Technologies LLC

DRAFT

EPRI Perspective on Thermally-Induced Steam Generator Tube Rupture Issues

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Outline

- Describe the various steps in an evaluation of thermally-induced steam generator tube rupture (TISGTR)
- For each step, highlight specific areas where NRC and Industry approaches have differed
  - Also summarize benchmarking data that is available to help resolve these issues
- Note: Not every analyst will approach TISGTR the same way; our perspective is based on the EPRI Steam Generator Tube Integrity Risk Assessment Methodology (TR-107623-V1)

Key Question: What Ruptures First?

- We focus today on SBO with one or more depressurized SGs (“high/dry/low” accidents)
- High temperatures that develop threaten tubes and also hot legs and surge line
- Thermally-induced tube rupture is of concern only if a hot leg or surge line does not fail first
  - Such failures cause system to rapidly depressurize
- While hot legs inevitably see higher temperatures than tubes, they aren’t corroded and respond more slowly as temperatures increase
- Needing to know only the order in which things fail makes the results more robust than they would otherwise be

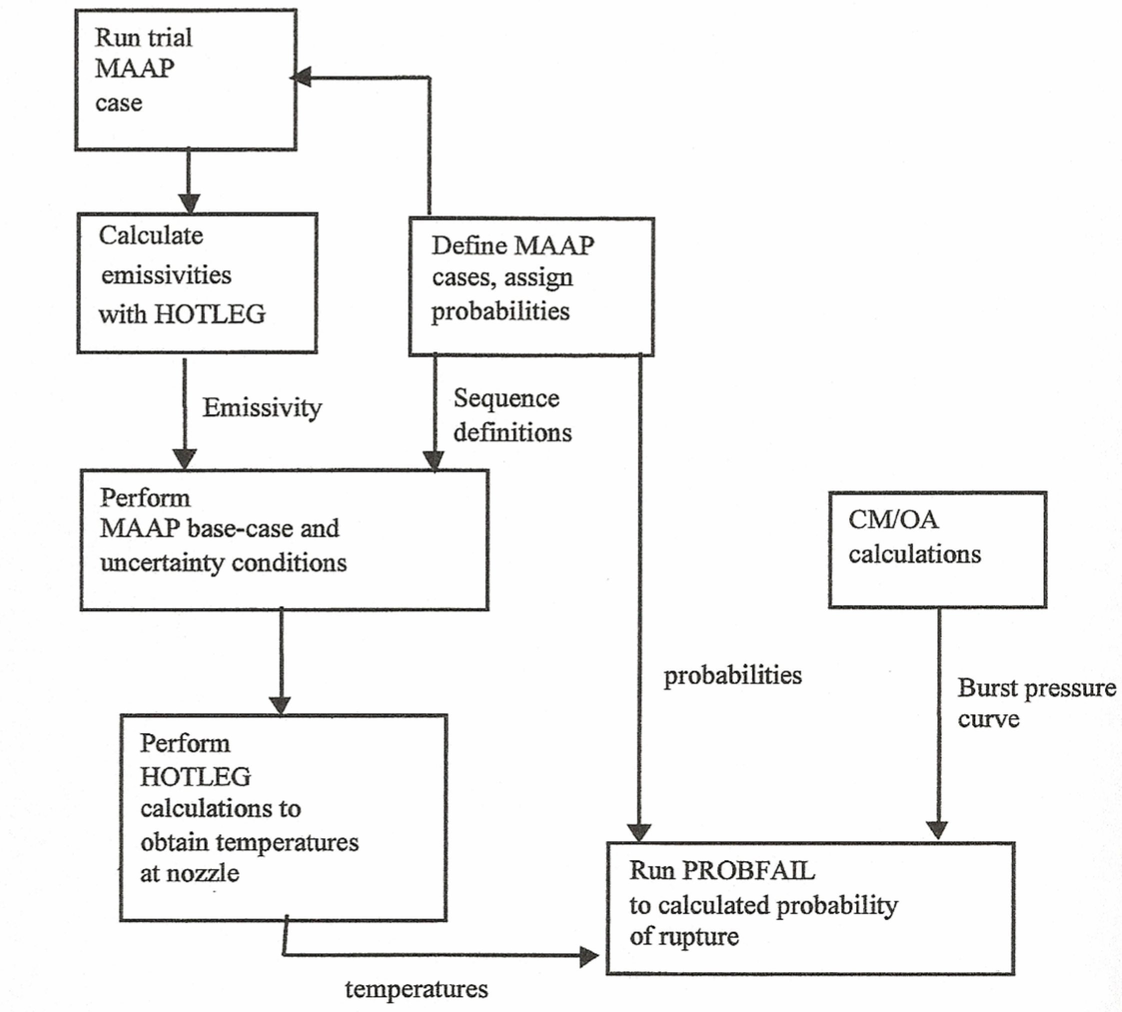
Good News/Bad News

- TISGTR analyses are complicated due to the presence not only of the usual severe accident complications, but also the need to:
  - Treat complex natural circulation flow patterns
  - Model structural failure, including corroded tubes
- The good news is that one of the most difficult complications, uncertainties in core degradation processes, are second order because:
  - Core damage affects hot leg, surge line, and steam generator tube temperatures more or less in same way
  - Geometry changes generally happen after something fails

Steps in a Complete Analysis

- EPRI methodology covers HRA, PRA, as well as deterministic analyses; focus today on last of these
- A series of MAAP calculations of temperatures and RCS pressure are performed to reflect T/H uncertainties, e.g. high, nominal, and low thermal radiation estimates
- “Run-time” code calculation is performed (or taken from a SG condition monitoring/operational assessment program) to characterize spectrum of expected tube defects
- Given these inputs, PROBFAIL code estimates the probability a tube fails before hot leg or surge line

EPRI Methodology: T/H and Structural Calculations



Sequence Definition

- In the interest of time, will not discuss operator actions and related sequence definition issues today, but we note that there have historically been significant differences in approach on:
  - Seal LOCA modeling
  - Loop seal clearing
  - Likelihood of steam generator depressurization
- Also, EPRI program has demonstrated that influence of operator actions can be overwhelming
  - For example, there are several ways that an operator might leverage availability of turbine-driven AFW
  - Some of these strategies can enormously extend the time available for recovery of power

I. Structural Evaluation

PROBFAIL Code

- Inputs:
  - Temperatures and pressures, usually from MAAP calculation
  - List of defect geometries from a “run-time” code, i.e. depths, lengths, and orientations predicted by Monte Carlo simulation applied to eddy current inspection results
  - Note that the run-time code may supply 100,000 or more such defect geometries to PROBFAIL; these represent a probability distribution of the dimensions of (say) ~100 actual defects in SG
- Outputs include:
  - Probability a tube will rupture prior to RCS depressurization
  - Timing of initial tube failure (to support operator action studies)
  - Total tube leakage rate and leaked mass prior to rupture

Overview of PROBFAIL Calculation

- For a given tube defect and 1 pressure-temperature history from a single code run (e.g. MAAP):
  - Calculate time-dependent probability that a given component (tube, hot leg, surge line) will fail at time t for a given temperature/pressure history
  - Combine these results to determine the probability a tube will rupture before something else
  - Option to credit possibility of pop-through without rupture
- Sum the above over all the defect geometries predicted by run-time code
- Sum the above over various MAAP runs' pressure-temperature histories

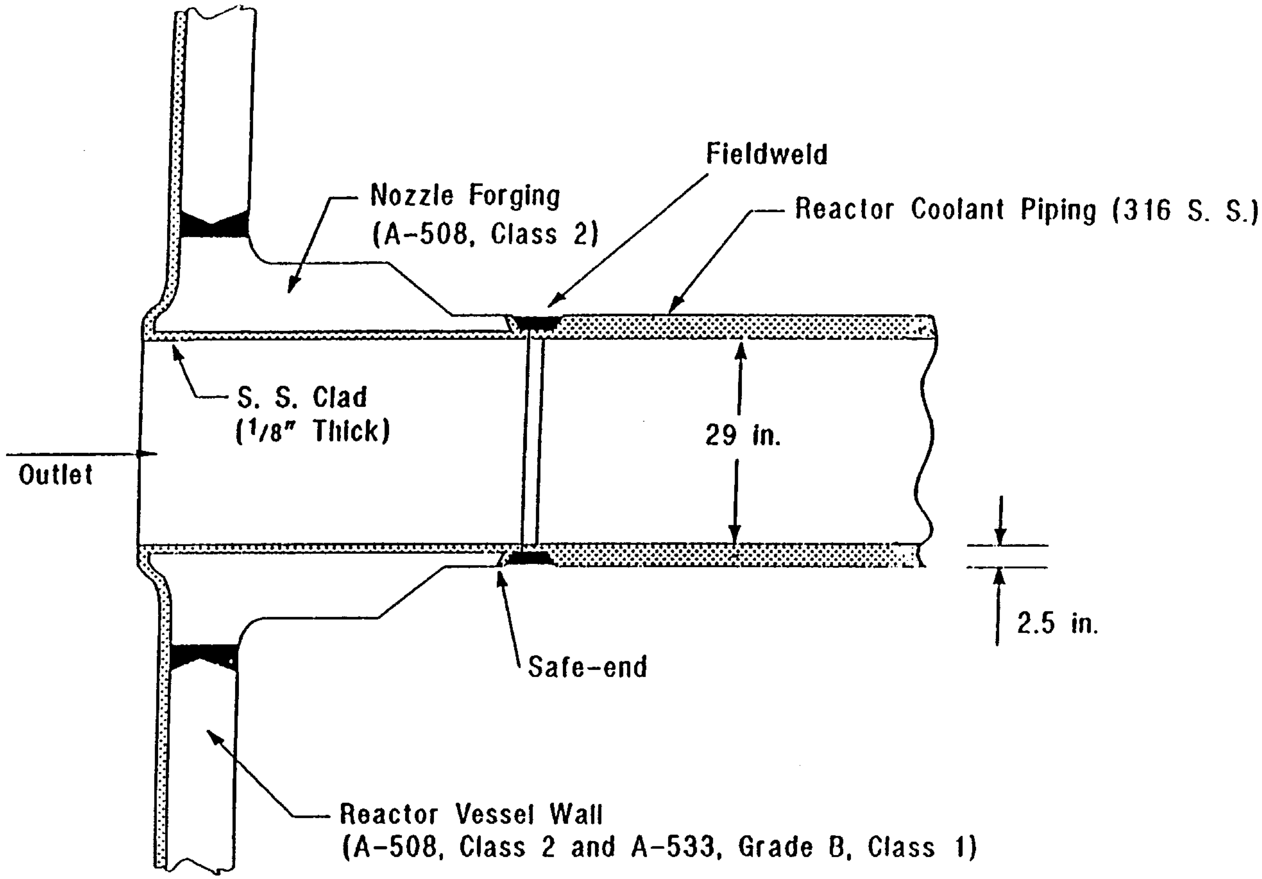
Summary of Uncertainties Treated by PROBFAIL

- Thermal-Hydraulic, by supplying a series of temperature/pressure histories, each weighted by "degree of belief"
- Tube defect geometry, by supplying a list of calculated depths and lengths from Monte Carlo simulation
- Defect location, by specifying the probability that a given defect sees "peak", "average", or "back" gas temperature
- Material properties: an advanced algorithm is used to account for uncertainties in Larson Miller correlations without having to assume failure times follow normal distribution as in NUREG-1570

Outstanding Issue: Hot Leg Failure

- Calculations performed for EPRI methodology usually calculate (as in NUREG-1150) probability hot leg <u>nozzle safe end</u> region fails
- Others (e.g. most SCDAP/RELAP5 calculations) calculate failure of hot leg <u>piping</u>
  - In Westinghouse plants, the hot leg is stainless steel and will fail considerably later than the alloy steel nozzle safe end
- Both approaches use a Larson-Miller type analysis based on hoop stress that ignores:
  - Thermal stresses
  - Restraint provided by adjacent structures
- Limited benchmarking data available (Stuttgart)

Westinghouse Hot Leg



Background: Ligament Failure

- Majumdar et al. (ANL) investigated the behavior of defected steam generator tubes at high temperatures experimentally and theoretically
- Terminology: a crack becomes through-wall (“pops-through”) when remaining ligament fails
- ANL established that ligament failure time can be calculated using conventional Larson-Miller analysis if nominal stress is multiplied by same stress multiplication factor m_p used to predict ligament failure in DBAs at low temperature
- Factor is function of defect type, length and depth

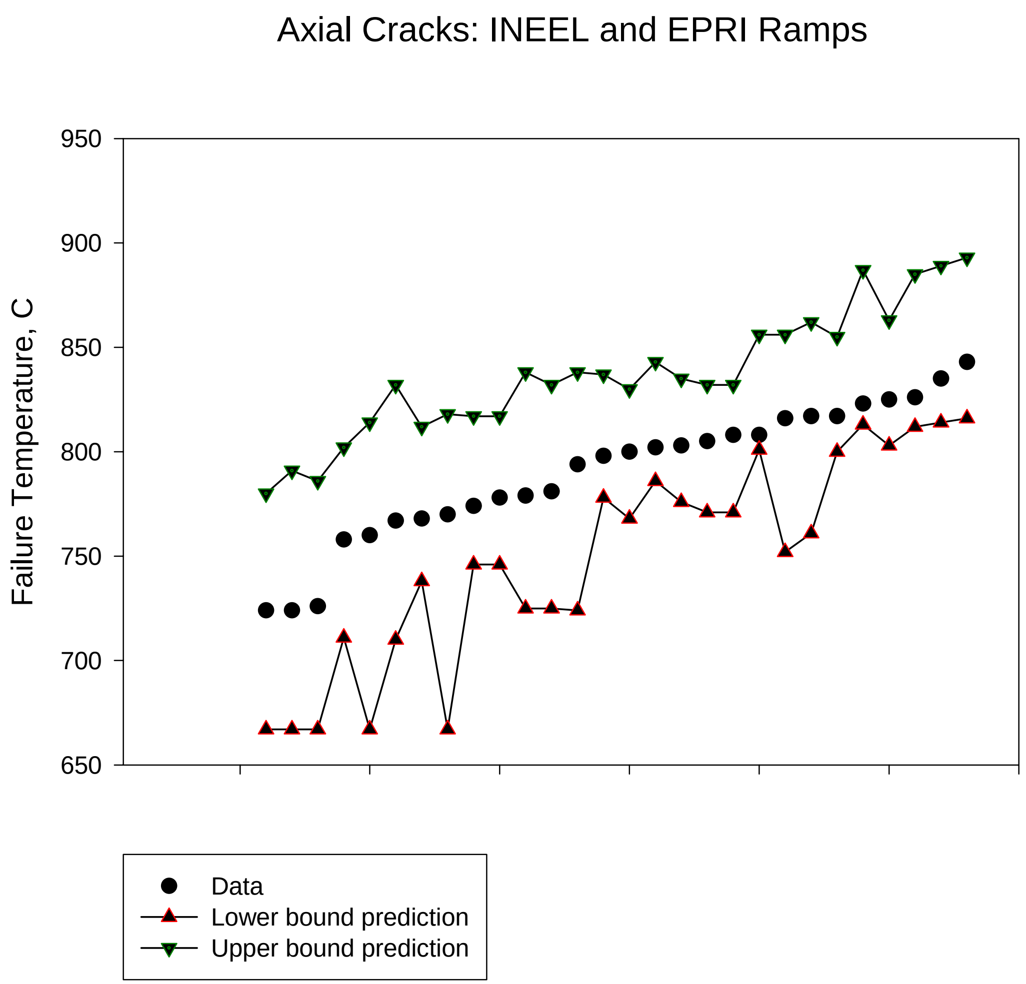
Background: Tube Failure Mode

- Most NRC and older industry calculations have assumed ligament failure necessarily implies rupture and thus a large fission product release
- However, in low-temperature (DBA-type) burst experiments, short, deep cracks tend to fail at a pressure too low to cause unstable crack growth
- Besides qualifying a method to calculate time of ligament failure, Majumdar et al. also demonstrated that the same thing happens at high temperatures:
  - Short, deep cracks leak but do not develop “fishmouth” failures, at least not right away
- PROBFAIL offers an option to credit this phenomenon

Issue: Is Crediting Failure Mode Justified?

- ANL experiments were terminated at pop-through
- Can't be sure that a leaking crack would not have grown in length and ruptured soon after
  - Fortunately, pop-throughs usually occur right around the time of hot leg failure, so not much time is available for crack growth
  - PROBFAIL doesn't calculate crack growth rate, but will predict a later rupture if material properties degrade enough
- On the other hand, if you <u>don't</u> credit failure mode, how do you treat through-wall defects we expect are in the steam generator after initial blowdown?
  - A defect allowable under current maintenance rules could become a "rupture" as soon as we enter "severe accident space"

PROBFAIL Code Benchmarked to ANL Data



Summary of Outstanding Issues on Structural Modeling

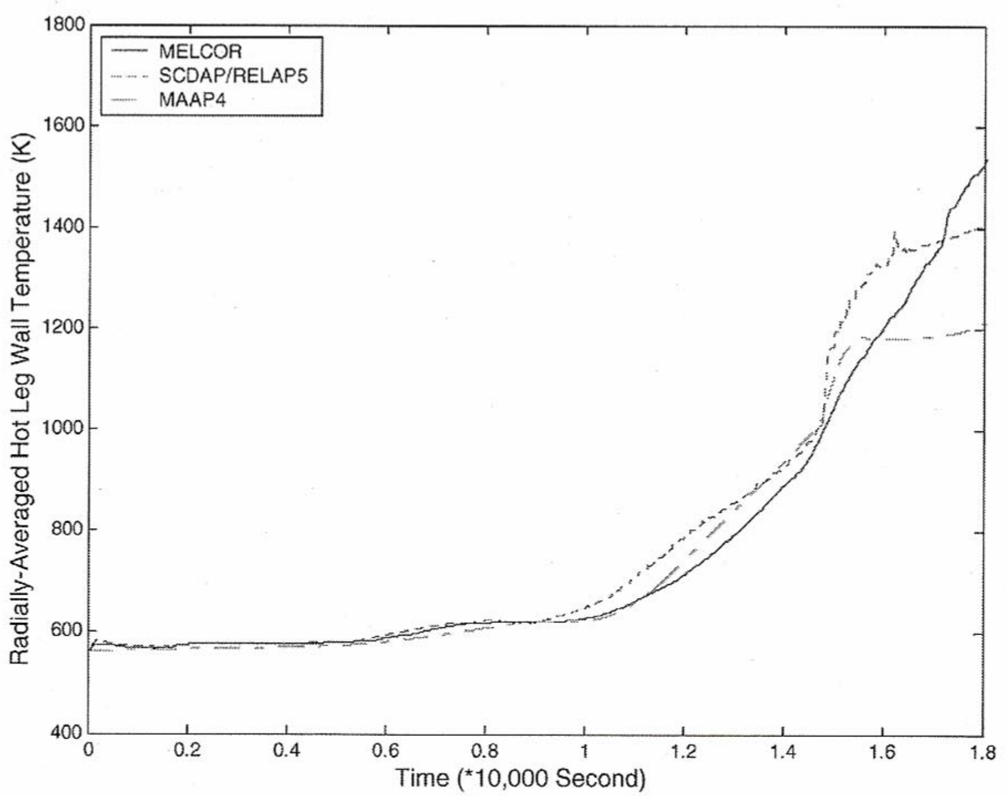
- Sufficient to use Larson-Miller type analysis for hot leg and surge line?
  - If so, do we base evaluation on hot leg nozzle or piping?
- Do we credit possibility that pop-throughs don't lead immediately to rupture of the tube?
  - If not, do we say that through-wall cracks after SG depressurization always lead to rupture, even though allowed by a Condition-Based Maintenance program?

2. Thermal-Hydraulic Modeling

Some History…

- Concerns have long been raised over substantial differences between MAAP and SCDAP/RELAP5 TISGTR predictions
  - Even when the two codes agreed that there was no threat to tubes, in MAAP this was because hot leg failed whereas surge line usually failed first in S/R5
- To shed light on this, efforts were performed at Creare and later at Purdue and Creare that:
  - Configured MAAP to act as similarly as possible to S/R5 (Purdue study added MELCOR), based on a priori knowledge of modeling approaches in different codes
  - If this is done, codes' predictions were very similar through the time of first RCS failure
  - Then looked at the various changes made to MAAP to force agreement and assessed how important each was

Vierow et al: Hot Leg Average Temperature (MAAP Configured to Mimic S/R5 Modeling)



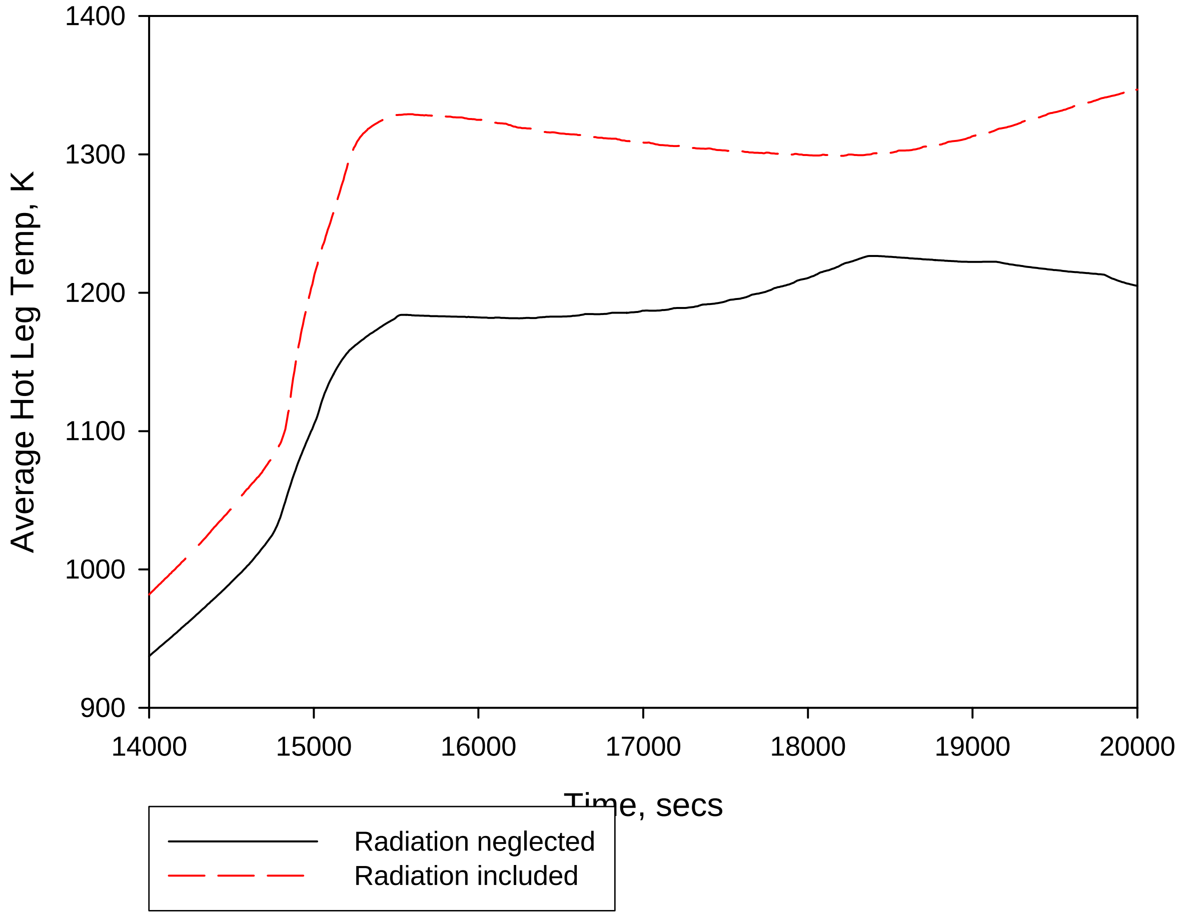
Conclusions of These Studies

- When configured to mimic S/R5 modeling, MAAP results very similar to S/R5's until after first calculated RCS failure
  – Thus, differences between the two codes for TISGTR are due to a small number of assumptions
- At later times, S/R5 temperatures were somewhat higher, but this is not of interest for TISGTR
- Note: this is the first time MAAP had ever calculated surge line failure prior to hot leg failure

What Changes Had to be Made to MAAP to Get Agreement with S/R5?

- By far the most important of the changes made to MAAP was neglecting thermal radiation
- All cases with thermal radiation resulted in hot leg failure prior to surge line failure, and vice versa
- Neglect of thermal radiation in S/R5 contradicted conclusions of Appendix C of NUREG/CR-6285:
  - Radiation ~3x as strong as convection near time of hot leg failure
  - While latest S/R5 calculations do credit thermal radiation, is relatively weak (~60 percent as strong as convection)
  - Importance of radiation confirmed by EPRI calculations using a detailed conjugate heat transfer model

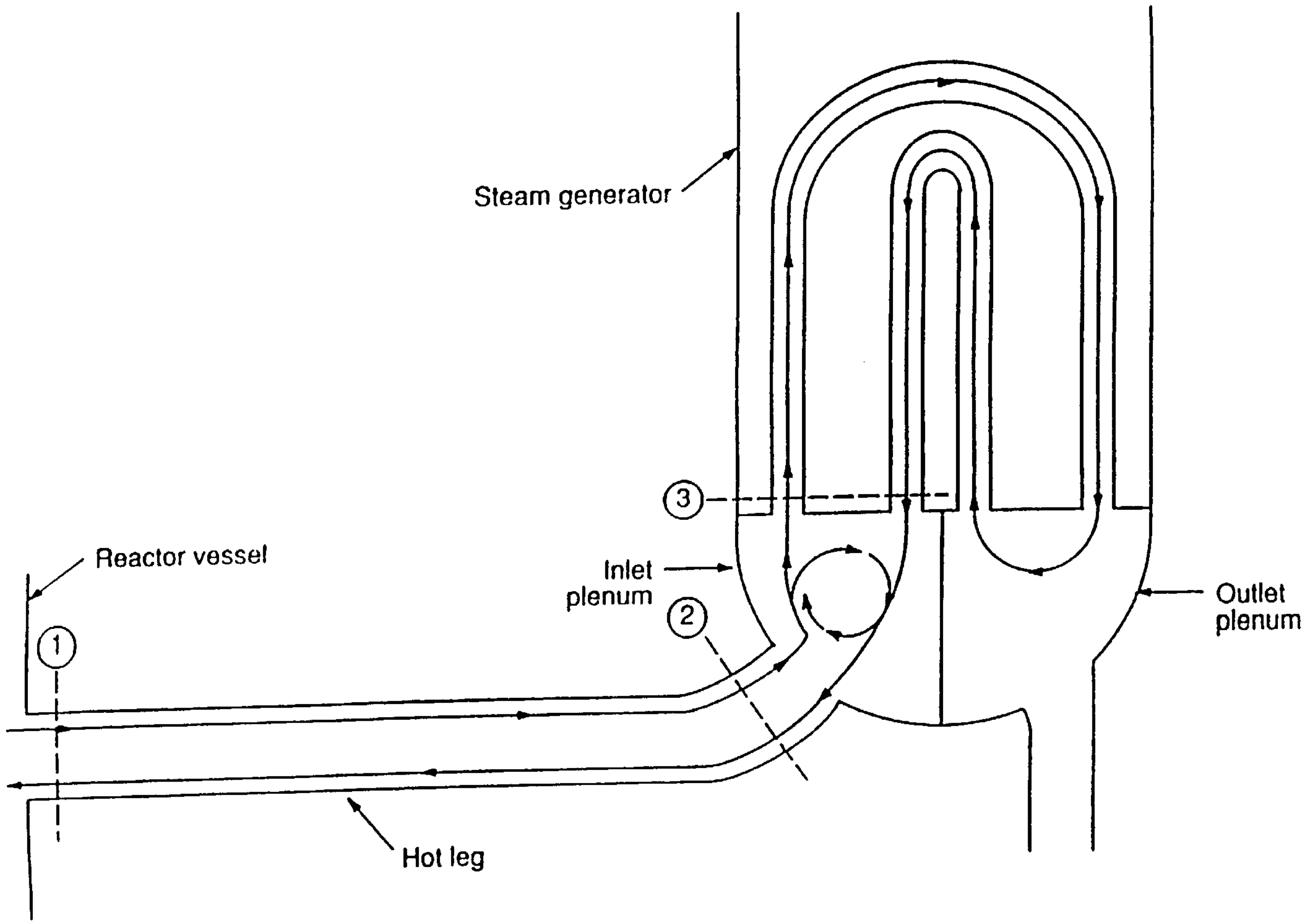
Radiation Greatly Affects Hot Leg Temps



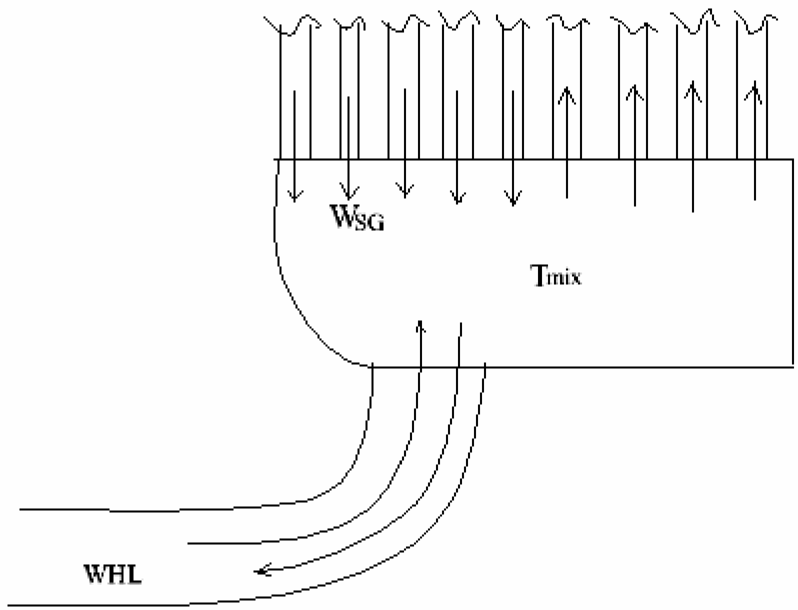
Natural Circulation

- SG/HL recirculation ratio largely controls magnitude of convective heat transfer to hot leg relative to tubes: larger ratio reduces plenum temperature and threat to tubes
- S/R5 modeling tuned to match Westinghouse experiment data (ratio of ~2)
- MAAP uses a simple model to calculate this as function of time:
  - Yields ~2 ratio for Westinghouse experiments, but
  - Calculates larger ratio for reactor case (~3 in Purdue calculation because of tube plugging)
- NRC's CFD calc. predicted ~2.7 for reactor case
  - Sensitive to boundary condition applied to tube

Flow Patterns (Intact Loop Seals)



Importance of Recirculation Ratio

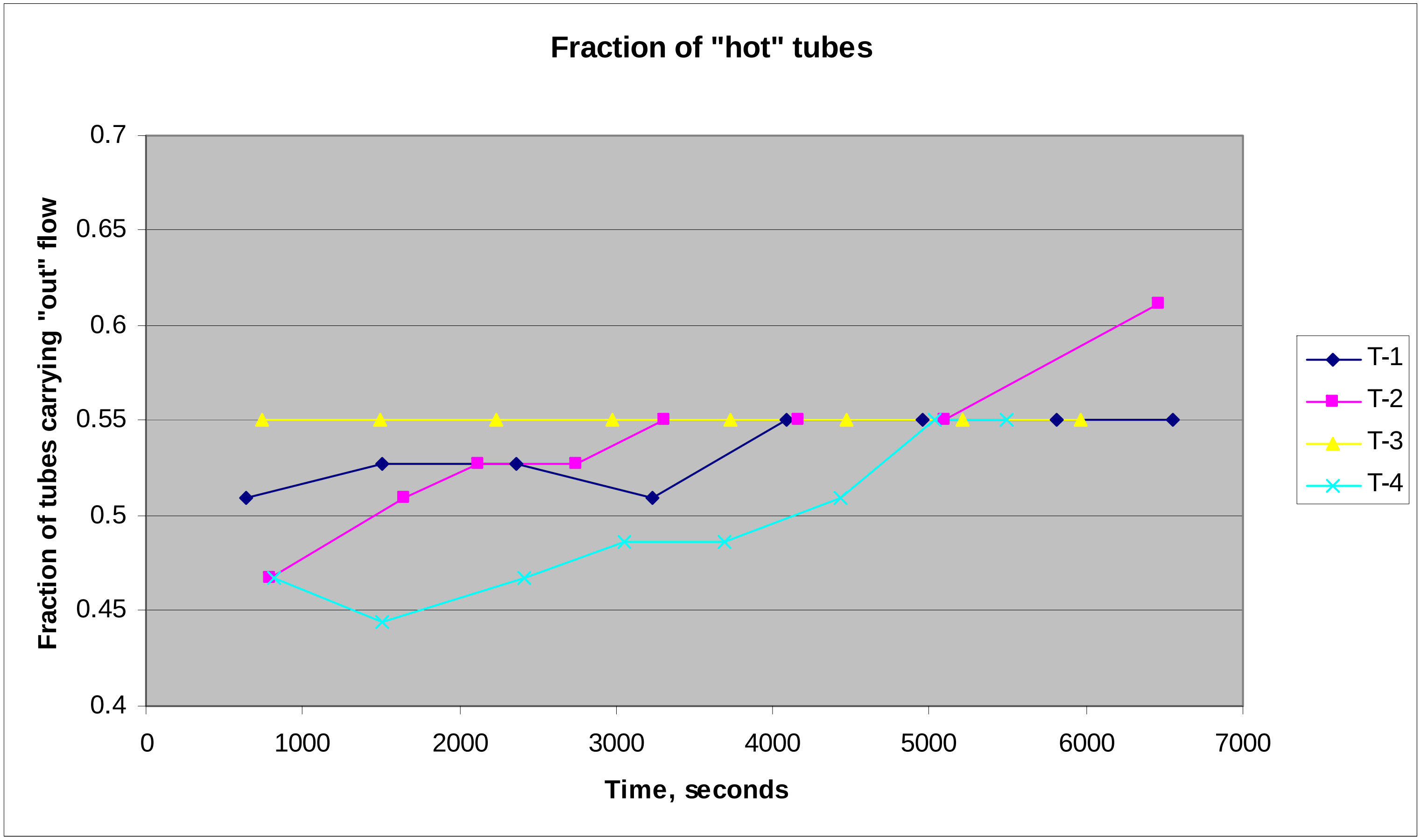


$$T_{mix} \approx \frac{T_{HL} + \frac{W_{SG}}{W_{HL}} T_{CT}}{1 + \frac{W_{SG}}{W_{HL}}}$$

Fraction of “Hot” Tubes

- NRC and older industry analyses assume ~35 percent of tubes carry flow from inlet plenum to outlet plenum based on steady-state Westinghouse 1/7 results
- NRC CFD calculation for steady-state, reactor case obtained similar result: ~41 percent
- EPRI assumes 50 percent, based on physical reasoning and behavior seen in transient 1/7 scale results
  - Actual value believed to be higher, i.e. given a chance system acts so as to maximize steam generator flow
- Note: This issue only really affects EPRI’s calculation of SG/HL flow ratio

Fraction Hot Tubes In Transient 1/7-Scale Tests



T/H Issues: Benchmarking Status

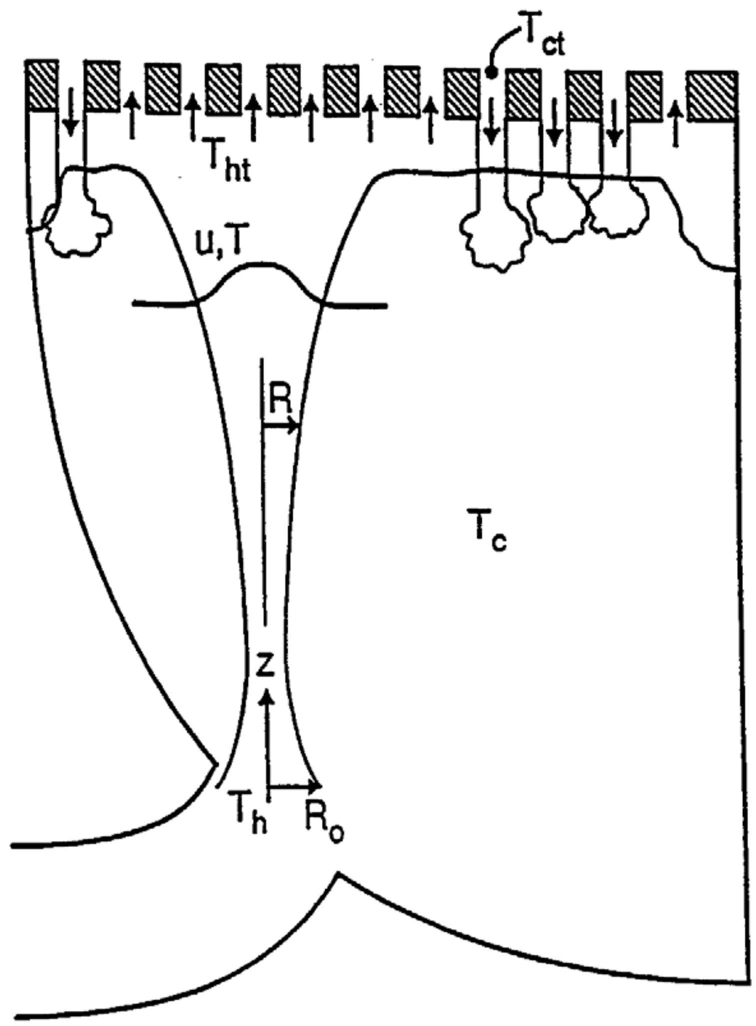
- The Westinghouse 1/7 scale tests are a rich source of benchmarking data and form the fundamental basis for all TISGTR modeling
- Both NRC and EPRI have compared the predictions of their tools to this data
- However, the scale model tests are not scaled "perfectly", and we don't think you should directly apply quantitative conclusions from the tests to the reactor scale without justification
- To our knowledge, no one has looked hard for relevant thermal radiation benchmarks

3. Inlet Plenum Mixing

MAAP SG Plume Model

- As gasses enter the SG inlet plenum from the upper portion of hot leg, they form a plume that rises toward tubesheet
- The plume spreads and cools as it entrains colder gasses returning from SG outlet plenum
- MAAP models the plume and separately calculates the temperature of the gasses entering tubes:
  - From the average plume condition
  - From the center of the plume (least mixed, hottest temperatures)
- Model assumes an idealized plume configuration

MAAP Inlet Plenum Plume Model



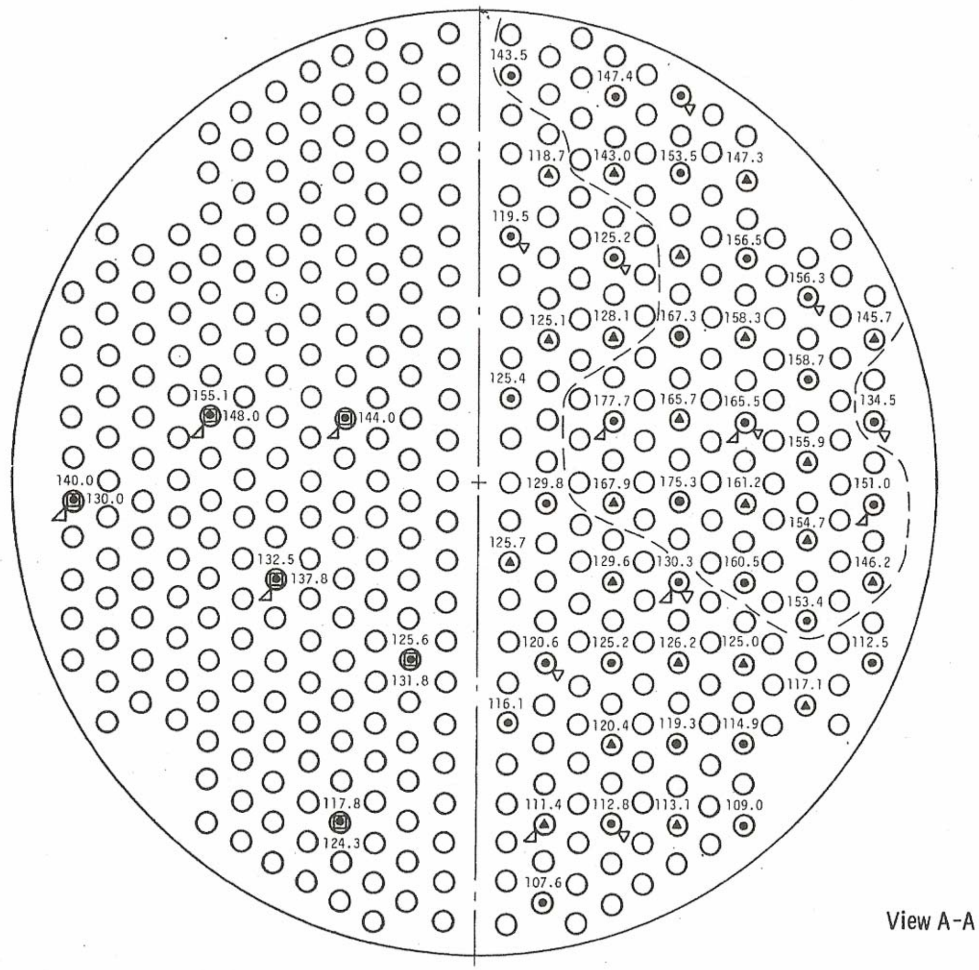
Benchmarking MAAP Mixing Model to 1/7-Scale Experiments

- MAAP model tends to over-predict the average temperature by under-predicting entrainment
- MAAP sometimes under-predicts the peak to average temperature difference in transient tests
- The two effects largely cancel, and MAAP's prediction of peak gas temperature in the experiments is fairly accurate
- Largest discrepancies seen in experiments that were observed to have a highly irregular cross-section compared to assumed circular cross-section
- Note: the MAAP model uses parameter values from the literature and was not tuned to the experiments

Benchmarking of MAAP Mixing Model

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**

Experiment T-4 “Hot” Tubes



Benchmarking MAAP Model, Cont’d

Test:	Peak Temperature (C)	
	Experiment	MAAP model
S1	85	89
S2	83	89
S3	107	113
S4	102	105
T1	181	176
T2	199	197
T3	171	171
T4	178	177

How do the two approaches compare?

- NRC assumes an average mixing *f* of ~0.85, taken from experiment
  - This represents more efficient mixing than MAAP calculates and is close to the 1/7-scale data
- NRC defines the peak-to-average gas temperature difference using the quantity:

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

  - NRC assumes NTR=0.625 for reactor cases, based on CFD calculation
- MAAP calculates NTR ~0.40 for reactor case, and larger values for 1/7-scale case and other situations having a smaller recirculation ratio
- This is a <u>big</u> difference

Variation in NTR Values is Striking

Test	Experiment NTR	MAAP NTR	CFD NTR
S-1	0.44	0.49	
S-2	0.45	0.55	
S-3	0.44	0.51	0.525
S-4	0.47	0.51	
T-1	0.49	0.45	
T-2	0.47	0.44	
T-3	0.46	0.46	
T-4	0.47	0.47	
Reactor case		~0.4	0.625
Reactor case, reduced recirc ratio		~0.45	

Mixing: What Can We Conclude?

- MAAP model fairly accurately predicts peak temperatures for transient 1/7-scale tests
- Admittedly, part of MAAP model’s accuracy may be due to canceling errors:
  - Non-cylindrical cross-section gives rise to more entrainment than predicted and also a larger peak-average spread
- NRC CFD model predicts a lower NTR for 1/7-scale test than for reactor case, opposite of MAAP prediction
- Need to understand better how computed NTR varies with conditions: 1/7 vs. reactor scale, recirculation ratio, etc.
- Could also ask: is NTR best way to parameterize?

Summary

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**