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The Simulation of Semicale Natural Circulation Test S-NC-3, S-NC-4 Using RELAP5/Mod3.1

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Abstract

RELAP5/Mod3.1 code was assessed with the semiscale experiment S-NC-3, and S-NC-4, which simulated the two-phase natural circulation and reflux condensation for the SBLOCA of PWR, respectively. Test S-NC-3 and S-NC-4 calculation results showed that RELAP5/Mod3.1 quite well describes the influence of steam generator secondary side heat transfer degradation on both two-phase natural circulation and reflux condensation. A comparison between the calculated and measured two-phase mass flow rate in test S-NC-3 shows good agreement for primary mass inventory more than 92%. And RELAP5/Mod3.1 have a good mass flow rate prediction capability for the transient such as S-NC-4 except some flow oscillations. The reflux flow rate for S-NC-4 test is under predicted, and the overall results verify that the correct prediction of the reduced liquid level appears to be required for the correct calculation of the overall phenomena.

1. Introduction

The RELAP5/Mod3 [1] code has been extensively used for various areas since it was developed under the auspices of United States Nuclear Regulatory Commission (USNRC) and by the international effort through the International Code Assessment and Application Program (ICAP). After the termination of ICAP by 1992, the international experience and experts of the code recognized that the code be improved and maintained more usefully and reliably, and initiated a new program, Code Applications and Maintenance Program (CAMP), as post-ICAP. Korea, as a CAMP member country since August 1993, has a responsibility to conduct ten cases of code assessment and report them by August 1997, as specified in the Agreement on CAMP between USNRC and Korea Institute of Nuclear Safety (KINS). This present study aims to evaluate the performance of RELAP5/Mod3.1 in predicting the Small Break Loss-of-Coolant-Accident (SBLOCA) specific thermal-hydraulic phenomena in pressurized water reactor (PWR). Those phenomena include system depressurization, loop seal forming and clearing, single and two phase break flow, core heatup, two-phase natural circulation and reflux cooling, etc. Especially, S-NC-3, and S-

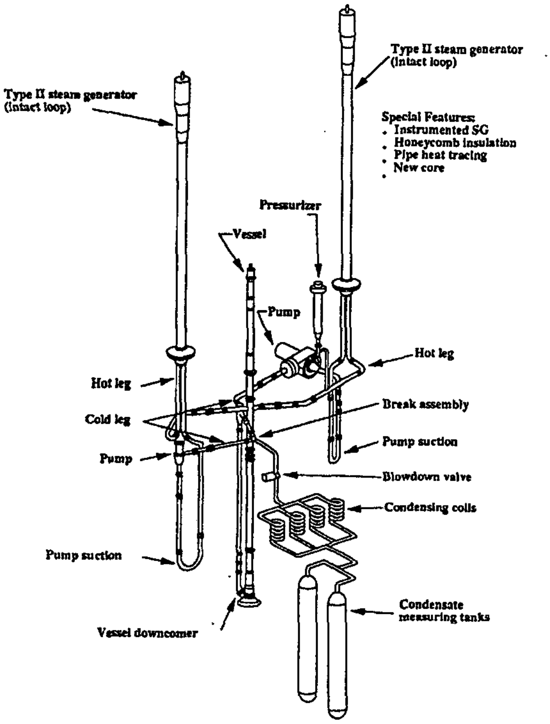

Fig. 1. Configuration of Semiscale Mod-2A Facility

NC-4 were two-phase and reflux natural circulation test which investigated the effect of various steam generator secondary side hydraulic conditions on the natural circulation flow rate, with constant core power and primary inventory.

2. Description of Semiscale Mod-2A Facility

The S-NC-3 and S-NC-4 experiment have ever been simulated with RELAP5/Mod1 by Loomis and Soda [2, 3]. Input models used in this study was basically adopted from Wong and Kmetyk' s study [4] and some of them were modified[5]. The Semiscale Mod-2A test facility is shown in Figure 1. It is an approximately 2:3411 scale (based on the core power ratio) model of a four-loop PWR, and consists of two primary coolant loops connected to an electrically-heated reactor pressure vessel which has an external downcomer. While both experimental loop are active, each loop contains a circulation pump and a steam generator. One loop (the intact loop) has, however, three times water volume and mass flow of the other loop (the broken loop).

The facility has been used for S-NC test series, major objects of which were to provide thermal-hydraulic data for the assessment and development of nuclear safety grade computer codes. Since natural circulation is an important core heat removal mechanism during certain kinds of accidents or transients in a PWR, such as SBLOCAs or loss of forced pump circulation[2], some Semiscale tests (from S-NC-1 to S-NC-6) were focused on the separate effect of natural circulation, other tests (from S-NC-7 to S-NC-9) were on the integral one.

3. RELAP5 Modeling

The RELAP5/Mod3.1 modeling for the simulation of the experiment can be described as a nodalization as shown in Figure 2.

The input deck was modified suitable to RELAP5/Mod3.1 standard frozen version and standard (default) mode options were specified at each volume, junction, and heat structure. This nodalization contains 118 volumes, 117 junctions and 175 heat structures. They represent the intact loop pipings, the reactor vessel, the steam generators and the auxiliary feedwater line of a intact loop.

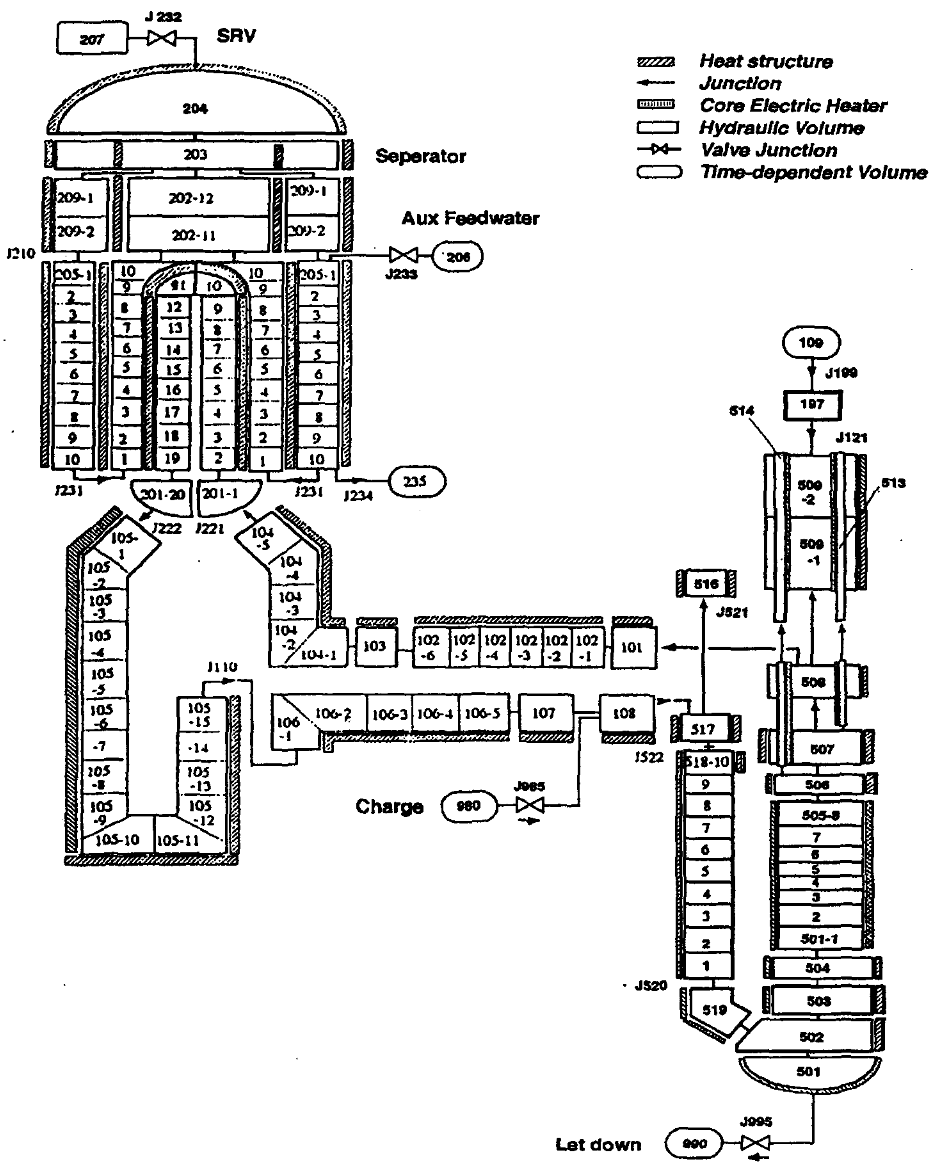

Fig. 2. Node Scheme of Semiscale Mod-2A Facility

4. Analysis Results and Discussion

4.1. S-NC-3

Test S-NC-3 is a two-phase natural circulation test using the partial Mod-2A system.

At first, the core power was held at 30 kW and the primary mass inventory at 92%, and adjusted the core power to 60 kW. Also the steam generator feedwater mass flow rate was reduced and let the secondary liquid boil off slowly until the collapsed liquid level in the steam generator downcomer dropped to the

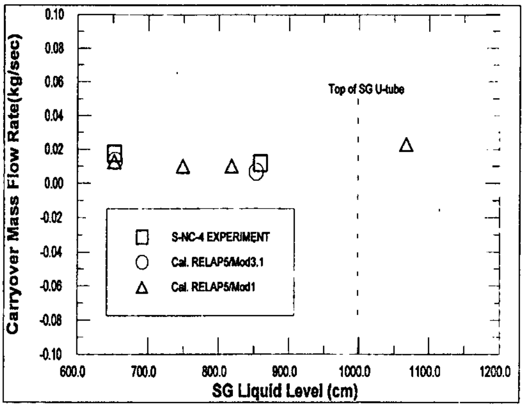

Fig. 3. Measured and Calculated Mass Flow Rates for Test S-NC-3

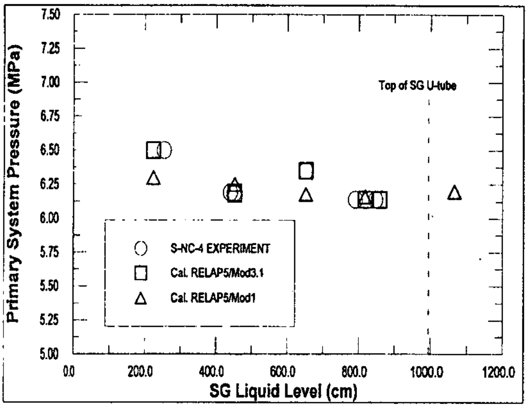

Fig. 4. Measured and Calculated Primary System Pressures for Test S-NC-3

specified value. When the system reached a steady state, the steady state calculation is stopped. In Table 1, only 9 data points (the third set of tests) of the 19 experiments in test S-NC-3, show the effect of secondary inventory on two-phase natural circulation flow rate in the primary system. And the results of these first S-NC-3 calculations are presented in from Figure 3 through Figure 6.

Figure 3 shows the calculated and measured mass flow rates in the primary system for different effective steam generator heat transfer areas. Qualitatively, RELAP5/Mod3.1 does reasonably well predict the two-phase natural circulation flow rate. Both the calculated and experimental results show that, for effective heat transfer area of the steam generator above 50%(600㎝), secondary inventory does not affect the steady two-phase natural circulation flow rate. However, as the heat transfer area falls below 50%, the natural circulation flow rate decreases with decreasing secondary inventory, and the difference appears between the calculation and the experiment. Quantitatively, calculated mass flow rates at low secondary inventories are bigger than that measured.

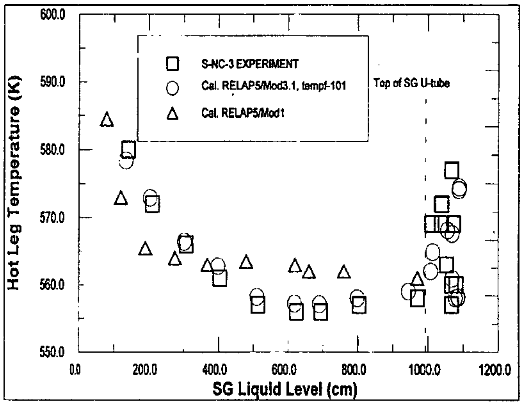

Fig. 5. Measured and Calculated Hot Leg Temperatures for Test S-NC-3

As shown in Figure 4 and Figure 5, the primary system pressure and hot leg temperature are well predicted for the overall steam generator water level.

Also shown in Figure 6, if the steam generator water level is below 500 cm, there is some deviation between the prediction and the experiment. The code under-predicted the cold leg temperature about 3 ~ 10℃.

The results for test S-NC-3 show that

Table 1. Experimental and Calculated Results for Test S-NC-3

Case	NO.	Mass Inventory(%)		Primary Pressure(MPa)		Cold Leg Temp.(K)		Hot Leg Temp.(K)		SG Pressure(MPa)		SG Sec. Liquid Level(cm)		Core Power (kW)		Mass Flow Rate (kg/s)	
		EXP.	RELAP5 /M3.1	EXP.	RELAP5 /M3.1	EXP.	RELAP5 /M3.1	EXP.	RELAP5 /M3.1	EXP.	RELAP5 /M3.1	EXP.	RELAP5 /M3.1	EXP.	RELAP5 /M3.1	EXP.	RELAP5 /M3.1
1	1	100	100	11.2	11.2	540	537.7	560	558.0	5.0	5.0	1080	1078	32.8	32.8	0.33	0.323
	2	100	100	12.5	12.5	539	537.9	569	567.6	5.0	5.0	1073	1069	62.6	62.6	0.39	0.401
	3	94.1	94.1	8.2	8.2	540	537.9	569	564.9	5.0	5.0	1039	1014	62.6	62.6	0.40	0.536
	4	93.1	93.2	8.3	8.3	540	537.8	569	562.0	5.0	5.0	1011	1008	62.6	62.6	0.40	0.591
2	5	100	97.8	10.1	10.1	549	548.2	577	574.5	5.9	5.9	1067	1089	62.6	62.6	0.40	0.395
	6	98.0	97.7	9.2	9.2	550	548.3	577	574.1	5.9	5.9	1067	1088	62.6	62.6	0.40	0.402
	7	95.7	95.7	8.0	8.0	550	548.4	572	568.1	5.9	5.9	1039	1056	62.6	62.6	0.50	0.488
	8	93.6	93.6	7.2	7.2	550	548.5	563	560.9	5.9	5.9	1053	1069	62.6	62.6	0.63	0.628
	9	92.6	92.6	6.9	6.9	550	548.5	560	558.1	5.9	5.9	1067	1086	62.6	62.6	0.70	0.696
	10	91.8	91.8	6.9	6.9	550	548.5	557	558.1	5.9	5.9	1067	1085	62.6	62.6	0.75	0.707
3	11	91.8	91.8	7.0	7.0	550	548.6	558	559.0	5.9	5.9	970	944.5	62.0	62.0	0.69	0.690
	12	91.8	91.8	6.9	6.9	550	548.6	557	558.0	5.9	5.9	804	797.9	62.0	62.0	0.76	0.710
	13	91.8	91.8	6.8	6.8	551	548.5	556	557.1	5.9	6.2	694	689.9	62.0	62.0	0.75	0.718
	14	91.8	90.1	6.8	6.81	551	549.8	556	557.2	6.0	6.0	624	618.5	62.0	62.0	0.77	0.736
	15	91.8	91.2	6.9	6.9	553	550.2	557	558.2	6.0	6.0	514	510.7	62.0	62.0	0.68	0.679
	16	91.8	91.8	7.4	7.4	556	550.9	561	562.8	6.0	6.0	404	398.3	62.0	62.0	0.59 ±0.06	0.636
	17	91.8	91.8	7.8	7.8	559	552.7	566	566.4	6.0	6.0	307	301.9	62.0	62.0	0.45 ±0.11	0.517
	18	91.8	91.8	8.7	8.7	564	552.2	572	572.9	6.0	6.0	210	203.6	62.0	62.0	0.30 ±0.17	0.459
	19	91.8	91.8	9.6	9.6	566	555.1	580	578.4	6.0	6.0	141	134.1	62.0	62.0	0.20 ±0.13	0.395

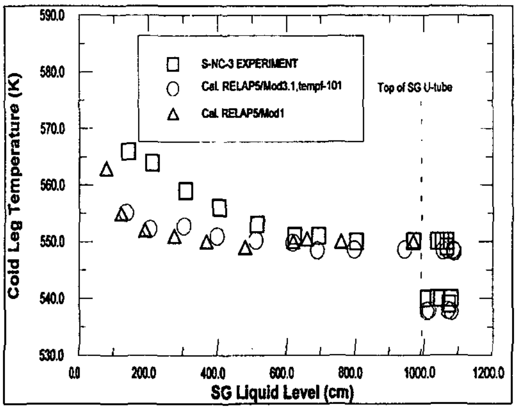

Fig. 6. Measured and Calculated Cold Leg Temperatures for Test S-NC-3

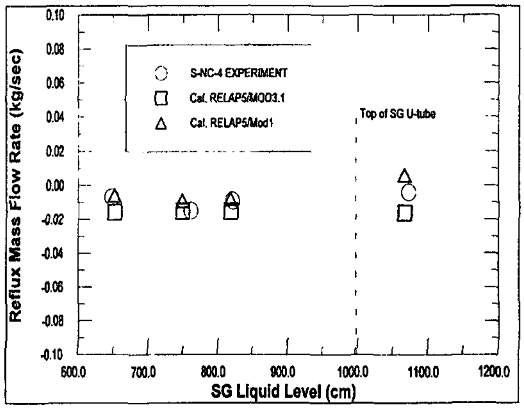

Fig. 7. Measured and Calculated Reflux Mass Flow Rates for Test S-NC-3

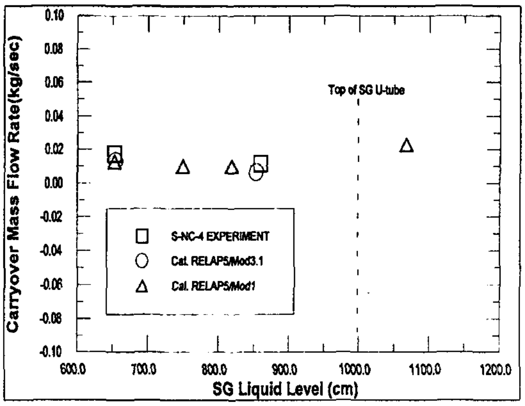

Fig. 8. Measured and Calculated Carryover Mass Flow Rates for Test S-NC-4(60kW Power Case)

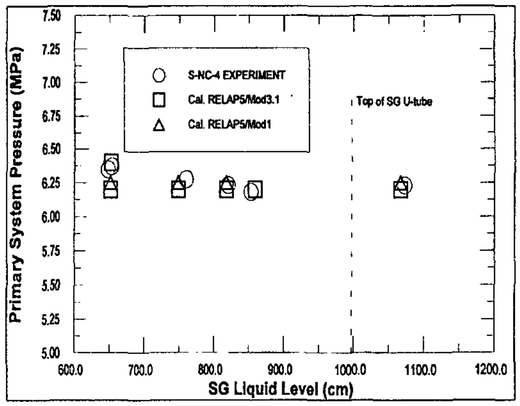

Fig. 9. Measured and CalculatedPrimary System Pressures for Test S-NC-4(60kW Power Case)

RELAP5/Mod3.1 predicts the reasonable qualitative behavior, with the quantitative discrepancies at low secondary side inventories for 92% primary mass inventory.

For steam generator secondary side collapsed liquid level above 55% of the total tube heat transfer area, primary side natural circulation mass flow rate does not change much at all, while dropping the steam generator secondary side collapsed liquid level below 500㎝ (50% heat transfer area) causes a corresponding reduction in loop mass flow. Quantitative agreement between calculated and measured flow rate of the primary mass inventory in the calculations is set at 92%, and agreement for other important parameters such as improves substantially when the primary inventory is 92%.

4.2. S-NC-4

A total of 12 measurements of reflux or carryover mass flow were obtained, for various

Table 2. Experimental and Calculated Results for Test S-NC-4.

NO.	Primary Pressure (MPa)		Core Inlet Temp. (K)		Core Outlet Temp.(K)		Core Power (kW)		S.G. Condition				Pri. System Mass Inventory				Refluxing Rate			
									Pressure (MPa)		Liq. Level (cm)		Start of Meas. (%)		End of Meas. (%)		Carryover (kg/s)		Reflux (kg/s)	
	Exp.	R5M3.1	Exp.	R5M3.1	Exp.	R5M3.1	Exp.	R5M3.1	Exp.	R5M3.1	Exp.	R5M3.1	Exp.	R5M3.1	Exp.	R5M3.1	Exp.	R5M3.1	Exp.	R5M3.1
1	6.2	6.23	540	552.1	550	555	60.9	60.9	5.72	5.72	1067	1073	58.5	58.5	48.1	48.1	–	–	0.0162	0.004
2	6.2	6.23	539	552.7	550	551	60.9	60.9	5.74	5.74	818	820.7	61.1	61.1	52.3	52.3	–	–	0.0154	0.009
3	6.1	6.14	530	548.9	549	557	31.4	31.4	5.74	5.74	818	790.8	60.7	60.7	53.8	53.8	–	–	0.0092	0.029
4	6.1	6.14	545	549	549	549	31.4	31.4	5.74	5.74	859	847.5	62.4	62.4	62.4	62.4	0.0101	0.004	–	–
5	6.2	6.18	540	550.3	567 -596	558.0	60.9	60.9	5.74	5.74	859	853.1	62.4	62.4	62.4	62.4	0.0116	0.0067	–	–
6	6.2	6.273	535	553.2	550	552.4	60.9	60.9	5.74	5.74	749	760.4	64.4	62.4	51.9	51.9	–	–	0.0154	0.015
7	6.2	6.35	535	545.6	551	557.3	60.9	60.9	5.75	5.75	652	647.9	65.9	65.9	58.6	58.6	–	–	0.0158	0.007
8	6.4	6.37	550	557.4	552	559.2	60.9	60.9	5.75	5.75	652	653.4	71.7	71.7	71.7	71.7	0.0175	0.0132	–	–
9	6.2	6.35	548	549.12	551	553.1	31.4	31.4	5.75	5.75	652	651.7	71.7	71.7	71.7	71.7	0.0127	0.011	–	–
10	6.2	6.19	548	553.3	550	558.1	31.4	31.4	5.76	5.75	452	439.6	71.7	71.7	71.7	71.7	0.0229	0.0143	–	–
11	6.2	6.18	538	546.8	550	557.0	31.4	31.4	5.76	5.76	452	448.9	70.1	71.7	65.8	65.8	–	–	0.0092	0.0041
12	6.9	6.5	535	550.1	558	555	31.4	31.4	5.79	5.78	224	254	69.9	69.9	63.2	63.2	–	–	0.0070	0.009

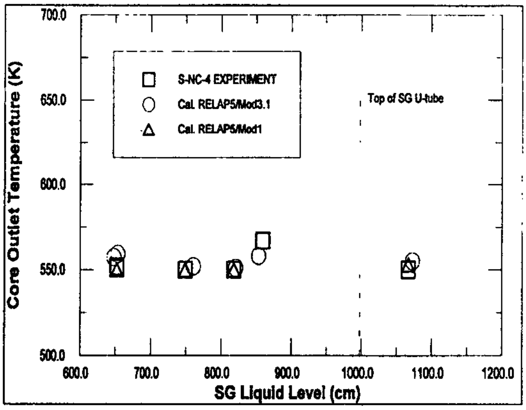

Fig. 10. Measured and Calculated Core Outlet Temperatures for Test S-NC-4(60kW Power Case)

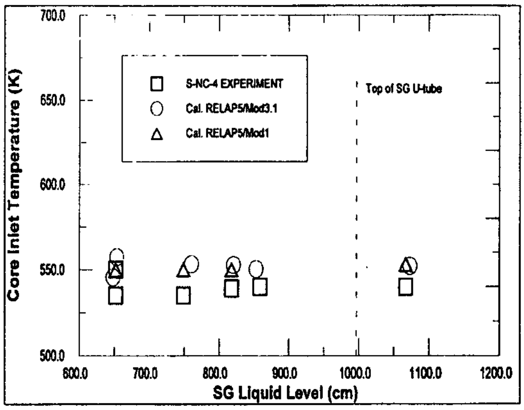

Fig. 11. Measured and Calculated Core Inlet Temperatures for Test S-NC-4(60kW Power Case)

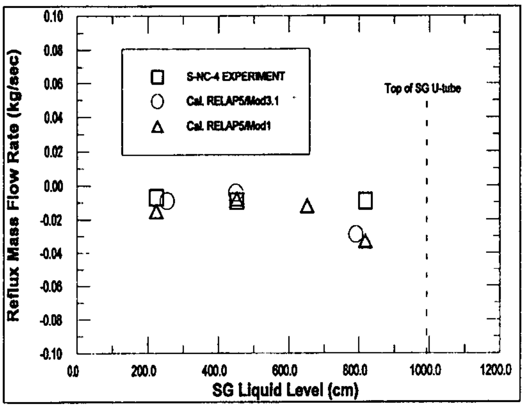

Fig. 12. Measured and Calculated Reflux Mass Flow Rates for Test S-NC-4(30kW Power Case)

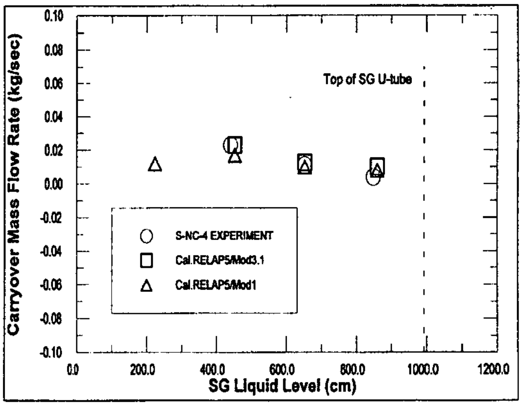

Fig. 13. Measured and Calculated Carryover Mass Flow Rates for Test S-NC-4(30kW Power Case)

combinations of primary and secondary conditions. The secondary liquid level was changed from 1067 cm (100%) to 224 cm (24%).

Two core power levels were used (31.4 and 60.9 kW). The initial conditions were established, and the primary system pressure was allowed to vary. The secondary side pressure was maintained constant at ~ 5.7~5.8 MPa (Table 2).

For the 60kW power case of test S-NC-4 (from table 2 - No. 1,2 and 5 to 8), the comparisons between the calculation and measurement of the reflux and carryover flow rates are shown in Figure 7 and 8, respectively.

In general, the calculated and measured primary pressures, and the core inlet and outlet temperatures, show pretty good agreements.

In Figure 7, reflux flow rate at high secondary liquid levels are overpredicted with the experiment, and in Figure 8 carryover mass flow rate are underpredicted, but these results shows a good

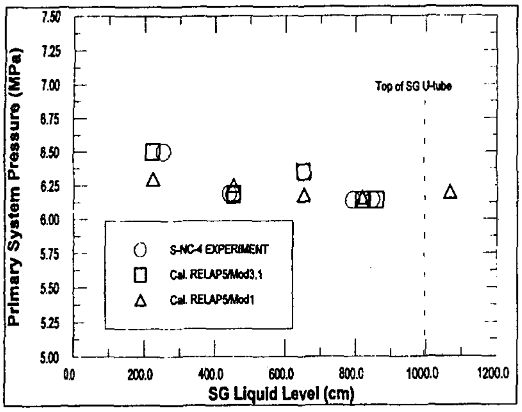

Fig. 14. Measured and Calculated Primary Pressures for Test S-NC-4(30kW Power Case)

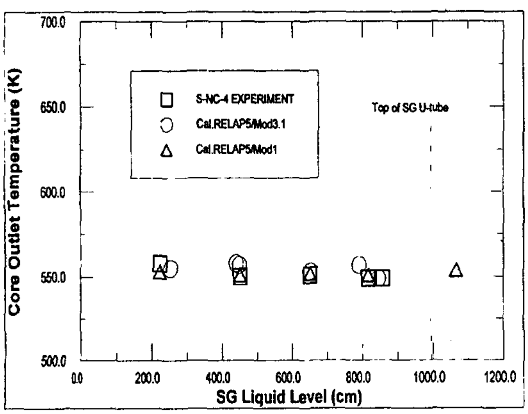

Fig. 15. Measured and Calculated Core Outlet Temperatures for Test S-NC-4(30kW Power Case)

calculation. From Figure 9 through 11 are shown these comparisons as a function of steam generator effective heat transfer area.

This shows predicts the reasonable qualitative behavior for the overall steam generator water level.

From Figure 12 through 16 show the results of the RELAP5/Mod3.1 analysis for 30kW core power (from table 2 - No. 3, 4 and 9 to 12). The

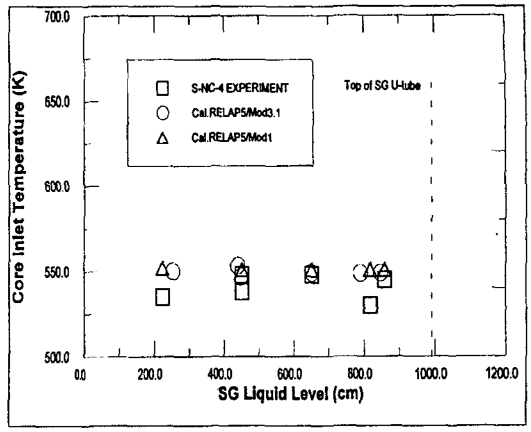

Fig. 16. Measured and Calculated Core Inlet Temperatures for Test S-NC-4(30kW Power Case)

overall thermal/hydraulic behavior of the system is quite similar to that seen for 60 kW core power.

All the important parameters such as primary pressure, cold leg temperature, hot leg temperature, carryover mass flow rate are not affected much by the change of steam generator effective heat transfer area.

The calculation of test S-NC-4 show good agreement between the measured and the calculated except of the reflux mass flow rate in the calculation. Similar to S-NC-3, reflux mass flow rate was underpredicted at lower primary and high secondary inventories.

All these natural circulation experiments are persuasive tests for the liquid entrainment models in RELAP5/Mod3.1. At reduced inventories, since essentially all the core power is used in generating steam since there is little subcooling, the mass flow of this steam is a small fraction of the total flow rate. The most of the mass flow is due to the liquid water entrainment by the steam. Mass flow rates at 100% inventory (single phase) are generally well matched with the code.

The mass flows at very low inventories are small because there is very little entrainment of liquid, and reflux flow rate is also usually well calculated. The mass flow rate between these two limiting cases is governed by the account of the entrained liquid.

All the natural circulation assessment calculations done in this study indicate the potential deficiencies in the interface drag model (affecting the amount of liquid entrained at any given inventory), the two-phase wall friction, loss coefficient for abrupt area changes (affecting the peak values in two-phase natural circulation).

5. Conclusions

After assessment calculation of the S-NC-3 and S-NC-4 by RELAP5/ Mod3.1, the following conclusion was derived.

The results for test S-NC-3 show that RELAP5/Mod3.1 predicts correct qualitative behavior, with some quantitative discrepancies in loop mass flow rate at low secondary side inventories, for 92% of primary mass inventory. For steam generator secondary side collapsed liquid level is above 55% of the total tube heat transfer area, primary side natural circulation did not change much while the steam generator side collapsed liquid level is below 500 cm (50% heat transfer area). The reduction of loop mass flow was remarkable.

Quantitative agreement between calculated and measured flow rate is the primary mass inventory in the calculations is set at 92%, and agreement for other important parameters such as improves substatially when the primary inventory is 92%.

In the reflux cooling test S-NC-4, the reflux mass flow was underpredicted by RELAP5/Mod3.1. Except this reflux mass flow rate between the measured and calculated, the results were reasonably good. Similar flow differencies were seen in the test S-NC-3 at lower primary and secondary inventories, suggesting that they probably occured in test S-NC-4. However the large uncertainties in system conditions introduced by reflux flowmeter and the uncertainties on measured flow rate preclude more quantitative comparison, also the measurements were not fine enough to verify their existence.

All these natural circulation experiments are persuadable tests for the liquid entrainment models in RELAP5. At reduced inventories, essentially all the core power is used in generating steam since there is little subcooling. The mass flow associated with this steam is very small and then most of the mass flow is due to the liquid entrainment by the steam. Mass flows at 100% inventory are generally well matched with the code. The mass flows at very low inventories are small because there is very little entrainment of liquid, and reflux flow rate is also usually well calculated. The mass flow between these two limiting cases is governed by the entrained liquid. All the natural circulation assessment calculations, done in this study indicate the potential differencies in the interface drag model, two-phase wall friction, and loss coefficient for abrupt area changes .

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