RESPONSES TO EPRI COMMENTS ON SCDAP/RELAP5 CONTAINMENT BYPASS ANALYSIS

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OBJECTIVE

Address EPRI comments related to the SCDAP/RELAP5 containment bypass analyses:

D. J. Modeen (EPRI), "Draft Reports Prepared by NRC on High-Dry Station Blackout Scenarios, letter to F. Eltawila (USNRC), April 23, 2007

2004 AND 2006 SCDAP/RELAP5 BASE CALCULATIONS FOR WESTINGHOUSE FOUR-LOOP PLANT CONTAINMENT BYPASS ANALYSIS

2004

Presented at the Advisory Committee on Reactor Safeguards Joint Materials and Metallurgy Subcommittee Meeting, February 4, 2004, Rockville MD

Tube stress multipliers for coincident failure of SG tube and primary coolant system piping:

Average Tube: 4.90
Hottest Tube: 1.59

2006

Documented in ISL Report "SCDAP/RELAP5 Base Case Calculation for the Station Blackout Uncertainty Study," Draft, August 2006

Tube stress multipliers for coincident failure of SG tube and primary coolant system piping:

Average Tube: 2.10
Hottest Tube: <1.0 (1.0 multiplier tube fails 155 s before the hot leg fails)

SUMMARY OF MODELING, EVENT SEQUENCE AND MIXING PARAMETER CHANGES FROM 2004 BASE CASE TO 2006 BASE CASE

Recirculation ratio decreased from 2.75 to 2.0

Hot and cold mixing fractions increased from 0.81 to 0.85

Hot/Cold tube split changed from 50%/50% to 41%/59%

Hot leg flow prediction changed from 30.2% SG power fraction method to 0.12 hot leg discharge coefficient method

SG depressurization assumption changed from stuck-open relief valve in the pressurizer-loop SG to 0.5 in^2 steam leakage in all SGs

Assumed station battery life changed from infinite to 4 hours

Pressurizer surge line connection relocated from top to side of the hot leg pipe

SUMMARY OF MODELING, EVENT SEQUENCE AND MIXING PARAMETER CHANGES FROM 2004 BASE CASE TO 2006 BASE CASE (Continued)

Representation of pressurizer spray system added to the model

Core axial nodalization expanded from 10 cells to 40 cells

<u>Axial nodalization in region of tubesheet expanded</u>

From: one tubesheet cell and four tall cells to the top of the SG tube U-bend

To: two tubesheet cells and four 1-ft tube cells just above the tubesheet

A 50% enhancement of the hot leg fluid-to-wall convection heat transfer coefficient was implemented, primarily to account for entrance effects

ISSUE #1 – HOT LEG RADIATION

Model Used for Convective Heat Transfer From Hot Leg Fluid to Hot Leg Walls

The Dittus-Boelter correlation [1] is the basic SCDAP/RELAP5 convective heat transfer model for turbulent forced convection

In the plant model, the convective heat transfer coefficient for the hot leg was enhanced by 50% to account for entrance effects and the reduced hydraulic diameter associated with partitioning of the hot leg into upper and lower sections (as determined using CFD studies)

Model Used for Steam-to-Hot Leg Wall Radiation

A constant wall emissivity is used, 0.5 for stainless steel hot leg

Emissivity and absorptivity of steam calculated using subroutine EMISS from the TRAC-B computer code [2]

In the subroutine, the steam emissivity is calculated using the Thomson model, as described by Hottel and Sarofim [3]

Fuel rod oxidation and rupture processes release noncondensible gases into the RCS and, unlike steam, noncondensibles are virtually transparent to thermal radiation [4, 5]

To adjust for the presence of noncondensibles, a multiplier (equal to the local mass fraction of steam) is applied to the steam-to-wall thermal radiation heat transfer

The adjusted steam-to-wall radiation heat transfer coefficient is added to the convective heat transfer coefficient, combining together those two processes, which transfer heat from the fluid to the hot leg wall

Model Used for Upper Hot Leg Section Wall to Lower Hot Leg Section Wall Radiation

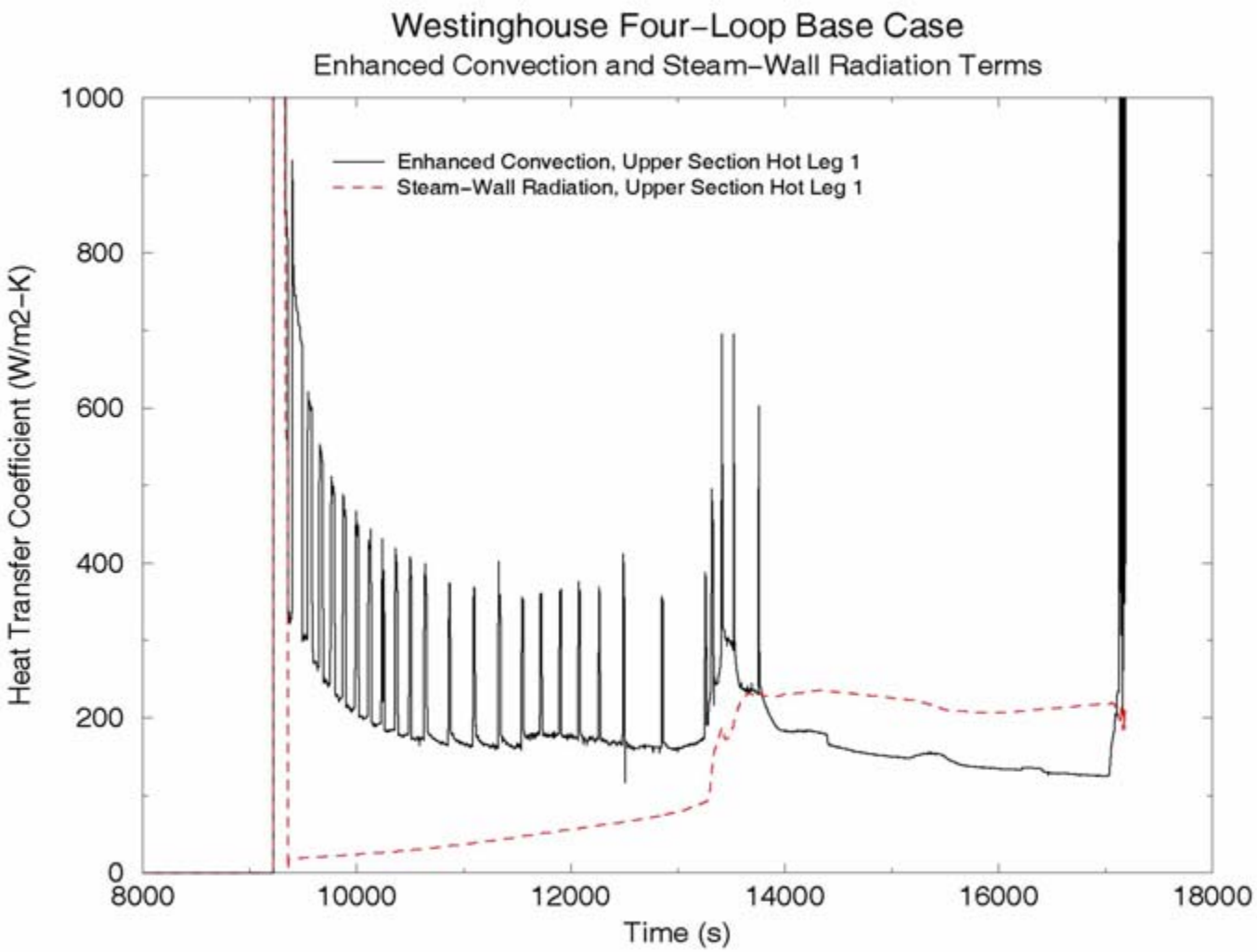
A constant wall emissivity is used, 0.5 for the stainless steel hot leg

The SCDAP/RELAP5 “radiation enclosure” model is used, which assumes that heat exchange occurs through a transparent, non-absorbing medium

It is noted that this non-absorbing medium assumption is not consistent with the absorbing-medium assumption used in the steam-to-wall radiation modeling

For each hot leg, the enclosure consists of 12 heat structures, 5 for the upper hot leg sections, 5 for the lower hot leg sections, 1 representing the core barrel wall penetration (at the reactor vessel end of the hot leg) and 1 representing the SG plenum partition plate (at the SG end of the hot leg)

View factors are calculated for the 12 structures in the enclosure


Westinghouse Four-Loop Base Case
Enhanced Convection and Steam-Wall Radiation Terms
Enhanced Convection, Upper Section Hot Leg 1
Steam-Wall Radiation, Upper Section Hot Leg 1
Heat Transfer Coefficient (W/m2-K)
Time (s)
0
200
400
600
800
1000
8000
10000
12000
14000
16000
18000

Comparison of SCDAP/RELAP5 Hot leg Convection and Steam-to-Wall Radiation Heat Transfer

Data shown on the previous slide are for the upper hot leg section in Coolant Loop 1 (pressurizer loop), in the cell adjacent to the reactor vessel

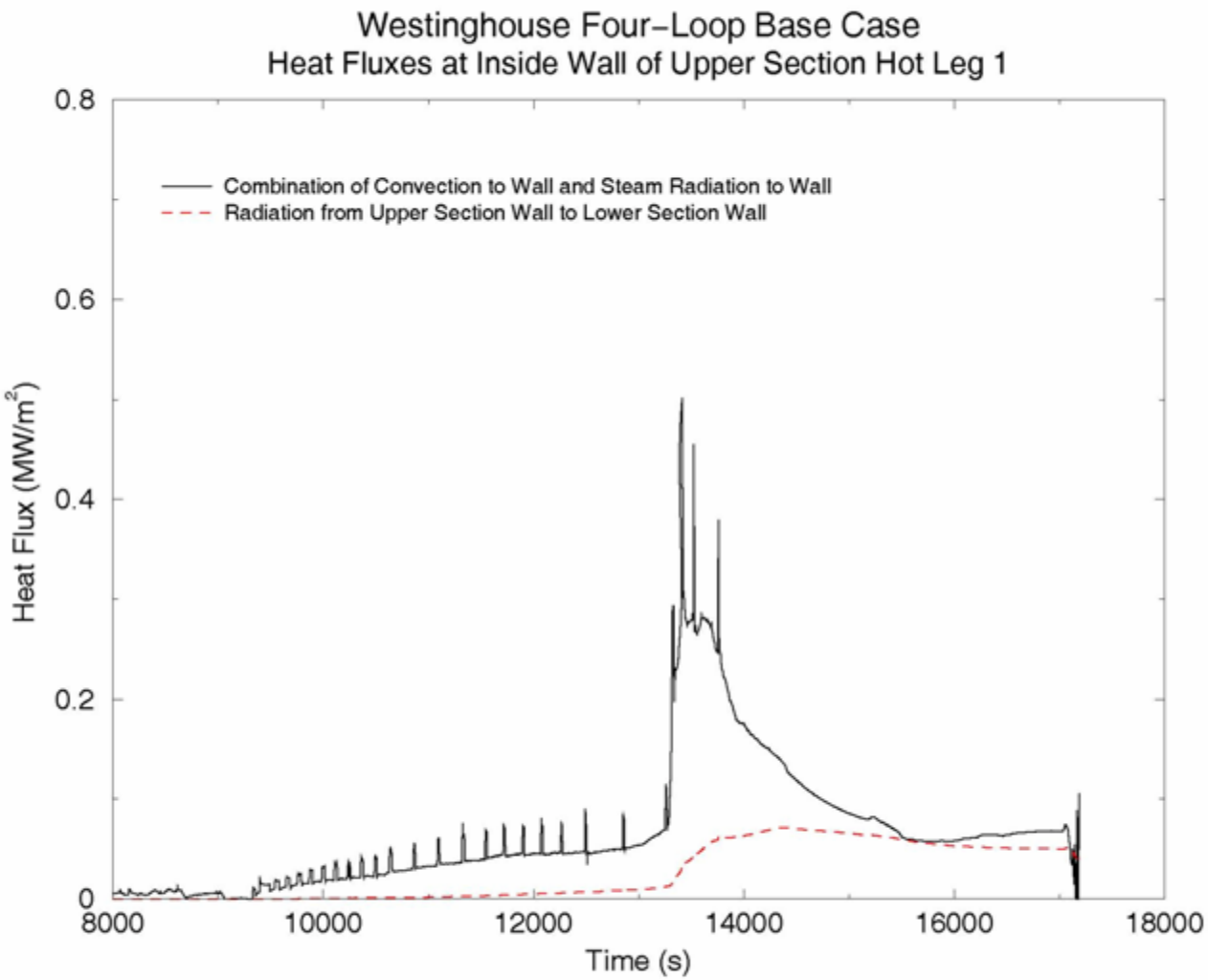
At the time of hot leg failure (13,630 s), temperatures have risen sufficiently to make the steam-to-wall radiation and enhanced-convection terms comparable; the steam-to-wall radiation heat transfer represents:

97% of the enhanced convection heat transfer
49% of the total heat transfer from fluid to wall
145% of the non-enhanced convection heat transfer

At that time, the local noncondensible quality is 0.11 and a multiplier of 0.89 is applied to the steam-to-wall radiation heat transfer term

As the heat-up continues following the time of hot leg failure, steam-to-wall radiation becomes the more dominant term (it is 175% of the enhanced convection term at 17,000 s)

Conclusion: Steam-to-wall radiation is an important, but not dominant, heat transfer mechanism up through the time of the hot leg failure. It therefore has a moderate effect on the SG tube failure margin.


Westinghouse Four–Loop Base Case
Heat Fluxes at Inside Wall of Upper Section Hot Leg 1
Combination of Convection to Wall and Steam Radiation to Wall
Radiation from Upper Section Wall to Lower Section Wall
Heat Flux (MW/m2)
0.8
0.6
0.4
0.2
0
8000
10000
12000
14000
16000
18000
Time (s)

Comparison of SCDAP/RELAP5 Hot leg Fluid-to-Wall and Wall-to-Wall Heat Transfer

Data shown on the previous slide are for the upper hot leg section in Coolant Loop 1 (pressurizer loop), in the cell adjacent to the reactor vessel

At the time of hot leg failure (13,630 s), the radiation from the upper hot leg section to the lower hot leg section represents 18% of the total heat transfer from the steam to the wall (due to enhanced convection and fluid-to-wall radiation)

As the heat-up continues after the time of hot leg failure, most of the heat transfer from the fluid to the upper hot leg section wall is radiated to the lower hot leg section wall

Conclusion: Radiation heat transfer between the walls of the upper and lower hot leg sections represents a minor portion of the total heat transfer from the fluid to the wall of the upper hot leg section. It therefore has a limited effect on the SG tube failure margin.

Thermal Radiation Sensitivity Study Results

In March 2004, a SCDAP/RELAP5 sensitivity study was performed on the effects of variations in thermal radiation

A multiplier of 2.0 was placed on all thermal radiation heat transfer processes (steam-to-wall, and wall-to-wall) at all locations in the plant model

The evaluation showed that only a small beneficial effect is obtained as a result of this significant increase in the radiation heat transfer

Tube stress multipliers resulting in coincident failure of the SG tube and primary coolant system piping:

	Average Tube	Hottest Tube
Base Case	4.90	1.59
Radiation * 2.0	5.17	1.62

Information from NUREG/CR-6285 [6]

Page 27, regarding a 20% change in the hot leg heat transfer coefficient in a Surry sensitivity calculation:

"The timing of the surge line failure was virtually unchanged from the base case with nominal heat transfer coefficients, and the heat-up rates in the core and ex-core structures showed little change from the base case."

Page 27, regarding a sensitivity study of thermal radiation between the fluid streams in the upper and lower hot leg sections:

"The results of the calculations showed that the modeled radiation heat transfer had a negligible effect on the timing of the ex-vessel piping failures."

"Most of the creep damage occurred before radiation heat transfer was a significant contributor to the heat transfer from the vapor. The calculated radiation heat flux peaked after the surge line failure was predicted to occur."

SCDAP/RELAP5 Analysis Hot Leg Radiation - Summary

Hot leg steam-to-wall thermal radiation is comparable to enhanced convection heat transfer at the time of hot leg failure and much larger than it afterward

Radiation from the hot leg upper section wall to the hot leg lower section wall is a minor factor at the time of hot leg failure and a dominant factor afterward

A sensitivity study indicates that a 100% increase in thermal radiation heat transfer has only small beneficial effects on the SG tube failure margins

A sensitivity study indicates that a 20% change in the fluid-to-wall heat transfer resulted in little difference in the relative timing of the component failures

ISSUE #2 – RECIRCULATION RATIO

A SCDAP/RELAP5 sensitivity calculation was performed to evaluate the effect of increasing the recirculation ratio from 2.0 to 2.3

The evaluation showed only a small increase in the average tube failure margin

The SG tube stress multiplier resulting in coincident failures of the average tube and hot leg increased from 2.10 in the base case run (recirculation ratio 2.0) to 2.18 in the sensitivity run (recirculation ratio 2.3)

ISSUE #3 – MIXING IN SG INLET PLENUM (NORMALIZED TEMPERATURE RATIO)

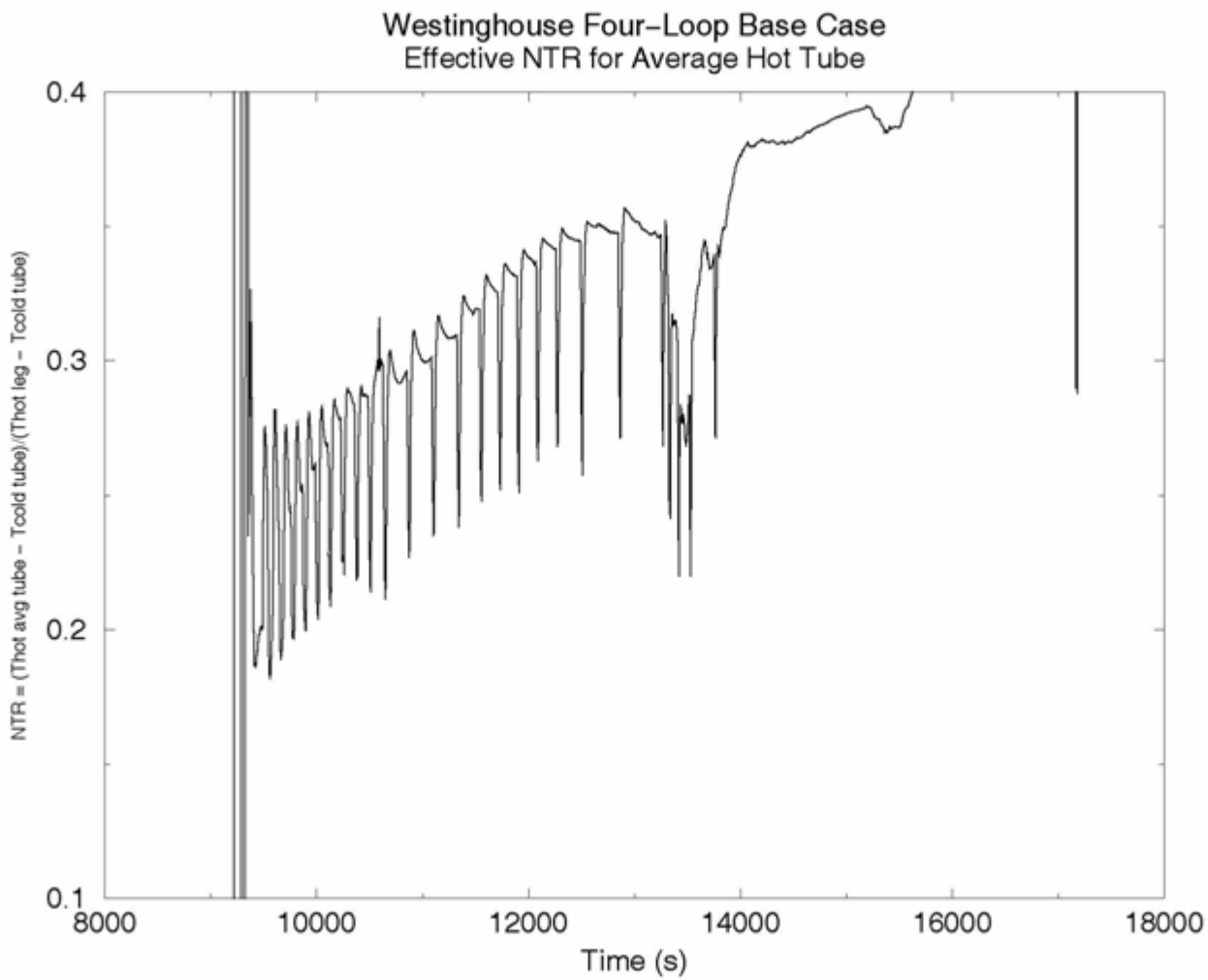
In the SCDAP/RELAP5 model for the Westinghouse four-loop plant, fluid entering the <u>hottest tube</u> is based on a normalized temperature ratio (NTR) of 0.625, where:

$$NTR = (T_{hottest\ tube} - T_{cold\ return}) / (T_{hot\ leg} - T_{cold\ return})$$

EPRI suggested that the effective SCDAP/RELAP5-calculated <u>average tube</u> NTR response (i.e., with $T_{hottest\ tube}$ replaced by $T_{hot\ average\ tube}$) be evaluated

The figure which follows displays the effective <u>average tube</u> NTR from the current SCDAP/RELAP5 base case calculation

Using data from the periods when the pressurizer relief valves are closed, the effective SCDAP/RELAP5 <u>average tube</u> NTR is seen to range from about 0.26 at 10,000 s to about 0.35 over the period up to the time of hot leg failure (13,630 s)


Westinghouse Four–Loop Base Case
Effective NTR for Average Hot Tube
NTR = (Thot avg tube – Tcold tube)/(Thot leg – Tcold tube)
0.4
0.3
0.2
0.1
8000
10000
12000
14000
16000
18000
Time (s)

ISSUE #4 – LOOP SEAL CLEARING

Base Case RCP Shaft Seal Leakage Assumptions

The SCDAP/RELAP5 base case model for the Westinghouse four-loop plant simulates reactor coolant pump (RCP) shaft seal leakage at the RCP discharge and at the elevation of the cold leg centerline

The base case calculation assumes an initial 21 gpm per pump leakage rate, starting at the time of accident initiation

Sensitivity calculations were performed using assumptions of other leakage rates starting at 2 hours after event initiation: 1, 61, 90, 120, 182, 300, 390 and 480 gpm per pump

In the calculations with leakage rates of 300 gpm per pump and lower, no loop seal clearing in any loop is seen prior to the time of hot leg failure (in some of the calculations, subsequent loop seal clearing related to severe core damage behavior is seen)

In the calculation with a leakage rate of 390 gpm/pump, minor voiding is intermittently seen in the loop seals, but water remains at the bottom of the downcomer skirt and none of the loop seals reaches a steadily-cleared condition before the time when the hot leg fails

In the calculation with a leakage rate of 480 gpm/pump:

- **One of the loop seals clears at 9,165 s**
- **The RCS depressurization caused by steam flow through that loop seal and out the shaft seal leak path causes the water at the bottom of the downcomer skirt to flash**
- **The downcomer skirt path is cleared of water at 12,374 s**
- **The unflawed average tube fails 25 s before the hot leg fails at 13,575 s**

For the base case RCP shaft seal leakage assumptions (leakage on RCP discharge side, at the elevation of the cold leg centerline) the evaluation indicates that loop seal clearing leading to SG tube failure is expected for leakage rates of ~400 gpm per pump and higher

RCP Shaft Seal Leakage Assumed to be Located at Lower Elevation

SCDAP/RELAP5 sensitivity calculations were also performed with the shaft seal leakage path moved from the discharge to suction side of the RCP and located 39” below the cold leg centerline

Calculations were performed with these assumptions for leakage rates that increase at 2 hours after the initiating event to: 90, 120, 182, 300 and 390 gpm per pump

In these runs loop seal clearing is not seen for assumed leakage rates of 90 and 120 gpm per pump and is seen for the higher assumed leakage rates

With the leakage situated at a lower elevation and on the RCP suction side, loop seal clearing occurs at a lower assumed RCP shaft seal leakage rate for two reasons:

1. **Pressure fluctuations, created by the cycling of the pressurizer relief valve, cause the water slugs to swing back and forth in the loop seal piping; water is more easily lifted to the lower-elevation leakage site, and the oscillatory flow process removes more water from the RCS, depleting more of the loop seal liquid inventory**

2. **With the leakage located on the inlet side of the RCP, both the resistance for damping the flow oscillations and the resistance for the passage of liquid out of the RCS through the leak path are minimal (because they do not include the resistance to flow through the RCP itself)**

Loop Seal Clearing Issue - Summary

With RCP shaft seal leakage located at the cold leg centerline elevation on the discharge side of the RCP, loop seals are expected to remain filled for RCP leakage rates of 390 GPM per pump and lower

With RCP shaft seal leakage located 39” below the cold leg centerline elevation on the suction side of the RCP, loop seals are expected to remain filled for RCP leakage rates of 120 GPM per pump and lower

ISSUE #5 – HOT LEG CREEP RUPTURE ANALYSIS

Two SCDAP/RELAP5 sensitivity calculations were recently performed to provide a rough indication of the effect of changing the basis for the hot leg Larson-Miller creep rupture calculation from stainless steel to carbon steel

Sensitivity Calculation 1

Use the base case model, except change only the material specified for the hot leg creep rupture calculation

Results show large beneficial effects on the SG tube failure margins

The average SG tube stress multiplier resulting in coincident failures of the tube and hot leg increased from 2.10 in the base case run (stainless steel) to 2.93 in the sensitivity run (carbon steel)

The unflawed hottest SG tube failed 155 s before the hot leg in the base case run (stainless steel) but failed 50 s after the hot leg in the sensitivity run (carbon steel), with a stress multiplier of 1.31 needed for hottest tube failure coincident with the hot leg failure

Sensitivity Calculation 2

Use the same model as for Calculation 1, except also change the thermal material properties used for the upper hot leg section: thermal conductivity, thermal capacitance, steam-to-wall radiation emissivity (but unable to change the wall-to-wall radiation emissivity without significant additional work)

Results show moderate beneficial effects on the SG tube failure margins.

The average SG tube stress multiplier resulting in coincident failures of the average tube and hot leg increased from 2.10 in the base case run (stainless steel) to 2.48 in the sensitivity run (carbon steel)

The unflawed hottest SG tube failed 155 s before the hot leg in the base case run (stainless steel) and 45 s before the hot leg in the sensitivity run (carbon steel)

Hot Leg Material Creep Rupture Sensitivity - Summary

General improvements in the SG tube failure margins look to result from performing the hot leg creep rupture calculation based on a carbon steel material

None of the scoping sensitivity calculation results reported here should be considered definitive because of potentially-important compromises in the SCDAP/RELAP5 modeling

SCDAP/RELAP5 heat structure modeling not appropriate for representing behavior in complex geometries, such as at the reactor vessel hot leg nozzle

Some considerations:

What thickness to use? What fluid conditions (temperatures and flows) to use? Is horizontal axial conduction between the stainless steel hot leg and carbon steel nozzle base material important? Is vertical axial conduction between the vessel cylinder and the hot leg nozzle important? What is an appropriate wall-to-wall thermal radiation model for the vessel hot leg nozzle?

MISCELLANEOUS ISSUES

CCFL at the Pressurizer Tank to Surge Line Connection

The SCDAP/RELAP5 base case model represents this as a simple connection, using the surge line flow area and using the surge line diameter as the hydraulic diameter

In 2004, several sensitivity calculations were performed to evaluate the effects of varying the CCFL model and changing the geometrical configuration of the connection to represent a sparger

Consistent with EPRI's view, the sensitivity calculations indicated no significant effects from varying the CCFL model applied at the pressurizer to surge line connection

REFERENCES

1. F. W. Dittus and L. M. K. Boelter, “Heat Transfer in Automobile Radiators of the Tubular Type,” Publications in Engineering, Vol. 2, University of California, Berkeley, 1930, pp. 443-461.

2. J. A. Borkowski, et al., “TRAC-BF1/MOD1: An Advanced Best-Estimate Computer Program for BWR Accident Analysis,” Idaho National Engineering Laboratory, NUREG/CR-4356, EGG-2626, August 1992.

3. H. C. Hottel and A. F. Sarofim, Radiative Transfer, McGraw Hill, New York, 1967, pp. 219-221.

4. F. Krieth, Principles of Heat Transfer, Second Edition, Intext Educational Publishers, New York, 1973, pp. 273-274.

5. D. A. Mooney, Introduction to Thermodynamics and Heat Transfer, Prentice-Hall, Englewood Cliffs, 1955, p. 375.

6. P. D. Bayless, et al., “Severe Accident Natural Circulation Studies at the INEL,” Idaho National Engineering Laboratory, NUREG/CR-6285, INEL-94/0016, February 1995.