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Lawrence Livermore Laboratory

NATURAL CIRCULATION FLOW DURING LPTR OPERATION
AT LSSS OPERATING CONDITIONS

Werner Stein

November 1976

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NATURAL CIRCULATION FLOW DURING LPTR OPERATION
AT LSSS OPERATING CONDITIONS*

Werner Stein

A. INTRODUCTION

It is desired to determine the rate of flow of water coolant through the core of the Livermore Pool Type Reactor (LPTR), at Lawrence Livermore Laboratory during steady natural circulation flow at a reactor power of 0.15 MW, 51.7°C pool temperature and pool water height at least 7.2 m above tank bottom.

In this analysis it is assumed that water flows upward through the core with some of the water flowing through the piping system that includes the circulation pump and heat exchanger and some of the water flowing through holes, gaps, etc., in the core and the grid plate enclosure.

The forces considered in determining flow were: friction forces, buoyancy forces, entrance and exit loss forces, and fluid accelerational forces.

The most severe operating configuration consists of a reactor configuration of 16 standard and 5 special fuel elements. A plan view of the core configuration is shown in Figure 1. Comparisons are made to experimental data by Gambill¹ to verify that burnout will not occur.

B. RESULTS

At a reactor power of 0.15 MW, the coolant flow during natural circulation is calculated to be 22.9 GPM ($1.44 \text{ dm}^3/\text{sec}$) flowing upward through the core. The core inlet temperature is 125°F (51.7°C) and the calculated core average outlet temperature is 169.4°F (76.3°C),

The flow paths followed by the coolant during natural circulation operation consist of two parallel paths, Figure 2. One path involves 6.4 GPM ($0.40 \text{ dm}^3/\text{sec}$) flow from the reactor pool through the piping system containing the pump and heat exchanger into the grid plate enclosure just below the core. The other path

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Fig. 1 Typical core loading for the LPTR.

involves 16.5 GPM ($1.04 \text{ dm}^3/\text{sec}$) flow from the reactor pool through various openings directly into the grid plate enclosure. These openings consist of: gaps between the grid plate and the grid plate enclosure plates; ten holes of one-half inch diameter in the grid plate; gaps between the five control rod channels and the control rods; and three holes of one-half inch diameter in the beryllium reflector elements. Inside the grid plate enclosure, the two flows merge and together flow up through the core, back to the reactor pool.

At 0.15 MW reactor power the average heat flux in the hottest fuel plate is $4.053 \times 10^3 \text{ Btu/hr-ft}^2$ (0.013 MW/m^2) with a burnout heat flux of $6.24 \times 10^4 \text{ Btu/hr-ft}^2$ (0.197 MW/m^2) resulting in a burnout ratio of 15.

C. CALCULATIONS

The values calculated below are the results of numerous iterations. The iterations involve assuming a total coolant flow, Q , through the core and calculating, in Parts I and II, the friction losses and buoyancy forces resulting in the core. Then, in Parts III and IV, a division of the total flow is assumed with one part flowing through the piping system and the other part flowing through the holes and gaps leading to the grid plate enclosure and the corresponding pressure losses are determined. The total pressure losses for flow through the piping system and the core and also for flow through the gaps and holes and the core are then compared, in Section D, to the buoyancy forces generated in the core. Adjustments in the total coolant flow rate and in the division of flow are then made to result in balanced pressures.

A list of symbols and values of various constants are given in Appendix A.

I) BUOYANCY FORCE

The force driving water through the core is due to changes in density of the water coolant as it passes through the core. This buoyancy force creates a driving pressure rise across the core, ΔP_G :

$$(1) \quad \Delta P_G = (\rho_{in} - \rho_M) \frac{L_A g}{g_c}$$

The differential expression for the energy balance between coolant and fuel is:

$$(2) \quad \dot{m} C_p dT = \phi 2 w_F dL$$

where $\dot{m} = \rho_{in} V_{in} w_g w$

the average flux $\phi = \frac{P_T}{A} = \frac{(0.15)(3,412,200)}{276.74} = 1849.5 \frac{\text{BTU}}{\text{hr ft}^2}$

The total core flow rate is chosen after numerous iterations to be:

$$Q = 22.9 \text{ GPM}$$

$$V_{in} = \frac{Q}{A_{TS}} = \frac{(22.9)(2.222 \times 10^{-3})}{0.704} = 0.072278 \text{ ft/sec}$$

Integrating equation (2) gives:

$$\dot{m} C_p (T_{out} - T_{in}) = \phi 2 w_F L_F$$

Solving for T_{out} gives:

$$T_{out} = T_{in} + \frac{2\phi w_F L_F}{\dot{m} C_p}$$

Where: T_{in} = Coolant inlet temperature = 125°F

ρ_{in} = Coolant inlet density at $125^\circ\text{F} = 61.63328 \text{ lbm/ft}^3$

T_{out} = Coolant outlet temperature, $^\circ\text{F}$.

$$T_{out} = 125 + \frac{(2)(1849.5)(2.5)(23.62)}{(.998)(.117)(2.63)(61.63328)(3600)(0.072278)}$$

$$T_{out} = 169.35^\circ\text{F}$$

The density of the coolant at 169.35°F is:

$$\rho_{out} = 60.79979 \text{ lbm/ft}^3$$

ENGINEERING NOTE

5

SUBJECT

FIGURE 2 - COOLANT FLOW DIAGRAM

NAME

DATE

The average coolant density in the core is:

$$\rho_M = (\rho_{in} + \rho_{out})/2 = \frac{61.63328 + 60.79979}{2} = 61.21654 \text{ lbm/ft}^3$$

From equation (1), the buoyancy force is calculated to be:

$$\Delta P_G = (61.63328 - 61.21654) \frac{(24.62)}{1728} = 5.9 \times 10^{-3} \text{ PSI}$$

II. PRESSURE LOSS ACROSS CORE; ΔP_e

Pressure loss across the core is due to friction losses, entrance and exit losses and acceleration of the water as it passes through the core.

1) $\Delta P_{in, out}$; SUM OF ENTRANCE AND EXIT LOSSES

$$\Delta P_{in, out} = \frac{1}{2} \frac{\rho_{in} V_{in}^2}{g_c} + \frac{\rho_{out} V_{out}^2}{2g_c}$$

The average coolant exit velocity from the core is:

$$V_{out} = \frac{\rho_{in} V_{in}}{\rho_{out}} = \frac{(61.63328)(0.072278)}{60.79979} = 0.073269 \frac{\text{FT}}{\text{SEC}}$$

$$\Delta P_{in, out} = \frac{(61.63328)(0.072278)^2}{(4)(32.17)144} + \frac{(60.79979)(0.073269)^2}{(2)(32.17)144}$$

$$\Delta P_{in, out} = 5.26 \times 10^{-5} \text{ PSI}$$

2) ΔP_{ACC} ; ACCELERATIONAL LOSSES:

$$\Delta P_{ACC} = \frac{\rho_{in} V_{in} (V_{out} - V_{in})}{g_c}$$

$$= (61.63328)(0.072278)(0.073269 - 0.072278) / (144)(32.17)$$

$$\Delta P_{ACC} = 9.53 \times 10^{-7} \text{ PSI}$$

3) ΔP_{f_1} ; PRESSURE LOSS DUE TO FRICTION FOR CORE

The hydraulic diameter of the coolant channels is:

$$D_H = \frac{4w_g w}{2(w_g + w)} = \frac{4(2.63)(.117)}{(12)(2)(.117 + 2.63)} = 0.0186695 \text{ FT}$$

The Reynolds number for the channels is:

$$R_e = \frac{\rho_{in} D_H V_{in}}{\mu}$$

$$\mu @ 150^\circ F = 0.292 \times 10^{-3} \text{ lbm/ft sec}$$

$$R_e = \frac{(61.63328)(0.0186695)(0.072278)}{.292 \times 10^{-3}} = 285$$

The friction factor is:

$$f = \frac{64}{R_e} = \frac{64}{285} = 0.225$$

The average coolant velocity in the core is:

$$V_M = (V_{in} + V_{out})/2 = \frac{0.072278 + 0.073269}{2} = 0.072774 \text{ FT/sec}$$

$$\Delta P_{f_1} = f \frac{L_A}{D_H} \frac{\rho_M V_M^2}{2g_c} = \frac{(0.225)(24.62)(61.21654)(0.072774)^2}{12(0.0186695) 2(32.17) 144}$$

$$\Delta P_{f_1} = 8.7 \times 10^{-4} \text{ PSI}$$

4) ΔP_e ; TOTAL PRESSURE LOSS ACROSS THE CORE

$$\Delta P_e = \Delta P_{f_1} + \Delta P_{ACC} + \Delta P_{in,out}$$

$$\Delta P_e = 0.9 \times 10^{-3} \text{ PSI}$$

III. PRESSURE LOSS THROUGH HOLES AND GAPS BETWEEN REACTOR POOL AND GRID PLATE ENCLOSURE

- 1) ΔP_{PL} ; PRESSURE LOSS ACROSS GAPS BETWEEN BOTTOM OF GRID PLATE AND TOP OF GRID PLATE ENCLOSURE PLATES

$$\Delta P_{PL} = \frac{1.5 \rho_{in} V_{PL}^2}{2g_c}$$

where V_{PL} = VELOCITY THROUGH GAP = 0.708 ft/sec (See III-7)

- 2) ΔP_H ; PRESSURE LOSS THROUGH GRID PLATE HOLES

$$\Delta P_H = 1.5 \frac{\rho_{in} V_H^2}{2g_c} + f \frac{L}{D} \frac{\rho_{in} V_H^2}{2g_c}$$

where V_H = VELOCITY THROUGH HOLES;

$$V_H = 0.89 V_{PL} = (0.89)(.708) = 0.630 \text{ ft/sec (See III-6)}$$

The length-diameter ratio for these 5 inch long, 1/2 inch diameter holes is:

$$\frac{L}{D} = \frac{5''}{1/2''} = 10$$

$$Re = \frac{\rho_{in} D V_H}{\mu} = \frac{(61.63328)(0.630)}{(24)(.375 \times 10^{-3})} = 4314$$

From reference 2, the friction factor is:

$$f = .04$$

thus:

$$\Delta P_H = [1.5 + 10(.04)] \frac{\rho_{in} V_H^2}{2g_c} = 1.9 \frac{\rho_{in} V_H^2}{2g_c}$$

- 3) ΔP_{HE} ; PRESSURE LOSS THROUGH HOLES IN THE CENTRAL ELEMENT.

$$\Delta P_{HE} = 1.5 \frac{\rho_{in} V_{HE}^2}{2g_c}$$

Where V_{HE} = Velocity through central element holes

- 4) ΔP_{BE} ; PRESSURE LOSS THROUGH HOLES IN THE BERYLLIUM ELEMENTS

$$\Delta P_{BE} = 1.5 \frac{\rho_{in} V_{BE}^2}{2g_c} + f \frac{L}{D} \frac{\rho_{in} V_{BE}^2}{2g_c}$$

where V_{BE} = Velocity through beryllium holes.

The length-diameter ratio for these 9 inch long and 1/2 inch diameter holes is:

$$\frac{L}{D} = \frac{9''}{1/2''} = 18$$

$$V_{BE} = 0.82 V_{PL} = (0.82)(0.708) = 0.581 \text{ ft/sec (See III-6)}$$

$$Re = \frac{\rho_{in} V_{BE} D}{\mu} = \frac{(61.63328)(0.581)}{(24)(.375 \times 10^{-3})} = 3979$$

From Reference 2, the friction factor is:

$$f = .04$$

THUS

$$\Delta P_{BE} = [1.5 + 18 (.04)] \frac{\rho_{in} V_{BE}^2}{2g_c} = 2.22 \frac{\rho_{in} V_{BE}^2}{2g_c}$$

- 5) ΔP_{CE} ; PRESSURE LOSS THROUGH CONTROL ROD CHANNELS

$$\Delta P_{CE} = 1.5 \frac{\rho_{in} V_{CE}^2}{2g_c} + f \frac{L}{D_H} \frac{\rho_{in} V_{CE}^2}{2g_c}$$

Where V_{CE} = Velocity in control rod channels = $0.65 V_{PL} = 0.460 \text{ ft/sec (See III-6)}$

The hydraulic diameter for the channel shown in Section V of Appendix B is:

$$D_H = 0.353 \text{ inches}$$

The length-diameter ratio is:

$$\frac{L_A}{D_H} = \frac{24.62''}{0.353} = 70$$

$$R_e = \frac{\rho_{in} D_H V_{CE}}{\mu} = \frac{(61.63328)(0.353)(.460)}{(12)(.375 \times 10^{-3})} = 2224$$

The friction factor is:

$$f = \frac{64}{R_e} = 0.029$$

Thus:

$$\Delta P_{CE} = 3.53 \frac{\rho_{in} V_{CE}^2}{2g_c}$$

- 6) The pressure losses in parts 1 through 5 are all equal, thus one can relate the velocities as follows:

$$\Delta P_{PL} = \Delta P_H = \Delta P_{HE} = \Delta P_{BE} = \Delta P_{CE}$$

$$\text{OR } 1.5 V_{PL}^2 = 1.9 V_H^2 = 1.5 V_{HE}^2 = 2.22 V_{BE}^2 = 3.53 V_{CE}^2$$

THUS

$$V_{PL} = V_{HE} = 0.708 \text{ ft/sec}$$

$$V_H = 0.89 V_{PL} = 0.631 \text{ ft/sec}$$

$$V_{BE} = 0.82 V_{PL} = 0.581 \text{ ft/sec}$$

$$V_{CE} = 0.65 V_{PL} = 0.460 \text{ ft/sec}$$

- 7) From a mass balance one can determine the coolant velocity through the gaps between the grid plate and grid plate enclosure. After numerous iterations, 16.5 GPM of the 22.9 GPM total flow is found to flow into the grid plate enclosure through the gaps and holes.

The mass balance for this 16.5 GPM flow is:

$$\frac{16.5}{22.9} \rho_{in} V_{in} A_{TS} = \rho_{in} (A_{PL} V_{PL} + A_H V_H + A_{HE} V_{HE} + A_{CE} V_{CE} + A_{BE} V_{BE})$$

where A_{TS} is the total core cross sectional area for coolant flow and $A_{PL}, A_H, A_{HE}, A_{CE}$ and A_{BE} represent cross sectional areas that are described and calculated in Appendix B.

Substituting into the above equation the velocity relations for (6) above and solving for V_{PL} gives:

$$V_{PL} = \left(\frac{16.5}{22.9} V_{in} A_{TS} \right) (A_{PL} + 0.89 A_H + A_{HE} + 0.65 A_{CE} + 0.82 A_{BE})^{-1}$$

$$V_{PL} = 0.708 \text{ ft/sec}$$

8) THE PRESSURE LOSS ΔP_{PL} IS:

$$\Delta P_{PL} = 1.5 \frac{\rho_{in} V_{PL}^2}{2g_c} = \frac{1.5 (61.63328)(0.708)^2}{(2) (32.17) (144)} = 5.0 \times 10^{-3} \text{ PSI}$$

IV. ΔP_p ; PRESSURE LOSS FOR 6.4 GPM FLOW THROUGH THE PIPING SYSTEM

1) VELOCITIES:

$$V = \frac{\text{GPM Flow}}{(\text{Area})(7.5)(60)}$$

$$V_8 = \frac{6.4}{(7.5)(60)A_8} = \frac{6.4}{(7.5)(60)(0.3474)} = 0.04094 \text{ ft/sec}$$

$$V_6 = \frac{6.4}{(7.5)(60)A_6} = \frac{6.4}{(7.5)(60)(0.2006)} = 0.07090 \text{ ft/sec}$$

$$V_4 = \frac{6.4}{(7.5)(60)A_4} = \frac{6.4}{(7.5)(4)(60)(0.0884)} = 0.04022 \text{ ft/sec}$$

2) ΔP_{ENT} ; ENTRANCE AND EXIT LOSSES FOR THE 8" AND 4" DIAMETER PIPES:

Entrance losses occur for flow from the reactor pool into the 8 in. pipes and from the holdup tank into the 8 in. pipe. Exit losses occur for flow from the 8" pipe to the holdup tank and from the 8 in. pipe to the grid plate enclosure.

$$\Delta P_{ENT} = \frac{3\rho_{in} V_8^2}{2g_c} = \frac{3(61.63328)(0.04094)^2}{(2) (32.17) 144} = 3.345 \times 10^{-5} \text{ PSI}$$

3) ΔP_4 ; PRESSURE LOSS THROUGH 4" DIA. PIPE SYSTEM:

$$R_e = \frac{\rho_{in} V_4 D_4}{\mu} = \frac{(61.63328)(0.04022)(0.3355)}{0.375 \times 10^{-3}} = 2218$$

$$f_4 = \frac{64}{R_e} = \frac{64}{2218} = 0.029$$

From Appendix B, the length-diameter ratio is

$$\frac{L}{D} = 138$$

$$\Delta P_4 = f_4 \frac{L}{D} \frac{\rho_{in} V_4^2}{2g_c} = \frac{(0.029)(138)(61.63328)(0.04022)^2}{(2)(32.17)(144)}$$

$$= 4.31 \times 10^{-5} \text{ PSI}$$

4) ΔP_8 ; PRESSURE LOSS THROUGH 8" DIAMETER PIPING SYSTEM.

$$R_e = \frac{\rho_{in} D_8 V_8}{\mu} = \frac{(61.63328)(.6651)(0.04094)}{.375 \times 10^{-3}} = 4475$$

From Reference 2, the friction factor is:

$$f_8 = 0.04$$

From Appendix B, the length-diameter ratio is:

$$\frac{L}{D} = 447$$

$$\Delta P_8 = f_8 \frac{L}{D} \frac{\rho_{in} V_8^2}{2g_c} = \frac{(0.04)(447)(61.63328)(0.04094)^2}{(2)(144)(32.17)}$$

$$= 1.99 \times 10^{-4} \text{ PSI}$$

5) ΔP_6 ; PRESSURE LOSS THROUGH 6" DIAMETER PIPING SYSTEM.

$$R_e = \frac{\rho_{in} D_6 V_6}{\mu} = \frac{61.63328 (.5054) (0.07090)}{.375 \times 10^{-3}} = 5889$$

From Reference 2, the friction factor is:

$$f_6 = 0.036$$

From Appendix B, the length-diameter ratio is:

$$\frac{L}{D} = 454$$

$$\begin{aligned} \Delta P_6 &= f_6 \frac{L}{D} \frac{\rho_{in} V_6^2}{2g_c} = \frac{(0.036)(454)(61.63328)(0.07090)^2}{(2)(32.17)(144)} \\ &= 5.47 \times 10^{-4} \text{ PSI} \end{aligned}$$

6) ΔP_{OR} ; PRESSURE LOSS ACROSS ORIFICE PLATE:

$$R_e = 5889$$

From Equation 2-14 of Reference (2):

$$\Delta P_{OR} = \frac{(q)^2}{(CA_T)^2} \frac{\rho_{in}}{2 g_c 144}$$

Where:

$$q = V_6 A_6$$

$$A_T = \text{THROAT AREA} = 0.0879 \text{ ft}^2$$

$$C = \text{A coefficient determined from Figure A-19 of Reference (2)}$$

$$\text{Also let: } d_o = \text{orifice diameter} = 0.3346 \text{ ft}$$

$$d_1 = D_6 = 6 \text{ in. pipe diameter} = 0.5054 \text{ ft}$$

Thus:

$$\frac{d_o}{d_1} = 0.662$$

$$\text{Using } R_e = 5889 \text{ and } d_o/d_1 = 0.662 \text{ in Figure A-19 of Reference 2 gives } C:$$

$$C = 0.72$$

$$\Delta P_{OR} = \frac{((0.07090) \cdot 2006)^2}{(0.72(0.0879))^2} \cdot \frac{61.63328}{(2)(32.17)(144)} = 3.36 \times 10^{-4} \text{ PSI}$$

7) ΔP_{PUMP} ; PRESSURE LOSS ACROSS PUMP.

Estimate pressure loss by reverse direction flow of water through circ. pump by assuming an $\frac{L}{D}$ of the pump equal to one globe valve and two tees (Branch Flow):

$$\frac{L}{D} = 450 + 60 + 60 = 570$$

$$f_6 = 0.036$$

$$\Delta P_{PUMP} = f_6 \frac{L}{D} \frac{\rho_{in} V_6^2}{2g_c} = \frac{(0.036)(570)61.63328(0.07090)^2}{(2)(144)32.17}$$

$$= 6.86 \times 10^{-4} \text{ PSI}$$

- 8) ΔP_{STR} ; PRESSURE LOSS ACROSS STRAINER

Assume strainer $\frac{L}{D}$ is equal to that of a globe valve (450)

$$\Delta P_{STR} = f_6 \frac{L}{D} \frac{\rho_{in} V_6^2}{2g_c} = \frac{(0.036)(450)(61.63328)(0.07090)^2}{(2)(144)(32.17)}$$

$$= 5.42 \times 10^{-4} \text{ PSI}$$

- 9) ΔP_{COND} ; PRESSURE LOSS ACROSS HEAT EXCHANGER.

This pressure loss is the result of the sum of the entrance and exit loss, the pressure loss across five baffles inside the exchanger, and the pressure loss across the tube bundles.

- a) $\Delta P_{e,x}$; HEAT EXCHANGER ENTRANCE AND EXIT PRESSURE LOSSES:

$$P_{e,x} = 1.5 \frac{\rho_{in} V_6^2}{2g_c} = \frac{(1.5)(61.63328)(0.07090)^2}{(2)(32.17)(144)}$$

$$= 5.02 \times 10^{-5} \text{ PSI}$$

- b) ΔP_B ; PRESSURE LOSS ACROSS THE 5 BAFFLES INSIDE THE EXCHANGER.

From Reference (3), the length-diameter ratio for one baffle

$$\text{is } \frac{L}{D} = 20$$

$$A_B = \text{Area available for water flow across baffle} = 0.986 \text{ ft}^2$$

$$D_H = \text{Hydraulic Diameter of baffle flow area} = 1.0 \text{ ft}$$

$$V_B = \text{Average baffle water velocity}$$

$$V_B = \frac{\text{GPM Flow}}{(7.5)(60)A_B} = \frac{6.4}{(7.5)(60)(0.986)} = 0.014423 \text{ ft/sec}$$

$$R_e = \frac{\rho_{in} D_H V_B}{\mu} = \frac{(61.63328)(1)(0.014423)}{.375 \times 10^{-3}} = 2370$$

$$f = \frac{64}{Re} = \frac{64}{2370} = 0.027$$

$$\Delta P_B = \epsilon f \frac{L}{D} \frac{\rho_{in} V_B^2}{2g_c} = \frac{(5)(0.027)(20)(61.63328)(0.014423)^2}{(2)(32.17) 144}$$

$$= 3.74 \times 10^{-6} \text{ PSI}$$

c) ΔP_T ; PRESSURE LOSS ACROSS TUBE BUNDLES

From Reference (4), Equation 9-11, the pressure loss, for non-cooled tube bundles, is given by:

$$\Delta P_T = \frac{f G_{MAX}^2 N}{\rho_{in} 2.09 \times 10^8}$$

Where: N = Number of tube rows traversed = 300

G_{MAX} = Maximum mass velocity, lbm/hr-ft²

f = Friction factor

From Reference 3, the value of G_{MAX} is 807,000 lbm/hr-ft² for a mass flow rate of 500,000 lbm/hr. For our case the mass flow rate is W :

$$W = \rho_{in} V_6 A_6 = (61.63328)(0.07090)(0.2006)(3600)$$

$$= 3156 \text{ lb m/hr}$$

The mass velocity, G_{MAX} , for the W flow is thus determined from the following ratio:

$$\frac{G_{MAX}}{W} = \frac{807,000}{500,000}$$

and solving for G_{MAX} gives:

$$G_{MAX} = \frac{807,000 W_M}{500,000} = \frac{(807,000)(3156)}{500,000} = 5094 \text{ lbm/hr-ft}^2$$

The Reynolds number is:

$$R_e = \frac{G_{MAX} D_o}{\mu} = \frac{(5094)(0.04167)}{(3600)(0.375 \times 10^{-3})} = 157$$

From Figure 9-18 of Reference (4), the friction factor is:

$$f = 0.6$$

The pressure loss ΔP_T is now evaluated as:

$$\Delta P_T = \frac{(0.6)(5094)^2 300}{(61.63328)(2.09 \times 10^8)(144)} = 2.52 \times 10^{-3} \text{ PSI}$$

d) ΔP_{COND} ; TOTAL PRESSURE LOSS ACROSS HEAT EXCHANGER

$$\Delta P_{COND} = \Delta P_T + \Delta P_B + \Delta P_{e,x} = 2.57 \times 10^{-3} \text{ PSI}$$

10) ΔP_p : TOTAL PRESSURE LOSS IN PIPING SYSTEM FROM REACTOR POOL TO GRID PLATE ENCLOSURE.

$$\Delta P_p = \Delta P_{ENT} + \Delta P_4 + \Delta P_6 + \Delta P_8 + \Delta P_{OR} + \Delta P_{PUMP} + \Delta P_{STR} + \Delta P_{COND}$$

$$\Delta P_p = 5.0 \times 10^{-3} \text{ PSI}$$

D. SUMMARY OF CALCULATIONS

1) DIVISION OF FLOW

Flow through piping system	=	6.4 GPM
Flow through holes and gaps	=	16.5 GPM
Total flow through core	=	22.9 GPM

2) PRESSURE DROPS:

For 6.4 GPM through piping	=	5.0×10^{-3} PSI
For 16.5 GPM through holes and gaps	=	5.0×10^{-3} PSI
For 22.9 GPM through core	=	0.9×10^{-3} PSI

Thus for the two parallel paths the total pressure loss is:

Core and piping system	=	5.9×10^{-3} PSI
Core and holes and gaps	=	5.9×10^{-3} PSI
3) BUOYANCE FORCE	=	5.9×10^{-3} PSI

Thus one can see that buoyancy forces balance friction losses to allow 22.9 GPM total flow through the core.

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APPENDIX ALIST OF SYMBOLS

A	=	Heat transfer area for minimum core = 276.7 ft^2
A_B	=	Heat exchanger baffle flow area
A_{BE}	=	Cross sectional area of holes in beryllium elements
A_{CE}	=	Cross sectional area of control rod channel gaps
A_D	=	Cross sectional area for flow to core through holes and gaps = 9.74 in^2
A_{element}	=	Heat transfer area for one fuel element = 15.07 ft^2
A_H	=	Cross sectional area of holes in grid plate
A_{HE}	=	Cross sectional area of holes in central element plate
A_{PL}	=	Cross sectional area of gap beneath grid plate
A_{TS}	=	Total core cross sectional area for water flow = $0.704 \text{ ft}^2 = 653.5 \text{ cm}^2$
A_T	=	6 inch pipe orifice diameter
A_4	=	Cross sectional area of 4" diameter pipe = 0.0884 ft^2
A_6	=	Cross sectional area of 6" diameter pipe = 0.2006 ft^2
A_8	=	Cross sectional area of 8" diameter pipe = 0.3474 ft^2
C	=	Orifice throat coefficient
C_p	=	Specific heat of coolant = $0.998 \text{ BTU/lbm-}^\circ\text{F}$
D	=	Diameter
D_H	=	Hydraulic diameter
D_o	=	Diameter of tubes in heat exchanger
D_4	=	Diameter of 4 in. pipe = 0.3355 ft
D_6	=	Diameter of 6 in. pipe = 0.5054 ft
D_8	=	Diameter of 8 in. pipe = 0.6651 ft
f	=	Friction factor

f_{axial}	=	Axial fuel element heat flux peaking factor
f_B	=	Friction factor for baffles in heat exchanger
f_4	=	4" pipe friction factor
f_6	=	6" pipe friction factor
f_8	=	8" pipe friction factor
g	=	Gravity, 32.17 ft/sec ²
g_c	=	32.17 lhm-ft./sec. ² /lhf
G_{MAX}	=	Maximum mass velocity across heat exchanger tube bundles
H_2	=	Reactor pool water height above core top
L	=	Length
L_A	=	Length of fuel plate = 24.62 in.
L_F	=	Length of fuel plate containg fuel = 23.62 in.
$\frac{L}{D}$	=	Length/Diameter
$\dot{m}$	=	MASS/SEC flow rate
N	=	Number of tube bundle rows in heat exchanger
Q	=	Flow rate of water through core, GPM
q	=	Volume flow rate through orifice in 6" diameter pipe
P_2	=	Coolant pressure on top of fuel element
$P_{\text{BURNOUT}_{\text{MAX}}}$	=	Reactor power at burnout based on ϕ_{m1}
P_{BURNOUT_A}	=	Reactor power at burnout based on ϕ_{A1}
P_{in}	=	Average core water pressure
P_T	=	Total reactor power = 0.15 mW
ΔP_{ACC}	=	Change in pressure due to accelerating water in core
ΔP_B	=	Pressure loss through baffles of heat exchanger
ΔP_{BE}	=	Pressure loss through holes in beryllium elements
ΔP_{CE}	=	Pressure loss thorough control rod gaps

ΔP_{COND}	=	Pressure loss through heat exchanger
ΔP_e	=	Pressure loss through core
ΔP_{ENT}	=	Entrance and exit pressure losses for piping system
$\Delta P_{e,x}$	=	Entrance and exit pressure loss for heat exchanger
ΔP_{f_1}	=	Pressure loss due to friction in core
ΔP_G	=	Pressure rise due to buoyancy
ΔP_H	=	Pressure loss through 1/2" diameter holes in grid plate
ΔP_{HE}	=	Pressure loss through 3/16" diameter holes in central element plate
$\Delta P_{in,out}$	=	Entrance and exit pressure loss through the core
ΔP_{OR}	=	Pressure loss through orifice
ΔP_p	=	Total pressure loss for piping system
ΔP_{PL}	=	Pressure loss across gap between grid and enclosure plates
ΔP_{PUMP}	=	Pressure loss through backflow in the pump
ΔP_{STR}	=	Pressure loss through strainer
ΔP_T	=	Pressure loss through tube bundles in heat exchanger
ΔP_4	=	Pressure loss through pipe, 4" diameter
ΔP_6	=	Pressure loss through pipe, 6" diameter
ΔP_8	=	Pressure loss through pipe, 8" diameter
R	=	Burnout ratio based on maximum heat fluxes
R_A	=	Burnout ratio based on average heat fluxes in hottest fuel plate
R_e	=	Reynolds number
R_H	=	Hydraulic radius
Δt_{sub}	=	Core coolant inlet subcooling
T_{in}	=	Core inlet water temp = 125°F
T_{out}	=	Core exit water temp

V	=	Velocity
V_B	=	Average water velocity across baffles in heat exchanger
V_{BE}	=	Water velocity in beryllium element holes
V_{CE}	=	Water velocity in control rod channel gaps
V_H	=	Water velocity in grid plate holes
V_{HE}	=	Water velocity through central element plate holes
V_{in}	=	Core inlet water velocity
V_M	=	Average core water velocity
V_{out}	=	Core outlet water velocity
V_{PL}	=	Velocity through grid-enclosure gap
V_4	=	Velocity of water in pipe, 4" diameter
V_6	=	Velocity of water in pipe, 6" diameter
V_8	=	Velocity of water in pipe, 8" diameter
W	=	Mass flow rate, lbm/hr, through piping system
w	=	Width of fuel plate coolant channel = 2.63 in.
w_F	=	Width of fuel part of fuel plate = 2.50 in.
w_g	=	Spacing between fuel plates = 0.117 in.
ϕ	=	Average core heat flux
ϕ_A	=	Average burnout heat flux
ϕ_{A1}	=	Adjusted burnout heat flux
ϕ_m	=	Maximum burnout heat flux
ϕ_{m1}	=	Adjusted maximum burnout heat flux
ϕ_{MAX}	=	LPTR maximum heat flux
ϕ_{RA}	=	LPTR average heat flux for hottest plate
ρ_{in}	=	Core inlet density of water = 61.63328 lbm/ft ³
ρ_M	=	Average water density in core
ρ_{out}	=	Core outlet water density
μ	=	Viscosity of water = 0.375×10^{-3} lbm/ft-sec @ 125°F

APPENDIX B

Cross Sectional Areas and Piping L/D:

I. CROSS SECTIONAL AREA OF GRID PLATE GAPS, A_{PL} :

Reference (5) shows the gaps between the bottom of the grid plate and the top of the grid plate enclosure plates. The area was measured to be:

$$A_{PL} = 1.41 \text{ in}^2$$

II. CROSS SECTIONAL AREA OF HOLES IN CENTRAL ELEMENT, A_{HE}

There are 16 holes of 3/16" diameter in the central element.

$$A_{HE} = 16 \frac{\pi}{4} \frac{(3)^2}{(16)^2} = .442 \text{ in}^2$$

III. CROSS SECTIONAL AREA OF HOLES IN GRID PLATE, A_H

There are 8 holes 1/2" diameter in the grid plate.

$$A_H = 8 \frac{\pi}{4} \frac{(1)^2}{(2)^2} = 1.57 \text{ in}^2$$

IV. CROSS SECTIONAL AREA OF HOLES IN BERYLLIUM ELEMENTS, A_{BE}

In a 16 + 5 core we have 3 beryllium elements which have a 1/2" diameter by 9" long hole along the centerline of the element.

$$A_{BE} = 3 \frac{\pi}{4} \frac{(1)^2}{(2)^2}$$

$$A_{BE} = 0.59 \text{ in}^2$$

V. CROSS SECTIONAL AREA OF GAPS IN FIVE CONTROL ROD ELEMENT CHANNELS, A_{CE}

The area available for water flow equals the cross sectional area of the channel minus the cross sectional area of the control rod,

Reference 6.

$$A_{CE} = 5[(2.857)(6.66) - (2.223)(3.490) - \frac{\pi}{4} (2.223)^2] \left(\frac{1}{6.4516} \right)$$

$$A_{CE} = 5.73 \text{ in}^2$$

VI. TOTAL CROSS SECTIONAL AREA OF HOLES AND GAPS, A_D

$$A_D = A_{PL} + A_{HE} + A_H + A_{BE} + A_{CE}$$

$$= 1.41 + 0.442 + 1.57 + 0.59 + 5.73 = 9.74 \text{ in}^2$$

VII. LENGTH-DIAMETER (L/D) RATIOS FOR PIPING SYSTEM

A) <u>4" DIAMETER PIPE</u>	<u>$\frac{L}{D}$</u>
6' PIPE	18
TEE (BRANCH FLOW)	60
2-90° ELBOWS	60
TOTAL	138
B) <u>6" DIAMETER PIPE</u>	
48' PIPE	96
4 GATE VALVES	68
TEE (BRANCH FLOW)	60
TEE (THROUGH FLOW)	20
7-90° ELBOWS	210
TOTAL	454
C) <u>8" DIAMETER PIPE</u>	
71' PIPE	107
TEE (BRANCH FLOW)	60
9-90° ELBOWS	270
2 - REDUCERS	10
TOTAL	447

APPENDIX C

BURNOUT RATIO:

I. INTRODUCTION:

It is desired to determine the burnout heat flux in the LPTR during natural circulation.

Reference (1) gives the burnout heat flux for fuel elements that are very similar to those in the LPTR, at operating conditions close to the operating conditions in the LPTR during natural circulation. Of the many tests in Reference (1), Test #13 most closely approximates the LPTR fuel element, return flow area, and operating conditions.

To determine the burnout heat flux in the LPTR, the burnout heat flux from Test #13 is taken and modified to reflect the slight differences in operating conditions between Test #13 and the LPTR. This resulting flux then is used to determine the corresponding reactor power. Burnout ratios at various lower powers are also determined.

II. TEST RESULTS AND OPERATING CONDITIONS:

A. The results and operating conditions of Test #13 of Reference (1) are:

1) Maximum burnout heat flux = ϕ_m

$$\phi_m = 151,400 \text{ BTU/hr-ft}^2$$

2) Average burnout heat flux, ϕ_A

$$\phi_A = 69,100 \text{ BTU/hr-ft}^2$$

3) Flow channel dimensions: 0.113 in. x 2.09 in.

4) Length of fuel plate containing fuel = L_F = 23.65 in.

5) Pressure on top of fuel element = P_2

$$P_2 = 26.1 \text{ PSIA}$$

6) Inlet water temperature = T_{in}

7) Inlet subcooling = Δt_{sub}

$$\Delta t_{sub} = 12^\circ\text{F}$$

8) Ratio of fuel element coolant flow area to return leg flow area

= A_{TS}/A_D : The return leg has the same length as the fuel element.

$$\frac{A_{TS}}{A_D} = 8.86$$

or $A_D = 11.29\%$ of A_{TS}

B. LPTR operating conditions used in the calculations:

1) Flow channel dimensions: 0.117 in. x 2.6 in.

2) $L_F = 23.62 \text{ in.}$

3) Inlet water temperature = T_{in}

$$T_{in} = 125^\circ\text{F}$$

4) Pool water height above tank bottom = 23.6 ft (7.2 m)

5) Pool water height above core = H_2

Top of core is 5.48 ft, above tank bottom

$$H_2 = 23.6 - 5.48 = 18.12 \text{ ft.}$$

6) Pressure on top of fuel element is = P_2

$$P_2 = \frac{(61.63328)(18.12)}{144} + 14.7$$

$$P_2 = 22.5 \text{ PSIA}$$

7) Inlet subcooling = Δt_{sub} ,

$$\Delta t_{\text{sub}} = 234 - 125 = 109^\circ\text{F}$$

8) Ratio of total fuel element flow area, A_{TS} , to return leg

flow area, A_D , is:

$$\frac{A_{\text{TS}}}{A_D} = \frac{(0.704)(144)}{9.74} = 10.41$$

or $A_D = 9.61\% \text{ of } A_{\text{TS}}$

C. ANALYSIS

1) Figures 10 and 11 of Reference (1) give curves indicating the effect of inlet subcooling and pressure (P_2) on burnout heat flux. These curves show that decreases in P_2 result in lower burnout fluxes, and decreases in inlet subcooling result in larger burnout fluxes.

From Figure 10 the effect of 109°F subcooling instead of 127°F results in burnout flux being $\frac{.40}{.38} = 1.05$ times larger.

From Figure 11 the effect of having a pressure on top of the reactor of 22.5 PSIA instead of 26.1 PSIA results in the burnout flux being $\frac{1.2}{1.4} = .86$ times lower.

Although it is cautioned that Figure 10 and 11 do not apply to test #13 because of uneven heat generation, they are used to indicate if a parameter will increase or decrease burnout flux.

Thus ϕ_m is adjusted to give ϕ_{m1}

$$\phi_{m1} = (.86)(1.05) \phi_m = (.86)(1.05)(151,400)$$

$$\phi_{m1} = 136,710 \text{ BTU/hr-ft}^2$$

and ϕ_A is adjusted to give ϕ_{A1}

$$\phi_{A1} = (.86)(1.05) \phi_A = (.86)(1.05)(69,100)$$

$$\phi_{A1} = 62,400 \text{ BTU/hr-ft}^2$$

2) Reactor Power

From section 4.4.3 of the LPTR SAR, Reference (7), the maximum flux is related to overall reactor power by:

$$\phi_{MAX} = \frac{P_T \times 0.078 \times 1.53 \times f_{axial}}{A_{element}}$$

Heat transfer area for one fuel element = $A_{element}$

$$A_{element} = 1.4 \text{ m}^2 = 15.07 \text{ ft}^2$$

P_T = total core power

f_{axial} = 1.62 Reference (7), Table 4.4-2

thus ϕ_{MAX} at 1 MW, .75 MW, .5 MW, .15 MW, .10 MW and at .05 MW gives:

@1MW:

$$\phi_{MAX} = (3.4122 \times 10^6)(1MW)(.078)(1.53)(1.62)/15.07$$

$$\phi_{MAX} = 43,770 \text{ BTU/hr-ft}^2$$

@.75MW:

$$\phi_{MAX} = 32,830 \text{ BTU/hr-ft}^2$$

@.5MW:

$$\phi_{MAX} = 21,890 \text{ BTU/hr-ft}^2$$

@.15MW:

$$\phi_{MAX} = 6566 \text{ BTU/hr-ft}^2$$

@.10MW:

$$\phi_{MAX} = 4377 \text{ BTU/hr-ft}^2$$

@.05MW

$$\phi_{MAX} = 2189 \text{ BTU/hr-ft.}$$

- 3) Reactor Power at burnout based on ϕ_{m1} , the maximum burnout flux:

$$P_{BURNOUT_{MAX}} = A_{element} \phi_{m1} / (0.078 \times 1.53 \times f_{axial})$$

$$= (15.07)(\phi_{m1}) / (3.4122 \times 10^6 \times .078 \times 1.53 \times 1.62)$$

$$P_{BURNOUT_{MAX}} = (2.28 \times 10^{-5})(\phi_{m1})$$

$$P_{BURNOUT_{MAX}} = 3.1 \text{ MW}$$

- 4) Burnout ratio based on maximum fluxes, R:

$$R = \frac{\phi_{m1}}{\phi_{MAX}}$$

@1MW:

$$R = \frac{136,710}{43,770} = 3.1$$

@.75MW:

$$R = \frac{136,710}{32,830} = 4.2$$

@.5MW:

$$R = \frac{136,710}{21,890} = 6.2$$

@.15MW:

$$R = \frac{136,710}{6566} = 21$$

@.10MW:

$$R = \frac{136,710}{4377} = 31$$

@.05MW:

$$R = \frac{136,710}{2189} = 62$$

5) Average flux in hottest element, ϕ_{RA}

$$\phi_{RA} = \frac{P_T(0.078)(1.53)}{A_{\text{element}}}$$

Thus at the following powers the average flux in the hottest reactor plate is:

@1MW:

$$\phi_{RA} = 27,020 \text{ BTU/hr-ft}^2$$

@.75MW:

$$\phi_{RA} = 20,270 \text{ BTU/hr-ft}^2$$

@.5MW:

$$\phi_{RA} = 13,510 \text{ BTU/hr-ft}^2$$

@.15MW:

$$\phi_{RA} = 4,053 \text{ BTU/hr-ft}^2$$

@.1MW:

$$\phi_{RA} = 2,702 \text{ BTU/hr-ft}^2$$

@.05MW:

$$\phi_{RA} = 1,351 \text{ BTU/hr-ft}^2$$

And the burnout ratio based on average fluxes in the hottest reactor plate is, R_A :

$$R_A = \frac{\phi_{A1}}{\phi_{RA}}$$

@1MW:

$$R_A = \frac{62,400}{27021} = 2.3$$

@.75MW:

$$R_A = 3.1$$

@.50MW:

$$R_A = 4.6$$

@.15MW:

$$R_A = 15.4$$

@.1MW:

$$R_A = 23.1$$

@.05MW:

$$R_A = 46.2$$

6) The power corresponding to ϕ_{A1} is $P_{BURNOUT_A}$

$$P_{BURNOUT_A} = \frac{A_{element} \phi_{A1}}{(0.078)(1.53)} = \frac{(15.07)(62,400)}{(3.4122 \times 10^6)(.078)(1.53)}$$

$$P_{BURNOUT_A} = 2.3 \text{ MW}$$

D. CONCLUSIONS

Two methods were used to determine reactor power at burnout. One was based on average burnout flux and the other on maximum burnout flux in the hottest channel in the reactor.

The burnout powers are:

$$P_{BURNOUT_{MAX}} = 3.1 \text{ MW}$$

$$P_{BURNOUT_A} = 2.3 \text{ MW}$$

The burnout ratios R and R_A , the max flux and average flux cases, are:

<u>REACTOR POWER</u>	<u>R</u>	<u>R_A</u>
3.1 MW	1	-
2.3 MW	-	1
1 MW	3.1	2.3
.75 MW	4.2	3.1
.5 MW	6.2	4.6
.15 MW	21	15
.1 MW	31	23
.05 MW	62	46

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