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VALIDATION OF SSC USING THE FFTF NATURAL-CIRCULATION TESTS*

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ABSTRACT

As part of the Super System Code (SSC) validation program, the 100% power FFTF natural-circulation test has been simulated using SSC. A detailed 19 channel, 2 loop model was used in SSC. Comparisons showed SSC calculations to be in good agreement with the Fast Flux Test Facility (FFTF), test data. Simulation of the test was obtained in real time.

1. Introduction

The Super System Code (SSC)[1] was developed at the Brookhaven National Laboratory (BNL) for the thermohydraulic analysis of natural circulation transients, operational transients, and other system wide transients in nuclear power plants. SSC is a best estimate code that models the in-vessel components, heat transport loops, plant protection systems, and plant control systems. Recently, SSC has been coupled with the BNL developed code MINET,[2] which has extended its analysis capability to the balance of plant. SSC is also designed to be fast running, i.e., faster than real time on a CDC-7600. Thus, validation of SSC not only involves determination of the accuracy of the simulation, but determination of the computing time required to achieve that accuracy.

Previous SSC validation efforts have focused on two procedures: 1) comparison to numerically generated reference solutions,[3,4] and 2) comparisons to other computer codes.[5,6] Prior to system-wide evaluations, individual modules are tested on a stand-alone basis. Strict adherence to standard coding practices and naming conventions allows changes to be made to individual models and then incorporated into the main system code with minimal errors.[7]

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Comparisons to numerically generated reference solutions are usually restricted to one specific module (i.e., the core, piping, etc.) to isolate the model and to minimize computer core storage requirements. The reference solution is generated by refining the nodalization and then extrapolating (if possible) to a fine mesh solution with an infinite number of nodes. In practice, however, the benchmark is a solution with a sufficiently large number of nodes such that further refinement of the mesh does not lead to significant changes in the calculated results. This procedure also provides information on the detail of nodalization necessary to analyze various transients in addition to checking the accuracy and consistency of the numerical algorithms. Even though SSC has been successfully tested using this method, the procedure is inadequate for determining deficiencies in the physical models used.

Comparisons between computer codes tend to be difficult and time consuming while providing minimal validation. To claim a code is valid simply because its analysis agrees with a reference code simply shifts the burden of validation to the reference code. However, useful information can be obtained especially the detection of Fortran coding errors.

The main difficulty in comparing any two codes is that their physical models are generally different. Thus differences in calculational results must be explained in terms of these modeling differences rather than induced by numerical or coding errors. In some cases, this means modification or relaxation of the code's model to conform to the reference code. For example, when comparisons were made between IANUS,[8] a proprietary code developed specifically for transient system analysis in the Fast Flux Test Facility (FFTF), and SSC,[6] it was necessary to suppress the transient core flow redistribution model in SSC since IANUS did not have this feature, even though core flow redistribution is an important effect in some of the transients analyzed in the comparison.

In summary, previous SSC system-wide validation studies were made with a numerically generated data base. Recently, a series of natural circulation transients at various powers and flows, including 100% power and flow, have been run at the FFTF as part of the facility's startup program. Since FFTF, which was designed for testing of materials for use in fast breeder reactors, is highly instrumented, an extensive experimental data base now exists which can be used in validating system codes for natural circulation transients. The SSC code has been used to simulate the 100% power and flow natural circulation transient. Comparisons were made between the SSC predictions and the experimental data. These comparisons have demonstrated SSC's capability to simulate natural circulation transients, within the limits of the experimental data, while retaining its fast running capability.

2. Modeling of the FFTF Natural Circulation Transients Using SSC

2.1 Description of the Fast Flux Test Facility (FFTF)

The FFTF is a 400 MWt, sodium cooled, fast reactor having three independent heat transport trains.[9] Figure 1 is a schematic showing one of these trains, each consisting of a primary coolant loop, an intermediate heat exchanger (IHX), a secondary coolant loop, and a dump heat exchanger (DHX).

The FFTF heat transport trains are instrumented with electromagnetic flow meters located in the cold legs and temperature sensors located in the hot and cold legs of the primary and secondary loops. The inlet and outlet temperatures of the IHXs and DHXs are also monitored.

The FFTF core consists of 73 fuel assemblies, 3 safety rods, 6 control rods, and 9 unfueled assemblies. The flow rate and coolant exit temperature for each assembly are monitored by a flow meter and thermocouple located in an instrument tree above the core. A guide tube directs the assembly flow to the appropriate sensors (the sensors are physically located in the guide tubes.) Two of the fuel assemblies are referred to as Fueled Open Test Assemblies (FOTAs). Physically identical to the other fuel assemblies, they are located near the center of the core (Row 2 FOTA) and the outer edge of the core, adjacent to the reflector (Row 6 FOTA). A series of wire wrap thermocouples provide detailed temperature information along the axial length of each FOTA. The FOTAs also differ from the other fuel assemblies in that the guide tubes for the instrument tree are physically connected to the top of the assemblies. All the other fuel assemblies have a 1" to 2" gap between the top of the assembly and the guide tube. Therefore, at the low flow conditions typical of natural circulation events, the measured flow rates of the fuel assemblies (except the FOTAs) are unreliable. Moreover, the long response time of the thermocouples used in the instrument tree limits the usefulness of the transient assembly exit coolant temperature data.

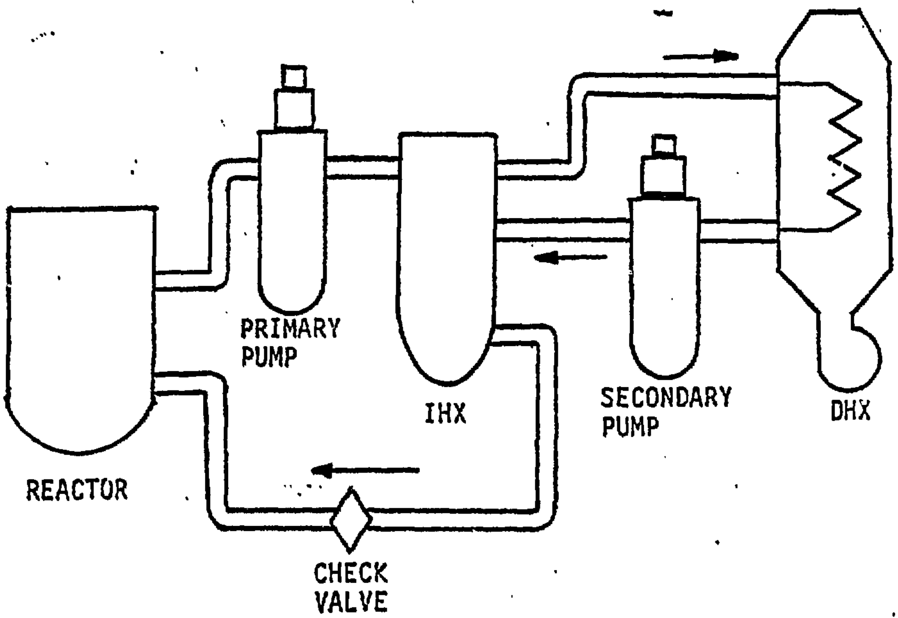

FIGURE 1: SCHEMATIC OF FFTF HEAT TRANSPORT TRAIN

2.2 SSC Modeling of FFTF

To model the FFTF, it was decided to use a 2 loop representation, with one loop representing two physical loops. Although no large asymmetries were observed in the 100% test simulated for this study, two loops were modeled for future studies where such asymmetries may occur.

Although a DHX module is part of the SSC program library, it was decided for this study that no validation of these modules would be done. This decision was made since the DHX modules are unique to FFTF and thus validation of these modules would be of limited value. Therefore, for this study the experimentally measured DHX outlet temperature was input as a forcing condition to SSC. The pressure drop across the DHX was simulated using a form loss coefficient and a buoyancy term.

The remainder of the secondary loop was modeled by five pipes, a pump with surge tank, and the tube side of the IHX. The nodalization was chosen on the basis of an earlier study for natural circulation transients (Table 1)[4].

Table 1 - SSC Nodalization of FFTF

Module	Number of Nodes
Secondary Loop:	
Pipe 1	38
Pipe 2	3
Pipe 3	3
Pipe 4	15
Pipe 5	19
IHX	21
Primary Loop:	
Pipe 1	29
Pipe 2	15
Pipe 3	10
Pipe 4	14
Reactor Core:	19 channels (including Row 2 and Row 6 FOTA explicitly modeled) 12 axial nodes per channel 3 radial fuel nodes per axial node 1 gap node per axial node 1 clad node per axial node 1 coolant node per axial node 1 structure node per axial node

The primary loop was modeled by 4 pipes, a pump, the shell side of the IHX, and a check valve in the cold leg. The nodalization is also shown in Table 1.

The in-vessel representation included: a one node, perfect mixing, lower plenum; core inlet module; a 19 channel core representation with bypass; core exit module; and a two region upper plenum. It is important to note that SSC dynamically calculates transient flow redistribution for all the core channels and the bypass. Each flow channel is hydrodynamically coupled to the others. Inter-assembly and intra-assembly heat transfer however, are not modeled. Each channel is represented by an average rod with its associated coolant channel and structure. The channel is divided into 12 axial nodes; the fuel pin has 3 radial nodes in the fuel and one in the clad. An earlier numerical study showed this representation to be adequate for natural circulation type transients [3]. The steady state assembly powers and flow rates were determined from the experimental data and checked against pre-test numerical predictions.

The decay curve and initial decay power were obtained from the FFTF project office. The fission power was calculated using SSC's point kinetics package.

3. Results and Error Analysis

3.1 FOTA Coolant Temperatures

The average coolant temperatures at the top of the fuel axial level and at the top of the pin axial level for the Row 2 and Row 6 FOTA were obtained by averaging the thermocouple readings at these locations [13 at each level for the Row 2 FOTA; 14 at the top of fuel level and 16 at the top of pin level for the Row 6 FOTA.] The experimental data (shown with a ±3^{o}K error bar at 10s intervals) are compared to the SSC calculations in Figs. 2-5. As can be seen, the SSC results are in good agreement with the FOTA test data. The lower test data temperature for the Row 6 FOTA top of pin location is probably caused by inter-assembly heat transfer (which is not modeled in SSC) to the adjacent reflector.

An error analysis was performed using the experimental data as the benchmark. The results are summarized in Table 2. Since SSC is a best estimate code, positive and negative maximum errors are shown. The maximum negative error in all cases occurs at 10(s), which is the time of the first transient test data point. Although the absolute temperature difference at this time is about 50^{o}K the relative error is still less than 9%. The maximum positive errors occur around 180(s) and are small with the exception of the Row 6 FOTA top of pin location; however, the relative errors are again small. The average absolute error of 3-4^{o}K is particularly good since the experimental data have an error band of ±3^{o}K.

3.2 Loop Temperatures and Flow Rates

The hot leg temperature, cold leg temperature, and loop flow for the pump loop are shown in Figs. 6-8. The corresponding parameters for the secondary loop are shown in Figs. 9-11. As can be seen, the SSC simulations are in good agreement with the experimental data. A detailed error analysis was not done for these data since the temperature profiles are relatively constant and the flow data have a wide error band (±16 kg/s).

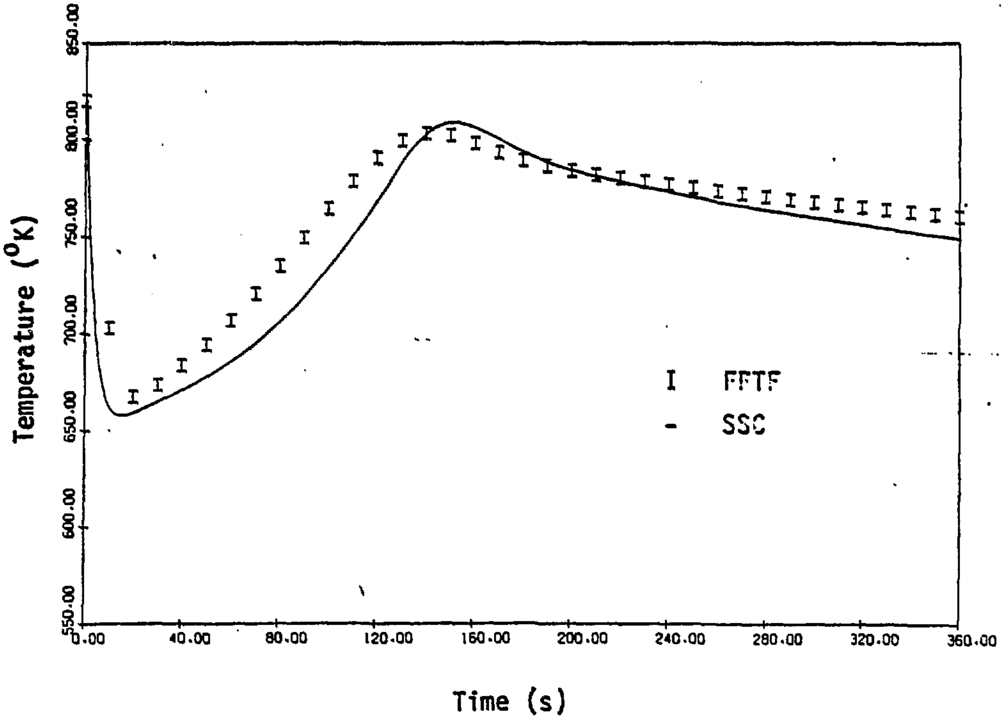

FIGURE 2: COMPARISON OF FFTF TEST DATA AND SSC CALCULATION FOR THE ROW 2 FOTA AVERAGE COOLANT TEMPERATURE AT THE TOP OF FUEL LOCATION

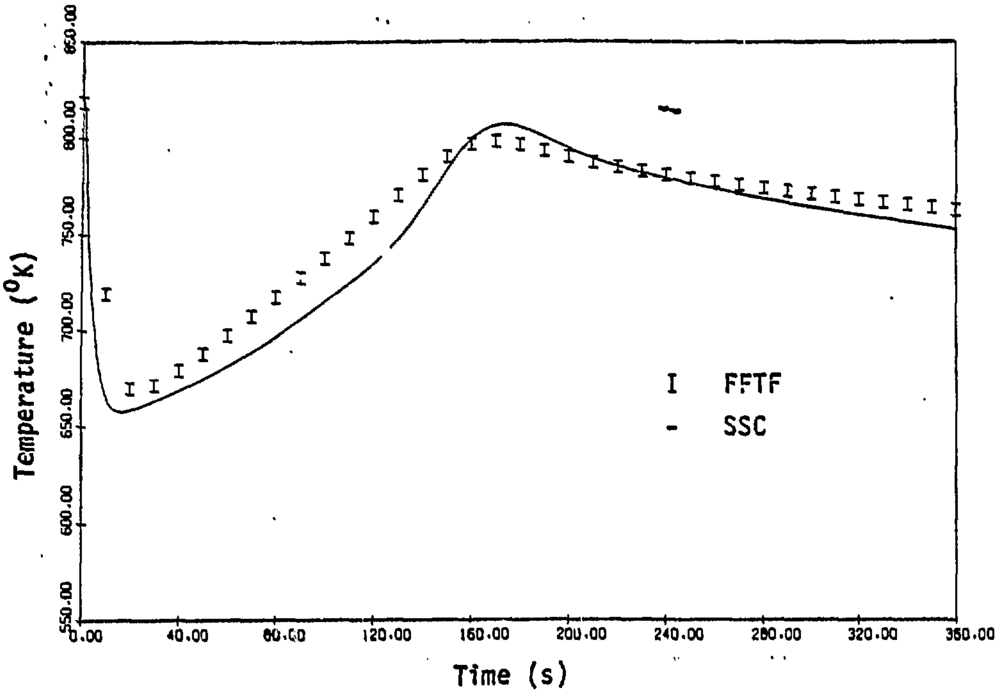

FIGURE 3: COMPARISON OF FFTF TEST DATA AND SSC CALCULATION FOR THE ROW 2 FOTA AVERAGE COOLANT TEMPERATURE AT THE TOP OF PIN LOCATION

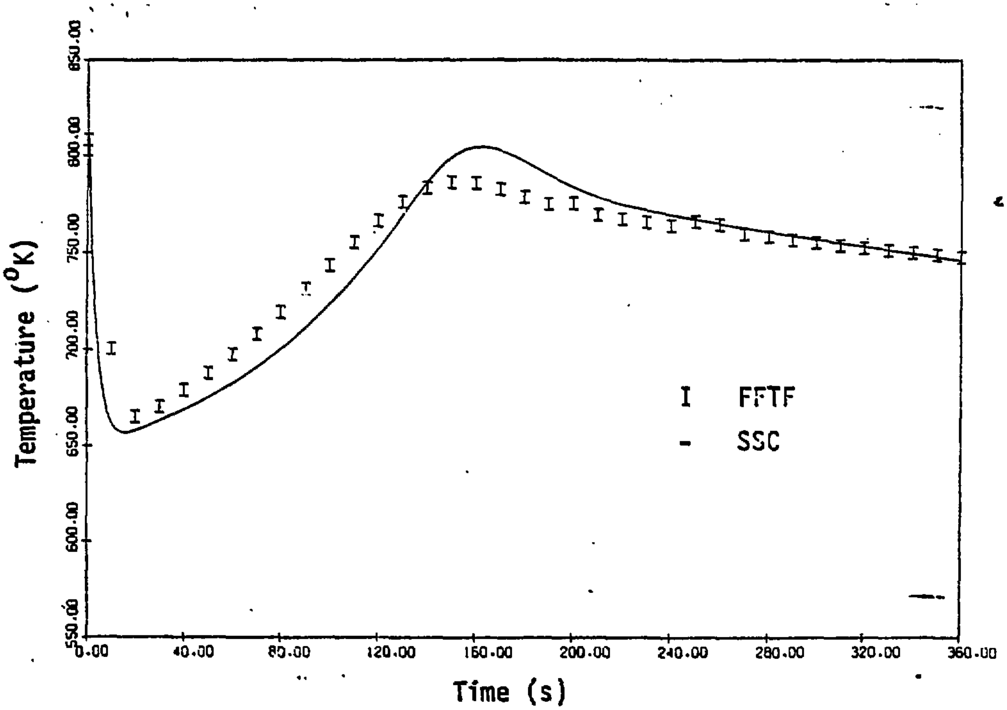

FIGURE 4: COMPARISON OF FFTF DATA AND SSC CALCULATION FOR THE ROW 6 FOTA AVERAGE COOLANT TEMPERATURE AT THE TOP OF FUEL LOCATION

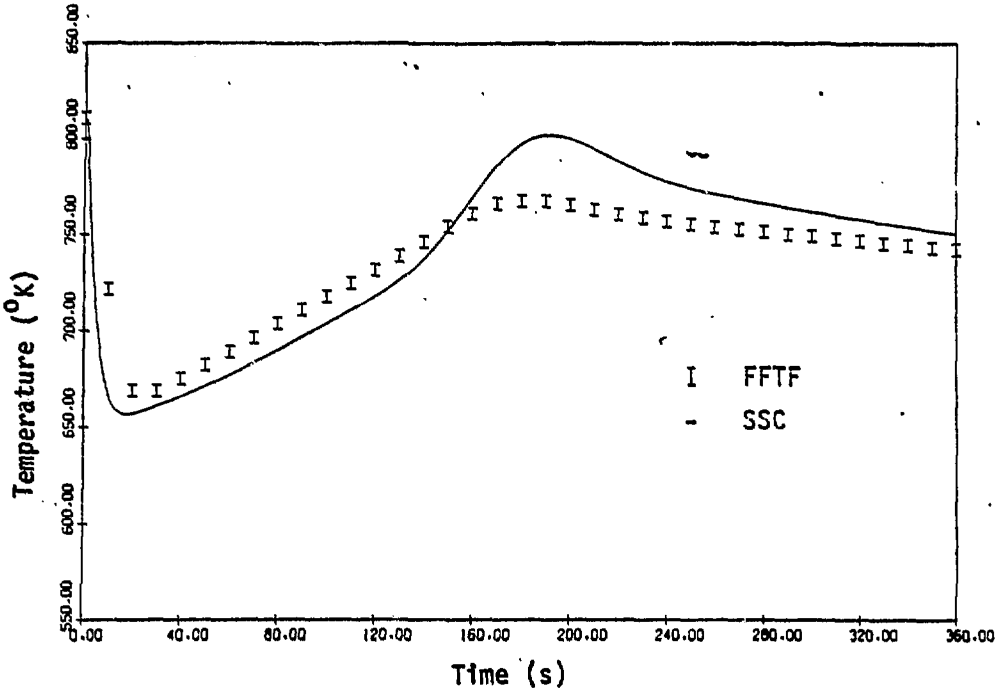

FIGURE 5: COMPARISON OF FFTF TEST DATA AND SSC CALCULATION FOR THE ROW 6 FOTA AVERAGE COOLANT TEMPERATURE AT THE TOP OF PIN LOCATION

Table 2 - FOTA Temperature Comparison Error Analysis

Maximum Negative Error	Absolute (^{o}K)[a]	Relative (%)[b]	Time(s)
Row 2 FOTA, top of fuel	41.	6.	10.
Row 2 FOTA, top of pin	54.	8.	10.
Row 6 FOTA, top of fuel	38.	6.	10.
Row 6 FOTA, top of pin	55.	8.	10.
Maximum Positive Error			
Row 2 FOTA, top of fuel	8.	1.	160.
Row 2 FOTA, top of pin	8.	1.	180.
Row 6 FOTA, top of fuel	20.	1.	170.
Row 6 FOTA, top of pin	34.	4.	190.
Average Error[c]			
Row 2 FOTA, top of fuel	3.	.4	-
Row 2 FOTA, top of pin	3.	.4	-
Row 6 FOTA, top of fuel	3.	.4	-
Row 6 FOTA, top of pin	4.	.6	-

a -- absolute error = $T^{FFTF}(^{o}K) - T^{o}K)$
b -- relative error = $[(T^{FFTF}(^{o}K)-T(^{o}K))/T^{FFTF}(^{o}K)] \times 100\%$
c -- averaged over the first 300 (s) of the transient

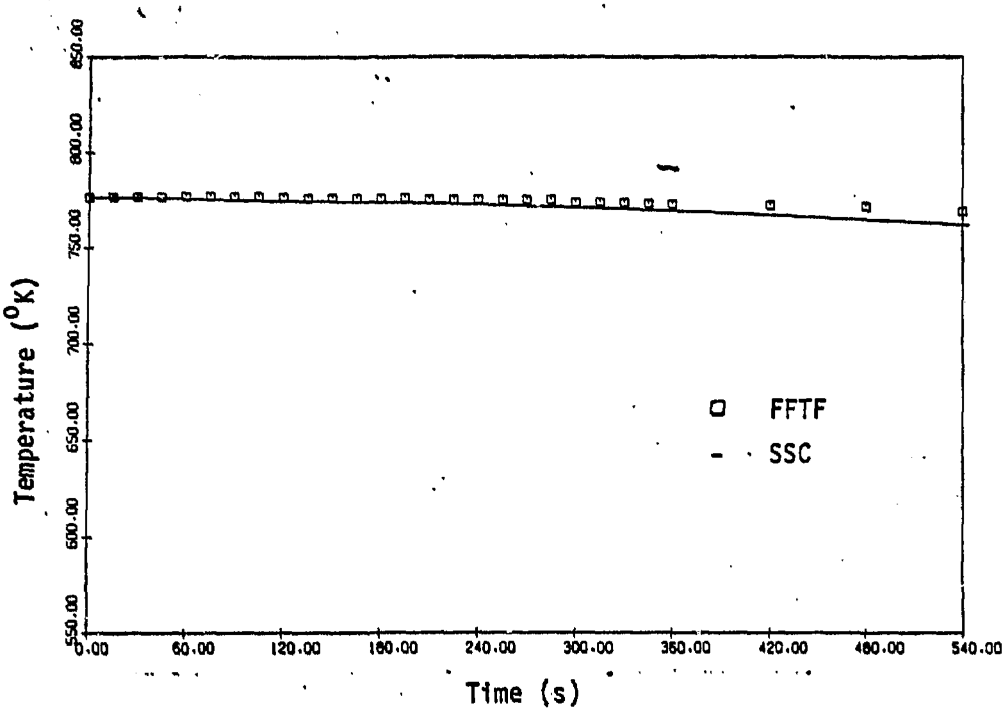

FIGURE 6: COMPARISON OF FFTF TEST DATA AND SSC CALCULATION FOR THE PRIMARY LOOP HOT LEG TEMPERATURE

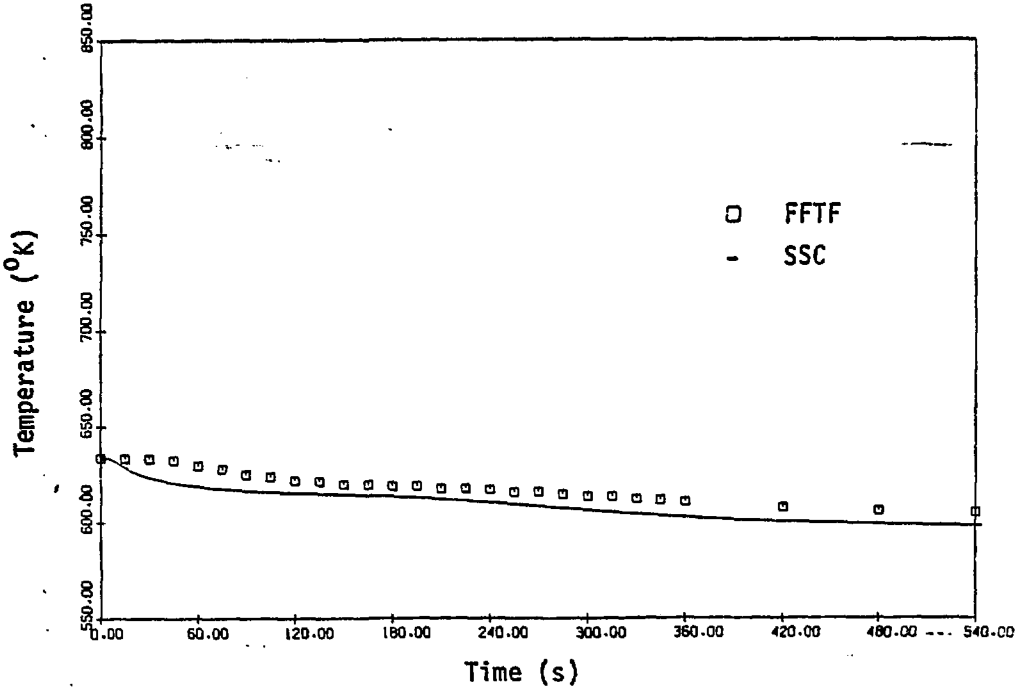

FIGURE 7: COMPARISON OF FFTF TEST DATA AND SSC CALCULATION FOR THE PRIMARY COLD LEG TEMPERATURE

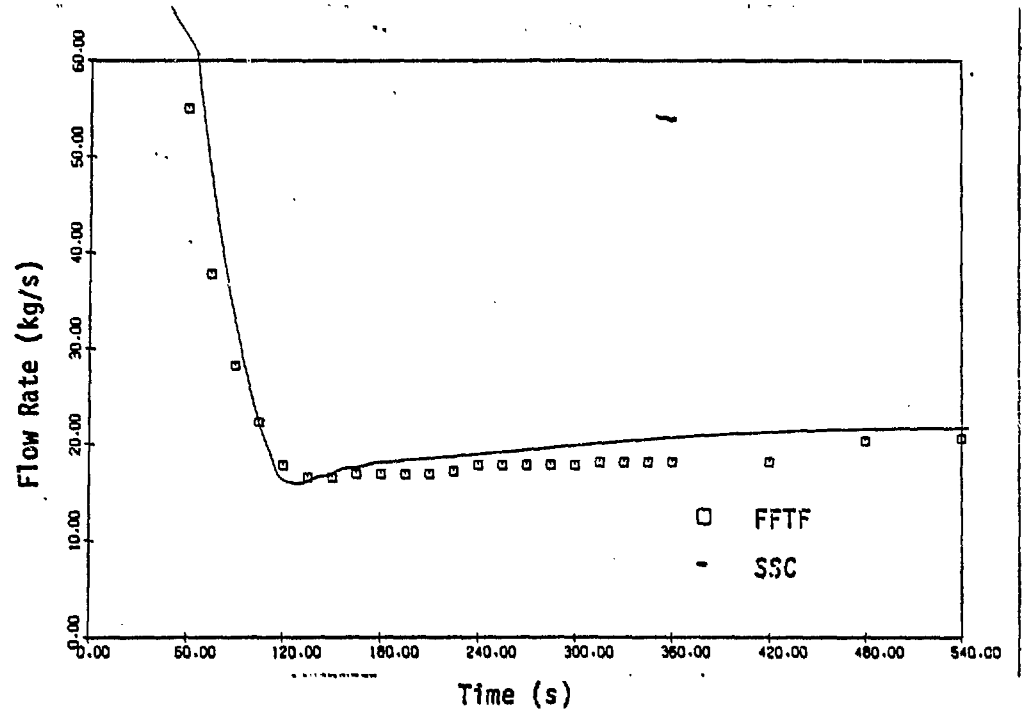

FIGURE 8: COMPARISON OF FFTF TEST DATA AND SSC CALCULATION FOR THE PRIMARY LOOP FLOW RATE

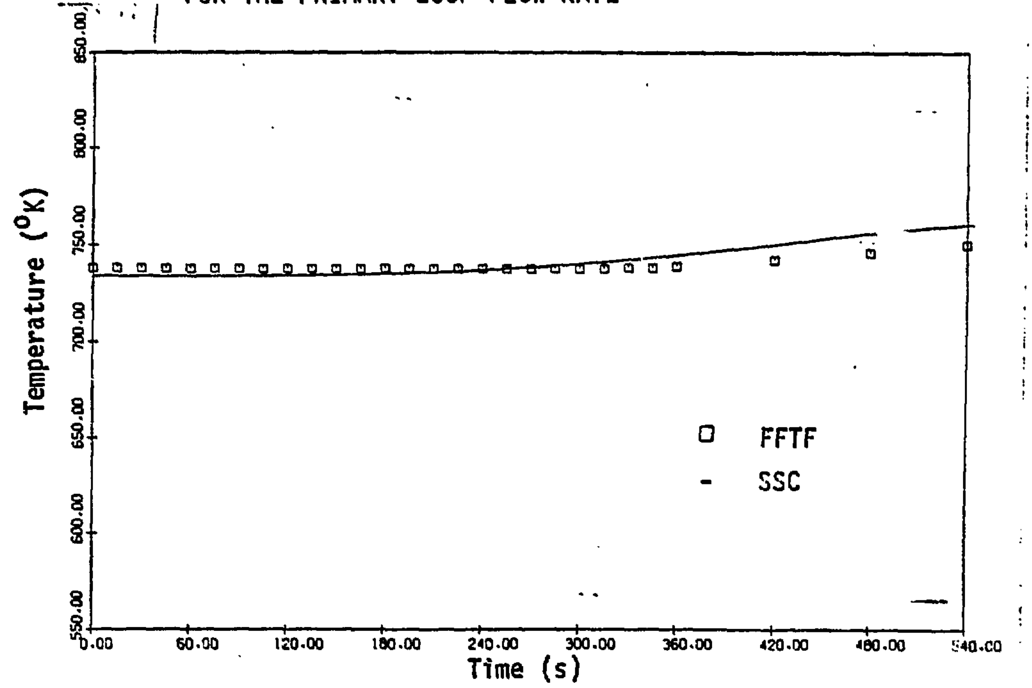

FIGURE 9: COMPARISON OF FFTF TEST DATA ANS SSC CALCULATION FOR SECONDARY LOOP HOT LEG TEMPERATURE

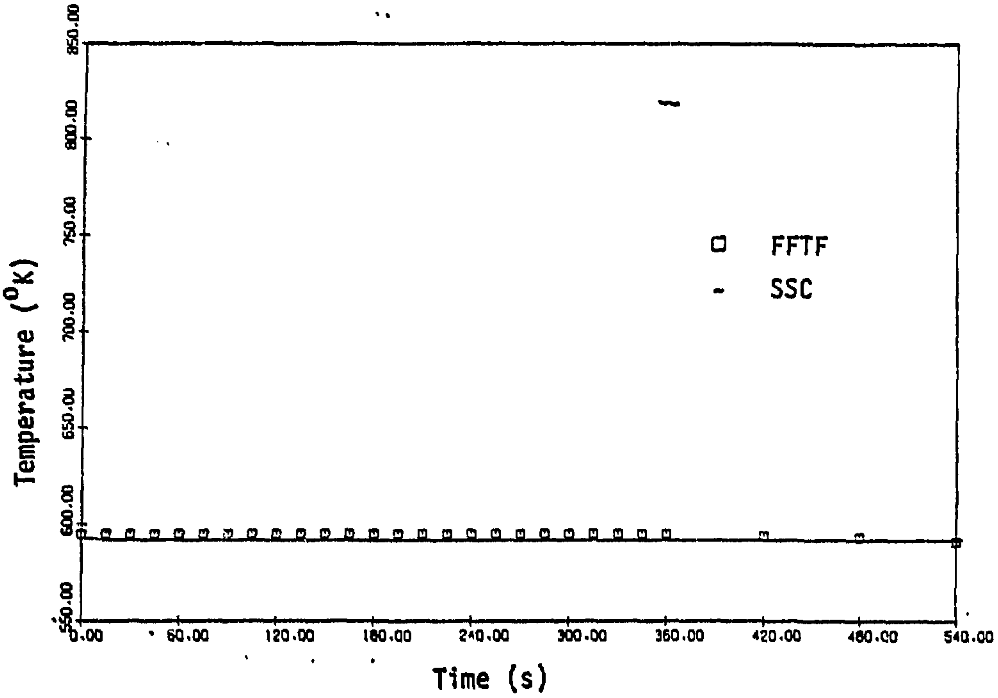

FIGURE 10: COMPARISON OF FFTF TEST DATA AND SSC CALCULATION FOR THE SECONDARY LOOP COLD LEG TEMPERATURE

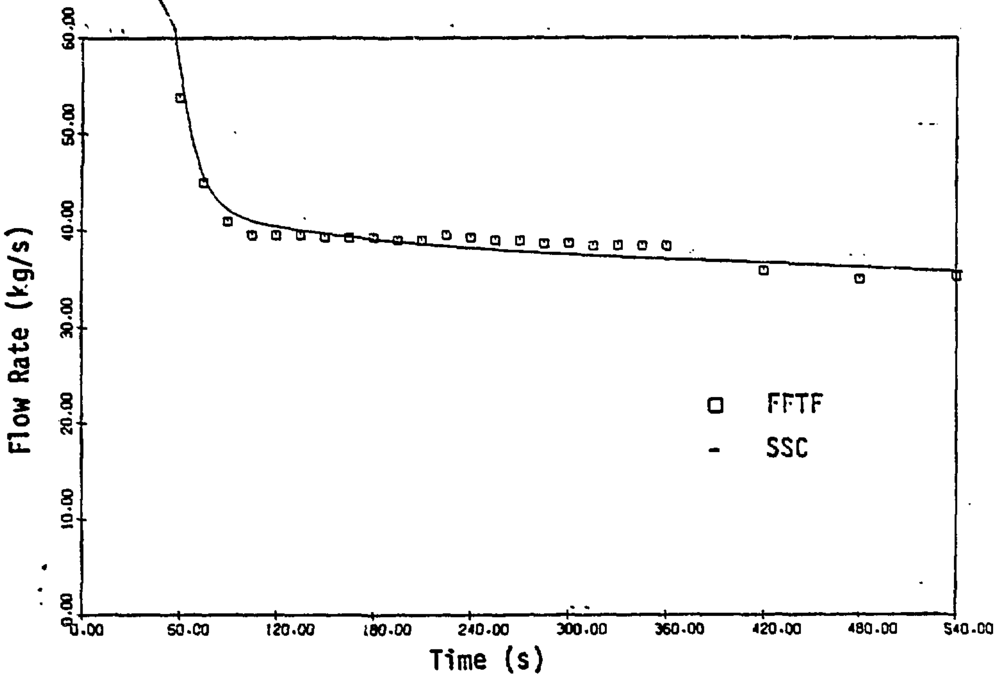

FIGURE 11: COMPARISON OF FFTF TEST DATA AND SSC CALCULATION FOR THE SECONDARY LOOP FLOW RATE

4. Conclusion

As part of the SSC validation program, the FFTF 100% power natural test was simulated using SSC. The FFTF test data and SSC calculations were found to be in good agreement. While the limited in-core instrumentation prevented a complete validation of the in-vessel energy transfer module of SSC, the FOTA data comparisons show that the flow redistribution model and heat transfer model are accurate in at least those two assemblies. The comparisons of loop parameters provide experimental validation of earlier numerical studies. It should be noted that even though a detailed 19 channel, 2 loop model was used in SSC, simulation in real time was achieved.

Further studies using FFTF experimental data include a long term (∿1 hr) simulation of the 100% and 75% power tests. Aysmmetric heat transfer through the loops will also be studied.

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