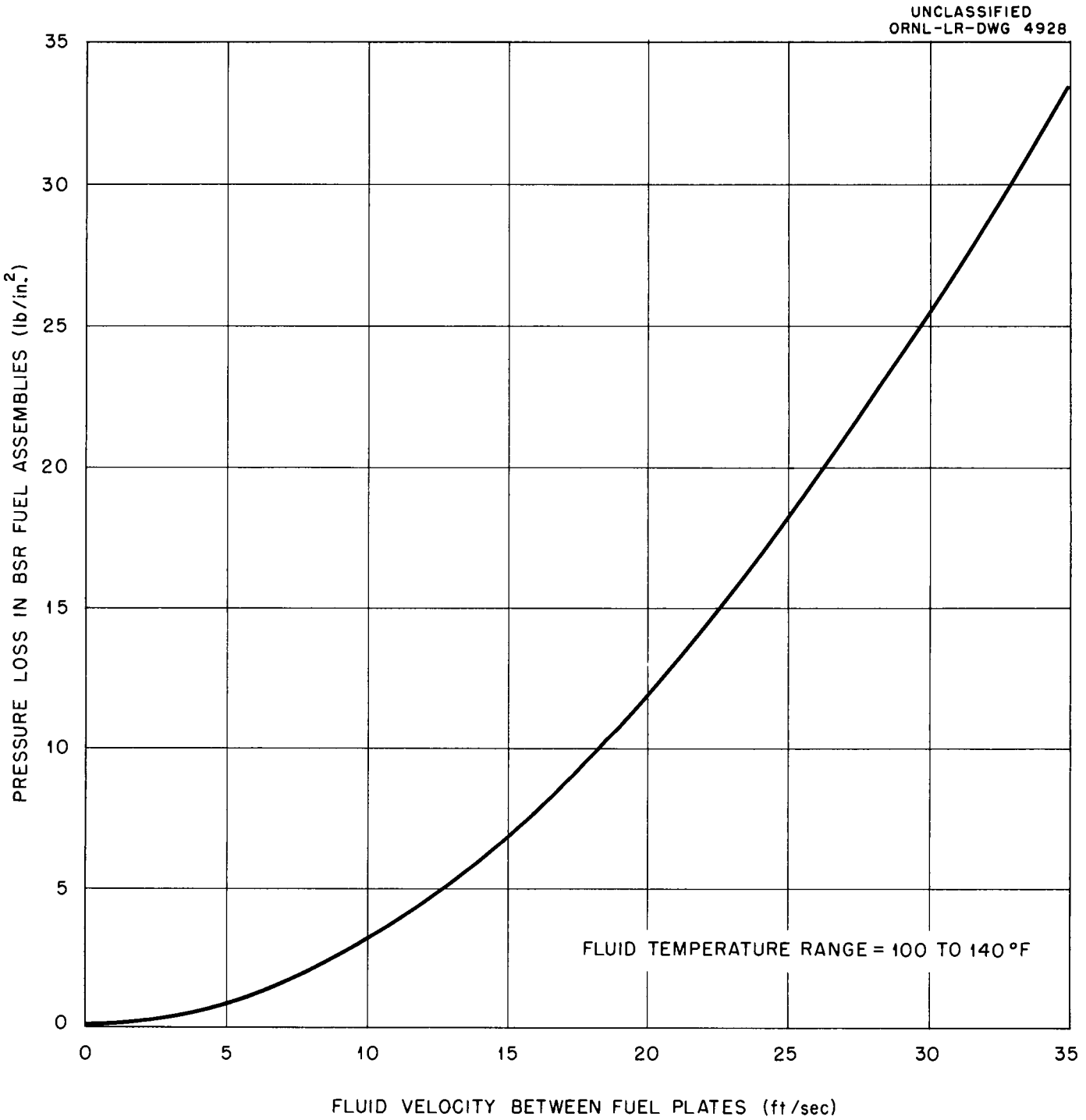


Fig. 12. Pressure Loss Through Fuel Assembly vs. Flow Velocity Between Fuel Plates.

Table 2

Final Design Requirements of BSR (One-Pass-Flow)[a]

Power Level (megawatts)	LITR Flow (gpm)	BSR Flow (Theoretical) (gpm) $T_1 = 100^oF$	T_2 (BSR) (^oF)	BSR Design Flow (gpm)[b]
1	376	210	132.6	230
3	1070	645	132.0	710
5	1760[c]	1160	129.5	1275
8	2800[c]	2080	126.0	2210
10	3352[c]	2780	124.0	3060

a All flows for power levels above 1.5 megawatts have Reynolds numbers $\succ$ 2100.
b Contains 10% safety contingency.
c Extrapolated estimates.

Controls

The same modifications and additions to the control system as applied to the free convection system would be applicable here. In addition, provisions would have to be made for rotameters, manometers, orifices, thermocouples, Brown recorders (period), interlocks, positive rod driving mechanism, etc. for maintaining proper control and safety of operation.

Corrosion

It has been noted[14] that if the demineralized water in the pool could be maintained at a pH of 5.5 to 6.2 with a resistivity of 600,000 to 800,000 ohms, the corrosion problem would be minimized. As mentioned in the section on free convection cooling, the use of an open system of demineralized water poses the problem of maintaining the proper pH and resistivity as well as preventing the contamination of the water by foreign matter, atmospheric carbon dioxide and nitrogen and fungus formations such as algae.

The initial charge of demineralized water for filling the pool would be supplied from a nearby source at ORNL. The erection of a storage tank is contemplated so that large quantities of demineralized water can be supplied to the proposed Oak Ridge Research Reactor on short notice. If this materializes, the filling time of the BSR pool could be cut from 2 days to several hours. A return line from the BSR pool to the ORNL storage tank is also considered so that in cases where it would be necessary to drain the BSR pool, the demineralized water could be returned, reprocessed, and stored for future use, presuming of course that the water is not contaminated.

Amercoating would be applied to all concrete walls and floor of the pool and to most metallic surfaces.

Cooling Systems

The flow cycles for the various pump forced convection cooling systems were divided into two general classes, the open system and the closed system. The open system is one in which the coolant water enters the reactor from the pool, flows through the heat exchanger, and returns to the pool. The closed system differs in that the water is pumped to and from a surge tank instead of from the pool.

14 J. L. English, ORNL, private communication.

The open system water-to-water heat exchanger would not be practical for long-time operation above 1.5 megawatts because of the cost of the excessive quantity of water which would be required. In a closed system with its higher outlet temperatures, the water-to-water method could be used more economically. Perry's Chemical Engineers' Handbook, page 479 (3rd ed., McGraw-Hill Book Co., Inc., New York, 1950) makes reference to detailed computations available for computing the most economical flow relationships for this type of system.

A second system would use air coolers which are essentially air radiators. The efficiency and size of an air cooler is dependent upon two primary factors: (1) the design ambient temperature, which is taken as 90°F in this region, and (2) the approach temperature, which is the spread between the ambient temperature and the cooling water outlet temperature from the air cooler. However, if the approach temperature falls below 30 to 35°F, the use of the air cooler is not recommended. Below this point, the water cooling tower becomes the more desirable system. In light of the above, it is recognized that air coolers would only be applicable to the closed system in case a sufficient temperature spread is possible.

The third system, using water cooling towers, would be best if air coolers are not applicable. In order to utilize the total cooling capacity of the water tower and yet not contaminate the demineralized water, a system must be used in which the demineralized water of the reactor cooling system is not brought into physical contact with the process water of the water cooling tower. This could be accomplished by using coil banks or plate coils mounted in the tower's water basin or above the basin in the drip region. It is believed that the system offering the larger heat transfer coefficient is that of plate coils located in the drip region. The manufacturers of the plate coils state that an over-all heat transfer coefficient of 300 Btu ft^{-2} hr^{-1} $^{o}F^{-1}$ is attainable with their largest stainless steel plate coils as compared to the coil bank heat transfer coefficient of 150 to 300 Btu ft^{-2} hr^{-1} $^{o}F^{-1}$. For purposes of this report, computations have been based on the plate coil system.

The efficiency of the water cooling tower would be controlled by the wet-bulk temperature and approach temperature. The minimum approach temperature considered for this study was 8.5°F, while the design wet-bulb temperature in this region is 76°F. The water losses on the tower system seldom exceed 3% of the circulating rate.

Cost Analysis

The cost analysis for this proposal has been divided into the following categories:

a. Flow requirements
b. Shielding
c. Controls
d. Cooling systems (heat exchangers)
e. Demineralizer

The specifications, requirements, and general remarks on the cost analyses are contained in Appendix C.

The final systems as presented on the cost versus power curves (Fig. 13) are based on a modified BSR with an adjustable carriage which is located in a pool which has Amercoated wall and floor surfaces and which is filled with demineralized water. The other necessary components are a circulating pump, heat exchanger and cooling system, and purge demineralizer. The systems are presented as follows:

Case I. Water-to-water fixed-tube-sheet heat exchanger based on $T_m - T_1 = 100^oF$; $T_1 = 100^oF$ and $T_m = 200^oF$. Process water temperature approximately 75^oF. Open system.

Case II. Water cooling tower with plate coil heat exchanger based on $T_m - T_1 = 100^oF$; $T_1 = 100^oF$ and $T_m = 200^oF$. Open system.

Case III. Air cooler (dry type) heat exchanger based on $T_m - T_1 = 80^oF$; $T_1 = 120^oF$, and $T_m = 200^oF$. Closed system.

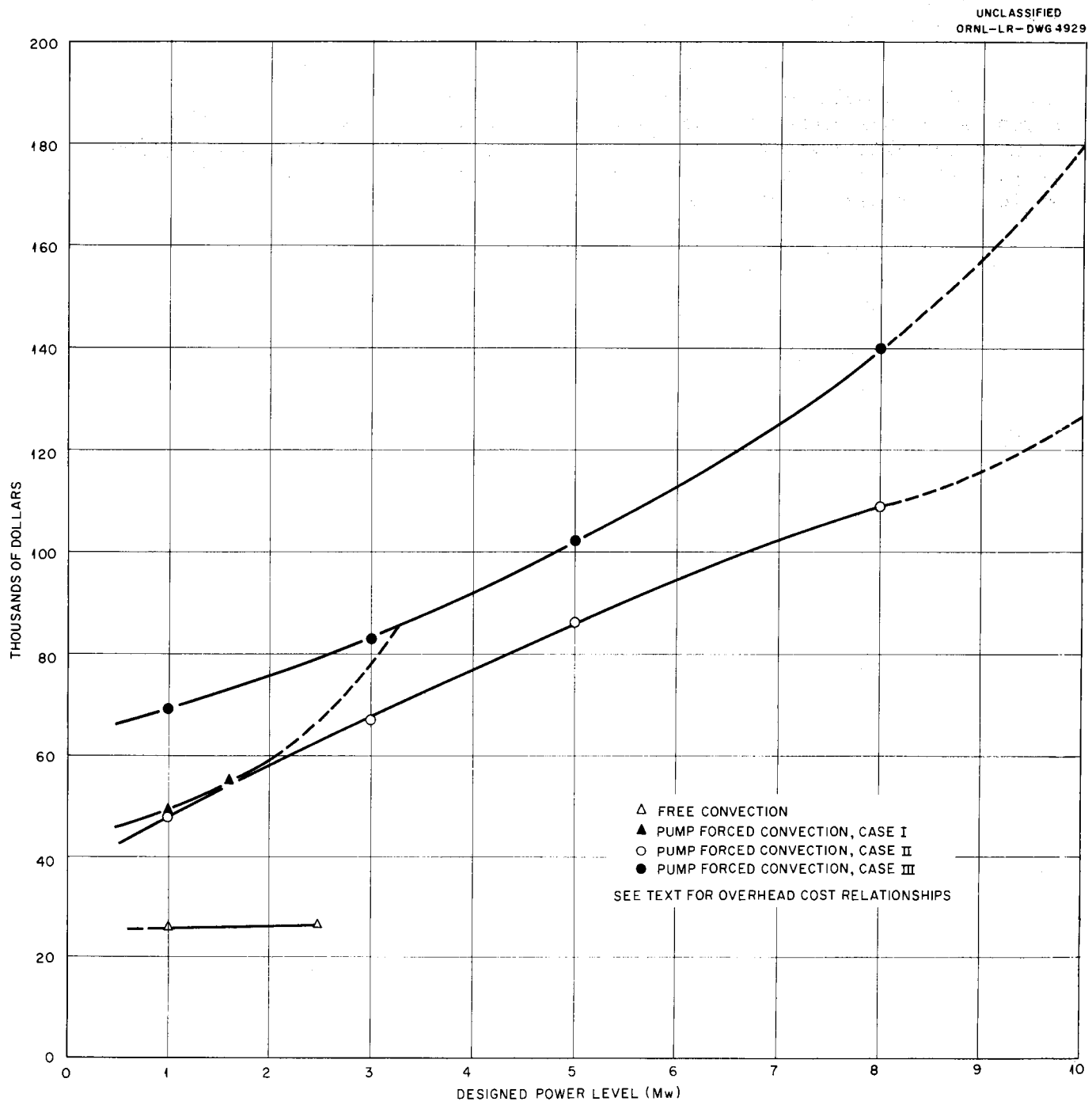
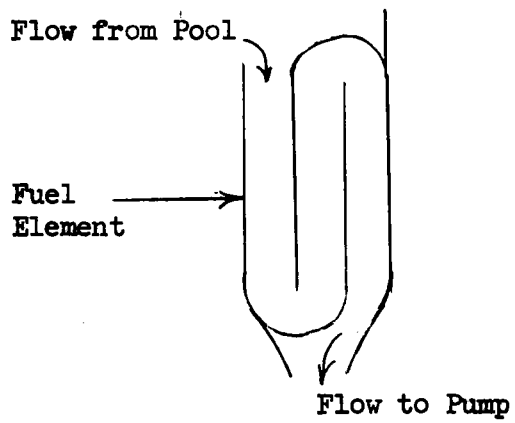


Fig. 13. Design Power Level vs. Cost of All Material and Installation of Major Components.

III. THREE-PASS-FLOW PUMP FORCED CONVECTION COOLING SYSTEM

The question of a three-pass-flow pump forced convection system has been studied to determine its merits as compared to those of the one-pass-flow through the element system. In this system the three-pass-flow would be accomplished by dividing the flow channels into three separate sections.



The coolant water would enter the first section from the top and flow to the bottom, where its direction would be reversed by a "U" turn and it would then flow up the second section; on reaching the top of the element its direction would again be reversed by a "U" turn and it would flow down and out the bottom of the third section to the pumps.

The heat transfer coefficients for a range of reactor powers of 1 to 8 megawatts and the required flow rates are conventional. The reactor heat could be removed without boiling, while the final outlet temperature of the water through the element would be higher. This final outlet temperature would be conducive to better heat removal properties of the cooling system as well as to the reduction in the cost of the initial installation.

The greatest difficulty in this system results from the two 180-deg reversals required of the water passing through the element, which will probably cause large pressure drops and thus require much higher pumping power. It is planned that a dummy fuel element will be fabricated according to the sketch shown above and tested for pressure drops, structural strains, and fuel channel flow patterns.

In considering the minimum required flow through this type of element, it is merely assumed that there are three separate elements with three individual inlet water temperatures. In this way, interpolations between the curves on Figs. 8, 9, and 10 can be made to determine the required flow

rate. Using $T_1 = 100^{o}F$, it is found that the minimum flow rate for any particular power level is approximately one-half the rate shown in Table 2. Be reducing the flow rate and increasing the final outlet temperature, the over-all cost curve for a particular power level is reduced by approximately one-third.

In light of the above, it is quite evident that the three-pass-flow system offers good economic incentives if the flow pattern and pressure drops are acceptable. With future reports on the dummy element, it should be possible to further evaluate the cost aspects as noted in this report.

IV. CONCLUSIONS AND RECOMMENDATIONS

On the basis on the above and empirical data, it was found that a 2.5 to 2.8-megawatt power level with free convection cooling would be possible for as little as $15,200 while the cost of one-pass-flow pump forced convection for 10 megawatts would be in the neighborhood of $180,000. The free convection system would cost about $25,000 if demineralized water were used in conjunction with a purge demineralizer in place of process water.

In order to obtain an estimate of overhead costs from the cost curves (Fig. 13), the costs of a particular design power level and cooling system should be multiplied by 1.3 for equipment purchased outside ORNL and by 1.7 for equipment fabricated within ORNL. All specification and cost estimates are presented in Appendix C.

It is recommended that the BSR be tested for the highest attainable power under the free convection cooling system and that at the same time an acceptable method of reducing gamma-ray levels in the room from N^{16} activity be developed.

It is recommended that the reactor pool be Amercoated and charged with demineralized water and that a purge demineralizer and possibly a filter be incorporated into the system to maintain the proper pH and resistivity and to minimize water contamination. A mixing rake will be required in a free convection cooling system to minimize the radiation hazard associated with the formation of N^{16}.

Appendix A

CALCULATION OF MAXIMUM SURFACE TEMPERATURE OF FUEL PLATES

In order to determine the minimum flow requirements for cooling the reactor, it is necessary to know the maximum surface temperature of the fuel plates as a function of water flow rates, inlet water temperatures, heat source distribution, and power levels. Reference was made to McAdams[15] and Sanders[13] for the following derivation.

It is assumed that the vertical neutron flux distribution in a BSR-type fuel plate is a sine function and that the heat flux or source is proportional to the thermal-neutron flux within the fuel plates. It is further assumed that the distribution is such that the value of heat flux at the ends of the fuel plates is 0.4 times the maximum value along the plate. This was based on the MTR flux distribution.[4] With the completion of current experimental work on the BSR, the 0.4 factor may be modified to fit the BSR flux distribution more exactly. Present indications are that the new value will be around 0.46. If this be the case, little change will be required in the design flow rates.

The heat flux at a distance x(ft) from the entrance end of a fuel plate is

$$Q = Q_o \sin \frac{\pi x}{L}$$

where

Q = heat flux, Btu ft^{-2} hr^{-1},

Q_o = maximum heat flux, Btu ft^{-2} hr^{-1},

L = extrapolated length of fuel plate at which neutron flux is zero, ft.

L is related to the actual length of fuel plate, a (ft), by

$$L = \frac{a}{1 - \frac{2(0.4116)}{\pi}} = \frac{a}{0.7380} = 2.781 \text{ ft} \qquad (1)$$

Designate the temperature of the coolant water as $T_i(x)$ at any point and that of the fuel plate surfaces T_m. An equation for the heat balance along a fuel plate can then be established as

15 W. H. McAdams, op. cit., p. 183.

$$3600GC_p\left[T_i(x) - T_1\right] = 2\int_{\frac{0.4116L}{\pi}}^{x} Q_o \sin\frac{\pi x}{L}\,dx \qquad (2)$$

where

G = water flow rate, lb (width of fuel plate, ft)$^{-1}$ sec^{-1},

C_p = specific heat = 1 Btu lb^{-1} ^{o}F^{-1},

T_1 = coolant water inlet temperature, ^{o}F.

The factor 2 accounts for one flow channel removing heat from the face of two fuel plate surfaces. Equation (2) becomes

$$T_i(x) = T_1 + \frac{Q_o}{2033G}\left(0.9165 - \cos\frac{\pi x}{L}\right) \qquad (3)$$

Since it is assumed that all the heat generated within the plate is transferred directly to the water (i.e., there is no heat flow along the plate), the following should hold for any point x:

$$h\left[T_m - T_i(x)\right] = Q_o \sin\frac{\pi x}{L} \qquad (4)$$

$$T_m = T_i(x) + \frac{Q_o}{h}\sin\frac{\pi x}{L} \qquad (5)$$

where h is the film heat transfer coefficient, Btu ft^{-2} hr^{-1} ^{o}F^{-1}.

Equations (3) and (5) combine to give

$$T_m - T_1 = \frac{Q_o}{2033G}\left(0.9165 - \cos\frac{\pi x}{L}\right) + \frac{Q_o}{h}\sin\frac{\pi x}{L} \qquad (6)$$

To find the point where the maximum value of T_m occurs, take $\partial T_m/\partial x$ (Eq. 6) and obtain

$$\tan\frac{\pi x}{L} = -\frac{2033G}{h} \qquad (7)$$

The value of h was then taken from an empirical equation[15] representing turbulent flow for water temperatures of 44 to 220°F. The value is

$$h = 5.6\,(1 + 0.011t)(G')^{0.8}/(D')^{0.2} \qquad (8)$$

where

t = average bulk water temperature, ^{o}F,

G' = water flow rate, lb ft^{-2} sec^{-1},

D' = hydraulic diameter, in.

To evaluate t, the total heat removed is obtained by

$$H = \frac{2}{3600} \int_{0.4116L/\pi}^{2.730L/\pi} Q_o \sin\frac{\pi x}{L}\, dx$$

where H is the total heat generated, Btu (width of fuel plate, ft)$^{-1}$ sec^{-1}. Integrating

$$H = 3.24 \times 10^{-4}\, Q_o L \text{ Btu ft}^{-1} \text{ sec}^{-1} \tag{9}$$

The temperature rise of the water flowing by the plate is

$$\Delta T = \frac{H}{GC_p} = 9.02 \times 10^{-4}\, Q_o/G \tag{10}$$

Now

$$t = \frac{2T_1 + \Delta T}{2} \tag{11}$$

With the above information calculated, some specific calculations of $T_m - T_1$ using Eq. (6) can be made. The results of these values as functions of flow rates, power level, and inlet temperature are found in Figs. 8, 9, and 10. The value of Q_o used for all calculations was the value of heat flux at the hottest point in the reactor, that is, element 25, where the thermal-neutron flux is 1.95 times the average thermal-neutron flux.[3]

By fixing T_1 and T_m the $T_m - T_1$ on the curve is immediately established which in turn determines the minimum flow requirement for a specific power level. These minimum requirements, increased by 10% for contingencies, are the resulting design flows presented in Table 2.

Appendix B

COST ANALYSIS FOR EACH COOLING SYSTEM

Free Convection Cooling

Power Level: 1 to 2.5 megawatts

Shielding	$ 945
Controls	1,550
Corrosion	21,325
Contingency	1,382
Total	$25,202

Pump Forced Convection Cooling

Case I*

Water-to-water fixed-tube-sheet heat exchanger based on $T_m - T_1 = 100^oF$; $T_1 = 100^oF$ and $T_m = 200^oF$; process water inlet temperature = 75^oF; open system.

Power level: 1 megawatt

Controls	$ 2,340
Cooling System	13,420
Demineralizer	28,850
Contingency	4,461
Total	$49,071

Case II

Water cooling tower with plate coil heat exchanger based on $T_m - T_1 = 100^oF$; $T_1 = 100^oF$ and $T_m = 200^oF$; open system.

Power level:	1 megawatt	3 megawatts	5 megawatts	8 megawatts
Controls	$ 2,340	$ 2,340	$ 2,340	$ 2,340
Cooling System	12,731	29,755	74,882	67,994
Demineralizer	28,850	28,850	28,850	28,850
Contingency	4,400	6,095	7,820	9,920
Total	$48,320	$67,050	$85,970	$109,100

* The cost of the water required for the water-to-water type cooling system for power levels above 1500 kw is prohibitive.

Case III

Air cooler (dry type) heat exchanger based on $T_m - T_1 = 80^\circ F$; $T_1 = 120^\circ F$ and $T_m = 200^\circ F$; closed system.

Power level:	1 megawatt	3 megawatts	5 megawatts	8 megawatts
Controls	$17,340	$17,340	$ 17,340	$ 17,340
Cooling System	16,293	29,830	55,463	80,733
Demineralizer	28,850	28,850	28,850	28,850
Contingency	6,250	7,600	10,160	12,690
Total	$68,700	$83,600	$110,800	$139,600

Appendix C

ANTICIPATED HRP REQUIREMENTS FOR RADIATION FACILITIES
(Letter from J. A. Swartout to A. M. Weinberg,
Dec. 3, 1953)

The HRP radiation damage program and the reactor facilities required for it were reviewed with Bohlmann, McDuffie and Secoy to provide our portion of the answer to your question about the need for the modified BSF.

The current situation with respect to irradiation facilities and manpower, the anticipated status at the end of 1954 and that at the end of 1955 when the ORR should be available are summarized in Table C-1.

Conclusions

(1) For calendar year 1954, currently assigned facilities in the graphite reactor and LITR plus two vertical facilities in the LITR and two facilities in the MTR for static bomb tests will be all we can handle.

(2) The limitation on the magnitude of effort in 1954 will be manpower with 26 additional required. Of these, 6 are required for the MTR irradiations, 16 for the LITR loops (6 to bring the over-all loop program to desired current status and 8 technicians and 2 technical for in-pile loops), 3 for out-of-pile tests to support the static irradiation program and 1 for blanket studies.

The proposed FY 1955 operating budget allots $\$1.7 \times 10^6$ to these programs corresponding to 37% of the total for HRP. To plan at this time to increase this fraction would, I believe, be injudicious and result in an unbalanced reactor development program.

(3) The major limitations on the rate of progress have been the time required to develop details of the in-pile installations and procurement. The shops have not been, and are not expected to be, the bottleneck.

(4) For calendar year 1955 a third facility at the MTR will probably be required for the first MTR in-pile loop. A loop facility with LITR flux will be required for blanket studies. This is the only foreseeable requirement which will not be met by currently assigned or anticipated facilities in the LITR and MTR within the next two years. A fourth beam hole in the LITR, freed by availability of the BSF for other work, would be preferable to an underwater BSF facility.

The increase of 12 in personnel will bring the monetary requirements to $\$2.1 \times 10^6$ corresponding to about the same percentage of the total HRP program as in 1954 (FY 1955).

Table C-1

Program Involved	Present		End of 1954		End of 1955	
	Facility	Personnel	Facility	Personnel	Facility	Personnel
HR Fuel System						
Static Tests	LITR HB-5 LITR HB-6	6	LITR HB-6 LITR Vertical MTR (2) (1st by 7/54) (2nd by 12/54)	9 6	LITR HB-6 LITR Vertical MTR (2)	9 6
In-Pile Loops	LITR-HB-4	24*	LITR HB-4 LITR HB-5	40*	LITR HB-4 LITR HB-5 MTR (1)	40* 12**
HR Blanket System						
Static	Graphite Hole No. 11	3	Graphite No. 11 LITR Vertical	4	LITR Vertical LITR or BSF ?	4 **
In-Pile Loops		—		—		—
Total	4	33	8	59	9	71

* Personnel for entire loop program, which E. G. Bohlmann believes cannot be logically segregated into out-of-pile and in-pile.

** Total required for additional loops in 1955, fuel and blanket.

Appendix D

PROPOSED CONVERSION OF THE BSF REACTOR TO A 10-MEGAWATT REACTOR, AND ITS UTILITY FOR ENGINEERING TYPE IN-PILE EXPERIMENTS

(O. Sisman, May 3, 1954)

The proposed increase in power of the BSF reactor to 10 megawatts and a maximum thermal-neutron flux of 10^{14} will provide an additional useful facility for engineering type experiments. For capsule experiments it should be just as good as any other facility of equal flux. For dynamic (loop type) "in-pile" experiments it will probably be a little less convenient to use than some other reactors, and therefore the experiments will be more expensive to build, but there is nothing that I can see that will keep one from performing any experiment in this reactor that we now plan in other existing reactors.

For large complicated engineering experiments it is becoming more and more evident that the experiment will control the operation of the reactor. If one wishes to perform very many of these experiments an additional facility will certainly be valuable in speeding up this work. In some cases it would be impossible to conduct even two of these experiments concurrently in the same reactor.