Conf-920903--12

ANL/CP--74685

DE92 019588

INTEGRATED INTRA-SUBASSEMBLY TREATMENT IN THE SASSYS-1 LMR SYSTEMS ANALYSIS CODE*

by

Floyd Dunn
Argonne National Laboratory

for presentation at the
Fifth International Topical Meeting
on
Nuclear Reactor Thermal Hydraulics
NUREH-5

September 21-24, 1992
Salt Lake City, Utah

* Work supported by the U.S. Department of Energy, Nuclear Programs under Contract W-31-109-ENG-38.

INTEGRATED INTRA-SUBASSEMBLY TREATMENT IN THE SASSYS-1 LMR SYSTEMS ANALYSIS CODE

by Floyd Dunn

Argonne National Laboratory

ABSTRACT

A hot channel treatment has been added to the SASSYS-1 LMR systems analysis code by providing for a multiple pin treatment of each of one or more subassemblies. This is an explicit calculation of intra-subassembly effects, not a hot-channel adjustment to a calculated average channel. Thus, the code can account for effects such as transient flow redistribution, both within a subassembly and among subassemblies. The code now provides a total integrated thermal hydraulic treatment including a multiple pin treatment within subassemblies, a multi-channel treatment of the whole core, and models for the primary coolant loops, the intermediate coolant loops, the steam generators, and the balance of plant. Currently the multiple-pin option is only implemented for single-phase calculations. It is not applicable after the onset of boiling or pin disruption. The new multiple pin treatment is being verified with detailed temperature data from instrumented subassemblies in EBR-II, both steady-state and transient, with special emphasis on passive safety tests such as SHRT-45. For the SHRT-45 test, excellent agreement is obtained between code predictions and experimental measurements of coolant temperatures.

INTRODUCTION

The SASSYS-1 code[1] is an integrated LMR (Liquid Metal Reactor) systems analysis code. It includes a point kinetics treatment for core neutronics and reactivity feedback. It also includes a thermal hydraulic treatment of the core, the primary coolant system, and the intermediate coolant loops, coupled to a steam generator model[2] and a balance-of-plant model[3,4]. In addition, the code contains a control system model[5]. The SASSYS-1 code can handle any LMR design, loop or pool, with an arbitrary arrangement of components. The code is capable of analyzing a wide range of transients, from mild operational transients through more severe transients leading to sodium boiling in the core and possible melting of cladding and fuel. The main applications of the code have been in the analysis of passive safety and the analysis of shut-down heat removal.

SASSYS-1 uses a multi-channel treatment to represent the reactor core. A channel models one pin, its associated coolant, and a structure which represents the wrapper wire and/or the subassembly duct wall. The whole length of the subassembly from coolant inlet to coolant outlet is modeled, including the pin section and reflector regions above and below the pins. The pin section includes the core and the axial blankets, as well as a gas plenum region. An axial mesh is used for a channel. At each axial node one coolant temperature is calculated. Also at each axial node two radial temperature nodes are used for the structure and a number of radial nodes are used for the pin or the axial reflector. Previously, SASSYS-1 used one channel to represent a subassembly or a group of similar subassemblies. The multi-channel treatment provided a means to represent different subassemblies with different power levels, flow rates, and fuel burn-ups. Usually an average pin was modelled for each group of subassemblies. Thus, detailed average temperatures were calculated for various subassemblies, but peaking within a subassembly was not calculated. The new multiple pin treatment was added to the code to account for pin-to-pin variations within a subassembly.

MULTIPLE PIN MODEL DESCRIPTION

The new multiple pin treatment allows a number of coupled channels to be used to model a single subassembly. Thus a channel can represent a part of a subassembly instead of the whole subassembly. Peaking factors can be mechanistically calculated by reducing coolant flow areas and flow rates or increasing pin power levels in some channels.

Physical Model

In the new multiple pin option, the regions above and below the pin section of a subassembly are still represented by a single channel; but up to nine channels can be used to represent the pin section. Each channel in the pin section can represent one or more concentric rows of pins and their associated coolant. It is also possible for channels to represent slices of pins for a subassembly with a strong lateral power skew or for one with a hot subassembly on one side and a cool subassembly on the opposite side. Figure 1 illustrates one way that a number of channels can be used to model the pin section of a subassembly as concentric rings of pins and coolant

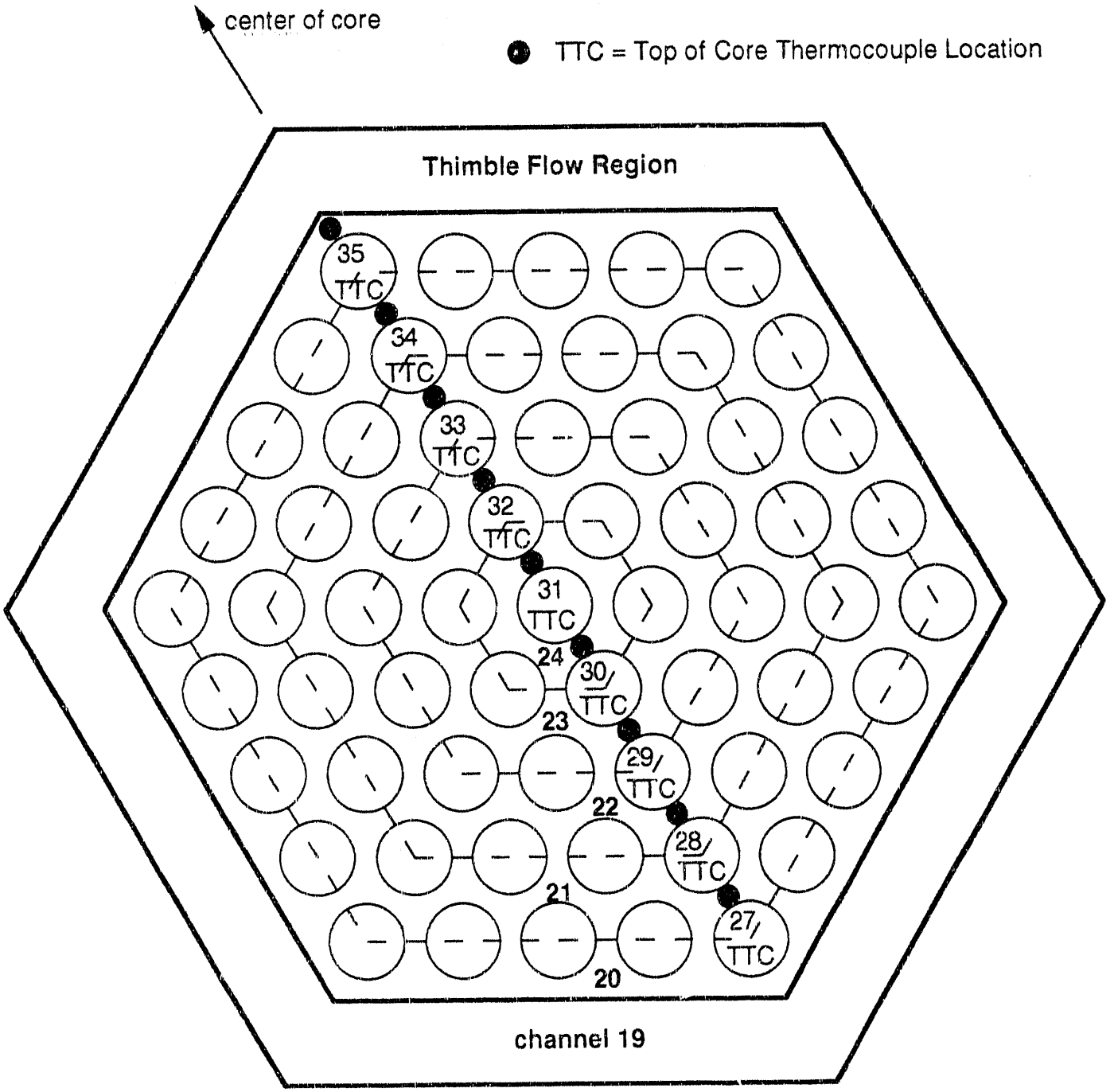

Fig. 1, SASSYS-1 Multi-Channel Representation and Thermocouple Locations for the EBR-II XX09 Instrumented Subassembly

subchannels. The thimble flow region in this figure is a feature of the EBR-II XX09 instrumented subassembly and is not found in ordinary subassemblies. This case concentrates on the coolant subchannels and splits the pins. It is also possible to shift the channel boundaries half a pin and use a pin-based representation with intact pins and split coolant subchannels.

The new option accounts for coolant-to-coolant heat transfer between adjacent channels, including the effects of both conduction and turbulent mixing. It also accounts for subassembly-to-subassembly heat transfer from the duct wall of a subassembly, through the interstitial sodium, to the duct wall of a neighboring subassembly. In addition, axial conduction in the coolant is accounted for.

Figure 2 illustrates the axial representation of the subassembly flow, with parallel flow paths through the pin section. Each channel used to represent the pin section of a subassembly has its own separate time-dependent flow rate, and the flow rates in all channels in a subassembly are driven by common pressures at the inlet and outlet of the pin section. Thus, transient flow redistribution among channels is accounted for. The single flow rate in the regions above and below the pin section is the sum of the pin section flow rates, so the subassembly flow orifice sees the correct total flow rate. Even though the coolant-to-coolant heat transfer coefficient includes a term for turbulent mixing between coolant subchannels, one effect that the flow calculation does not account for is mass flow between channels in the pin section, although cross-flow at the ends of the pin section is allowed. Therefore, if recirculation loops occur within a subassembly at low flows, the model would calculate them; but the recirculation loops would go to the ends of the pin section.

In the new model the coolant in channel i can transfer heat directly to the coolant in channel i-1 and channel i+1. Using correlations of the same form as those used in the THI3D code[6] and the HOTCHAN code[7], the channel-to-channel heat flow per pin per unit height from channel i to channel i+1 is calculated as:

$$Q_{i,i+1} = \left[U_1 \bar{k} + U_2 \ \bar{C} \ (w_i + w_{i+1})\right] (T_i - T_{i+1}) \qquad (1)$$

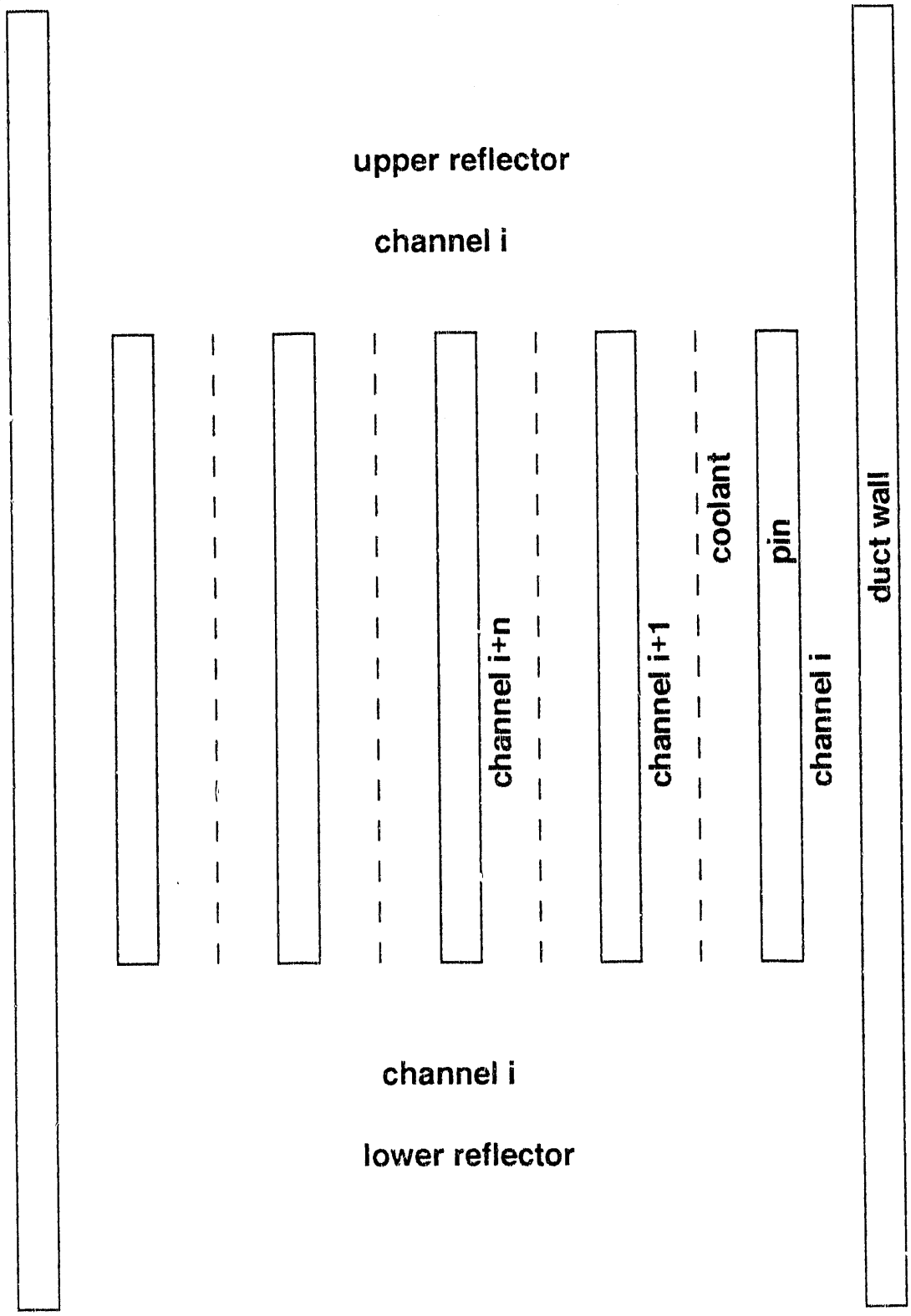

Fig. 2, SASSYS-1 Multiple Pin Treatment of a Subassembly

where

$\bar{k}$ = average thermal conductivity of the coolant

$\bar{C}$ = average specific heat

w_i = coolant mass flow per pin (kg/s) in channel i,

and

T_i = coolant temperature

In this equation U_1 is a geometry factor for thermal conduction, and U_2 is a product of a turbulent-mixing coefficient and a geometry factor for turbulent mixing between channels. Since a SASSYS-1 channel usually models a group of coolant sub-channels, the values used for U_1 and U_2 must account for a combination of parallel and series heat flow paths between the middle of channel i and the middle of channel i+1. Subassembly-to-subassembly heat transfer is handled in a somewhat simpler manner. For heat transfer from the outer surface of the structure in channel i to the outer surface of the structure in channel j, a constant value is used for the product of the heat transfer coefficient and the heat transfer area per unit height.

Numerical Methods

Most of the transient heat transfer calculations and flow rate calculations in SASSYS-1 use semi-implicit time differencing in order to obtain stable and accurate solutions with reasonably long time steps. Before the onset of coolant boiling or pin disruption, time step sizes of a second or more are commonly used; and the code usually runs significantly faster than real time on a Cray XMP computer.

From a numerical computation point of view, the two main tasks in adding the multiple pin model to the code were the coolant-to-coolant heat transfer calculation and the coolant flow rate calculation with parallel flow paths in the pin section. Both of these calculations use semi-implicit time differencing. In the single-pin model, coolant temperatures for all of the

radial temperature nodes in the pin, coolant, and structure at one axial node are solved for simultaneously in order to obtain a semi-implicit time differencing solution without iteration. In the new multiple-pin treatment, this concept is carried one step further. At a given axial node, temperatures at all of the radial nodes for all channels representing a subassembly are solved for simultaneously. In the heat transfer calculations, the axial conduction terms, which are small, are treated with explicit forward time differencing so that axial nodes are decoupled and can be treated separately except for the coolant convection terms. The axial coupling due to the coolant convection terms is handled by starting at one end of the subassembly and solving for axial nodes one at a time in the direction of the flow. If flow has reversed in some channels but not in others, the calculation progresses in the direction of the dominant flow; and explicit forward differencing is used for the coolant convection terms in the non-dominant flow direction channels. The subassembly-to-subassembly heat fluxes are calculated with explicit forward differencing in time, and this does impose a stability limit on the time step size. For typical subassembly duct wall thicknesses, the explicit subassembly-to-subassembly heat flux calculation limits the maximum time step size to a value in the range from .25 to .5 seconds. For the coolant flow rate calculations, the incompressible flow momentum equations are linearized about conditions at the beginning of the time step. Then, flows at the end of the step are calculated for all channels in a subassembly simultaneously.

A null transient is used to obtain steady-state temperatures at the start of the regular transient. First all coolant, pin, structure, and reflector temperatures in all subassemblies are set to the coolant inlet temperature. Then, the power levels and coolant flow rates are held constant while a number of transient heat transfer time steps are made. Since the pin thermal time constant and the coolant transit time through a subassembly are both less than a second, the null transient results converge rapidly if reasonably large time steps are used.

EXPERIMENTAL VERIFICATION

A series of thermal-hydraulics tests[8] has been performed in EBR-II (Experimental Breeder Reactor-II) to demonstrate that a properly designed LMR with metal fuel can survive a number of anticipated transients without scram[9]. One of these tests[10], the SHRT-45 (Shut-down Heat

Removal Test-45) was a loss-of-primary-flow-without-scram from full power and full flow. This test was picked to use for verification of the new multiple pin model for a number of reasons. First, this is the type of transient that SASSYS-1 was designed for and is often used for. Second, detailed temperature data is available for this test from thermocouples in the coolant in the XX09 instrumented subassembly. Third, this was the most severe of the loss-of-flow-without-scram tests run in EBR-II.

SHRT-45 Test Description and Calculational Model

The SASSYS-1 model for this test included a multi-channel core description with emphasis on the details of the XX09 instrumented subassembly, a detailed thermal hydraulic model for the primary coolant system, a detailed thermal hydraulic model for the intermediate heat transport system, and a simple steam generator model. Nothing beyond the steam generators was modeled, and even the steam generators had very little influence on the core during the time scale of interest in this test. On the other hand, the primary coolant system behavior was important in this test; and one important aspect was the behavior of the two primary loop centrifugal pumps which drove the coolant through the core in the earlier part of the transient. In the later part of the transient the pumps had stopped, and primary loop natural circulation heads were dominant. The centrifugal pump model used in these calculations was the homologous pump model described in reference 11, based on the work of Wylie and Streeter[12,13].

The whole core was represented in the calculational model. Eight channels were used for single pin treatments of the bulk of the driver subassemblies, the control rod channels, the stainless steel reflector subassemblies, and some low power irradiation experimental subassemblies that were in the core. In addition, two channels were used for single pin representations of XX09 and another instrumented subassembly, XX10. Some of the subassemblies neighboring XX09 were similar enough in power and flow to be lumped together, so eight channels were used for two-pin representations of each of four neighboring subassemblies. For each of the neighboring subassemblies, one channel was used to represent the outer coolant and pins near XX09, and the other channel was used for the rest of the

subassembly. Six channels were used for a multiple pin representation of XX09.

The XX09 instrumented subassembly[14] is a 61 element subassembly containing 59 Mark II fuel elements and two conduit tubes. The conduits provide a passage through the core for thermocouple leads. Twenty-two of the fuel elements have their standard spacer wires replaced by spacer wire thermocouples, providing temperature measurements at various elevations. XX09 simulates a driver subassembly. It is almost identical to a Mark II driver subassembly, except in XX09 the outer row of fuel pins is replaced by an extra hex can wall and a thimble flow region.

Figure 1 shows the SASSYS-1 channel model used to treat XX09 for these calculations. This figure also shows the locations of a row of spacer wire thermocouples running from corner to corner at the top of the core. The readings from these thermocouples were used for comparison with calculated temperatures. The SASSYS-1 channels model concentric rows of coolant channels, and the thermocouples are located in the centers of these rows.

Outside of the subassembly wall there is a thimble flow region separating the subassembly wall from an outer thimble wall. This region is filled with coolant, and there is a small flow rate through the region. A separate SASSYS-1 channel (channel 19) is used to model the thimble flow region. This region required special modeling in SASSYS-1. There are no fuel pins in the thimble flow region, but SASSYS-1 puts a pin in each channel. Therefore, the pin in channel 19 was made very small, with negligible heat capacity and no power. The heat flow from the outside of the subassembly wall to the thimble flow region was a special problem. The structure in channel 20 models the subassembly wall, so the multiple pin model was modified to allow for heat transfer directly from the outer structure node of one channel (channel 20) to the coolant of another channel (channel 19). The structure of channel 19 represents the thimble wall. Subassembly-to-subassembly heat flow was modeled from this wall to the neighboring subassemblies.

Table 1 lists some of the channel parameters used in the SASSYS-1 model for XX09.

Table 1. Parameters Used to Model XX09

Channel	Number of Pins	Coolant Flow Area per Pin (m^2)	Initial Coolant Flow Rate per Pin (kg/s)	Coolant-to-Coolant Heat Transfer Parameters	
				U_1	U_2
19	1	6.9640×10^{-4}	.467	--	--
20	13	2.3080×10^{-5}	.07419	1.04	1.785
21	21	1.1583×10^{-5}	.03313	.41	.872
22	15	1.1583×10^{-5}	.03313	.36	.756
23	9	1.1583×10^{-5}	.03313	.34	.734
24	3	1.1192×10^{-5}	.03123	--	--

The nominal size of the hex can is slightly larger than the size needed to accommodate the pin bundle with a pitch determined by the nominal values for the pin diameter and the spacer wire, leaving a slight amount of extra room in the subassembly. For these calculations, it was assumed that the center 7 pins were spaced as tight as the spacer wire would allow, and the extra space was distributed evenly over the rest of the subassembly. For the thermal conduction part of the coolant-to-coolant heat transfer coefficients, an empirical shape factor correlation by Fukuda[15] was used to obtain the shape factors for heat transfer between adjacent coolant subchannels. The correlation is:

$$U_1 = 1.38\ (S/D)^{.674} \tag{2}$$

where

S = spacing between pins

and

D = pin diameter.

The subchannel values had to be added in parallel and in series to obtain overall channel values. Also, a small correction was made to the thermal conduction terms to account for heat conduction through the pins. For the turbulent mixing term, the heat transfer coefficient between neighboring coolant subchannels was calculated as:

$$U_2 = \frac{C_T\, S}{A_i + A_{i+1}}$$

where

C_T = turbulent mixing coefficient

and

A_i = coolant flow area in channel i.

For these calculations, a value of .03 was used for the turbulent mixing coefficient, C_T. Again subchannel values had to be added in parallel and in series to obtain overall channel values.

Since the purpose of these calculations was to verify the multiple pin thermal hydraulic model, reactivity feedback was not calculated. Instead, the power level was specified as a function of time during the transient, using the measured fission power and a computed decay heat power. The decay heat was calculated from the ANSI light water reactor standard[16] using the irradiation history for the core loading.

Results

Figure 3 shows the normalized power history used in these calculations, as well as the computed normalized total flow for XX09. The pumps trip and start coasting down at time zero. Pump 1 stops at 100.6 seconds, and pump 2 stops at 91.9 seconds. Figure 4 shows the resulting coolant temperatures at the top of the core in XX09. The peak calculated temperature is for channel 24. The peak measured value is an average of the values for TTC30 and TTC31. The average values are weighted values, weighted by the number of pins per channel in the SASSYS-1 model. The agreement between measured and calculated values is remarkably good.

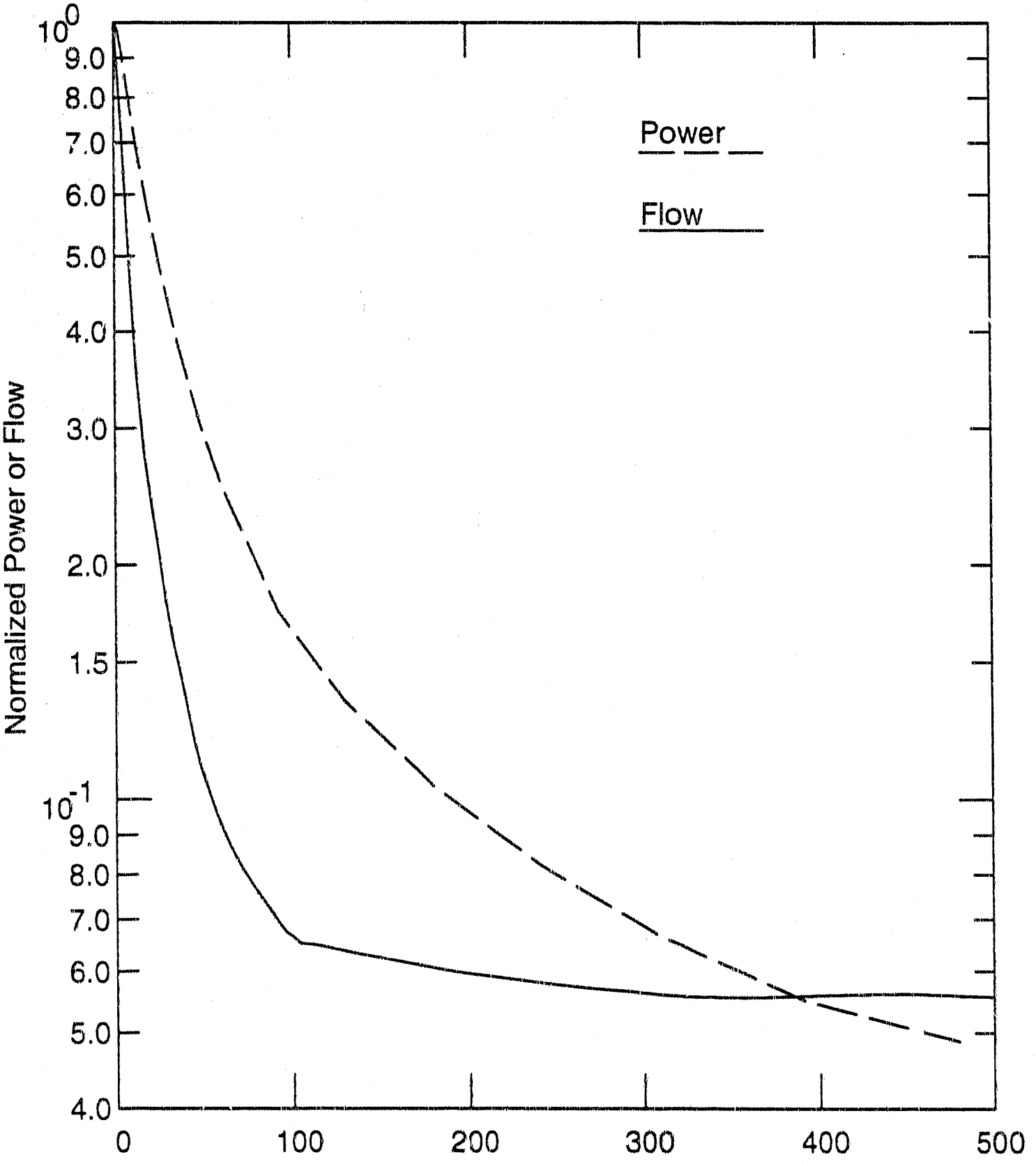

Fig. 3, SHRT45 Power and Flow

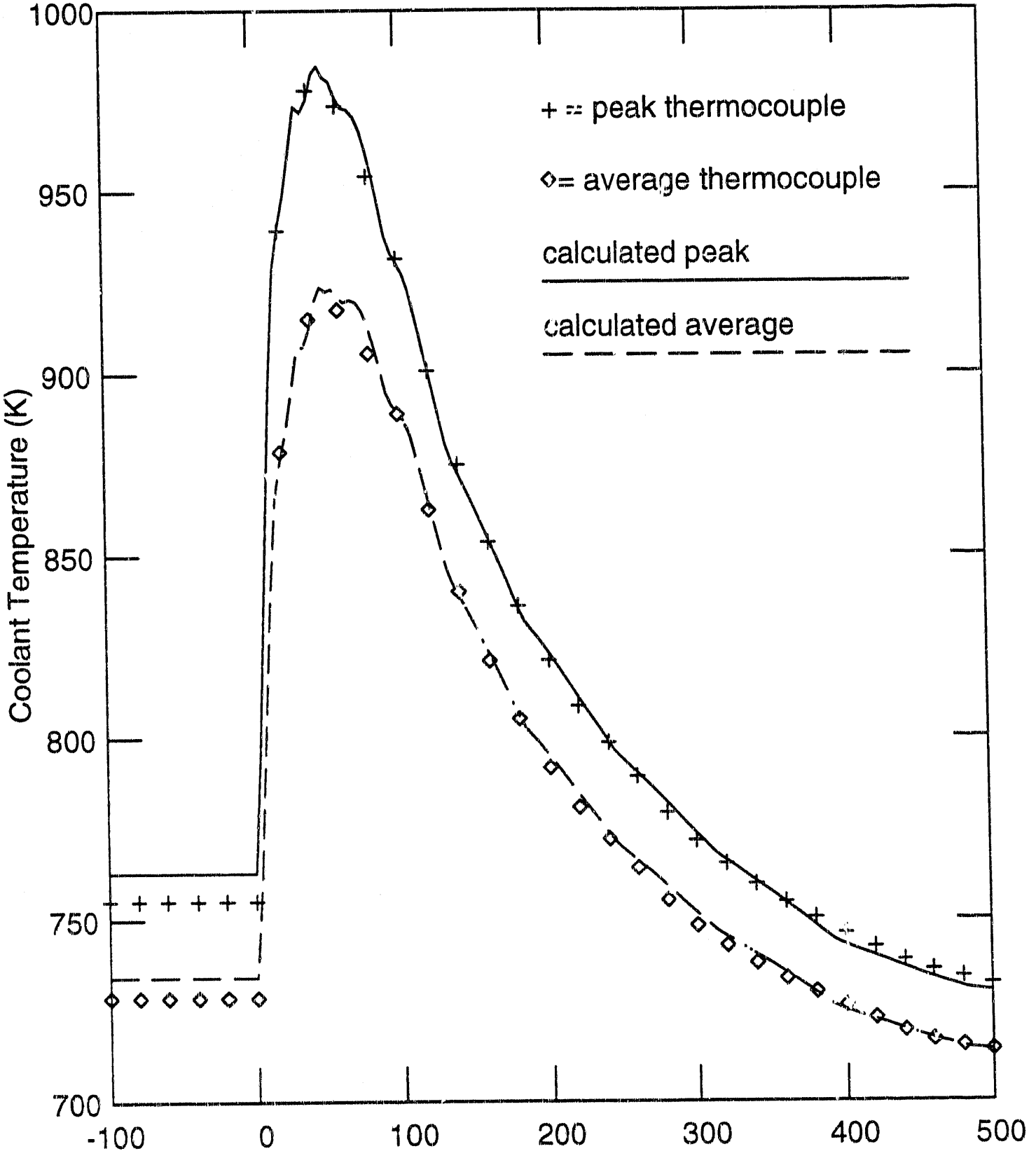

Fig. 4, SHRT45 Top of Core XX09 Coolant Temperatures

Figure 5 shows the computed transient flow redistribution for the center channel (channel 24). As the flow drops during the transient, buoyancy effects become more important, and the flow in the hotter center channel increases relative to the average. The coolant temperature peaks at about 40 seconds, whereas the flow redistribution does not peak until the pumps stop at 90-100 seconds. At 40 seconds, flow redistribution added only about 4.4% to the center channel flow, corresponding to a change of about 15 K in peak temperature. At 90 seconds, the change in center channel flow was about 7.9%, corresponding to a change of about 26 K in peak temperature.

Assessment of Results

The two main aspects of computing accurate temperatures for a case like this are getting the time-dependent average temperature right and getting the correct peak-to-average temperature difference. The peak-to-average temperature difference is determined mainly by the transient channel-to-channel flow distribution and the channel-to-channel heat transfer coefficients. On the other hand, the average temperature is determined mainly by the power level, the average coolant flow rate, and the heat flow to the thimble flow region and to neighboring subassemblies. In turn, the average coolant flow rate is determined mainly by the pressure drop vs. flow characteristics of the subassembly and by the pump head vs. flow and speed characteristics of the primary pumps, as well as the total coolant flow through the pumps. In the later parts of the transient, gravity heads in the whole primary system also have a large effect on coolant flows. Note that the earlier parts of this transient involve forced convection and turbulent flow, whereas the later parts involve natural circulation and laminar flow. In order to obtain the good agreement between measured and computed temperatures indicated in figure 4, all of these factors must be computed fairly accurately. Thus, these calculations provided a test of not only the new multiple pin model, but also of the overall thermal hydraulic modeling of the whole primary coolant system.

MODEL ASSESSMENT

This new multiple pin model has some large advantages, as well as some definite limitations.

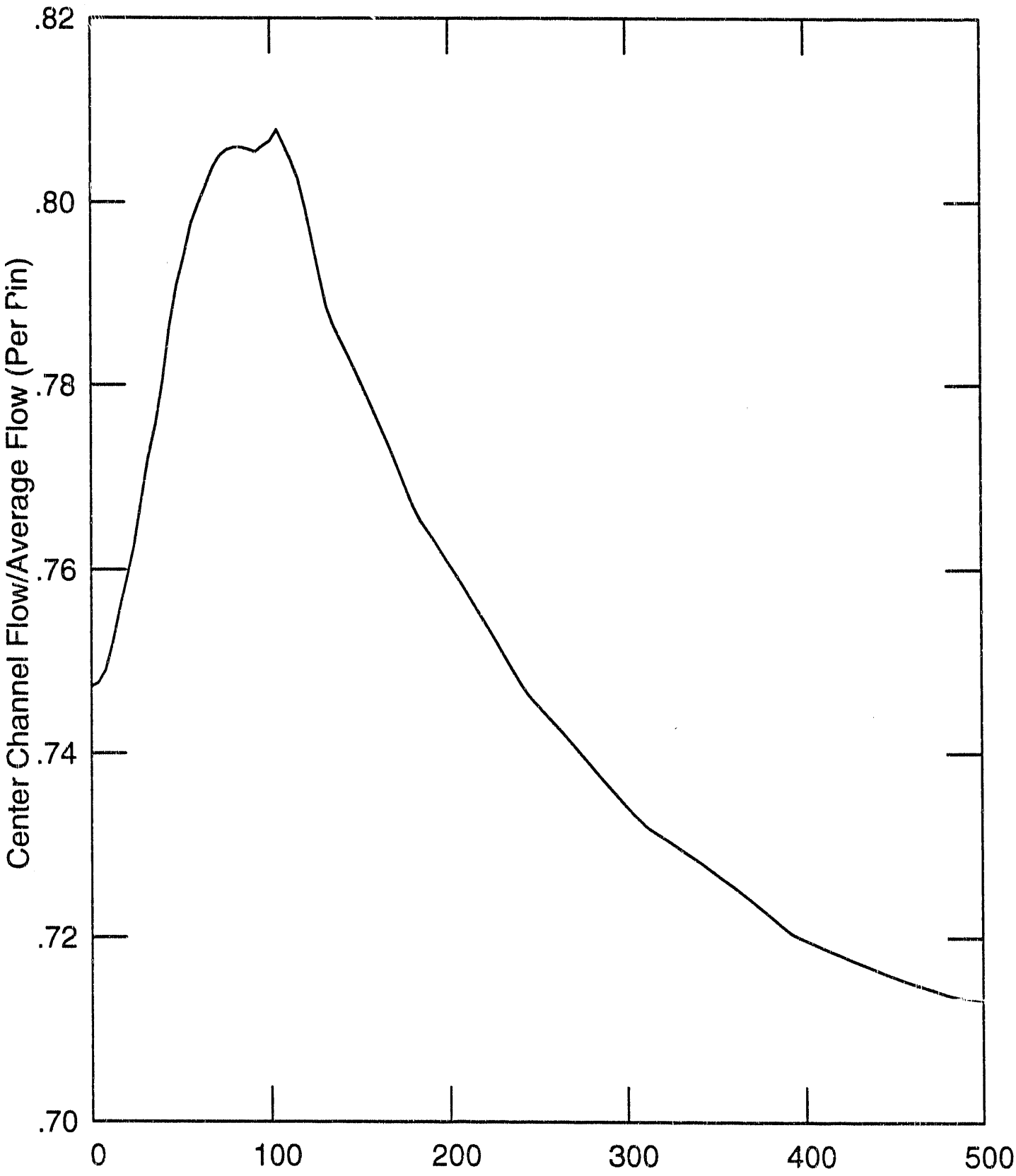

Fig. 5, SHRT45 Transient Flow Redistribution

One limitation is that it is basically a two dimensional (r-z) model. A good analysis of a subassembly with a strong side-to-side power skew plus the normal overcooling of the edge pins would probably require a model in which coolant in channel i communicates with more than just channels i-1 and i+1. Such a capability may be added to the code in the future. Another limitation is that since there is no cross-flow between channels in the pin section, it can not analyze an internal flow blockage. An important limitation of this model is that it only handles single phase coolant and no pin failure or pin disruption. Thus, it can not handle either severe accidents or the analysis of voiding due to gas release from pin failures as described in reference 17. Finally, the explicit forward time differencing treatment of the subassembly-to-subassembly heat transfer and the heat transfer to the thimble flow region limit the maximum time step size that can be used, and thereby limit the computational speed. For the SHRT-45 analysis, a time step size of .2 seconds was used; whereas time steps of 1 second or larger are often used for SASSYS-1 runs; and time steps as large as 16 seconds have been used. If the detailed steam generator model is used, the time step size used for the core channel analysis does not matter very much; since the detailed steam generator calculations and possibly some of the balance-of-plant calculations can dominate the computation time. On the other hand, SASSYS-1 cases, including this one, are often run with a simple steam generator model; and then the core channel time step size determines the computation time. The SHRT-45 case ran 1.5 times as fast as real time on a Cray XMP computer, whereas the SASSYS-1 shut-down heat removal case reported in reference 18 ran 180 times as fast as real time on the same computer. Since shut-down heat removal cases sometimes involve transients lasting for days, a very rapid computational speed is desirable for such cases. If such cases are to be run routinely with subassembly-to-subassembly heat transfer in SASSYS-1, then the code will probably have to be modified to solve for temperatures in all interacting subassemblies simultaneously. Note that this time step limitation does not apply to the multiple pin treatment within a subassembly; only the subassembly-to-subassembly or the subassembly-to-thimble flow region calculations are numerically unstable with large time step sizes.

The new multiple pin model has some tremendous advantages. It allows SASSYS-1 to calculate accurate time dependent peak temperatures mechanistically in addition to the average temperatures the code previously calculated. For many uses, peak temperatures are of more

interest than average temperatures. Another advantage is that the peak temperature calculation is part of an integrated, single code approach to the whole problem. Also, even with the time step limitations imposed by the subassembly-to-subassembly heat transfer calculations, the multiple pin analysis still runs fast enough to be used for routine analysis in most cases. Finally, a very important consideration is that the detail provided by the multiple pin model makes it possible to make detailed comparisons with experimental data at a level never before possible with the code. Previously, a temperature calculated for an average pin could be compared with thermocouple data; but the fact that the computed data fell somewhere within the range of the various thermocouples could mask significant model limitations. Being able to calculate the temperatures seen by individual thermocouples gives a much better indication of the adequacy of the modeling. Also, having the total calculation in a single integrated code provides much better model validation than having the hot channel analysis in one code and the rest of the analysis in one or two other codes. Discrepancies between calculated and measured values can not be blamed on errors in another code or on inadequate coupling between codes. On the other hand, errors in other codes or inadequate coupling between codes do not confuse the issue and indicate poor agreement in cases where the hot channel analysis itself is adequate. Thus, an integrated treatment allows one to concentrate on the real modeling issues. Another aspect of model validation or verification is that even with subassembly-to-subassembly heat transfer, the code runs fast enough that for a given experiment it is feasible to run many calculations exploring the influence of variations in model parameters or the use of different models.

CONCLUSIONS

A multiple pin treatment has been added to SASSYS-1 in order to calculate pin-to-pin and coolant subchannel-to-coolant subchannel temperature distributions. Computed transient peak and average coolant temperatures agree well with XX09 thermocouple data from the SHRT-45 test in EBR-II; indicating that not only are the intra-subasembly effects handled well, but the whole primary coolant system is modeled well. The new multiple pin treatment provides a way to compute accurate time-dependent peak temperatures within the framework of a single unified code. The new treatment also makes possible exact comparisons with detailed experimental data.

ACKNOWLEDGEMENTS

This work was supported by the U.S. Department of Energy, Nuclear Energy Programs under Contract W-31-109-ENG-38. Also, the author wishes to thank Earl Feldman and Dale Mohr, who provided the experimental data from the SHRT-45 test, as well as numerous discussions about EBR-II in general and the test in particular.

REFERENCES

1. F. E. Dunn, F. G. Prohammer, D. P. Weber, and R. B. Vilim, "The SASSYS-1 LMFBR Systems Analysis Code," ANS International Topical Meeting on Fast Reactor Safety, Knoxville, TN, pp. 999-1006 (April 1985).

2. P. A. Pizzica, "An Improved Steam Generator Model for the SASSYS Code," Trans. Am. Nucl. Soc., 60, 712 (1989).

3. Laural L. Briggs, "A New Balance-of-Plant Model for the SASSYS-1 LMR Systems Analysis Code," Trans. Am. Nucl. Soc., 60, 709 (1989).

4. J. Y. Ku, "SASSYS-1 Balance-of-Plant Component Models for an Integrated Plant Response," Trans. Am. Nucl. Soc., 60, 716 (1989).

5. R. B. Vilim, T. Y. C. Wei, and F. E. Dunn, "Generalized Control System Modeling for Liquid-Metal Reactors," Nucl. Sci. and Eng., 99, 183 (1988).

6. William T. Sha, Frank J. Goldner, Paul R. Huebotter, and Robert C. Schmitt, "Thermal Hydraulic Multichannel Analysis," Proceedings of the International Meeting on Reactor Heat Transfer, Karlsruhe, Germany, p. 180, October 9-11, (1973).

7. Dale Mohr, Lu-Kang Chang, and H. P. Planchon, "Validation of the HOTCHAN Code for Analyzing the EBR-II Core Following an Unprotected Loss of Flow", Trans. Am. Nucl. Soc., 57, 318, (1988).

8. H. P. Planchon, R. M. Singer, D. Mohr, E. E. Feldman, L. K. Chang, and P. R. Betten, "The Experimental Breeder Reactor II Inherent Shutdown and Heat Removal Tests - Results and Analysis," Nucl. Eng. and Design, 91, 287 (1986).

9. G. H. Golden, H. P. Planchon, J. J. Sackett, and R. M. Singer, "Evolution of Thermal Hydraulics Testing in EBR-II," Nucl. Eng. and Design, 101, 3 (1987).

10. D. Mohr, L. K. Chang, E. E. Feldman, P. R. Betten, and H. P. Planchon, "Loss-of-Primary-Flow-Without-Scram Tests: Pretest Predictions and Preliminary Results," Nucl. Eng. and Design, 101, 45, (1987).

11. F. E. Dunn and D. J. Malloy, "LMR Centrifugal Pump Coastdowns," Proceedings of an International Conference on Anticipated and Abnormal Transients in Nuclear Power Plants, Atlanta, Georgia p. VIII-21, April 12-15, (1987).

12. E. B. Wylie and V. L. Streeter, Hydraulic Transients; Chapter Nine, McGraw-Hill, New York, 1967.

13. E. B. Wylie and V. L. Streeter, Fluid Transients; Chapter Six, McGraw-Hill, New York, 1978.

14. J. Poloncsik, E. C. Filewicz, G. J. Kamis, and J. T. Natoce, "The Experimental Breeder Reactor II (EBR-II) Instrumented Subassemblies, Inset XX09 and XX10," Proceedings of the Conference on Fast, Thermal, and Fusion Reactor Experiments, Salt Lake City, Utah, American Nuclear Society, pp. 1-276 to 1-287, April 12-15, (1982).

15. A. Fukuda, Oak Ridge National Laboratory, personal communication (1972).

16. Decay Heat Power in Light Water Reactors, American Nuclear Society, ANSI/ANS-5.1-1979.

17. F. E. Dunn and J. P. Herzog, "Thermal-Hydraulic Impact of Failure of Highly Irradiated Fuel Pins on LMR Passive Safety," Trans. Am. Nucl. Soc., 62, 673 (1990).

18. F. E. Dunn, R. A. Wigeland, and R. K. Lo, "RACS Shutdown Heat Removal in a Modular Sized LMR," Collected Papers in Heat Transfer 1988, Vol. II, ASME HTD-Vol., 104 pp. 211-215 (1988).

END

DATE FILMED

10/15/92