FRAMATOME
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Subject: Modeling Refinements to Framatome Technologies' RELAP5-Based, Large Break LOCA Evaluation Models—BAW-10168 for Non-B&W-Designed, Recirculating Steam Generator Plants and BAW-10192 for B&W-Designed, Once-Through Steam Generator Plants.

Gentlemen:

Framatome Technologies Incorporated (FTI) maintains two NRC-approved large break loss-of-coolant accident (LBLOCA) evaluation models (EMs) to demonstrate compliance with the requirements of 10CFR50.46. The EM described in BAW-10168P-A, Revision 3, December 1996 applies to plant designs incorporating recirculating steam generators (RSGs) and the EM described in BAW-10192P-A, Revision 0, June 1998 is applied to the B&W NSS design. FTI is refining the modeling of the hot rod/hot assembly in its LBLOCA EMs to improve the simulation of the LOCA cooling process. The refinements apply equally to LBLOCA licensing calculations performed with the RSG and the B&W EMs.

FTI's existing LBLOCA evaluations do not resolve the difference between the hot rod within the hot fuel assembly and the hot fuel assembly. Without such differentiation, it becomes necessary to apply all fuel temperature uncertainties and margins considered appropriate to the hot rod to the entire hot assembly. This places an undue burden on the calculation of the coolant properties within the hot assembly. To reduce this effect and remove over-conservatism from the evaluations, the heat structure simulating the hot rod/hot assembly is being split, one structure for the hot assembly and one for the hot rod. The refinement allows for the application of more realistic, steady state, volume-averaged, fuel temperature, uncertainty factors.

Future LBLOCA analyses will be performed in the following manner:

> The average core heat structure will be initialized with no uncertainty. The hot assembly heat structure will be initialized at a statistical-based, uncertainty providing 95 percent confidence in 95 percent of all instances that the average fuel temperature in the assembly is bounded. The maximum 95/95, fuel temperature uncertainty will be imposed only on the hot rod heat structure. [Note that a correction to TACO3 predictions at high burnup will still be applied.]

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This approach to the simulation of the thermal evolution of the peak cladding temperature is consistent with generally accepted industry practice and does not, in Framatome Technologies' opinion, comprise a change or revision to the existing approved LBLOCA EMs. Rather, the change in simulation can be accomplished under the dictates of the existing EMs because it lies within the modeling prerogatives retained by FTI.

The heat structure refinements affect the RELAP5 and BEACH (a set of subroutines within the RELAP5 computer code) simulations because they involve the prediction of hot rod cladding temperatures. REFLOD3B is unaffected because only the average core is included in the calculation scheme. Computer code updates were incorporated, as a user convenience, into RELAP5/MOD2-B&W Version 24.0HP, including its BEACH subroutines. They were submitted to the NRC as Revision 4 of the RELAP5/MOD2-B&W topical in April 1998 and replaced in toto in September 1998. The submittal was part of the RELAP5/MOD2-B&W M5 advanced clad implementation package.

Currently, these refinements are not being considered for application to FTI's small break LOCA methods. Framatome Technologies will continue to apply the TACO3-based, hot rod, volume-averaged, fuel temperature, uncertainty factor to all fuel assemblies in its small break LOCA evaluation models.

The attached material is presented to continue close communications with the NRC regarding the status of Framatome Technologies' LOCA licensing applications and modeling techniques. If the NRC disagrees with or is concerned over Framatome Technologies' large break LOCA refinements, an expeditious response to this letter is requested.

Framatome Technologies intends to apply these refined modeling techniques in future large break LOCA analyses. The first application is scheduled for the TVA Sequoyah plants starting in August 2000. Framatome, also requests the approval of the RELAP5/MOD2-B&W changes included in the proposed Revision 4 to BAW010164 by August 2000. Framatome requests that the NRC inform us, by May 2000, of any disagreement with our position on the implementation of these heat structure refinements.

The attachment is considered non-proprietary to Framatome Technologies. If you require additional information, please contact John Biller at 804/832-2600 or John Klingenfus at 804/832-3294.

Sincerely,

J. J. Kelly, Manager
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I. Introduction

Framatome Technologies Incorporated (FTI) maintains two NRC approved large break loss-of-coolant accident (LBLOCA) evaluation models (EMs) to demonstrate compliance with the requirements of 10CFR50.46. The EM described in BAW-10168P-A, Revision 3, December 1996 [(1)] applies to plant designs incorporating recirculating steam generators (RSGs) and the EM described in BAW-10192P-A, Revision 0, June 1998 [(2)] is applied to the B&W NSS design. FTI is refining the modeling of the hot rod/hot assembly in our LBLOCA EMs to improve the simulation of the LOCA cooling process. The refinements apply equally to LBLOCA licensing calculations performed with the RSG and the B&W EMs.

FTI's existing LBLOCA evaluations do not resolve the difference between the hot rod within the hot fuel assembly and the hot fuel assembly. Without such differentiation, it becomes necessary to apply all uncertainties and margins considered appropriate to the hot rod to the entire hot assembly. This places an undue burden on the calculation of the coolant properties within the hot assembly. To reduce this effect and remove over-conservatism in the evaluations, the heat structure simulating the hot rod/hot assembly is being split, one structure for the hot assembly and one for the hot rod. This approach does not, in Framatome Technologies' opinion, comprise a change or revision to the existing approved LBLOCA EMs. Rather, the change in simulation can be accomplished under the dictates of the existing EMs because it lies within the modeling prerogatives retained by FTI.

Both the RSG and the B&W LBLOCA evaluation models are composed of three (3), NRC-approved computer codes:

- RELAP5/MOD2-B&W [(3)], which is used to compute the system thermal-hydraulic response during blowdown including hot rod/hot assembly temperatures.
- REFLOD3B [(4)], which predicts the refill/reflood system thermal-hydraulic response.
- BEACH [(5)], which comprises a set of subroutines within the RELAP5 code used to calculate hot rod/hot assembly refill and reflood thermal behavior.

Figure 1 shows the basic interface between these three (3) codes. The heat structure refinements affect the RELAP5 and BEACH simulations because they involve the prediction of hot rod cladding temperatures. Because only the average core is included in the calculation scheme, REFLOD3B is unaffected. Figures 2a and 2b show representative blowdown (RELAP5)/refill-reflood (BEACH) core noding schemes. [Note that for simplicity the blowdown crossflow junctions are not shown in Figures 2a and 2b. During blowdown, each elevation-pair of hot and average core nodes is cross-connected. At the start of refill—the BEACH calculation—the blowdown crossflow junctions are deleted from the problem. The use of and the deletion of crossflow junctions in the LBLOCA simulation is unchanged by the refinements discussed herein.] For the current simulations, the average core and the hot channel each connect to a single heat structure. The heat structure for the hot channel represents one complete fuel assembly (the hot assembly plus the hot rod) with maximum uncertainties and margins applied to all rods. All rods are driven at the maximum allowable peaking. The heat structure in the average core represents all core fuel assemblies less the one hot channel assembly.

Core heat structures are initialized using steady state, volume-averaged, fuel temperature inputs calculated by the TACO3 fuel code [6]. While not required by the EMs [1,2], the TACO3-specified "hot rod" uncertainty factor (1.115) has usually been applied to both the hot assembly heat structure and the average core heat structure. This provides a conservative overestimation of the initial core stored energy. Some current analyses have removed the hot rod uncertainty factor from the average core heat structure but in all current calculations the full factor is applied to the hot assembly heat structure. This practice substantially overestimates the initial enthalpy of the heat structures. Of particular importance is the overestimation of the enthalpy in the hot assembly and its resultant impact on the coolant properties during blowdown, refill, and reflood. In future LBLOCA analyses, FTI will impose the following conservatism:

> The average core heat structure will be initialized with no uncertainty. The hot assembly heat structure will be initialized at a statistical-based, uncertainty providing 95 percent confidence in 95 percent of all instances that the average fuel temperature in the assembly is bounded. The maximum 95/95, fuel temperature uncertainty will be imposed only on the hot rod heat structure. [Note that a correction to TACO3 predictions at high burnup will still be applied.]

To accomplish this, it is necessary to resolve the heat structure modeling of the hot rod/assembly from one to two heat structures with a shared coolant channel. One structure simulates the hot rod of the hot assembly and the other the hot assembly less the hot rod. Figure 2c illustrates the resulting coolant channel heat structure scheme. The maximum fuel temperature uncertainty is used to initialize the hot rod heat structure and an appropriately conservative fuel temperature uncertainty is used for the hot assembly heat structure. The following sections describe minor RELAP5 code adjustments necessary for multiple heat structure modeling, specific parameter derivations and assignments between the multiple heat structures, and comparative results of the revised modeling for both the B&W and the RSG EMs.

II. RELAP5/MOD-B&W Modifications

For any given core fluid channel, a wide range of reasons exists for use of multiple heat structure capabilities—that is, supplemental rods. Simulation of fuel rod differences within an assembly or a group of fuel assemblies is the essential reason. The capability is particularly useful in modeling gadolinium rods, lead test rods, or in the quantification of peaking or initial enthalpy differences between rods. RELAP5/MOD2-B&W [3], including its BEACH [5] subroutines, has the general ability to model multiple heat structures per coolant channel. However, the code was update to facilitate proper simulation of bundle and individual rod parameters within the confines of a LBLOCA calculation. It becomes important, in a multiple heat structure environment, to distinguish between characteristics created by and important to individual rods and those created by the fuel assembly as a whole. Updates were incorporated, as a user convenience, into RELAP5/MOD2-B&W Version 24.0HP, including its BEACH subroutines. They were submitted to the NRC as Revision 4 of the RELAP5/MOD2-B&W topical in April 1998. The submittal was part of the RELAP5/MOD2-B&W M5 advanced clad implementation package. (These changes have nothing to do with the M5 cladding but that submittal was convenient and timely.) The changes were replaced in toto in September 1998 because an additional code upgrade required by the M5 cladding had been recognized. The following is a brief discussion of the RELAP5/BEACH upgrades incorporated in Version 24.0HP to support multiple heat structure simulation.

The occurrence of rupture, being dependent on cladding temperature and internal rod pressure, is a heat structure calculation. The effect of rupture, however, may be on individual rods or through an impact on the coolant channel and, hence, on all heat structures within the channel. Therefore, the effects of rupture must be properly sorted and related to the appropriate causative heat structure. The cladding strain and heat transfer area prior to or after rupture, to the extent that they are included in the LOCA calculations, are individual rod- or rod group-related and should be determined from the individual heat structure status. RELAP5/MOD2-B&W has always associated the calculation of these parameters with individual heat structures and that is unchanged. The rupture-induced droplet breakup model, the resultant inter-phase heat transfer parameters, and the rupture flow resistance factor are assembly effects and should be queued to the assembly regardless of the status of individual rods or any other supplemental rods. Accordingly, the hot pin rupture location is hot assembly-based. Within the RELAP5/MOD2-B&W and BEACH rod models, the quench front and incipient boiling locations are determined by the heat structure routines. These parameters are rod- or rod group-related and should be determined from the status of an individual heat structure.

With Version 24.0HP of RELAP5/MOD2-B&W and its BEACH options, a user option specifies each rod or rod group as primary or supplemental. This allows form loss, rupture-induced droplet breakup (BEACH), and quench front and incipient boiling location calculations to be performed based on the appropriate heat structure. Thus, even after an individual rod ruptures, rupture-induced droplet breakup cooling will be based on the specified primary bundle, heat structure prediction of rupture.

The RELAP5/MOD2-B&W and BEACH updates in Version 24.0HP allow each heat structure to have an individual material makeup. One heat structure, for example, could represent Zircaloy-4 fuel rods while a second heat structure in the same fluid channel could represent a set of gadolinium fuel rods or perhaps clad with an advanced material. An "IF" check has also been added to automate compliance with the NRC-imposed limitation on the amount of blockage that can be used in the rupture-induced droplet breakup model. Regardless of the amount of coolant channel blockage calculated, no more than a 60 percent channel blockage will be used in the droplet breakup calculations.

III. Steady State, Volume-Averaged, Fuel Temperature Distribution

The reason for making these refinements in the modeling of the hot rod/hot assembly is to mechanistically incorporate into the solution differences between the two regions in the LOCA predictions. One of these differences occurs in the amount of uncertainty to be used in the initialization of the fuel pellet enthalpy. The large break LOCA evaluation models [1, 2] indirectly specify the value of the fuel temperature uncertainty factor through reference to an approved fuel code, TACO3 [6] (BAW-10162P-A). TACO3 provides essentially a best estimate prediction of the fuel pellet steady state temperature. To assure conservatism in the LOCA initialization, the predicted fuel temperature is increased by the published TACO3 uncertainty providing 95 percent confidence in 95 percent of all instances that the temperature is not underpredicted. The TACO3 topical report specifies an 11.5 percent uncertainty value for the hot spot. The topical report also demonstrates that the average channel uncertainty is zero, and provides data necessary to determine an appropriate hot assembly uncertainty factor. For exposures above 40 GWd/mtU, a bias is added to TACO3 temperature predictions in accordance with the extended burnup topical report [8].

A probabilistic analysis was performed for the immediate vicinity of the hot rod. Based on the TACO3 uncertainty distribution function, a three-percent value was found to assure with a 95/95 percent confidence that the average fuel temperature within this region was bounded. For convenience and ease of application, past evaluations applied the full TACO3 uncertainty to the entire hot assembly and average core. This practice is not specified or required by TACO3 [6] nor is it specified or required by either LBLOCA EM [1, 2]. FTI's prior use of a single, large uncertainty factor (1.115) was a self-imposed conservatism that is now being removed. Discussions of the development of appropriate fuel assembly uncertainties and representative evaluations of the impact for both B&W-designed and RSG plants follow.

1. Fuel Temperature Uncertainty for the Average Core

The recommended uncertainty factor to use for the TACO3 [6], LOCA fuel temperature predictions is one (1) for exposures below 40 GWd/mtU. The value is based on probabilistic analysis (the results of which are documented in Reference 6) performed with TACO3-predicted fuel temperatures. The probabilistic analysis, based on a sample size of over 700, yielded a mean measured-to-predicted fuel temperature quotient of 1.00. (Note that an average channel in either evaluation model easily comprises more than 20,000 fuel rods.) Furthermore, no significant bias was observed with respect to temperature, power, or burnup. Therefore, nearly half of the TACO3 temperature predictions were less than measurements and half were greater than measurements. In essence, TACO3 predictions are best estimate. It follows directly that the mean measured-to-predicted quotient of 1.00 should be applied to core average channel temperature predictions. Again, for exposures above 40 GWd/mtU, a bias is added to TACO3 temperature predictions in accordance with the extended burnup topical report [8].

While not explicitly stated, the recommended fuel temperature, uncertainty factor in the NRC-approved, TACO3 topical report was formulated to apply within hot rods only. Figure I-4 in the topical report illustrates this point. The LOCA rod average linear heat rates in this figure correspond to typical hot rod F_Q's. An average channel fuel temperature uncertainty factor of one (1), therefore, is appropriate and consistent with the intent and approval of the fuel temperature probabilistic predictions and with the LOCA applications uncertainty factor presented in the TACO3 topical report. Average channel modeling remains unchanged. Only an overt and unnecessary input conservatism is being removed.

2. Fuel Temperature Uncertainty for the Hot Assembly

As discussed in Section II, FTI increased the hot channel heat structure detail—a switch from one to multiple heat structures. The large break LOCA hot channel (in both evaluation models) comprises a single fuel assembly, all rods of which are driven at the maximum allowable peaking. In the evaluation of homogeneous fuel assemblies, one heat structure represents the hot rod and a second hot channel heat structure represents the remainder of the hot assembly. Both heat structures are coupled to a single coolant channel representing the hot channel. If the assembly is not homogeneous—a gadolinium or MOX application, for example—an individual heat structure is used to represent each of the hot rods (or rod groups) to be evaluated and another structure represents the remainder of the hot assembly. Again all of these heat structures are coupled to a single coolant channel representing the hot channel.

Using the measured-to-predicted data in the TACO3 [(6)] topical report, a probabilistic analysis was performed to determine the appropriate initial fuel enthalpy (fuel temperature) uncertainty factor for application to the rods (the hot assembly rods) surrounding the hot rod. For the purpose of this discussion, the term hot spot will be used as the location on the hot rod that will eventually produce or be the location of the peak cladding temperature. The probabilistic evaluation proceeded in three steps:

1. Determination of the region within the hot assembly that drives interactions (heat transfer) with the hot spot and generation of a large number of randomly distributed sets of fuel pellet enthalpy uncertainties within that region.

2. Determination and assignment of importance factors for each individual pellet and computation of the average weighted uncertainty for each set.

3. Ordering of the sets to determine the probability distribution of the average uncertainty within the region.

The premise of the separate heat structures is that certain aspects of the heat transfer process occurring at the hot spot are not controlled by hot spot conditions but rather by surrounding conditions. Locally the interaction or coupling between the hot spot and its surroundings is through heat transfer to the coolant and the physical state of the coolant. Although the hot spot influences the coolant state, preconditioning and mixing within the entire hot assembly is far more influential. In this conditioning, however, the fuel in immediate proximity to the hot spot dominates. A proper determination of the drivers for the coolant conditions at the hot spot would reflect the varying influence of the fuel surrounding the hot spot, making remote fuel of low importance and nearby fuel of higher importance. To conservatively specify the region of influence, FTI uses only the fuel pellets within the hot rod, within the rods in contact with the four coolant subchannels directly associated with the hot rod, and within the same grid span as the hot spot. Weighting factors for each rod are determined in accordance with their association with the four subchannels. Because the average uncertainty of a group will vary inversely with the membership count of the group, this limitation will overpredict the uncertainty. This uncertainty, in the FTI approach, is then assigned to the entire hot assembly, excepting the supplemental rods, to assure a conservative representation of the coolant drivers near the hot spot.

Following the determination of the region, a series of possible uncertainty distributions is assembled by randomly assigning an enthalpy uncertainty to each fuel pellet in accordance with the TACO3 uncertainty distribution function. Each set represents a physically possible distribution of the fuel steady state enthalpies within the region but there is no assurance of conservatism. Weighting factors for the contribution of each pellet are then assigned according to the dominant physical process for the coupling. There are two of these. During periods of flow, the coupling is via convective heat transfer and the importance is assigned in accord with the individual pellet influence on the coolant temperature. During stagnant conditions, the coupling is via radiation heat transfer and the importance is assigned via the influence of pellets on cladding temperatures and the corresponding view factors. For flow periods, the region is limited to only one half of the grid span and all pellets within the region contribute according to their association with the hot subchannel. This includes the pellets in the hot rod that are assigned an importance of 1.0. For the regional uncertainty, the pellets in the hot rod below the hot spot are assigned uncertainties according to the TACO3 uncertainty distribution but those at the hot spot are forced to the TACO3 95/95 percent confidence level. For stagnant periods, none of the pellets within the hot rod are included because there is no axial radiation within a rod. However, the entire grid span is allowed because the heat transfer process is unrelated to direction. The importance factors are determined from the view factor relating the hot spot to the clad surrounding each pellet.

With the appropriate weighting factors assigned to each pellet, the average uncertainty of each set is computed. The resulting array of average uncertainties is ordered and the average uncertainty that bounds 95 percent of the values in the array (in 95 percent of all instances) is determined. If the fuel temperature uncertainty for the hot bundle heat structure is set to a value equal to or greater than this 95/95 percent bound, the fuel temperature impact of the hot assembly modeling will be suitably bounding for the LOCA calculation. For the TACO3 uncertainty distribution, the computed 95/95 percent confidence uncertainty value for flowing conditions was determined to be 2.1 percent. For stagnant conditions, the value was determined to be 2.6 percent. Within the FTI LOCA evaluations a fuel temperature uncertainty of 3 percent will be assigned for the heat structure modeling the hot assembly when the bundle exposure is up to 40

GWd/mtU and the fuel temperature prediction is generated by TACO3. Above 40 GWd/mtU, the uncertainty will be linearly increased in accordance with the extended burnup topical report [8].

3. Fuel Temperature Uncertainty for the Hot Rod

The recommended fuel temperature uncertainty factor presented in the NRC-approved, TACO3 topical report was formulated for the hot spot. The TACO3-recommended uncertainty factor, 11.5 percent, will continue to be applied to the simulation of the entire hot rod for rod average burnups up to 40 GWd/mtU. For rod average burnups above 40 GWd/mtU, the uncertainty is increased in accordance with the extended burnup topical report [8]. By preserving the application of the recommended pellet uncertainty factor to the entire hot rod, the appropriate initial fuel enthalpy will have been applied at the location of peak cladding temperature regardless of where in the hot rod that temperature occurs.

IV. Heat Transfer During Refill

The RSG- and B&W-designed EMs present slightly differing interpretations as to heat transfer from the reactor core during the refill period. Previously, this phase of the accident was mostly termed the adiabatic heatup period because minimal heat transfer from the core was possible and most evaluation models simply chose not to model any. There is actually no requirement in the regulation to restrict heat transfer during this period, other than application of the reflood restriction on convective heat transfer to steam cooling models. Recently, radiation models have been approved within the industry for heat transfer during refill/reflood. These models do not allow large amounts of heat transport, but over the course of refill small contributions accumulate and are significant. The RSG EM implies that this period is modeled as adiabatic. The B&W-design EM more correctly describes the period as nearly adiabatic. In fact, in Revision 3 of the RSG evaluation model, when RELAP5/MOD2-B&W replaced FRAP-T6-B&W for the calculation of the hot spot temperature during blowdown and the application of BEACH was expanded to initiate at the end of blowdown, heat transfer to the stagnant steam resident within the core was included. For the BEACH application, it was possible to input zero incoming flow but it was not possible to eliminate the resident steam. Therefore, for the last several years a description of nearly or essentially adiabatic is more appropriate. The NRC understood this when the FRAP-T6-B&W replacement was approved for the RSG EM.

When all rods in the hot bundle are identical, as with the previous LOCA implementations, the slight amount of heat transfer possible to the resident steam is divided equally between each rod in the assembly and the heat flow to the resident steam has an insignificant effect on an individual rod. However, when most of the rods within the hot assembly are initialized such that they will have lower temperatures than the hot rod during refill, the potential for heat transfer from the hot rod is increased and the result is noticeable. The effect is created because only about 0.5 percent of the energy transmitted to the steam is from the hot rod. Thus the steam maintains the temperature of the hot bundle heat structure creating a temperature difference to the hot rod that leads to the transport of significant energy. To assure that this energy is not an over prediction of the actual available heat transport, the energy transfer was compared to what could have been transported by rod-to-rod radiation. The amount of energy released to the resident steam from the hot spot by the FTI model during refill amounts to approximately 2.5 percent of the decay heat rate at the hot spot. Rod-to-rod radiation would allow the transport of approximately 5 percent of the hot spot decay heat to surrounding rods. Thus, during the refill period, the heat transfer allowed by FTI's modeling remains conservative by a factor of two (2).

V. Comparisons

This section presents the results of cases that were used to assess the impact of updating from one to two hot channel heat structures and, more importantly, that of reducing the uncertainty factors. Results are shown for both B&W lowered-loop and RSG plants. Expectations for the B&W raised-loop design would fall between the results for the above mentioned plant types. The initial comparison cases are based on a uniform uncertainty of 11.5 percent. They demonstrate that the addition of a second heat structure in the hot channel has no effect of any significance whatsoever on case results. Minor noted differences result from normal computer code numerical issues—round off. The comparisons confirm proper RELAP5 implementation and no impact on prior licensing calculations.

The final comparison cases show the predictive changes achieved by reducing the self-imposed conservatism on the steady state, volume-averaged, fuel temperature, uncertainty factors. Factors of 1.0, 1.03, and 1.115 were applied to the average core, the hot assembly, and the hot rod, respectively. Primarily, the final comparison cases are discussed below.

1. Once-Through Steam Generator Plants

B&W-designed plants would be expected to show a greater sensitivity to reductions in initial stored energy than would U-tube steam generator plants. Experience indicates that the peak-clad temperature for once-through steam generator plants (notably the lowered-loop design) generally occurs late in or immediately following the end of the refill period. The refill period is the period required for the ECCS to completely fill the depleted inventory of the reactor vessel lower head and lower plenum. Since B&W plants peak early in the transient, the large break LOCA is substantially influenced by stored energy. (On the other hand, U-tube plants generally peak well past the end of the refill period. Accordingly, recirculating steam generator plants are largely controlled by decay heat and are less influenced by initial stored energy levels.)

The large break LOCA plant model used for TMI-1 nuclear plant reload licensing application was selected for the multiple core heat structure evaluation. The axial peak power at the 2.5-ft level yields the limiting PCT based on the currently licensed axial power limit (K_z). The plant configuration is presented in Table 1. The evaluation of cladding temperature transients is performed with three computer codes, interconnected as depicted in Figure 1. The computer code models are consistent with the EM described in Reference 2. The core is radially divided into two fluid channels, hot and average fluid channels as shown in Figure 2a. Each channel consists of 22 axial volumes, numbered 325 through 346 and 425 through 446 for the hot and average fluid channels respectively. The bottom and top volumes (325 and 346 and 425 and 446) in each channel are unheated core volumes. The active core regions for the hot and average fluid channels are volumes 326 through 345 (heat structures 2 through 21) and volumes 426 through 445 respectively. The RELAP5/MOD2-B&W code [(3)] is used to predict the reactor coolant system thermal-hydraulic transients during the blowdown and post-blowdown core thermal analysis (BEACH). The REFLOD3B code [(4)] is used to generate post-blowdown hydraulic boundary conditions to be used in the core thermal analysis with the BEACH code. The initial volume-averaged fuel temperatures are calculated by the TACO3 code [(6)], and are adjusted to account for uncertainties for LOCA application. The following three analyses were performed to evaluate the effects of the uncertainty on the PCT.

- Case 1 (Base EM): The current licensing model has two core heat structures, one representing the hottest assembly, and the other representing the remaining 176 assemblies. The volume-averaged fuel temperatures for both heat structures have 11.5 percent uncertainty added.

- Case 2: This is Case 1 with three core heat structures. The base EM hot assembly heat structure is split into two heat structures within the hot fluid channel, one representing one (1) hot rod and the other representing the remaining 207-rod hot assembly. The temperature uncertainty remains at 11.5 percent. The average heat structure remains unchanged.

- Case 3: This is Case 2 with reduced uncertainty in the hot and average assembly heat structures. The uncertainty in the 207-rod hot assembly heat structure in Case 2 is reduced from 11.5 to 3 percent. The uncertainty for the average assembly heat structure is reduced from 11.5 to 0 percent. The hot rod heat structure remains unchanged.

The results of the B&W reduced uncertainty case are compared to the unreduced uncertainty case in Table 2 and in Figures 3 through 7. Both cases use three (3) core heat structures, one (1) in the average fluid channel, and two (2) in the hot fluid channel.

The results of the evaluation are summarized in Table 2. The peak cladding temperatures for the hot rod unruptured (node 6) and ruptured (node 7) nodes are presented in Figures 3 and 4, respectively. The cladding burst occurred near the end of blowdown due to the high peak power (16.8 kw/ft) and the low core downflow during blowdown. A brief period of enhanced local cooling following the rupture was observed. However, this is more than offset by energy addition from the metal-water reaction during the subsequent refill period. Thus, the heatup rate at the ruptured node is substantially greater than unruptured locations. In addition, high flooding rates during the early phase of the reflood transient are sufficient to provide cladding temperature turnaround a few seconds after the start of reflood. Thus, the ruptured node PCT becomes limiting. The hot spot (node 7) mass flow rate during the blowdown in Figure 5 is relatively insensitive to the core stored energy. Figure 6 shows slightly higher flooding rates for Case 3 during the early phase of the reflood transient. The hot spot vapor temperature plots in Figure 7 show that the Case 3 vapor temperature is generally lower than those of Cases 1 and 2 due to lower energy deposition in the hot channel.

The results of Cases 1 (base EM) and 2 confirm that the multiple-core heat structure model is properly implemented in the RELAP5/MOD2 code. The clad rupture occurred at node 7 for both the hot rod and hot assembly heat structures. Case 3 with the lower hot channel fluid temperature and higher flooding rate results in a lower heatup rate. The PCT for Case 3 decreased by more than 150 F below the base EM case. The PCTs for the base EM and the revised EM (Case 3) with the reduced uncertainties are 2055 F and 1904 F respectively. Both values are substantially below 10CFR50.46 limits.

2. U-Tube Steam Generator Plants

The large break LOCA plant model used for the Sequoyah nuclear plant reload licensing application was selected for the multiple core heat structure evaluation. The axial peak power at the 9.7-ft level yields the limiting PCT based on the current licensed axial power limit (K_z). The plant configuration is presented in Table 3. The evaluation of cladding temperature transients is performed with three computer codes. Their connectivity is depicted in Figure 1. The computer code models are consistent with the EM described in Reference 1. The core is radially divided into two fluid channels, hot and average fluid channels as shown in Figure 2b. Each channel consists of 20 axial volumes, numbered 326 through 345 and 426 through 445 for the hot and average fluid channels respectively. The RELAP5/MOD2-B&W code [3] is used to predict the reactor coolant system thermal-hydraulic transients during the blowdown and post-blowdown core thermal response (BEACH). The REFLOD3B code [4] is used to generate post-blowdown hydraulic boundary conditions to be used in the core thermal analysis. The initial volume-averaged fuel temperatures are calculated by the TACO3 code [6], and are adjusted to account for uncertainties for LOCA application. The following three analyses were performed to evaluate the effects of initial fuel temperature uncertainty on PCT.

- Case 1 (Base EM): The current licensing model has two core heat structures, one representing the hot assembly and the other representing the remaining 192 assemblies. The volume-averaged fuel temperatures for both heat structures have 11.5 percent uncertainty added.

- Case 2: This is Case 1 with three core heat structures. The base EM hot assembly heat structure is split into two (2) heat structures within the hot fluid channel, one representing one (1) hot rod and the other representing the remaining 263 rods in the hot assembly. The temperature uncertainty remains at 11.5 percent. The average heat structure remains unchanged.

- Case 3: This is Case 2 with reduced uncertainty in the hot and average assembly heat structures. The uncertainty on the 263 rods in the hot assembly heat structure in Case 2 is reduced from 11.5 to 3 percent. The uncertainty for the average assembly heat structure is reduced from 11.5 to 0 percent. The hot rod heat structure remains unchanged at 11.5 percent.

The results of the evaluation are summarized in Table 4. The peak cladding temperatures for the hot rod unruptured (node 15) and ruptured (node 17) nodes are presented in Figures 8 and 9 respectively. In RSG plants with lower peak power (12.43 kw/ft), clad burst occurs during reflood and rupture-induced local cooling reduces rupture node heatup. For the unruptured node, clad temperature turnaround occurs later due to low flooding rates. Thus, the unruptured node yields the limiting PCT. The hot spot (node 15) mass flow rate during blowdown (Figure 10) is relatively insensitive to the core stored energy. Figure 11 shows slightly higher flooding rates for Case 3 during the early phase of the reflood transient (80 seconds). The hot spot vapor temperature curves in Figure 12 show that the Case 3 vapor temperature is generally lower than those in Cases 1 and 2. This is due to a lower energy deposit in the hot channel. The combined effects of lower hot channel energy and higher flooding rate in Case 3 produce a lower PCT. The effects of lower hot channel energy and higher flooding rate on the PCT in Case 3 are less pronounced than in the OTSG study due to a longer temperature turnaround time. The Case 3 PCT is 60 F less than the base EM case.

Again, the results of Cases 1 (base EM) and 2 confirm that the multiple-core heat structure model is properly implemented in the RELAP5/MOD2 code. The PCTs for the current EM (Case 1) and the revised EM (Case 3) with reduced uncertainty are 2159 F and 2098 F respectively. Both PCT values are below 10CFR50.46 limits.

VI. Conclusions

Framatome Technologies is refining the modeling of the hot rod/hot assembly in its LBLOCA EMs by separating these regions into separate heat structures. The refinements apply equally to LBLOCA licensing calculations performed with the RSG and B&W EMs. The changes affect the modeling in RELAP5 (including BEACH) and do not affect REFLOD3B modeling or usage.

First, additional modeling detail was added to the hot fluid channel. The hot channel contains two (2) heat structures, one representing the hot rod and one representing the hot assembly (less the one hot rod). Previously only one (1) heat structure was modeled in the hot fluid channel. Hot channel fluid conditions drive both heat structures and both structures are initialized at the same maximum allowable peaking or kilowatts per foot. The evaluation model results are not affected by the insertion of additional hot channel modeling detail. However, the modeling refinement allows the incorporation and simulation of differences between the hot rod and the remainder of the hot rods in the hot bundle that can affect the results of EM calculations. The added detail is appropriate for inclusion in future large break LOCA analyses and the continued licensing validity of the evaluation models is demonstrated and retained.

Secondly, unwarranted conservatism in the specification of volume-averaged fuel temperature uncertainties was removed. Previously, the TACO3-specified "hot rod" uncertainty factor was applied to all core fuel rods, substantially overestimating the initial core stored energy. Neither evaluation model [1, 2] imposed the conservatism, nor was it required by TACO3 [6]. The recommended uncertainty specified in the TACO3 topical report was formulated for hot rods. Essentially the over conservatism is self-imposed and subject to removal without affecting the licensing basis of the large break LOCA evaluation models. Based on work reported in the TACO3 topical report, no volume-averaged fuel temperature uncertainty will be applied to the average core heat structure (a standard industry practice), and a three (3) percent uncertainty on TACO3 was justified and will be applied to the hot assembly heat structure. The TACO3-specified uncertainty will continue to be applied to the hot rod.

[*Note*: The future will likely hold changes to fuel code technology—the replacement of TACO3 with an improved code, COPERNIC [7], for example. Under such circumstances, fuel temperature uncertainty factors—appropriate to the new technology—for the average core, hot rod, and hot assembly heat structures will be developed. The uncertainty factors would be used in LBLOCA analyses based on the advanced fuel code. Framatome Technologies would inform the NRC of such a change.]

Comparison cases demonstrate the impact of reverting to normal industry volume-averaged fuel temperature uncertainties. Clad temperature reductions in the representative B&W plant case are substantial. This results from the transient being largely dominated by the initial stored energy. The PCT, normally occurring immediately after the end of refill, is substantially reduced. The U-tube steam generator plants generally experience a late transient peak, well after the end of the refill period. These plant transients are largely dominated by decay heat and show less impact to a reduction in initial core stored energy.

The unwarranted conservatism in setting the initial core stored energy will be removed in the next applications of either of the LBLOCA EMs. This refinement is considered to lie within the confines of the existing EMs and does not comprise a change to the EMs. The applicability and NRC licensing status of the EMs are not perturbed and the EMs incorporating the refinements remain valid for use in LBLOCA licensing applications.

VI. References

1. BAW-10168P-A, “RSG LOCA, BWNT Loss-of-Coolant Accident Evaluation Model for Recirculating Steam Generator Plants,” Revision 3, December 1996.

2. BAW-10192P-A, “BWNT LOCA, BWNT Loss-of-Coolant Accident Evaluation Model for Once-Through Steam Generator Plants,” Revision 0, June 1998.

3. BAW-10164P-A, “RELAP5/MOD2-B&W, An Advanced Computer Program for Light Water Reactor LOCA and Non-LOCA Transient Analysis,” Revision 3, July 1996.

4. BAW-10171P-A, “REFLOD3B, Model for Multinode Core Reflooding Analysis,” Revision 3, December 1995.

5. BAW-10166P-A, “BEACH, Best Estimate Analysis Core Heat Transfer, A Computer Program for Reflood Heat Transfer During LOCA,” Revision 4, February 1996.

6. BAW-10162P-A, “TACO3, Fuel Rod Thermal Analysis Computer Code,” Revision 0, November 1989.

7. BAW-10231P, “COPERNIC Fuel Rod Design Computer Code,” Revision 0, September 1999.

8. BAW-10186P-A, "Extended Burnup Evaluation," Revision 0, June 1997.

Table 1. Initial Conditions for OTSG LBLOCA—2.5-ft Axial Peak.

Parameters	
Reactor Core Power (102 %), MWt	2827.4
Peak Linear Power, kw/ft	16.8
Total Peaking Factor, F_q	2.625
Radial Peaking Factor, $F_{\Delta H}$	1.544
Fuel Assembly	15 x 15 Mark-B9
Number Of Fuel Assemblies	177
Thermal Design Flow, lbm/hr	133.9×10^6
Bypass Flow, percentage	7.5
RCS Average Temperature, F	579.0
Pressurizer Pressure, psia	2199.0
Pressurizer Level, in	220.0
Steam Generator Tube Plugging, percentage	20.0
Accumulator Water Volume, ft^3/tank	985.0
Accumulator Gas Pressure, psia	580.0

Table 2. Summary of Results for OTSG LBLOCA—2.5-ft Axial Peak.

Parameters	Base EM	Case 2	Case 3
End of Blowdown, s	20.71	20.69	20.72
Beginning of Core Recovery, s	27.45	27.43	27.40
Hot Rod PCT, F	N/A*	2050	1904
Hot Rod PCT Node	N/A*	7	7
Hot Rod PCT Time, s	N/A*	30.7	28.1
Hot Assembly PCT, F	2055	2050	1787
Hot Assembly PCT Node	7	7	7
Hot Assembly PCT Time, s	30.8	30.7	28.1
Average Assembly PCT, F	1447	1447	1327
Average Assembly PCT Node	8	8	8
Average Assembly PCT Time, s	7.4	7.4	35.9
Hot Rod Rupture Node	N/A*	7	7
Hot Rod Rupture Time, s	N/A*	17.95	18.4
Hot Rod Rupture Node PCT, F	N/A*	2050	1904
Hot Assembly Rupture Node	7	7	7
Hot Assembly Rupture Time, s	17.9	17.95	20.2
Hot Assembly Rupture Node PCT, F	2055	2050	1787

* Note this model does not distinguish between the hot rod and the hot assembly, as such the hot rod PCT is the hot assembly PCT.

Table 3. Initial Conditions for RSG LBLOCA—9.7-ft Axial Peak.

Parameters	
Reactor Core Power (102 %), MWt	3479.2
Peak Linear Power, kw/ft	12.43
Total Peaking Factor, F_q	2.3
Radial Peaking Factor, $F_{\Delta H}$	1.471
Fuel Assembly	17 x 17 Mark-BW
Number Of Fuel Assemblies	193
Thermal Design Flow, gpm	348,000
Bypass Flow, percentage	7.0
RCS Average Temperature, F	578.2
Pressurizer Pressure, psia	2250
Pressurizer Level, percentage	60
Steam Generator Tube Plugging, percentage	15
Accumulator Water Volume, ft^3/tank	1095
Accumulator Gas Pressure, psia	614.7

Table 4. Summary of Results for RSG LBLOCA—9.7-ft Axial Peak.

Parameters	Base EM	Case 2	Case 3
End of Blowdown, s	25.69	25.69	25.76
Beginning of Core Recovery, s	46.92	46.92	46.10
Hot Rod PCT, F	N/A*	2171	2098
Hot Rod PCT Node	N/A*	15	15
Hot Rod PCT Time, s	N/A*	119.1	130.9
Hot Assembly PCT, F	2159	2173	2090
Hot Assembly PCT Node	15	15	15
Hot Assembly PCT Time, s	118.6	119.1	152.7
Average Assembly PCT, F	1653	1654	1657
Average Assembly PCT Node	15	15	17
Average Assembly PCT Time, s	122.8	123.5	122.6
Hot Rod Rupture Node	N/A*	17	17
Hot Rod Rupture Time, s	N/A*	56.7	59.5
Hot Rod Rupture Node PCT, F	N/A*	2025	1745
Hot Assembly Rupture Node	17	17	17
Hot Assembly Rupture Time, s	56.7	56.7	60.8
Hot Assembly Rupture Node PCT, F	2016	2029	1736

* Note this model does not distinguish between the hot rod and the hot assembly, as such the hot rod PCT is the hot assembly PCT.

FIGURE 1. LBLOCA EM Computer Code Interface.

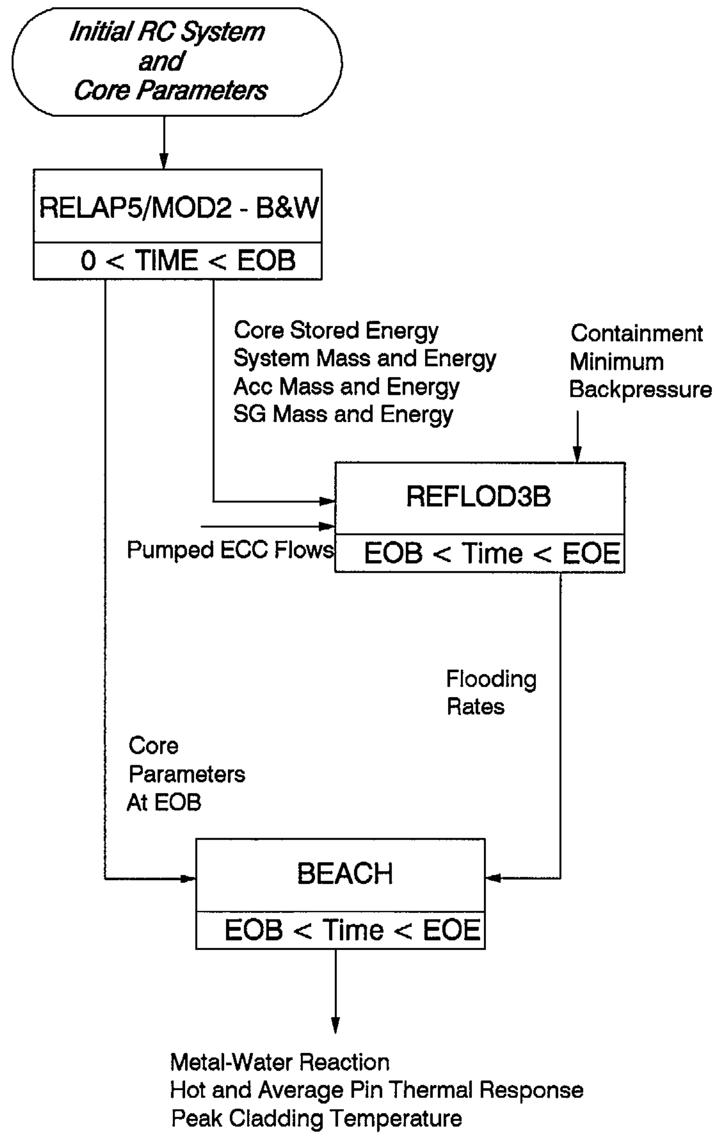

FIGURE 2a. RELAP5-BEACH Core Noding Arrangement For OTSG.

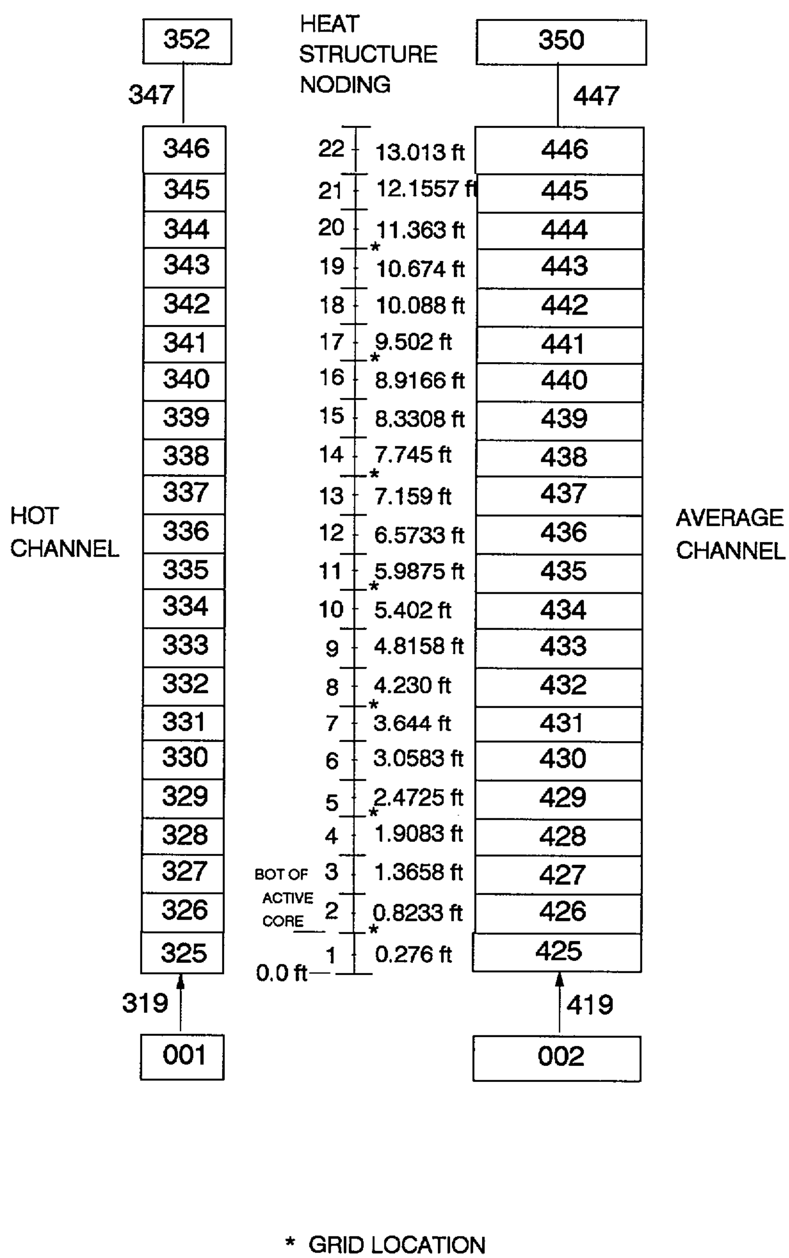

FIGURE 2b. RELAP5-BEACH Core Noding Arrangement For RSG.

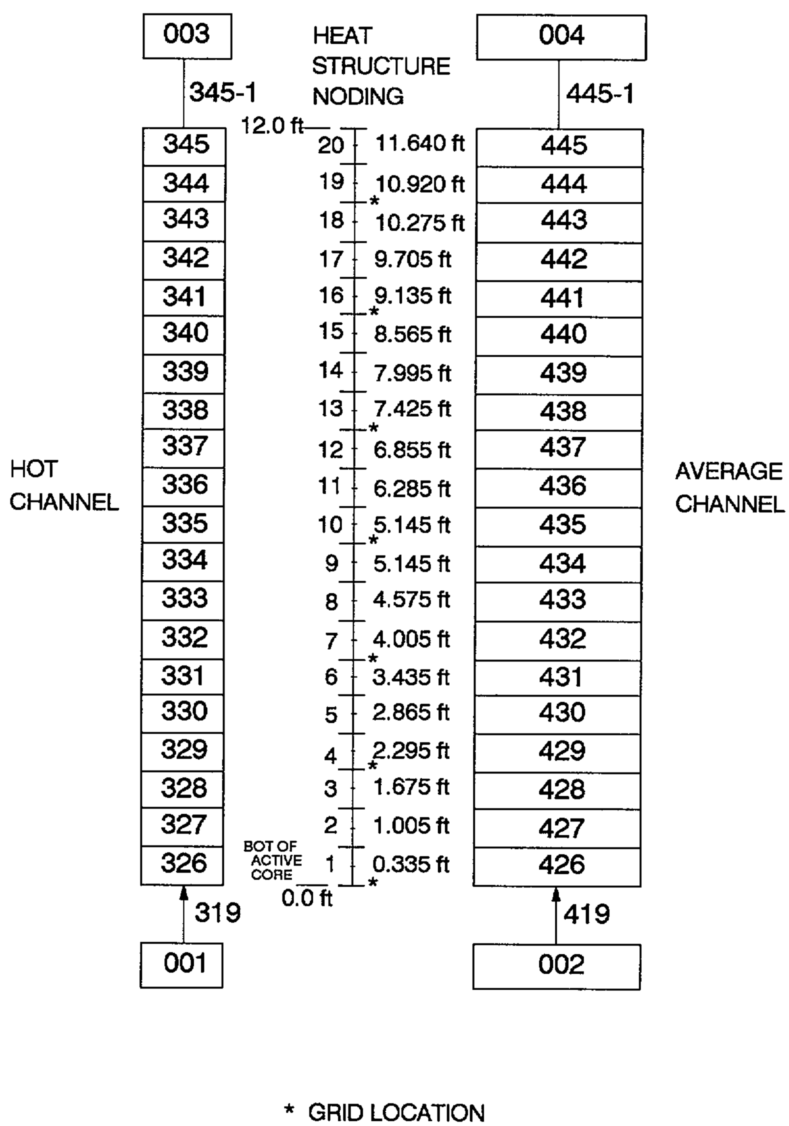

FIGURE 2c. Representative RELAP5-BEACH Core Heat Structure Arrangement.

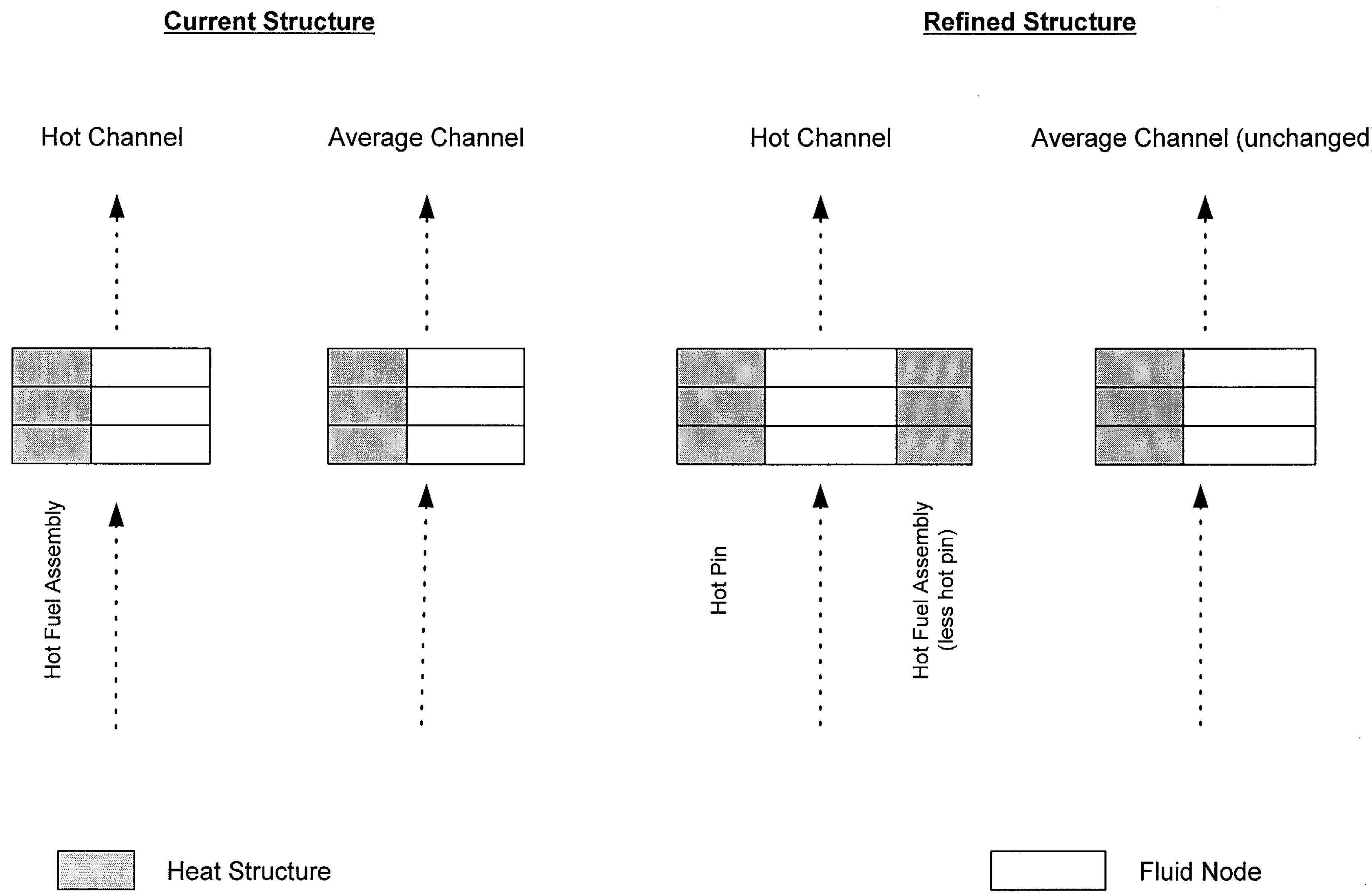

FIGURE 3. OTSG Unruptured Node PCT
2.5-ft Axial Peak.

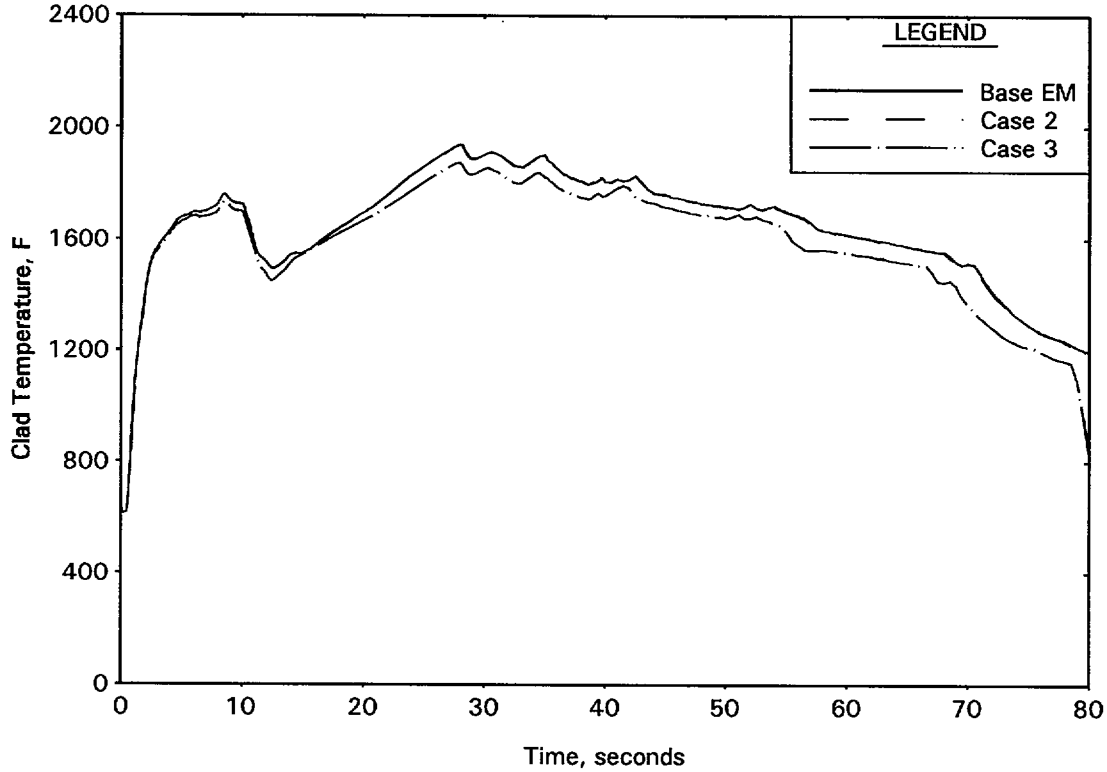

FIGURE 4. OTSG Ruptured Node PCT
2.5-ft Axial Peak.

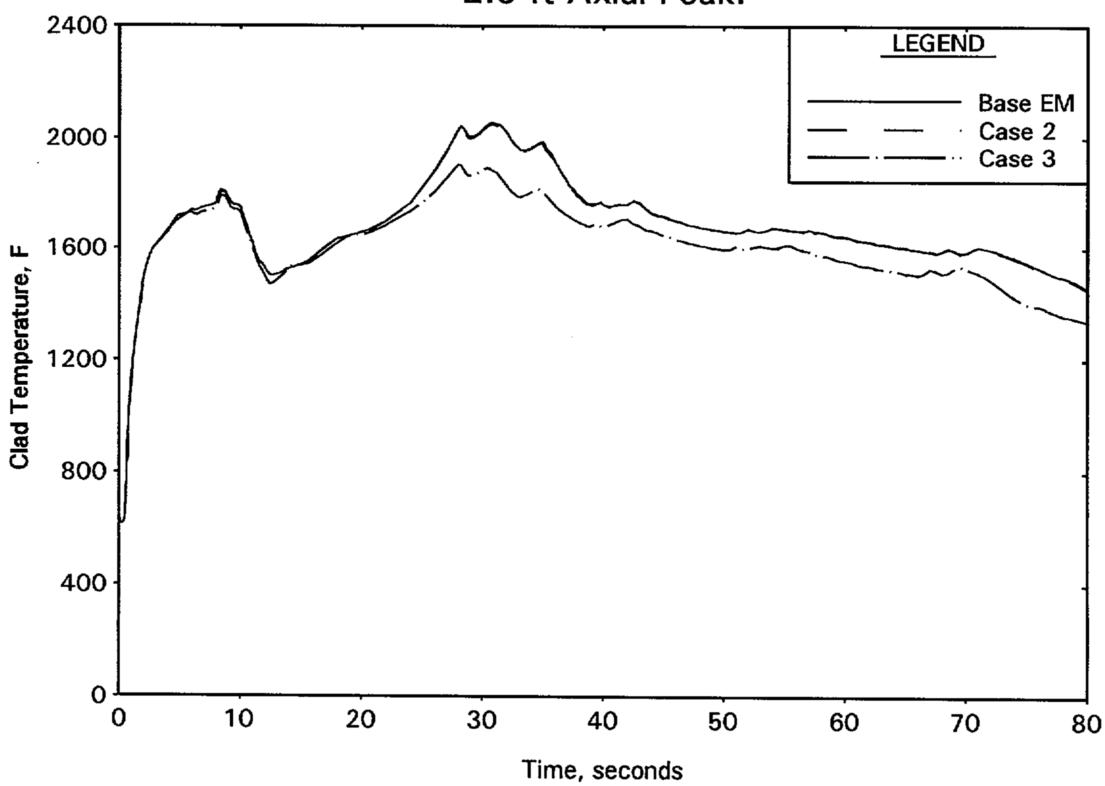

FIGURE 5. OTSG Blowdown Hot Channel Flow At PCT Location
2.5-ft Axial Peak.

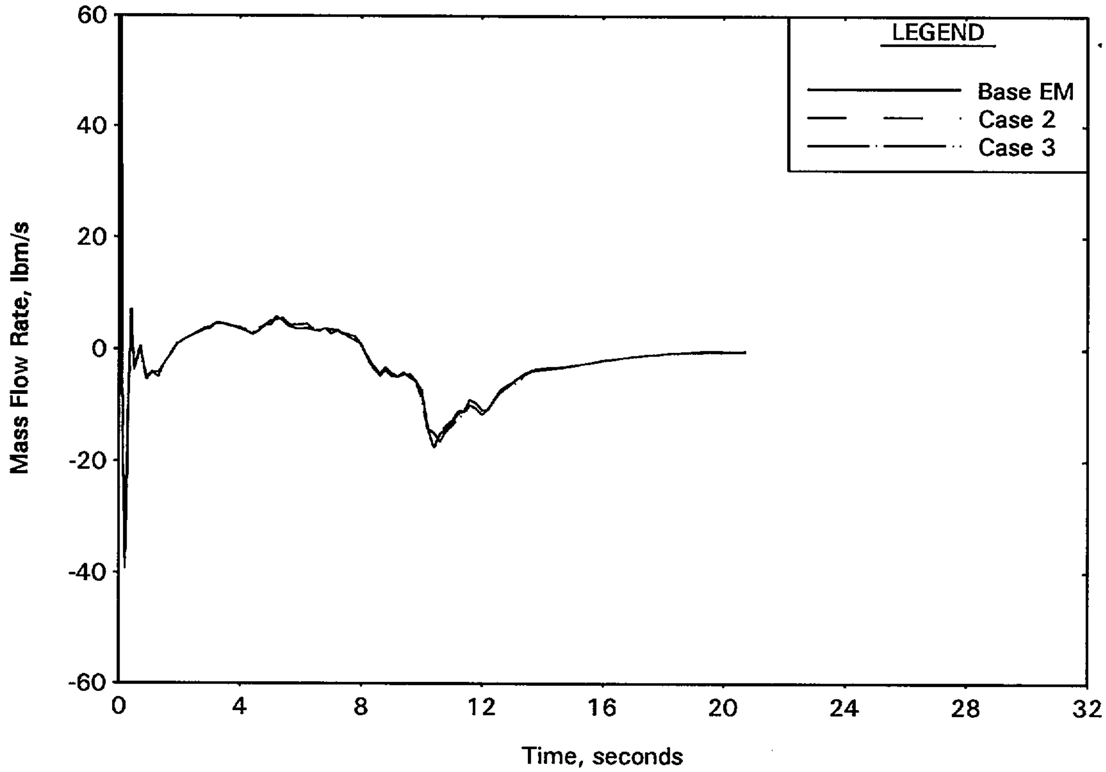

FIGURE 6. OTSG Core Flooding Rate
2.5-ft Axial Peak.

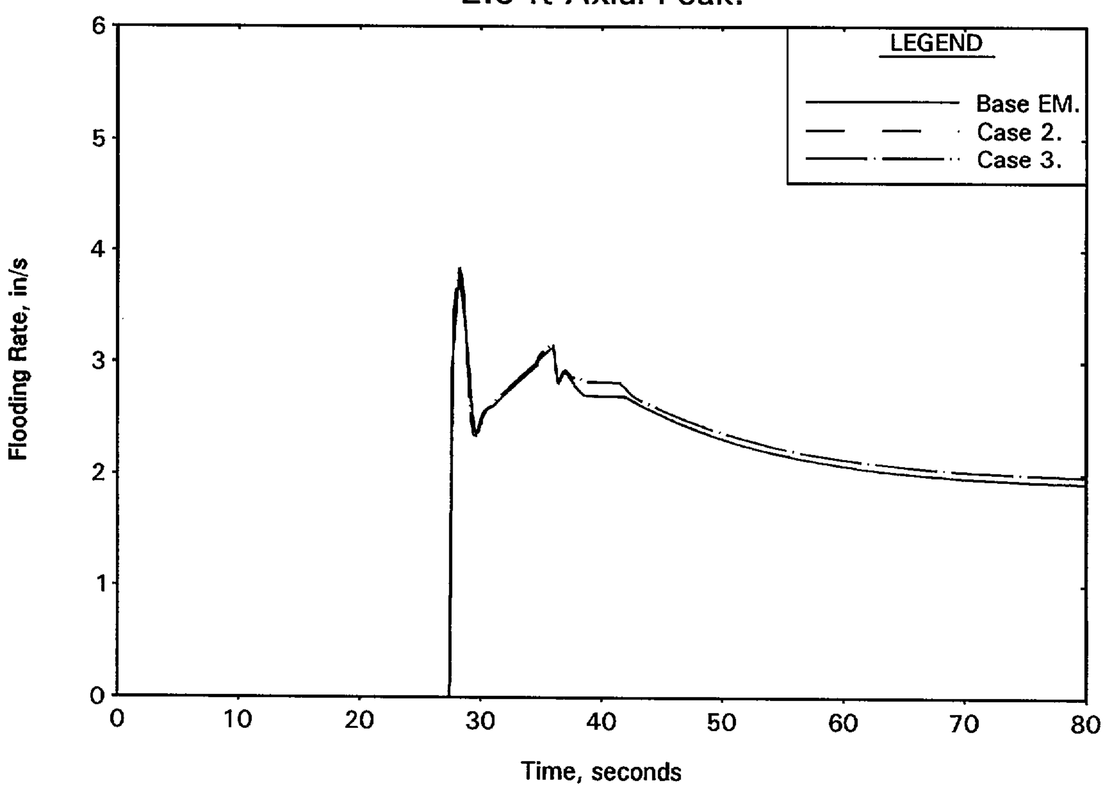

FIGURE 7. OTSG Hot Spot Vapor Temperature
2.5-ft Axial Peak.

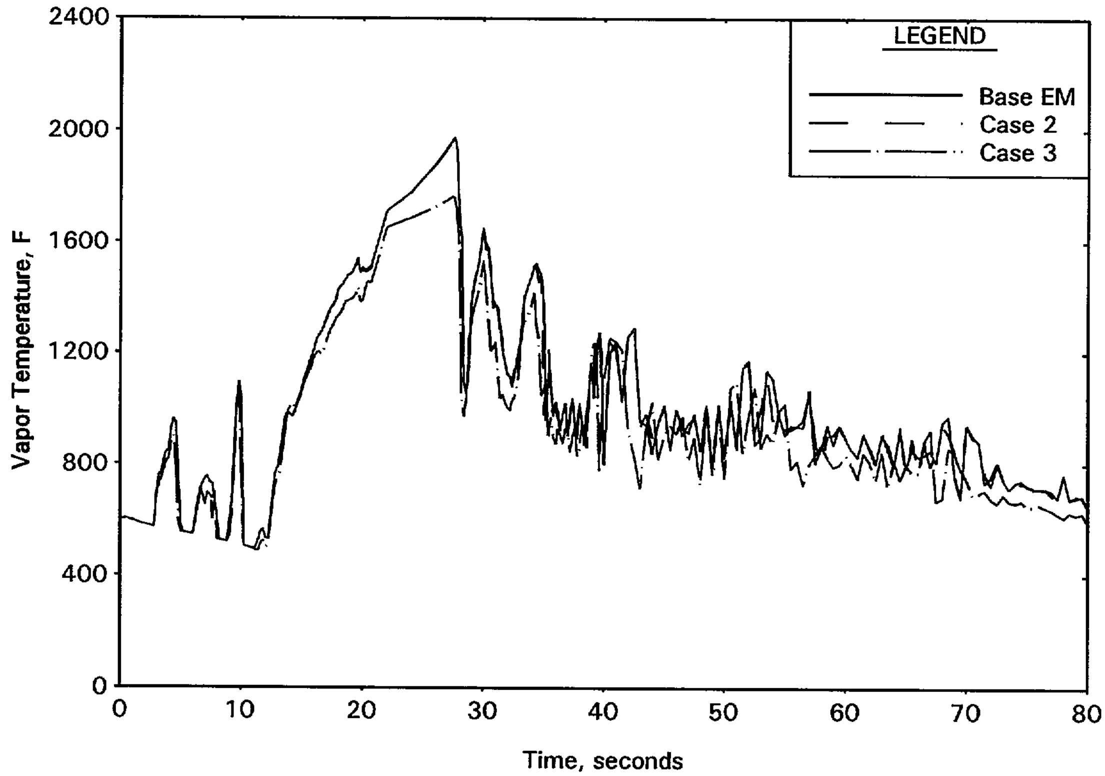

FIGURE 8. RSG Unruptured Node PCT-Node 15
9.7-ft Axial Peak.

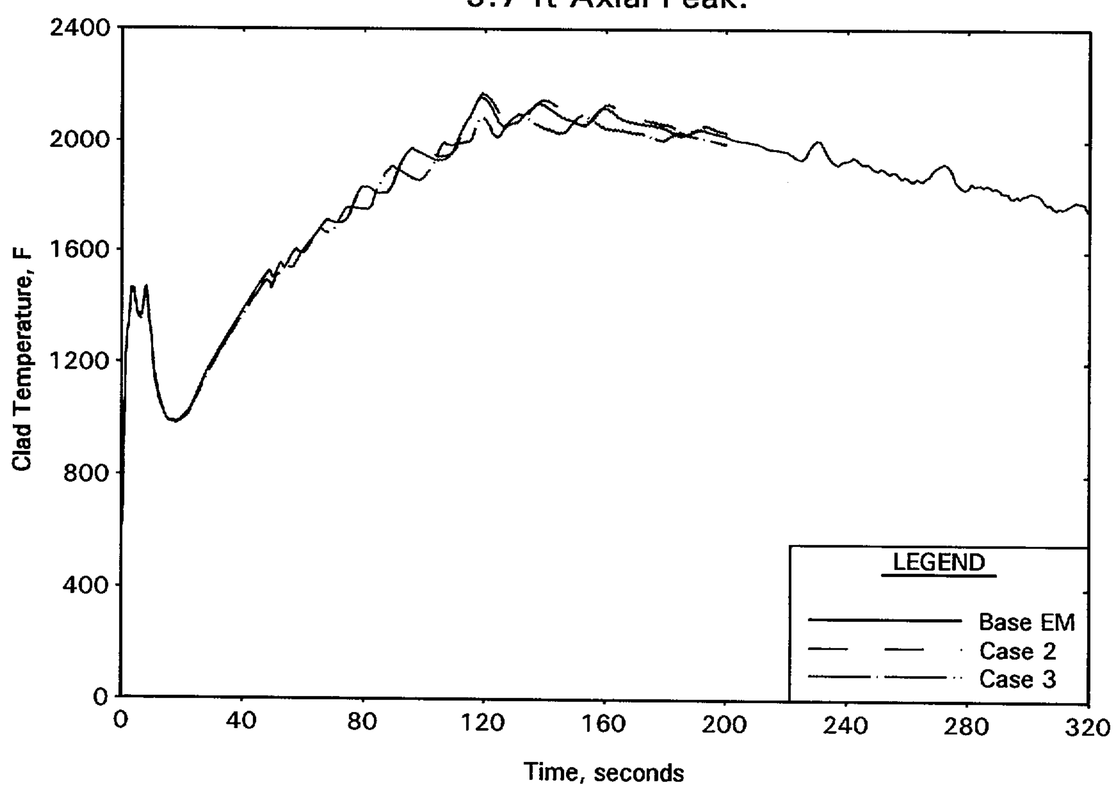

FIGURE 9. RSG Ruptured Node PCT-Node 17
9.7-ft Axial Peak.

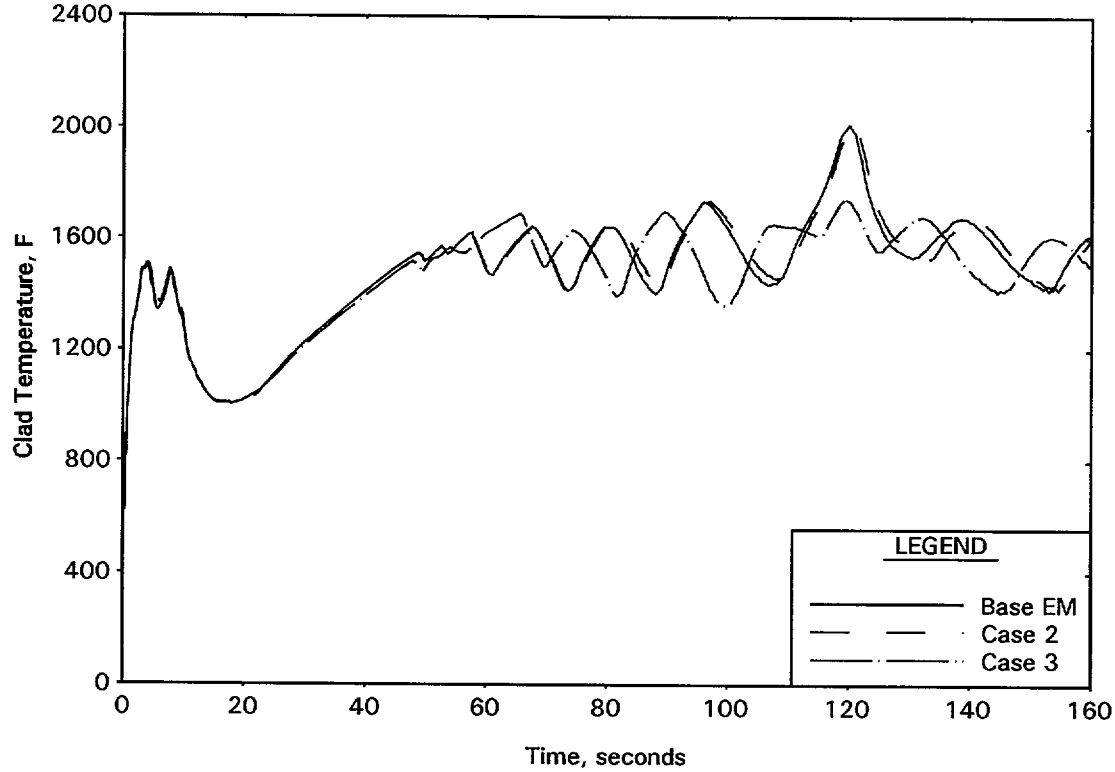

FIGURE 10. RSG Blowdown Hot Channel Flow At PCT Location
9.7-ft Axial Peak.

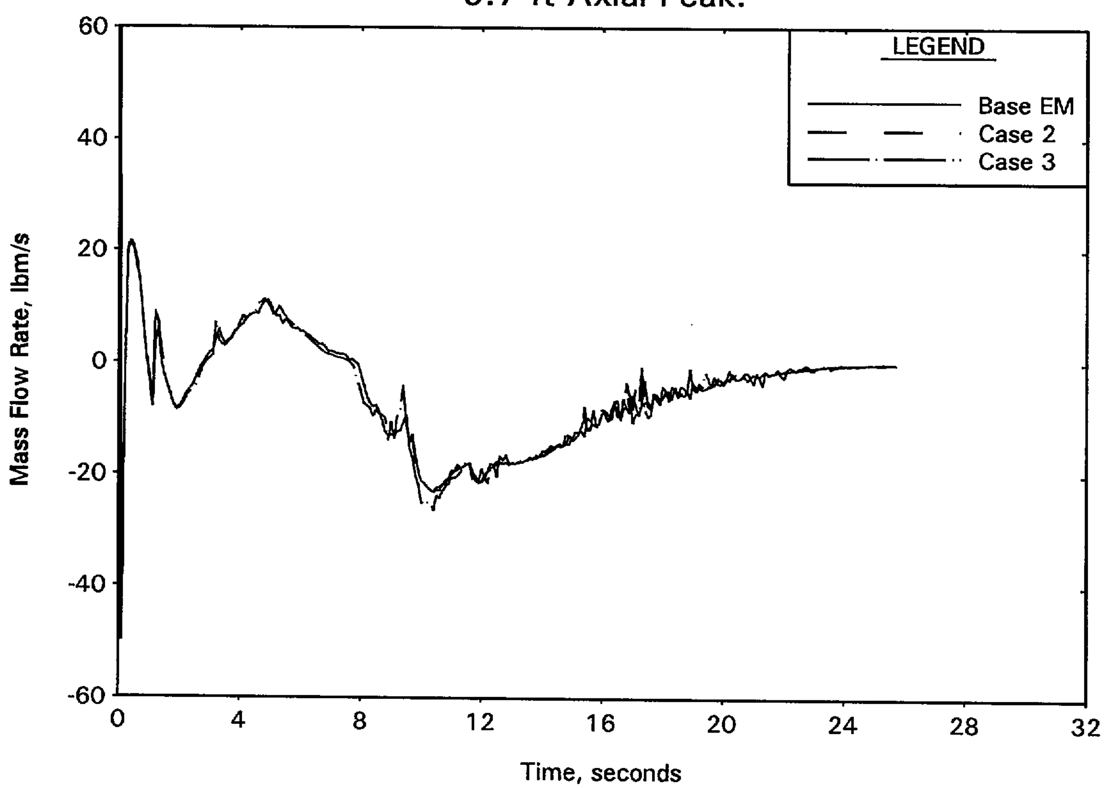

FIGURE 11. RSG Core Flooding Rate
9.7-ft Axial Peak.

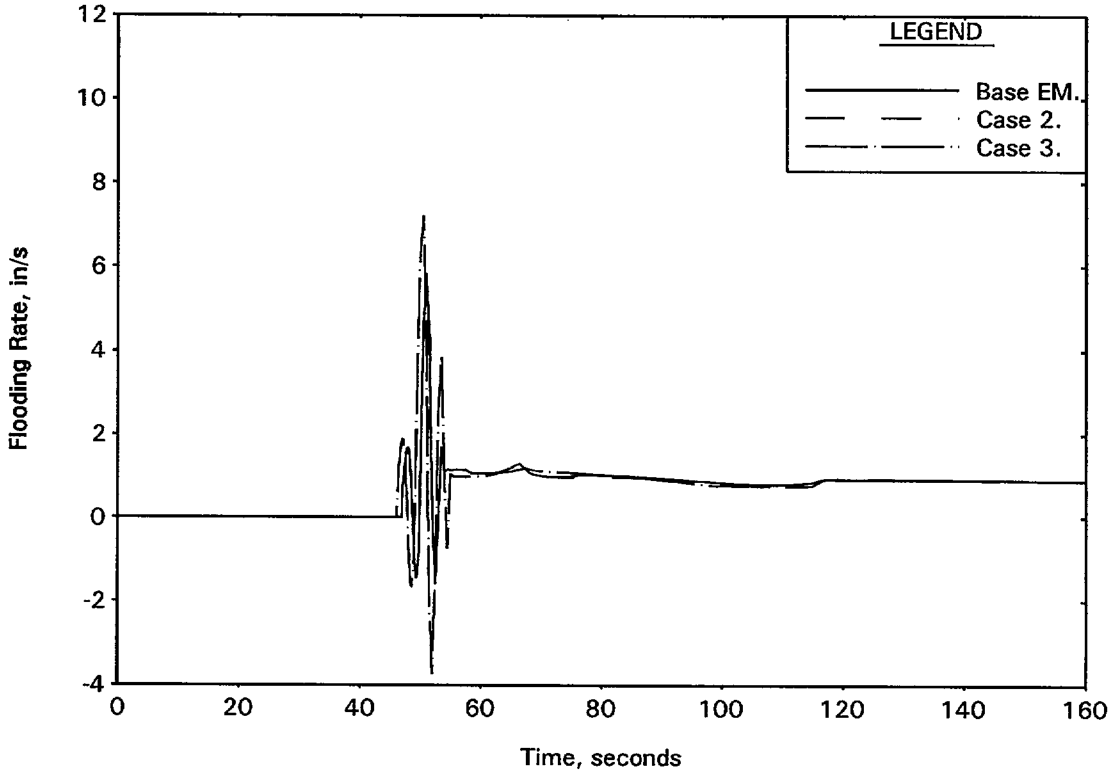

FIGURE 12. RSG Hot Spot (Node 15) Vapor Temperature
9.7-ft Axial Peak.