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# A Review of Recent NRC-Sponsored Station Blackout Analyses

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# 1 Background

## 1.1 Introduction

NRC and EPRI have had a long-running series of technical discussions about the best methods for analyzing thermally-induced steam generator tube rupture (ISGTR). ISGTR is a safety concern in postulated nuclear power plant severe accidents involving high reactor coolant system (RCS) pressure, especially when one or more steam generators are depressurized. Analysis of ISGTR is challenging, even by severe accident standards, since these accidents involve a number of complex, interacting phenomena, including the structural behavior of defected steam generator tubes, creep rupture behavior of the hot leg and surge line piping, natural convection of hot gasses in a complex geometry, convective and radiative heat transfer between high temperature gasses and adjacent structures, and core degradation. As in all severe accident studies, the uncertainties in operator actions and the possibilities of additional equipment failures further compound the difficulty of obtaining definitive results.

In this report, we first review the status of various unresolved differences between the NRC and EPRI analysis methodologies. We then discuss recent NRC-sponsored work and assess their impact on these differences.

## 1.2 Previously Identified Differences between NRC- and EPRI-Sponsored Calculations

The key result of an ISGTR analysis is predicting whether one or more steam generator tubes will fail prior to the failure of another RCS component, usually the surge line or hot leg. If a tube failure occurs first, this can allow radioactive materials to be released to the environment through the secondary side of the steam generators. On the other hand, if the hot leg or surge line fails first, the RCS will depressurize and largely eliminate the threat to the tubes.

The likelihood that the tubes will fail before another RCS component has generally been found to be higher in NRC-sponsored studies than in those performed for EPRI. In previous work, we have identified what are believed to be the most important causes for these differences in results:

1) Neglect of <u>thermal radiation</u> between hot gasses and the surface of the hot leg in the SCDAP/RELAP5 code used for most NRC-sponsored calculations. Industry calculations with a standalone detailed radiation model indicate that radiation is the dominant heat transfer mechanism in the hot leg. Also, sensitivity calculations indicate that the neglect of radiation heat transfer greatly increases the probability that the tubes will be calculated to fail prior to the hot leg.

2) The use of <u>different methodologies to estimate the flow rates of gasses in the hot legs and steam generator tubes</u>. In particular, the NRC calculations nearly always assume a steam generator to hot leg natural circulation flow rate ratio (“recirculation ratio”) of 2, based on an interpretation of scale model experiments run at Westinghouse. EPRI contractors, on the

other hand, use a simplified analytical formulation implemented in the MAAP code. If the fraction of the tubes carrying flow from the inlet plenum to the outlet plenum is assumed to be 50 percent, the MAAP model typically predicts recirculation ratios of 3 or higher for accidents occurring in Westinghouse 4-loop plants. All else being equal, use of a smaller recirculation ratio in the NRC calculations increases the temperature of the gasses entering the steam generator tubes.

3) Different methodologies are also used to estimate mixing of hot and cold gasses in the inlet plenum of the steam generator. Mixing is often characterized by a "mixing fraction" *f*. This constant is set to a value around 0.85 in most NRC calculations, again based directly on the scale model experiment results. MAAP contains a plume model for analyzing the mixing process and obtains similar values for *f* in full-scale Westinghouse plants. Taken together, the recirculation ratio and mixing fraction characterize the relative values of the gas temperatures heating the hot legs and the *average* steam generator tubes. Further, in MAAP calculations the temperatures of a relatively small number of tubes receiving the hottest gas from the inlet plenum are also calculated. In most NRC calculations, only the average tube behavior is calculated. All else being equal, this difference makes the EPRI calculations more conservative by exposing a small number of tubes to relatively high gas temperatures.

4) Different modeling details and assumptions in some NRC calculations have resulted in clearance of the loop seals in the cold legs and at the base of the core barrel. Clearance of two or more loop seals gives rise to a strong "unidirectional" flow of hot gasses that greatly increases the likelihood of tube failure. Clearance of more than one cold leg loop seal was assumed not to occur before hot leg failure in the EPRI calculations (based on an interpretation of what were considered the most realistic of the various available RELAP calculations), and clearance of the core barrel loop seal is calculated to occur long after hot leg failure in MAAP.

5) The more recent NRC-sponsored SCDAP/RELAP5 calculations estimate the time of hot leg failure by analyzing creep rupture of the stainless steel hot leg piping using a simplified Larson-Miller formulation that ignores the presence of the adjacent nozzle. EPRI-sponsored work uses the same technique but typically focuses on the rupture of the low alloy steel hot leg nozzle safe end area without considering any stiffening effect provided by the adjacent stainless steel. Neither of these simplified methodologies considers the effect of bending stresses. This difference in assumptions delays hot leg failure in the NRC calculations, since the stainless steel is considerably more resistant to creep rupture.

6) Recent EPRI studies have utilized a detailed model for the behavior of steam generator tubes exposed to high temperatures. This model, based on NRC-sponsored work performed at Argonne National Laboratory, credits the possibility that sufficiently short cracks in steam generator tubes will "pop-through" the tube wall and leak without rupturing, analogous to the way that design basis tube rupture accidents are analyzed. NRC calculations do not credit this effect; i.e., any defect exposed to high pressure and high temperatures that penetrates all the way through the tube wall is treated as a rupture.

Except for issue 3, these differences in assumptions all tend to reduce the margin to tube failure in previously reported NRC calculations compared to those performed for EPRI. When the assumptions in the MAAP calculations are made consistent with those of NRC, the two codes produce very similar results [Vierow et al., 2004]. Thus, we believe that the issues identified above are the most important differences between the NRC and EPRI analysis methods for ISGTR.

# 2 Recent NRC Standalone Calculations

NRC has initiated several efforts to help resolve these differences in methodology.

While not yet documented in a publicly available report, we understand that a detailed creep rupture analysis effort is currently being conducted at ANL using the ABAQUS finite element code. This analysis will hopefully shed light on whether simplified Larson-Miller analyses are adequate for assessing hot leg failure, and, if so, whether the nozzle safe end region or the hot leg piping will fail first (issue 5 in the list provided above).

In a meeting between NRC and industry held in 2004, it was stated that the relatively rapid uncovering of the core barrel by the receding water level in SCDAP/RELAP5 calculations had been traced to an improper nodalization of this region. This should resolve issue 4 unless multiple clearing of cold leg loop seals is predicted. The probability of the latter is believed to be low, especially if realistic modeling of the core bypass flow area and reactor coolant pump seal LOCAs is employed.

A set of steady-state CFD calculations of the hot leg and steam generators was performed by NRC to provide insights into natural convection-related differences summarized above as issues 2 and 3 [Boyd et al., 2004]. Key findings from this study are:

- The fraction of the total number of tubes carrying flow from the steam generator inlet plenum to the outlet of the steam generator should be 50 percent. This can be contrasted with the value of 35 percent assumed in early EPRI and most NRC analyses that were based on the results of steady-state scale model experiments. The 50 percent result from the CFD calculations agrees with an EPRI assessment that concluded that the scale model experiments demonstrated close to a 50-50 split for transient experiments. This ratio influences the calculated magnitude of the steam generator flow and thus the recirculation ratio in MAAP calculations.
- A target value for the recirculation ratio in SCDAP/RELAP5 modeling should be set to 2.7. This is considerably closer to the value calculated by MAAP (3.0 or larger depending on gas density and other factors) than is the 2.0 assumed value used in previous NRC analyses.
- The mixing fraction in the inlet plenum should be set to 0.81, slightly lower than the value of 0.85 assumed previously (which is also approximately the value calculated by MAAP).

# 3 Recent NRC-Sponsored Integrated SCDAP/RELAP5 Calculations

As a follow-up to the NRC CFD calculations, two recent draft reports document new SCDAP/RELAP5 calculations [Fletcher and Beaton, 2006a and 2006b]. The two reports detail base-case and uncertainty sensitivity studies of station blackout accidents, focusing on issues related to ISGTR. A formal Phenomena Identification and Ranking Table exercise was conducted as part of the uncertainty analysis. This assessment changed some of the base case assumptions and also informed an uncertainty analysis. The review provided below focuses on the base-case report, but we will comment on a few of the notable findings of the uncertainty analysis.

A major, surprising conclusion of the base-case analysis is that the hottest tubes will fail before the hot leg or surge line, even if they have no corrosion damage. This represents a considerably more pessimistic result than was obtained in most previous NRC studies.

The major changes in the base-case calculation assumptions relative to previous work are as follows:

1) Based on a comment by ACRS, the value of the hot leg flow is calculated using essentially the same formula used in MAAP. This replaces an energy scaling argument based on experiment that has been the previous practice.
2) The fraction of tubes carrying flow from the inlet plenum to the outlet plenum was increased from 0.35 to 0.41.
3) The recirculation ratio continues to be set to 2.
4) The inlet plenum mixing fraction continues to be set to 0.85.
5) A parametric scheme was implemented for evaluating the temperature of the hottest tubes in the steam generator relative to the average tube. This is used together with the average tube temperatures calculated by SCDAP/RELAP5 to estimate the maximum tube temperature.
6) Thermal radiation in the hot leg is now modeled.
7) Nodalization of both the core and the steam generator tubes is more detailed than in previous SCDAP/RELAP5 analyses.
8) Changes characterized as minor were made in the modeling of the surge line and pressurizer spray system.

The impact of these individual changes on the results, and how these compare to the assumptions used in the EPRI-sponsored work are discussed below.

# 4 Implications of Recent Work for ISGTR Modeling Issues

## 4.1 Hot leg radiation (Issue 1)

The methodology used by NRC to calculate thermal radiation in the most recent calculations is not documented in the reports. However, it is stated that around the time of hot leg failure, thermal radiation is about 60 percent as large as convection. Further, 15 percent of the energy transported to the upper hot leg wall is radiated to the cooler lower wall. When the convective and radiative heat transfer coefficients were doubled in a SCDAP/RELAP5 sensitivity calculation, a significant increase in the margin to failure was obtained; the latter is qualitatively consistent with EPRI sensitivity studies.

EPRI utilizes a detailed, standalone coupled convection/thermal radiation model to determine appropriate values for the coefficients used in the simplified MAAP model [Fuller, et al., 2002]. This model predicts that thermal radiation is about 3 times as large as convection around the time of hot leg failure [Kenton, 2000]. Assuming that convection is modeled similarly in the two codes, this implies that the total heat transfer to the hot leg would be roughly 2.5 times larger in MAAP than in the NRC base case calculations; i.e., would be even greater than in the NRC uncertainty calculation.

In a separate NRC-sponsored study performed at INEL, it was concluded that thermal radiation would peak at about 3 times the magnitude of convection, very similar to the result obtained by EPRI [Bayless et al., 1995].

The reason for the modest contribution of thermal radiation in the latest NRC calculations should be investigated, since this can be expected to substantially change the results that would be obtained using the EPRI methodology.

## 4.2 Recirculation ratio (issue 2)

As noted above, the NRC is now using essentially the same formula as in MAAP to calculate the absolute magnitude of the counter-current hot leg flow. However, the parameters in the SCDAP/RELAP5 calculations are still explicitly tuned to give a steam generator flow rate that is twice that of the counter-current flow in the hot leg. The flow rate ratio, rather than the absolute value of the flow rate, primarily controls the gas temperature experienced by the hot leg relative to that seen by the tubes. Thus, we do not expect that the change made by NRC in how they calculate hot leg flow will make a substantial difference in the relative timing of hot leg and steam generator creep rupture.

The authors of the earlier NRC CFD study acknowledged that some judgment was necessary to translate their results, which were performed under steady-state conditions, to the transient case of interest for the accident. Indeed, the recirculation ratio they calculated was shown to depend strongly on the bundle heat transfer rate. This is expected, since a high rate of heat transfer causes the gas flowing up the “out” tubes to cool off quickly, reducing the hydrostatic head imbalance across the bundle that drives the flow. For the case of a depressurized steam generator, we expect the heat transfer rate to depend on the tube heat-up rate; i.e., most of the heat is deposited in the tube material rather than being convected to the steam generator secondary. The CFD report does not state precisely what boundary conditions were applied for each of the sensitivity cases, but apparently this was done with a constant external temperature and heat transfer coefficient, rather than a term that reflects the heat capacity of the tube wall and an assumed heat-up rate.

A related issue is the number of tubes carrying flow in the "out" direction from the inlet plenum to the outlet plenum. This affects the recirculation ratio calculated in MAAP by changing the pressure drop caused by flow in the tubes. (A simplified closed-form analysis indicates that the recirculation ratio increases as the 2/3 power of the fraction of tubes carrying the "out" flow). The latest NRC report provides the following justification for a change in this number:

> For the base case analysis presented in Section 3.2, flow coefficients in the four SG inlet plenum regions of the SCDAP/RELAP5 model were adjusted to achieve the above target values for hot leg $C_D$, hot and cold mixing fractions and recirculation ratio. The model was also modified to represent a desired 41%/59% hot/cold split of the SG tube regions. Recent analyses (References 8 and 9) had assumed a 50%/50% tube split. (It is noted that in the earlier analyses a 35%/65% split was used, based on Westinghouse $1/7^{th}$-scale transient tests. The change to a 50%/50% split was subsequently made based on Westinghouse $1/7^{th}$-scale steady state tests).

This is confusing, and believed incorrect. The original assumption of a 35/65 split was used by both NRC and EPRI based on an interpretation of the early <u>steady-state</u> experiments run in the Westinghouse $1/7^{th}$-scale facility. EPRI later recommended a 50/50 split, based on an interpretation of <u>transient</u> tests run at Westinghouse as well as a physical argument that an ever-increasing temperature difference between the core and the upper plenum that would develop under transient conditions should serve to create a pressure difference that would overcome the resistance to flow of relatively stagnant tubes seen to persist in the steady-state tests. It appears that the NRC's use of 41/59 in the most recent analyses is derived from steady-state CFD results, whose definitiveness in this regard is arguable.

Given that NRC independently sets the recirculation ratio, the main effect of using a fewer number of "out" tubes in their analysis would be to increase the velocity of gas and thus the calculated convective heat transfer coefficient in the tubes. This will probably have relatively little effect, and the NRC results are mainly dependent on the assumed recirculation ratio, not the flow split between out-flow and back-flow tubes. On the other hand, assuming 41 percent "out" tubes in a MAAP analysis would have a more significant effect by reducing the recirculation ratio, which is calculated by the code.

Granting the uncertainties in the CFD calculations, it is unclear why NRC is continuing to use a value of 2 for the base case recirculation ratio (indeed, the maximum value considered in their uncertainty evaluation was only 2.3). Even though this is close to the values observed in the 1/7-scale experiments, there appears to be ample evidence to question its relevance to full-scale experiments. Besides the CFD calculations, the simplified MAAP model computes a value close to 2 for the 1/7-scale experiments, but much larger values for the full-scale case even when, as in the NRC calculations, a significant number of the tubes (10 percent) are assumed to be plugged.

We expect this issue will be relatively difficult to resolve, since performing transient CFD calculations could be beyond the state-of-the-art.

### *4.3 Mixing in inlet plenum (issue 3)*

The NRC CFD calculations resulted in estimated mixing fractions *f* in the range from 0.81 to 0.93, with larger values signifying better mixing and less thermal challenge of the tubes. The MAAP plume model calculates values around 0.85 or slightly larger for the reactor scale case in Westinghouse plants. Thus the continued NRC assumption of 0.85 does not represent a departure from the previous work.

Of more significance is a new parametric scheme introduced by NRC for evaluating the temperature of a small fraction of the tubes that receive less well-mixed and thus hotter gas from the hot leg. A “normalized temperature ratio” is defined as follows:

$$NTR = \frac{T_{hottest\ tube} - T_{coldest\ tube}}{T_{hot\ leg} - T_{coldest\ tube}}$$

The quantities used in this expression are all gas temperatures. The numerator represents the difference between the hottest gas temperature entering any tube (the temperature of gas entering the tubes carrying “out” flow from the inlet plenum is denoted $T_{ht}$ in Figure 1) and the coldest gas returning from the outlet plenum of the steam generator ($T_{ct}$ in Figure 1). The denominator represents the difference between the hot gas entering the inlet plenum from the hot leg ($T_h$ in Figure 1) and $T_{ct}$. While unrealistic, note that a value of 1 would indicate that one or more tubes would see completely unmixed gas from the hot leg.

The NRC base case calculation utilizes a value of 0.625 for *NTR*. NRC personnel have stated that this is taken from Figure 19 in Boyd et. al [2004].

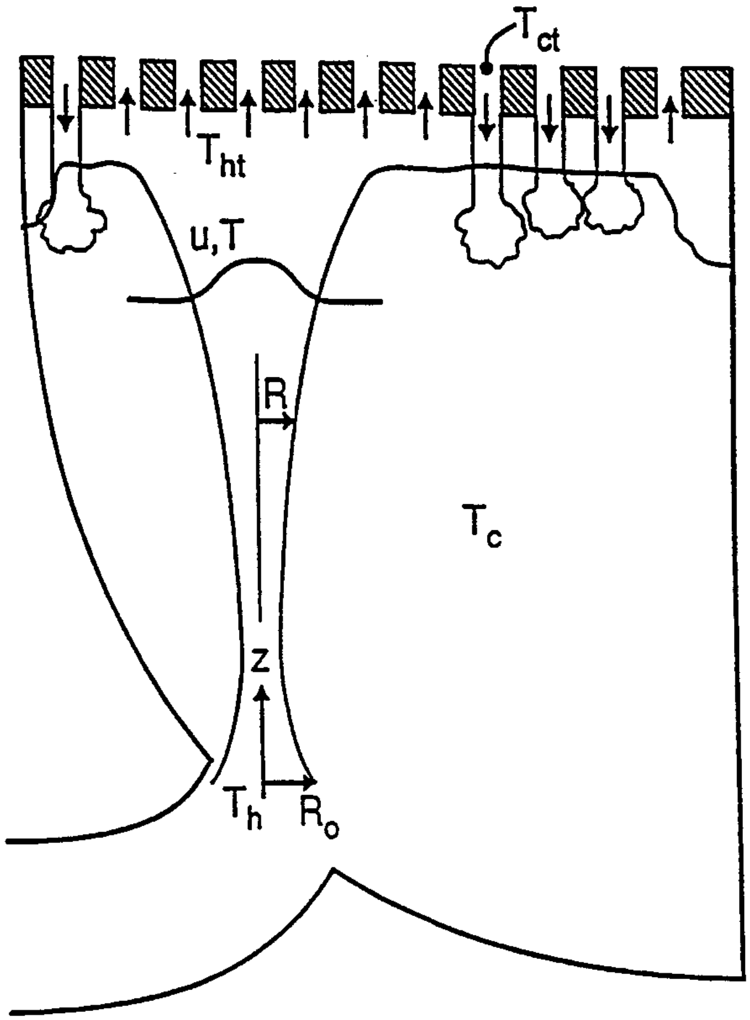


Figure 1: Schematic Depiction of Inlet Plenum Mixing, as Represented by the MAAP Model. The high-temperature gas entering the inlet plenum from the top of the hot leg forms a plume that entrains the relatively cold gas returning from the outlet plenum. The most severely challenged tubes experience the least well-mixed gas drawn from the center of the plume.

MAAP calculates the equivalent of *NTR* by modeling the inlet plenum mixing process using a mechanistic (if admittedly idealized) plume model. In this model, schematically illustrated in Figure 1, "average" "out" tubes receive fluid from plume-average conditions (whose value can be associated with the mixing fraction *f*), and the hottest tubes receive fluid from the center of the plume. The center of the plume is least mixed with the cold gas returning from the outlet plenum via the "back" tubes and is thus the hottest region. For a typical Westinghouse 4-loop design, the peak NTR calculated by the MAAP plume mixing model is around 0.39; the corresponding value for the average tubes is about 0.28. These values increase to about 0.45 and 0.35, respectively, if the recirculation ratio is reduced to 2.0 as in the NRC calculations (this may be somewhat misleading since the recirculation ratio was higher than 2 in the CFD calculations from which the *NTR* was obtained). Thus, the MAAP results exhibit a smaller variation in temperatures across the plume than is seen in the NRC calculations.

The introduction of *NTR* into the NRC calculations is a welcome advance since it explicitly allows consideration of the increased thermal challenge faced by a relatively small number of tubes seeing higher temperatures. Resolving the reasons for the larger *NTR* values calculated by NRC's CFD model compared to the MAAP mixing model will be challenging. One fundamental issue is whether normalizing the temperatures using the return gas temperature is the best choice when applied to transient simulations. To shed light on this question, it would be helpful to understand how well the average tube behavior calculated by SCDAP/RELAP5 results compares the average tube value for *NTR* calculated by the CFD calculations. If these quantities do not compare well, this could suggest that it would be more appropriate to parameterize the difference of the peak and average tube inlet gas temperatures, rather than their differences to the return gas temperature. Figure 19 of Boyd et al. indicates that the most likely value of *NTR* is about 0.3, nearly the same as in the MAAP calculation, but there is a pronounced tail to the distribution that skews the average value higher.

To assess the accuracy of the MAAP model, we can compare the results of simulations of the Westinghouse tests to the data in those tests. The table below shows the mixing fraction *f* computed by the plume model along with a factor *g* that characterizes the breadth of the temperature distribution; this is defined by:

$$g = \frac{T_{ht,\max} - T_{ht,avg}}{T_{ht,avg} - T_c}$$

In the MAAP model, *g* depends directly on a plume parameter $\lambda$ whose value is taken from the fluid mechanics literature and regarded as constant.

| Test: | Overall mixing fraction *f* | | Peaking factor *g* | |
|---|---|---|---|---|
| | Experiment | MAAP model | Experiment | MAAP model |
| S1 | 0.87 | 0.75 | 0.61 | 0.75 |
| S2 | 0.89 | 0.74 | 0.38 | 0.75 |
| S3 | 0.86 | 0.74 | 0.41 | 0.75 |
| S4 | 0.85 | 0.88 | 0.26 | 0.75 |
| T1 | 0.79 | 0.75 | 0.66 | 0.75 |
| T2 | 0.83 | 0.75 | 0.96 | 0.75 |
| T3 | 0.77 | 0.66 | 0.65 | 0.75 |
| T4 | 0.86 | 0.68 | 1.4 | 0.75 |

Two observations can be made from this table:

1) The overall degree of mixing in the experiment is usually conservatively under-estimated by the MAAP model. This is evidenced by the generally lower values of *f*. Similarly, while not shown here MAAP computes conservatively higher values for the average temperature experienced by the “hot” tubes, $T_{ht}$. MAAP typically calculates larger values for $f$ in full-scale simulations (around 0.85, close to what is seen in most of the experimental data).
2) As characterized by $g$, the <u>variation</u> in temperatures experienced by the outflow tubes in the experiments is conservatively over-predicted by MAAP in the case of the steady-state experiments, but is inconsistently conservative in the 4 transient experiments.

As a result, the temperature of the hottest tubes $T_{ht,\max}$ is generally characterized in a conservative fashion by the MAAP model for the steady-state tests. However, the MAAP model is not necessarily conservative in all of the transient tests.

The variation in temperatures seen in the experiments seems higher in the transient experiments than in the steady-state experiments. The reason for this is not known, but the most obvious difference between these two sets of tests is seen in the envelope of the region of the tubesheet that contains the tubes that are carrying the flow away from the inlet plenum. This is a fairly symmetrical region in the case of the steady-state experiments, but is much more irregular in the transient experiments. The most variation in the transient experiments is seen in experiment T-4, which is also the experiment that exhibits the most asymmetrical “out” tube region. The MAAP model is steady-state, and cannot in any case explain such complex behavior.

When assessing the accuracy of the MAAP model for steady-state and transient experiments, it is worth emphasizing that the model assumes that the jet has a circular cross-section throughout its passage through the inlet plenum. In the model, the cross-section initially thins due to acceleration as the fluid turns upward and subsequently thickens due to entrainment of the surrounding, cooler gas. The actual jet, however, has somewhat of an elliptical shape after it leaves the hot leg and begins to traverse the plenum. The more the jet deviates from the idealized circular cross-section, the more entrainment that will occur over a fixed rise length, and thus the more entrainment of the surrounding medium will reduce the peak temperature. Since the MAAP model does not represent this elliptical shape, it is not too surprising that the experimentally observed entrainment is somewhat greater, and this may help explain why the difference between the model-calculated and measured *f* factor is largest for experiment T-4. This under-prediction in entrainment rate should mitigate the errors that may be incurred by under-predicting the normalized temperature spread (*g* factor) across the plume. In experiment T-4, for example, the peak temperature is under-predicted by the MAAP model by only 1C.

NRC qualified their CFD approach using steady-state experiment S3 [Boyd and Hardesty, 2003]. In view of the differences between the transient and steady-state experiments noted above, it is not clear whether the good results obtained for experiment S3 necessarily implies that CFD can accurately model a reactor-scale transient case.

### 4.4 Loop seal clearing (Issue 4)

The current set of calculations does not involve loop seal clearing, either in the cold leg or at the base of the core barrel. This is in accord with EPRI base-case assumptions and MAAP core water level calculations. While encouraging, additional discussion is necessary with NRC to confirm that this issue has also been resolved for cases with relatively large RCP seal LOCAs.

### 4.5 Hot leg creep rupture analysis (Issue 5)

As mentioned previously, the NRC calculations perform a simplified Larson-Miller analysis of the stainless steel hot leg to evaluate its failure time. Industry does the same analysis, but usually focuses on the low alloy steel material adjacent to the reactor vessel outlet nozzle safe end. This by itself causes a substantial delay in hot leg failure in the NRC calculations relative to those of EPRI.

This issue can best be addressed after the detailed finite element calculations currently being performed at Argonne become available.

While a complete description of the plant model was not provided, it was also noted in the course of this review that the NRC is using a surge line thickness of 1.41 inch (probably corresponding to 14" Schedule 160 pipe) and a hot leg thickness of 2.5 inch. Some of the MAAP TISGTR calculations have utilized a smaller surge line thickness. The larger thickness used by NRC could delay surge line creep rupture at least as much as some of the other calculation details, and any future comparison calculations should endeavor to make these parameters consistent.

### 4.6 Tube failure analysis (Issue 6)

The SCDAP/RELAP5 analyses characterize the threat to the tubes by calculating a "stress multiplier" that will cause tube failure to occur coincident with hot leg (or surge line) failure. How to calculate the stress multiplier for a given defect geometry is not discussed, and to our knowledge the NRC has not yet explicitly taken a position on the validity of crediting the possibility that crack "pop-throughs" need not necessarily result in tube rupture. Such behavior was seen in high-temperature testing of defected steam generator tubes at ANL and is the default modeling option in the EPRI PROBFAIL code.

### 4.7 Sequence definition issues

While unrelated to differences in the two codes, it is worth noting that the latest NRC calculations assume that all the steam generators become depressurized due to steam leaks through valves (equivalent to a leak area of 0.5 square inch). EPRI studies have generally concluded that depressurization was unlikely, so that having at most one steam generator depressurized is considered a reasonable yet conservative assumption. Based on past sensitivity calculations, this difference probably has a second-order effect on the peak tube temperatures calculated in deterministic calculations. Rather, this issue is much more important as an input to probabilistic evaluations of the likelihood of tube rupture. In such calculations, assuming all steam generators become depressurized will make the results more severe by quadrupling (for a 4-loop plant) the total number of tubes that are exposed to severe temperature/pressure conditions.

On a related issue, the NRC uncertainty analyses consider the effect of tube leakage on the results, but do not address the possibility that any of the primary system relief valves will stick open due to their long exposure to liquid water. Based on EPRI analyses, this would probably have a large, beneficial effect on the sequence progression. Similarly, only a small reactor coolant pump seal leakage rate was analyzed.

Finally, we note for completeness that other EPRI analyses have emphasized the overwhelming importance of operator intervention, in particular depressurization of the primary or secondary system and plausible efforts to extend the operability of turbine-driven auxiliary feedwater systems past the point of battery depletion [Fuller et al., 2000]. The current set of NRC calculations assumes no operator actions and a total loss of feedwater at time zero.

### *4.8 Miscellaneous issues*

Aside from the long-running issues discussed above, a few additional changes were made in the most recent NRC base-case calculation:

1) The nodalization of the core was increased. This is stated to make little difference in the results until after the time the first creep rupture is calculated. In this regard, NRC confirms conclusions of earlier EPRI studies that creep rupture will generally precede core damage, making the results insensitive to the pronounced analytical uncertainties associated with core melt progression.

2) The nodalization of the steam generator tubes was greatly increased to obtain a higher level of detail near the tubesheet. Not surprisingly, this is stated to have increased peak tube temperatures significantly, contributing to the large change that was seen for these tubes after the *NTR* concept was introduced. The MAAP model has a comparable degree of nodalization to the new SCDAP/RELAP5 model.

3) A trickle of fluid was allowed to flow through the pressurizer spray system. This is stated by NRC to make little difference in the timing of creep rupture.

4) A change was made to better represent the temperature of the fluid drawn into a surge line mounted on the side of the hot leg during periods when one or more pressurizer PORVs opened. The net effect is to lower the temperature of the inlet gas and reduce the likelihood of surge line rupture. In MAAP, the modeling is similar to that used in the previous NRC analyses. However, surge line rupture nearly always follows hot leg rupture; this is due primarily to crediting thermal radiation and secondarily to basing the creep rupture evaluation on the nozzle rather than the pipe.

The PIRT study touched on some detailed issues that have previously been discussed in EPRI/NRC exchange meetings:

1) NRC concluded that the rate of pressurizer emptying, which somewhat influences the detailed course of events, is controlled by CCFL at the pressurizer/surge line connection. In MAAP, the drainage rate is further limited by explicitly modeling the perforated plate that

covers this junction. We do not believe this hardware is represented in the RELAP model, and this difference may have a small influence on the results by delaying the emptying of the pressurizer.

2) Previous SCDAP/RELAP5 calculations generally neglected the loss of heat to containment, and that has been rectified. Because of uncertainties in the performance of the insulation, a range of heat losses from 2-8 MW (evaluated at normal operating temperatures) is assumed. This is in the range of the values assumed in MAAP calculations.

# 5 Conclusions

Recent NRC studies have resolved or at least narrowed some of the areas of disagreement between NRC and EPRI on ISGTR analysis methodologies. However, the net result from the recent NRC work is to greatly increase the perceived risk of thermally induced steam generator tube rupture.

Several key differences in the two approaches persist, and resolution of these differences should greatly affect the perceived risk. The most important of these differences is judged to be the treatment of thermal radiation and mixing in the inlet plenum of the steam generator. Of somewhat less importance is the smaller recirculation ratio assumed by NRC. The status of the various unresolved issues is summarized in Table 2.

Table 2: Summary of Key Differences in the ISGTR Analysis Methodologies used by NRC and Industry tied to MAAP and SCDAP/RELAP5. Except for Item 4, all these differences tend to increase the thermal challenges faced by the tubes when evaluated using the NRC method when compared to the EPRI methodology. Not listed are issues that are not associated with the two codes; i.e., accident sequence definition and how the structural evaluation of defected steam generator tubes is performed.

| Issue Number | Issue Description | NRC Position | EPRI/Industry Position |
|---|---|---|---|
| 1 | Hot leg radiation | Modeled, but contributes relatively little to heating of hot leg | Dominant mode of heat transfer in hot leg |
| 2 | Recirculation ratio | Explicitly set to 2, based on 1/7 scale model experiments | Calculated by a simple model to be about 2 for the scale model experiment and 3 or larger in reactor scale case |
| 3 | Mixing in inlet plenum | Relatively wide temperature distribution, based on standalone steady-state CFD calculations | More narrow temperature distribution, based on an idealized, closed-form steady-state plume model |
| 4 | Loop seal clearing leading to unidirectional flow in steam generators | Appears to be considered unlikely, at least for small RCP seal LOCAs | Considered unlikely |
| 5 | Hot leg creep rupture | Simplified Larson-Miller analysis of stainless steel hot leg | Simplified Larson-Miller analysis of alloy steel located adjacent to nozzle safe end |

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