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LMR Core Flow Grouping Study

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Abstract

Coolant flow distribution to the assemblies and core coolant/component temperatures should be determined in LMR core steady state thermal-hydraulic performance analysis. Sodium flow is distributed to core assemblies with the overall goal of equalizing the peak cladding midwall temperatures for the peak temperature pin of each pin bundle, thus pin cladding damage accrual and pin reliability. The flow orificing analysis for conceptual design will be performed with Excel spreadsheet program ORFCE which was set up and tested, using the calibration factors based on available analyses data. For the verification of this program, flow orificing calculation for the MDP 840MWth core was performed. The calculational results are satisfactory compared to those of CRIEPI calculation.

1. Introduction

LMR core steady state thermal-hydraulic analysis includes coolant flow distribution to the assemblies and core coolant/component temperatures.

(1) Coolant flow distribution to the assemblies

Sodium flow is distributed to the assemblies with the overall goal of equalizing pin cladding damage accrual and thus pin reliability. In practice, initial orificing analysis attempts to equalize peak pin cladding midwall temperature in all assemblies. Assuming peak fuel burnup to be equal in all assemblies, this orificing analysis can equalize fission gas pressure, cladding stress and damage accrual. Hot channel factors are introduced in temperature predictions to account for core design, analysis, fabrication and operational uncertainties and variations. Two sigma uncertainty factors based on CRBR analyses are employed.

(2) Core coolant and component temperatures

The key core temperature parameters are; (a) peak subchannel coolant temperature, (b) peak cladding midwall temperature, (c) peak thermal striping potential, (d) peak assembly outlet temperature, (e) peak fuel surface temperature and (f) peak fuel centerline temperature. The peak subchannel coolant temperature indicates the margin to coolant boiling. The saturation temperature of sodium at the depth of the core is greater than 1750°F with the pump pressure off and greater than 1950°F with the pumps on. 1750°F is used as the conservative limit for this parameter.

The flow orificing analysis process for conceptual design relies upon PC spreadsheet software ORFCE and calibration factors based on prior detailed analyses data. Peaking factor type analysis models are coded into a spreadsheet and provide estimates of the peak coolant and pin inner temperatures for the hottest pin in each assembly. Flow is distributed to the core assemblies with the goal of equalizing the peak cladding midwall temperature for the peak temperature pin of each pin bundle. Once the flow is distributed so as to equalize peak cladding temperatures, the remaining thermal and flow criteria are checked within the spreadsheet to verify all criteria are met.

The orificing computation model includes factors to account for uncertainties in core design and performance and in analysis methods. These are called hot channel factors (HCFs). The HCFs used in ORFCE are based on the extensive R&D program that was part of the Clinch River Breeder Reactor (CRBR) project. Factors equivalent to a 2 sigma uncertainty allowance are included in these analyses.

As next core design stages, core thermal-hydraulic modeling will be performed using detailed bundle subchannel model codes. The code which provides temperature maps for all pins in all assemblies can facilitate core-wide failure probability studies. Based on their results, the basic flow distribution selected from the ORFCE models might be modified to better equalize pin failure probability.

2. Core Orificing

Table 1 lists the assembly flow orifice groups and associated flow rates for the MDP 840MWth core being developed by CRIEPI. Core flow orificing calculation results are shown on the 1/6 core configuration map in Figure 1. During conceptual design, shielding and IVS were not considered for orificing because their flowrates are small and the powers do not change significantly through life to complicate their orificing. Every assembly in the range of 10% power difference was put in the same group to have 12 orifice groups.

The first six orifice groups are used for fuel assemblies. The radial blanket assemblies are cooled by flow from orifice group 7 through 10. Group 11 provides coolant to the control assemblies. The USS assemblies are cooled by flow from orifice group 12. Both the control and USS assemblies have sliding rod bundles and are subject to a minimum flow that maintains turbulent flow cooling during a scram drop. The minimum flow is estimated to 25,000 lbm/hr based on ALMR design analyses. These assemblies strongly affect thermal striping potential during conceptual design.

Total primary loop flow is set by the core power and the desired reactor temperature rise. A portion of that flow is assumed to bypass the core and to be used for structural cooling within the reactor. In general, 1.5 % of primary loop flow is assumed to bypass the core and is thus not included in the flow distributed to the assemblies. An additional 0.6% of primary flow is omitted in the conceptual design study and is reserved for the perimeter assemblies not explicitly being orificed. Thus 2.1% of primary flow is not distributed in the initial orificing analysis.

3. Core Temperatures

Temperatures are computed by adding relevant temperature rises to the assembly inlet temperature. Each temperature rise is computed from energy input, heat capacity, thermal conductivity and heat transfer coefficient. The temperature rises included are: (a) coolant subchannel temperature rise from the inlet to the elevation modeled, (b) film temperature rise between the subchannel bulk coolant and the cladding surface, (c) cladding temperature rise, either to the midwall radius or to the inner surface, (d) gap temperature rise between the cladding and the fuel surface and (e) fuel temperature rise from the surface to the center.

The key peak core temperatures for each orifice group are listed in Table 2. Key parameters are shown for the peak power pin of each orifice group. The criteria used for steady state thermal performance are same as those for design basis events. As shown in this table, all the criteria are met with margin except the fuel surface temperatures at scram. Given the core power distribution and total flow rate, the equalized cladding midwall temperature is about 1250°F for fuel and radial blanket assemblies.

The peak thermal striping potential is a possible difference in assembly coolant discharge temperatures of adjacent assemblies. The maximum differences possible by combining +2 sigma outlet temperatures adjacent to -2 sigma are used. A limit of 370°F is applied to this parameter to control high cycle fatigue of the permanent upper internal structure. Mixing between the core and UIS, about 3 ft above the core assembly coolant discharge reduces this temperature difference to an acceptable level for permanent structural components. These become important during transient analysis of duty cycle events and primarily serve to set maximum rates of power and temperature change during plant maneuvering. Considerable damage accrual margin is reserved in assembly steady state structural analyses to accommodate these transients. The low powers in the control and USS assemblies permit use of the minimum flow. These assemblies have a low outlet temperature. As a result, the control assemblies and their immediate neighbors set the maximum thermal striping potential.

Table 3 lists some of the detailed flow distribution calculation results for the peak flow assemblies of inner and outer enrichment zones. It shows the assembly outlet temperature analysis, thermal striping analysis and assembly peak temperatures summary.

4. Conclusion

For the LMR core steady state thermal-hydraulic performance study, an Excel spreadsheet program ORFCE was set up and tested with the calibration factors based on prior detailed analyses data. MDP 840MWth core steady state thermal-hydraulic calculation was performed for the verification of this program. The calculational results are satisfactory compared to those of CRIEPI calculation.

ORFCE will be used in the KALIMER conceptual design study, for core steady state thermal-hydraulic performance analysis including coolant flow distribution to the assemblies and core coolant/component temperatures.

For the further development, the various coefficients and the calibration factors used in ORFCE should be updated from the available data.

References

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Table 1 Orifice Zone Flowrates

Orifice Group	Assembly Type	Assembly Count	Assembly Flow (lbm/hr)	Orifice Group Flow (lbm/hr)	Enrichment Zone Flow (lbm/hr)
1	inner fuel	19	291059	5530122	
2	inner fuel	30	257510	7725317	
3	outer fuel	30	279656	8389691	
4	outer fuel	6	255574	1533444	
5	outer fuel	18	225324	4055841	
6	outer fuel	12	206152	2473825	29708239 (87.8%)
7	radial blanket	6	112928	677569	
8	radial blanket	12	87644	1051732	
9	radial blanket	12	78240	938883	
10	radial blanket	12	51381	616582	3284767 (9.7%)
11	control rod	3	25000	75000	
12	USS	3	25000	75000	150000 (0.4%)
total primary loop flow including bypass flow (lbm/hr) :					33826993
total bypass flow					2.1%

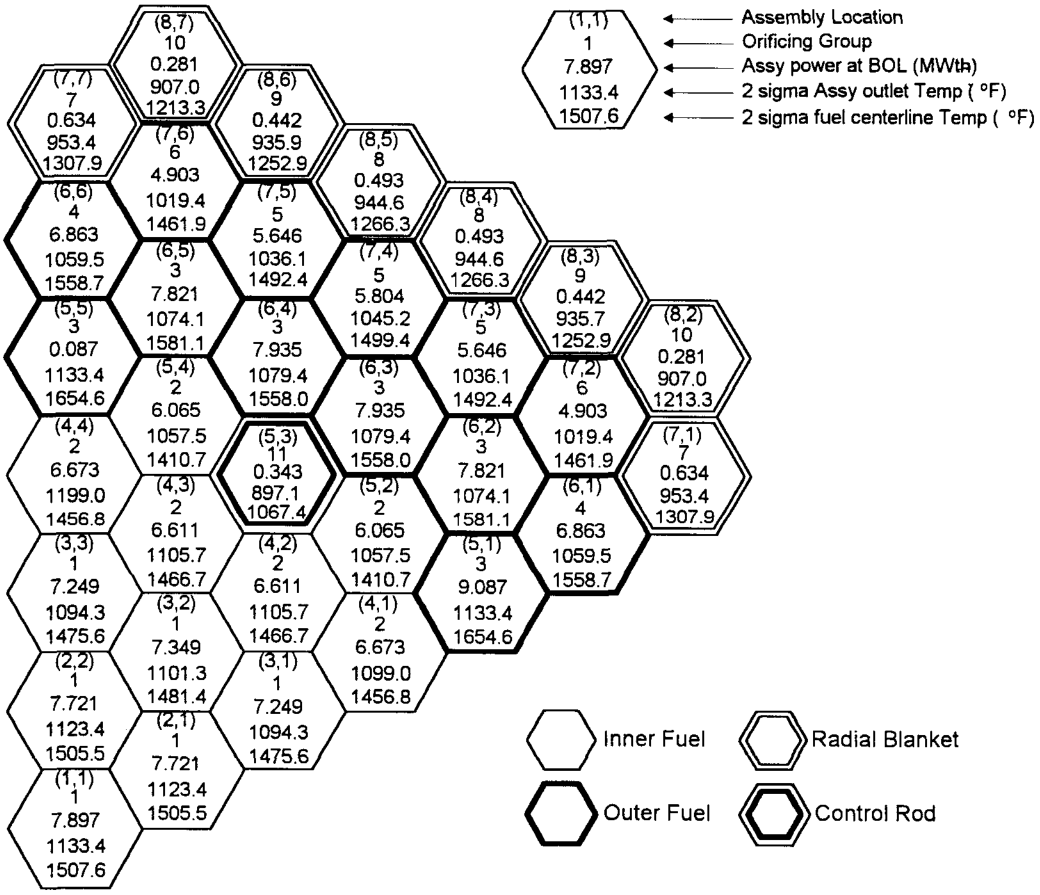

Figure 1 Core Flow Grouping Map (1/6 Core)

Table 2 Orifice Group Peak Summary Table (2σ temperatures, °F)

Orifice Group	Assembly Type	Assembly Outlet (°F)	Thermal Striping* (°F)	Cladding Midwall (°F)	Fuel Surface (°F)	Fuel Center (Scram) (°F)	Fuel Surface (Scram) (°F)	Fuel Center (°F)
	limit	1110	370	-	1300	1700	1300	1700
1	inner fuel	1133	106	1239	1257	1507	1328	1611
2	inner fuel	1117	306	1245	1261	1477	1333	1576
3	outer fuel	1133	290	1271	1291	1655	1366	1777
4	outer fuel	1059	288	1228	1245	1559	1314	1668
5	outer fuel	1059	286	1235	1250	1518	1319	1623
6	outer fuel	1024	254	1220	1234	1469	1301	1568
7	radial blanket	953	288	1211	1218	1308	1283	1385
8	radial blanket	953	286	1221	1226	1282	1293	1356
9	radial blanket	941	274	1217	1222	1265	1288	1336
10	radial blanket	910	254	1213	1216	1219	1282	1285
11	control rod	897	258	-	-	-	-	-
12	USS	844	306	-	-	-	-	-

* maximum difference in assembly coolant discharge temperatures of adjacent assemblies

Table 3 Flow Distribution Results Summary Table (Example)

ASSEMBLY & GROUP MODEL DATA	1 (Assy No.)		11 (Assy No.)	
Type & Location	F	(1,1)	F	(5,1)
Assembly Type Number (Key)	1		1	
Orifice Group & Flow Rate (lbm/hr)	1	285194	3	291528
Inlet Temp. (°F) & Avg. Cp (Btu/lbm-°F)	707.0	0.3030	707.0	0.3030
Film, Gap Coeffs.(Btu/sec-in^2-°F)	0.0450	0.0450	0.0450	0.0450
Pin OD & ID (in)	0.3150	0.2819	0.3150	0.2819
Cladding Thickness & Pellet OD (in)	0.0166	0.2521	0.0166	0.2521
Power Factor: Peak Clad, Peak Fuel	0.4100	0.9200	0.4100	0.9200
Temp. Factor: Peak Clad, Peak Fuel	1.0000	0.7100	1.0000	0.7100
Peak Pin kW/ft, BOL & EOL	9.364	11.116	11.426	9.210
	BOL	EOL	BOL	EOL
Assembly Total Power (MWth)	7.897	9.457	9.087	7.258
ASSEMBLY OUTLET TEMPERATURE ANALYSIS				
Assy Temp Rise Based On Core Cp (°F)	304.9	365.2	365.2	291.7
Assy Avg Temp Based On Core Cp (°F)	859.5	889.6	889.6	852.8
Cp (Btu/lbm-°F)	0.3028	0.3022	0.3022	0.3029
Assembly Nominal Temperature Rise (°F)	305.2	366.2	366.2	291.8
2 Sigma Aging Temp Rise Uncertainty (°F)	46.1	55.3	55.3	44.1
2 Sigma Striping Temp Rise Uncertainty (°F)	35.7	42.8	42.8	34.1
Nominal Outlet Temp (°F)	1012.2	1073.2	1073.2	998.8
+2 Sigma Outlet Temp (°F) (For Th. Aging)	1063.2	1133.4	1133.4	1047.8
+2 Sigma Outlet Temp (°F) (For Th. Strpg)	1052.8	1121.0	1121.0	1037.8
-2 Sigma Outlet Temp (°F) (For Th. Strpg)	981.4	1035.3	1035.3	969.6
SUMMARY: Assembly Peak Temps (°F)				
+2 Sigma Coolant Outlet	1133.4		1133.4	
+2 Sigma Thermal Striping (POS)	93.4		175.5	
+2 Sigma Cladding Midwall	1239.5		1271.7	
+2 Sigma Fuel Surface	1257.2		1291.4	
+2 Sigma Fuel Centerline	1507.6		1654.6	
+2 Sigma Peak Fuel Surface At Scram	1328.1		1366.8	
+2 Sigma Peak Fuel Center At Scram	1611.0		1777.2	