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7/17/78

THERMAL-HYDRAULIC DESIGN ANALYSIS REPORT
FOR THE
LACROSSE BOILING WATER REACTOR
HIGH DENSITY FUEL STORAGE RACKS

Prepared Under NES Project 5101
For The
DAIRYLAND POWER COOPERATIVE

NUCLEAR ENERGY SERVICES, INC.
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APPROVED ISSUE

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1. SUMMARY

The adequacy of natural circulation flow to cool the spent fuel assemblies in the rack matrix was verified by establishing, for the worst row of assemblies, a thermal-hydraulic balance between the driving head produced by decay heat generation and the pressure losses existing in the natural circulation flow path.

Calculations have shown that under conservative assumptions the maximum assembly exit temperatures are below the saturation temperature of the pool water at fuel assembly elevations. Consequently, local boiling will not occur in any fuel assembly even with the bulk temperature of the spent fuel pool at its maximum value.

2. INTRODUCTION

In the NES rack design the cross flow of water between adjacent fuel assemblies is prevented by the stainless cells in the fuel rack. The effect is such that each of the fuel assemblies becomes isolated and, therefore, sits in its own thermal chimney. The chief thermal-hydraulic concern is the possibility of local boiling due to flow starvation in some cells of the rack matrix as a result of excessive pressure losses in the natural circulation loops established in the spent fuel pool.

The adequacy of the natural circulation flow to cool the hottest assembly in the rack configuration has been verified by establishing a thermal-hydraulic balance for the worst row of assemblies. Pressure losses in the downcomers, in the rack inlet plenum, and along the fuel assemblies were explicitly considered in the analysis. Crossflows in the rack inlet plenum area have been conservatively neglected.

The analysis assumes a two-tier design with both upper and lower levels storing spent fuel assemblies. It is conceivable that at some time only the lower tier will be utilized. The full two-tier case, however, was determined to be more limiting and is therefore used in the calculations.

The purpose of the analysis is to demonstrate that, even under the most conservative circumstances, local boiling will not occur in the most adversely located fuel assemblies which, as a result of flow maldistribution, might receive less than the fuel pool average assembly flow rate.

3. METHOD OF ANALYSIS AND ASSUMPTIONS

The natural circulation flow is calculated by establishing a thermal hydraulic balance for the worst row of assemblies. The flow is maintained by the thermal driving head or draft produced by the decay heat generation in each assembly. The pool itself is modeled as a large volume with a bulk temperature unaffected by local disturbances. The pressure losses considered in the analysis include:

1. Friction losses in the downcomer region, in the rack inlet plenum and in the fuel assembly.
2. Losses in bends (including the right angle turn that the flow must negotiate to turn from the horizontal rack inlet plenum channel into the vertical fuel assemblies).
3. Form losses in the fuel assemblies at the inlet, outlet and grid spacer locations.
4. Form losses due to the lower fuel assembly inlet nozzle geometry.

The chief concern is the possibility of substantial pressure drop along the inlet manifold channel, causing flow starvation of the fuel assemblies in the limiting fuel assembly string. The effect of the bundle shroud has effectively been accounted for by utilizing a corresponding assembly flow area and hydraulic diameter. The friction loss due to the shroud wall alone is negligible. Cross-flows have been neglected. Flow to cells is assumed to be available only from the downcomer. Coolant from the central cask handling region is conservatively neglected. All fuel assemblies are assumed to be generating heat at a rate corresponding to 1.4 times the average power fuel assembly. A pool bulk temperature of 150°F is assumed.

The detailed thermal-hydraulic calculations are presented in Appendix A.

4. RESULTS OF ANALYSIS AND CONCLUSIONS

The thermal-hydraulic calculations indicate that even with the most conservative assumptions, the natural circulation in the spent fuel pool is adequate to preclude local boiling by a substantial margin. The maximum temperature increase in the assembly with the minimum flow is 23.2°F which would result in an outlet temperature of 173.2°F assuming a bulk pool temperature of 150°F.

The saturation temperature corresponding to the static head at the top of the fuel assembly is 236°F.

APPENDIX A

LACBWR EXPANDED FUEL POOL
VERIFICATION OF ADEQUATE COOLING

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LACBWR Fuel Rack

	REF.
LACBWR Expanded Fuel Pool Verification of Adequate Cooling	
1. Statement of Problem Perform the thermal-hydraulic analysis to verify that the flow maldistribution resulting from the fuel storage rack configuration allows adequate cooling of the assemblies.	
2. Assumptions 2.1 Figure 2-1 shows the general arrangement of the LACBWR Fuel storage Pool. The 1X8 rack array chosen for the analysis is considered to represent the most critical area in terms of sufficient cooling for the assemblies. The downcomer gap is 2.25".	6
2.2 The fuel bundles under consideration are hot assemblies (1.4 peaking factor).	

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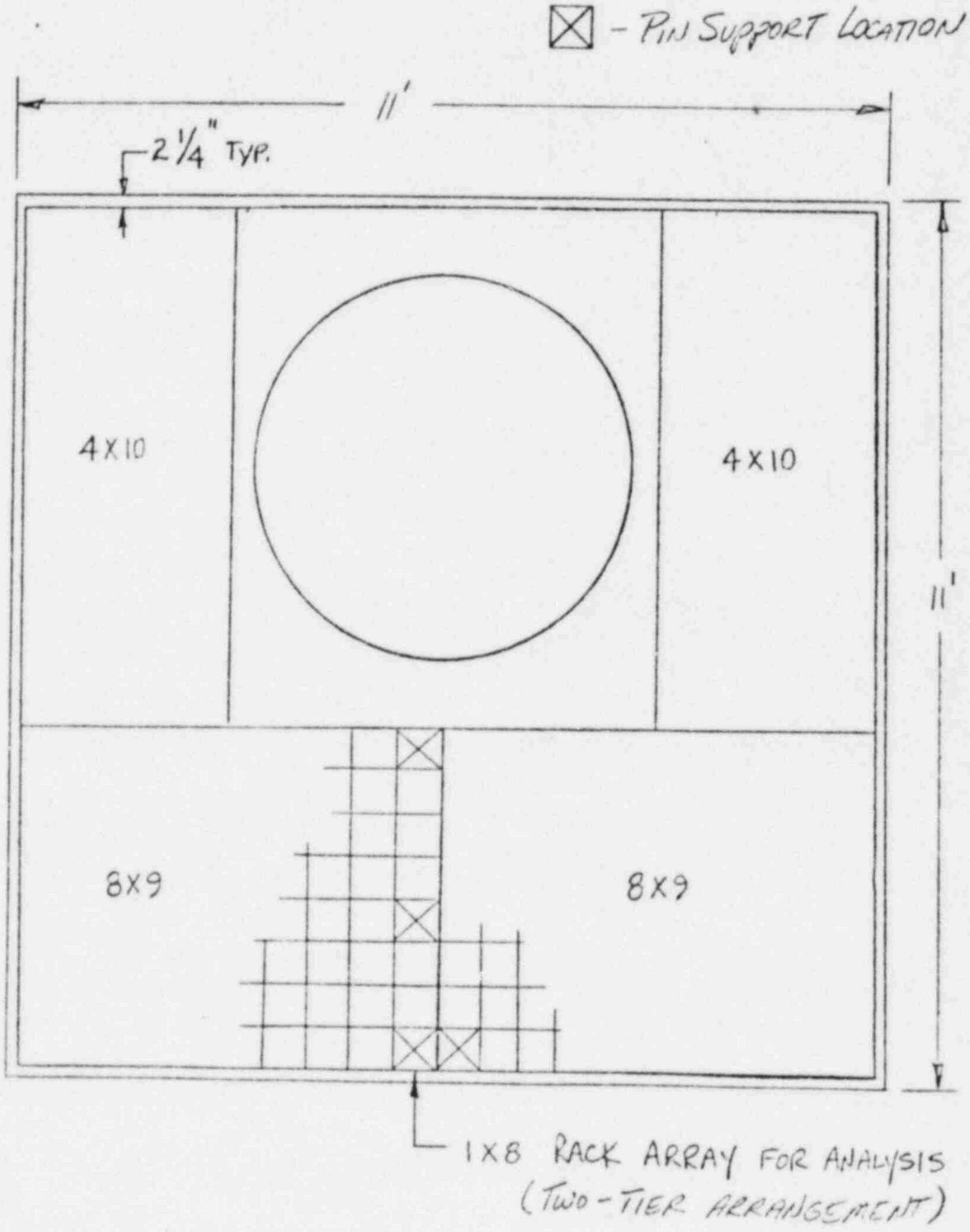

FIGURE 2-1 LACBWR FUEL STORAGE POOL AND RACK LAYOUT

	REF.
2.3 The Pool Bulk temperature is conservatively assumed to be 150°F (maximum pool temperature per LACBWR Technical Specifications).	
2.4 The pool water depth is ≈ 38 ft*. The top of the fuel rack is 18'-5¼".	6
2.5 The saturation temperature corresponding to a static head at the top of the fuel cell is 236°F.	
2.6 Each bundle is isolated from adjacent assemblies by the cell walls and sits in its own thermal chimney. No credit for crossflows between assemblies is assumed.	
2.7 Figure 2-2 shows an elevation view of a section through the 1X8 Rack Array chosen for the analysis. Flow to array is assumed to be available only from 2¼" downcomer. Coolant from central cask handling region conservatively neglected.	

* Normal water elevation for two-tier rack is 698'

REF.

2.8 Figure 2-3 shows the schematic of the flow model used in the analysis. The inlet to cell #1 is modeled using a TEE plus an Elbow joint. The inlet to cells #2 through 8 is a 7.0" x 9" channel (assuming symmetric flow in adjacent channels act as boundaries) serving as an inlet manifold with 7 ports. An S-Bend was assumed to model the flow in cells serving as support locations. The effect of obstructions in the open bottom channels [illegible] is this would tend to reduce flow stagnation. 6

2.9 Bundle form loss coefficients assumed:

$K_{bundle\ entrance} = 0.5$

$K_{bundle\ exit} = 1.0$

$K_{typical\ spacer} = 0.6$

$$\left[\Delta P = K \frac{\rho v^2}{2g}\right]$$

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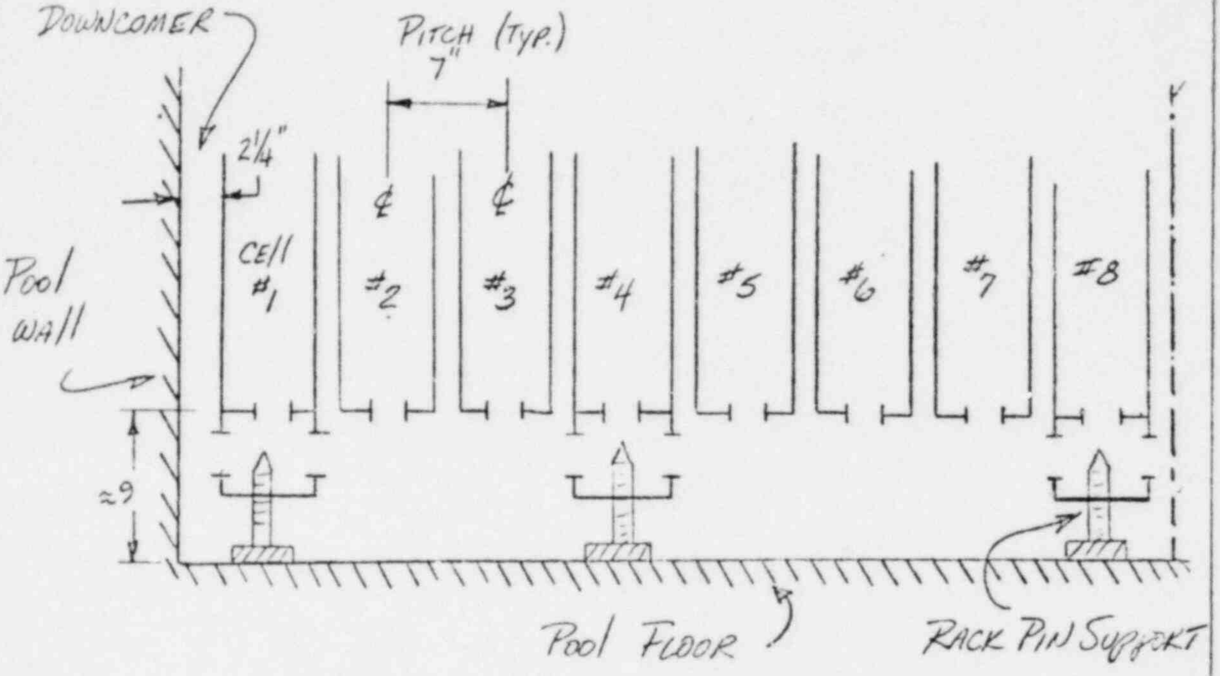


FIGURE 2-2 General Elevation View of 1X8 ARRAY

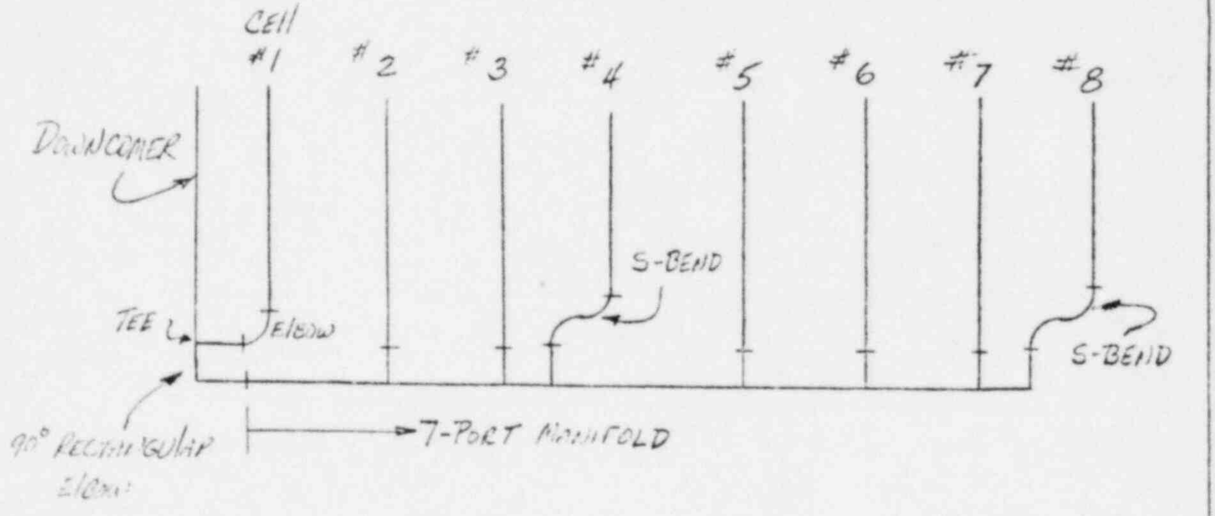


FIGURE 2-3 SCHEMATIC MODEL OF 1X8 ARRAY FOR ANALYSIS

REF.

2.10 Water properties based on estimated bundle average temperature of 170°F

2.13 Bundle decay heat calculated from NUREG-75/087, Section 9.2.5 (T_0 = 2.43 years, T_S = 3 days) : $P/P_0 = 4.186\,(10^{-3})$ 4,7

2.14 Reactor rated power = 165 Mwt; core is 72 assemblies

2.15 All pool and cell dimensions taken from Reference 6.

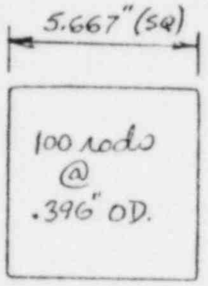
2.16 The downcomer friction, 90° bend losses, inlet plenum losses, floor losses, bundle and shroud friction losses, spacer grid losses, inlet and outlet form losses, lower fuel element nozzle losses and the 90° bend losses into the individual cells are considered. Pin support box structure losses are assumed negligible.

2.17 The analyses assumes a two-tier rack design with both the upper and lower tiers carrying assemblies. Although it is possible that only the lower tier will be utilized for a time, this case is less severe than the full two-tier situation.

	REF.

3. Pressure Drop Analysis

3.1 Bundle and Shroud Friction (ΔP_b)



Bundle Height = $90'' \times 2^{*} = 180'' = L$ — 1

Flow Area $= (5.667)^2 - 100\frac{\pi}{4}(.396)^2 = 19.80\text{ in}^2 = A$

Wetted Perim $= 100\pi(.396) + 4(5.667) = 147.08'' = P$

Hydraulic Dia. $= \dfrac{4(19.80)}{147.08} = .538'' = De$

Water Properties based on 170°F (assumed avg. temp.):

$\rho = 60.79$ lbs/ft^3

$\mu = 0.88$ lbs/hr-ft

$$\Delta P_b = f\,L/De\,\frac{\rho V^2}{2g}$$

Flow/cell (lb/hr)	Velocity (ft/sec)	$Re = \frac{De V \rho}{\mu}$	f^{**}	ΔP_b (PSI)	**5
2500	0.083	925	0.069	0.00104	
5000	0.166	1851	0.050	0.00302	
7500	0.249	2776	0.045	0.00612	
10000	0.332	3702	0.040	0.00967	

* Accounts for 2-tier rack

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3.2 Form Losses

3.2.1 Bundle Form Losses $\left(\Delta P_f = K \frac{\rho V^2}{2g}\right)$

$$K_{TOTAL} = \left(K_{entrance} + K_{exit} + 3K_{spacers}\right) 2$$

$$= \left(0.5 + 1.0 + 3(0.6)\right)(2)$$

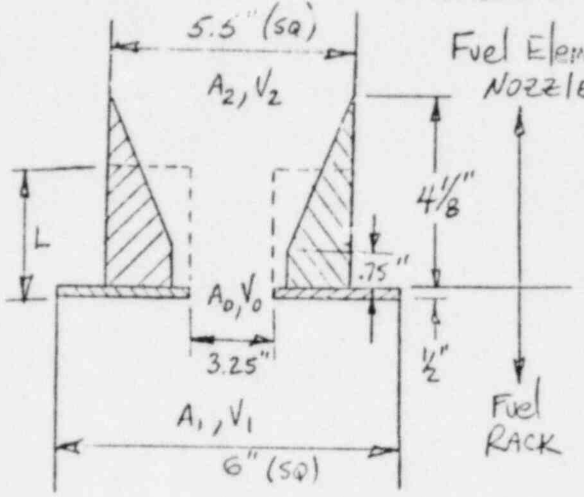
$$= 6.6$$

Flow/cell (lbs/hr)	Velocity (ft/sec)	ΔP_f (psi)
2500	0.083	0.00030
5000	0.166	0.00119
7500	0.249	0.00268
10000	0.332	0.00477

	REF.

3.2.2 Fuel Element Lower Nozzle Losses (ΔP_N)

(APPROXIMATE DIMENSIONS)



$A_0 = \pi (3.25)^2/4 = 8.30 \text{ in}^2$

$A_1 = (6.0)^2 = 36.0 \text{ in}^2$

$A_2 = (5.5)^2 = 30.25 \text{ in}^2$

NOTE: Dashed line in sketch represents model of tapered section

Let $L = \frac{1}{2}" + .75" + 2" = 3.25"$

$A_0/A_1 = 8.30/36.0 = .23$ $\qquad D_{H_0} = 3.25$ $\qquad$ 2 P.137

$A_0/A_2 = 8.30/30.25 = .27$ $\qquad L/D_{H_0} = \frac{3.25}{3.25} = 1.0 \Rightarrow \tau = .24$

$$K = .5(1 - A_0/A_1) + (1 - A_0/A_2)^2 + \tau\sqrt{(1 - A_0/A_1)}\left[1 - A_0/A_2\right]$$

$$= .5(1 - .23) + (1 - .27)^2 + .24\sqrt{(1 - .23)}\left[1 - .27\right]$$

$$= 1.07\,(2)^* = 2.14$$

flow/cell (lbs/hr)	Velocity (V_0) (ft/sec)	$\Delta P_N = K\frac{\rho V_0^2}{2g}$ (PSI)
2500	0.198	0.00056
5000	0.396	0.00110
7500	0.595	0.00496
10000	0.793	0.00882

* 2-tier rack

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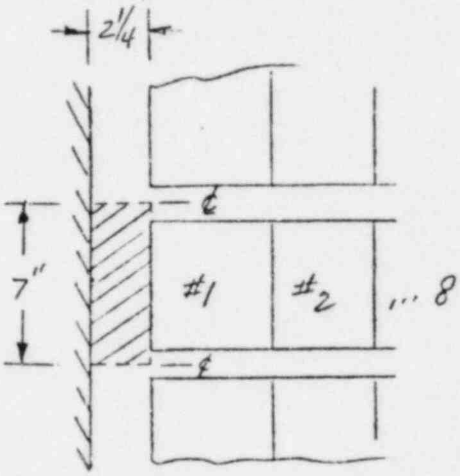
3.3 Downcomer Friction Losses ΔP_{df} $\left(= f \frac{L}{D_e} \frac{\rho V^2}{2g}\right)$

Area = 7" × 2¼" = 15.75 in²

Wetted Perimeter = 2(7) = 14.00"

$$D_e = \frac{4(15.75)}{14.00} = 4.5 \text{ in}$$

L = 221.25"



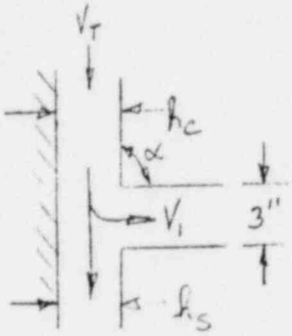
Assuming uniform flow in all cells

Flow/cell (lbm/hr)	Total Flow (lbm/hr)	Velocity (ft/sec)	Re	f	ΔP_{df} (psi)
2500	20000	0.835	77870	0.0189	0.00425
5000	40000	1.671	155844	0.0162	0.01458
7500	60000	2.507	233766	0.0151	0.03059
10000	80000	3.342	311688	0.0142	0.05112

3.4 Loss in Bend for cell #1 ΔP_{TE}

The pressure loss turning into cell #1 is modeled as a loss in a TEE plus a loss in an ELBOW.

3.4.1 Loss in TEE (ie. 90° WYE) ΔP_T 2 P. 280



Assume:
$\alpha = 90°$
$h_s / h_c = 1.0$
$\Rightarrow K = 1.0$

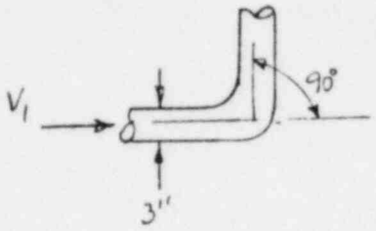
Flow/cell (lbs/hr)	Total Flow (lbs/hr)	Velocity (ft/sec)	ΔP_T (psi)
2500	20000	0.835	0.00457
5000	40000	1.671	0.01830
7500	60000	2.507	0.04120
10000	80000	3.342	0.07321

REF.

3.4.2 Loss in Elbow ΔP_E

2
p. 219

$K = A_1 B_1 C_1$



$$\text{Let} \left.\begin{array}{l} A_1 = 1.0 \\ B_1 = 1.0 \\ C_1 = 1.0 \end{array}\right\} K = 1.0$$

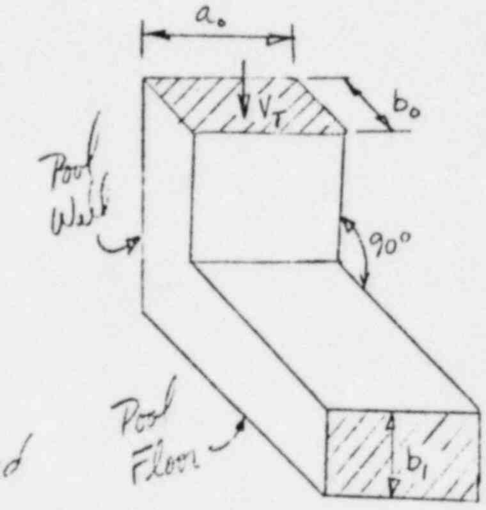
$\text{Area} = \pi (3)^2/4 = 7.07 \text{ in}^2$

Flow/cell (lbs/hr)	Velocity (ft/sec)	ΔP_E (psi)	$\Delta P_{TE} = \Delta P_T + \Delta P_E$ (psi)
2500	0.233	0.00036	0.00493
5000	0.465	0.00142	0.01972
7500	0.698	0.00319	0.04439
10000	0.931	0.00568	0.07889

3.5 Downcomer Turn Losses ΔP_{dT}

2
P. 214

$$\frac{a_0}{b_0} = \frac{7.0}{2.25} = 3.11$$



$$\frac{b_1}{b_0} = \frac{9.25}{2.25} = 4.11$$

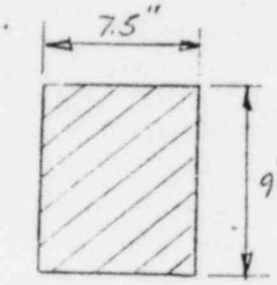
$\Rightarrow K = .7$

V_T based on total flow required for 7 cells (#2 thru 8)

Flow/cell (lbs/hr)	Total Flow (lbs/hr)	Velocity (ft/sec)	ΔP_{dT} (psi)
2500	17500	0.731	0.00245
5000	35000	1.462	0.00981
7500	52500	2.193	0.02207
10000	70000	2.924	0.03923

	REF.

3.6 Floor Losses $\Delta P_F \left(= C f \, L/D \, \frac{\rho V^2}{2g}\right)$



Assume flow channel bounded by upper and lower friction surfaces (ignore obstruction due to support pin box structure).

Flow area = $\overset{7.5}{7.0}(9) = 63.0 \text{ in}^2$

Wetted Perim. = $7.0(2) = 14.0 \text{ in}^2$

$De = \frac{4(63.0)}{14.0} = 18.0 \text{ in}$

$L = 56''$

Assume uniformly distributed flow in 7 cells (#2 thru 8)

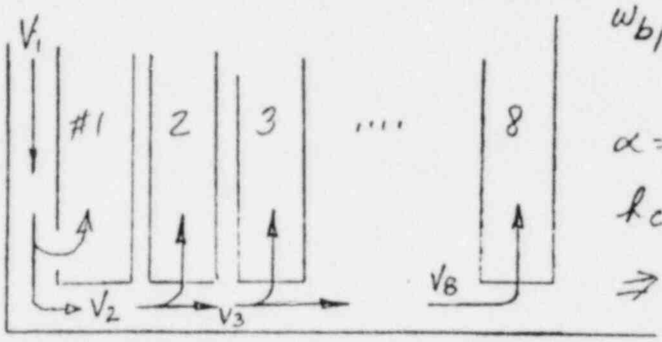
Correction factor C = .344 for # of parts = 7 — 3

Flow/cell (lbm/hr)	Total Flow (lbm/hr)	Velocity (ft/sec)	Re	f	ΔP_F (PSI)
2500	17500	0.183	68264	0.0191	0.000004
5000	35000	0.366	136529	0.0167	0.000016
7500	52500	0.548	204420	0.0155	0.000033
10000	70000	0.731	272685	0.0147	0.000055

	REF.

3.7 Bend Losses ΔP_{B2}, ΔP_{B8}

Conservatively assuming a diverging "WYE" configuration : — 2 p.280



$\omega_b/\omega_c = 1$ for cell #8

$\alpha = 90°$

$k_c = k_b$

$\Rightarrow K = 1.45$

- V_2 is based on the total flow required for 7 cells (#2 thru 8)
- V_8 is based on flow/cell
- use $K = 1.45$ (conservative for both cell #2 and cell #8

Flow/cell (lbm/hr)	V_2 (ft/sec)	V_8 (ft/sec)	ΔP_{B2} (PSI)	ΔP_{B8} (PSI)
2500	0.169	0.024	0.00027	0.00001
5000	0.339	0.048	0.00110	0.00002
7500	0.508	0.073	0.00247	0.00005
10000	0.678	0.097	0.00440	0.00009

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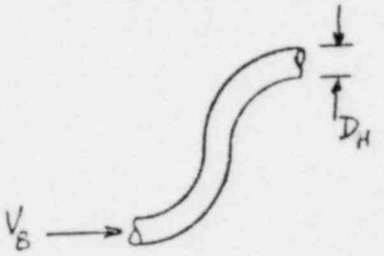
3.8 Bend Losses for cell #8 ΔP_S

Assume S-bend for the flow shape turning into the fuel cell. — 2 p. 213

$l/D_H = 0$

$\Rightarrow A = 3.0$



$K = 3\,K_{ELBOW}$; $K_{ELBOW} = 1.0$ (page 11)

$K = 3(1) = 3.0$

Flow/cell (lbs/hr)	V_8 (ft/sec)	ΔP_S (psi)
2500	0.024	0.00001
5000	0.048	0.00005
7500	0.073	0.00011
10000	0.097	0.00019

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3.9 Flow Maldistribution

$$\Delta P_1 = \Delta P_b + \Delta P_f + \Delta P_N + \Delta P_{df} + \Delta P_{TE}$$

$$\Delta P_2 = \Delta P_b + \Delta P_f + \Delta P_N + \Delta P_{df} + \Delta P_{dT} + \Delta P_{B2}$$

$$\Delta P_8 = \Delta P_b + \Delta P_f + \Delta P_N + \Delta P_{df} + \Delta P_{dT} + \Delta P_{B8} + \Delta P_F + \Delta P_S$$

Flow/cell (lbm/hr)	ΔP_1 (PSI)	ΔP_2 (PSI)	ΔP_8 (PSI)
2500	0.01106	0.00887	0.00862
5000	0.03961	0.03080	0.02979
7500	0.08814	0.06889	0.06661
10000	0.15327	0.11801	0.11395

REF.

4. Natural Circulation Head

The driving force for the natural circulation flow is the temperature differential between the average hot column in the storage cell and the cooler bulk temperature of the downcomer region.

The water column is assumed to be 15', conservatively neglecting any plume effects. The head is calculated by:

$$P_H = H(\rho_{cold} - \rho_{hot})$$

$$\rho_{170°F} = 60.8 \text{ lbs/ft}^3$$

$$\rho_{180°F} = 60.6 \text{ lbs/ft}^3$$

$$H = 180'' = 15'$$

$$\Delta P_H = 15(60.8 - 60.6)/144 = 0.021 \left(\frac{\text{PSI}}{10°\text{F}}\right)$$

$\Rightarrow$ .0021 psi/°F difference

°F difference = $\overline{T}_{HOT} - \overline{T}_{cold}$ (temp. difference between avg. hot bundle column and the downcomer)

$$\overline{T}_{HOT} = \frac{T_{in} - T_{out}}{2}$$

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5. Bundle Heat Generation

Core rated power = 165 Mwt (@ 3.413 Btu/w-hr)

= $5.632(10^8)$ Btu/hr

Average Ass'y Power = $\frac{5.632(10^8)}{72} = 7.822(10^6)$ Btu/hr

Fraction of operating power w/ 3 days cooling } = $4.186(10^{-3})$ 4

Ass'y heat generation = $7.822(10^6) \times 4.186(10^{-3})$

= 32741 Btu/hr-ass'y

Heat generation per cell = $32741\,(2)^*(1.4)$

= 91675 Btu/hr-cell

Cell Temperature increase vs flow:

Flow/cell (lbs/hr)	ΔT (°F)	$T_{OUT} = 150° + \Delta T$ (°F)	$T_{BOILING}$ @ OUTLET (°F)
2500	36.67	186.7	236.0
5000	18.34	168.3	↓
7500	12.22	162.2	↓
10000	9.17	159.2	↓

* accounts for 2-tier rack

REF.

6. Thermal-Hydraulic Balance

Flow/cell (lbs/hr)	ΔT (°F)	$T_H - T_C$ (°F)	ΔP_{HEAD} (PSI)	ΔP_1 (PSI)	ΔP_2 (PSI)	ΔP_B (PSI)
2500	36.67	18.34	0.03851	0.01108	0.00887	0.00862
5000	18.34	9.17	0.01926	0.03961	0.03080	0.02979
7500	12.22	6.11	0.01283	0.08874	0.06889	0.06661
10000	9.17	4.59	0.00964	0.15327	0.11801	0.11395

From Figure 6-1:

Cell #1 gets 3950 lbs/hr ; $T_{EXIT} = 150° + 23.2° = 173.2°F$

#8 gets 4300 lbs/hr ; $T_{EXIT} = 150° + 21.3° = 171.3°F$

In both cases, the outlet temperature is substantially below the saturation temperature of 236°F.

G. Suarez 7.12.78

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DATE: 7-14-78

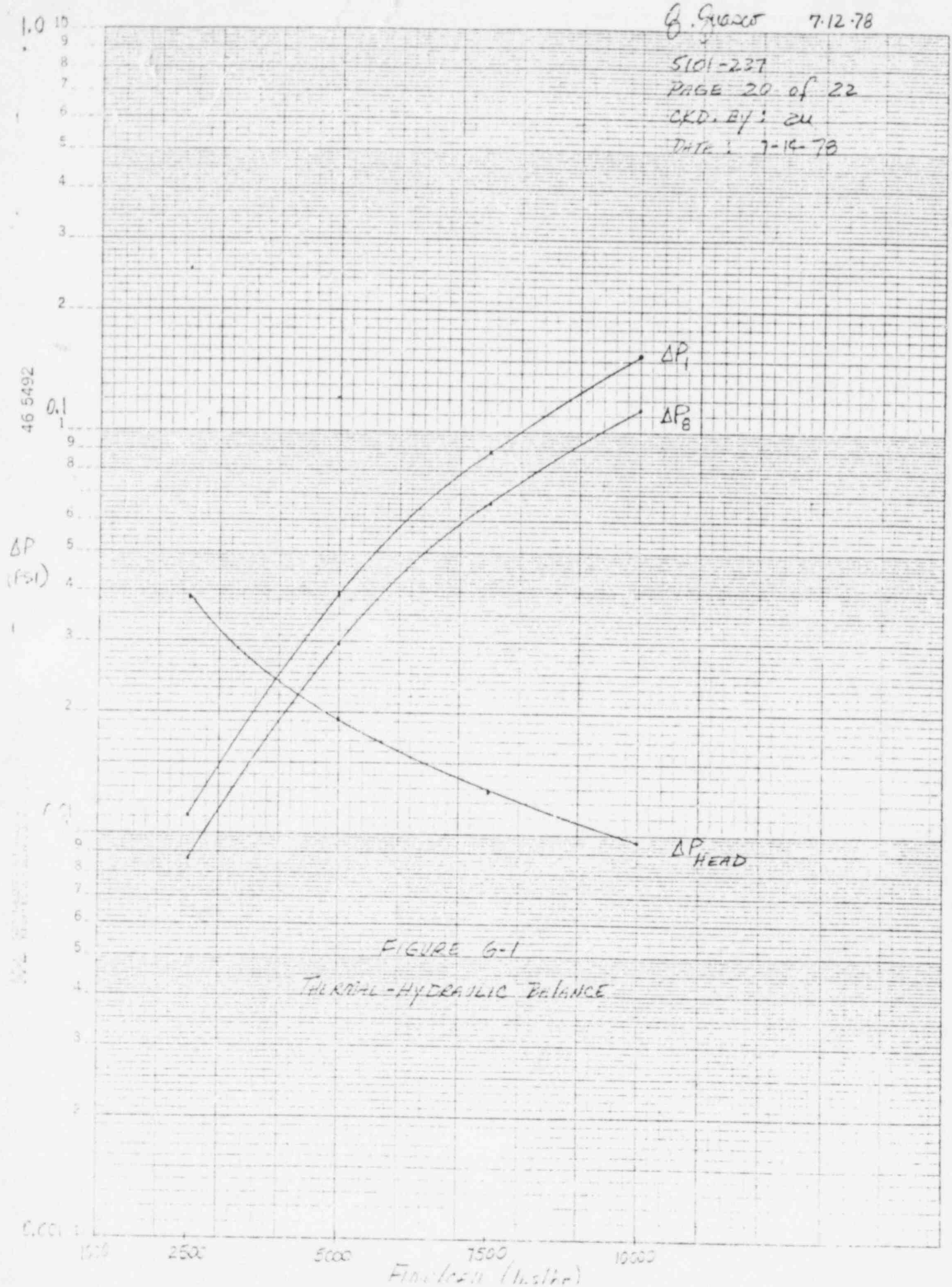

FIGURE G-1

THERMAL-HYDRAULIC BALANCE

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References

1. La Crosse Boiling-Water Reactor Safeguards Report for Operating Authorization, Vol. I.

2. I.E. Idel'chik, Handbook of Hydraulic Resistance, Coefficients of Local Resistance and of Friction, 1966.

3. L.L. Simpson, Process Piping: Functional Design, [illegible] Chemical Engineering, Deskbook Issue, April 14, 1969

4. DPC Letter, LAC-5341, Madgett to Director of Nuclear Reactor Regulation, dated June 7, 1978.

5. Crane, Flow of Fluids Through Valves, Fittings and Pipe, Technical Paper No. 410, 1957, Table A-24.

REF.

6. NES Drawings:

SK.NO. 5101-237-1 : LACBWR FUEL STORAGE RACK LAYOUT

SK.NO. 5101-237-2 : LACBWR Pool ARRANGEMENT LAYOUT FOR ALTERNATIVE 4-2

7. Branch Technical Position APCSB 9-2, NUREG-75/087, Section 9.2.5 "Residual Decay Energy for LWR's for Long-Term Cooling", 11-24-75