ACRS JOINT MATERIALS AND METALLURGY AND THERMAL-HYDRAULICS SUBCOMMITTEES

PROGRESS ON STEAM GENERATOR ACTION PLAN MILESTONES

February 3 and 4, 2004
Rockville, MD

Office of Nuclear Regulatory Research
Office of Nuclear Reactor Regulation

ADVISORY COMMITTEE ON REACTOR SAFEGUARDS
JOINT MATERIALS & METALLURGY AND
THERMAL-HYDRAULIC SUBCOMMITTEES MEETING
STEAM GENERATOR ACTION PLAN (SGAP) -
DIFFERING PROFESSIONAL OPINION (DPO) RELATED ITEMS
FEBRUARY 3 - 4, 2004
ROCKVILLE, MARYLAND

-PROPOSED SCHEDULE-

ACRS Contact: B.P. Jain (301-415-7270)

WEDNESDAY, FEBRUARY 3, 2004, CONFERENCE ROOM T-2B3, TWO WHITE FLINT NORTH, ROCKVILLE, MARYLAND

	Topics	Presenters	Time
I.	**Opening Remarks**	P. Ford/ G. Wallis ACRS	8:30- 8:45 a.m.
II.	**Overview**	J. Muscara, RES	8:45-9:00 a.m.
III.	**SGAP Items 3.6 -3.8** (Research on NDE of SG tubes)	D. Kupperman, ANL W. Shack, ANL L. Lund, NRR	9:00-10:30 a.m.
		BREAK	10:30-10:45 a.m.
III	**SGAP Items 3.6-3.8**	**Continue**	10:45-12:15 p.m.
		LUNCH	12:15-1:15 p.m.
IV.	**SGAP Items 3.1a-3.1j** (SG tube integrity under MSLB)	S. Majumdar, ANL W. Krotiuk, RES	1:15-3:30 p.m.
		BREAK	3:30-3:45 p.m.
V.	**SGAP Item 3.9** (Iodine Spiking Assessment-Status)	M. Hart, NRR	3:45-4:30 p.m.
VI.	**Subcommittee Discussion**		4:30-4:45 p.m
VII	**Adjourn** (Until February 4, 2004)		4:45 p.m

NOTE: Presentation time should not exceed 50% of the time allocated for a specific item. The remaining 50% of the time is for Subcommittee questions.

WEDNESDAY, FEBRUARY 4, 2004, CONFERENCE ROOM T-2B3, TWO WHITE FLINT NORTH, ROCKVILLE, MARYLAND

	Topics	Presenters	Time
VIII.	**SGAP Items 3.3(*), 3.4 a-3.4g**	C. Boyd, RES	8:30-10:30 a.m.
	(Thermal-Hydraulic conditions during Severe Accident)	D. Fletcher, ISL	
		BREAK	10:30-10:45 a.m.
VIII.	**SGAP Items 3.3 (*), 3.4 a-3.4g**	**Continue**	10:45-11:45 p.m.
		LUNCH	11:45-12:45 p.m.
IX.	**SGAP Item 3.4h (*)** (Primary System Component Response to Severe Accident Conditions)	S. Majumdar, ANL	12:45-2:45 p.m.
		BREAK	2:45-3:00 p.m.
X.	**SGAP Item 3.5(*)** (Integrated Methodology for PRA of Severe Accident Induced SG Containment by-pass))	D. Bradley, SAIC	3:00-4:45 p.m.
XI.	**Subcommittee Discussion**		4:45-5:00 p.m
XXII.	**Adjourn**		5:00 p.m

* Task in progress but not completed

NOTE: Presentation time should not exceed 50% of the time allocated for a specific item. The remaining 50% of the time is for Subcommittee questions.

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PROGRESS ON STEAM GENERATOR ACTION PLAN MILESTONES - OVERVIEW

February 3 and 4, 2004
Rockville, MD

Dr. Joseph Muscara, (301) 415-5844
Senior Technical Advisor for Materials Engineering Issues
US NRC Office of Nuclear Regulatory Research
Division of Engineering Technology

OVERVIEW

- Last detailed meeting with ACRS on SG technology and research activities was on September 26,2001
- In October 2001, the ACRS reviewed and endorsed the SGAP developed to address ACRS recommendations in NUREG-1740
- Considerable research and evaluations have since been completed
  - Inservice inspection and nondestructive evaluation
  - Steam generator tube integrity
  - Thermal Hydraulics
  - Primary system component response during severe accidents
  - Probabilistic Risk Assessment
  - Iodine spiking

OVERVIEW (Cont.)

- NRC staff and contractors will make presentations in the above areas
- Presentations emphasize the technical work conducted and the SGAP milestones completed
- Although some milestones have been closed, work in some of the same areas is continuing based on lessons learned and refinements
  - SGAP periodically updated to reflect changes
- Resolution of issues will be based on staff's utilization of completed and on-going research activities, scheduled in the SGAP for 2005 and 2006

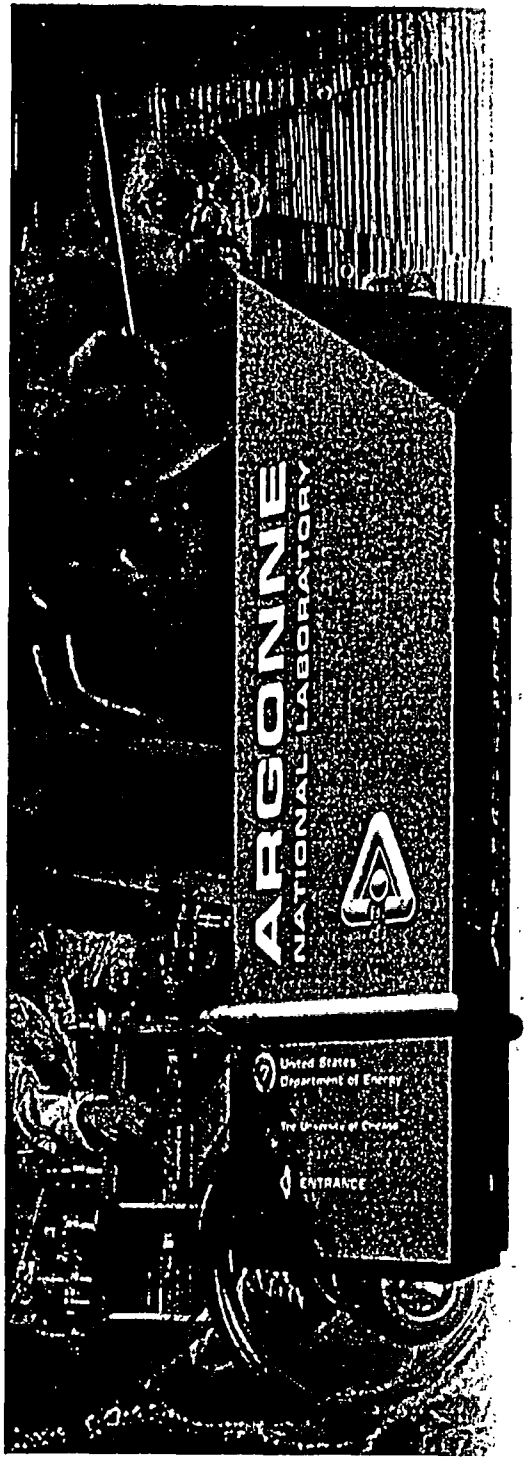
OVERVIEW (Cont.)

- RES staff has conducted integration effort for SG research programs in the different Divisions
  - Six one-day meetings during summer 2003
  - Discussed overall main goal of the research
  - Identified research needed, interdependencies of tasks and schedule
- Integrated program milestone chart developed for assessing potential of severe accident induced SG containment bypass (SAI-SGCB)
  - PRA integrates all the information, for example:
    - PRA identifies likely combination of events
    - T – H defines time/temperature/pressure conditions
    - SG: flaw distribution, POD, integrity to evaluate tube failure, burst, and leak rates
    - Other primary system component failure
    - Aerosol deposition
    - Feed back to T – H and PRA

OVERVIEW (Cont.)

- Integrated program will be completed end of FY-05
- Initial set of presentations address NDE, SG tube integrity under MSLB, and Iodine spiking

NDE OF SG TUBES



Steam Generator Eddy Current NDE

Presented by
David Kupperman and William Shack
February 3, 2004

Argonne National Laboratory

Office of Science
U.S. Department of Energy

A U.S. Department of Energy
Office of Science Laboratory
Operated by The University of Chicago

Issues addressed

- Steam Generator Action Plan [Item 3.6]
  - Need to address ACRS report conclusion(NUREG-1740; p. 47) that improvements can be made over the current use of a constant probability of detection for flaws in SG tubes as POD depends on flaw size
- The completed eddy current NDE analysis round robin using industry qualified teams and the ANL/NRC mock-up provides POD as function of flaw depth, voltage, location and m_p for 7/8-in alloy 600 tubing.

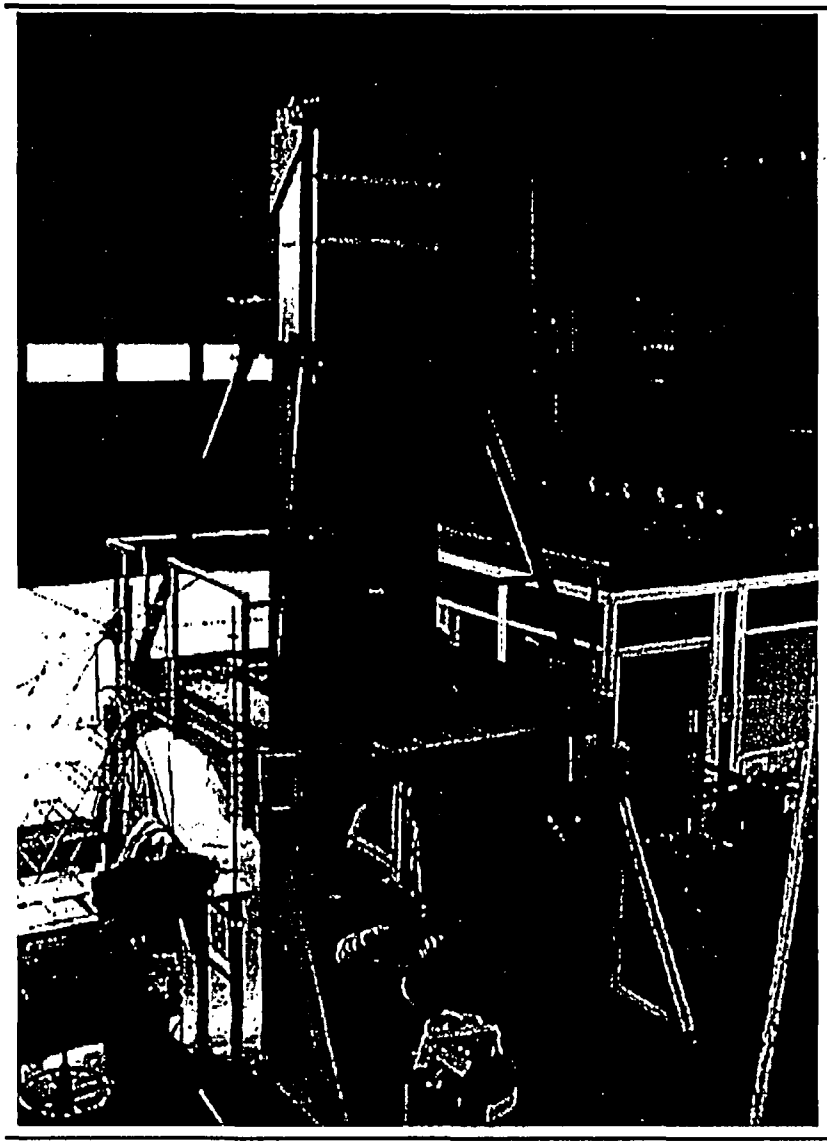
Outline of Presentation

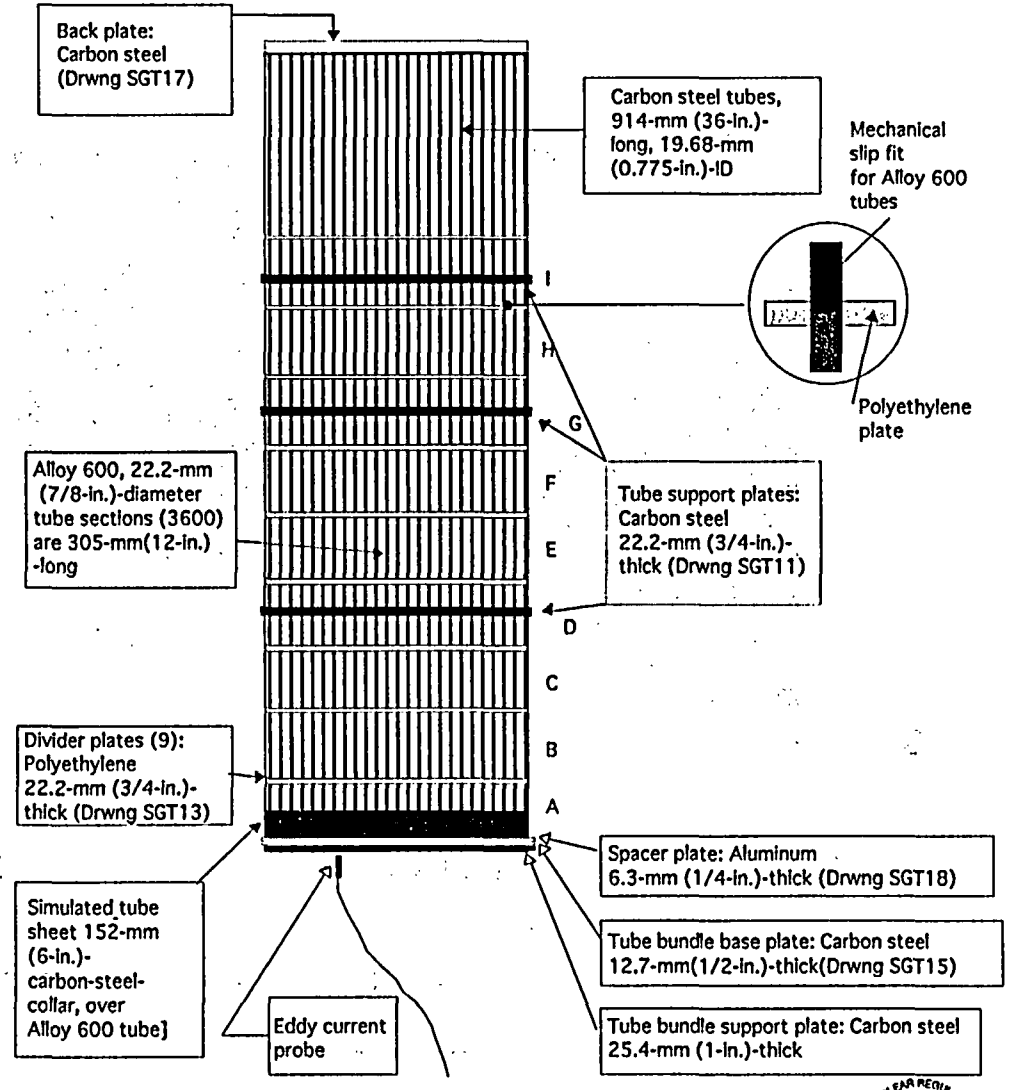
- Review of the Eddy Current NDE Round Robin to establish POD using the ANL/NRC Steam Generator Mock-up
  - Mock-up design and fabrication of flaws
  - Round robin procedures
  - Validation of similarity of EC signals/morphology to field data
  - Characterization of mock-up flaws
  - Validation of depth sizing
- RR results
  - POD as function of flaw type, depth and m_p
  - Team-to-team variation in POD
  - Cause of false calls and misses
- BC volts issues
- Signal-to-Noise issues
- The X-Probe as a potential advancement in EC NDE

EC analysis round robin using steam generator mock-up to develop POD curves

- Objective
  - Evaluate and quantify inspection reliability of current methods of inspection for current-day flaws providing
    - *POD*
    - *Sizing accuracy*
  - Validate methods employed using
    - *Laboratory grown flaws*
    - *Field generated flaws*

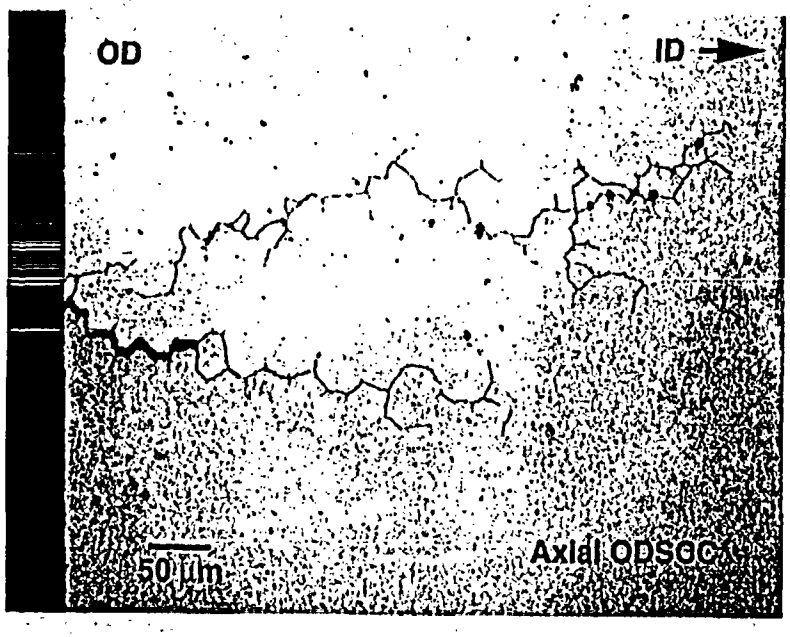
ANL/NRC Steam Generator Mock-up

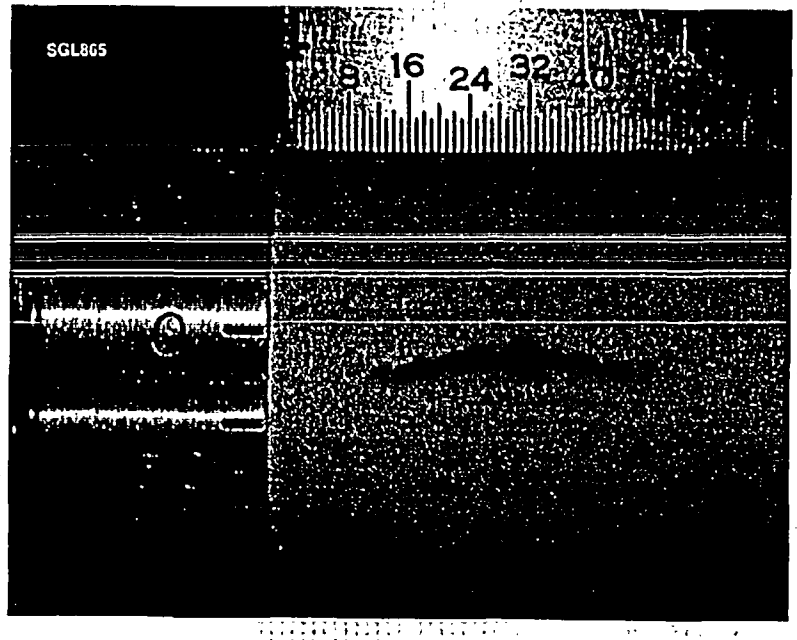




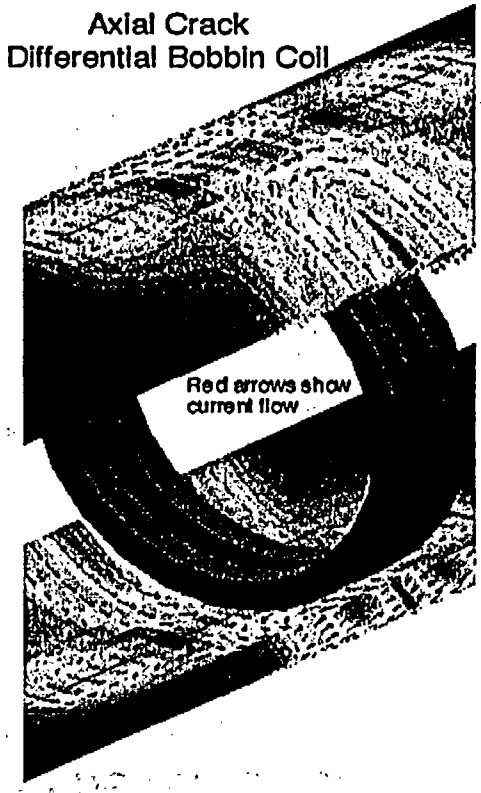
Fabrication of SCC

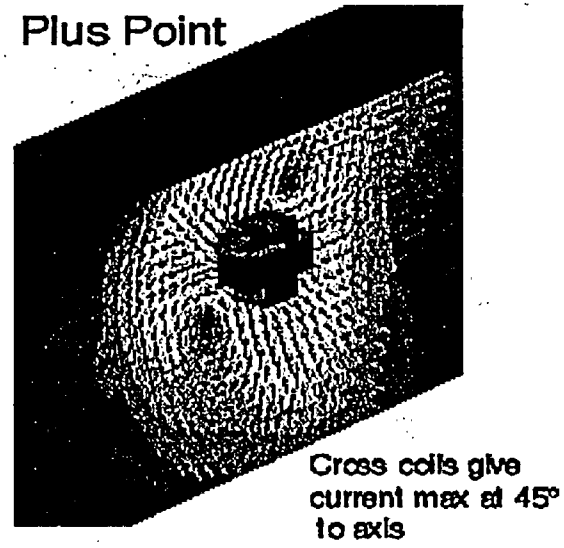
- Most Alloy 600 test sections were cracked at Argonne using a 1M aqueous solution of sodium tetrathionate at room temperature and atmospheric pressure. Other test sections were cracked using a doped steam technique (Westinghouse).





Eddy current inspections are carried out with bobbin coils (BC) and motorized rotating pancake coils (MPRPC)

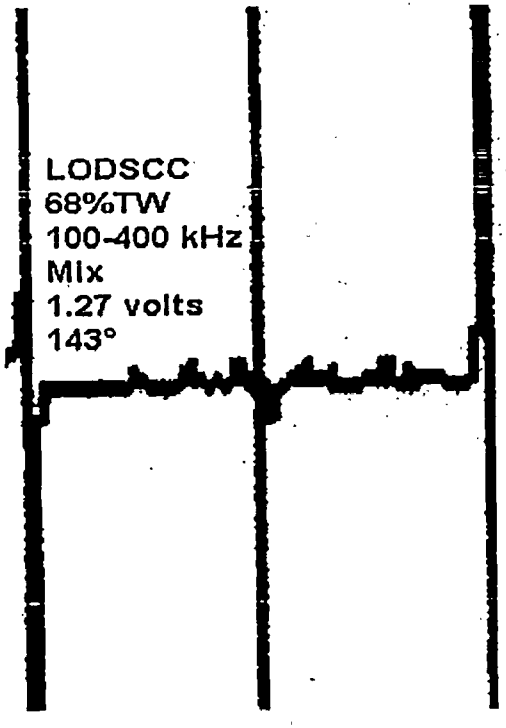


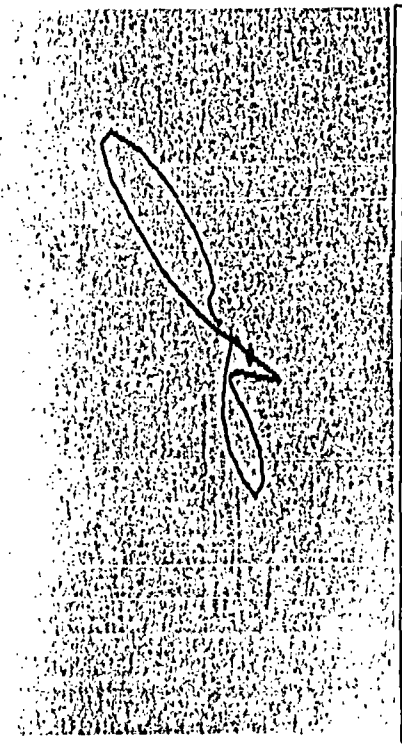


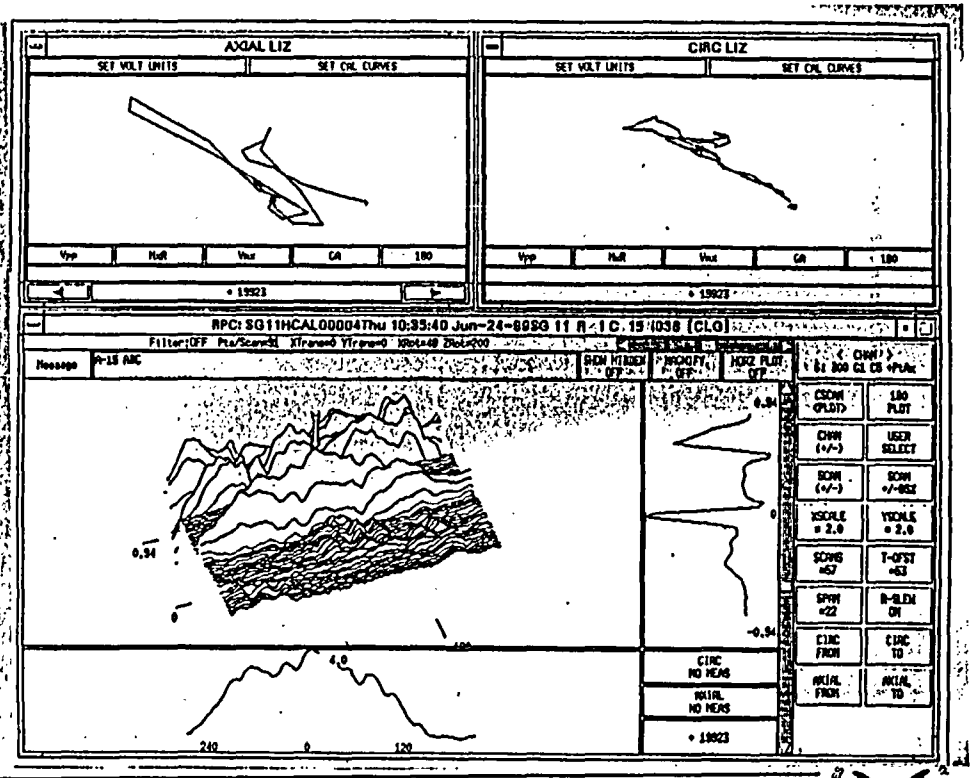
- BC coils (left) integrate signal around the circumference but are not sensitive to circumferential cracks; linear inspection speed is about 20 in./s
- Surface riding pancake coils (right) provide localized information about axial and circumferential cracks; inspection speed is about 2 in./s

Flaws can be revealed in a variety of ways

- Bobbin coils provide a linear trace and Lissajous figures from which flaw information can be extracted (ID or OD and depth)
- MRPCs provide Lissajous figures and 3- D amplitude plots giving more detailed information (orientation, ID or OD and depth)

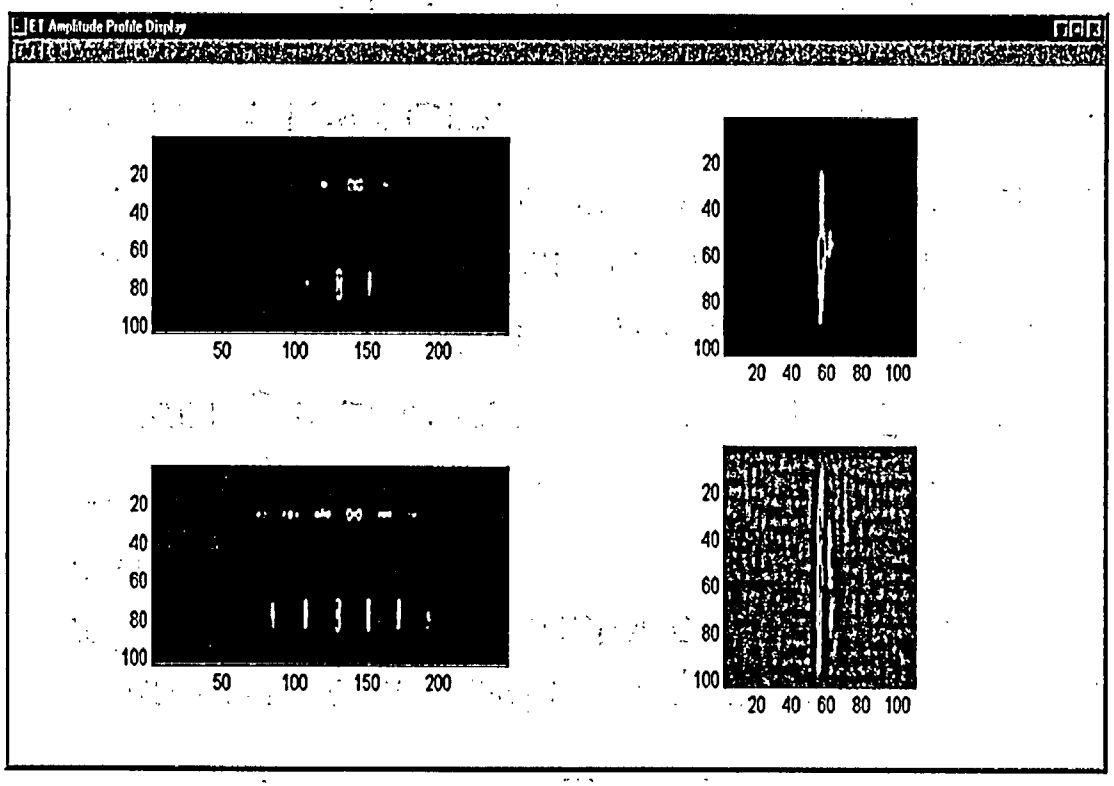


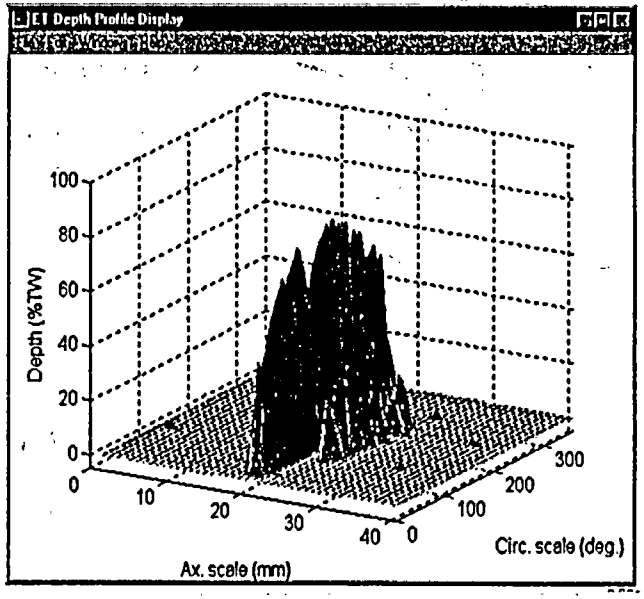




Advanced imaging techniques can provide significantly improved data on flaws

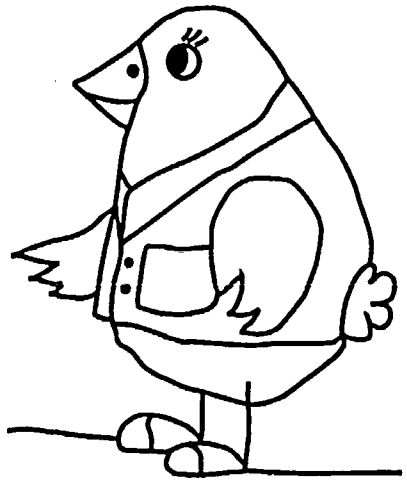
- The Argonne multiparameter algorithm (MP) uses amplitude and phase information at multiple frequencies to provide 2-D and 3-D flaw profiles





RR Procedures

- Data were collected by a qualified industry team following current industry practices and qualification procedures
- Eleven qualified analysis teams participated in the RR including teams from Canada and South Korea
- Teams consisted of a primary, a secondary and two resolution analysts along with a qualified data analyst for resolving disagreements among resolution analysts
- An NDE Task Group (from EPRI, Framatome ANP, Westinghouse, Duke E&S, Northern States Power, and Zetec) provided input on data collection and the development of the RR documentation (analysis guidelines, data acquisition, degradation assessment, training manual, and examination technique specification sheets).



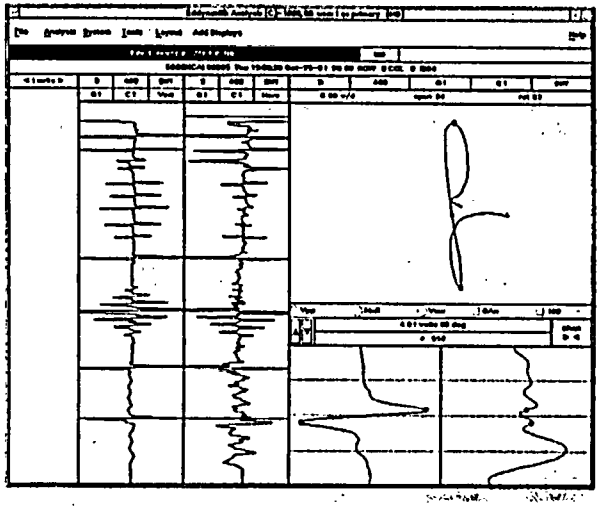
RR Procedures (continued)

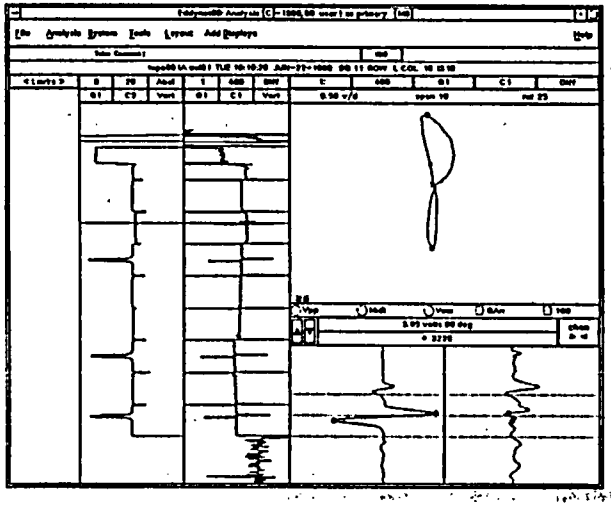
- Task Group concluded the documentation used for the RR met current industry practices and that flaws in the mock-up had EC signals similar to those observed under field conditions.
- Following industry practice TSP and FS flaws were analyzed using BC data. Tube sheet and special interest test sections were analyzed by MRPC
- Analysts' RR reports on optical disks were collected from RR teams by ANL proctors and reviewed at Argonne.
- Logistic fits to data for POD as a function of crack depth and m_p with confidence limits that include errors in the reference state were developed.

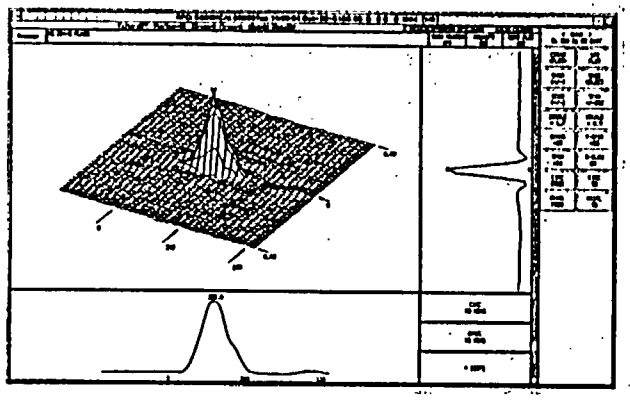
Similarity of McGuire and Argonne EC signals

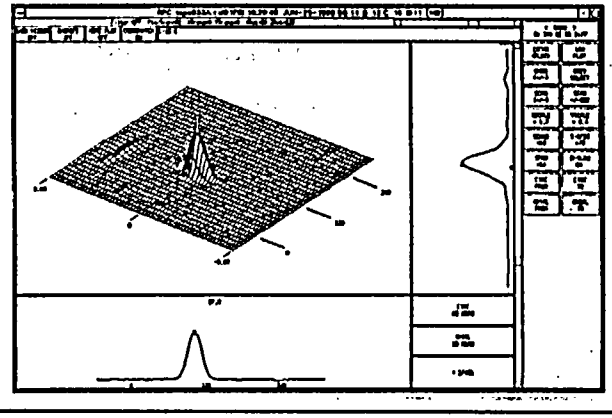
- BC and MRPC signals
  McGuire LODSCC

Argonne LODSCC

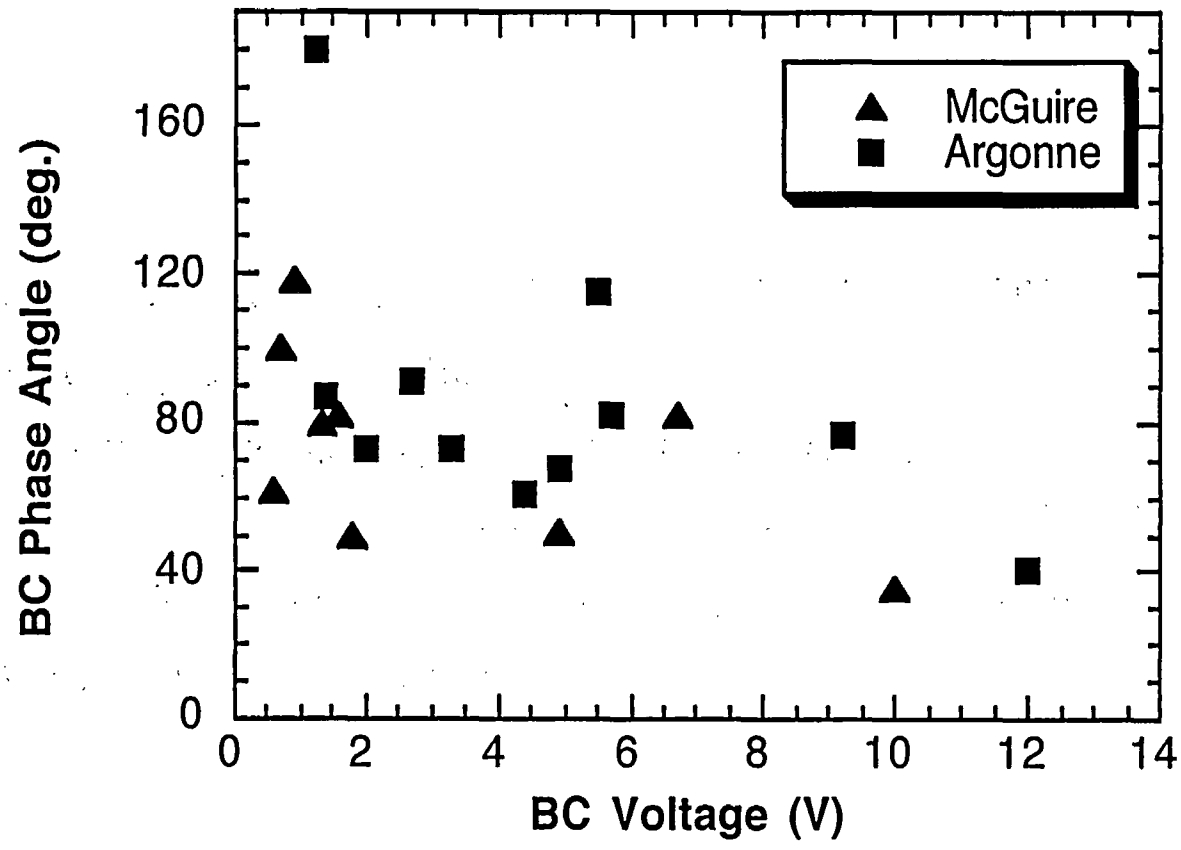








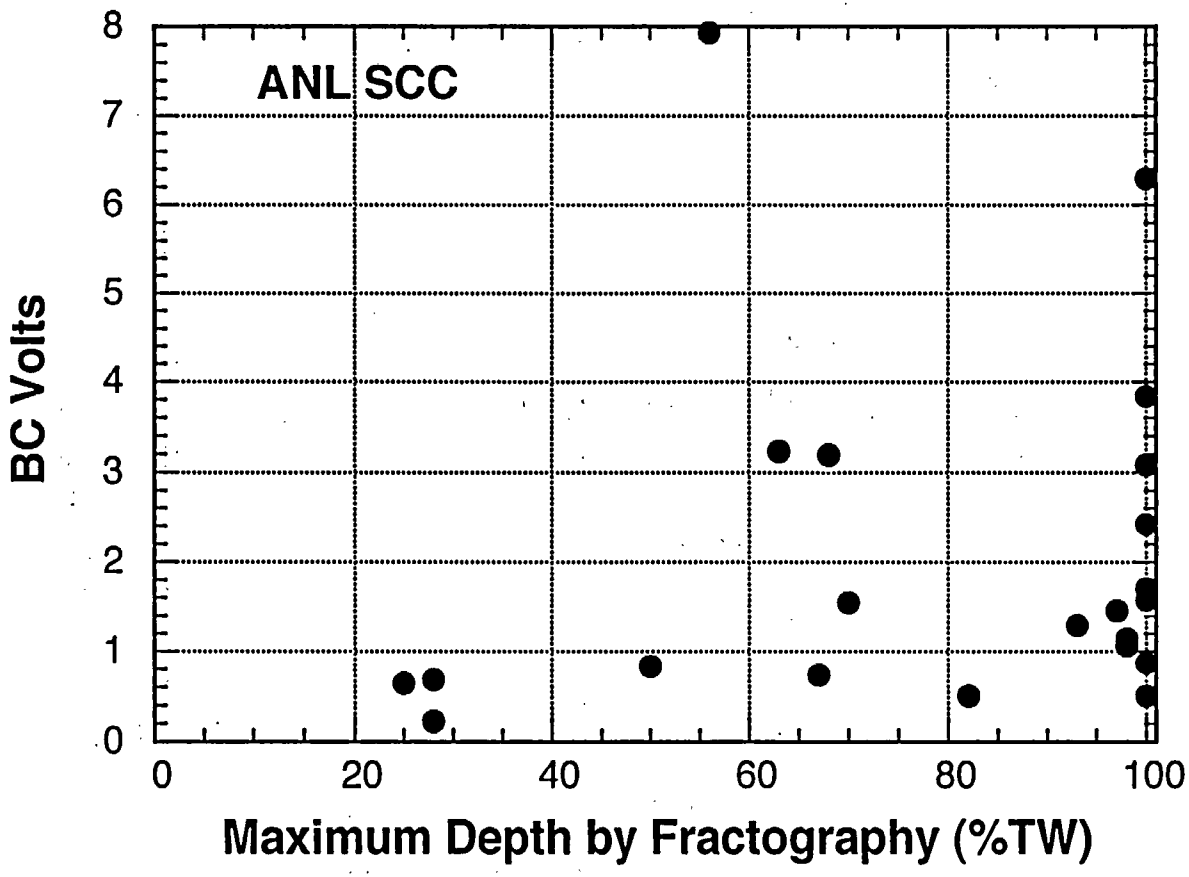
BC voltage and phase angle for representative SCC in mock-up and McGuire field data



Characterization of mock-up flaws

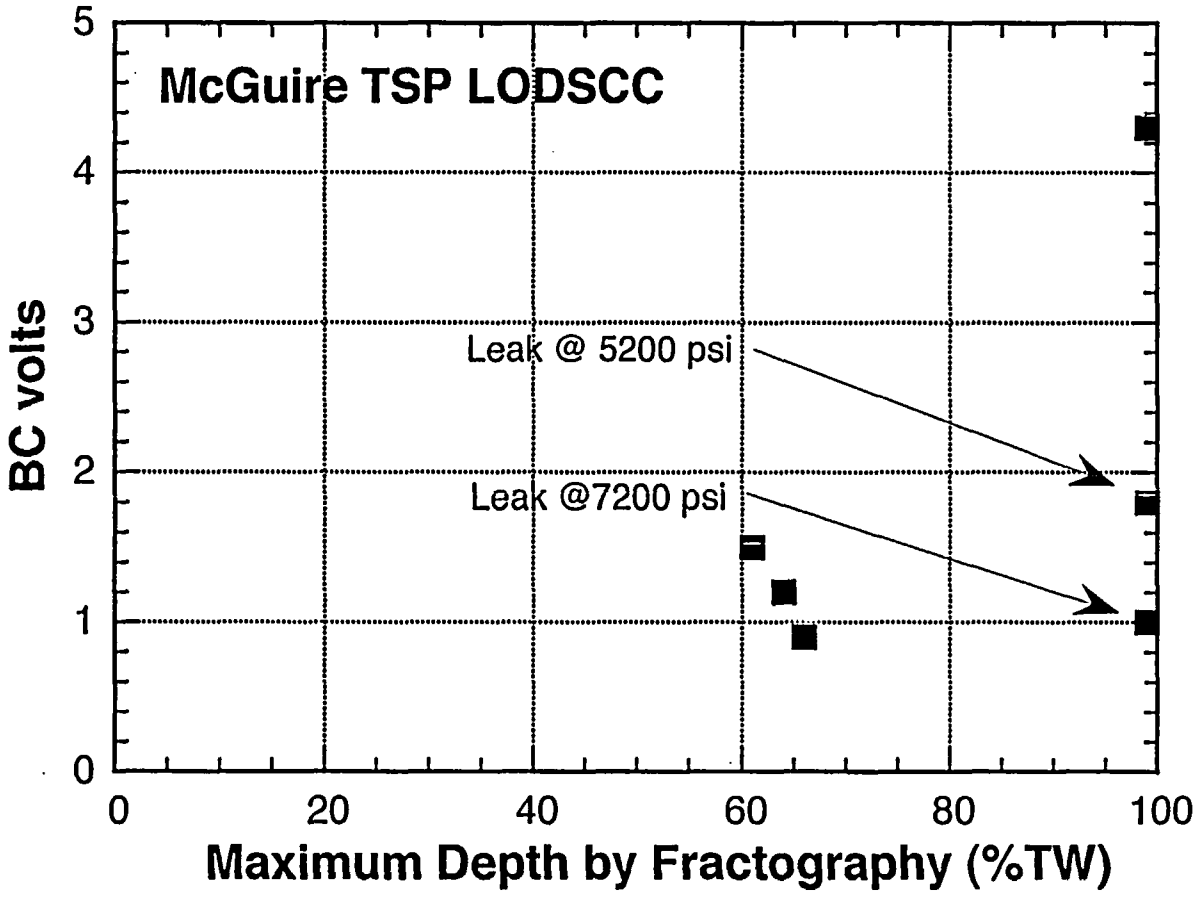
- Dye penetrant for OD flaws
- Destructive evaluation of a sample of mockup specimens
  - DE of all cracks impractical; chose sufficient number of samples to characterize accuracy of sizing technique
- Enhanced EC crack profiles
  - Algorithm using amplitude and phase at multiple frequencies

BC volts vs. depth for lab SCC



There is little correlation between actual depths and BC voltage

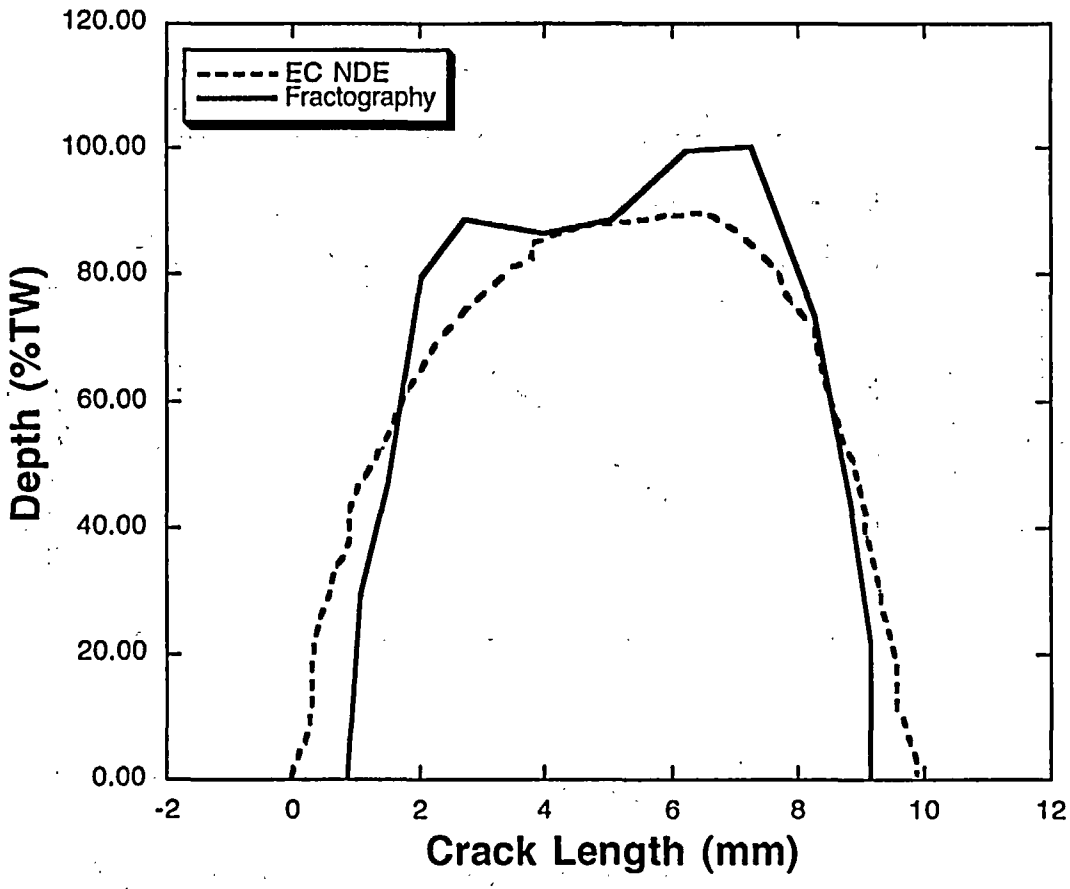
Depth vs. BC volts for McGuire TSP LODSCC



Poor correlation of depth with voltage consistent with results for lab cracks

Leakage vs volts consistent with current leak vs voltage correlations for 3/4 in. tubes

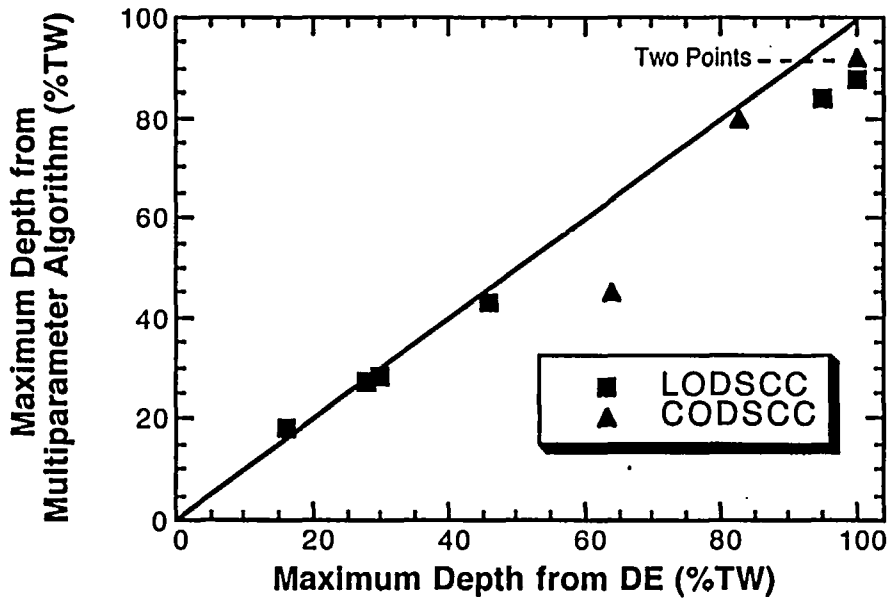
Example of fractography vs. EC Multiparameter (MP) algorithm profile

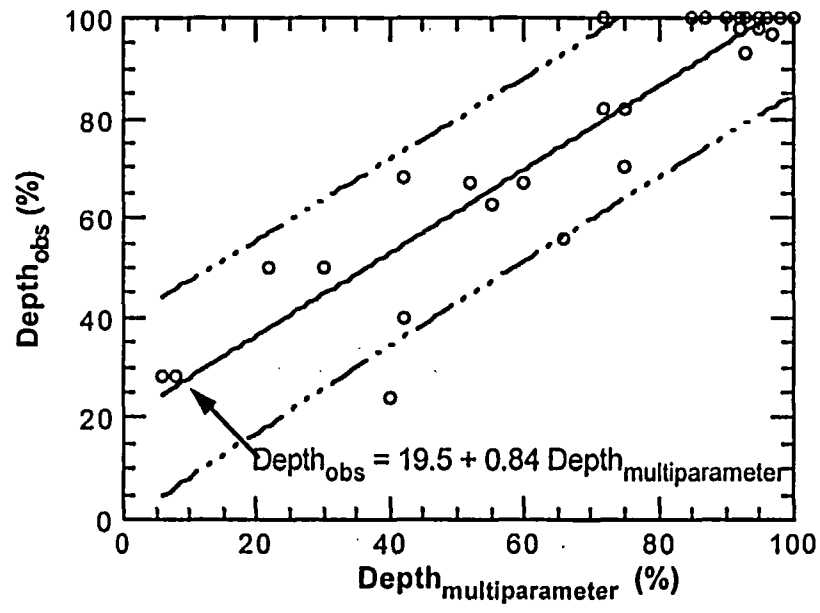


- Profiles from 37 SCC were used to establish accuracy of the multiparameter algorithm for depth sizing
- An additional 30 were used for further evaluation

Validation of Argonne multiparameter depth sizing

- MP depths can be very accurate for planar in straight tubes (left)
- More complex cracks and geometries result in more scatter (right)





Determination of POD Curves

- Actual results of round robin hits and misses–x of 11 teams detected the crack
- Problem is to determine POD curves that describe the round robin results
- Probability of detection depends on many variables: crack depth and length, orientation, morphology, material grain size and degree of cold work, presence of magnetite and copper, training and expertise of inspectors, sensitivity of instrumentation, presence of geometric artifacts like roll transitions, dents, tube support plates, etc.
  - Much of this is dealt with by restricting consideration to data acquired by very specific procedures for inspectors with specific training
  - Different geometric configurations (tube sheet, free span, tube support plate) and different crack geometries (ID, OD, circumferential, axial) dealt with through individual correlations
  - Only variable considered explicitly is crack depth

Maximum Likelihood Estimates

- Detection data are binomial—detection is 1, failure to detect is 0
  - Least squares linear regression assumes that the model response varies continuously and is inappropriate as a method to determine fitting parameters a and b for binary data.
- Maximum Likelihood Estimates choose parameters to fit data so that the likelihood of the observed round robin outcomes is maximized
  - It can be shown that least squares regression is a special case of MLE for observations of a continuous variable that has normally distributed errors.
- Detection is not a normally distributed quantity. If the probability of detecting a crack with depth x_k is p_k, the likelihood that n_k out of N teams detect the kth crack is described by binomial probabilities and the likelihood is

$$L = \prod_{k=1}^{K} \binom{N}{n_k} p_k^{\,n_k} (1-p_k)^{N-n_k}$$

Generally work with D = ln(L) to simplify the math

Maximum Likelihood Estimates (cont.)

- The most widely used forms for the probability of detection curve p(x) are the probit and logit functions:

$$p_k = p(x_k) = \int_{-\infty}^{a+bx_k} \frac{1}{\sqrt{2\pi}} e^{\frac{-u^2}{2}} du \qquad \text{probit}(p_k) \equiv \Phi^{-1}(p_k) = a + bx_k$$

$$p_k = p(x_k) = \frac{1}{1+e^{a+bx_k}} \qquad \text{logit}(p_k) \equiv \ln\left(\frac{p_k}{1-p_k}\right) = a + bx_k$$

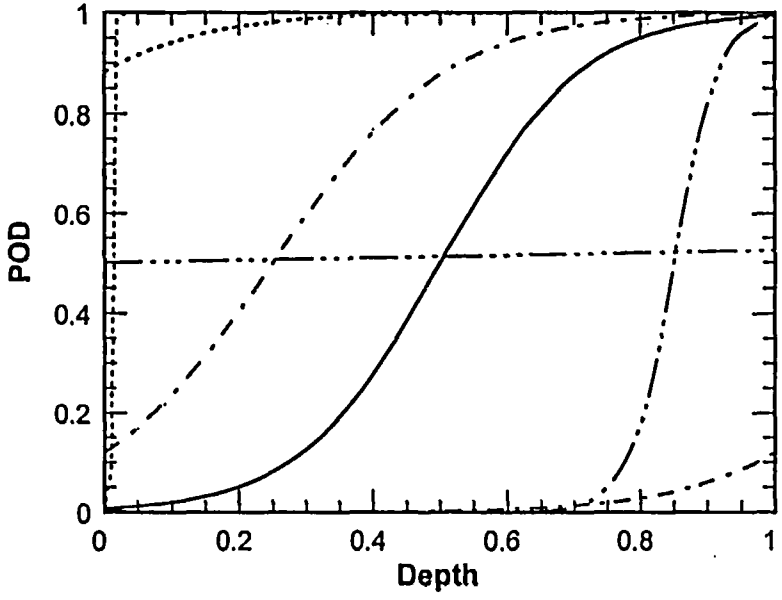
  - Physically plausible: if mean response amplitude is linearly related to the defect, the responses are normally distributed, and the POD is assumed equal to the probability that the signal exceeds the noise, then the POD is given by the probit function (Berens)

    From this point of view logit is just a mathematically simpler approximation (normal distribution approximated by the logistic distribution)

  - Mathematically convenient: for MLE with binomial probabilities, associated algebra is simplified

Maximum Likelihood Estimates (cont.)

- Logit and probit curves flexible enough to accommodate wide range of conceivable POD shapes



By suitable choices of a and b a wide range of shapes can be represented by the logit distribution: "perfect", "call everything", "typical", "detect when it leaks"

Non-zero POD at zero depth is false call rate; except for cracks in dents small for mockup (1% freespan, 6% roll transition)

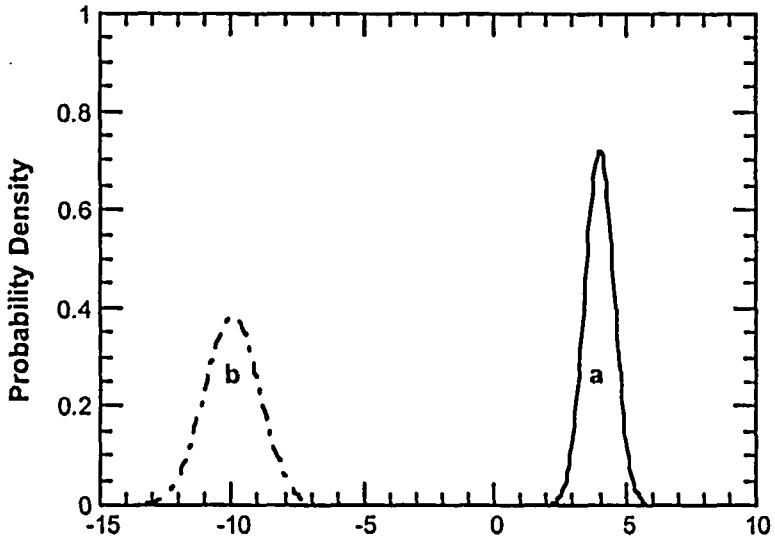
Maximum Likelihood Estimates (cont.)

- To maximize likelihood: $\frac{\partial D}{\partial a} = 0, \quad \frac{\partial D}{\partial b} = 0$
- For the logistic fit can show vanishing derivatives require:

$$\sum_{k=1}^{K} (n_k - Np_k) = 0$$

$$\sum_{k=1}^{K} (n_k - Np_k) x_k = 0$$

Maximum Likelihood Estimates (cont.)



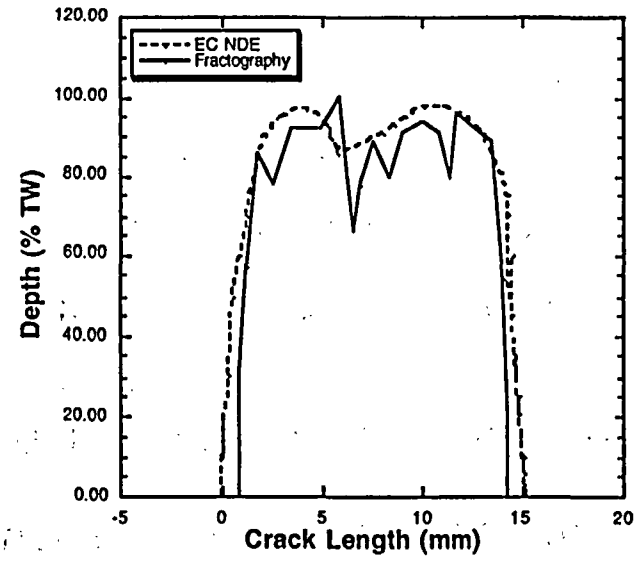
Solving equations gives mean values of a and b. Uncertainties due to finite number of teams and samples in RR and uncertainties in the depth.

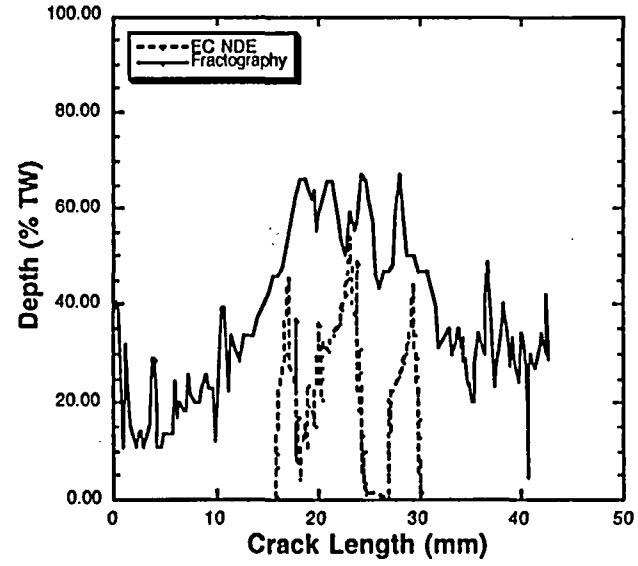
Uncertainty in parameters determined by breadth of likelihood peak. Uncertainties in depth change mean values of a,b.

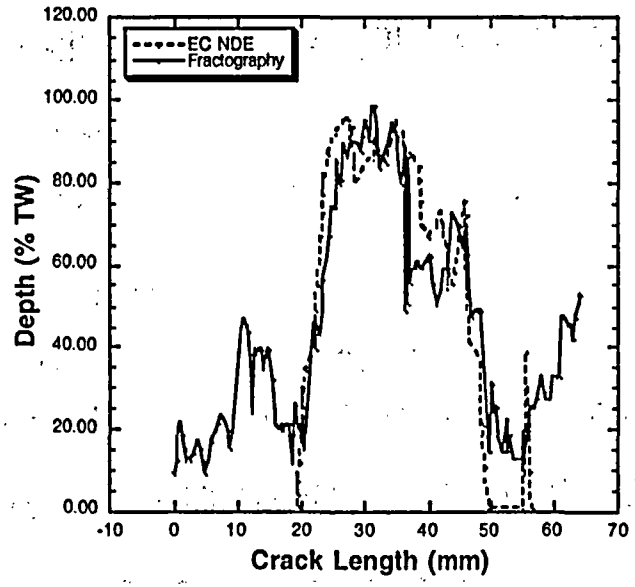
Shape of likelihood maximum controlled by 2nd derivatives:

$$\frac{\partial^2 D}{\partial a \partial a}, \frac{\partial^2 D}{\partial a \partial b}, \frac{\partial^2 D}{\partial b \partial b}$$

Error Estimates for Multiparameter NDE







Error in depth for NDE determined by benchmarking against fractographic results for a set of 37 tubes

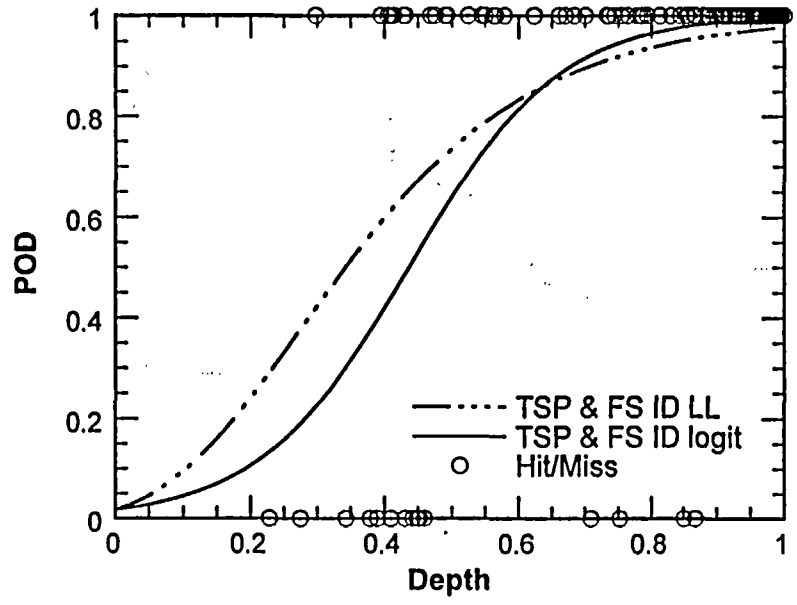
Sensitivity Studies

- Use of POD curves other than logistic/probit
  - Log–log link: log[-log(p)] = a + bx; p(x) = exp[–exp(a + bx)] (detection described by extreme value statistics)
  - For shallow cracks, small p
    - *Logistic: log(p) ≈ (a + bx)*
    - *Log-log: log(p) = -exp(a + bx)*

    Very different behaviors which can be thought of as perhaps bounding the range of responses for the POD with depth

  - Lognormal distribution: like probit with x replaced by ln(x); log-logistic: like logit with x replaced by ln(x)
    - *Widely used but singular at x=0*
    - *Like logistic if forced to false call rate at say 15%, like log-log link if forced to false call rate near zero (0.1%)*

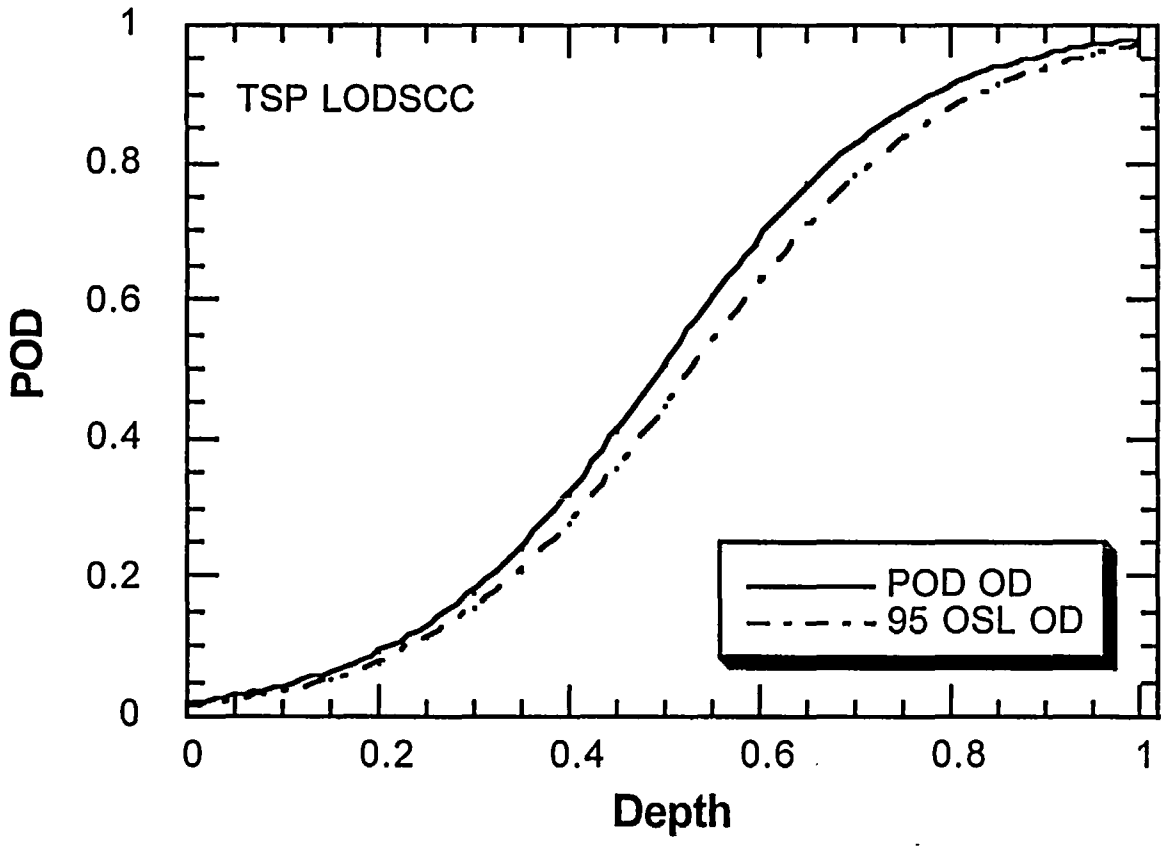
Sensitivity Studies (continued)



Logit and log–log models to the tube support plate and free span inspection results for one of the round robin teams

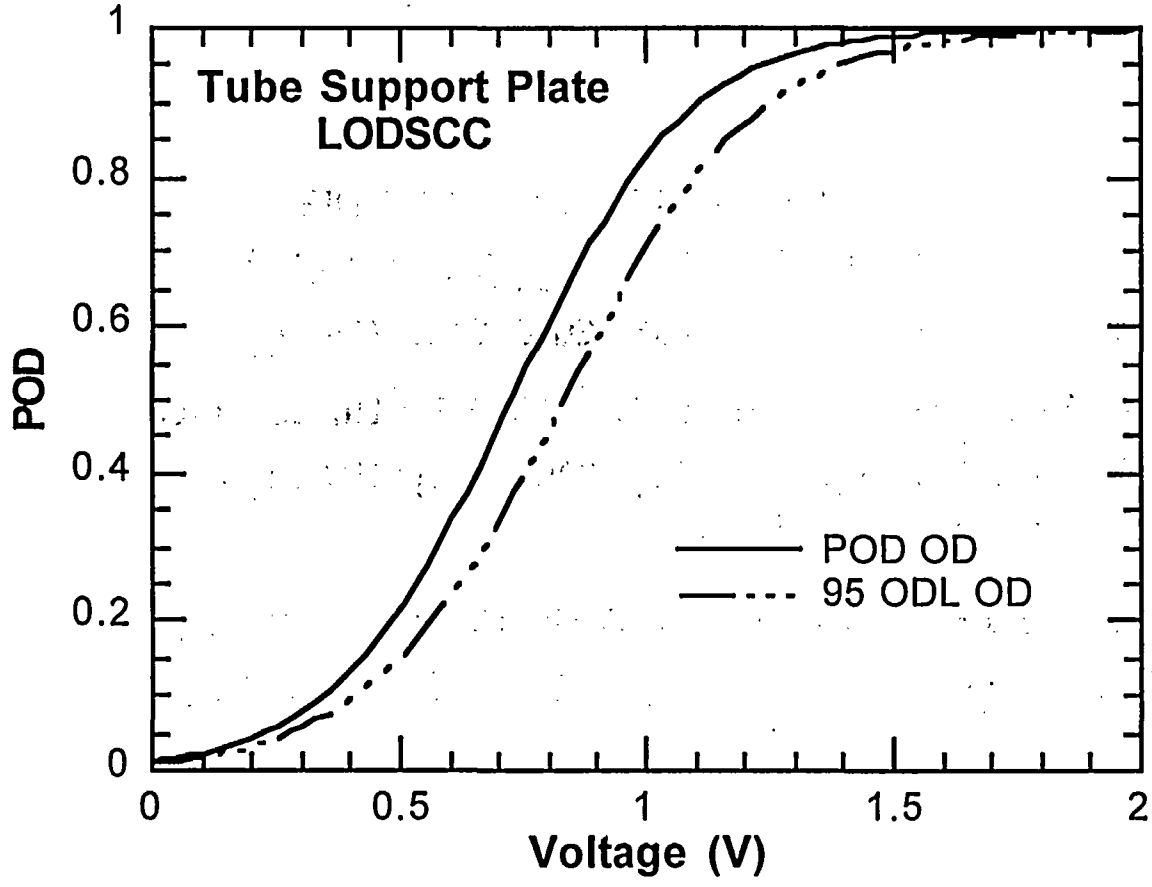
Log-log models generally give somewhat better statistical fits, but logit

BC POD vs. depth for LODSCC at TSP



- POD normally expressed as function of depth
- POD varies with location
- For most types of cracks in TSP or FS the false call rate is low (<2%)
- Final POD is not based on BC alone, but is important because it triggers MRPC evaluation (or plugging)

BC POD vs. voltage for LODSCC at TSP



- NUREG 1740; p.33 notes that some data indicate POD approaches 0.9 for signals >1-2 volts
  - RR POD results consistent with that statement
- Cracks are missed even if signal is visible because:
  - Noise is too high
  - Signal too complex
  - Human factors

Nature of false calls

- Some overcalls are the result of geometrical distortions and deposits which produce signals that are confused with flaws.
- In a round-robin exercise, participants tend to make calls that might not be made under field conditions because there is no penalty for overcalling as long as the overcalling is not abused.
  - There was a reasonably low overcalling rate for the free span (0.1%) and TSP (1.7%). The overcalling in the tube sheet level is significantly higher (6%).

Nature of missed flaws

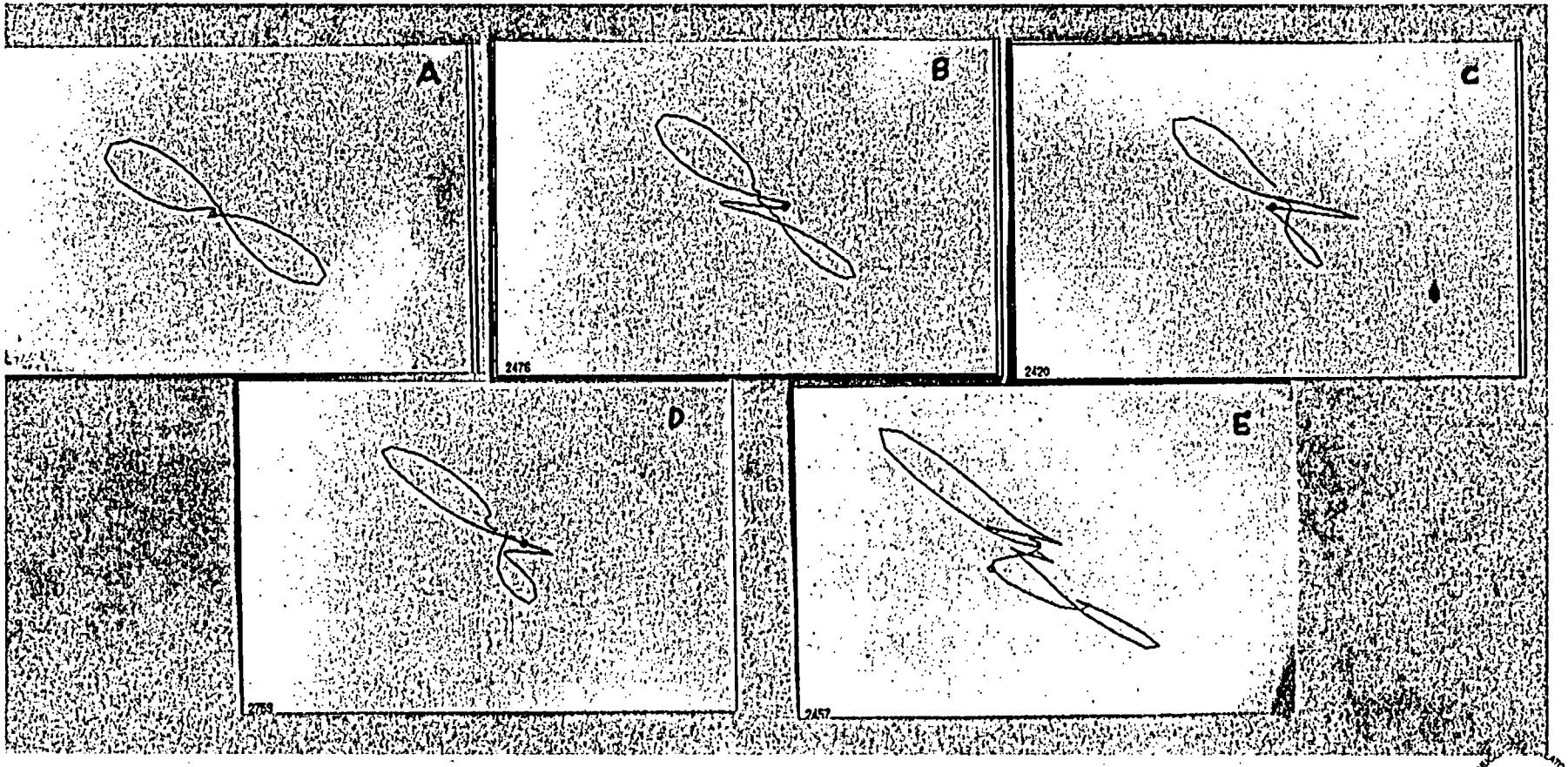
- The primary cause of missed flaws is distortion of the flaw signal by geometry or deposits.
- Extremely tight cracks or small flaws that do not generate a significant EC signal (signal-to-noise is too low)
- Very long flaws may be missed because the analysts concentrate on a small portion of the flaw, thereby missing the overall response.
- Confusion could also arise from conflicting indications from different probes. For example, there could be a clear bobbin coil signal but nothing reportable from an MRPC. On the other hand, some cracks that could be detected with an MRPC are not detected by the bobbin coil because the indication has a very high phase angle or is out of the flaw plane.

Nature of missed flaws (continued)

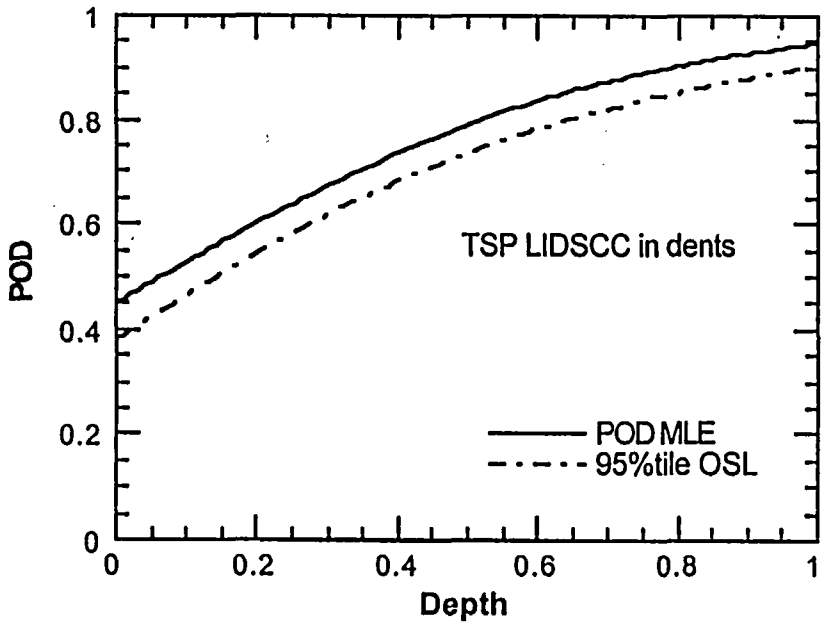
- Analysts have a preconceived idea of what flaw responses at various locations should be like, and might not pursue anomalous indications that are actually from a flaw.
- Human error accounts for some misses (I.e. recording error, temporary lack of concentration)

Effect of dent on TSP BC signal

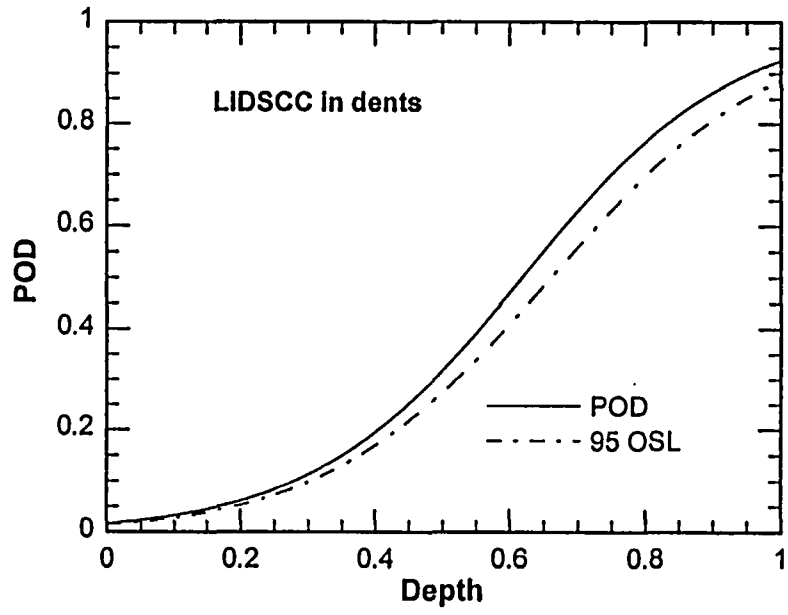
- Bobbin coil Lissajous figures for TSP without dent or SCC (A), TSP with dent (B and C), shallow LIDSCC in dent at TSP (D) and deep LIDSCC in dent at TSP (E).



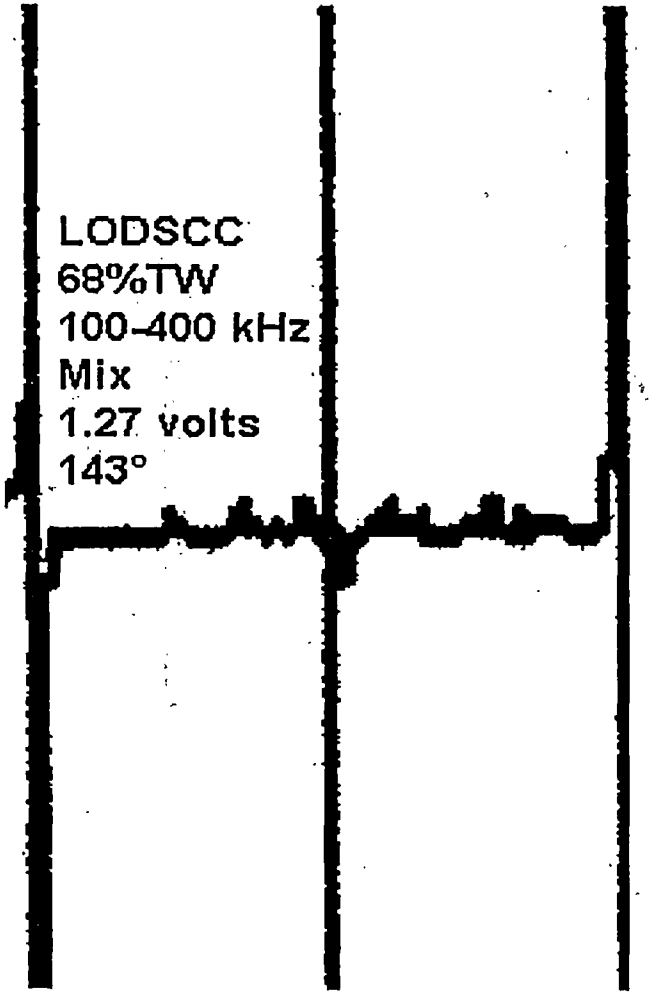
POD vs. depth for LIDSCC in dent at TSP

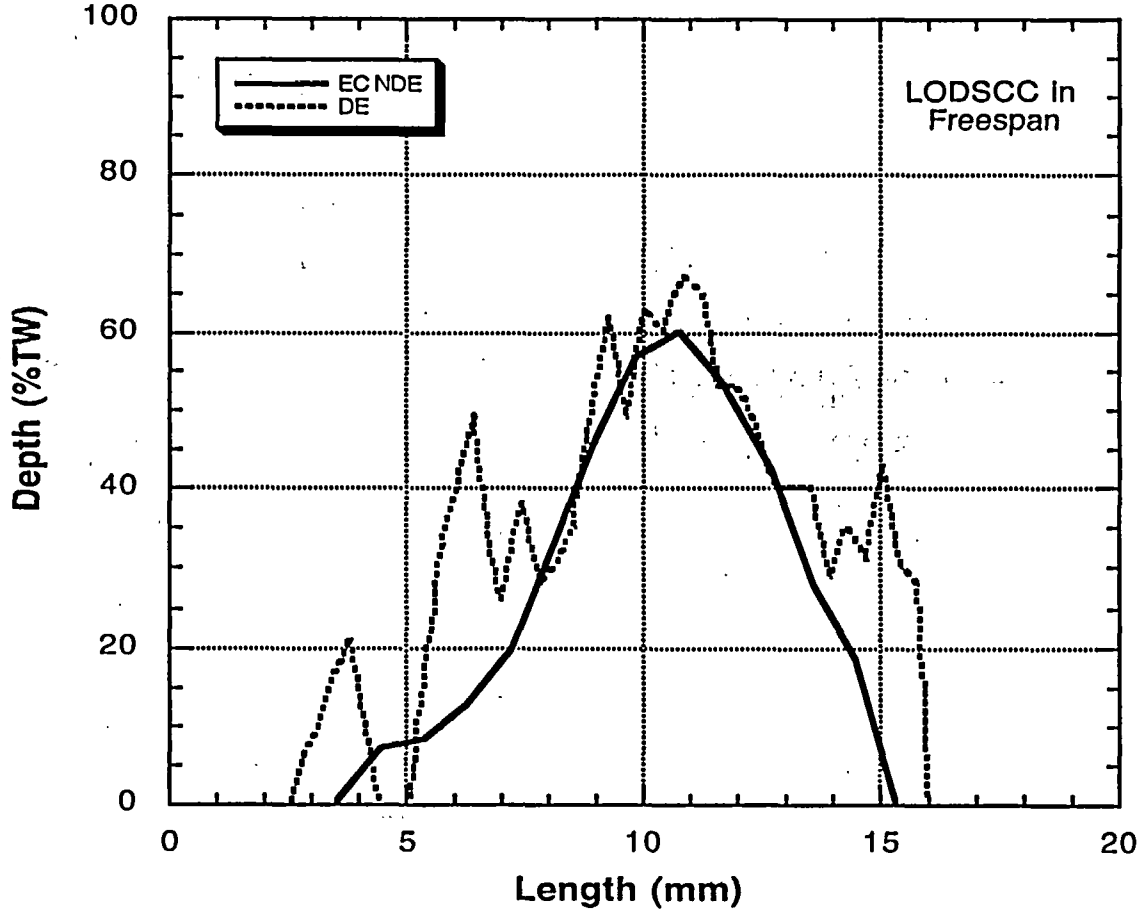


- BC POD high false call rate compensated by follow-up MRPC analysis
- Some correct BC calls are dismissed following MRPC analysis.

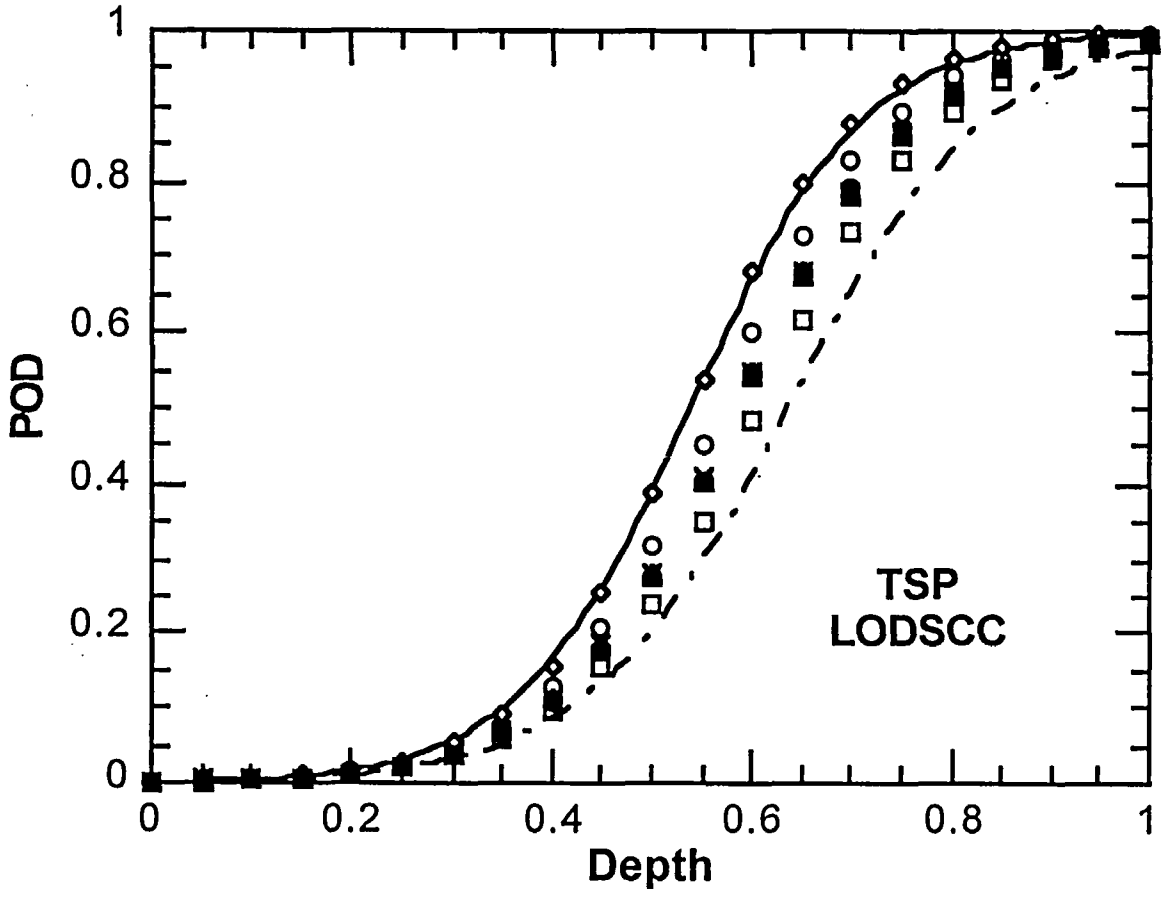


Missed mock-up LODSCC in FS. BC signal on left, Argonne multiparameter profile and DE on right



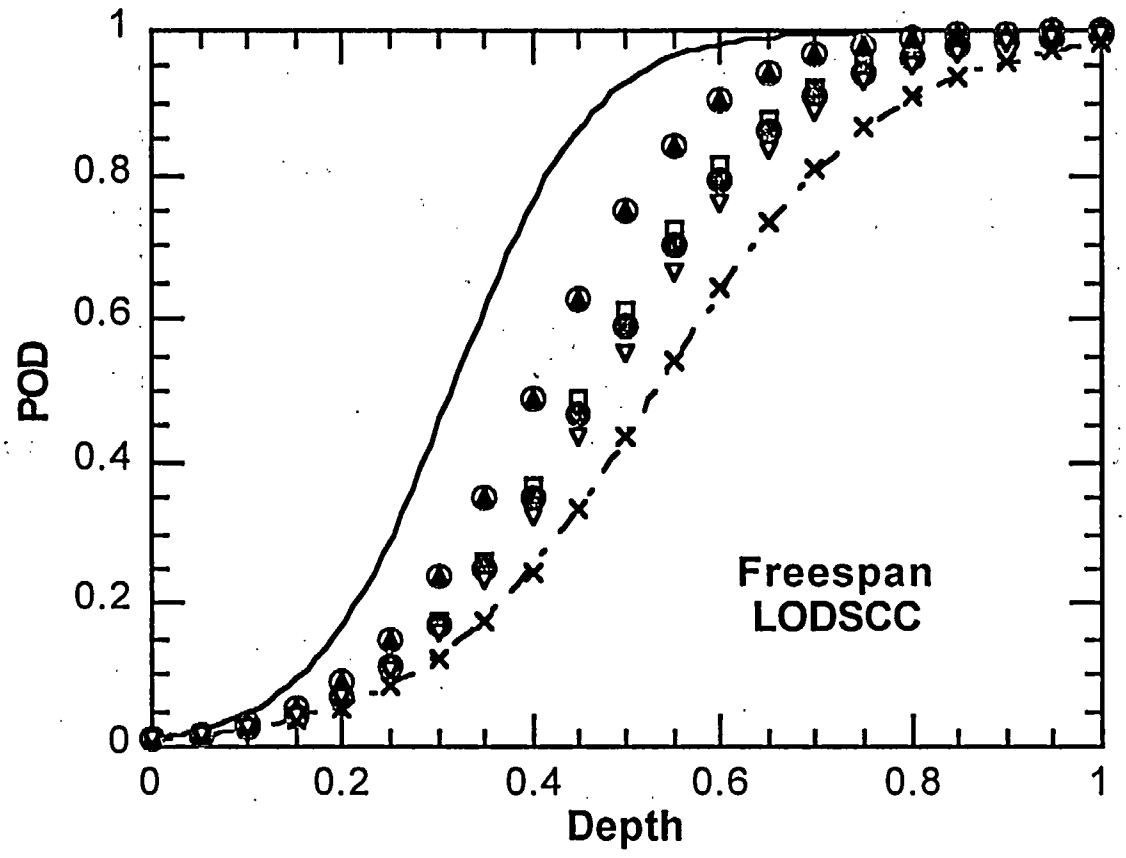


BC POD vs. depth by team for LODSCC at TSP



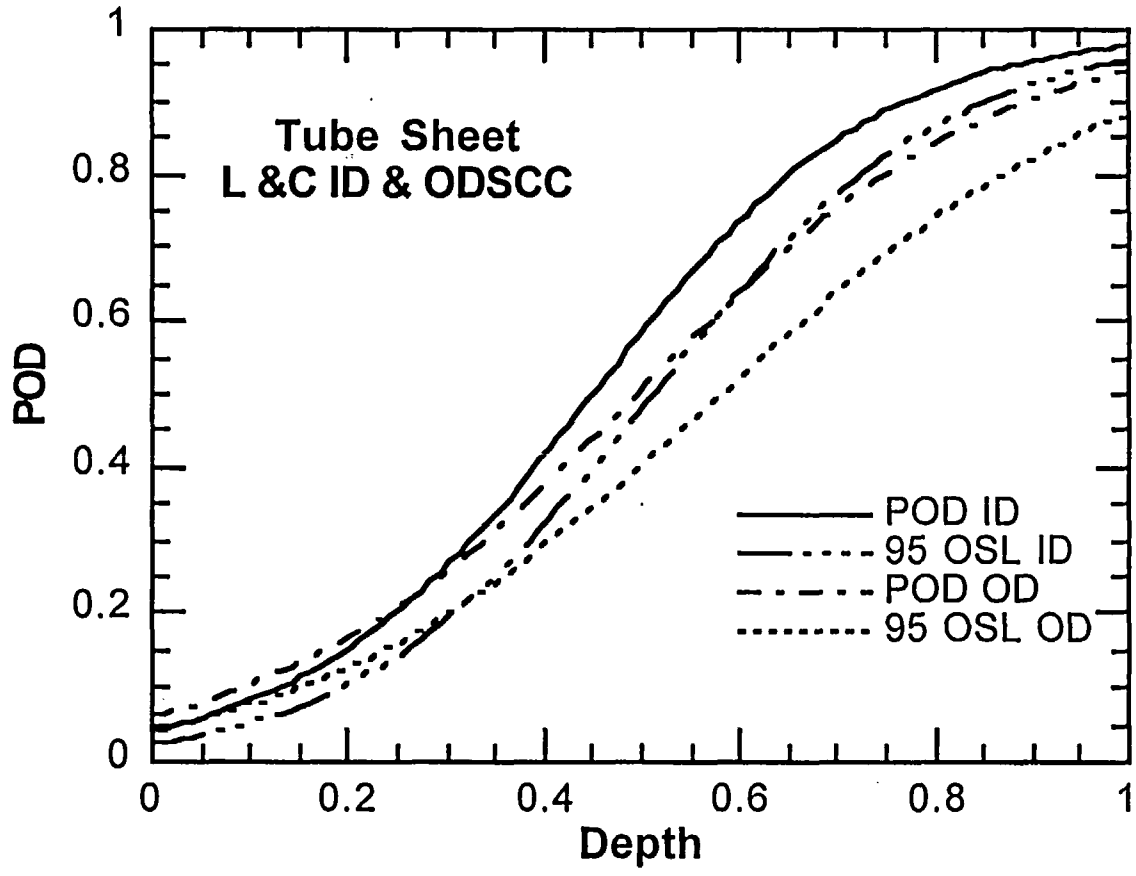
- Qualification and adherence to procedures generally leads to consistent results between teams

BC POD vs. depth by team for LODSCC in freespan



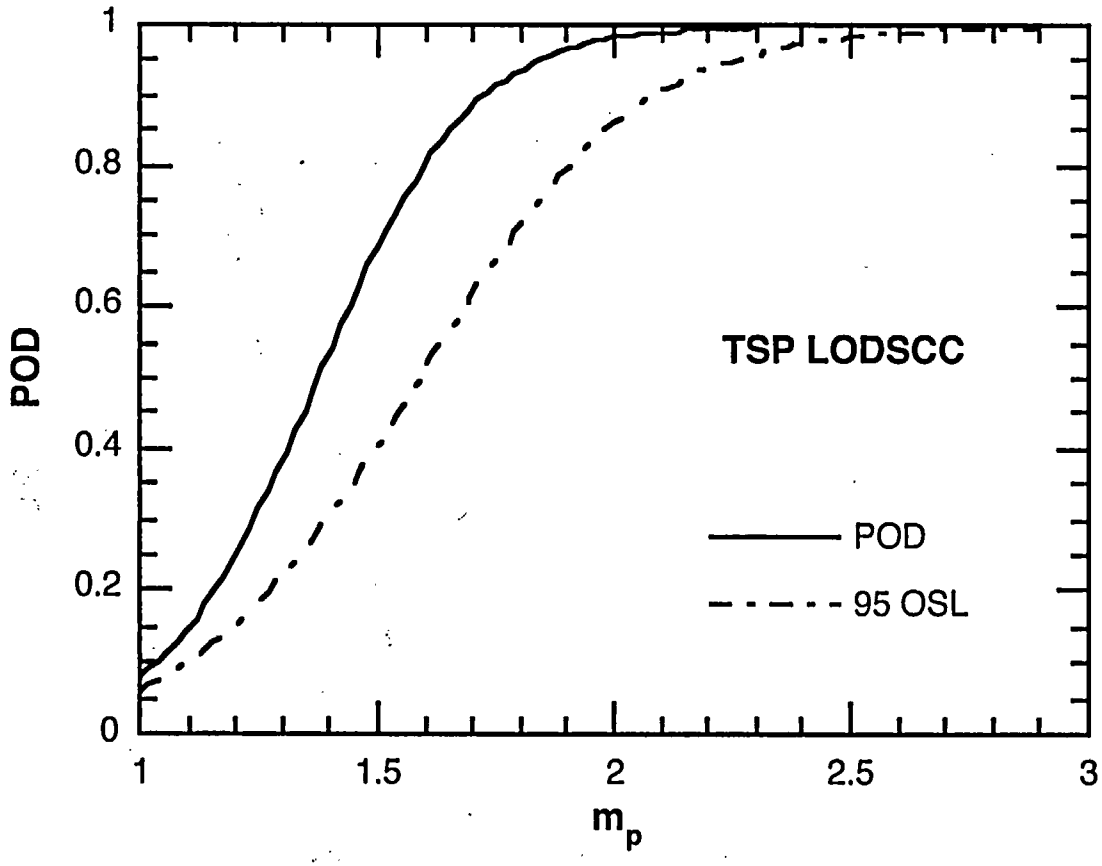
- Sometimes it is difficult to explain variations between teams

Tube-sheet MRPC POD vs. depth



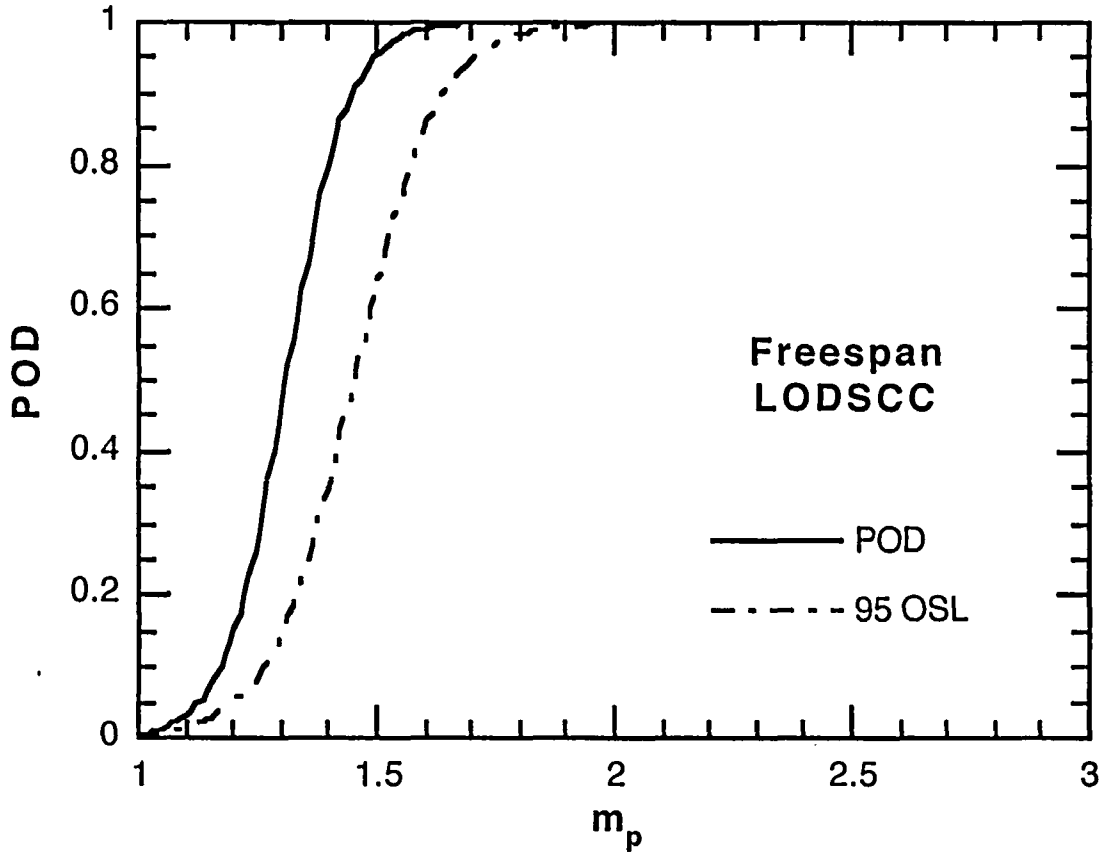
- Roll transition adds complexity to analysis of SCC
- PODs decrease and false call rate increases to about 6%

BC POD for TSP LODSCC vs. m_p



- Depth does not fully characterize structural impact of crack
- Introduced fracture mechanics parameter m_p which includes both depth and length
- m_p characterizes stress concentration in un-failed ligament of crack; $m_p > 2.3$ to get failure at MSLB

BC POD for freespan LODSCC vs. m_p



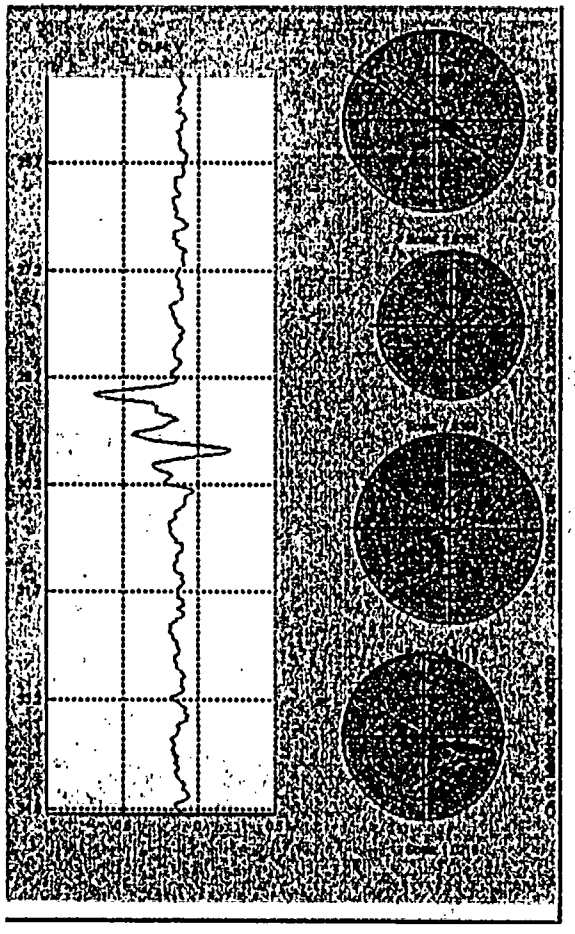
EC signal noise issues

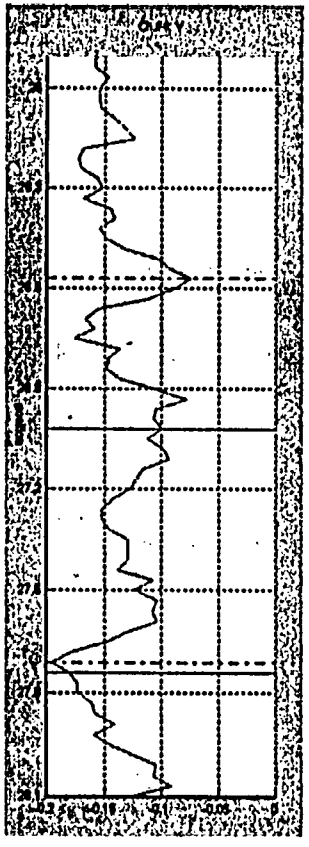
- How much EC noise can be tolerated before data quality is affected and detection capability degraded
- Possible actions for low signal to noise
  - Recollection of data
  - Change technique
  - Determine if flaws can be detected in presence of noise
  - Adjust POD and sizing uncertainty
  - Repair tube
- How are mock-up POD curves related to POD curves for situations with higher noise.

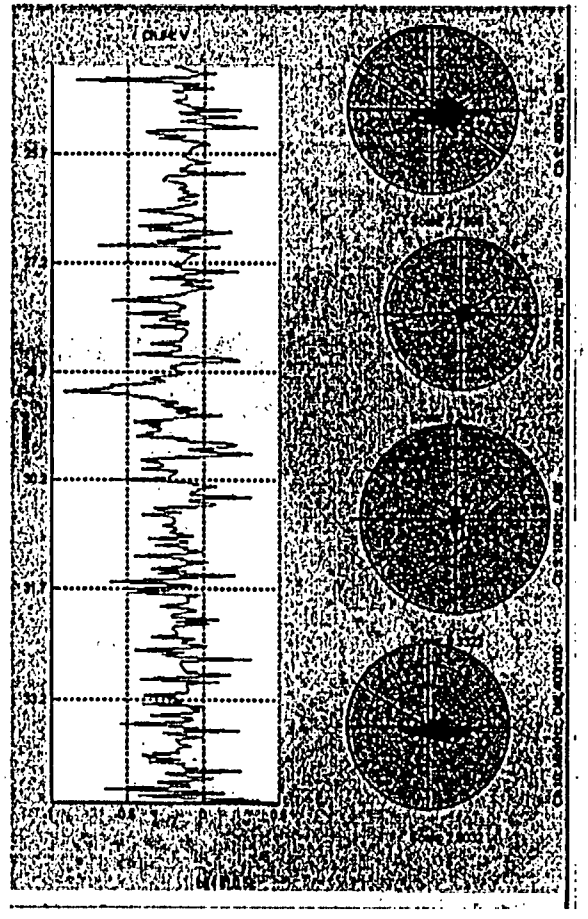
EC signal noise issues (continued)

- RMS noise may not be a good measure of noise for detection as it is often dominated by the horizontal component of EC data
  - Vertical component of data is most critical for detection
- Noise levels that may not significantly affect detection can have profound effect on sizing results
- Measurement of noise is not a straightforward procedure
  - Limits on EC noise are given in inspection procedures in terms of RMS levels at specific locations
  - Such noise measurement only provide general information about the data quality and may not reflect the noise at the flaw.
- Minimum signal-to-noise ratio at the flaw needs to be > 2:1 to assure >90% probability of detection of mock-up flaws

Electronic addition of noise to mock-up EC signals







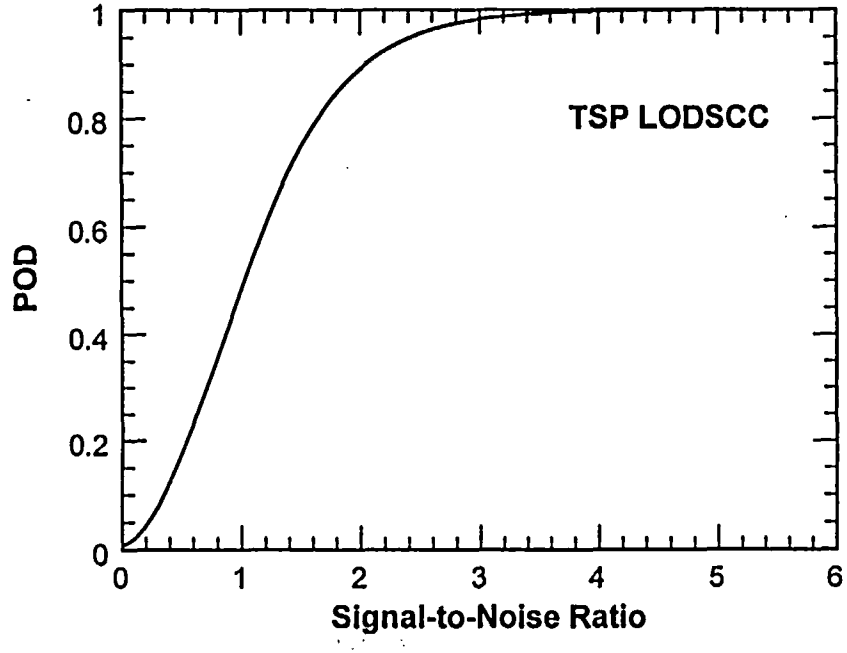
Estimating impact of noise on POD

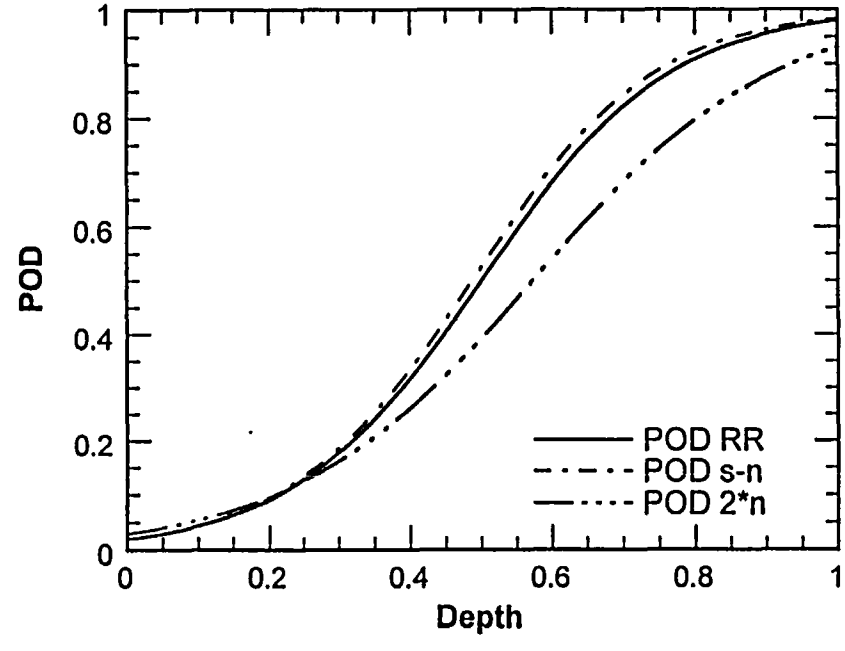
- Correct characterization of noise has been discussed
  - Noise level in mockup less than in most plants
  - Need to estimate impact of higher noise on PODs determined in round robin

Estimating impact of noise on POD (cont.)

- Two approaches used
  - Through Berens model for POD discussed previously where mean response amplitude is related to defect size, the noise is normally distributed, and the POD is assumed equal to the probability that the signal exceeds the noise
    - *Shift in mean value of curve is just Δnoise/σ where σ describes the distribution of responses about the mean for a given depth*
      - σ can be determined from the data from the mockup
    - *Limitation is as noted before that we can use the vertical component of the BC but the true response is a pattern recognition with a variance that may not be the same as that of the voltage*
  - Empirical determination of POD as a function of POD and S/N as a function of depth from mockup; adjustment of S/N for higher noise, and convolution back to get POD as function of depth
    - *Limitation of BC voltage as response accounted for in POD vs S/N curve*

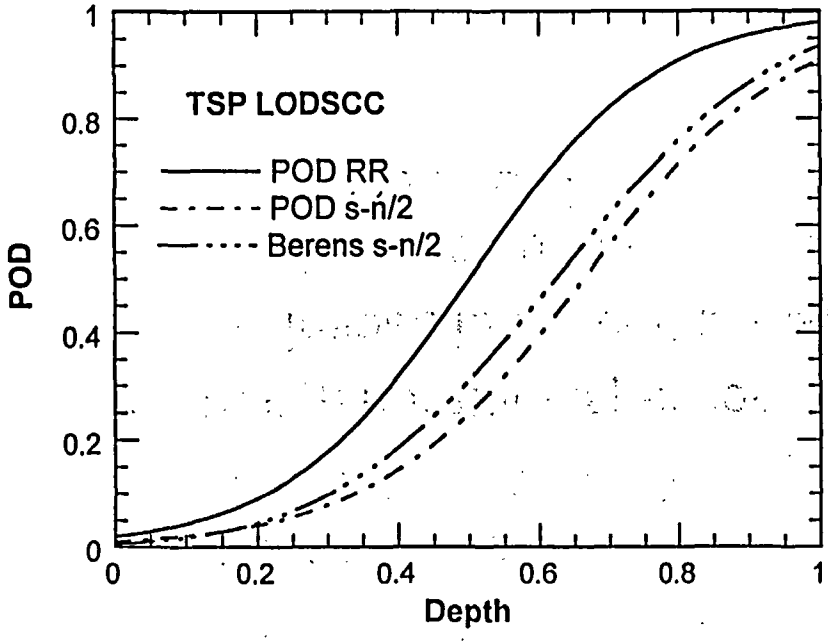
Estimating impact of noise on POD (cont.)





- Convolving POD as a function of S/N with the S/N data as a function of depth reproduces the round robin POD curve. Decreasing the S/N values for the cracks results in a lower POD curve.

Estimating impact of noise on POD (cont.)

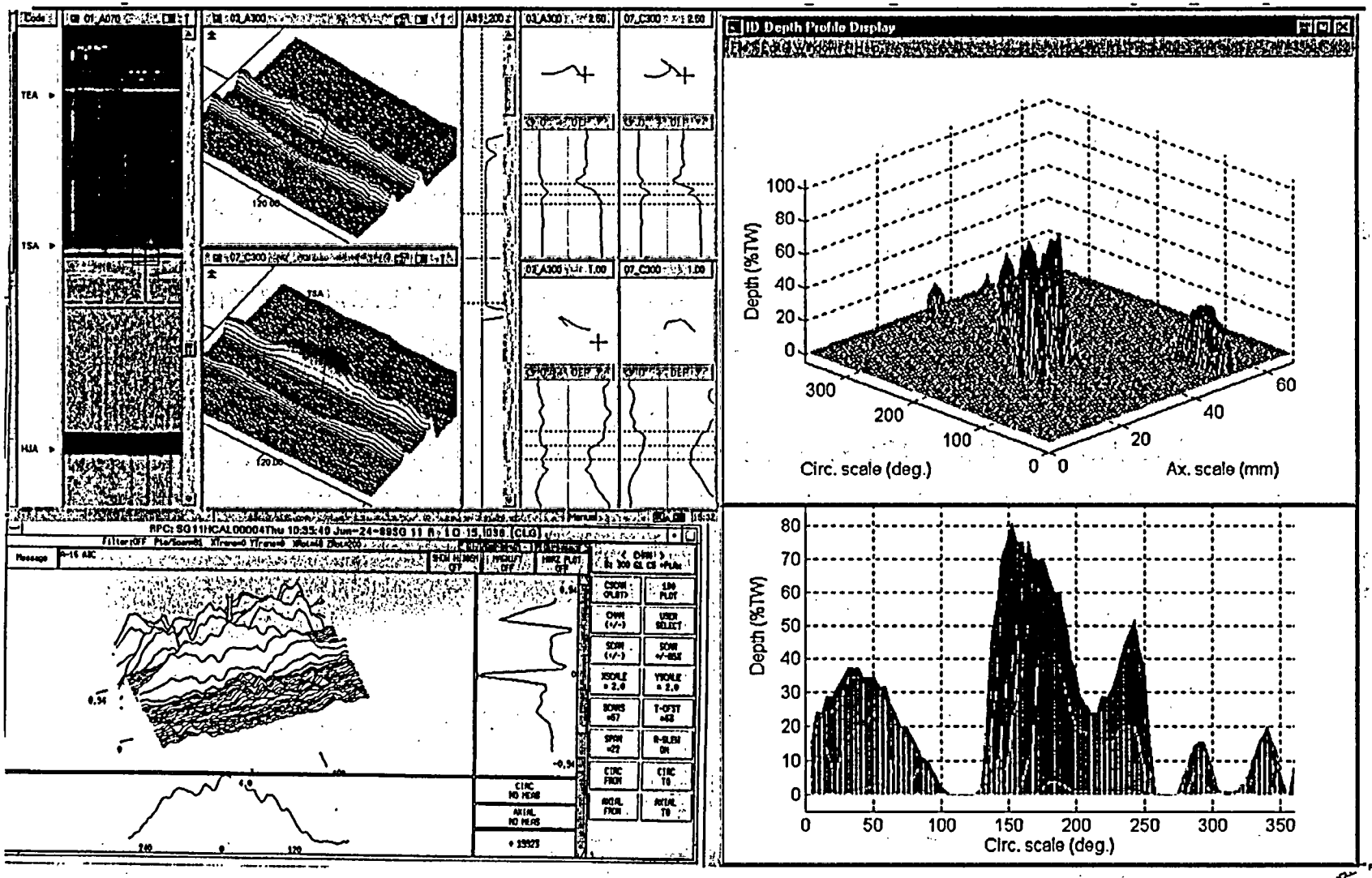


Results from the two different approaches are reasonably consistent

Potential for ISI advances with the X-Probe

- X-Probe is a 36 coil transmit–receive array probe
- Designed to be sensitive to both circumferential and axial cracks
- Inspection speed is comparable to bobbin coil, detail of information comparable to MRPC
- Full generator inspection by X-Probe generates terabytes of data
  - Inspection speed is fast, but analysis is slow
  - Wide use of array probes is probably unlikely until automated procedures for data analysis are available

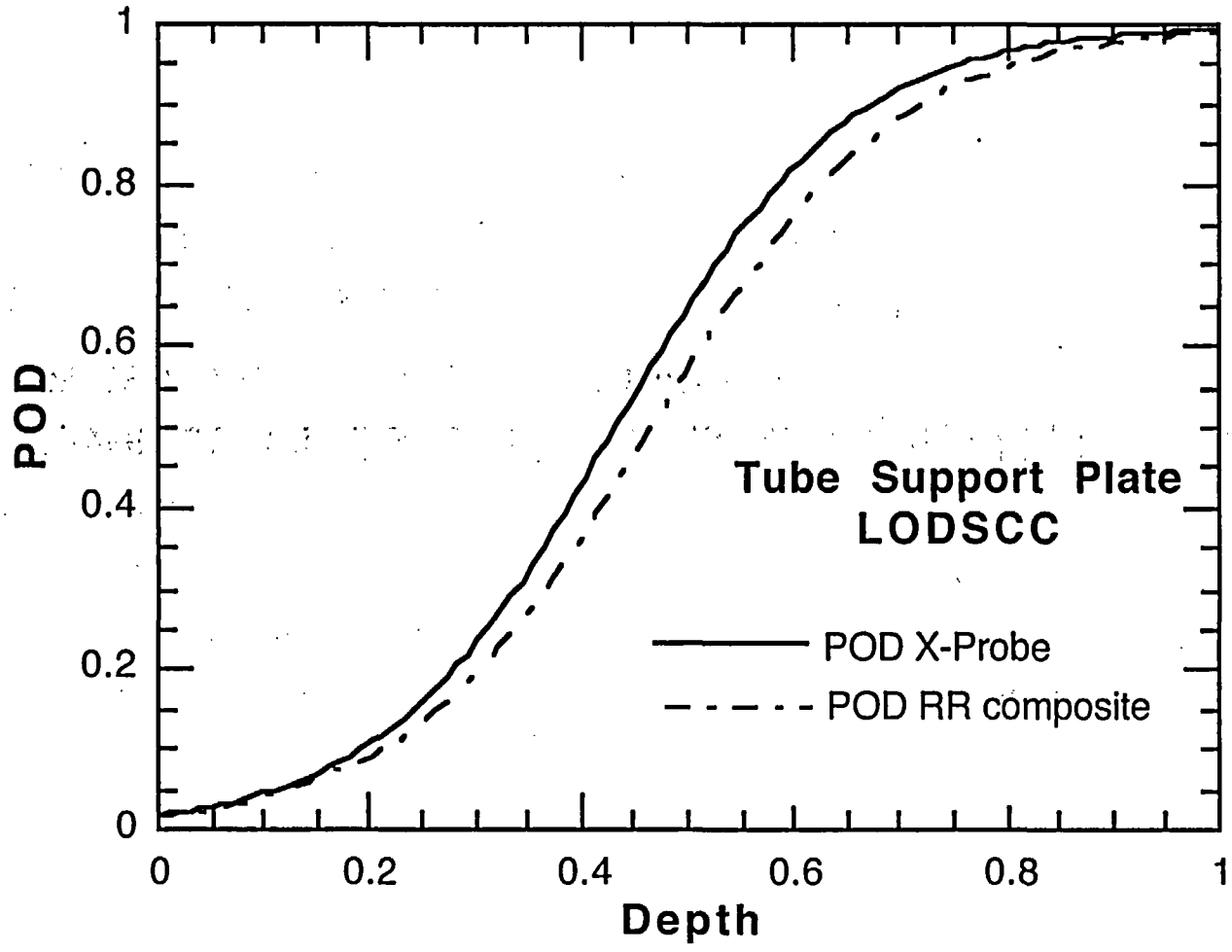
Comparison of X-Probe(upper left), +Point(lower left) and multiparameter imaging of flaw (right).



Results for X-Probe Inspection of Mockup

- The X-Probe shows a high POD for shallow ID SCC at the TSP without overcalls.
- There were many flaws detected by the X-Probe that were missed by at least some RR teams.
- Less effective than bobbin or MRPC probes for relatively shallow OD flaws and cracks in dents. Confusion is also possible for complex cracks, especially SCC at top of the tube sheet
- The X-Probe collects data as fast as a bobbin coil with characterization comparable to +Point but time to analyze data is significant and the net effort with current computers is comparable to MRPC evaluations. Automated data analysis could dramatically reduce the data analysis time
- Data evaluated by two teams with the experts team doing better.

Comparison of X-Probe (AECL/RDTech) POD to RR BC POD for TSP LODSCC



Summary: EC analysis round robin

- The completed eddy current NDE analysis round robin using industry qualified teams and the ANL/NRC mock-up provides POD as function of flaw depth, voltage, location and m_p for 7/8-in alloy 600 tubing.
  - Eleven qualified analysis teams participated in the RR including teams from Canada and South Korea
- This project addressed the issue raised in NUREG 1740 that improvements can be made over the current use of a constant probability of detection for flaws in SG tube

Summary: EC analysis round robin (cont.)

- Input on the development of the RR protocols provided by NDE Task Group made up of recognized industry experts to help ensure consistency with current practice
- Input from Task Group also helpful in assuring that flaws in the mock-up had EC signals similar to those observed under field conditions.
- A computer algorithm to determine crack profiles by use of multifrequency EC amplitude and phase information was developed and validated in blind tests for the mock-up
- Logistic fits to data for POD as a function of crack depth and m_p with confidence limits that include effect of errors in the crack depths were developed

Summary: EC analysis round robin (cont.)

- POD as function of voltage for TSP SCC > 0.9 for signals >1 volts
- Qualification and adherence to procedures led to consistent results between teams in most cases
- POD were very high for m_p>2.3 (m_p characterizes stress concentration in un-failed ligament of crack; m_p > 2.3 to get failure at MSLB)
- Cracks were missed because:
  - Signal too complex and misinterpreted
  - Low signal-to-noise
  - Human error

Summary: Noise issues

- Measurement of noise is not a straightforward procedure
  - RMS value generally provides reproducible results (in part due to averaging over a large number of data points)
  - Measurement results are position dependent
  - RMS noise as currently measured may not be a good measure of detection as it is often dominated by the horizontal component of EC data
- Noise levels that may not significantly affect detection can have profound effect on sizing results

Summary: Potential for array probes

- Data collected from the mock-up using the X-Probe was evaluated by experts
- The X-Probe shows a significantly higher POD for the shallow ID SCC at the TSP.
- There were many flaws detected by the X-Probe that were missed by at least some RR teams.
- Less effective than bobbin or MRPC probes for relatively shallow OD flaws and cracks in dents. Confusion is also possible for complex cracks, especially SCC at top of the tube sheet.
- The X-Probe collects data as fast as a bobbin coil with characterization comparable to +Point but time to analyze data is significant.

ACRS JOINT MATERIALS AND METALLURGY AND THERMAL-HYDRAULICS SUBCOMMITTEES

PROGRESS ON STEAM GENERATOR ACTION PLAN MILESTONES – Items 3.7 and 3.8

February 3 and 4, 2004
Rockville, MD

Louise Lund, (301) 415-3248
US NRC Office of Nuclear Reactor Regulation
Division of Engineering

SGAP Item 3.7

"Assess the need for better leakage correlations as a function of voltage for 7/8-inch steam generator tubes."

Completed 4/25/03

Issue

- In NUREG-1740, ACRS Ad Hoc Subcommittee concluded that the leakage correlation used for the voltage-based alternative repair criteria (ARC) for the 7/8-inch diameter steam generator tubes was poor.
- Database for 3/4-inch tubes exhibited a better correlation.

Background

- Separate correlations exist for 3/4-inch and 7/8-inch databases
  - Both databases exhibit scatter.
- 3/4-inch database contains 48 data points
- 7/8-inch database contains 31 data points

Sources of Scatter

- Simple explanation for the differences in correlations could not be established
- Possible sources of scatter:
  - pre-pull voltages are used
  - plugging of cracks by deposits
  - French data

- Elimination of French Data due to statistical and mechanistic differences:
  - high voltage data with part TW cracks - US data above 4 volts almost all TW (lower leakage for same voltages for French data)
  - elimination of French data improved correlation
  - industry performs periodic confirmatory analysis to verify assumptions still valid

Summary

- Staff continues to evaluate data
- Addition of new data in 2001 and 2002 made correlation worse; addition of new data in 2003 made correlation better
- Staff concludes that leakage methodology is acceptable because:
  - Generic Letter 95-05 specifies necessary actions in the leak rate calculations when the correlation is weak and it specifies how to account for the uncertainty in the correlation.

Summary (cont'd)

- Overall methodology for determining the amount of leakage and assessing its consequences is conservative.
- Staff will continue to monitor database while plants are implementing ARC

SGAP Item 3.8

"Develop a program to monitor the prediction of flaw growth for systematic deviations from expectations."

Completed 1/3/02

Issue

- Relates to the growth rate of flaws in steam generator tubes that are allowed to remain in service under the voltage-based alternate repair criteria (GL 95-05).
- How well is flaw growth predicted by methodology?

Background

- Currently 9 plants are authorized to implement this ARC
- Important to conservatively project the condition of the steam generator tubes.

Projections

- Flaw growth is not linear. Flaws grow slowly until they can interlink. Once they interlink, it is possible for flaws to grow quite quickly.
- Projections include:
  - POD adjustment
  - flaw growth adjustment
  - NDE adjustment

Methodology

- Compare actual burst probability and leakage to projected burst probability and leakage
- If non-conservative .... investigate!
- Not uncommon to see deviations from projections and actual.
  - projections are conservative, but not always

Methodology (cont'd)

- Important to conservatively predict the number and severity of the larger voltage indications since these dominate leakage and burst.

Results

- For most plants, projections are conservative but we are addressing several issues that have arisen from plant-specific experience:
  - voltage dependent growth
  - very large voltage changes
  - revised POD model (i.e., POPCD rather than 0.6)

POPCD

- Based on the probability of prior cycle detection (POPCD)
- Approved on a one-cycle basis for Diablo Canyon

Current POD

- POD of 0.6 typically underpredicts the number of small voltage indications - POD of 0.6 is too high for this region
- POD of 0.6 typically overpredicts the number of high voltage indications

Other Issues

- Small voltage indications have high burst pressures and do not leak - safety significance is minimal
- High voltage growth has occurred occasionally throughout implementation of this repair criteria - may be mechanistic reason.
- Voltage dependent growth - not readily apparent at all plants

Summary

- Course of action:
  - Continue to address on plant-specific basis and assessing generic implications
  - Continue to review licensee reports that compare actual results to projections.
  - Continue to work with industry to understand deviations from expectations (growth, POD, NDE uncertainty).

SG TUBE INTEGRITY UNDER MSLB

Steam Generator Internal Loading Following MSLB or FWLB

Response to GSI-188,
SG TAC No. 3.1a, 3.1b, 3.1c

William J. Krotiuk

Office of Nuclear Regulatory Research
US Nuclear Regulatory Commission

SG Loading Following MSLB or FWLB

- Generic Safety Issue (GSI) 188

Steam Generator Tube Leaks or Ruptures Concurrent With Containment Bypass from Main Steam Line (MSLB) or Feedwater Line (FWLB) Breaches

- Steam Generator Action Plan Items 3.1a, 3.1b, 3.1c

- Use TRACE* to calculate loads on a Steam Generator tube support plate and tubes following a MSLB or FWLB to support stress, displacement and crack growth assessments outlined in SG Action Plan Items 3.1d through 3.1j.
- Perform sensitivity studies on code, model parameters and numerics.
- Compare TRACE predictions to a conservative load calculation and to predictions from similar analyses.

* TRACE is the latest name for the computer code previously called TRAC-M.

SG Loading Following MSLB or FWLB

- Specific Activities:

TRACE Verification Effort

- Compare TRACE code predictions to test results which are related to SG behavior following a MSLB or FWLB, and perform sensitivity studies on code and model parameters.

TRACE Loading Calculation

- Perform thermal-hydraulic analyses using TRACE to develop loads on the tube support plates (TSP) and primary tubes following a MSLB and FWLB.
- Compare predicted loads to results from similar analyses.

Conservative Bounding Loading Calculation

- Develop a conservative load estimate and compare to TRACE results.

TRACE Verification Effort

- Effort required to verify code predictions, especially the ability to:

  (1) follow acoustic wave transmission during system depressurization of a subcooled liquid vessel,

  (2) follow transient flow phenomena during system depressurization of a subcooled liquid vessel,

  (3) assess "pool swell" effects.

TRACE Verification Effort

- Edwards Pipe Blowdown Experiment

Objective: Study subcooled water depressurization in a horizontal pipe.

- Predictions with node length approximately equal to diameter are close to test pressure, temperature and void fraction measurements.

- LOFT Semiscale Blowdown Test

Objective: Compare TRACE predictions for subcooled water blowdown from and acoustic wave travel in a vertical vessel at high pressure against test data and Method of Characteristics (MOC) code predictions.

- TRACE predicts acoustic wave transmissions and reflections at area changes including decompression and recompression effects, but exhibits larger pressure attenuation than test results.
- TRACE pressure predictions with node length approximately equal to diameter matches data and MOC code results.

TRACE Verification Effort

- <u>GE Vessel Blowdown Tests</u>

Objective: Compare TRACE "level tracking" predictions to "pool swell" test data for saturated water blowdown from a high pressure vessel.

- TRACE analysis using the "level tracking" model better predicted "swell" effects, but calculations without "level tracking" are acceptable.
- TRACE successfully predicted the progression of the mixture "swell" for two tests.
- Differences between predicted and measured void fraction were observed.

- <u>Westinghouse Steam Generator Model Boiler (MB-2) Tests.</u>

Objective: Compare TRACE TSP load predictions to results from two MSLB tests from a 0.8% power-scaled Model F steam generator

- TRACE predicted overall system response reasonably well.

SG Loading Study

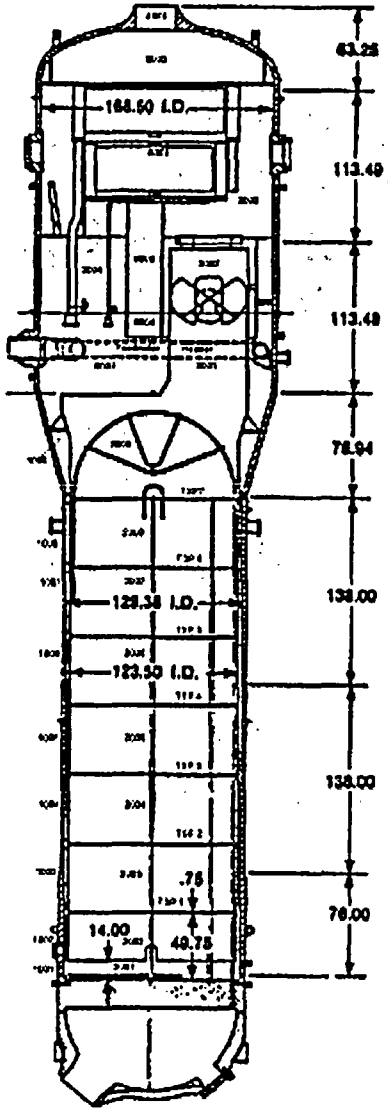
- TRACE analysis
  - Performed for Westinghouse Model 51 SG.
  - Compared to Westinghouse reported results obtained using the TRANFLO and RELAP5 computer codes.

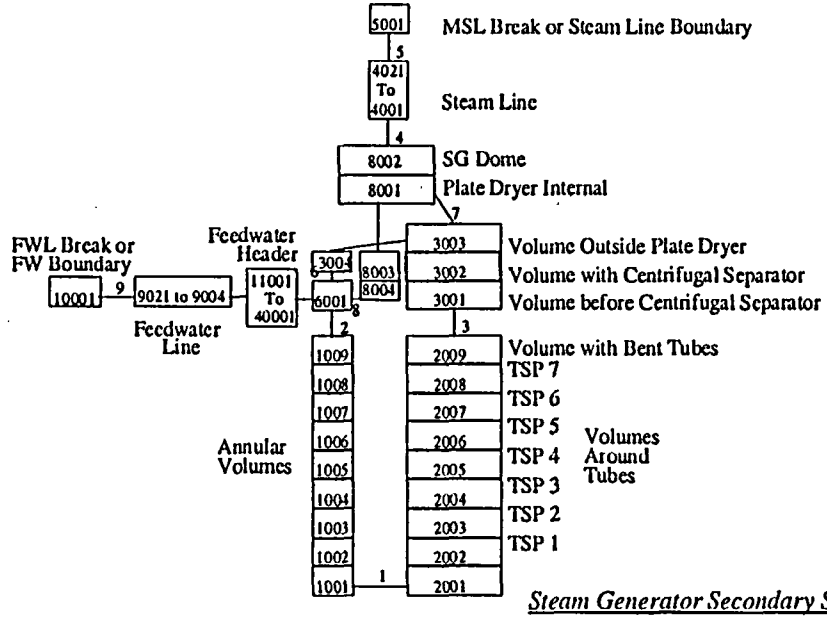
- SG initial conditions before break:
  - Hot Standby
  - 100% Power

- SG loads developed following:
  - a 4.6 ft^2 guillotine MSLB at the main steam nozzle,
  - a 1.4 ft^2 flow restrictor limited MSLB at the main steam nozzle, and
  - a 1.12 ft^2 guillotine FWLB at the FW nozzle.

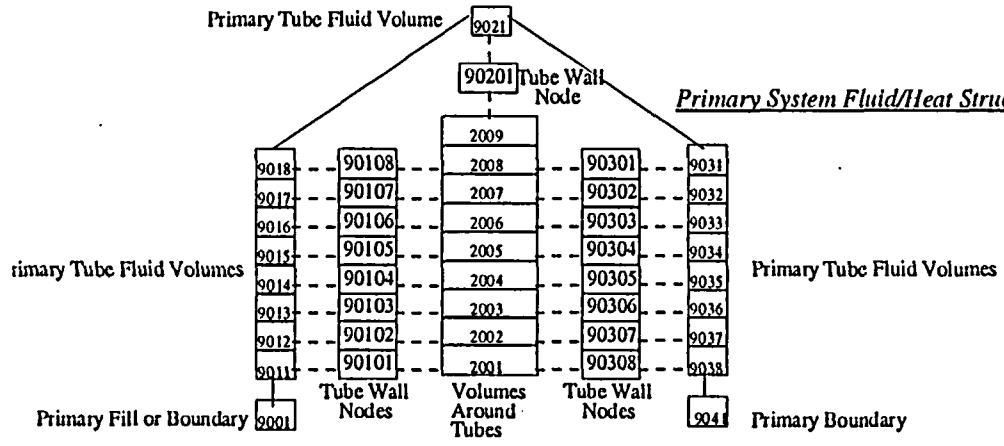
- SG loading developed for:
  - Tube support plates (TSP),
  - Primary tubes at tubesheet and at tube bend area, and
  - Cylindrical shroud between tube bundle and annular feedwater regions.

TRACE SG Analysis Model





Steam Generator Secondary System Fluid Model



Primary System Fluid/Heat Structure Model

TSP Loadings Calculation

$$\Delta p = \Delta p(\text{friction loss}) + \Delta p(\text{gravity head}) + \Delta p(\text{fluid acceleration})$$

$$\Delta p = K \frac{\rho_l v_l^2}{2} (1 - \alpha) + \rho_l g \Delta h (1 - \alpha) + \Delta h \left(\frac{\rho_l v_l (1 - \alpha) - (\rho_l v_l (1 - \alpha))_{-1}}{t - t_{-1}} \right) +$$
$$K \frac{\rho_v v_v^2}{2} \alpha + \rho_v g \Delta h \alpha + \Delta h \left(\frac{\rho_v v_v \alpha - (\rho_v v_v \alpha)_{-1}}{t - t_{-1}} \right)$$

where
- Δp = pressure difference
- K = TSP irreversible loss coefficient
- v_l = liquid velocity through TSP
- ρ_l = liquid density
- α = void fraction
- g = gravitational constant
- Δh = TSP thickness
- t = time
- v_v = vapor velocity through TSP
- ρ_v = vapor density

Subscripts
- -1 = previous timestep

TSP Loadings at Hot Standby

	4.6 ft^2 MSLB TRANFLO	4.6 ft^2 MSLB RELAP5	4.6 ft^2 MSLB TRACE
TSP 7 (top)	2.46 psi (3.69* psi)	9.6 psi	8.57 psi
TSP 6	1.82 psi (2.73* psi)	8.1 psi	5.06 psi
TSP 5	1.25 psi (1.88* psi)	6.1 psi	3.84 psi
TSP 4	0.91 psi (1.37* psi)	4.5 psi	2.63 psi
TSP 3	0.58 psi (0.87* psi)	3.2 psi	1.16 psi
TSP 2	0.31 psi (0.47* psi)	2.0 psi	0.15 psi
TSP 1(bottom)	-0.12 psi (-0.18* psi)	1.9 psi	-0.33 psi

	1.5 ft^2 MSLB TRANFLO	1.4 ft^2 MSLB RELAP5	1.4 ft^2 MSLB TRACE
TSP 7 (top)	1.67 psi (2.51* psi)	2.26 psi	2.68 psi
TSP 6	1.22 psi (1.83* psi)	2.14 psi	1.70 psi
TSP 5	0.83 psi (1.25* psi)	1.56 psi	1.23 psi
TSP 4	0.53 psi (0.80* psi)	1.35 psi	0.87 psi
TSP 3	-0.28 psi (-0.42* psi)	1.23 psi	0.43 psi
TSP 2	-0.23 psi (-0.35* psi)	1.25 psi	0.08 psi
TSP 1 (bottom)	-0.26 psi (-0.39* psi)	1.12 psi	-0.06 psi

Note, an upward directed pressure differential is defined as positive.
* TRANFLO values with Westinghouse recommended 1.5 uncertainty multiplier.

TRACE Calculated TSP Loadings

Initial Hot Standby Conditions

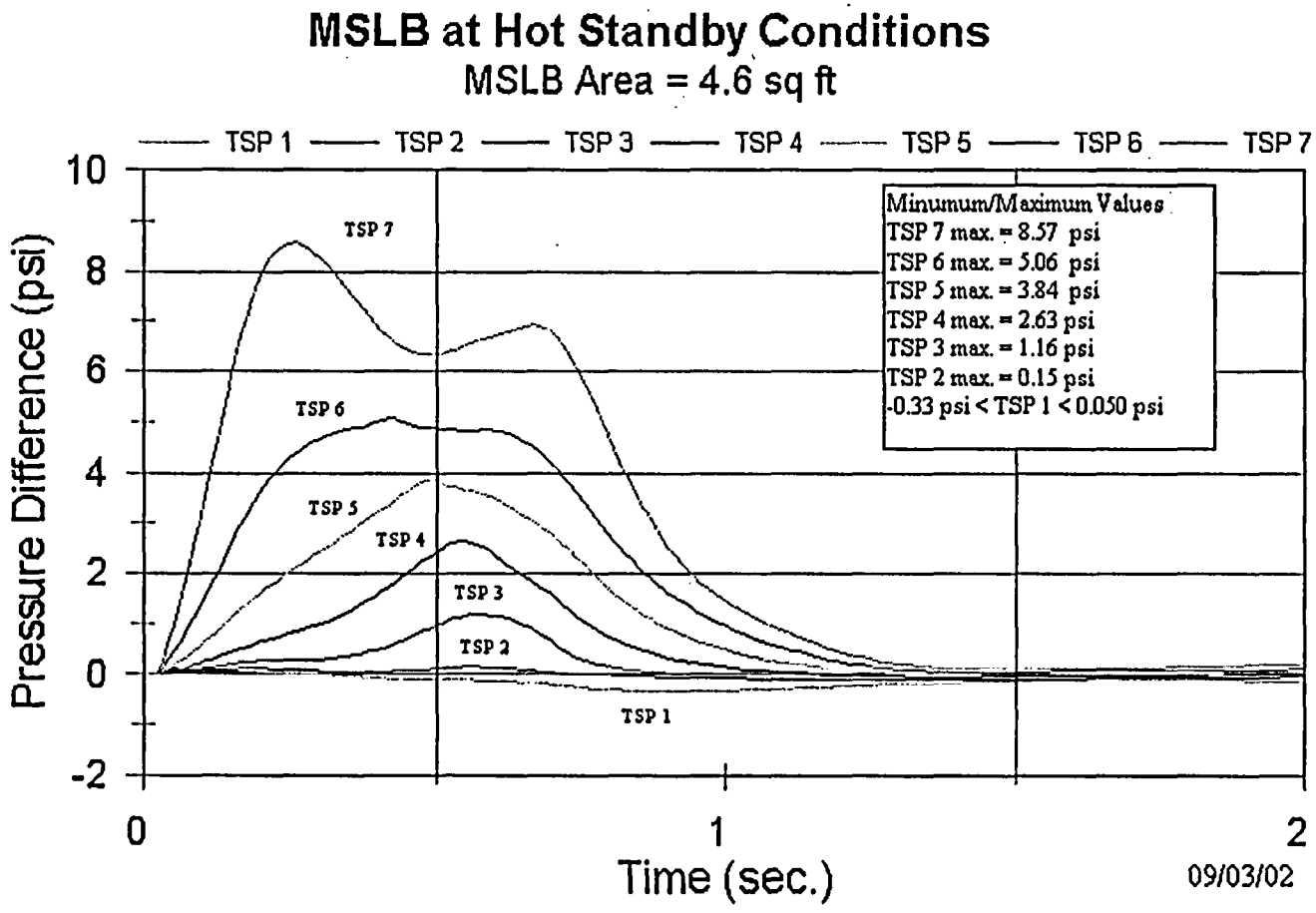
	4.6 ft² MSLB	1.4 ft² MSLB	1.12 ft² FWLB
TSP 7 (top)	**8.57 psi**	2.68 psi	0.050 psi
TSP 6	**5.06 psi**	1.70 psi	0.041 psi
TSP 5	**3.84 psi**	1.23 psi	0.034 psi
TSP 4	**2.63 psi**	0.87 psi	0.030 psi
TSP 3	**1.16 psi**	0.43 psi	0.026 psi
TSP 2	**0.15 psi**	0.08 psi	0.022 psi
TSP 1 (bottom)	**-0.33 psi**	-0.06 psi	0.021 psi

Initial 100% Power Condition

	4.6 ft² MSLB	1.4 ft² MSLB	1.12 ft²2 FWLB
TSP 7 (top)	6.82 psi	1.49 psi	0.42 psi
TSP 6	5.41 psi	1.27 psi	0.36 psi
TSP 5	4.34 psi	1.09 psi	0.31 psi
TSP 4	3.20 psi	0.87 psi	0.27 psi
TSP 3	1.91 psi	0.61 psi	0.23 psi
TSP 2	0.79 psi	0.33 psi	0.19 psi
TSP 1 (bottom)	0.16 psi	0.21 psi	0.20 psi

* An upward directed pressure differential is defined as positive.
The highest loading, highlighted in **bold** type, is for the 4.6 ft² MSLB at hot standby.

TRACE Calculated TSP Loadings



SG Conservative Bounding Calculations

- Conservative Bounding Calculation Method
  - TSP loads determined from blowdown calculation methods developed by F. J. Moody for BWRs.
  - Method also uses pressure wave transmission/reflections relations.

Transmission Ratio = Reflection Ratio + 1

$$\frac{P_T}{P_I} = \frac{2A_1/A_2}{A_1/A_2 + 1} = \frac{2A_1}{A_1 + A_2}$$

For dead end, $A_2=0$, $P_T/P_I=2$
For straight pipe, $A_1=A_2$, $P_T/P_I=1$ (full wave transmission)
For open end, $A2=\infty$, $P_T/P_I=0$

Reflection Ratio = Transmission Ratio - 1

$$\frac{P_R}{P_I} = \frac{A_1 - A_2}{A_1 + A_2} = \frac{A_1/A_2 - 1}{A_1/A_2 + 1}$$

For dead end, $A_2=0$, $P_R/P_I=1$ (reflected pressurization wave)
For straight pipe, $A_1=A_2$, $P_R/P_I=0$ (no wave reflection)
For open end, $A2=\infty$, $P_R/P_I=-1$ (reflected depressurization wave)

where A_1 is the flow area upstream of the area change.
A_2 is the flow area downstream of the area change.
P_R is the reflected pressure change.
P_I is the incident pressure change.
P_T is the transmitted pressure change.

SG Conservative Bounding Calculations

	TRACE Hot Standby Condition	TRACE 100% Power Condition	Moody/Acoustic Calculation[&]
4.6 ft^2 MSLB			$P_{discharge}$ = 520 psia
TSP 7 (top)	8.57 psi	6.82 psi	9.0 psi
TSP 6	5.06 psi	5.41 psi	7.6 psi
TSP 5	3.84 psi	4.34 psi	6.4 psi
TSP 4	2.63 psi	3.20 psi	5.4 psi
TSP 3	1.16 psi	1.91 psi	4.6 psi
TSP 2	0.15 psi	0.79 psi	3.8 psi
TSP 1 (bottom)	-0.33 psi	0.16 psi	3.3 psi (1.6[#] psi)
1.4 ft^2 MSLB			$P_{discharge}$ = 688 psia
TSP 7 (top)	2.68 psi	1.49 psi	3.6 psi
TSP 6	1.70 psi	1.27 psi	3.0 psi
TSP 5	1.23 psi	1.09 psi	2.6 psi
TSP 4	0.87 psi	0.87 psi	2.2 psi
TSP 3	0.43 psi	0.61 psi	1.8 psi
TSP 2	0.08 psi	0.33 psi	1.5 psi
TSP 1 (bottom)	-0.05 psi	0.21 psi	1.3 psi (0.7[#] psi)

* An upward directed pressure differential is defined as positive.
[&] Differential pressure conservatively calculated ignoring depressurization wave travel through annular feedwater region.
[#] TSP 1 pressure differential adjusted for depressurization wave travel through annular feedwater area.

SG Conservative Bounding Calculations

TSP Peak Pressure Differential Comparisons for 4.6 ft^2 MSLB
with System Initially at Hot Standby

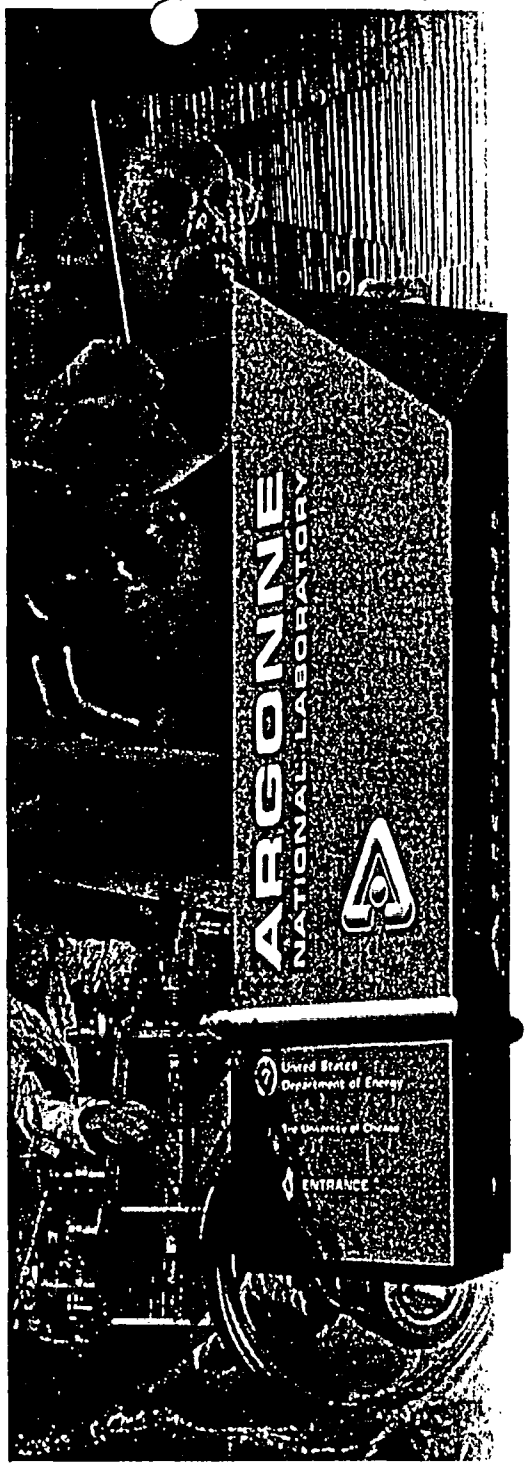
	TRANFLO	RELAP5	TRACE	Moody/Acoustic Calc.[&]
TSP 7 (top)	2.46 psi	9.6 psi	8.57 psi	9.0 psi
TSP 6	1.82 psi	8.1 psi	5.06 psi	7.6 psi
TSP 5	1.25 psi	6.1 psi	3.84 psi	6.4 psi
TSP 4	0.91 psi	4.5 psi	2.63 psi	5.4 psi
TSP 3	0.58 psi	3.2 psi	1.16 psi	4.6 psi
TSP 2	0.31 psi	2.0 psi	0.15 psi	3.8 psi
TSP 1(bottom)	-0.12 psi	1.9 psi	-0.33 psi	3.3 psi (1.6[#] psi)

Note, an upward directed pressure differential is defined as positive.
[&] Differential pressure conservatively calculated ignoring depressurization wave travel through annular feedwater region.
[#] TSP 1 pressure differential adjusted for depressurization wave travel through annular feedwater area.

SG Loading Following MSLB or FWLB

- Generic Safety Issue 188 and SG Action Plan Items 3.1a, 3.1b, 3.1c
  - Perform thermal-hydraulic calculations using TRACE to assess loads on a Steam Generator tube support plate and tubes following a MSLB or FWLB.

- Conclusions:
  - TRACE is capable of calculating the thermal-hydraulic conditions inside a PWR SG following a MSLB or FWLB.
  - TRACE successfully predicts the transient thermal-hydraulic conditions for acoustically and flow dominated blowdown tests.
  - The SG internal loading calculated by TRACE are comparative to conservative bounding calculations and to code results calculated by Westinghouse using RELAP5, but do not agree with Westinghouse TRANFLO calculations.
  - The largest SG internal forces are developed by the acoustic transients occurring in the first seconds following a break.



Dynamic Loading Effects on SG Tubes During MSLB and FWLB

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Office of Science
U.S. Department of Energy

A U.S. Department of Energy
Office of Science Laboratory
Operated by The University of Chicago

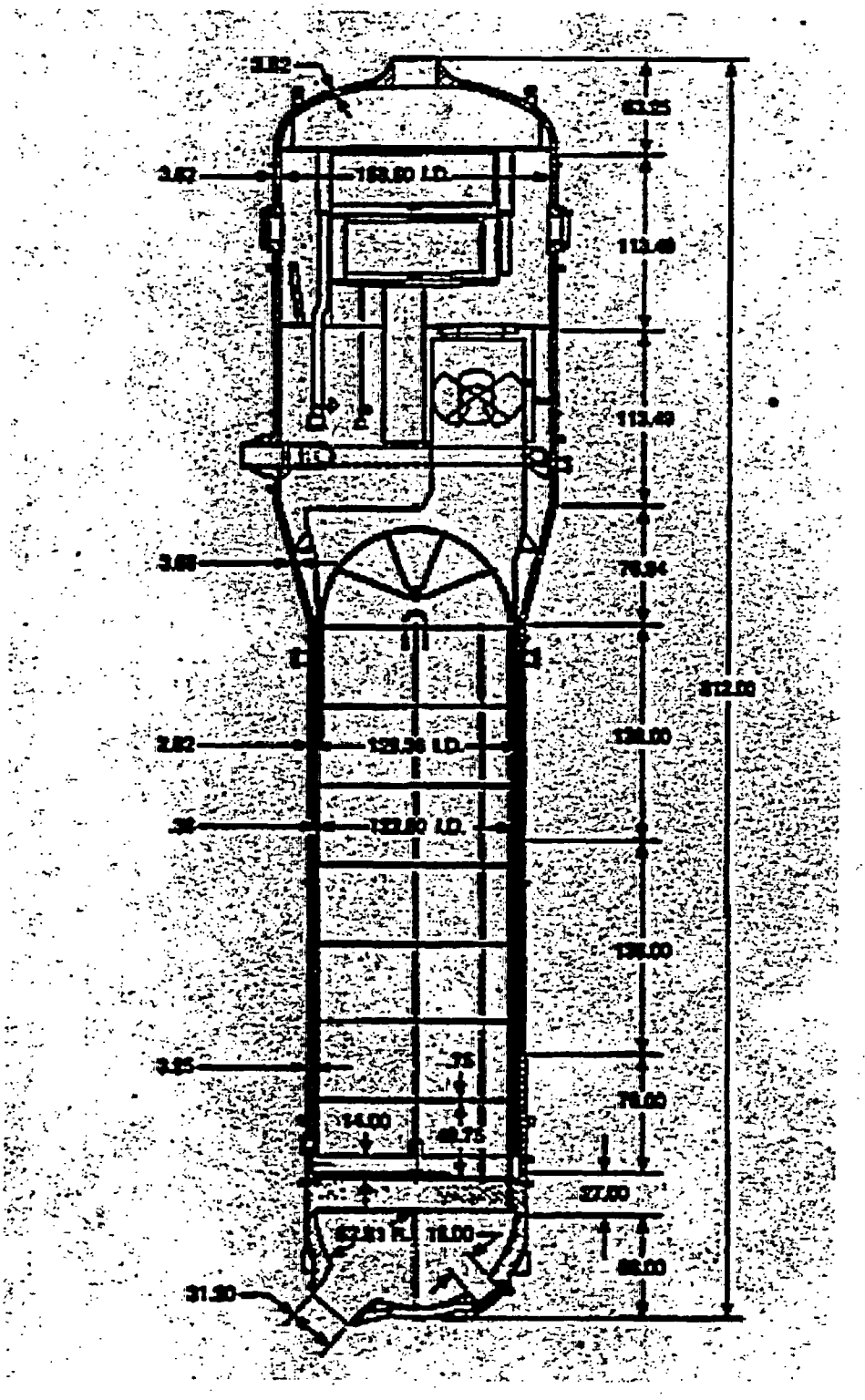
Introduction

- This presentation addresses Item No. (TAC No.) 3.1 d-i of the SG Action Plan
  - Develop understanding for potential damage progression of multiple SG tubes due to depressurization events, such as, MSLB and FWLB.
    - *Does TSP movement lead to single or multiple failure of SGTs containing cracks?*
    - *Can existing cracks grow cyclically during such events?*
    - *What are the margins against burst?*
    - *Is more refined TH analysis needed?*
    - *Validate analysis results by tests*

Review of Industry Analyses

- WCAP-14707 (Model 51 SG - no preheater)
  - Intended to demonstrate that cracks under TSPs would not be exposed during a large SLB and the maximum tube stress would be less than yield.
  - RELAP5 used to calculate the pressure drops across all TSPs
    - *Large SLB produces greater pressure drops across the TSPs than either the small SLB or the FWLB*
  - Detailed dynamic analysis of a 90° segment of the tube bundle, including TSPs, tie rods/spacers, welded tapered wedges at the periphery was performed
    - *All tube intersections assumed to be dented or packed*
  - Analysis showed that
    - *Pressure load acting on the TSPs was carried mostly by the locked tubes*
    - *Tube-to-TSP forces do not exceed breakaway forces expected for dented and/or packed TSPs*
      - TSPs displaced with the tubes and cracks are not exposed

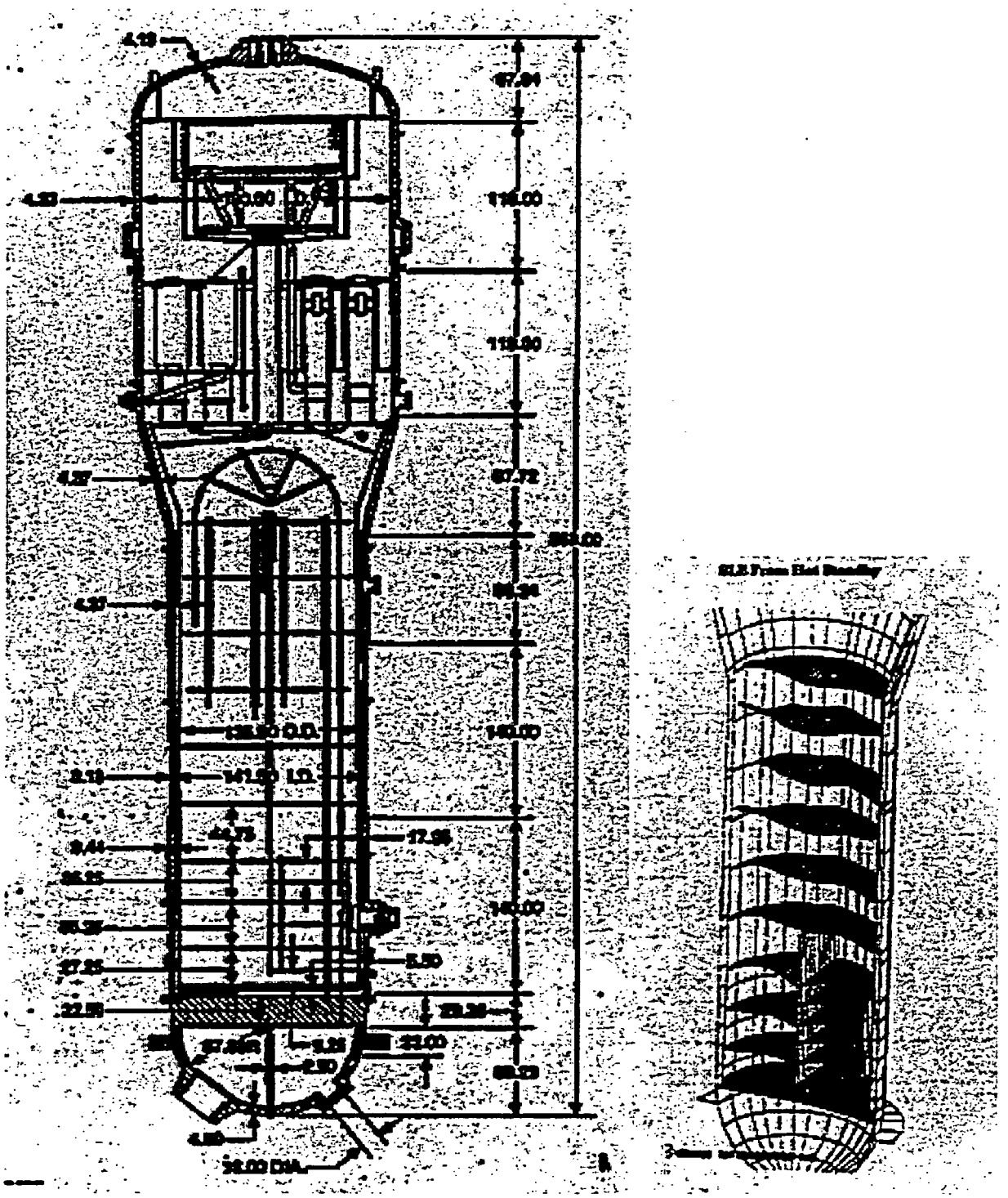
Model 51 SG Layout



Review of Industry Analyses (Cont'd)

- **WCAP-15163 (Model E2 - with preheater)**
  - Assumed ferritic stainless steel TSPs are not locked to the tubes
    - *Conservative assumption for computing TSP displacement*
  - RELAP5 again used to calculate pressure drops
    - *Pressure drops are higher for SLB from hot standby than from full power*
    - *TSPs at higher levels experience larger Δp than lower levels*
    - *Because of uncertainty due to mixing of hot leg and cold leg flow above TSP L, an upper bound Δp was calculated*
  - The upper bound Δp was used in a static structural analysis to determine tube–to–TSP displacements
  - Analysis showed that hydraulic expansion of 16 tubes at three TSPs sufficient to ensure that maximum TSP displacement relative to tube does not expose the SCCs under the TSPs
    - *Tube stresses will remain below yield.*

Layout of Model E2 SG



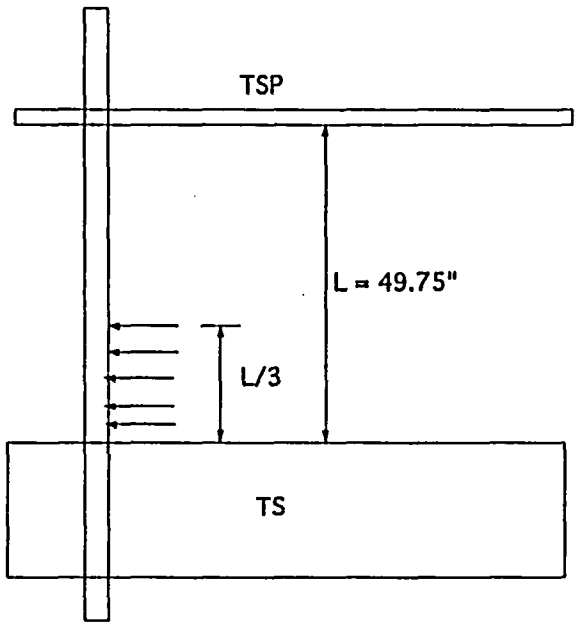
Conclusions from Industry Analyses

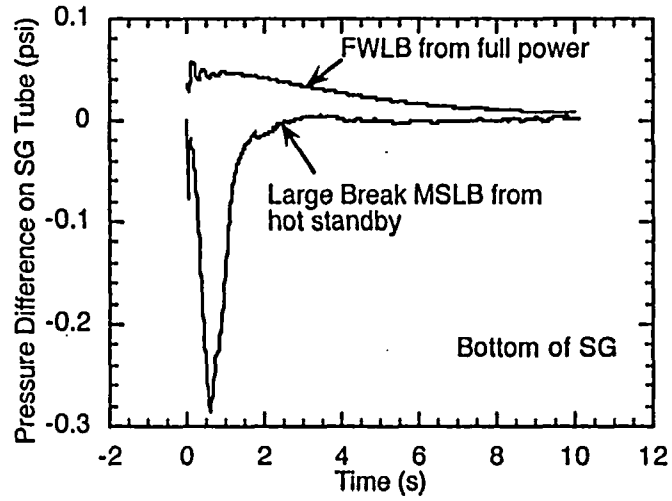
- The effective bending stiffness of the TSPs is much less than the axial stiffness of the SG tubes

Supplementary FEA

- Industry analyses did not consider effects of tube axial loads on cracks that are at the top of TS or TSPs or in the free span region
  - Most critical case is for single locked tube at the TSPs with all the remaining tubes free to slide at the TSP junctions.
- Assumption for Model 51 case that all tube intersections are dented or packed is limiting case (most benign)
  - Effect of smaller numbers of locked tubes on TSP displacements was considered
- Considered the case of large MSLB of Model 51 from hot standby with
  - Transverse dynamic pressure loading on SG tubes
  - Transverse dynamic pressure drop across TSPs
- Δp data were obtained from NRC-RES thermalhydraulic analyses

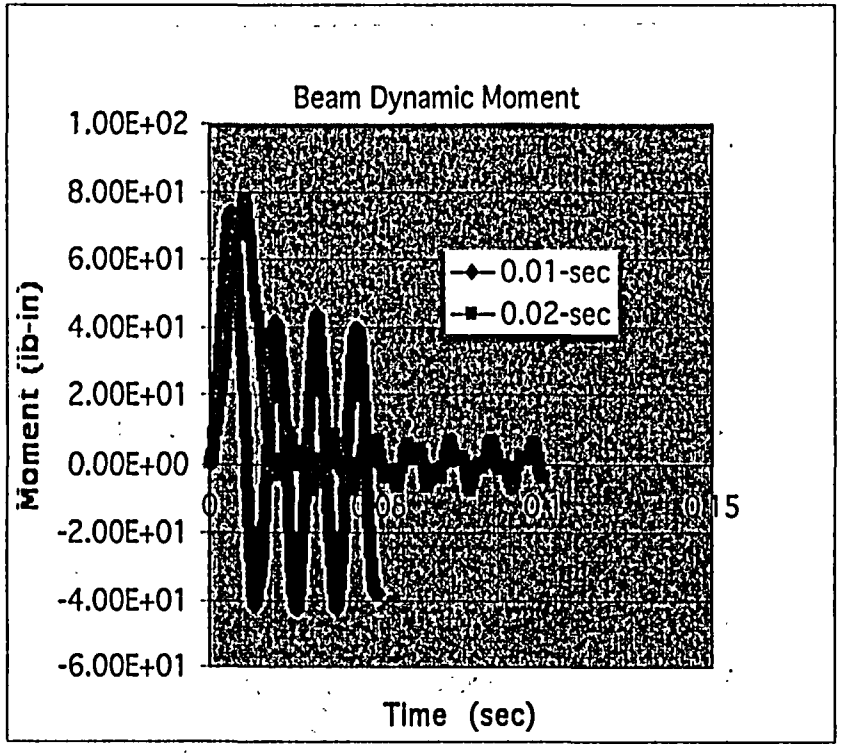
Transverse Dynamic Pressure Loading on SGT

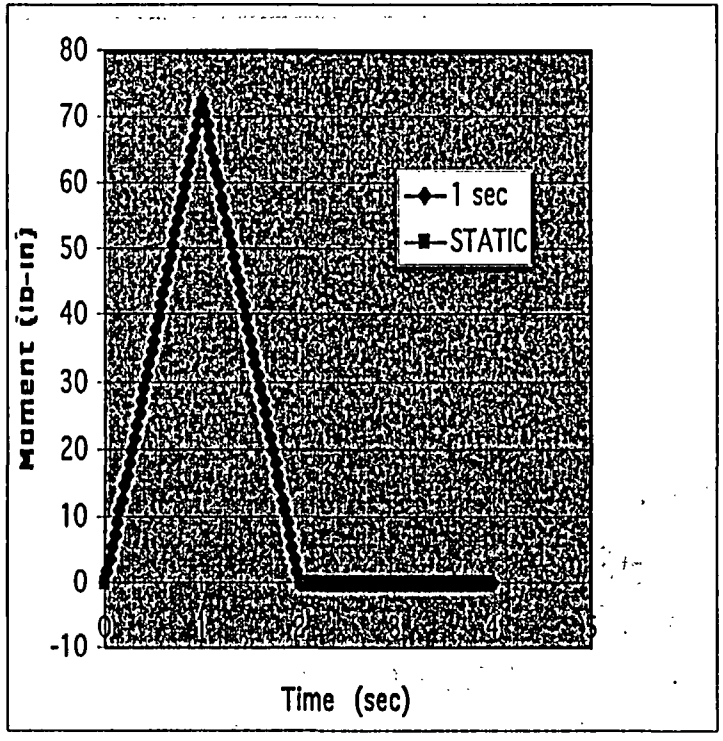




- The transverse pressure on a SGT during MSLB is highest in the bottom third section of the tube between the TS and the first TSP
- Typically, the rise time is of the order of 0.25 to 1 s

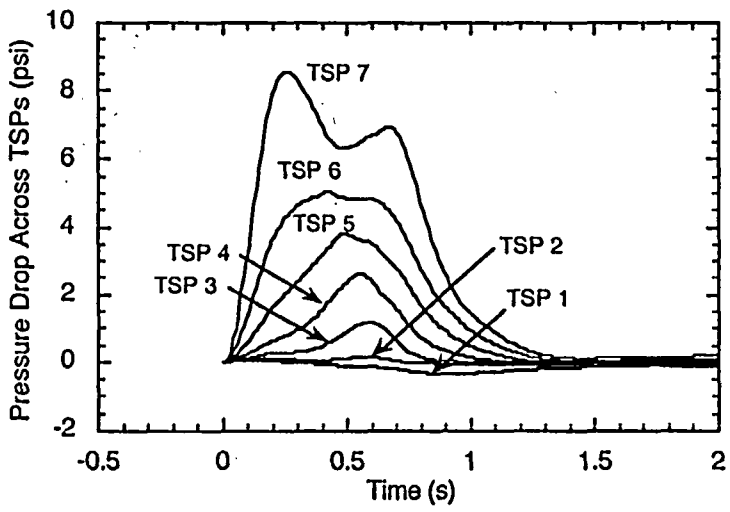
Is Transient Dynamic Analysis Needed?





- Dynamic bending effects may be important for rise time √ 0.02 s, although even then effect on peak bending stress is relatively small
- Static analysis is OK for rise times > 0.1 s
- The peak bending stress is only 775 psi (5.34 MPa)

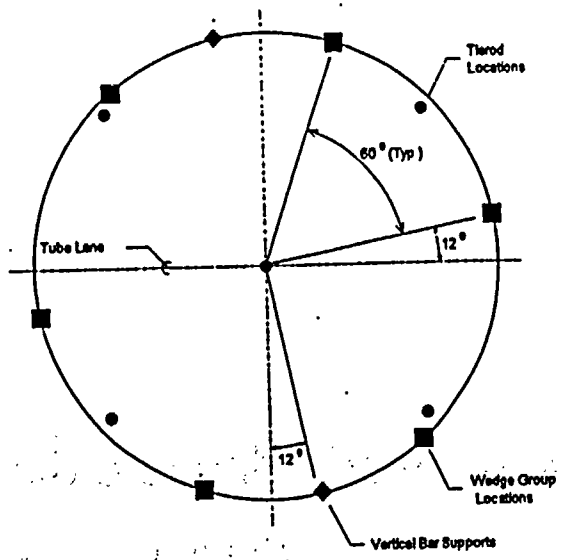
Dynamic Pressure Drops Across TSPs for Large MSLB from Hot Standby



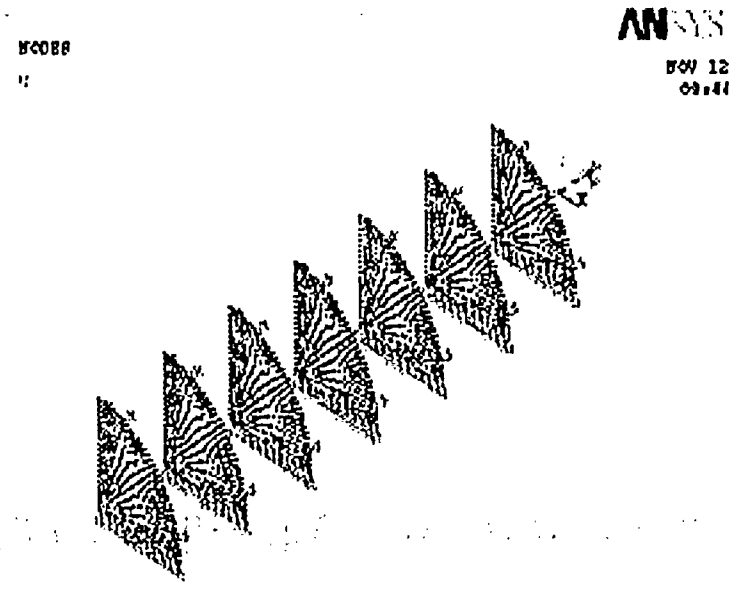
Krotiuk (TRAC-M) calculations

- Rise time for Δp varies from 0.25 s to 1 s.
- Rise time of load much larger than period corresponding to natural frequency of SGT /TSP
  - Static analysis should be OK

FEA of Single Tube/TSPs



TSP Support Locations



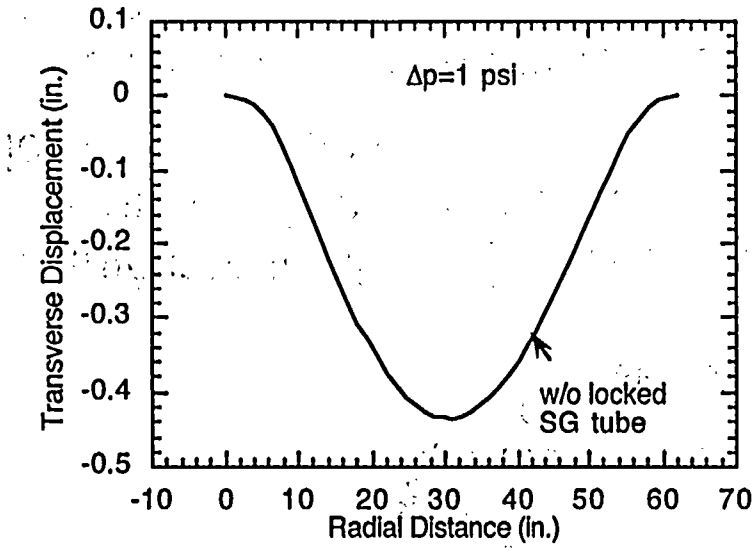
FEM of 90° Segment

- Single tube locked at all TSP junctions. All other tubes free to slide
- Shell elements were used to model the TSPs, and beam elements were used for the SG tube
- Supports were assumed to be rigid and the transverse displacement of the TS was ignored

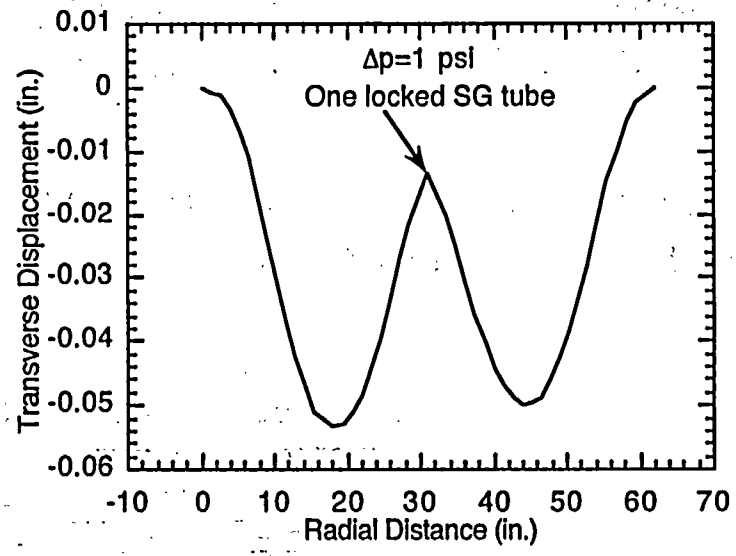
Unit Pressure Drop Analyses

- A series of elastic static unit pressure drop (upwards) analyses were carried out
  - Each analysis had unit pressure drop across a single TSP with the rest of the TSPs unloaded
- Principle of superposition was used to combine the pressure loading on all the TSPs.

Unit Pressure Drop Analyses for the First TSP



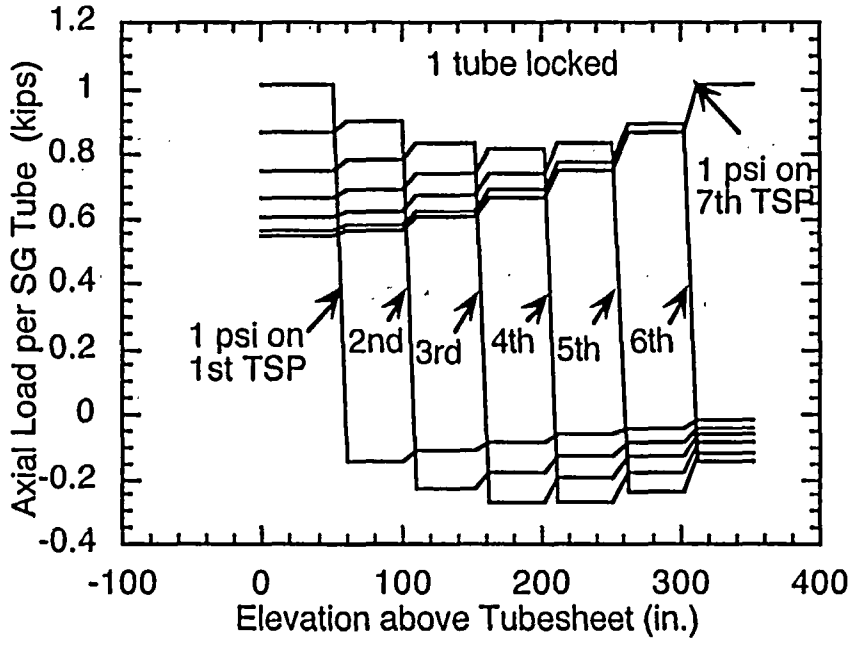
W/O Locked Tube



With a Single Locked Tube

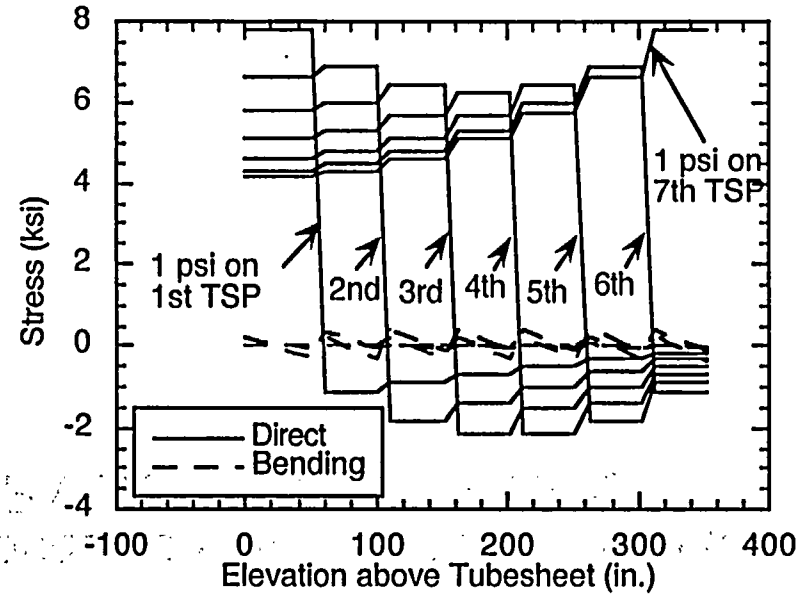
- The maximum displacement is reduced from 0.44 in. to 0.054 in. The tube is stretched 0.013 in.
- The maximum von Mises effective bending stress in the plate is reduced from 7 to 3 ksi.

Axial Load on A Single Locked Tube (Unit Pressure Drops)



- Significant fractions (~1/3) of the total pressure loading on the higher elevation TSPs are passed on as axial tensile loads on the SG tube at lower elevations
- Small fractions of the pressure loading on the lower TSPs are passed on as small compressive loads on the SG tube at higher elevations.

Axial Direct and Bending Stresses on A Single Locked Tube (Unit Pressure Drop Cases)

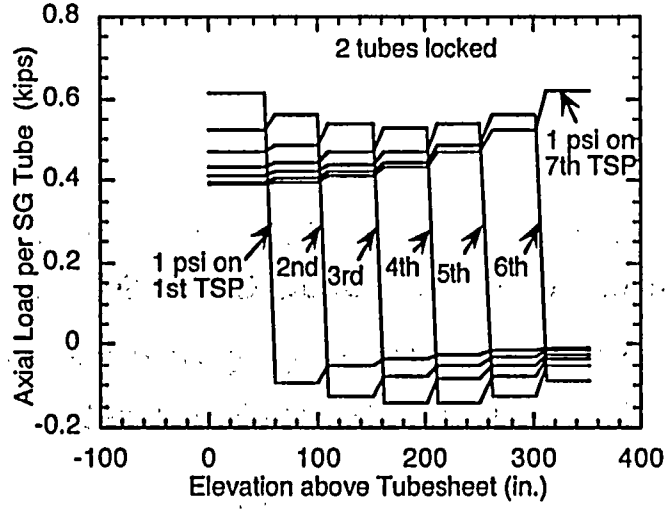


- The maximum bending stresses due to the transverse pressure loads on SGT are small compared with the tensile axial stresses produced by the displacement of the TSP
- The effect of bending stresses on the rupture of flawed tubes was investigated both analytically and experimentally
  - The results showed that the bending stresses can be ignored when analyzing rupture of the SG tubes.

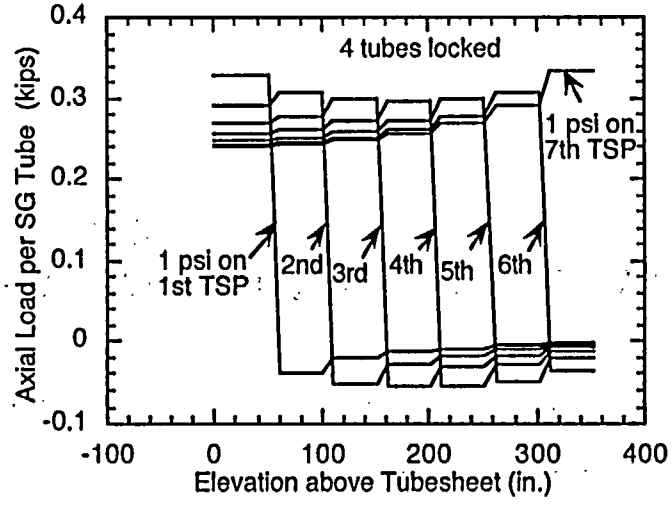
Multiple Locked Tube Case

- In the case of a drilled support plate it is highly unlikely that only a single tube out of more than 3000 tubes will be locked at the TSPs.
- Analyses were conducted for the cases where two and four tubes per quarter of the TSP were locked to the TSPs.

Results For Multiple Locked Tubes - Unit Pressure Drop Cases



2 Locked Tubes



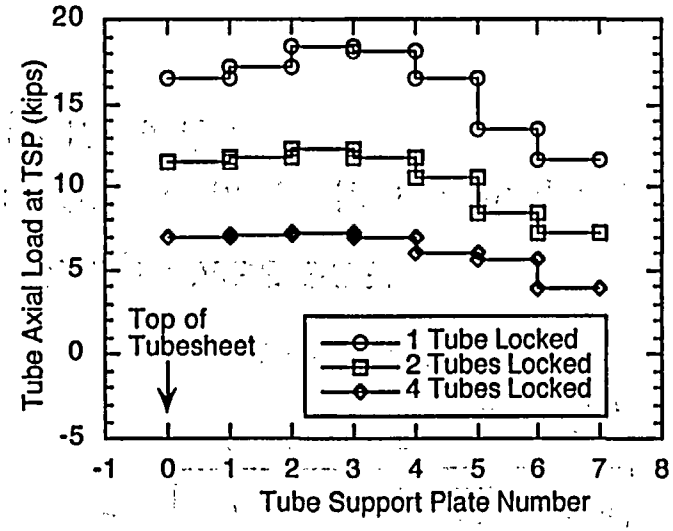
4 Locked Tubes

- The decrease in the axial load per tube is almost directly proportional to the number of tubes locked to the TSPs

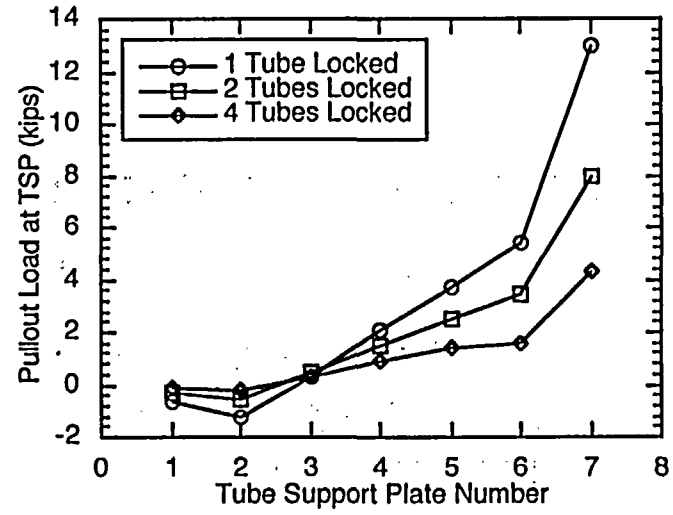
Large MSLB from Hot Standby

- The results for a large MSLB are obtained from the unit pressure drop results by multiplying them by the actual pressure drops across the TSPs
  - The peak pressures on the individual TSPs do not occur at the same time. This is accounted for in the analysis.
  - The pressure drops were multiplied by an uncertainty factor of 1.5 based on the recommendation of thermalhydraulic analysts.

Results for No Slippage Between TSPs and SG Tube (complete locking)



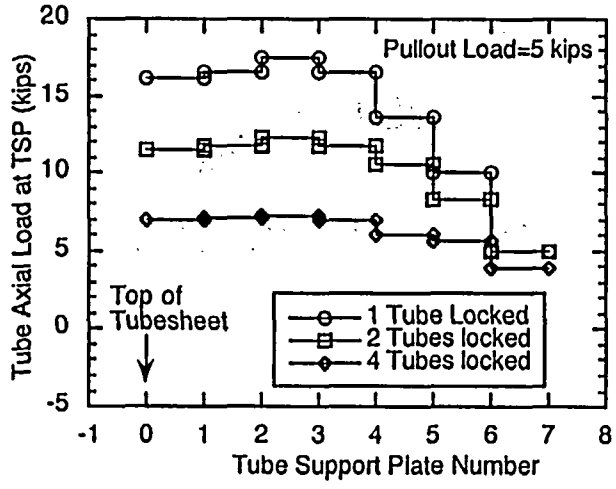
Tube Axial Load



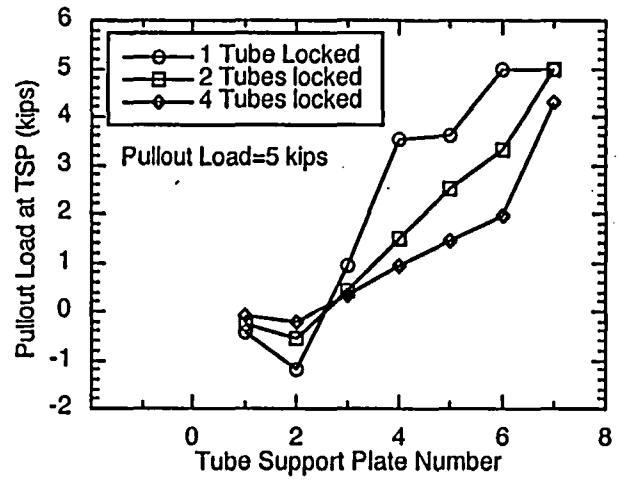
TSP-to-Tube (Pullout) Force

- The axial load needed to cause yielding in the SG tube is √ 5.4 kips
  - Significant plastic deformation will occur only when just one or two tubes are locked at all of the TSPs
- The maximum load exerted on the tubes is less than 5 kips if four or more tubes (per quarter TSP) are locked to the TSPs.

Effect of Tube Slippage (Pullout Load = 5 kips)



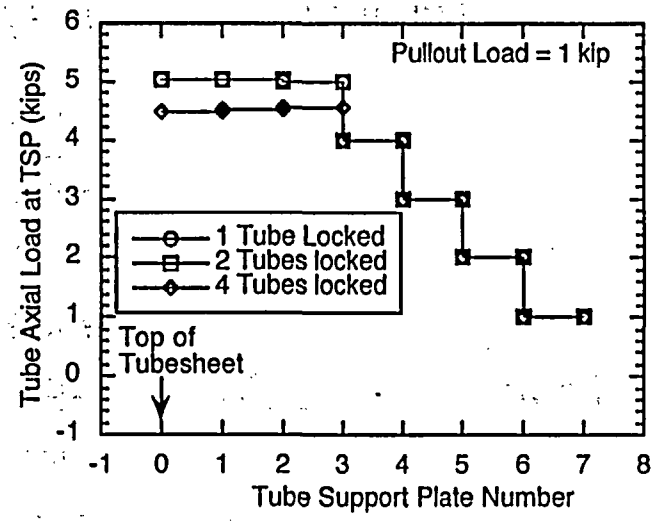
Tube Axial Load



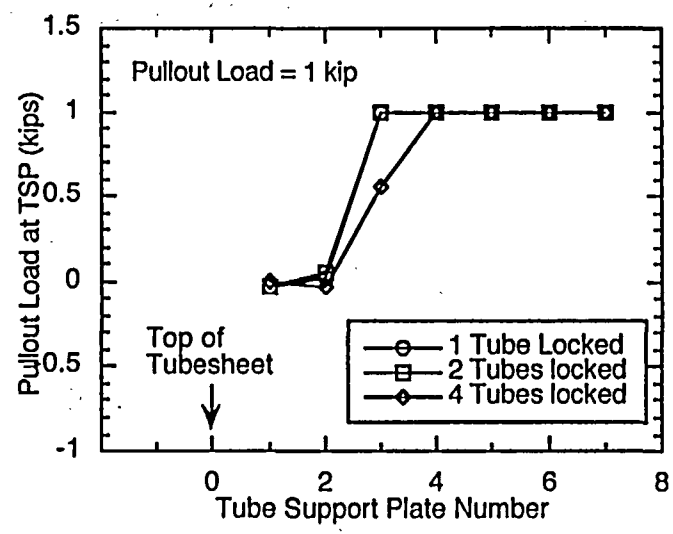
TSP-to-Tube Load

- Slippage was assumed to occur at constant pullout load
- For this pullout force slippage reduces the axial loads at the higher TSPs significantly.

Effect of Tube Slippage (Pullout Load = 1 kip)



Tube Axial Load



TSP-to-Tube Load

- For this pullout force, slippage occurs at all TSP higher than the third.
- Axial loads in all of the TSPs are reduced to √5 kips.

Tube (Non-Dented) Pullout Data From Dampierre-1

Parameter	Without chemical cleaning 70°F	Without chemical cleaning 547°F	After chemical cleaning 70°F	After chemical cleaning 547°F (286°C)
Mean Force	3120	2686	1559	1342 [a]
No. of tests	23	12	9	0
Standard deviation	792	821	405	405 [a]
Upper 95% confidence	4427	4041	2227	2010
Lower 95% confidence	1813	1331	891	674

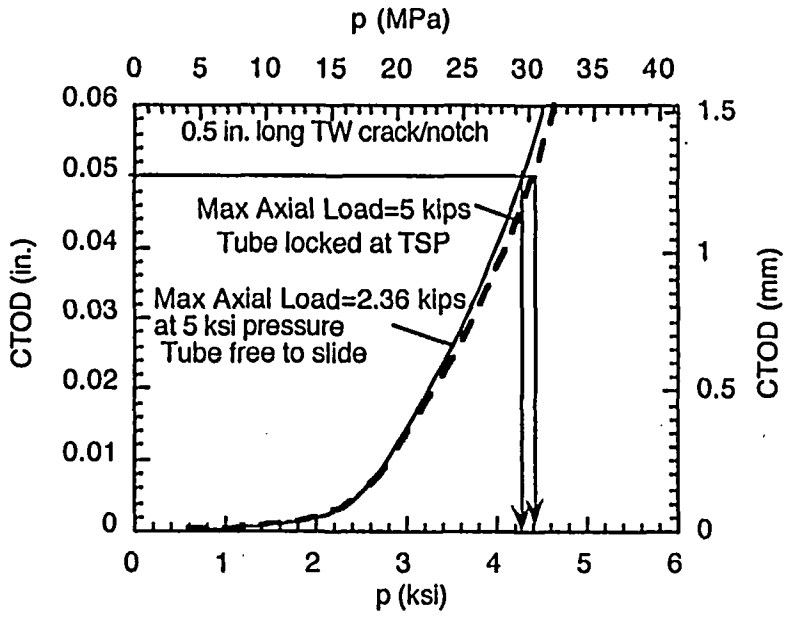
[a] Estimated from RT results

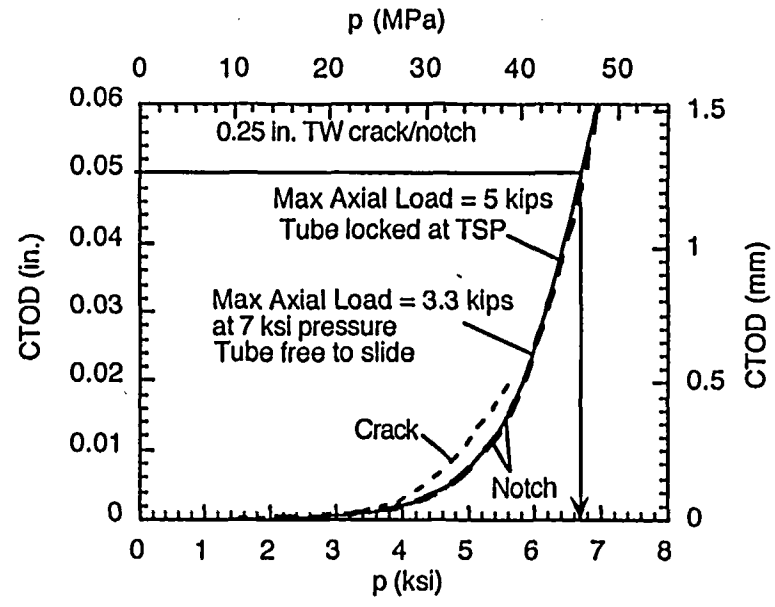
- We have used 4000 lbs as an upper bound and 2700 lbs as the average axial load transmitted from a TSP to a locked tube at 550°F (286°C)

Effect of MSLB on Flawed Tubes

- FEA results showed that the loads transmitted from the TSPs to the locked tubes are primarily axial.
  - Unflawed 7/8-in.-diam SG tubes can sustain axial loads of √5.1 kips before yielding and 11.7 kips before failure
  - Dynamic loads not important for unflawed tubes
- Effects of axial loads on the stability of both axial and circumferential cracks in the tube were considered
  - Material properties used for calculations correspond to those of an average Alloy 600 tube at 286°C (Yield=40 ksi, UTS=90 ksi)

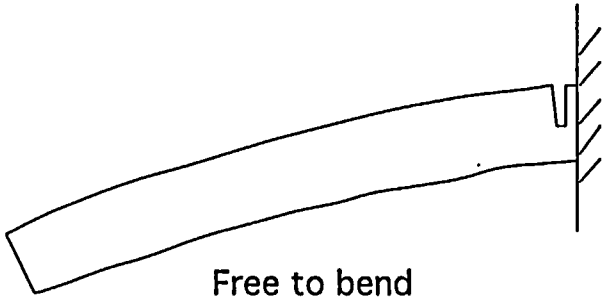
Effect of Axial Load on Stability of Axial Cracks

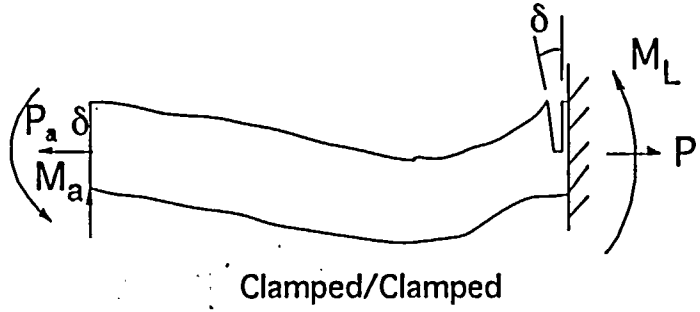




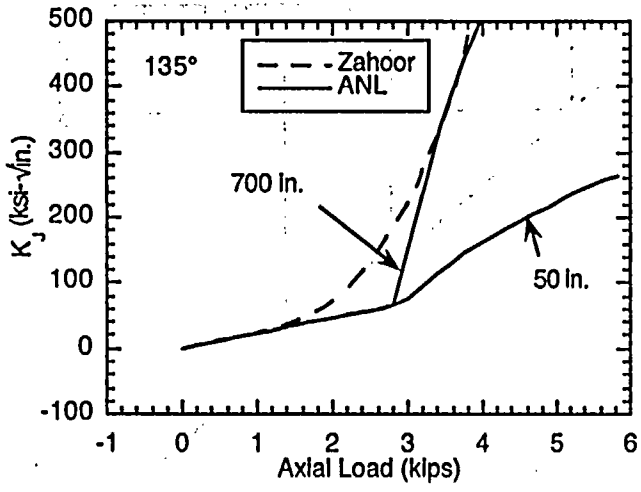
- Tests at ANL show that the burst pressure of a 7/8-in.-diam tube with a
  - 0.5-in TW crack varies between 3.8 and 4.8 ksi
  - 0.25-in TW crack varies between 6 and 7 ksi.
  - Axial loads due to internal pressure in burst tests are 2.4 kips at 5 ksi and 3.3 kips at 7 ksi
- Analysis show higher axial loads due to dynamic loads on a locked tube (√ 5 kips) have little effect on crack tip opening displacement (CTOD) and hence failure of tubes with axial cracks

Effect of Boundary Conditions on Stability of Circumferential Cracks

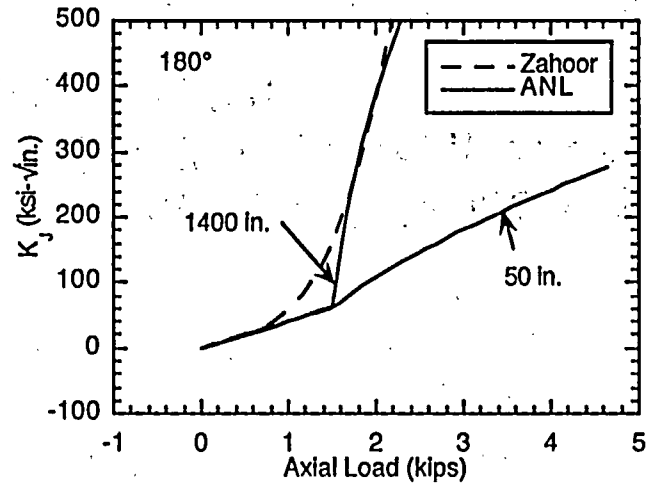




EPRI/Zahoor Model

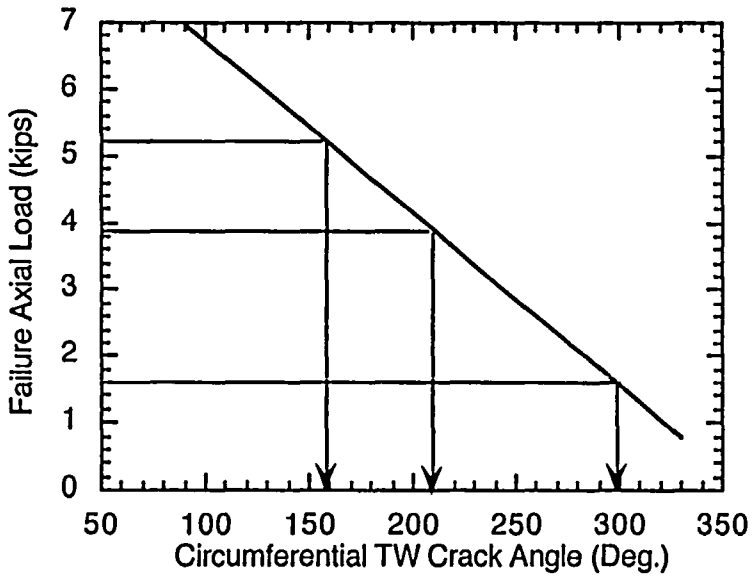


ANL Model



- Crack driving force, K_J, is greatly reduced by realistic lateral constraint due to TSP
  - ANL solution reduces to that of Zahoor for very large spacing of TSPs

Circ Crack in a Single Tube Locked at 1st TSP

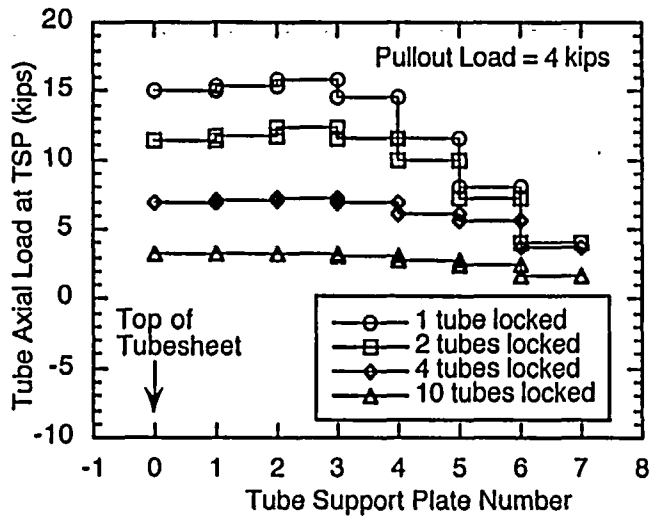


- For an upper bound dynamic load of 4 kips and an internal pressure induced load of 1.2 kips, TW cracks less than 160° in extent are stable.
- For the average TSP locking force of 2.7 kips, the maximum crack angle for stability is 210°.
- A single tube locked at all TSPs has much higher dynamic loads and cannot tolerate a significant circ flaw

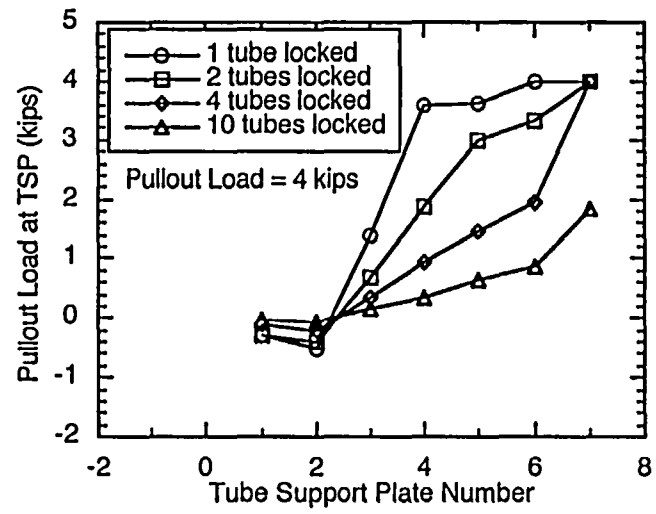
All Tubes Locked at All TSPs (Most Benign)

- Maximum axial load per tube during a large break MSLB is 1.6 kips
- TW cracks less than 300° in extent are stable.

Multiple tubes locked–UB Pullout Force (4 kips)



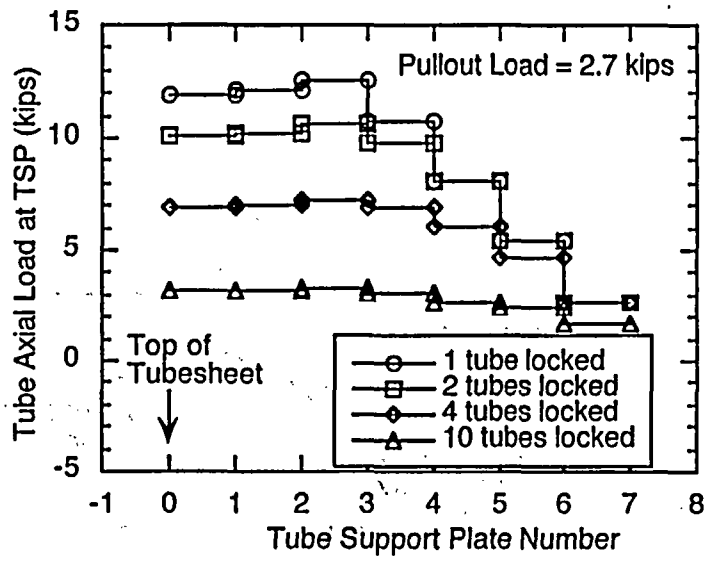
Tube axial load
(excluding end cap load)



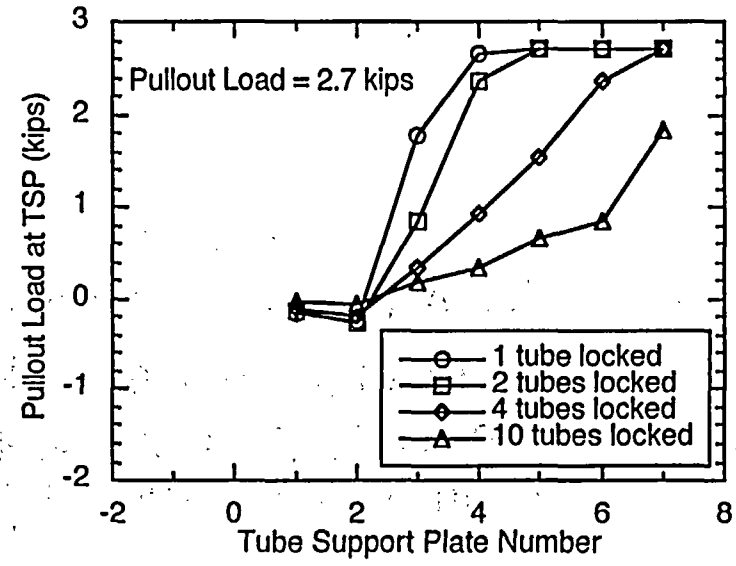
Pullout force

- If only 1 or 2 tubes are locked to all the TSPs, the maximum axial stresses in the locked tubes at mid to lower elevations are close to the ultimate tensile strength.
- The axial load decreases with increasing number of locked tubes
- The distribution of axial loads in the locked tubes becomes more uniform as the number of locked tubes is increased.
- A negative pullout force signifies load transferred from the TSP to the tube in the vertically downward direction.

Multiple tubes locked–Avg Pullout Force (2.7 kips)



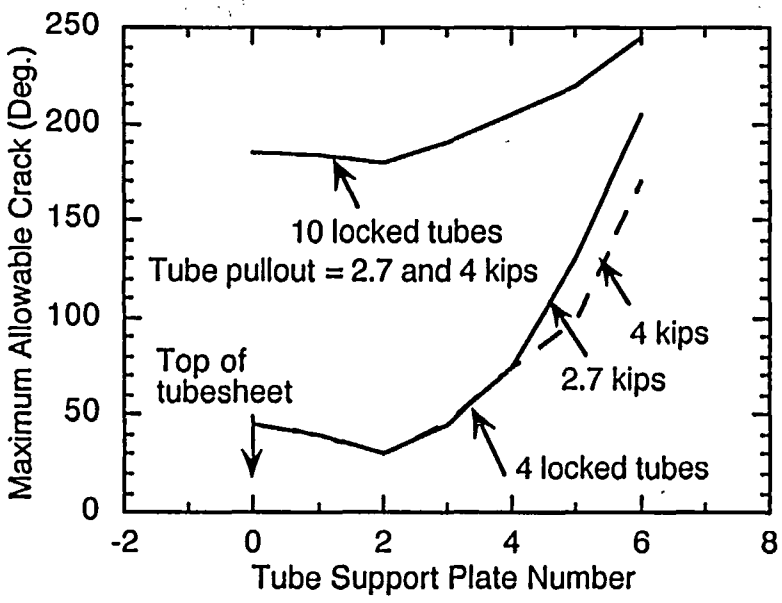
Tube axial load (excluding end cap load)



Tube pullout load

- Peak tube axial loads are reduced compared to the case with a tube pullout force = 4 kips.

Allowable Crack Angle for Multiple Locked Tubes



- For √ 4 locked tubes, TW circumferential cracks >30° can be tolerated
  - At higher elevations even longer cracks are tolerable
- For √ 10 locked tubes, unstable TW crack length > 150°Longer cracks will be acceptable if 10 tubes are locked.
- Results are only weakly dependent on maximum pull out force

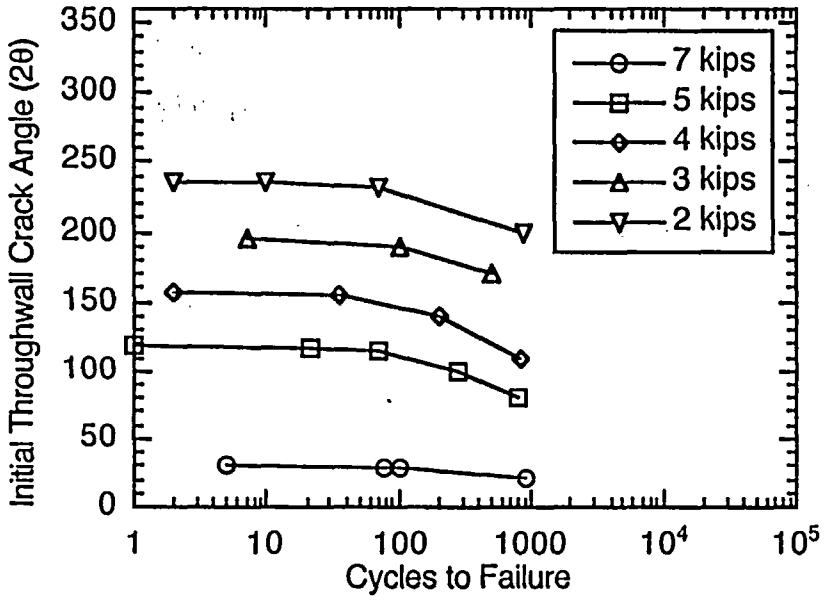
Cyclic Crack Growth Analysis

- Up to now only a one time loading of a crack has been considered
- The potential for crack growth by repeated application of the same load was considered next
  - Cyclic crack growth was analyzed using the ASME Code Section XI correlation (load ratio R=0) for Alloy 600 at 550°F in air environment (environmental effects small at frequencies of interest here)

$$\frac{da}{dN} = 3.43X10^{\Delta 12}\,\Delta K^{3.3}.$$

  - The stress intensity factor range ΔK for PTW circumferential cracks was calculated from the Zahoor J correlation and for TW circumferential cracks from the ANL J correlation for a span of 50 in. between supports
  - Crack growth was calculated in the depth direction until the crack became TW and then in the circumferential direction until rupture was predicted
  - Rupture was predicted to occur when either the uncracked section that contains the crack reached a plastic collapse state or a maximum K_J value of 300 ksi-$\sqrt{in}$ was attained. In most cases, the former criterion controlled the final rupture.

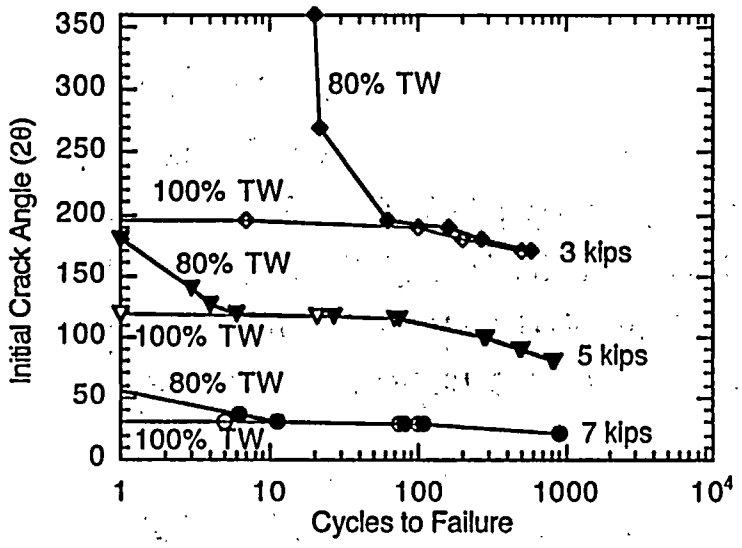
Cyclic Growth of Initially Throughwall Cracks



- The crack growth rates before instability are 0.01-0.07° per cycle.

- The axial loads on a crack range from 4 to 7 kips when 4 tubes are locked
  - At 7 kips, 75 cycles are required to grow the crack from 29° to instability at 30°
- The axial loads range from 2 to 3 kips when 10 tubes are locked
  - At 2 kips, 70 cycles are required to grow the crack from 230° to instability at 235°

Cyclic Growth of Part-Throughwall Cracks



- The additional cycles needed to grow the initially PTW crack through the wall thickness add significant margins at the low-cycle end at low axial loads.
- At the high cycle end, the numbers of cycles to failure for the TW and PTW cracks converge.

Conclusions

- Review of the available TH analyses of MSLB and FWLB for Westinghouse Model 51 and Model E2 SGs showed that the most critical transient, from a SG tube integrity standpoint, is a large MSLB event.
- Lateral pressure loads on tubes are highest during a large MSLB, but even in this case the loads are too small to cause significant bending stress (<1 ksi) in the tubes.
- FEAs of a Model 51 SG TSP, including the supports, with and without a single tube (at the maximum displacement point) locked to the TSP, showed that the maximum TSP displacement under a unit pressure loading is reduced from 0.44 to 0.054 in. The displacement of the TSP at the tube-to-TSP junction (which is the maximum displacement point for the unlocked case) is reduced to 0.013 in.
  - Results are not surprising because the axial stiffness of the SG tubes is much greater than the bending stiffness of the TSPs
  - Results are consistent with the analyses reported by industry

Conclusions (Cont'd)

- FEAs with 1, 2, 4, and 10 tubes in a local region locked to the TSPs (FEM modeled 90° segments of the TSPs) showed that
  - The axial load per tube decreased steadily as the number of locked tubes was increased
  - The maximum bending stress in the tubes is much smaller than the maximum direct axial stress
  - Only in the case where 1 or 2 tubes in a region are locked, do the loads on the tubes depend strongly on the values of the pullout forces

Conclusions (Cont'd)

- FEA results (cont'd)
  - Even when the maximum tube pullout forces are limited to realistic values, if only one or two tubes were assumed to be locked at the TSPs, the calculated axial tensile stresses on the locked tubes at lower elevations exceed the ultimate tensile strength of the tube
    - *Because the maximum displacement of an unlocked TSP is limited to ≈2-in., the locked tubes would not rupture if they were unflawed, but the tolerance for circumferential cracks in these tubes would be severely limited.*
- Fracture mechanics analysis (one-time loading) results showed that
  - The loads transferred to the SG tubes during the transients have virtually no effect on the burst pressure and leak rate integrity of tubes with axial cracks.
  - If the number of locked tubes in each region is √ 10, the maximum axial load in the locked tubes is reduced to √ 3 kips and the size of TW circumferential cracks in the tubes at all the TSP junctions required for instability is √ 180°
  - If all the tubes are locked to all the TSPs, then the maximum tube axial load is 1.6 kips and the unstable crack length is √ 300°

Conclusions (Cont'd)

- Although available TH analyses for the MSLB transient show at most one or two pressure pulse peaks, fatigue analyses were conducted to demonstrate that sufficient margin exists for crack growth even if the current analyses underestimate cyclic loading
  - The average crack growth rate for 100% throughwall circumferential cracks, just before rupture, is of the order of only 0.1°/cycle.
  - With as few as 16 tubes locked (4 tubes/region), circumferential TW cracks √ 85° would not grow to failure.
  - With 40 tubes locked (10 tubes/region), cracks √ 230° would not grow to failure.
  - If the cracks are PTW, longer cracks can be tolerated.
- Thus if even a few percent of the tubes in a SG are locked to the TSPs by corrosion or other chemical products, the dynamic loads associated with MSLB will have little impact of the integrity of SG tubes unless extensive circumferential cracking is present.

Conclusions (Cont'd)

- Anecdotal evidence and the study on pull out forces at Dampierre support the conclusion that SGs with drilled hole carbon steel tube support plates will have enough tubes locked that dynamic loads will have little impact on overall SG tube integrity.
  - A more extensive review of the industry data especially from US plants on pull out forces would strengthen this conclusion.
- The value of the maximum tube pullout force can have a significant impact if only a few tubes are locked.
  - If even a few percent are locked, however, the results are insensitive to the values of the pullout forces
- Industry calculations of pressure drops across the TSPs due to a MSLB with RELAP5, and NRC staff calculations with TRAC–M, give comparable results.
- In addition, both the industry and the staff have undertaken bounding analyses of the pressure drops that give comparable results and are about a factor of 2 higher than the code calculations.
- Thus, there seems to be little need for additional TH analysis of such transients at this time.

C. EVALUATION OF TRAINING

1. DID YOU COMPLETE THE COURSE?	☑ YES ☐ NO	2. IF TRAINING WAS AT A COLLEGE OR UNIVERSITY, AND GRADES WERE ASSIGNED, WHAT GRADE DID YOU RECEIVE?		3. IF THE COURSE WAS ONLY AUDITED, CHECK HERE (Explain in Block 12) ⟹ ☐

EVALUATION FACTORS	Read each item and check the appropriate rating column			
	A	B	C	D
4. STATED OBJECTIVE ACCOMPLISHED	☑ YES	☐ PARTIALLY	☐ NO	☐ NOT APPLICABLE
5. COVERAGE OF SUBJECT MATTER	☐ EXCELLENT	☑ SUFFICIENTLY	☐ POOR	☐ NOT APPLICABLE
6. ORGANIZATION OF SUBJECT MATTER	☐ WELL ORGANIZED	☑ ADEQUATE	☐ POORLY ORGANIZED	☐ NOT APPLICABLE
7. APPLICABILITY OF SUBJECT MATTER TO THE JOB	☑ SIGNIFICANT	☐ ADEQUATE	☐ INSIGNIFICANT	☐ NOT APPLICABLE
8. RECOMMENDATION TO COLLEAGUES	☐ HIGHLY RECOMMENDED	☐ RECOMMENDED	☐ NOT RECOMMENDED	☑ NOT APPLICABLE
9. MEETS CAREER DEVELOPMENT PLAN	☑ YES	☐ NO		☐ NOT APPLICABLE

10. SPECIFY THE AREAS YOU FEEL REQUIRE MORE EMPHASIS

11. SPECIFY THE AREAS YOU FEEL REQUIRE LESS EMPHASIS

12. REMARKS *(Please make any comments you wish about this course.)*

Usually, the course was taught in a 5-day workshop with computer practices. However, this one day seminar offered some basic knowledge to program Arc/Gis with VBA.
The quality of handout is poor.

13. I SUCCESSFULLY COMPLETED THE TRAINING IDENTIFIED ON PAGE 3.		14. NOTED	
SIGNATURE - EMPLOYEE	DATE	SIGNATURE - SUPERVISOR	DATE

PRIVACY ACT STATEMENT

The Privacy Act Statement that covers this form, NRC Form 368A, is located on NRC Form 368, "Training Request and Authorization," which was completed prior to this training.

IODINE SPIKING ASSESSMENT

ACRS JOINT MATERIALS AND METALLURGY AND THERMAL-HYDRAULICS SUBCOMMITTEES

PROGRESS ON STEAM GENERATOR ACTION PLAN MILESTONES – Item 3.9, Iodine Spiking

February 3 and 4, 2004
Rockville, MD

Michelle Hart, (301) 415-1265
US NRC Office of Nuclear Reactor Regulation
Division of Systems Safety and Analysis

Item 3.9 - Iodine Spiking

- Staff searched for more data on the iodine spiking phenomenon, both for SGTR and MSLB type events - none was found.

- In absence of further data, staff reexamined existing studies - *Adams and Atwood, Adams and Sattison.*
  - No data was found for MSLB-type pressure transients.

- The staff's reexamination of the unadjusted raw data indicates higher spiking factors at low activity concentrations (<0.01 μCi/gm DEI-131).
  - No clear dependency of spiking rate on pre-incident coolant iodine activity concentration was able to be determined.
  - Current mass balance modeling would give same dose for 1 μCi/gm DEI-131 and 500 times appearance rate spike (standard assumptions) as 50,000 times appearance rate spike for an assumed 0.01 μCi/gm DEI-131 concentration.
  - Currently, the lowest TS equilibrium value is 0.1 μCi/gm DEI-131.
  - Because of steam generator replacements, no further requests for lower activity expected.

Item 3.9 - Iodine Spiking Conclusions

- The staff thinks that the current modeling regime is conservative based on study of the existing data, so continuing to treat iodine spiking in this way protects the public health and safety.

- More data would need to be collected to develop a mechanistic or phenomenological model. This would be a large research effort.
  - NUREG-0933 (December 1984) prioritized development of a new model and recommended the issue be dropped.

- The staff would be receptive to an industry initiative to research and develop a more technically rigorous model of the iodine spiking phenomenon. There have been no overtures to date.

THERMAL HYDRAULIC CONDITIONS

ACRS Joint Subcommittees Meeting
on
Steam Generator Action Plan

Thermal Hydraulic Conditions During Severe Accident SGAP Items 3.3 – 3.4g

February 4, 2004

Outline For Presentations

1. Overview of T/H work and issues

   Christopher Boyd – NRC Research - (301) 415-0244

2. ARTIST PROGRAM (SGAP item 3.3)

   Christopher Boyd

3. CFD Related Work (SGAP item 3.4.e)

   Christopher Boyd

4. SCDAP/RELAP5 Analysis

   Don Fletcher – Information Systems Laboratories

   (208) 552-6408

Overview

- Thermal hydraulic analysis predicts the thermal and pressure loads used for failure analysis.

- Updated predictions of severe accident conditions are being completed for the ZION plant during a TMLB' (station blackout) transient.
  - more realistic boundary conditions and assumptions
  - updated mixing parameters based on CFD predictions and a re-evaluation of the 1/7th scale data
  - improved modeling in SCDAP/RELAP5

- Failure predictions indicate the surge line fails prior to the unflawed tubes. The failures at various locations remain relatively close in time.

Approach and Tools Used

- **SCDAP/RELAP5** is used to predict the reactor system behavior under a variety of conditions
  - provides thermal and mechanical loads on reactor components
- **1/7th scale experiments** provide mixing parameters during single phase counter current natural circulation.
  - **Computational Fluid Dynamics** (CFD) is used to predict the mixing parameters (and other aspects of the behavior) at full-scale conditions outside the range of the experiments.
- **MELCOR** will be used to predict fission product transport and release rates.
  - Data from the **ARTIST** program will be used to determine the aerosol retention in the steam generator secondary side.

- BACKGROUND –
Issues Raised in NUREG-1740

- 1D codes are tuned by comparison with experimental results
  - scale of experiments criticized
  - concern that "mixing may be overestimated"
  - the tests did not simulate leakage
- Sensitivity studies may not have covered the entire plausible range of variations and they did not cover simultaneous variation of multiple parameters.

Steam Generator Action Plan
- Related Milestones -

- 3.3 Use data from ARTIST program for mitigation of radionuclides in SG secondary.
- 3.4 a-f improve understanding of RCS conditions under severe accident conditions

	completed or planned completion
a - perform plant sequence variations	(9/01 + ongoing work)
b - re-evaluate SCDAP/RELAP5 assumptions	(4/02 + ongoing work)
c - examine data for tube-tube variations	(8/02)
d - perform more rigorous uncertainty analysis	(plan 11/04)
e - extend 1/7th scale data using CFD	(8/01 – 12/02)
f - estimate uncertainty due to core melt	(plan 2/05)

ARTIST PROGRAM
(Aerosol Trapping In Steam Generator)

- Objective: To provide data on the behavior of simulant aerosols in the secondary side of a steam generator.
- This program is being conducted at the Paul Sherrer Institut (PSI) in Switzerland (2003-2007)
- 5 test phases address the following phenomena
  - retention of aerosol in tubes
  - deagglomeration and deposition near a tube rupture
  - deposition of aerosol along the tube array above break
  - aerosol retention in full scale steam separators and dryers
  - combined effects of the entire steam generator secondary side
- Plan to incorporate data into MELCOR analysis

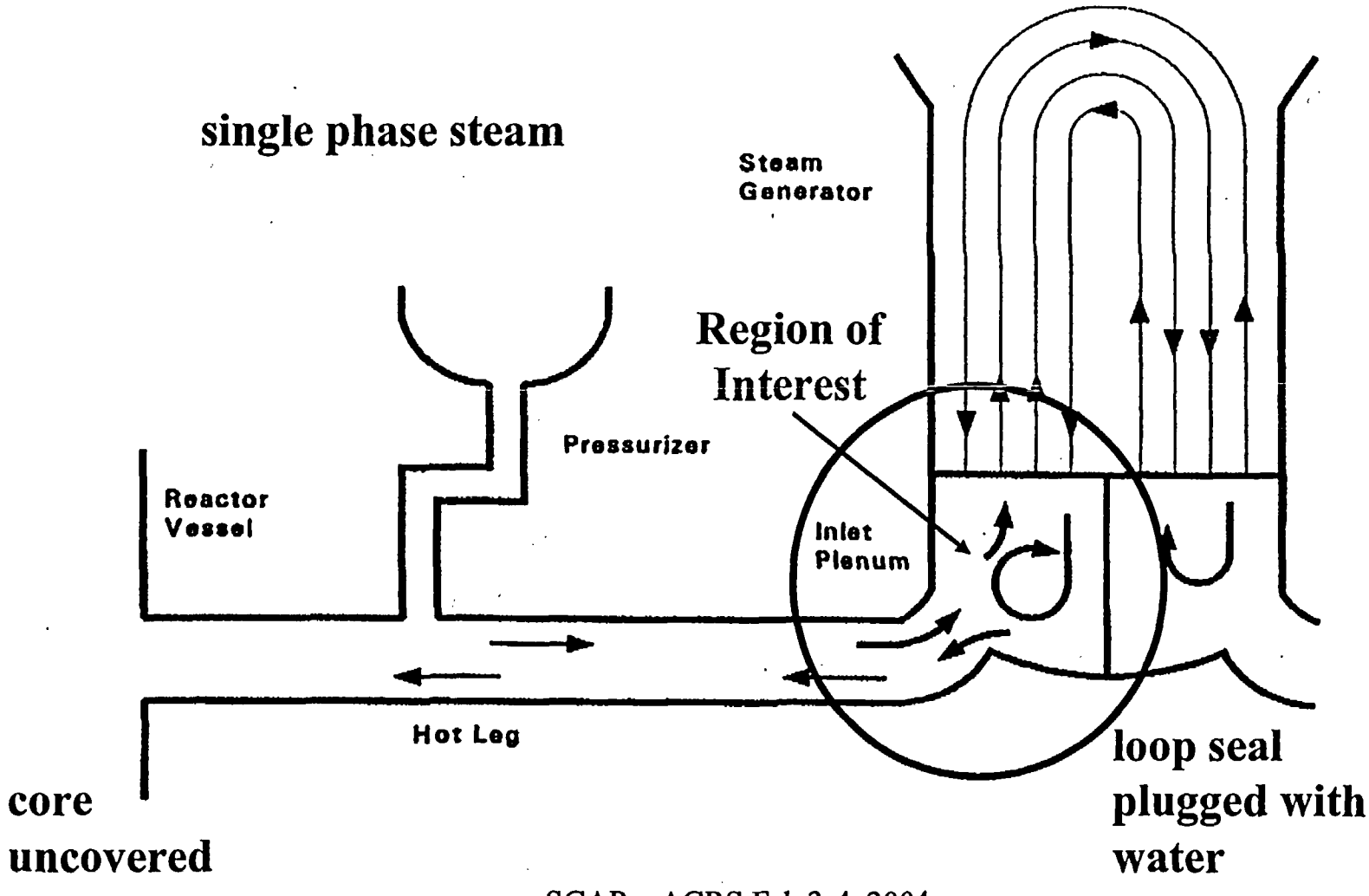
CFD Related Work

- Computational Fluid Dynamics (CFD) predictions have been completed within the Office of Research (RES) to extend our understanding of the inlet plenum mixing behavior beyond the available data at 1/7th scale.
- Issues addressed
  - applicability of method
  - scaling from 1/7th scale data to full-scale
  - tube leakage effect on mixing
  - sensitivity of results to governing parameters
  + geometrical distortions of 1/7th scale facility
  + a Combustion Engineering plant example

Summary of Work

- CFD plays a supportive role in the understanding of the mixing behavior and is being used to extend the mixing data available from 1/7th scale tests.
- The predictions indicate
  - The approach used does a good job of predicting key mixing parameters from 1/7th scale test.
  - A prototypical Westinghouse SG has somewhat different behavior than the 1/7th scale tests (mixing is similar).
  - Tube leakage does not cause the hot plume to pass through the inlet plenum without mixing.
  - A sample CE steam generator design results in **significantly less** mixing than the Westinghouse design SGs.
  - Secondary side heat transfer rates on the tube bundle have an impact on the inlet plenum mixing parameters.

Flow Pattern Considered



Parameters of Interest in SCDAP/RELAP5 model

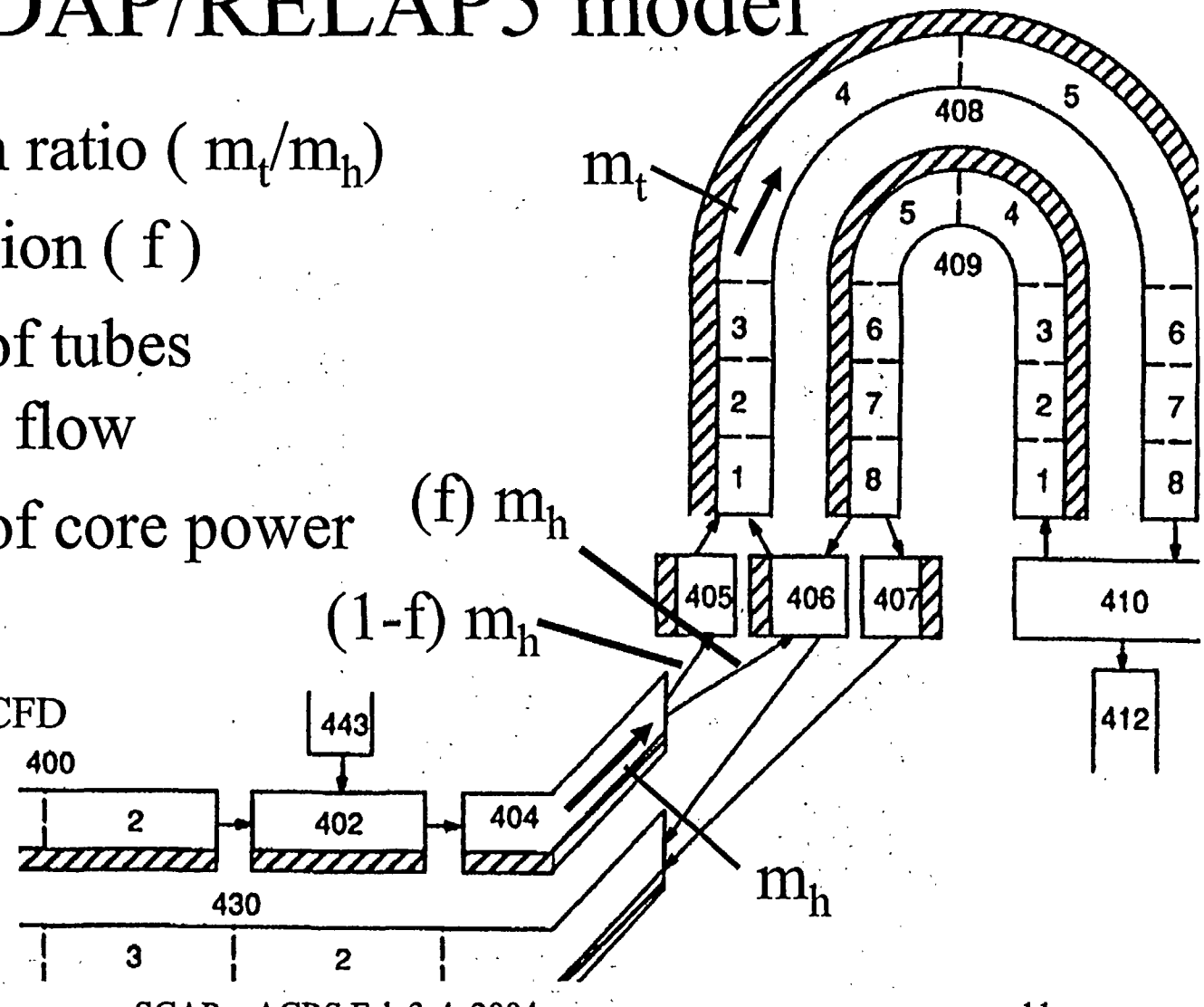
1 recirculation ratio (m_t/m_h)

2 mixing fraction (f)

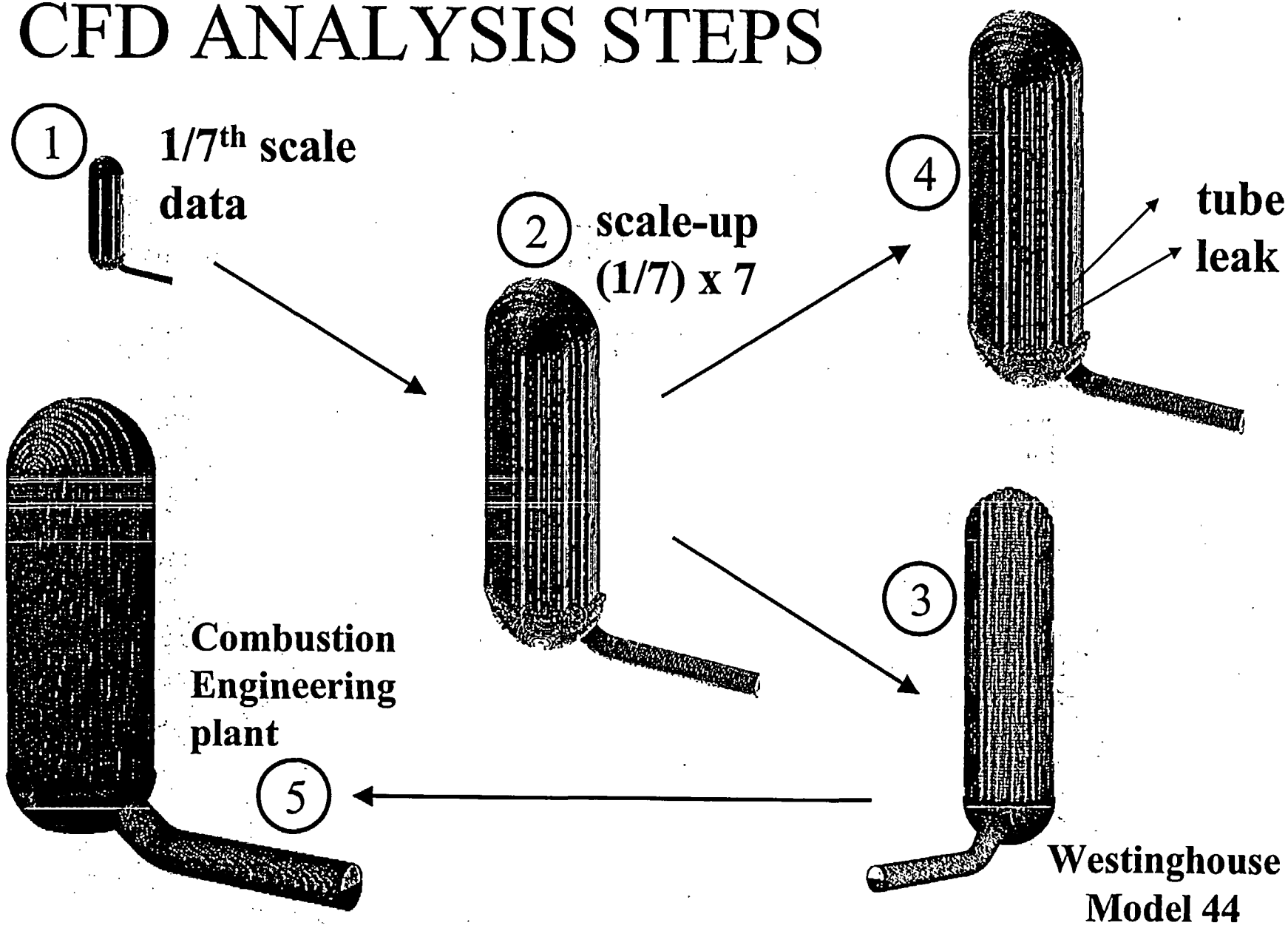
3 percentage of tubes carrying hot flow

4* percentage of core power to SGs

* not predicted with CFD

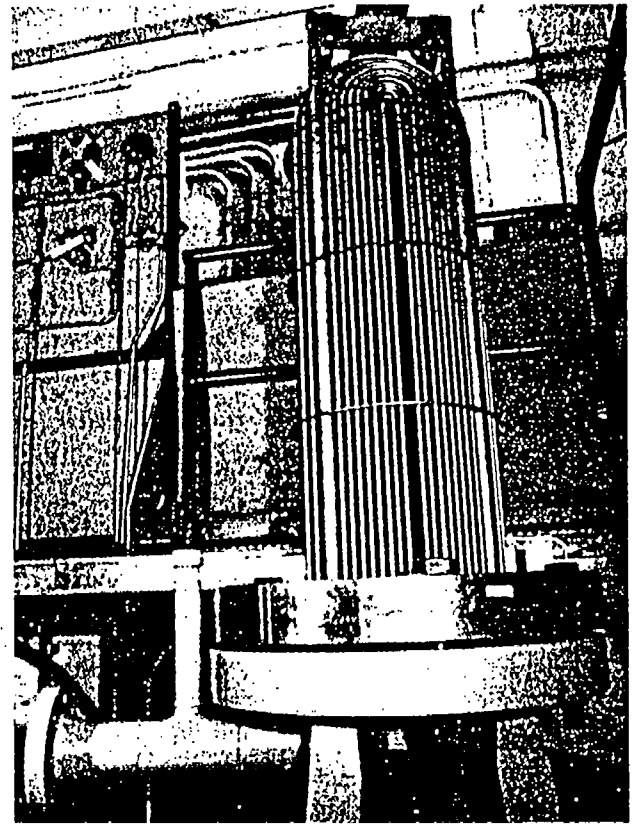


CFD ANALYSIS STEPS



CFD Step 1. Assess Method using 1/7th Scale Data

- A set of data at 1/7th scale is used to assess the modeling approach and assumptions.
- A good prediction of available flow and mixing parameters at 1/7th scale provides confidence that the approach is applicable for these types of predictions.
- Sensitivity studies quantify the significance of modeling inputs.



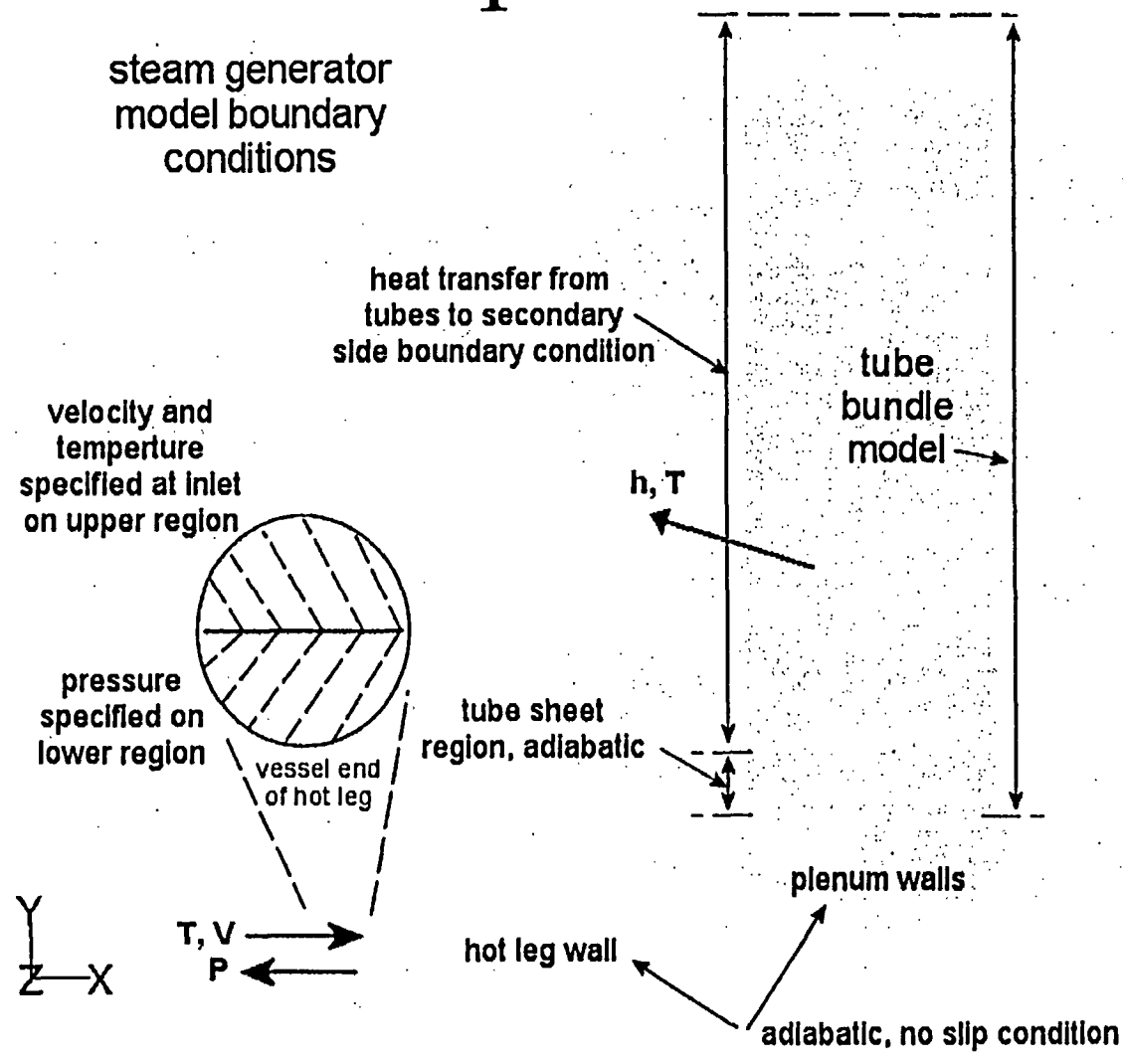
hot leg and steam generator from 1/7th scale facility

Model Setup

-Boundary conditions applied to hot leg and tube bundle model ("distanced" from inlet plenum).

-Hot leg mass flow and temperature are set at 1/7th scale conditions.

-Secondary side conditions are adjusted to match the heat loss rate from the 1/7th scale tests.

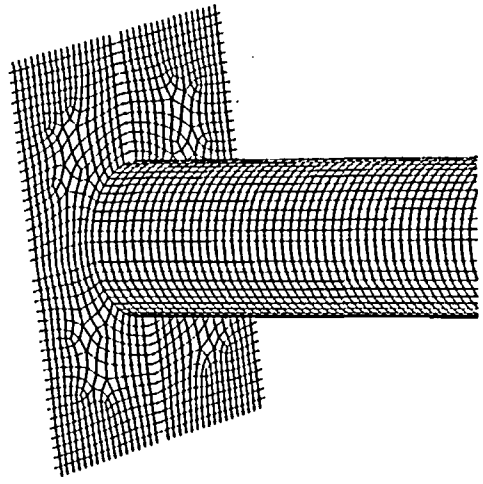


How Can You Model the Tubes?

- 3 Options considered
  - Directly
    - no modeling assumptions required
    - expensive at 1/7th scale, unaffordable at full-scale (3000+ tubes)
  - A smaller number of tubes
    - raises questions about heat transfer and flow losses
  - A porous media approach available in FLUENT
    - algebraic expressions determine viscous losses and tube sheet pressure drops
    - heat loss rate adjusted to match experimental observations
    - tube-tube variations maintained with individual flow paths
    - creates upper boundary to inlet plenum with appropriate tube bundle mass flows and temperatures.

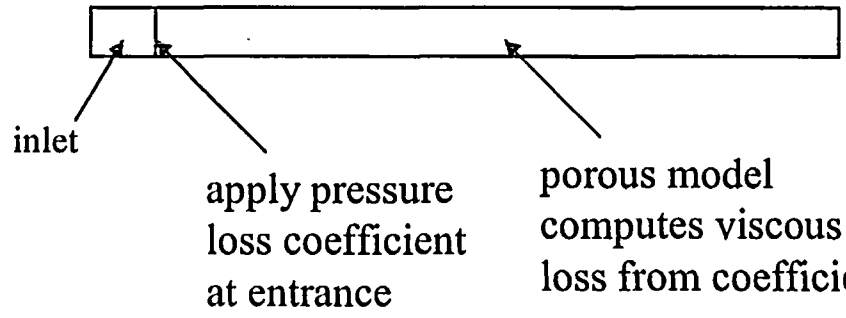
Example – Single Tube Model

1 entrance, 1m tube – 2 approaches



porous media approach

model each tube as a square tube filled with porous media. (no wall shear. Boundary layers are unnecessary.)

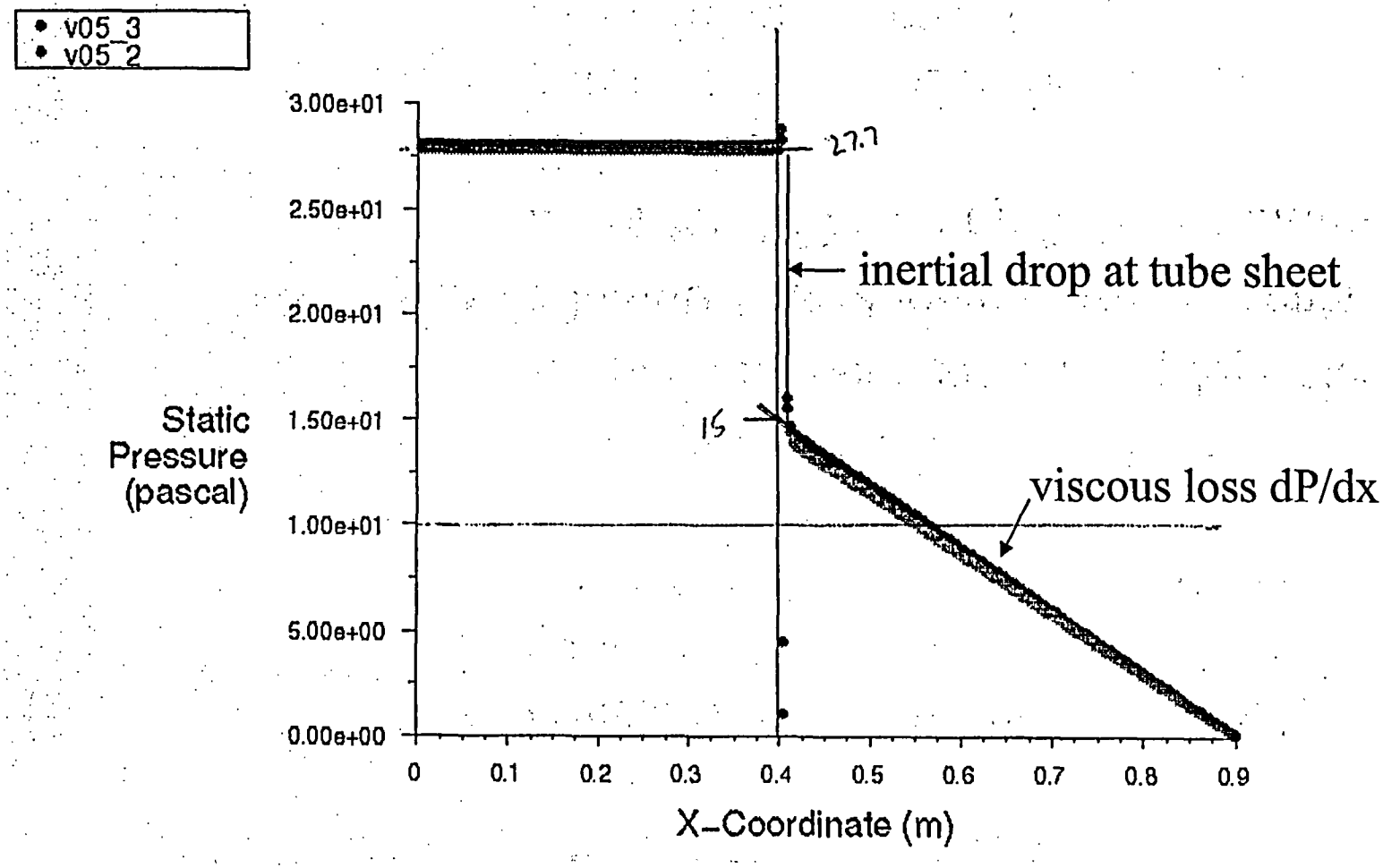


Ideal Mesh
y+ values = 30 on walls
hex mesh (AR nearly 1)
1.12 Million Cells

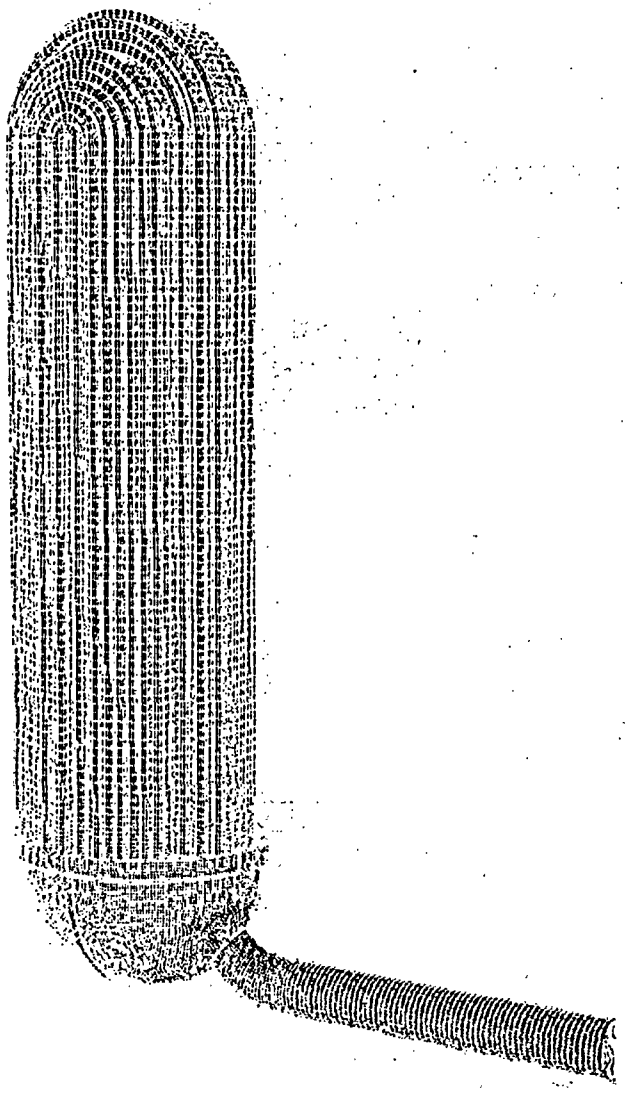
with a 4x4 square mesh for the porous tube 1.2 m long, only 4000 cells are needed

10^6 cells vs. $4x10^3$ cells

(pressure drop through model)

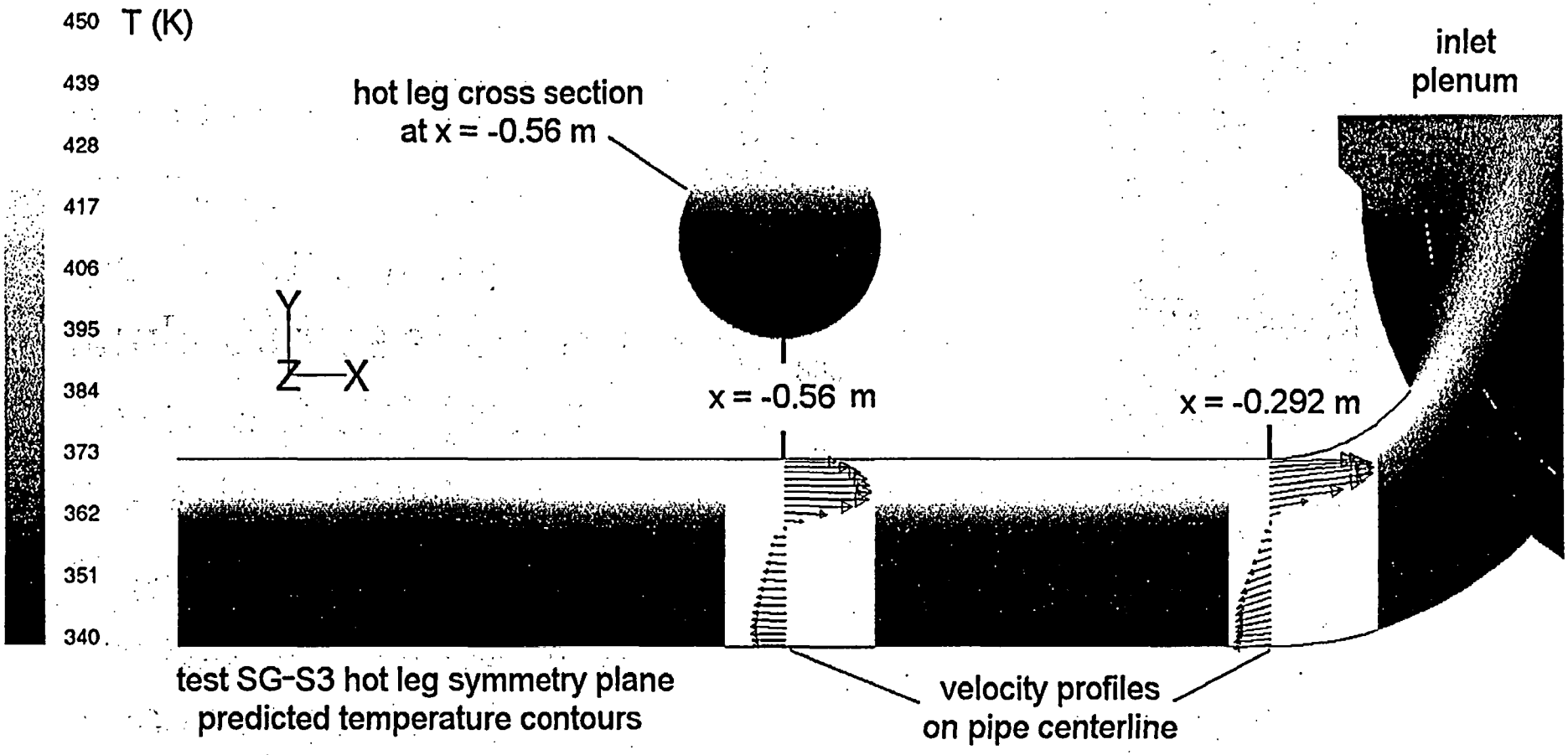


1/7th Scale Model Summary



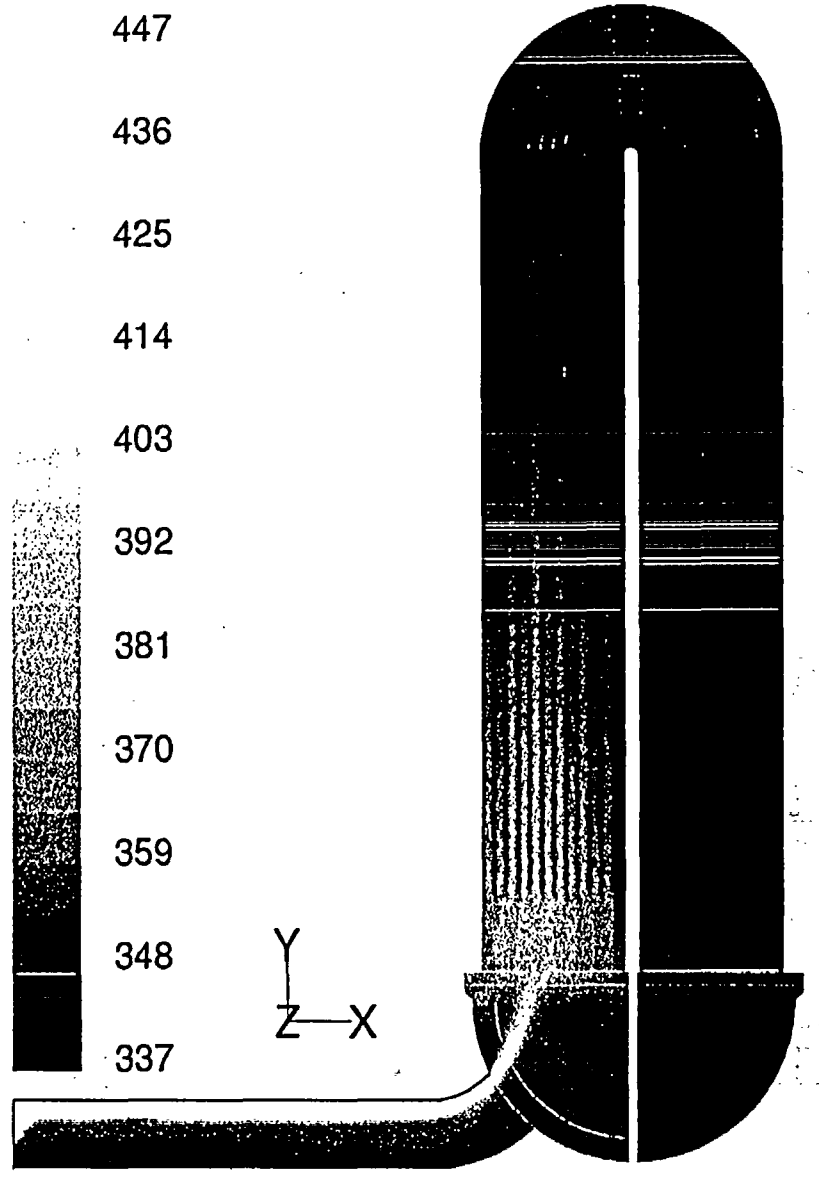
- transient CFD solution with steady boundary conditions
- Reynolds stress 2nd order Turbulence
  - non-isotropic
  - full buoyancy effects on turbulence
- temperature dependent SF_6 properties
- 500,000 + hexagonal mesh elements
- 2nd order differencing for momentum and energy
- porous media model for each of the 216 individual tube flow paths
- symmetry plane

Accelerating Stratified Flow in Hot leg

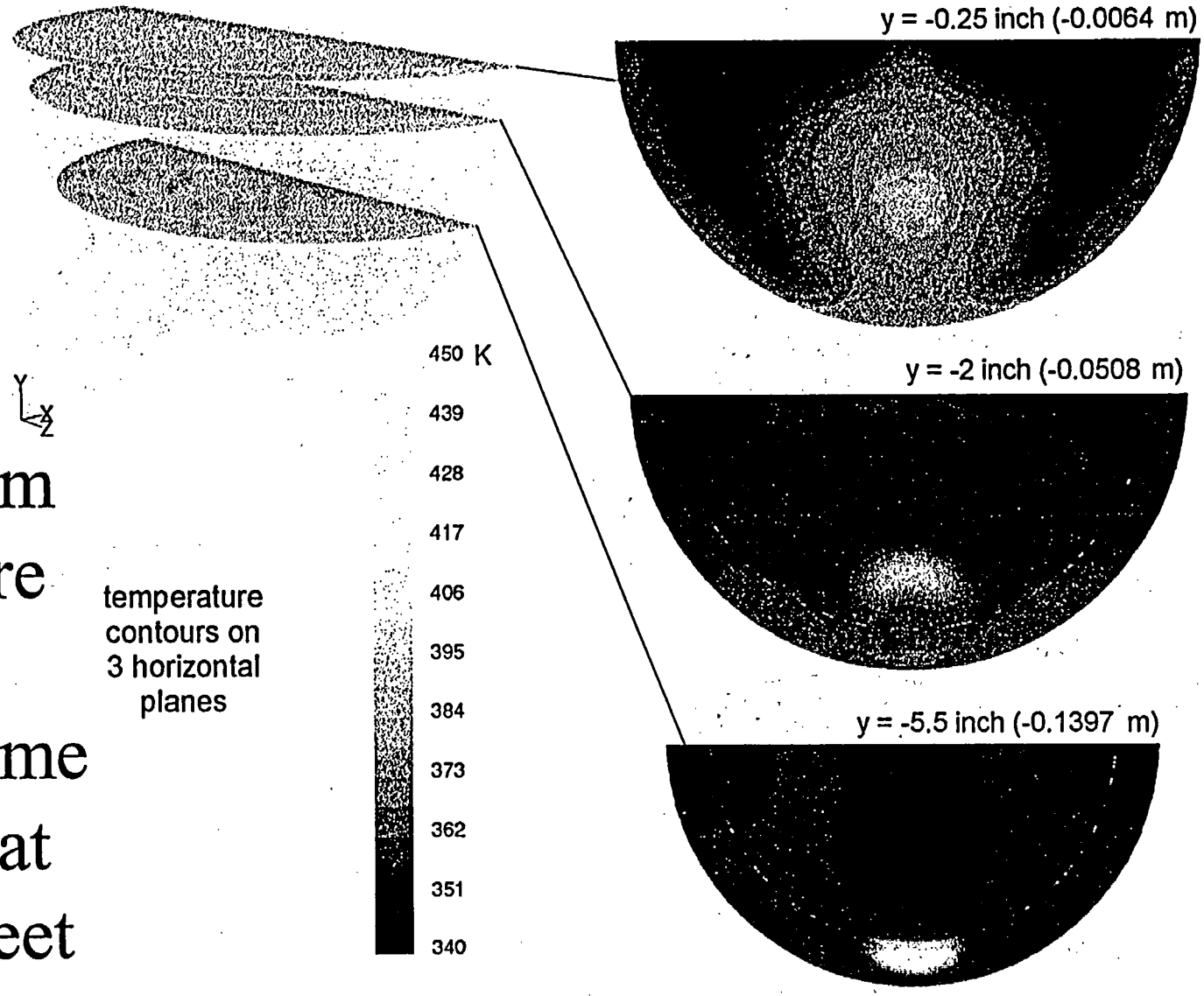


Symmetry Plane Temperatures

The tube bundle heat transfer rate is adjusted to be consistent with the experimental observations. The tube temperatures approach the secondary side temperatures at the top of the tube bundle.

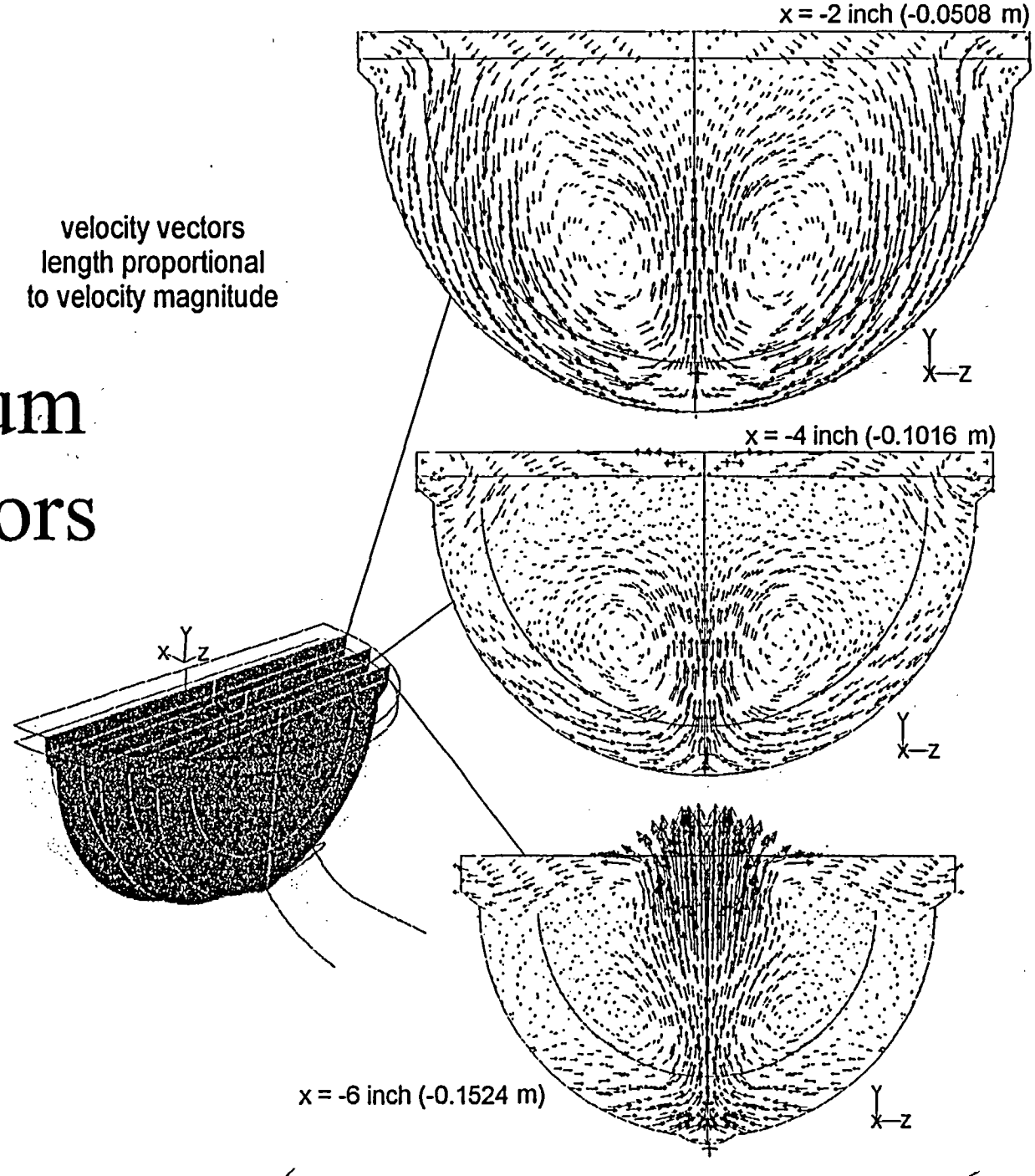


inlet plenum temperature contours indicate plume spreading at the tube sheet face

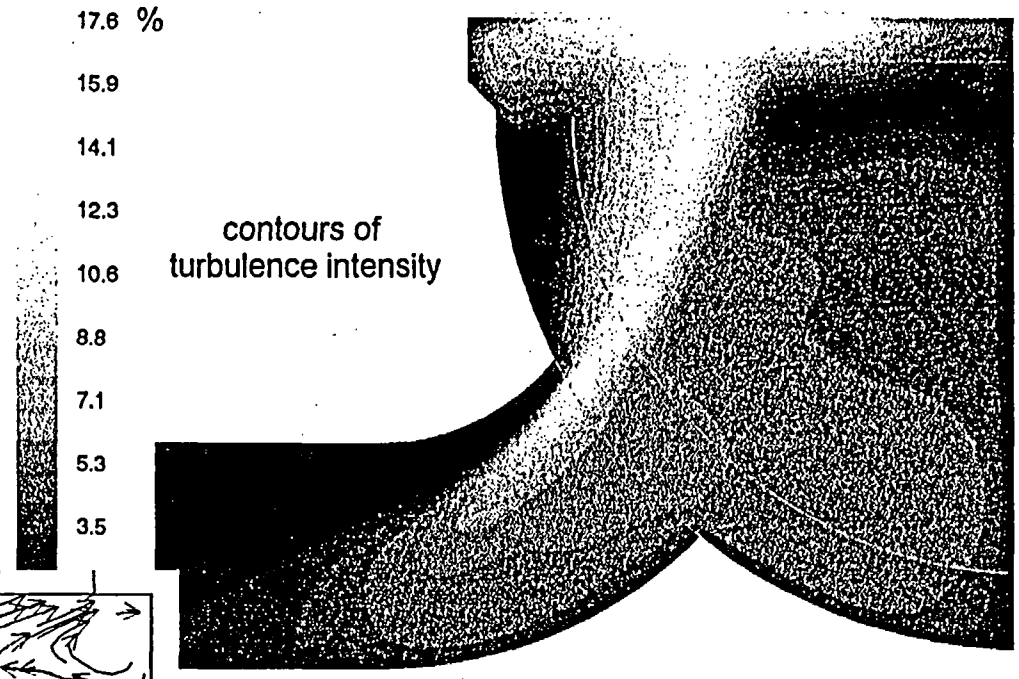


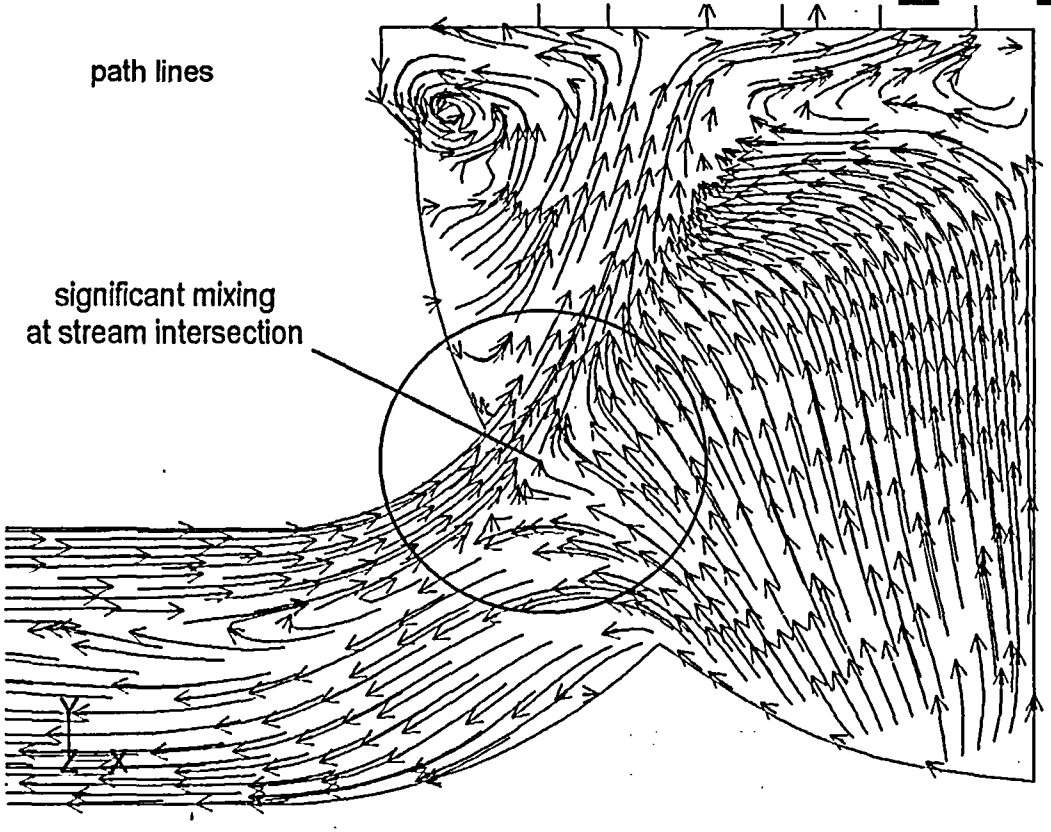
Inlet Plenum Flow Vectors

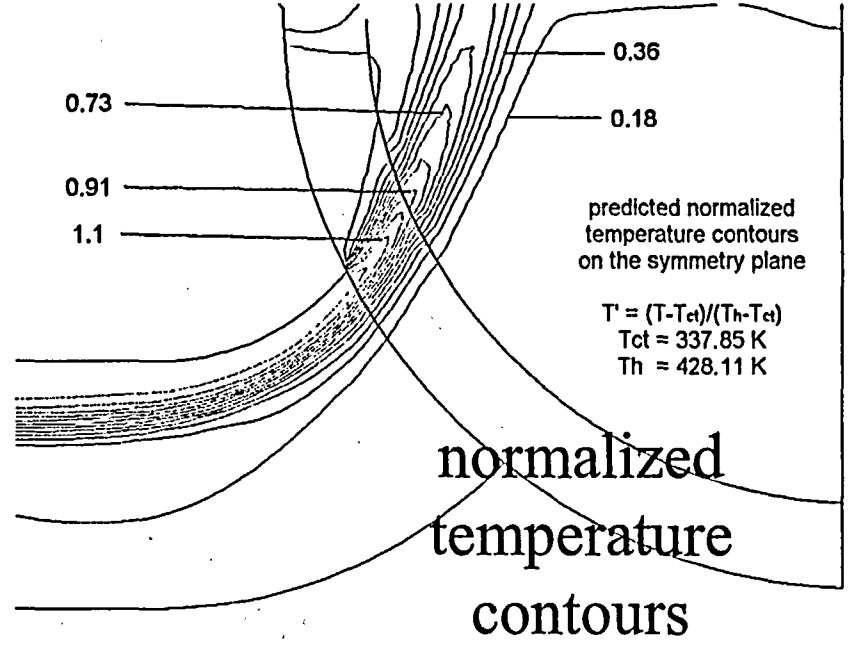
velocity vectors
length proportional
to velocity magnitude



significant mixing at nozzle exit

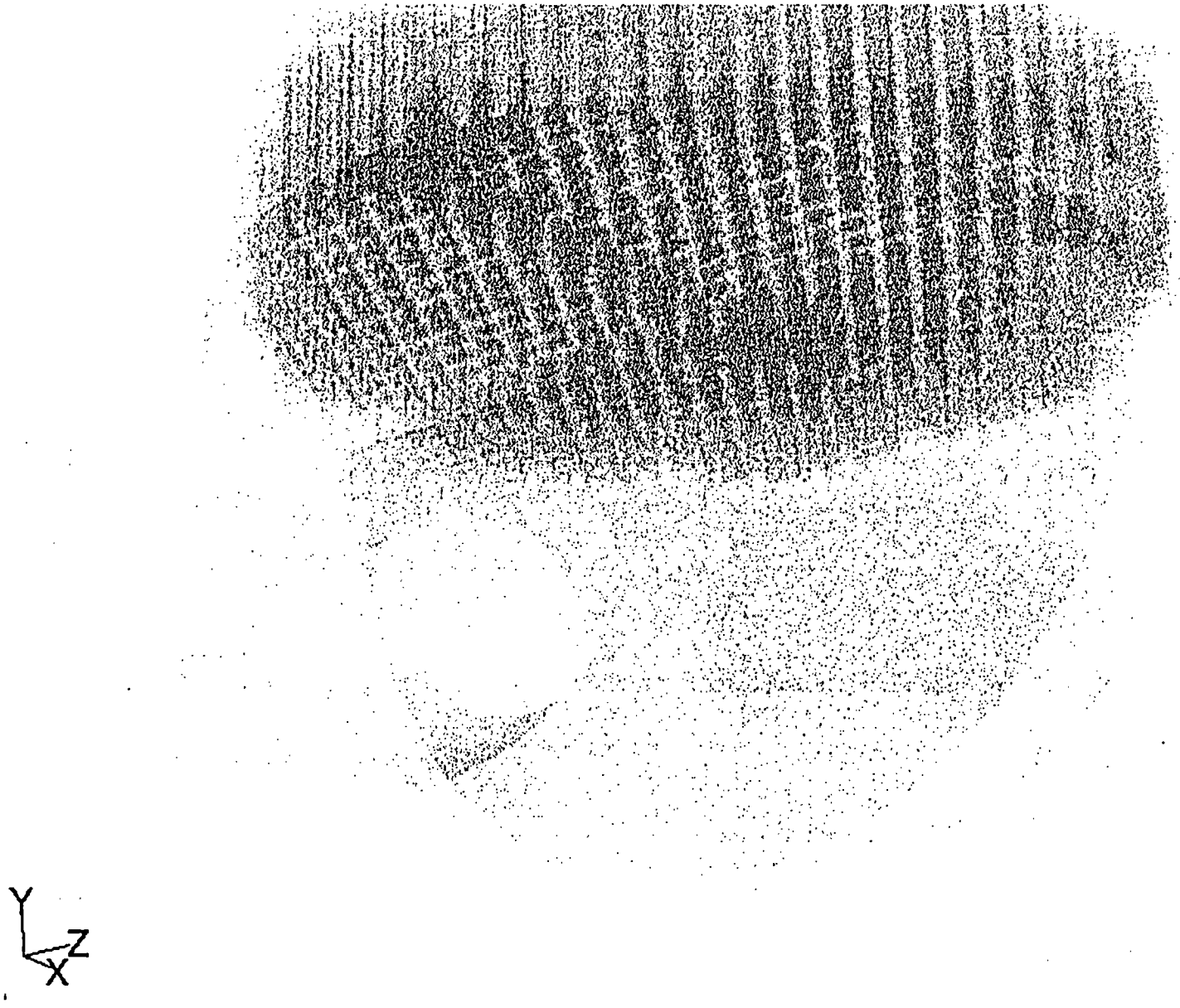




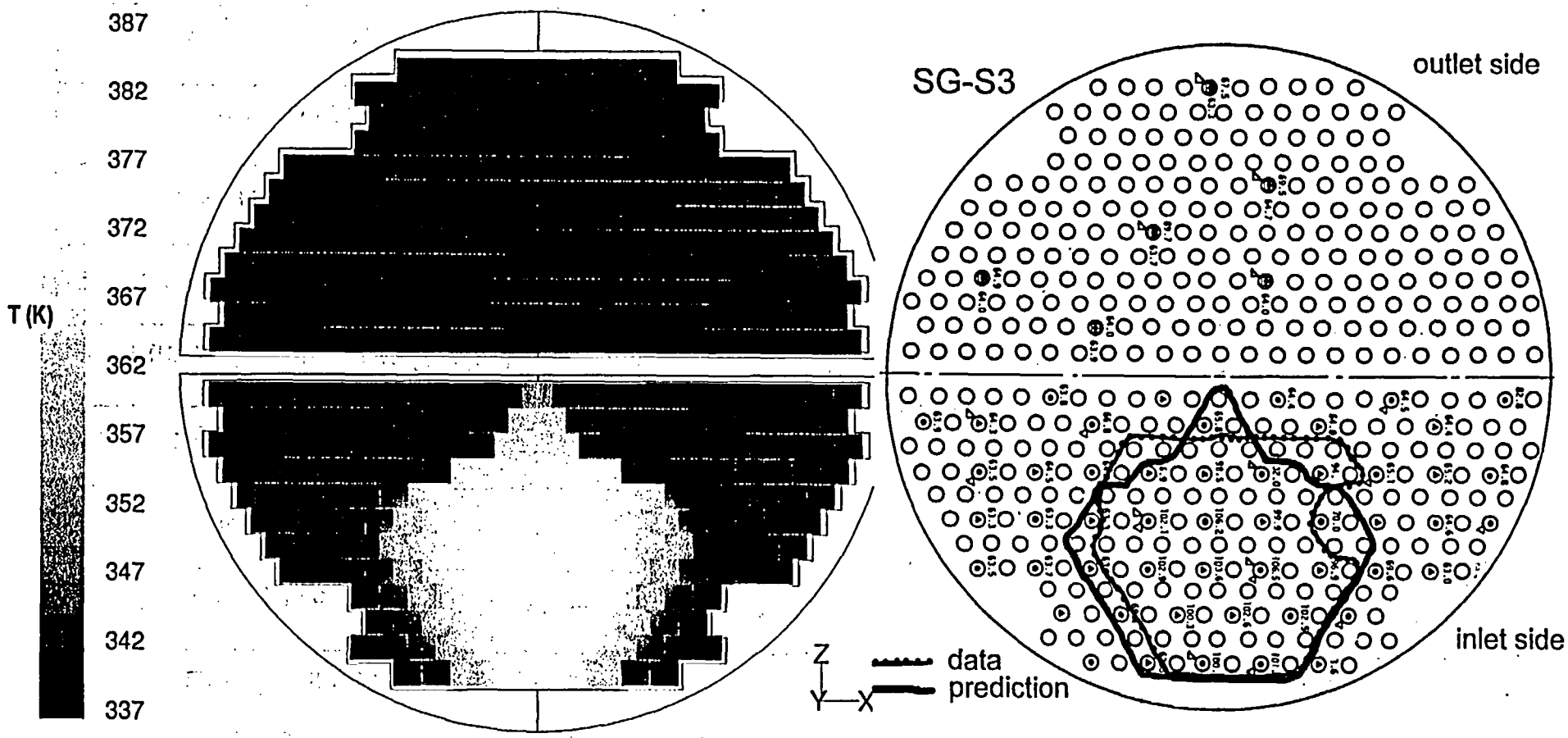


normalized temperature contours

Pathline Animation



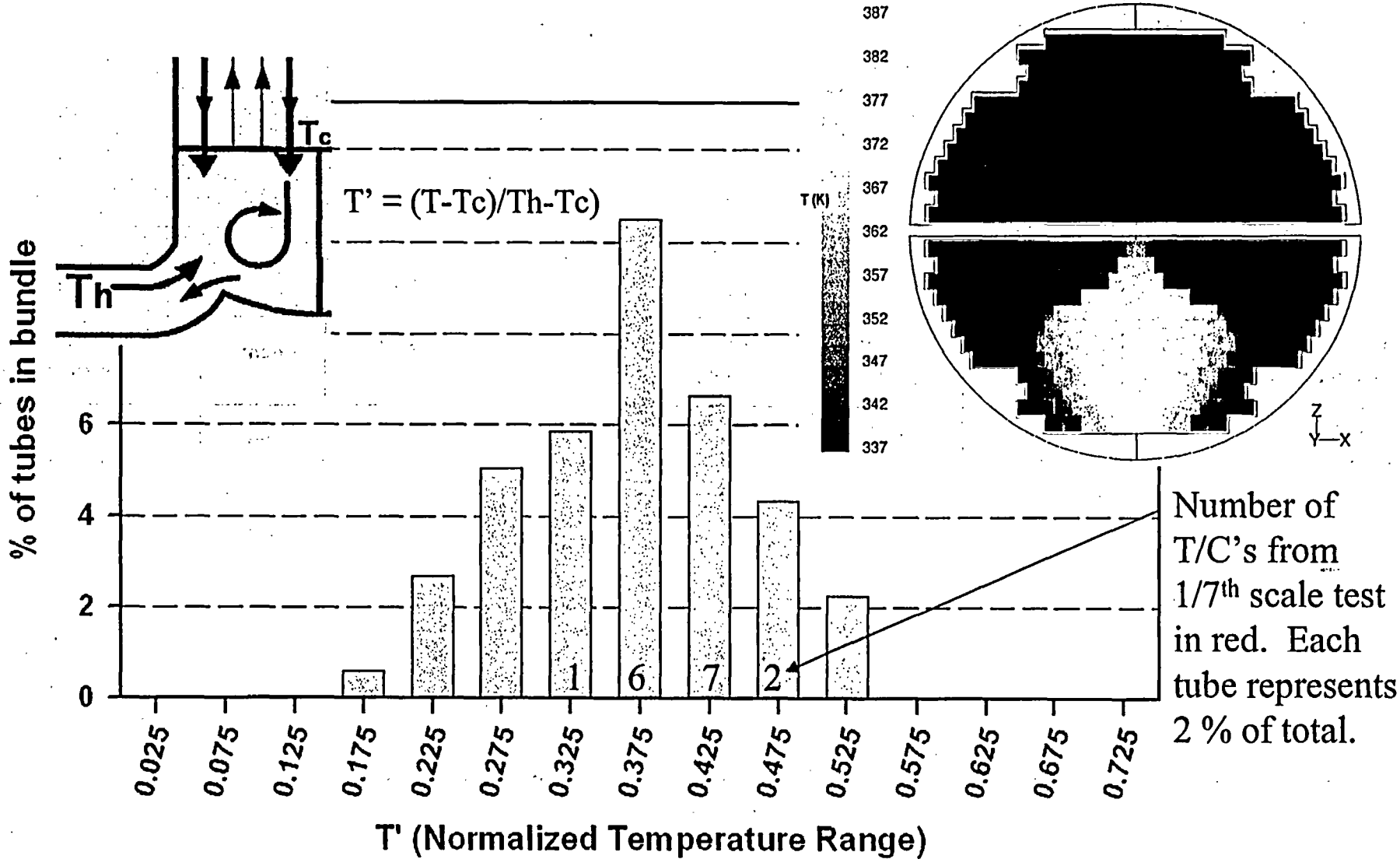
Tube Flow Split



Prediction of Key Parameters

Parameter	Westinghouse 1/7th Test Data*	FLUENT Prediction	Difference
m Hot Leg (mass flux (kg/s))	.06	.0586	-2.3 %
T_h Hot Leg (average Hot T (°C))	159.3	155	-4.3 °C
# Hot Tubes	75	82	7 tubes (3.2%)
T_{ht} Tubes (average Hot T (°C))	100.8	100	-0.8 °C
m_t Tubes (mass flux (kg/s))	0.12	0.1206	0.5 %
Heat Loss at Tubes (kW)	3.56	3.69	3.7 %
T_{ct} Tubes (average Cold T (°C))	64.7	64.7	0
T_c Hot Leg (average Cold T (°C))	86.8	80.1	-6.7 °C
f (mixing fraction)	0.85	0.81	-4.7 %
m_t/m (recirculation ratio)	2.01	2.06	2.5 %

Tube-Tube Variations



Number of T/C's from 1/7th scale test in red. Each tube represents 2 % of total.

Sensitivity Studies

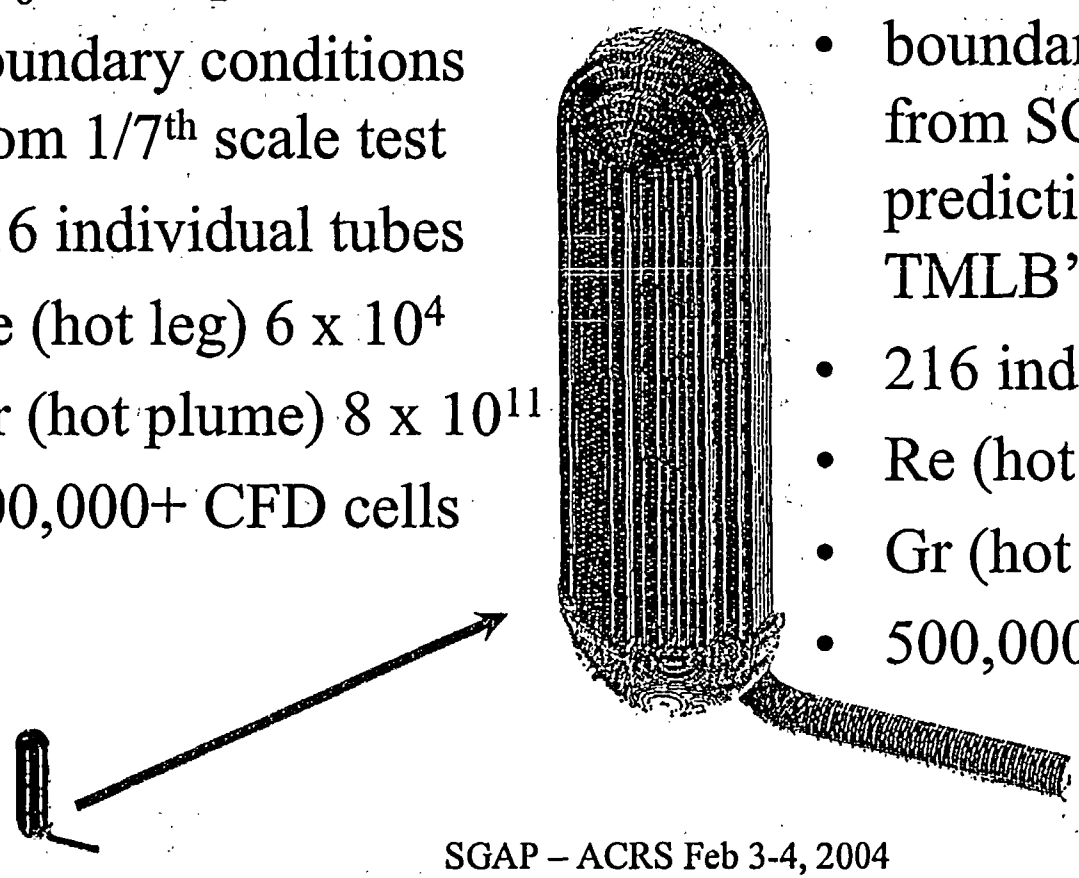
parameter	base case	inlet temperature (-15 deg)	hot leg inlet mass flow (+ 20%)	turbulence model (→ RNG)	tube sheet entrance loss (+25%)	viscous tube flow loss (+25%)	tube heat transfer (h = 5000)	tube heat transfer (h = 100)
heat loss at tubes (kW) (% difference)	3.69	3.21 (-13%)	4.33 (+17.3%)	3.85 (+4.3%)	3.69	3.58 (-3%)	3.53 (-4.3%)	3.85 (4.3%)
# hot tubes (difference)	82	82	82	82	82	82	88 (+ 6)	81 (- 1)
T_h - hot leg (°C) (difference (°C))	155	144.7 (-10.3)	160.1 (+5.1)	153 (-2)	155.2 (+0.2)	156.4 (+1.4)	157 (+2)	153 (-2)
T_c - hot leg (°C) (difference (°C))	80.1	79.8 (-0.3)	81.8 (+1.7)	76.8 (-3.3)	80.6 (+0.5)	82.9 (+2.8)	84 (+3.9)	76.6 (-3.5)
m - hot leg (kg/s) (% difference)	0.0586	0.0589 (+0.5%)	0.0653 (11.4%)	0.0601 (+2.6%)	0.0585 (-0.2%)	0.0577 (-1.5%)	0.0573 (-2.2%)	0.0598 (+2.0%)
T_{ht} - tubes (°C) (difference (°C))	100	97.1 (-2.9)	103.2 (+3.2)	97.3 (-2.7)	100.6 (+0.6)	102.7 (+2.7)	100.1 (+0.1)	96.8 (-3.2)
T_{ct} - tubes (°C)	64.7	64.7	64.7	64.7	64.7	64.7	64.7	64.7
m_t - tubes (kg/s) (% difference)	0.1206	0.1135 (-5.9%)	0.1299 (+7.7%)	0.1173 (-2.7%)	0.1191 (-2.2%)	0.1077 (-10.7%)	0.1028 (-14.8%)	0.1433 (+18.8%)
m_t/m - recirculation ratio (% difference)	2.06	1.93 (-6.3%)	1.99 (-3.4%)	1.95 (-5.3%)	2.04 (-1.0%)	1.87 (-9.2%)	1.79 (-13.1%)	2.4 (+16.5%)
f - mixing fraction[2] (% difference)	0.81	0.82 (+1.2%)	0.79 (-2.5%)	0.91 (+12.3%)	0.80 (-1.2%)	0.81	0.93 (+14.8%)	0.77 (-4.9%)

Summary of Step 1 - Model Assessment

- A comparison with 1/7th scale data provides confidence in the approach.
  - the extension to full-scale conditions is warranted
  - model behavior is stable under a wide variety of conditions
- Qualitative experimental characteristics are predicted.
- Quantitative comparisons of mixing parameters are good.
- Results are sensitive to the tube heat transfer rates.
  - explains difference between steady and transient test results
- The understanding of the experimental results is enhanced with the detail provided by the CFD predictions.
  - nozzle flows help explain observed mixing behavior
  - sensitivity studies provide further insight
  - flowfield patterns add insights to the behavior
  - tube-tube variations are predicted in detail

CFD Step 2. Scale-up Analysis

- **1/7th scale** facility geometry
- SF_6 – 300 psia
- boundary conditions from 1/7th scale test
- 216 individual tubes
- Re (hot leg) 6×10^4
- Gr (hot plume) 8×10^{11}
- 500,000+ CFD cells

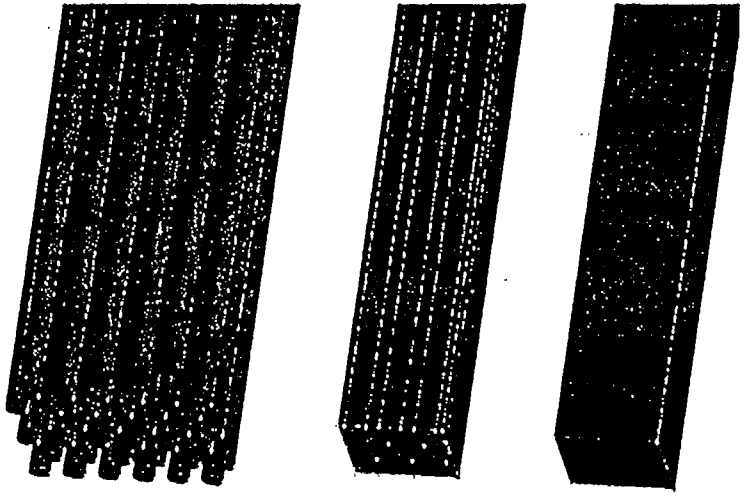


- **full-scale** geometry – 1/7th scale geometry x 7
- steam – 2400 psia
- boundary conditions from SCDAP/R5 prediction of ZION TMLB' transient
- 216 individual tubes
- Re (hot leg) 2×10^5
- Gr (hot plume) 6×10^{12}
- 500,000+ CFD cells

Scale-Up Model

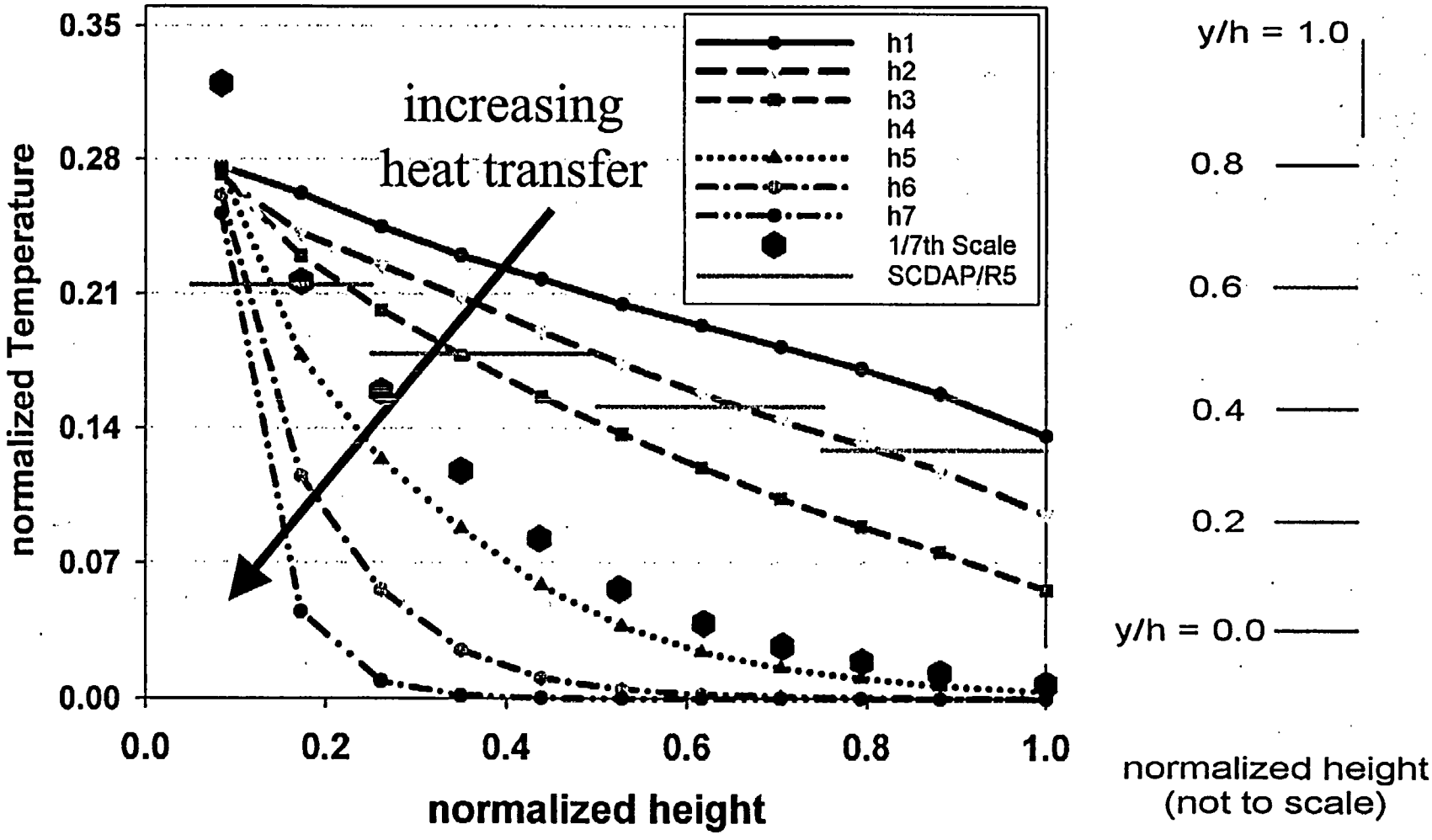
- Using scaled geometry with complete similarity to 1/7th scale facility eliminates geometrical effects.
- Tube bundle flow losses are adjusted to match model 44 bundle.
- Importance of heat transfer rate acknowledged. Sensitivity studies completed to ensure proper range is considered.

3200+ tubes grouped into 216 flow paths

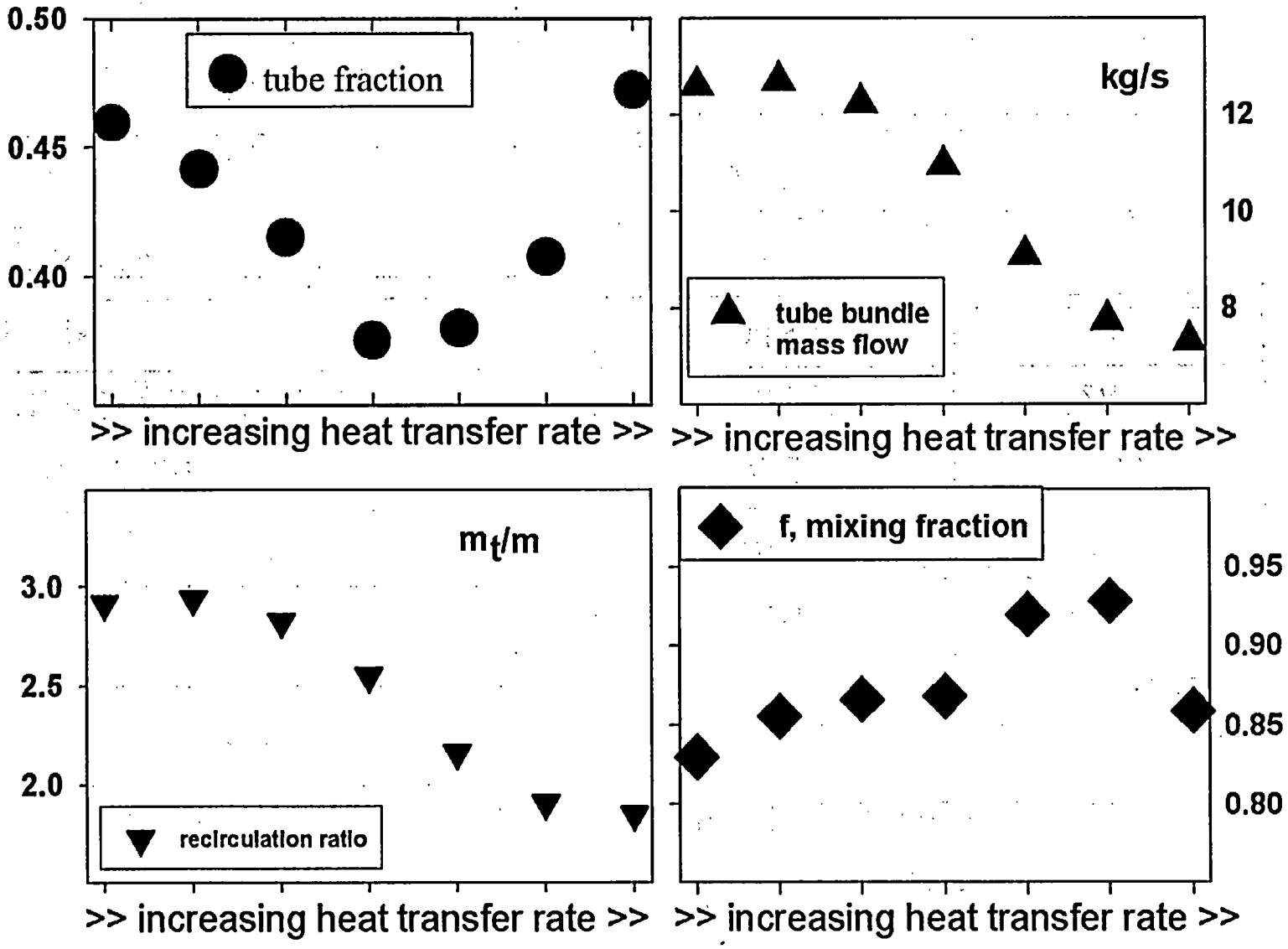


tubes >> grouped >> modeled

Heat Transfer Rate Sensitivity



Effect of Heat Transfer Rate



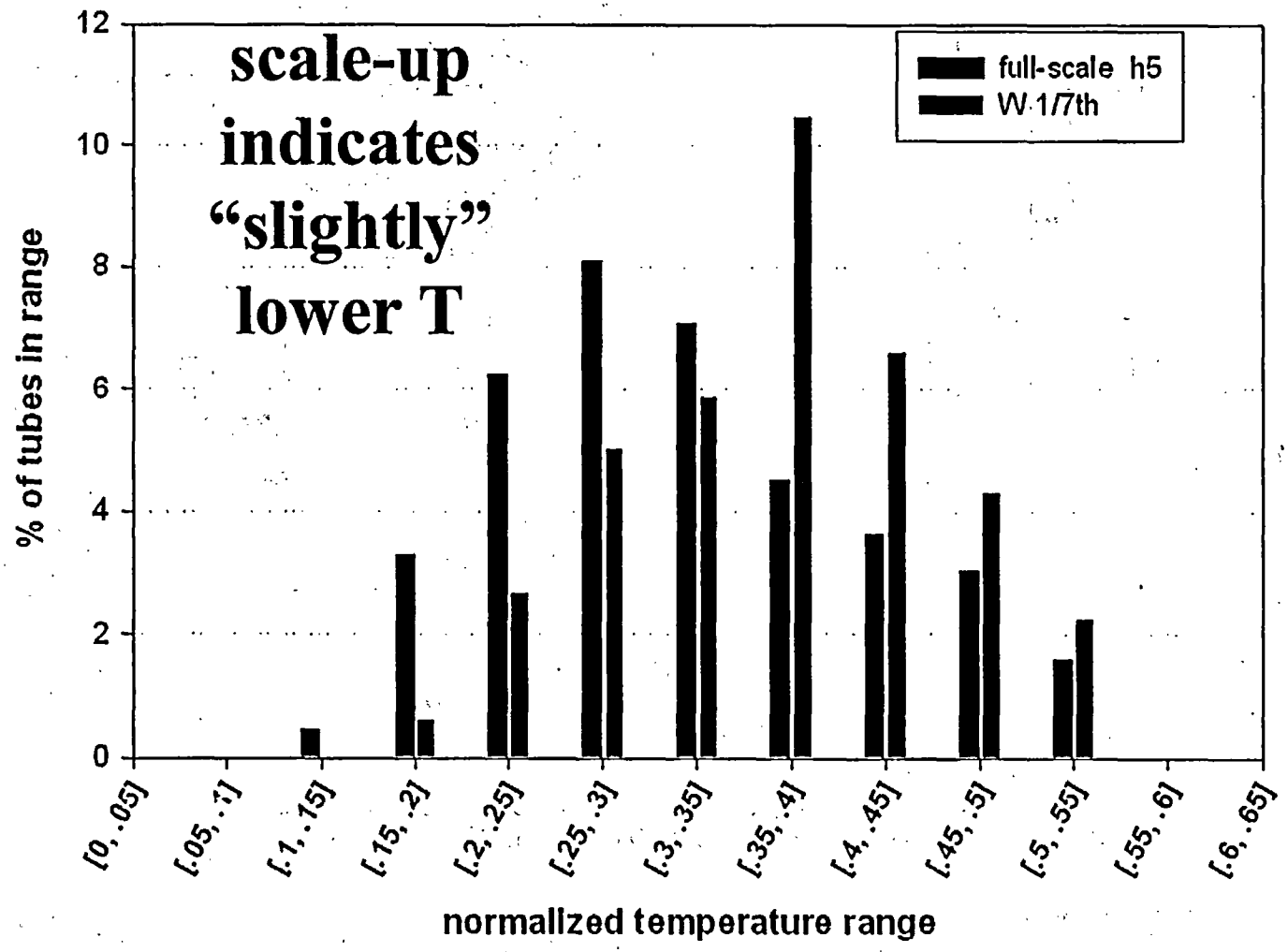
The "Scale-Up" Difference

(comparison of full-scale case with 1/7th scale predictions)

	full-scale h5	1/7th scale case
Tube heat loss (kW)	5047	3.7
m (hot leg flow – kg/s)	4.2	.059
Th (hot leg hot temp)	1404 K	428 K
Tht tubes	1046 K	373 K
mt (tube flow - kg/s)	9.1	0.12
m_t / m_L (recirc. Ratio)	**2.16**	**2.06**
% of Hot Tubes	**38**	**38**
f (mixing fraction)	**.92**	**.81**

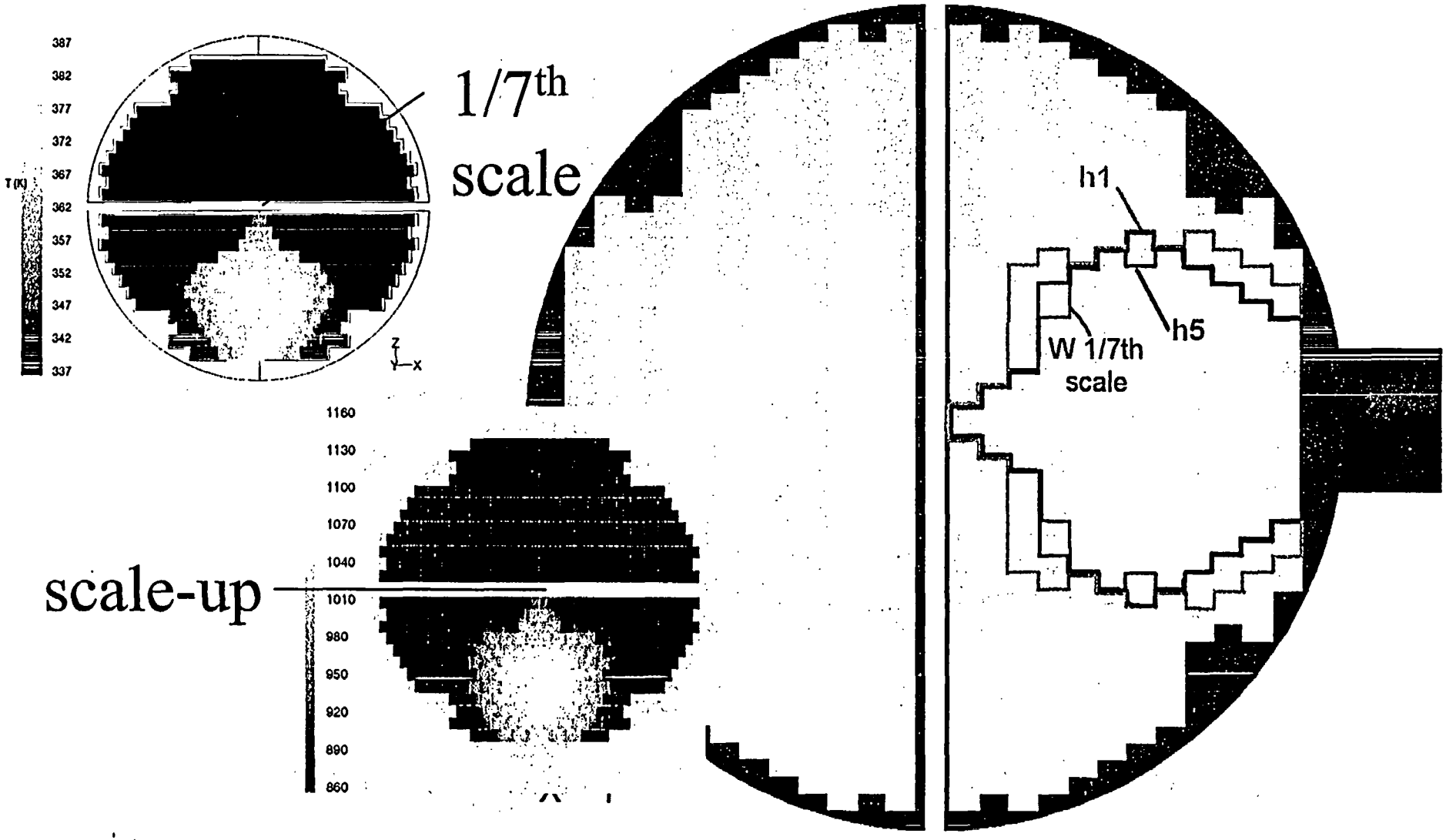
Variation in Tube Entrance Temperatures

1/7th scale vs scale-up predictions



Hot Flow Tube Boundary Predictions

1/7th scale vs Scale-up predictions

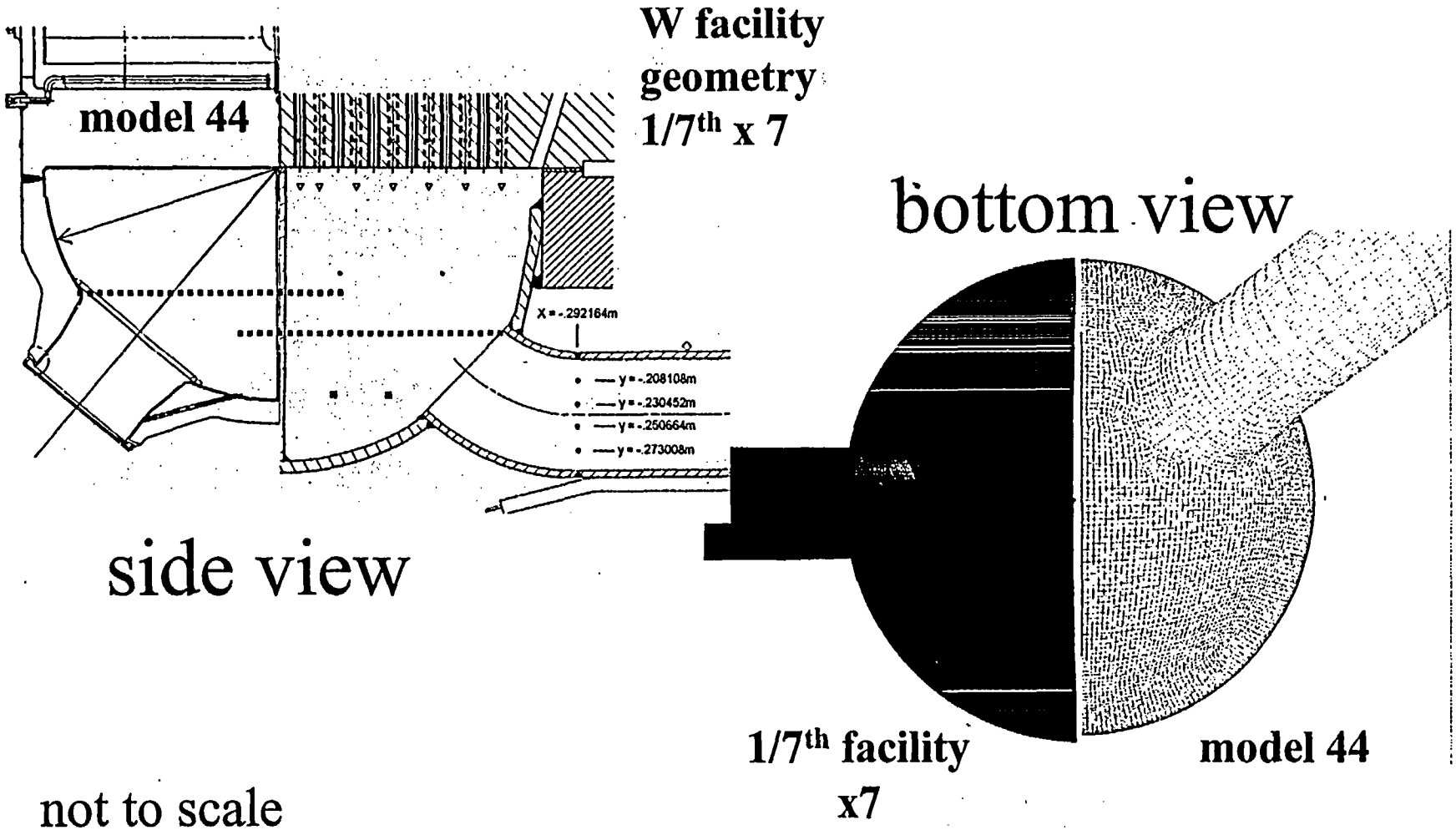


Summary of Step 2 – Scale Up

- The results at full-scale conditions in a geometry similar to the 1/7th scale facility are consistent with the 1/7th scale predictions (when the heat transfer rate from the tubes is consistent).
  - a slight increase in mixing at full-scale conditions is predicted
- The tube bundle heat transfer rate is a significant governing parameter.
- The purpose for these predictions is an isolation of the effect of scale.
  - Next … what is the effect of the geometrical distortion?

CFD Step 3. Predictions for Prototypic Geometry

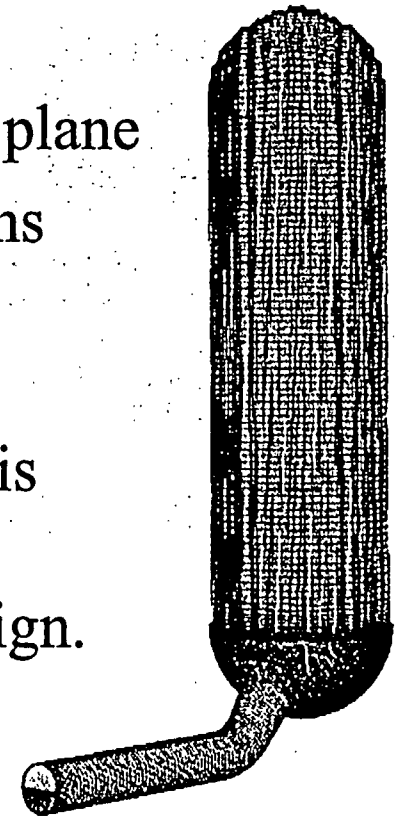
How does the facility geometry impact the results?

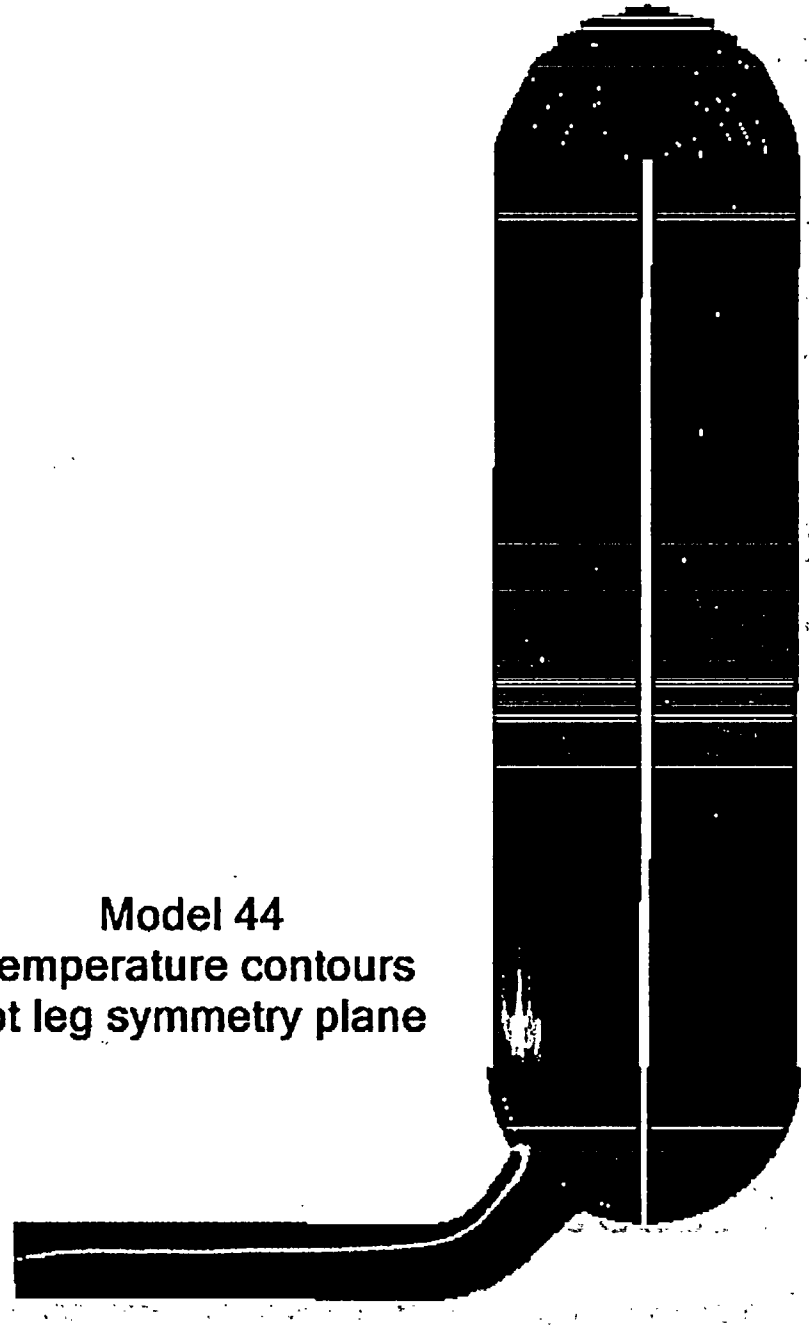


not to scale

CFD Step 3. Westinghouse Model 44 Steam Generator Predictions

- **full-scale** geometry based upon the Westinghouse Model 44 steam generator.
- boundary conditions and material properties from SCDAP/R5 match scale-up model
- 201 individual tube sections, no symmetry plane
- 10^6 computational cells with cell dimensions designed to be consistent with the scale-up model
- <u>**Summary**</u>: A repeat of the scale-up analysis with the geometry modified to represent a prototypical Westinghouse model 44 design.

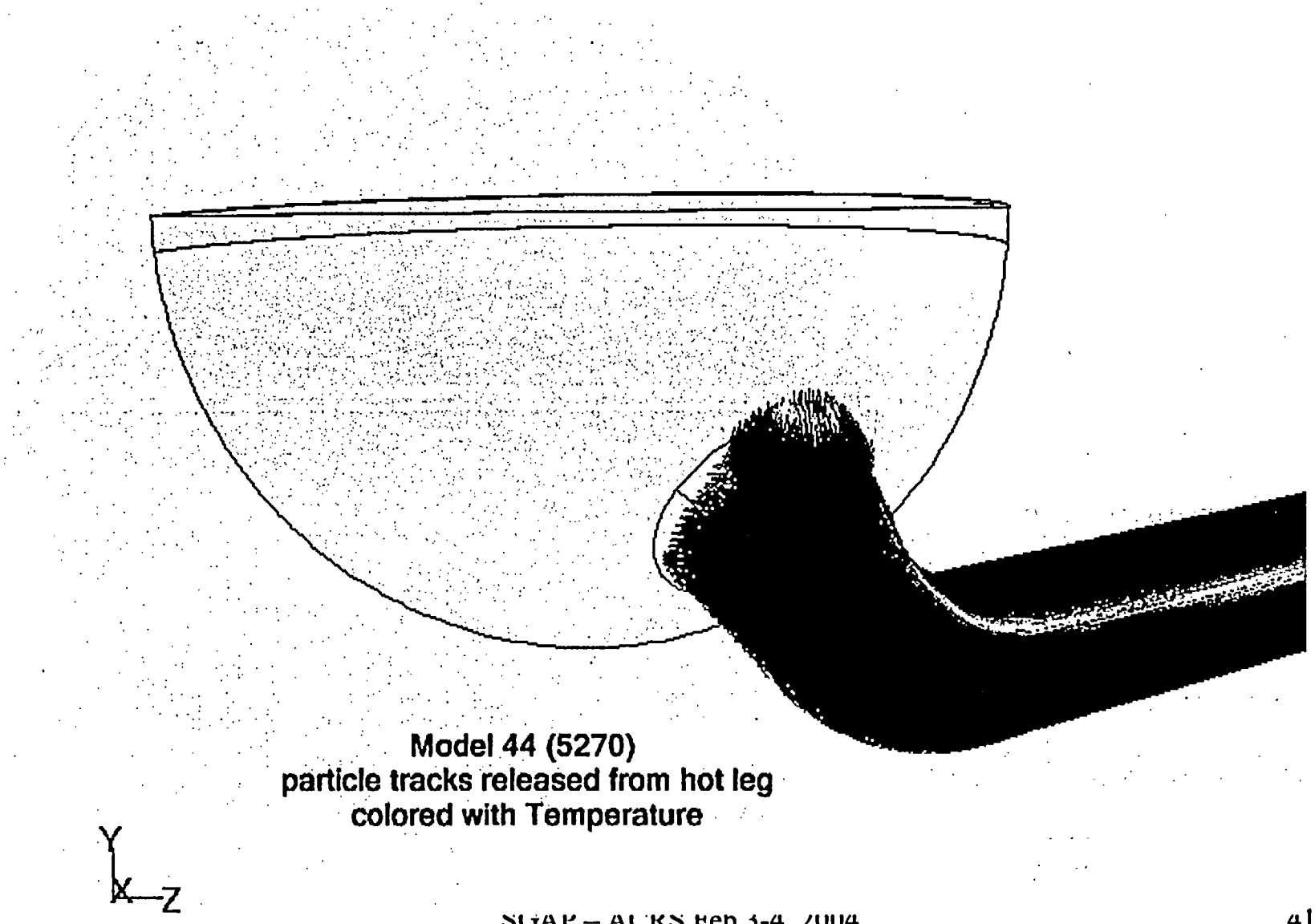


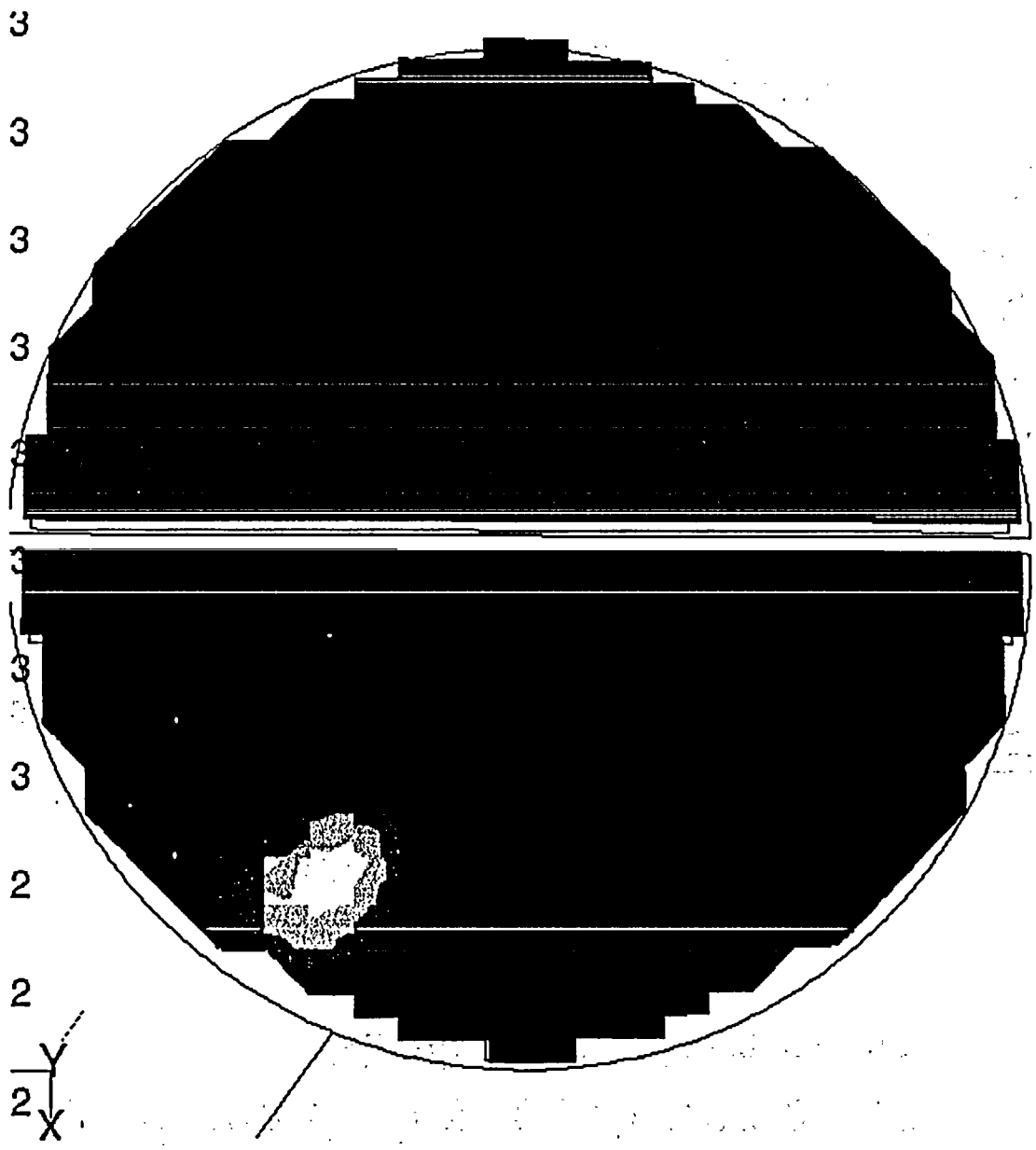


Animated temperature contours on HL symmetry plane (M44)

Animated view of Plume entering M44 Inlet Plenum

(simulated particle tracks released from hot leg)

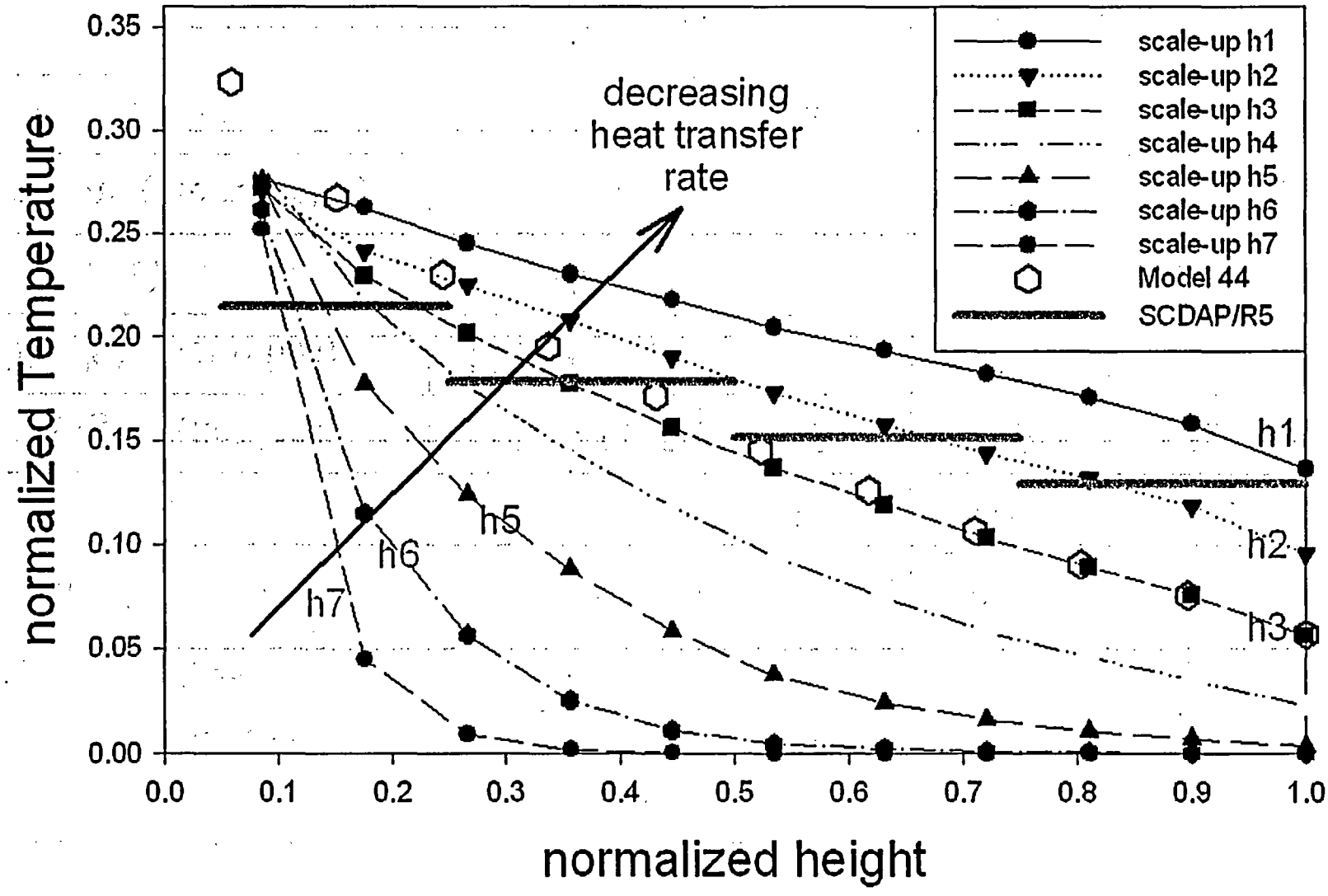




Animated temperature contours

(7 inches above plenum)
Model 44
Zion Conditions

Comparison of Temperature Drop in Tubes



Comparison of Key Mixing Parameters

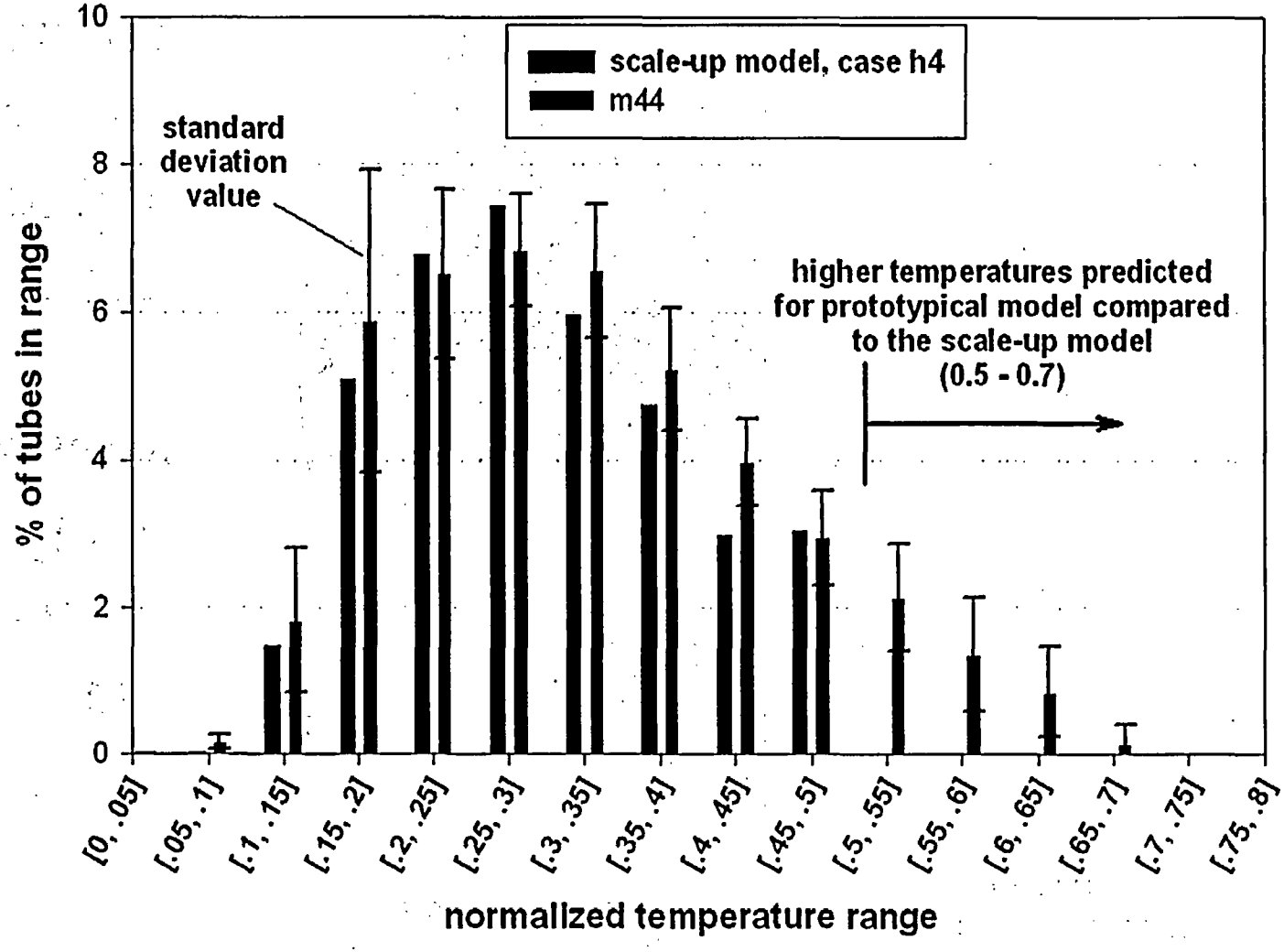
Prediction	**Model 44 (+/- stddev)**	**scale-up h2**	**scale-up h3**	**scale-up h4**
tube heat loss	5515 +/- 52	5426	5400	5310
% hot flow tubes	44 +/- 0.2	44.4	41.7	37.5
T_h (K) (hot leg)	1404 +/- 4	1402	1400	1402
m (kg/s) (hot leg)	4.35 +/- 0.15	4.3	4.3	4.3
T_{ht} (K) (hot tubes)	1049 +/- 12	1018	1020	1033
m_t (kg/s) (hot tubes)	10.7 +/- 0.03	12.7	12.2	10.9
m_t / m (recirc. ratio)	2.5 +/- 0.1	2.94	2.82	2.55
f (mixing fraction)	0.8 +/ .06	.86	.87	.87

higher temperature flow entering the tubes

less mixing in the inlet plenum

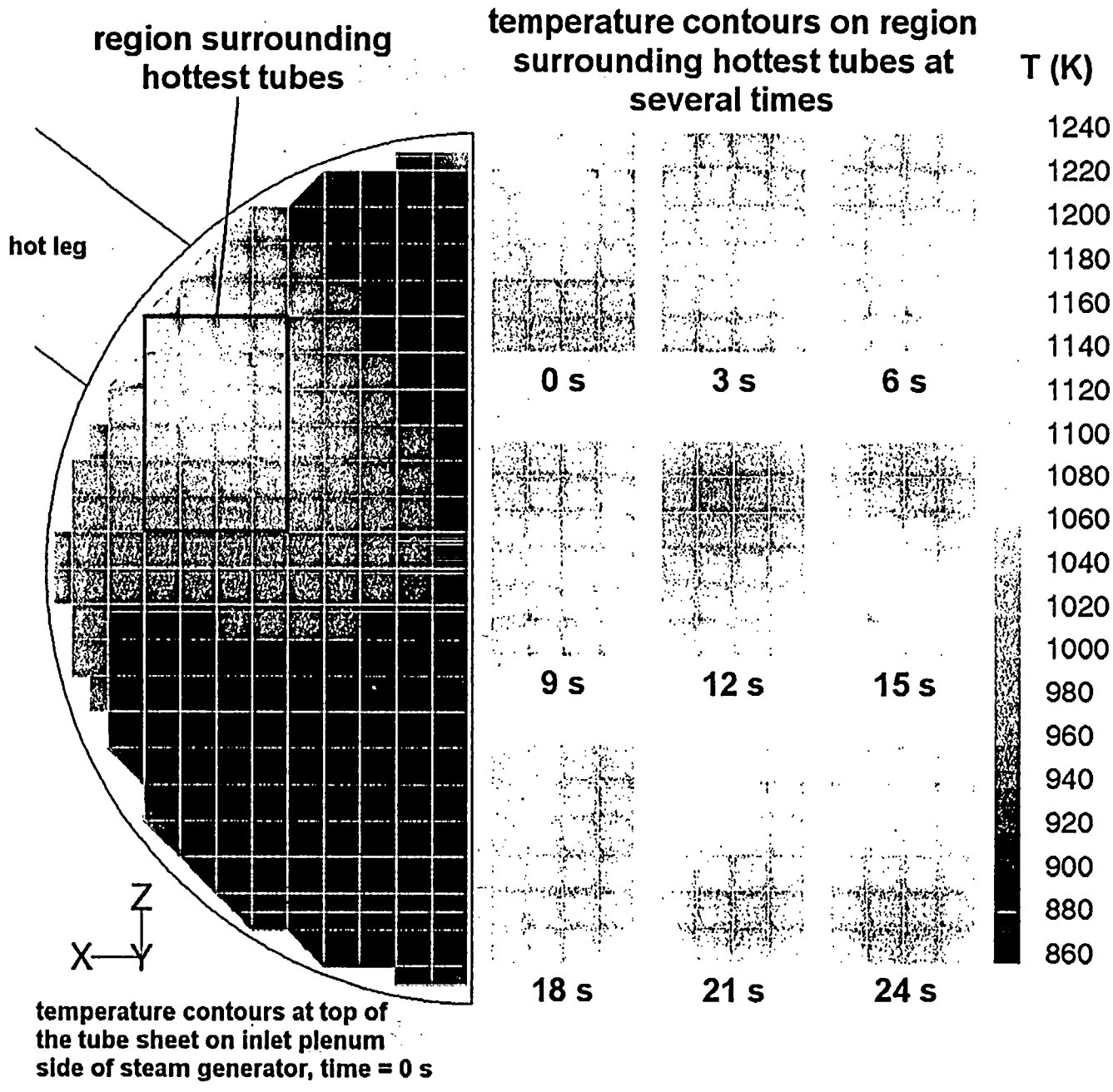
Variation in Tube Entrance Temperatures

Model-44 vs scale-up predictions

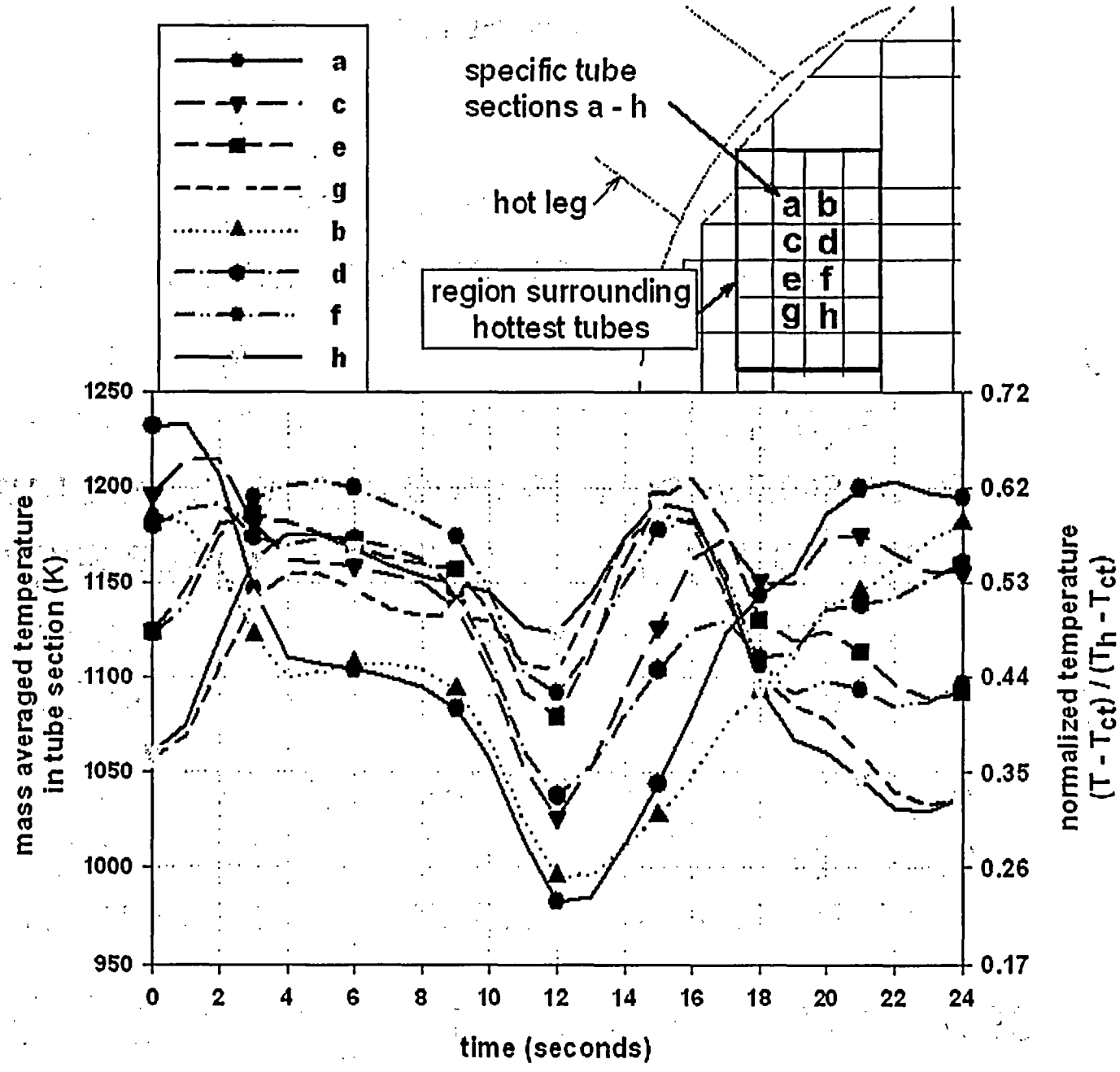


The Histogram alone does not tell the whole story.

The hottest tube region varies in magnitude and location.



Temperature variations with time for the hottest sections of the tube bundle.

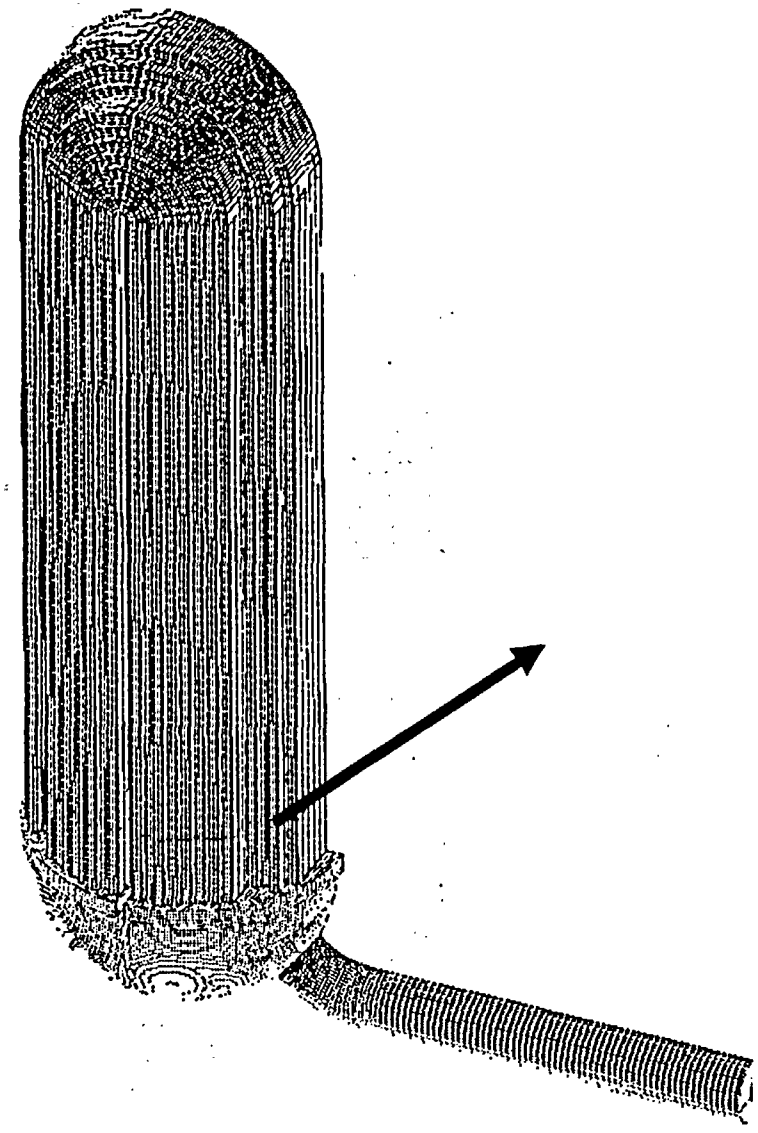


Summary of Step 3 – Model 44 Analysis

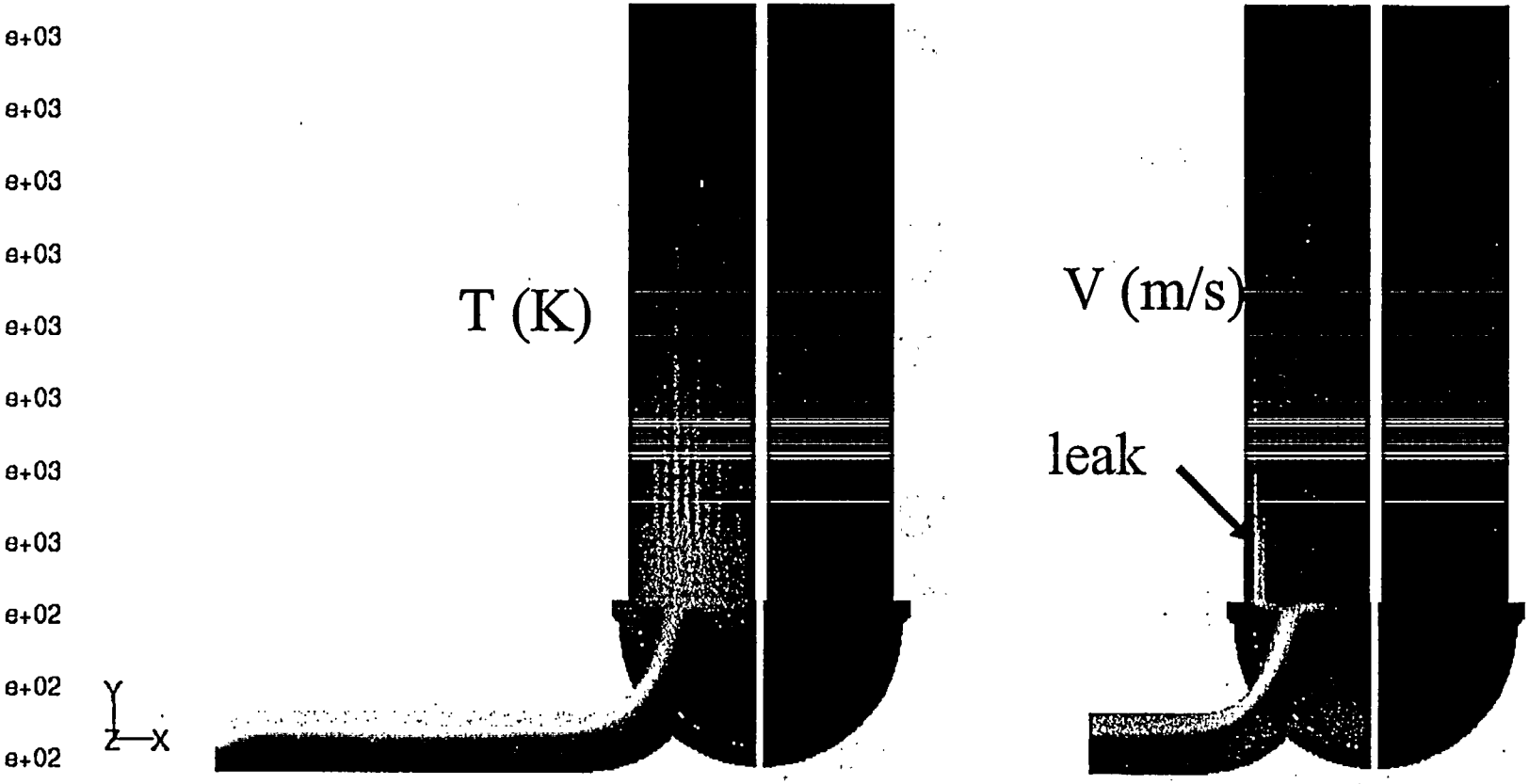
- A different flow pattern in the inlet plenum is observed for the non-symmetric Model 44 design compared to the test facility geometry.
- The hot leg is closer to the tube sheet and a reduced amount of plume mixing is predicted.
- Hotter tubes are predicted but the location and temperature level of the hottest tube varies with time. A more detailed consideration of tube heating is needed.
- Mixing is significant and not too far from what has been assumed based upon the $1/7^{th}$ scale experiments.

CFD Step 4. Tube Leakage Analysis

- **full-scale** geometry and mesh from prior scale-up analysis
- steam – 2400 psia
- re-use boundary conditions from SCDAP/R5 prediction of ZION TMLB'
- tube leakage rates of 0.014, 0.14, 1.4, and 2.8 kg/s span the range for leaks characterized as 1500 gpd to 200 gpm
- 3 leak locations + a distributed leak



Leak Example (1.4 kg/s)

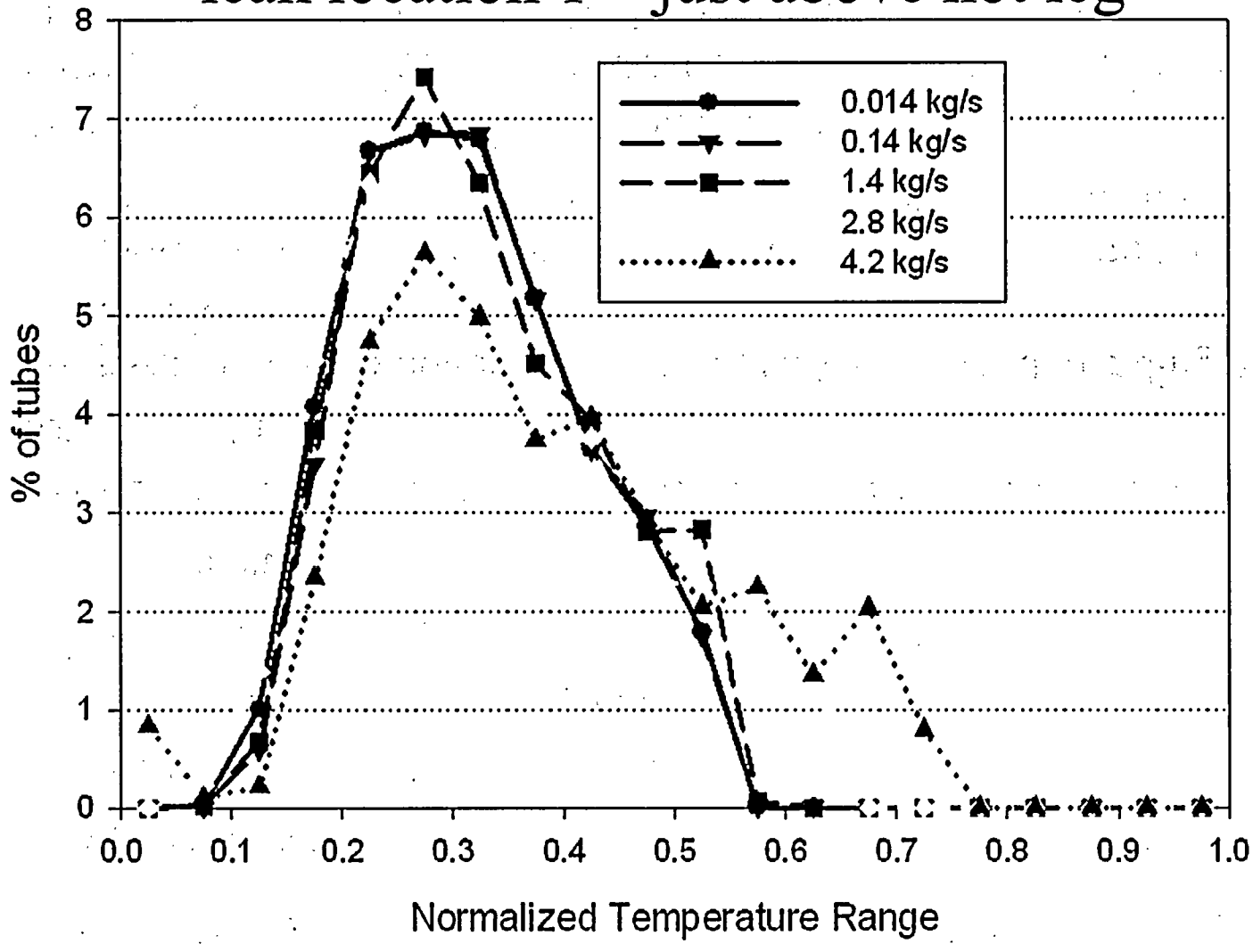


f Static Temperature (k) (Time=1.1811e+03) Mar 04, 2003
FLUENT 6.0 (3d, segregated, RSM, unsteady)

3+03) Mar 04, 2003
FLUENT 6.0 (3d, segregated, RSM, unsteady)

Tube Temperature Variations

leak location 1 – just above hot leg



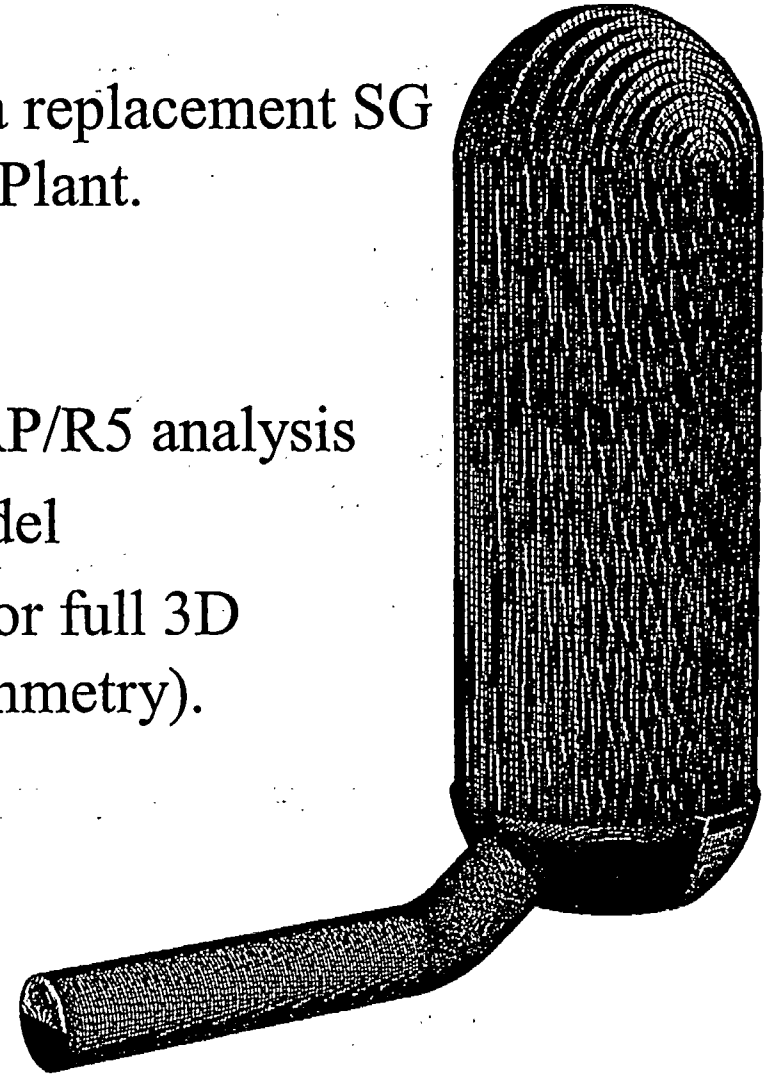
Summary of Step 4 – Leakage Analysis

- Smaller leaks, .014 and 0.14 kg/s showed little effect.
  - 0.14kg/s is less than 2% of 8kg/s tube bundle flow
  - part of the leakage flow comes from the outlet plenum
- Direct inlet plenum bypass is not predicted
  - mixing still occurs
- Some hotter tubes are predicted for the highest tube leakage rates.
  - partially due to hotter gas entering leaking tube (depending on location)
  - more importantly due to reduced mixing resulting from the reduced return flow rate from the cold tubes and in the hot leg
- **Assumption:** The CFD model is isolated. System response to the leak is ignored. Any increase in hot leg flow resulting from the leak is not accounted for.

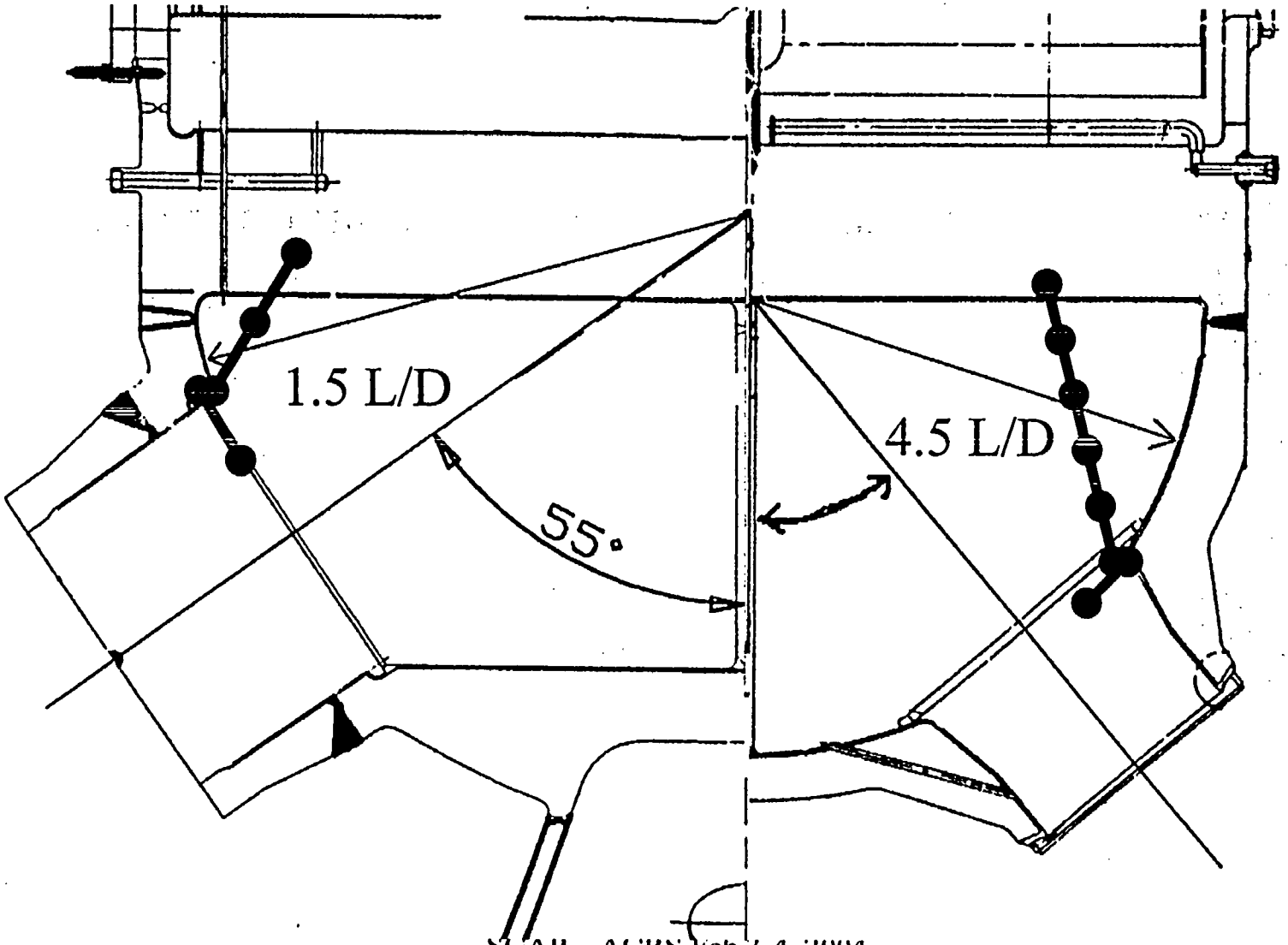
CFD Step 5. Prediction for Combustion Engineering (CE) Steam Generator

- **full-scale** geometry based upon a replacement SG from a Combustion Engineering Plant.
  - 8741 tubes (B&W model)
  - 42 inch hot leg
- boundary conditions from SCDAP/R5 analysis
- 282 individual tubes in CFD model
- 2.6 million computational cells for full 3D model (1.3 million used with symmetry).

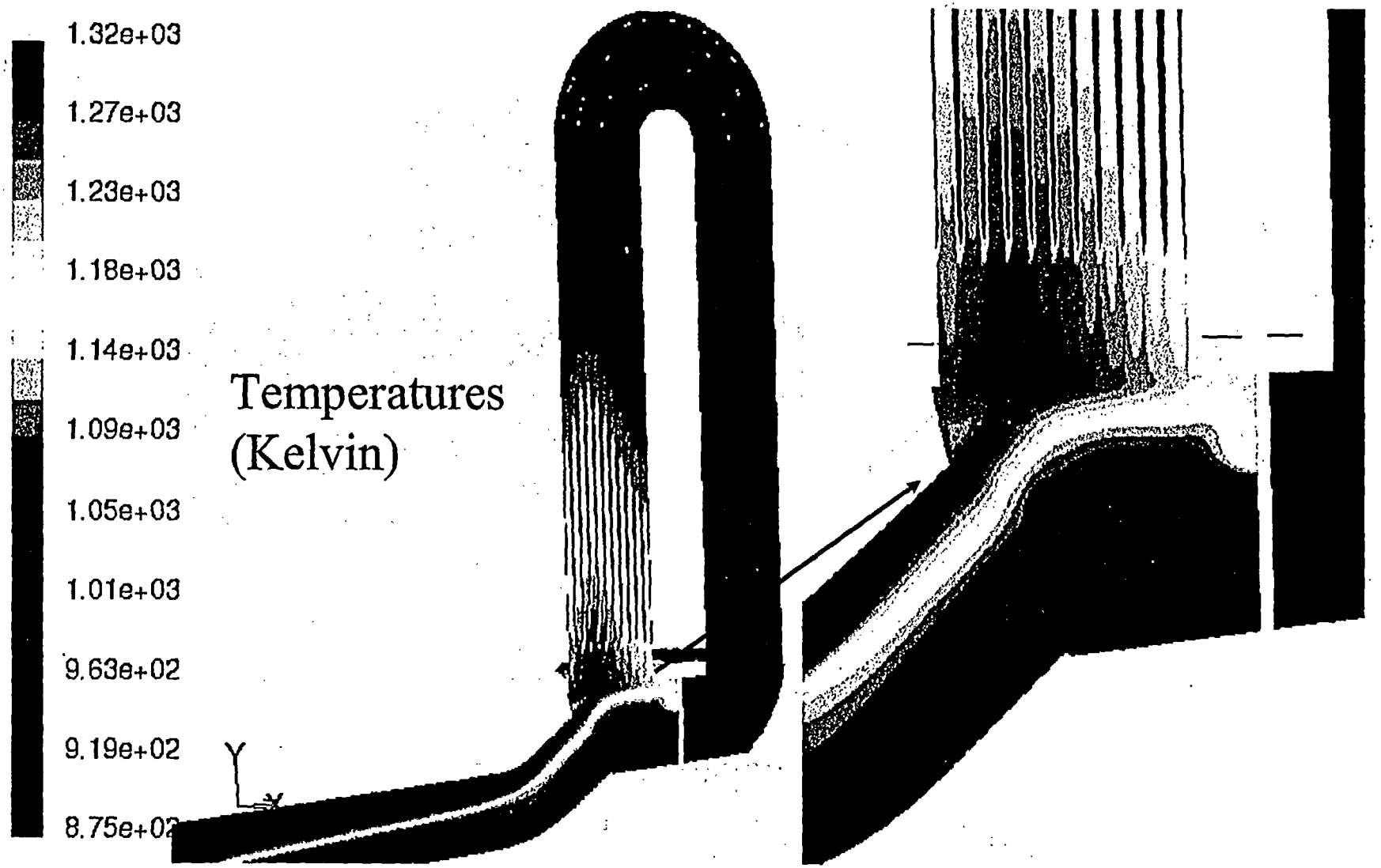
- Significantly different inlet plenum geometry



CE example vs. W-model 51

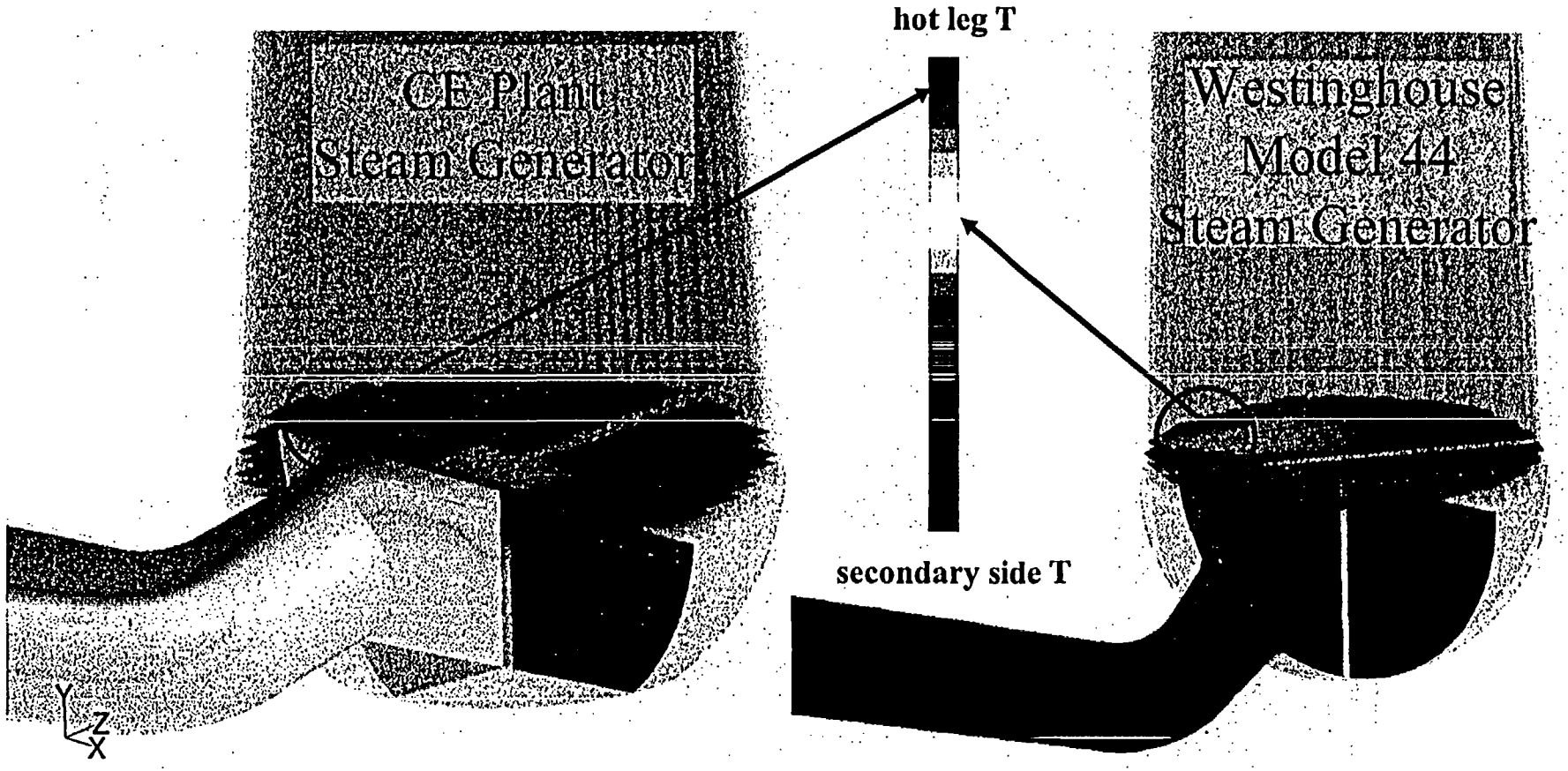


Temperature Contours on Symmetry Plane



Computational Fluid Dynamics Predictions for Westinghouse and CE design Generators

hottest tube region circled

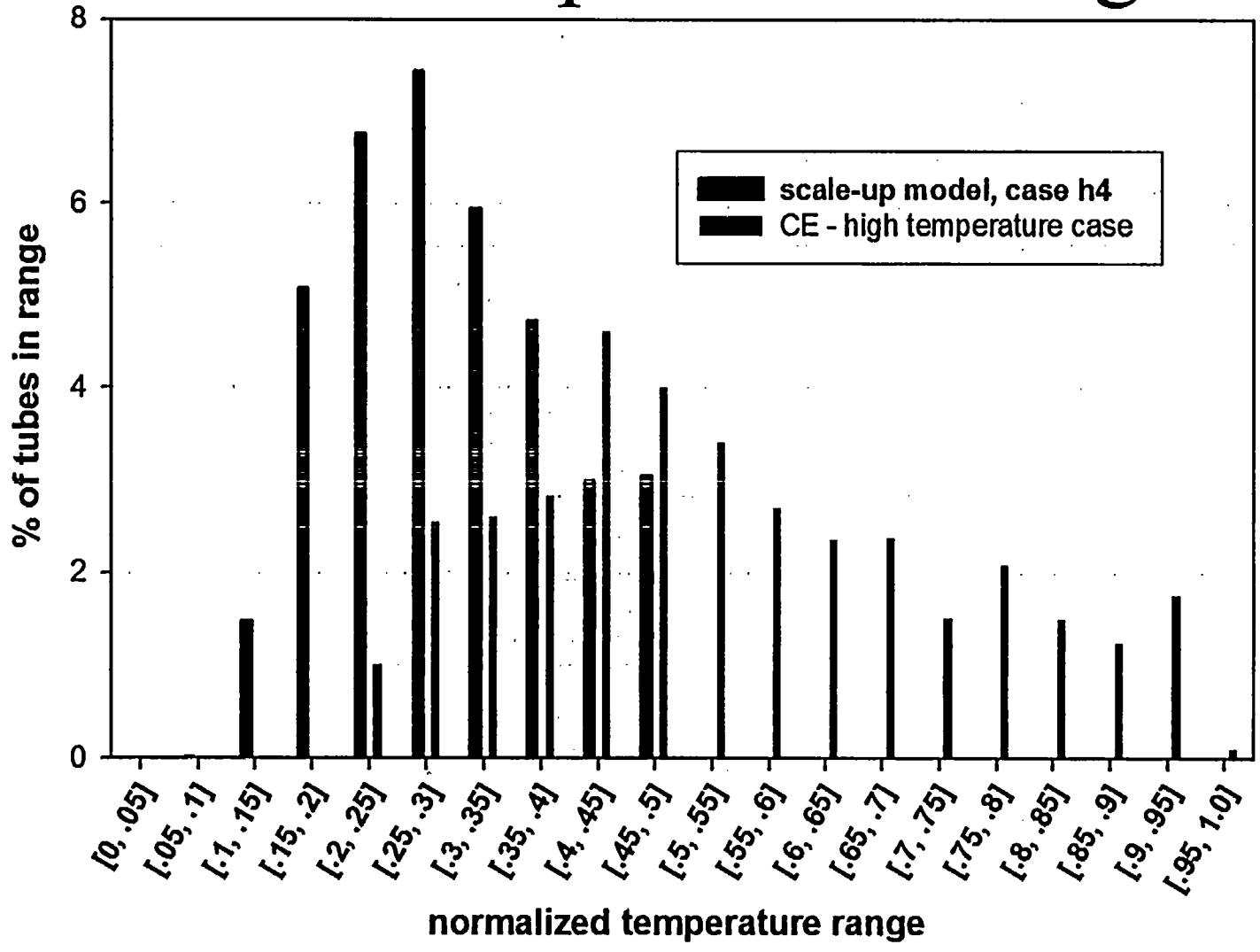


temperature contours on hot leg symmetry plane and 7 inches above the plenum

Comparison of Mixing Parameters

Prediction	**Model 44**	**CE Th = 1284 K**	**CE Th = 985 K**
tube heat loss (kW)	5515 +/- 52	11007	9285
% hot flow tubes	44 +/- 0.2	37	46
T_h (K) (hot leg)	1404 +/- 4	1284	985
m (kg/s) (hot leg)	4.35 +/- 0.15	12.5	16.5
T_{ht} (K) (hot tubes)	1049 +/- 12	1114	871
m_t (kg/s) (hot tubes)	10.7 +/- 0.03	17.9	27.0
m_t / m (recirc. ratio)	2.5 +/- 0.1	1.44	1.64
f (mixing fraction)	0.8 +/ .06	.58	.64

CE Plant Temperature Histogram



Summary of Step 5 – CE Plant Analysis

- Significant variation in inlet plenum geometry compared to the 1/7th scale experiments.
- Significant difference in inlet plenum mixing
- A small portion of the flow reaches the tube entrance with little or no mixing

- SCDAP/R5 analysis is planned for a CE plant with updated mixing assumptions based upon these results.

Summary of CFD predictions for Inlet Plenum Mixing Behavior

- Analysis of 1/7th scale tests provides a level of confidence in the technique.
- Analysis at full-scale conditions for a prototypical Westinghouse SG are complete.
  - Tube-Tube variations predicted
  - Tube temperatures vs time available
- Tube Leakage has been considered. Inlet plenum bypass is not expected. Some overall decrease in mixing at high leakage rates is predicted.
- Inlet plenum mixing is significantly different for a CE design example compared to the Westinghouse data.

Future CFD Related Work

- Hot Leg / Surge Line junction analysis planned
  - Failure models currently using one-dimensional boundary conditions from SCDAP/RELAP5
- Updated predictions during natural circulation flow phase could be completed if needed.

Overview of CFD Results

- The CFD predictions, along with a re-evaluation of the 1/7th scale test data, have been used to provide a better estimate of the inlet plenum mixing parameters.

- Inlet plenum flow and mixing behavior is more clearly understood. Tube-tube variations and the hottest tube temperature are predicted.

- The effect of tube leakage on inlet plenum mixing has been quantified.

- Analysis for a specific CE plant steam generator indicates significantly different mixing than the Westinghouse design.

STEAM GENERATOR ACTION PLAN

SCDAP/RELAP5 ANALYSES OF PWR THERMAL-HYDRAULIC CONDITIONS DURING SEVERE ACCIDENTS

Contributors

USNRC: Chris Boyd, David Bessette, Len Ward, Charles Tinkler

ISL, Inc.: Don Fletcher, Robert Beaton, Bill Arcieri

ACRS Joint Subcommittee Meeting

Rockville, MD

February 4, 2004

Information Systems Laboratories

Purpose of the SCDAP/RELAP5 Thermal-Hydraulic Analysis

- Evaluate the progression of PWR station blackout severe accidents to determine whether SG tubes are expected to fail prior to the failure of other reactor coolant system components

- Failure of primary coolant system piping components (such as the hot legs or pressurizer surge line) causes fission product release to the containment while failure of SG tubes can cause fission product release to the environment

- Risk is therefore affected by the order in which the reactor coolant system component structural failures occur and the top level figure-of-merit for the analysis is the time interval between SG tube and other primary coolant system boundary structural failures

Plant and Accident Descriptions

Plants Investigated

- Zion-1, Westinghouse four-loop PWR
- Calvert Cliffs-1, Combustion Engineering PWR

Accident Event Description: TMLB' Station Blackout

- Loss of off-site power
- Failure of all diesel-electric generators to start and failure of turbine-driven auxiliary feedwater
- Additional failure: stuck-open secondary PORV on the SG in the coolant loop containing the pressurizer

The accident sequence leads to core dryout and heatup at a high reactor coolant pressure, with one SG secondary depressurized

SCDAP/RELAP5 Code Description

RELAP5 solves conservation of mass, momentum and energy equations using a two-fluid (steam/water), nonequilibrium, nonhomogeneous model with a noncondensible gas phase that is tracked with the steam

SCDAP models severe accident plant behavior such as fuel rod heatup, oxidation, ballooning and rupture, fission product release, melting, flow and freezing of materials, and creep rupture failure of structures

The recent calculations have been performed with RELAP5 Version 3.3de, which contains the SCDAP source taken from SCDAP/MOD3.3 Version 3.3ld

Background

INEEL developed SCDAP/RELAP5 system models for several plants, performed calculations for the TMLB'/stuck-open SG PORV event sequence and evaluated the timing of surge line, hot leg and SG tube creep rupture failures

ISL evaluated a series of variations on the INEEL Zion-1 base case accident sequence description (reactor coolant pump shaft seal leakage, SG tube leakage, pressurizer PORV leakage, SG containing the failed secondary PORV)

ISL also evaluated the sensitivity of results to a variety of modeling parameters (time step size, heat structure mesh size, hot leg and SG secondary-side heat transfer)

Background (Continued)

ISL developed an empirical method (based on Westinghouse 1/7-scale test data) for predicting the maximum tube inlet temperature for situations where hot steam enters the SG inlet plenum from the hot leg

Using CFD methods, the NRC re-evaluated the Westinghouse 1/7-scale data set to determine a best estimate set of SG inlet plenum mixing parameters to be assumed in the SCDAP/RELAP5 system analyses

Summary of Current Work Scope

Task 1 - Zion-1 TMLB' SCDAP/RELAP5 Updated Base Case Calculation

Incorporate accident sequence and modeling changes based on findings from prior work and input from other project team members

Establish a new reference case for the project

This task is complete, results are summarized in this presentation

Task 2 - Zion-1 Sensitivity Studies

Perform studies to evaluate the effect on results of variations in plant configuration and operating parameters, natural-circulation mixing process parameters, and modeling parameters

Results will be used for focusing the uncertainty study that follows on the most important of these parameters

This task is nearing completion, preliminary results are summarized in this presentation

Summary of Current Work Scope (Continued)

Task 3 - Uncertainty Study

Evaluate the uncertainty in the Zion TMLB' updated base case calculation results

Currently considering response surface/Monte Carlo approach similar to CSAU

- Response parameter - considering use of Larson-Miller tube stress multiplier as this parameter is used in SCDAP/RELAP5 to determine whether the SG tubes fail before the hot leg or surge line
- Response surface developed for a set of important parameters as defined by the sensitivity studies (Task 2). Considering use of a fractional factorial (or Plackett Burman) experimental design to define the SCDAP/RELAP5 runs needed for developing the response surface.
- Use Monte Carlo sampling to obtain probability distribution for response surface variable
- Plan to use commercial statistical software

This task has not yet started and is scheduled for completion in August 2004

Summary of Current Work Scope (Continued)

Task 4 - Core Melt Progression Sensitivity Studies

Perform studies to evaluate the effect on the Zion base and sensitivity case results of variations in the core heatup and melt progression models

Select and modify key SCDAP/RELAP5 fuel rod heatup and melt progression models and repeat the cases

This task is starting now and is scheduled for completion such that the results can be used for defining additional independent variables for the uncertainty study in Task 3

Task 5 - Iterative Support for PRA

Support the PRA decision-making process for the project by providing engineering judgements (based on analyses performed to date) and new calculations regarding thermal-hydraulic plant response to variations in the the accident-scenario assumptions

This task has not yet started and will be scheduled as needed to support the PRA effort

Summary of Current Work Scope (Continued)

Task 6 - Additional Zion Calculations to Support PRA

Perform additional Zion-1 TMLB' calculations using revised accident sequence assumptions based on the PRA results

This task has not yet started and will be performed once PRA results have been generated

Task 7 - Calvert Cliffs Analyses

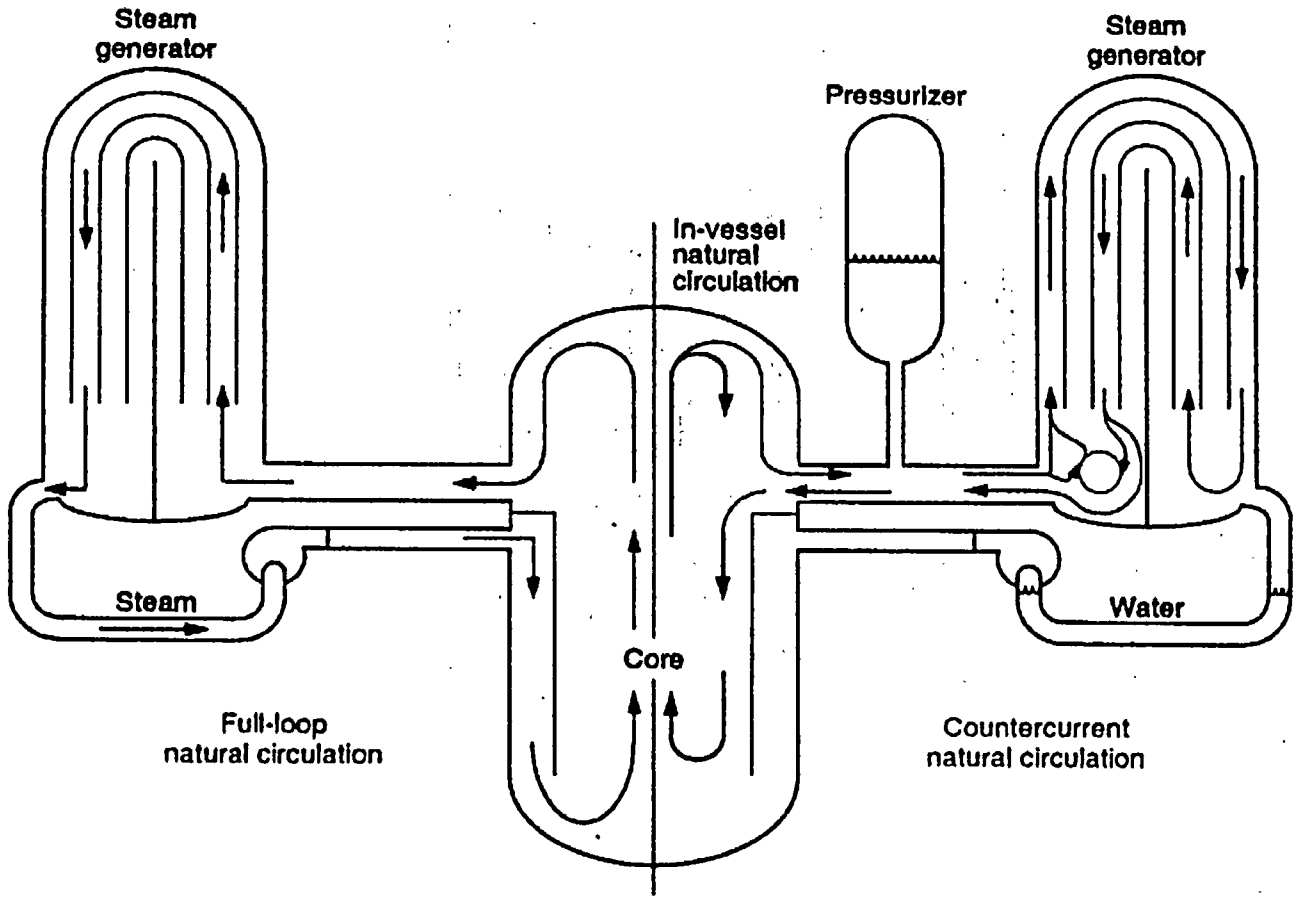
Revise the existing Calvert Cliffs-1 SCDAP/RELAP5 model for consistency with the final Zion-1 base case modeling approach

Revise the plenum-mixing parameter assumptions based on CFD analyses for the full-scale Calvert Cliffs hot leg/SG inlet plenum configuration

Perform a Calvert Cliffs TMLB' SCDAP/RELAP5 base case calculation and selected sensitivity calculations

This task is starting now and is scheduled for completion in June 2004

Natural Circulation Flow Patterns that Develop Following Severe Accidents in PWRs with U-Tube SGs and Cold Leg Loop Seals Blocked With Liquid



Zion SCDAP/RELAP5 Reactor Vessel Nodalization

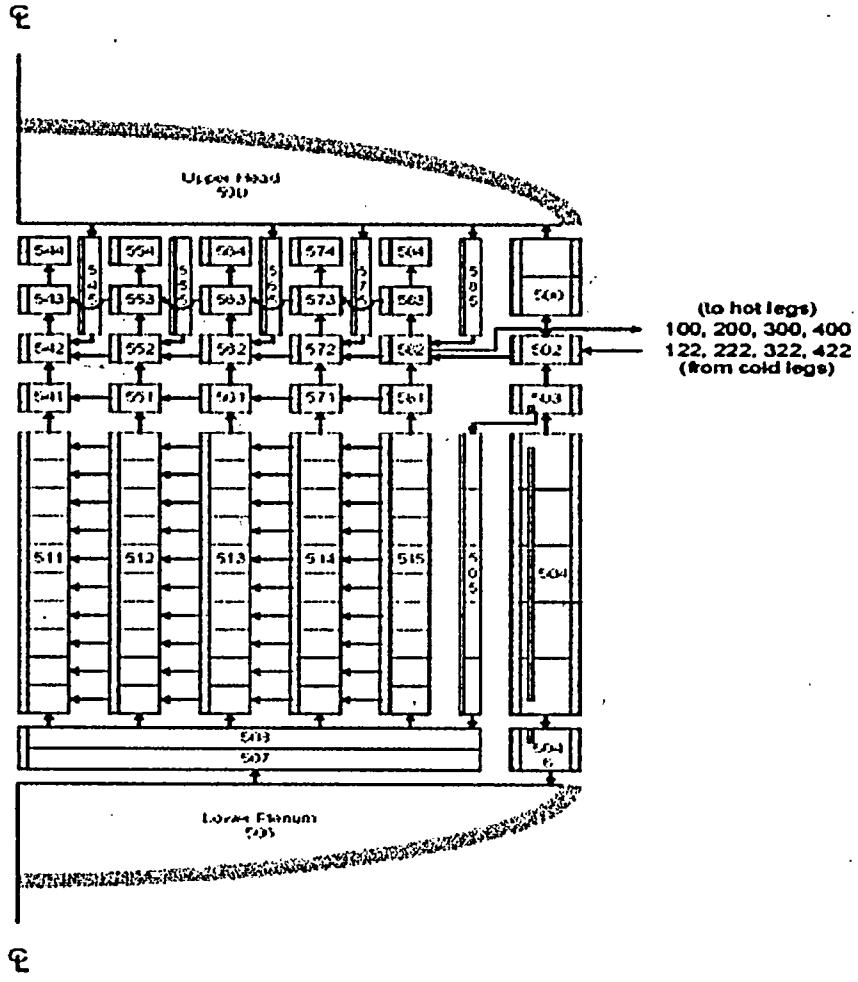


Figure 1. Zion Reactor Vessel Nodalization

Zion SCDAP/RELAP5 Nodalization of Coolant Loop 1 (Pressurizer Loop) Used Before Core Heatup Period

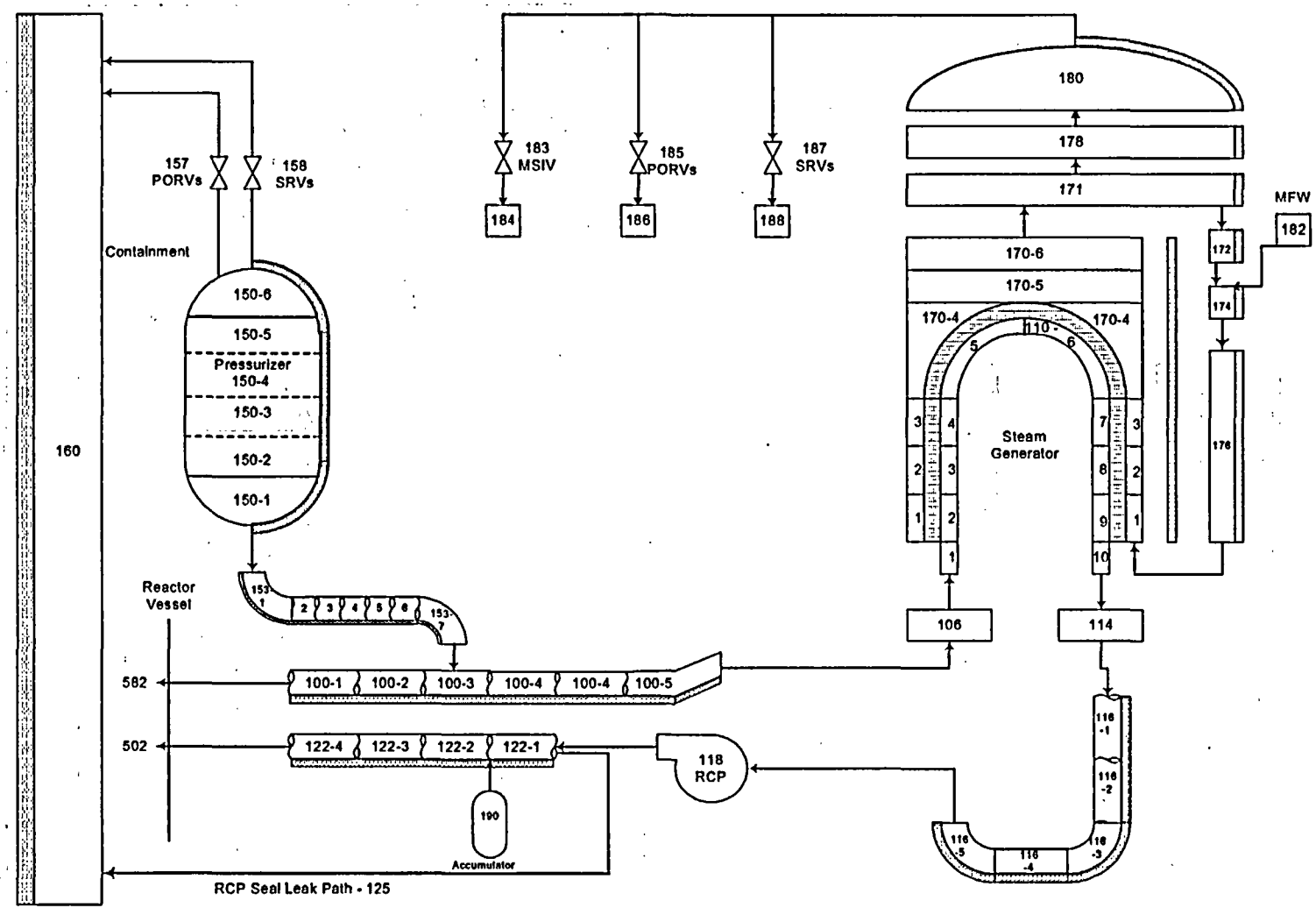


Figure 2. Zion Loop Nodalization Excluding Provisions for Hot Leg Countercurrent Natural Circulation

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Zion SCDAP/RELAP5 Nodalization of Coolant Loop 1 (Pressurizer Loop) Used During Core Heatup Period

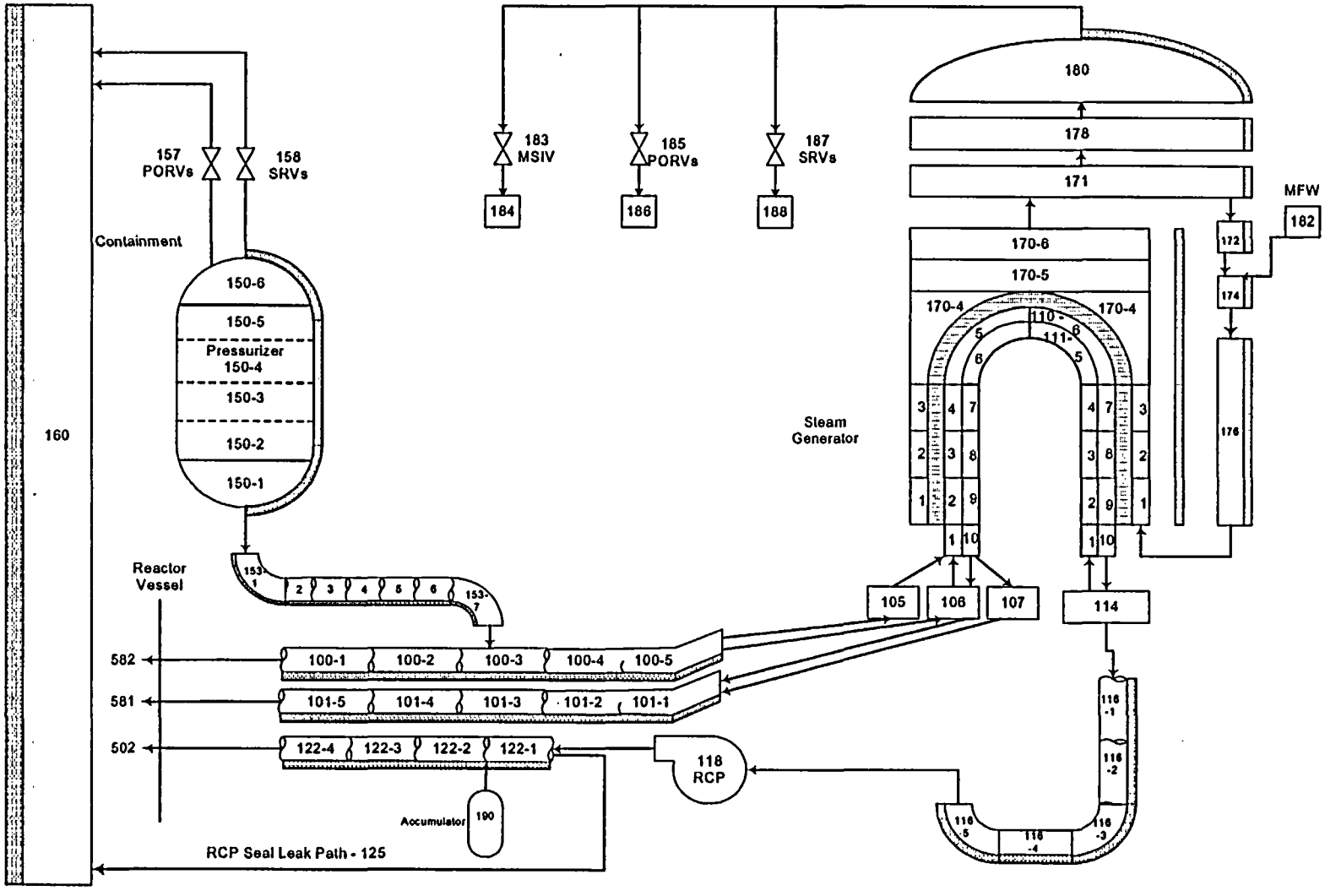


Figure 3. Zion Loop Nodalization with Provisions for Hot Leg Countercurrent Natural Circulation

SCDAP/RELAP5 Zion Model Changes Implemented for TMLB' Updated Base Case

- Expanded nodalization in reactor vessel lower plenum region to improve liquid level behavior during the core dryout period
- Revised structure material properties data for carbon steel, stainless steel and Inconel to agree with reference sources
- Added reactor coolant system heat losses to containment from exterior surfaces of primary and secondary coolant system boundary heat structures
- Added reactor coolant pump shaft seal leakage starting at transient event initiation (21 gpm per pump initial leakage rate)
- Added countercurrent flow limiting model at the pressurizer-to-surge line connection

SCDAP/RELAP5 Zion Model Changes Implemented for TMLB' Updated Base Case (Continued)

- Expanded number of radial mesh points in important heat structure component models
- Changed SG tube plugging assumption from 15% to 10% (middle of 0%-to-20% expected plant operating range)
- Added thermal radiation modeling
  - Wall-to-wall radiation between inner surfaces of upper and lower hot leg piping wall heat structures
  - Steam-to-wall radiation to internal surfaces of reactor coolant and steam generator secondary systems
- Changed modeling assumption for forward/reverse SG tube flow split from 53%/47% to 50%/50% based on reevaluation of the Westinghouse 1/7-scale test data

SCDAP/RELAP5 Zion Model Changes Implemented for TMLB' Updated Base Case (Continued)

- Revised SG inlet plenum mixing parameter assumptions based on reevaluation of the Westinghouse 1/7-scale test data and CFD predictions at full scale
  - Recirculation ratio target value changed from 1.9 to 2.75
  - Hot mixing fraction target value changed from 0.87 to 0.81
  - Cold mixing fraction target value changed from 0.87 to 0.81
  - SG power fraction target values left unchanged at 0.0756 per SG

SCDAP/RELAP5 Zion Model Changes Implemented for TMLB' Updated Base Case (Continued)

- Added SG-1 hottest tube hydrodynamic, heat structure and creep rupture modeling
  - Hottest tube inlet velocity and outlet pressure based on calculated average-tube response
  - Thermal conditions and heat transfer on hottest tube wall outer surface calculated based on average SG secondary conditions
  - Hottest tube inlet steam temperature calculated based on Normalized Temperature Ratio (NTR), relating the tube inlet steam temperature as a function of the upper hot leg and cold SG tube return steam temperatures
  - $NTR = (T_{hottest\ tube} - T_{cold\ tube}) / (T_{hot\ leg} / T_{cold\ tube})$
  - Model assumes a NTR of 0.625 based on CFD predictions for the Zion hot leg and SG inlet plenum configuration at full scale (revised from 0.4737 in prior calculations)

Comparison of Calculated and Target SG Inlet Plenum Mixing Parameters

Parameter	Target Value	SCDAP/ RELAP5 Value
Hot / Cold Split of SG Tube Region	50% / 50%	50% / 50%
Fraction of Core Energy Absorbed in each SG	0.0756	0.0747
SG Inlet Plenum Hot Mixing Fraction (fraction of upper hot leg flow going to SG inlet mixing plenum)	0.81	0.812
SG Inlet Plenum Cold Mixing Fraction (fraction of cold return tube flow going to SG inlet mixing plenum)	0.81	0.808
Recirculation Ratio (ratio of SG tube flow to hot leg flow)	2.75	2.785

Comparison of Zion Plant and SCDAP/RELAP5 Calculated Full-Power Steady-State Parameters Shows Excellent Agreement

Parameter	Plant Value	SCDAP/RELAP5 Value
Reactor Power (MWt)	3,250	3,250
Pressurizer Pressure (MPa)	15.51	15.509
Pressurizer Water/Steam Volumes (%)	60 / 40	61.2 / 38.8
Total RCS Coolant Loop Flow Rate (kg/s)	17,010	17,010
Cold Leg Temperature (K)	549.9	549.91
Hot Leg Temperature (K)	585.5	585.47
SG Secondary Pressure (MPa)	4.964	4.804
Feedwater Temperature (K)	493.5	493.48
Steam Flow Rate per SG (kg/s)	440.9	439.6
Liquid Volume per SG (m^3)	52.05	52.57

SCDAP/RELAP5 Calculated Sequence of Events for Zion TMLB' Updated Base Case

Event Description	Event Time (seconds)
TMLB' station blackout event initiation Loss of AC power, reactor/turbine trips, reactor coolant pump trip, reactor coolant pump shaft seal leakage begins, loss of all feedwater	0
Reactor coolant pump coast-down complete, loop natural circulation begins	111
First opening of pressurizer PORV	170
SG 1 secondary PORV assumed to fail open upon first challenge	190
SG secondary dry-out	1,606 SG 1 5,586 SGs 2, 3 & 4
Period of continual pressurizer PORV cycling begins	6,750
Collapsed liquid level falls below top of core fuel heated length	7,888
First opening of pressurizer SRV	8,510

SCDAP/RELAP5 Calculated Sequence of Events for Zion TMLB' Updated Base Case (Continued)

Event Description	Event Time (seconds)
Coolant loop natural circulation flow interrupted	8,560 Loop 1
	8,478 Loop 2
	8,421 Loop 3
	8,546 Loop 4
Steam at core exit begins to superheat (hot leg/SG countercurrent circulation begins)	9,062
Collapsed liquid level falls below bottom of core fuel heated length	10,039
Onset of fuel rod oxidation	10,406
Pressurizer empties	10,606
First control rod cladding rupture	11,895
First creep rupture failure of SG 1 hottest tube (7.5 Larsen-Miller stress multiplier)	12,240
First fuel rod cladding rupture	12,974

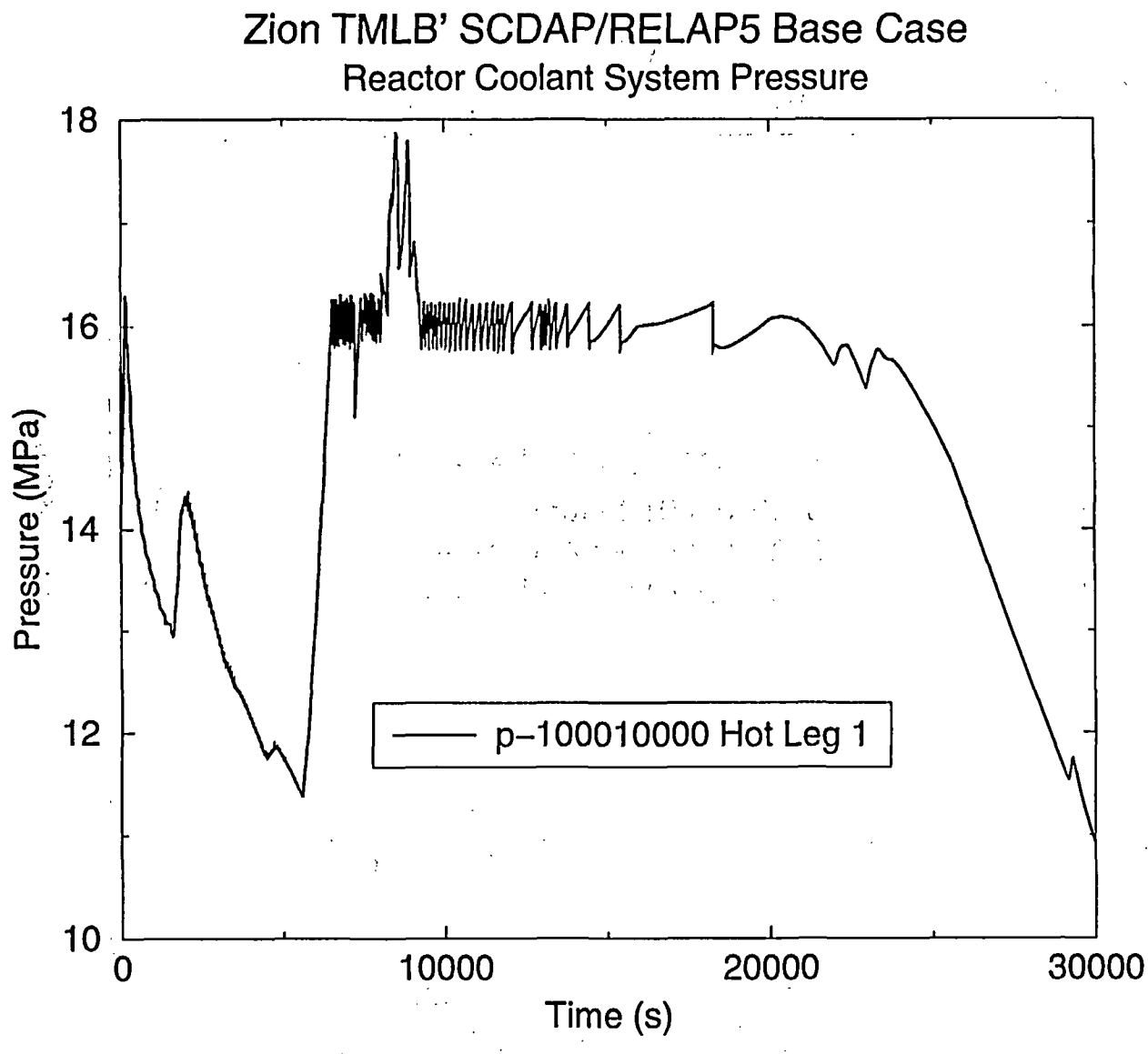
SCDAP/RELAP5 Calculated Sequence of Events for Zion TMLB' Updated Base Case (Continued)

Event Description	Event Time (seconds)
First creep rupture failure of SG 1 average tube (7.5 Larsen-Miller stress multiplier)	13,165
Pressurizer surge line fails by creep rupture	13,205
Last creep rupture failure of SG 1 hottest tube (1.0 Larsen-Miller stress multiplier)	13,420
Hot legs fail by creep rupture	13,845 Hot Leg 1 14,025 Hot Legs 2, 3 & 4
Last creep rupture failure of SG 1 average tube (1.0 Larsen-Miller stress multiplier)	17,020
First relocation of zirconium and steel to reactor vessel lower head (from control rod cladding and guide tube reaction)	21,976
End of calculation	30,000

Calculated Structure Creep Rupture Failure Times for Zion TMLB' Updated Base Case

Structure	Failure Times (seconds)
Pressurizer Surge Line	13,205
Hot Leg 1	13,845
Hot Legs 2, 3 & 4	14,025

SG 1 Tubes with Larsen-Miller Stress Multiplier of:	Average Tube	Hottest Tube
1.0	17,020	13,420
1.5	15,035	13,220
2.0	14,170	13,140
2.5	13,740	13,070
3.0	13,500	12,805
3.5	13,365	12,560
4.0	13,275	12,405
4.5	13,225	12,320
5.0	13,200	12,280
5.5	13,185	12,260
6.0	13,175	12,250
6.5	13,170	12,245
7.0	13,165	12,240
7.5	13,165	12,240



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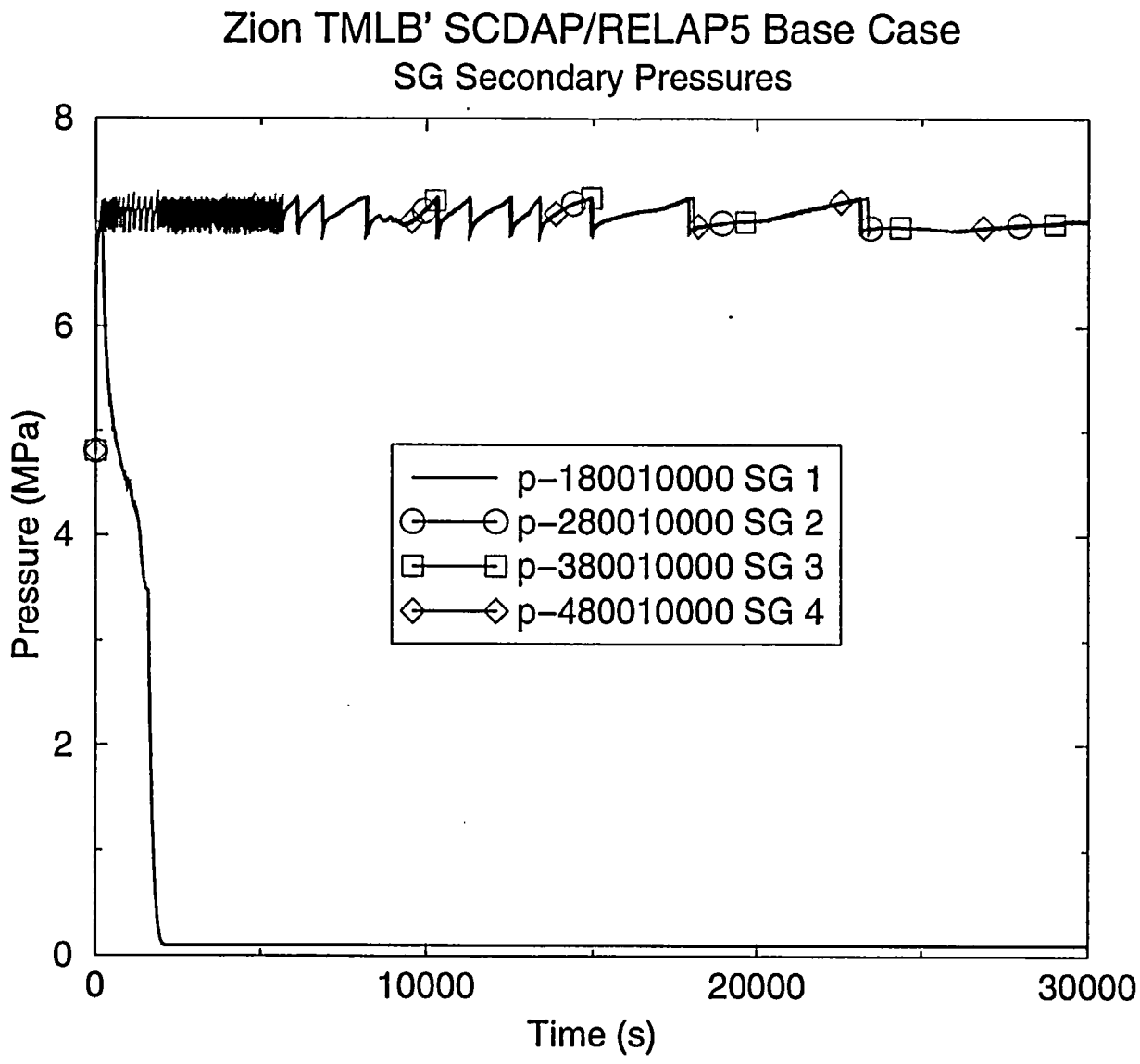

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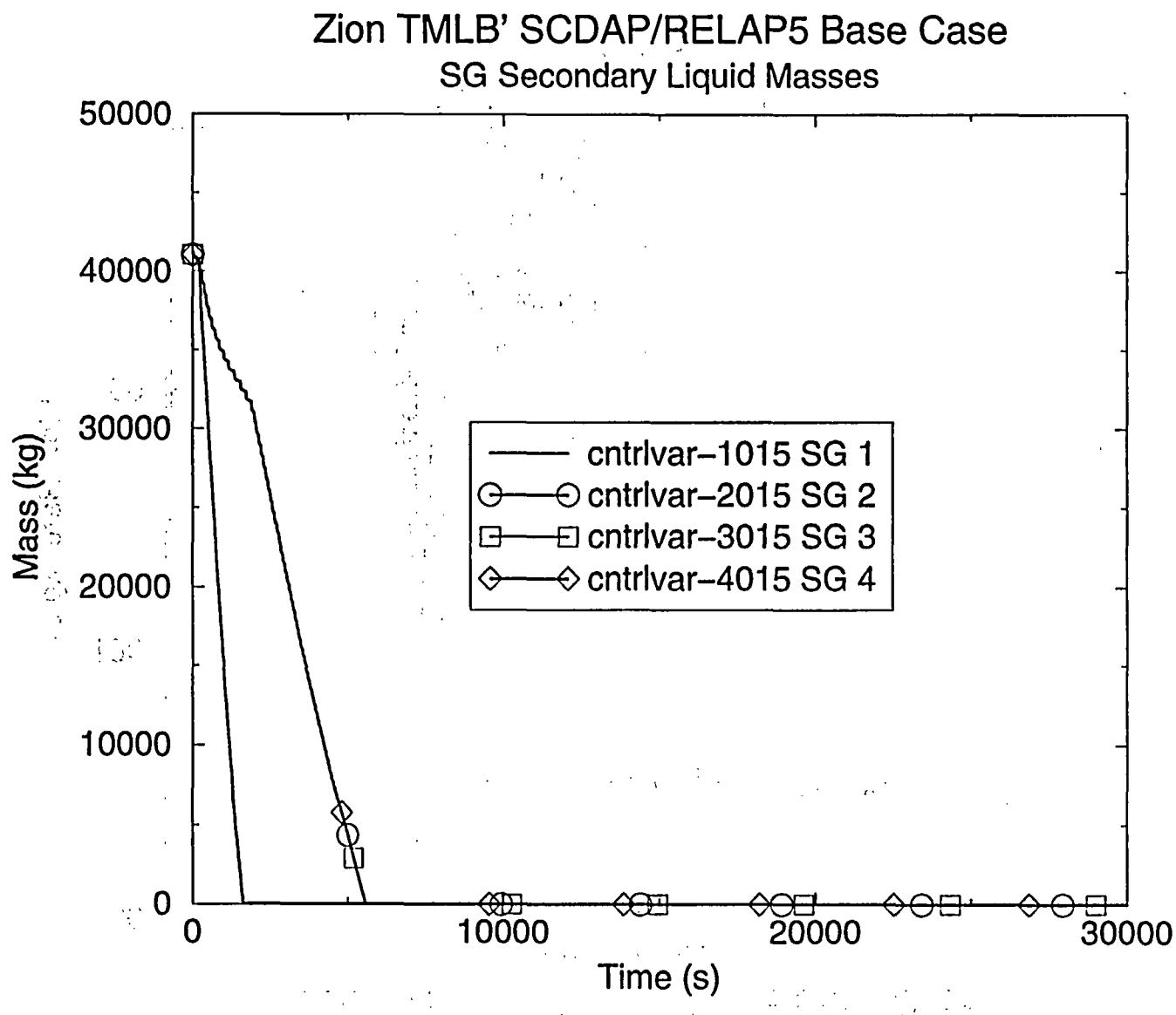

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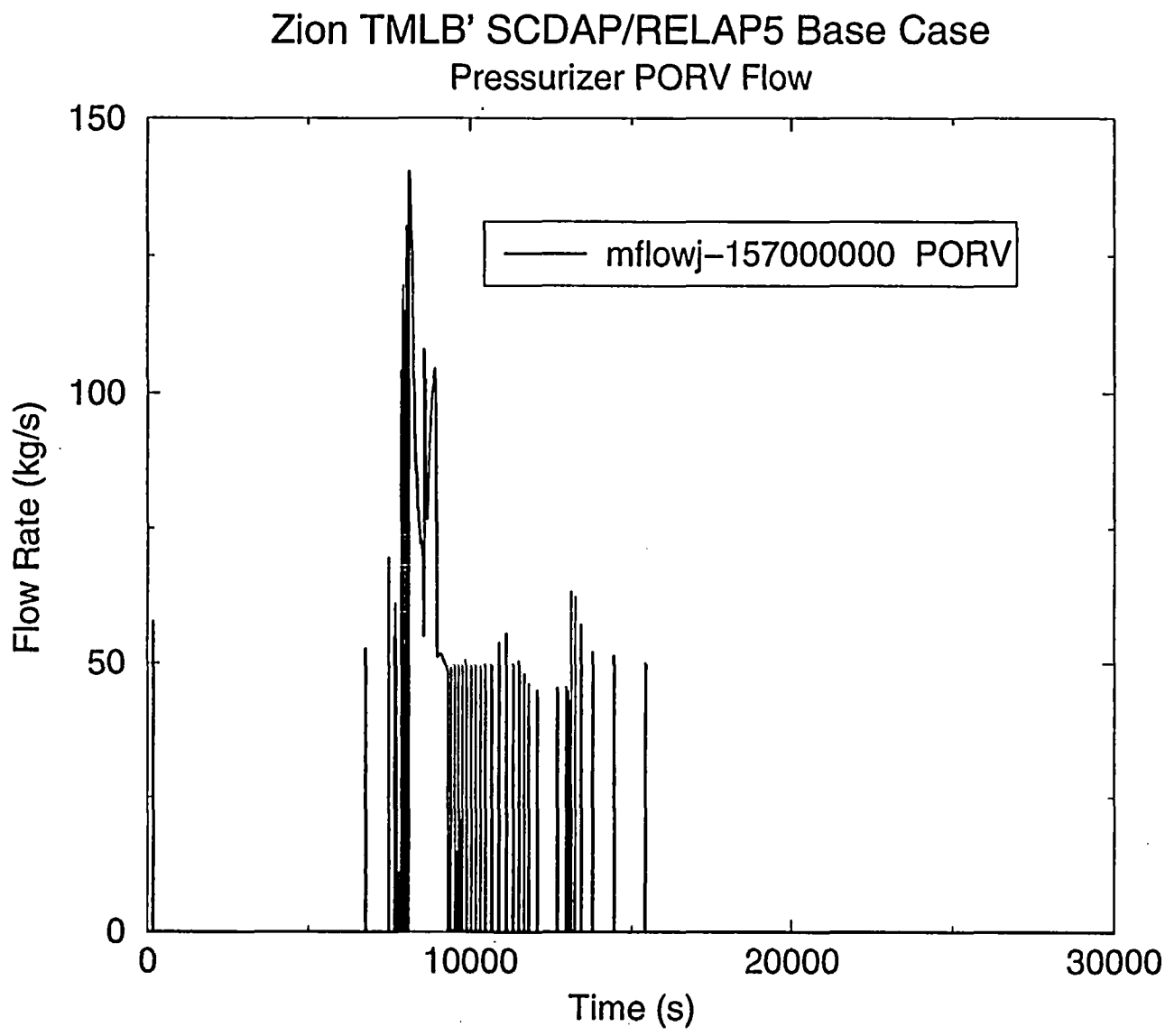

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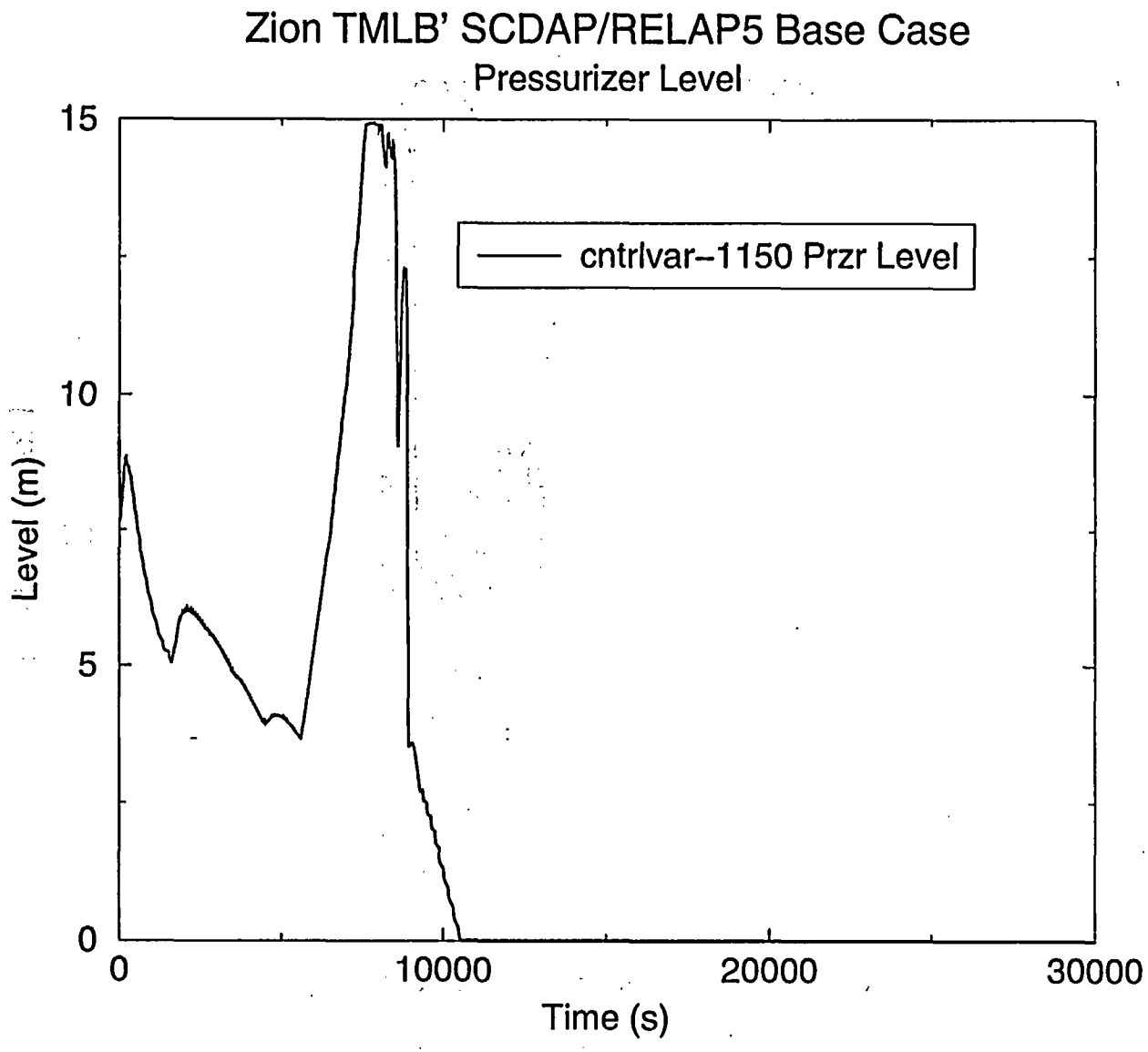

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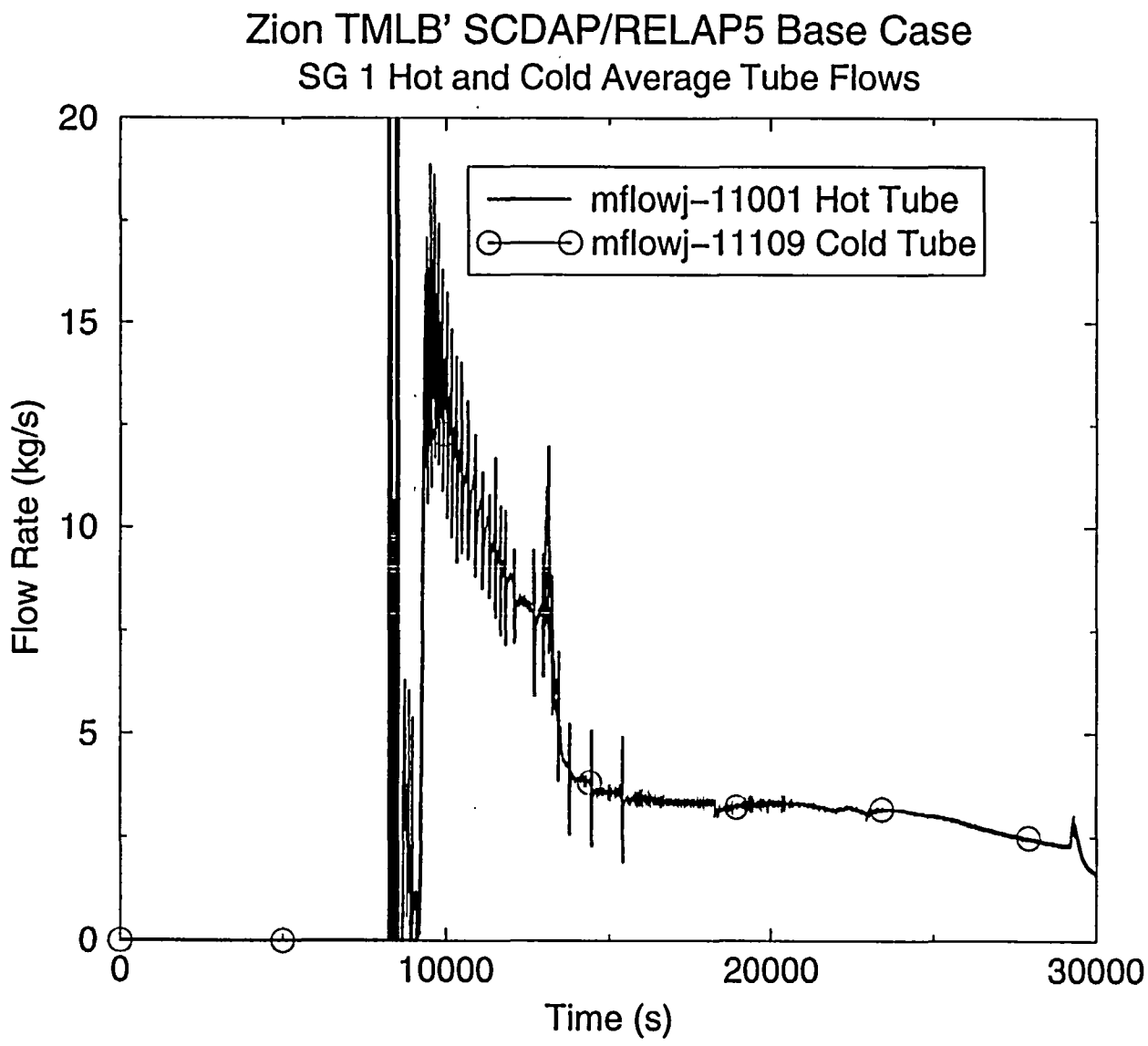

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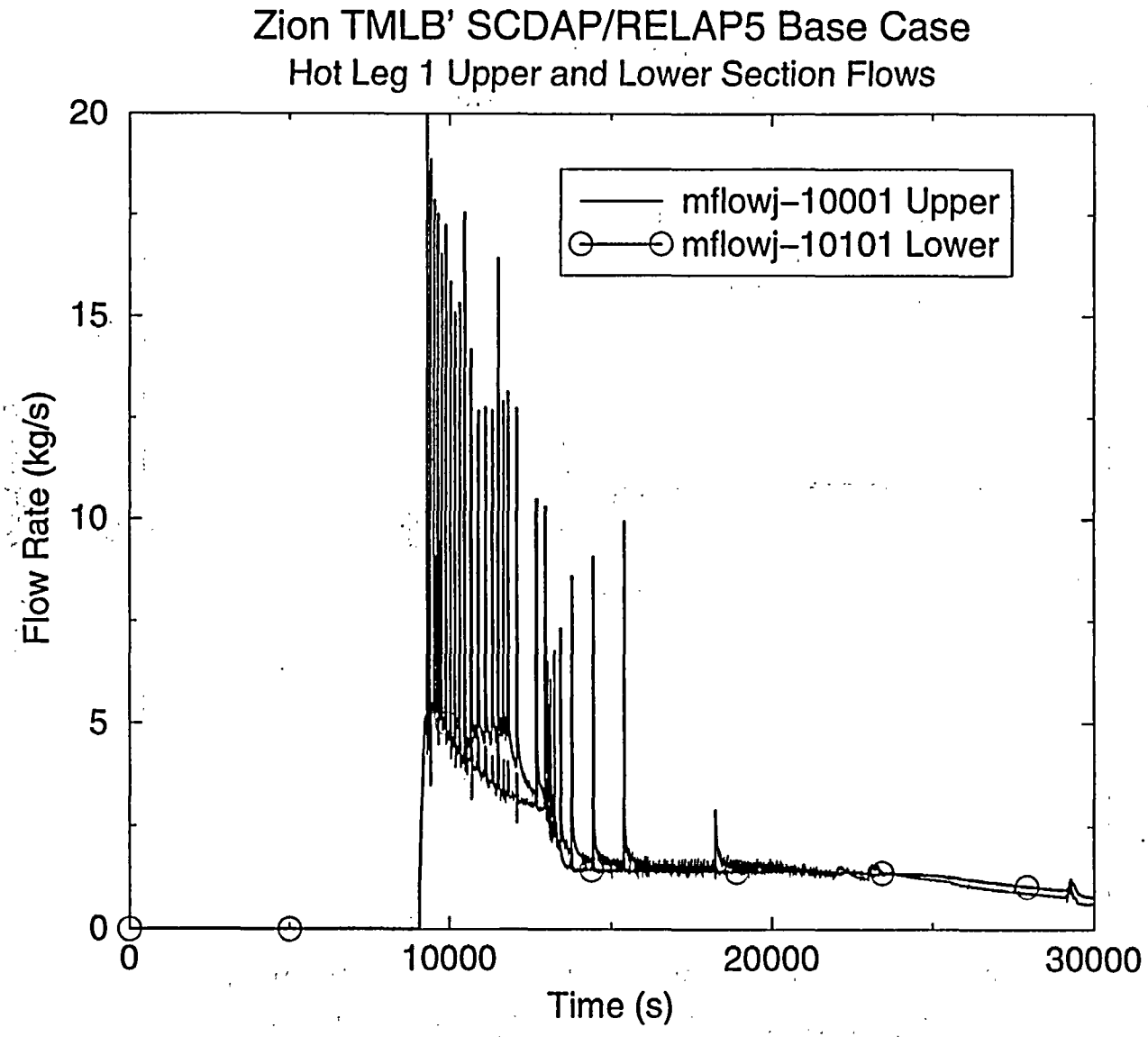

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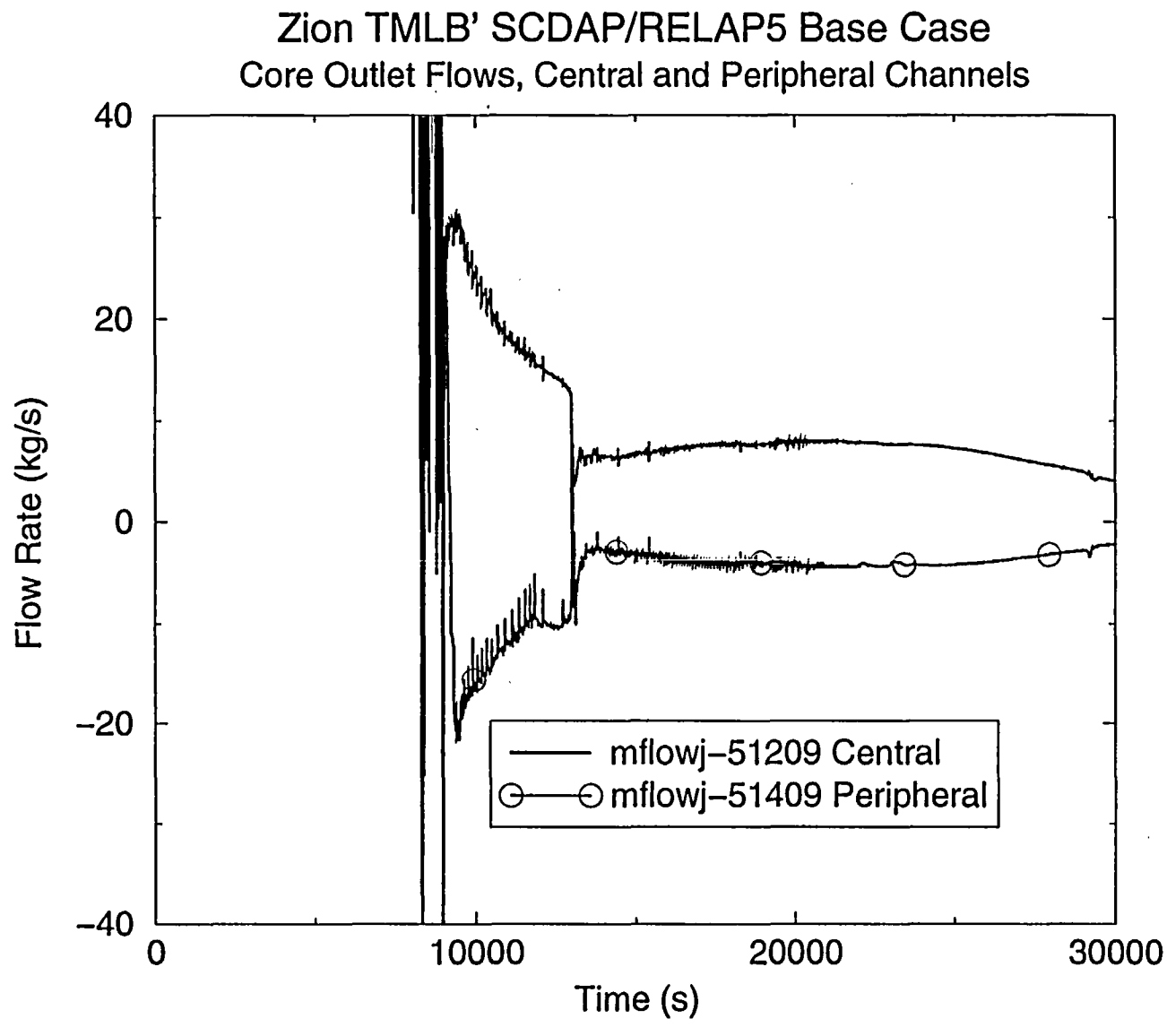

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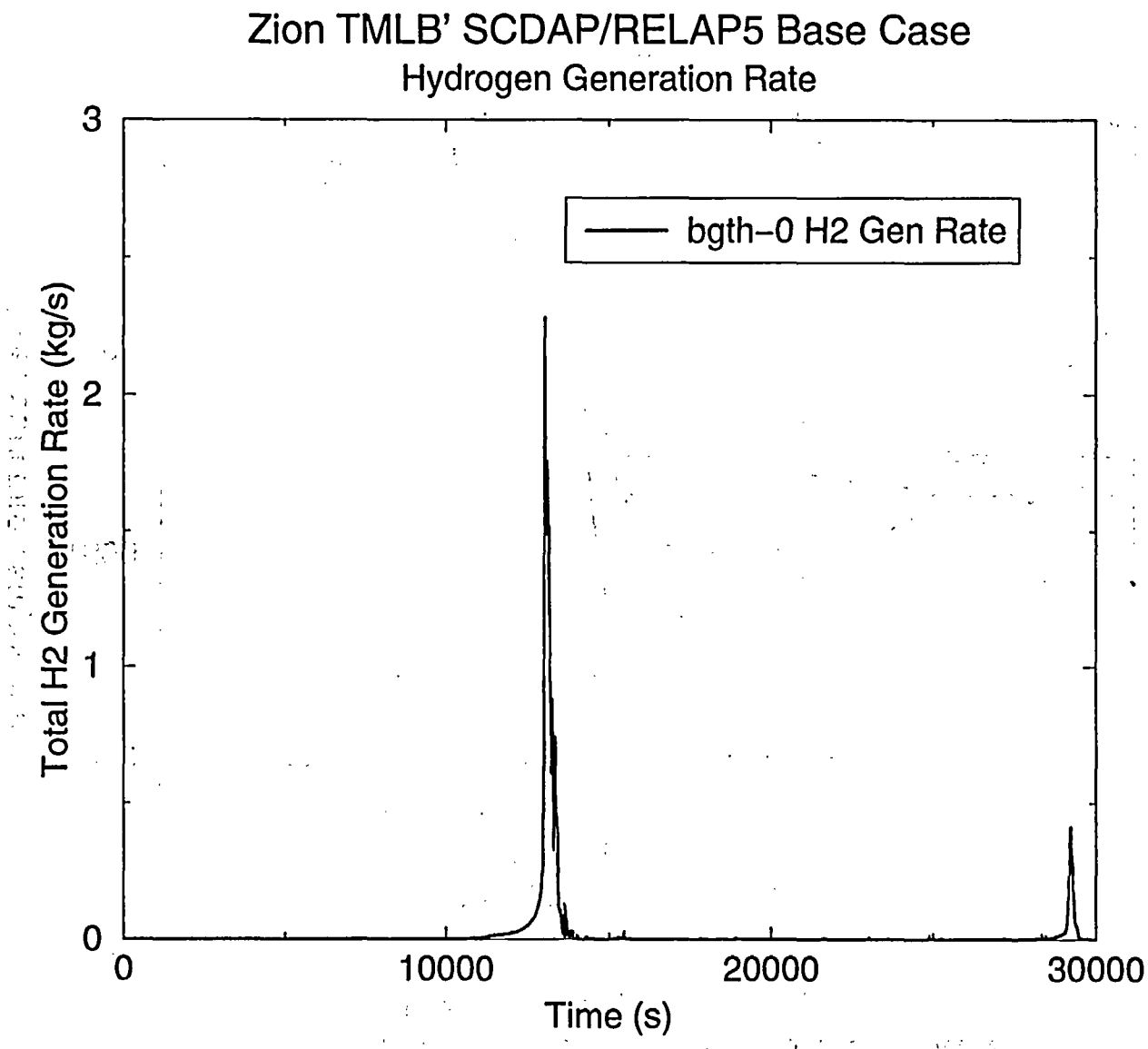

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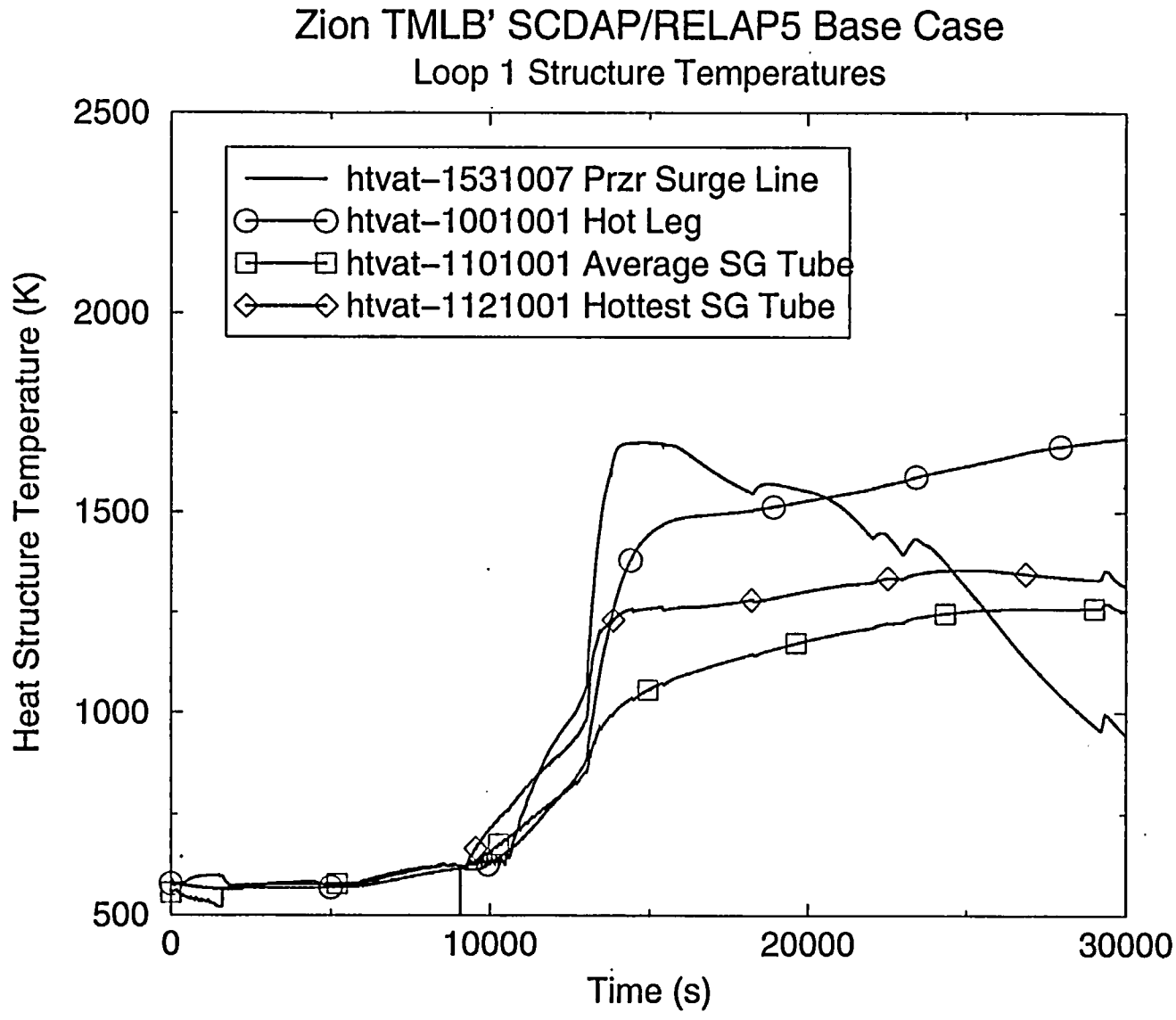

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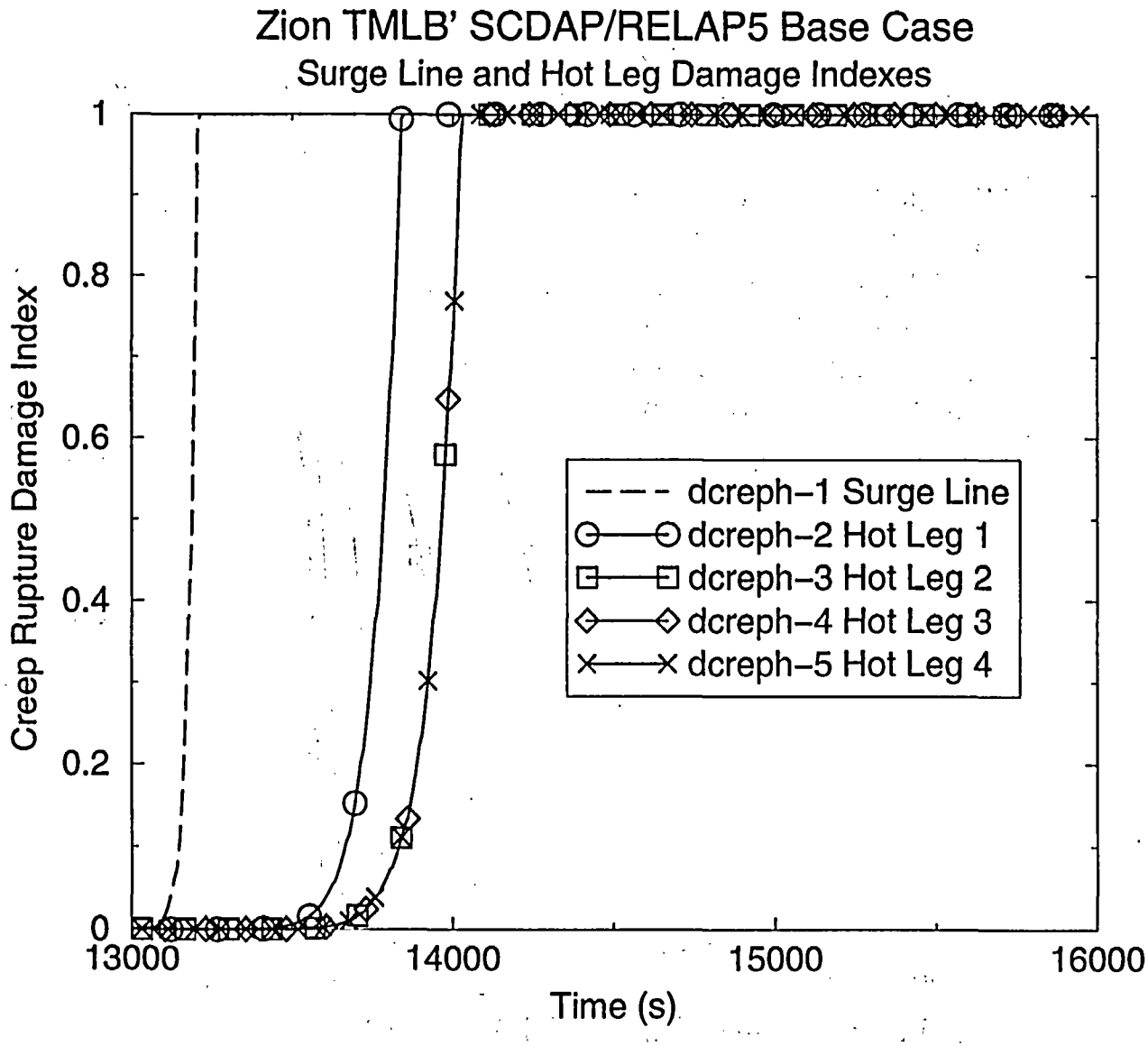

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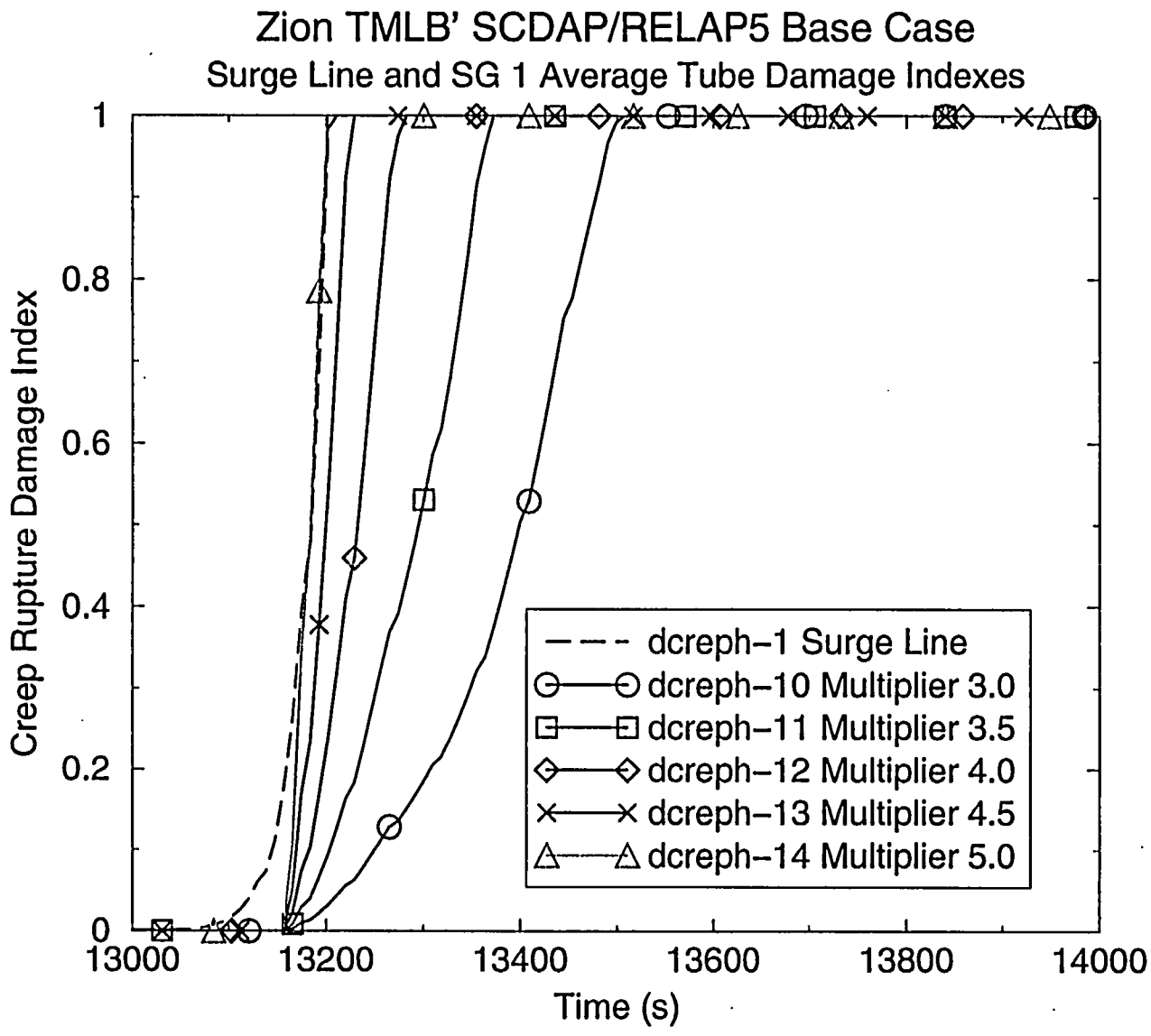

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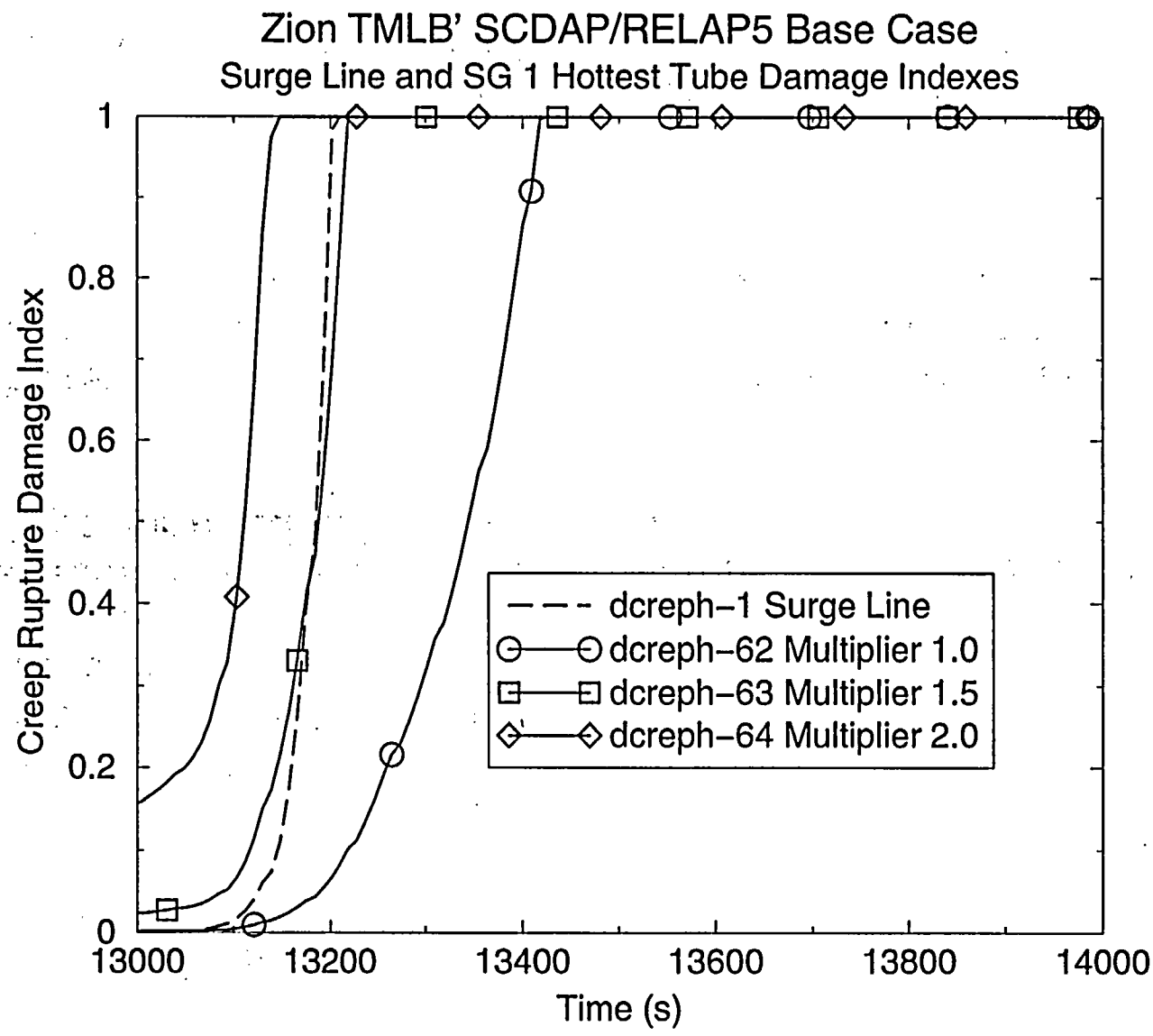

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Summary of Zion TMLB' Updated Base Case Calculation Results

The SG tube failure margins improved from those in the previous base case calculation

Numerous modeling changes are implemented, some of which reduce and others of which increase the SG tube failure margins, however a major factor in margin improvement is that changes are made in the target recirculation ratio and mixing fractions but that the target SG power fraction is not changed

The revised recirculation ratio and mixing fractions make the SGs more efficient; a reduction in the steam flow to the SGs is necessary so as not to increase the SG power fraction

The net effect of the modeling changes is greater relative heating of the hot legs and pressurizer surge line and lesser relative heating of the SG tubes

Summary of Zion TMLB' Updated Base Case Calculation Results (Continued)

The Larsen-Miller creep rupture stress multiplier required to fail the average SG tube prior to the pressurizer surge line increased from 2.5 in the previous base case calculation to 5.0 in the updated base case calculation

The Larsen-Miller creep rupture stress multiplier required to fail the hottest SG tube prior to the pressurizer surge line increased from 1.5 in the previous base case calculation to 2.0 in the updated base case calculation

Only SG tubes with structural strength degradations that are greater than represented by these higher stress multipliers are predicted to fail (and release fission products into the secondary coolant system) prior to the time when the pressurizer surge line fails

Zion SCDAP/RELAP5 Sensitivity Studies

- A series of calculations were run as variations on the updated base case to evaluate the sensitivity of the results to various problem variables
- The problem variables evaluated include plant configuration and operating parameters, natural circulation process parameters and modeling parameters
- The results from these evaluations will be used to focus the uncertainty studies that follow on the most significant parameters affecting the SG tube failure margin
- These sensitivity studies are a work in progress; preliminary results are described here

Zion SCDAP/RELAP5 Sensitivity Studies (Continued)

- **The sensitivity studies evaluated variations in:**
  - SG power fraction
  - Reactor coolant pump shaft seal leakage assumptions
  - Extent of SG tube plugging
  - SG tube outer-wall heat transfer coefficient
  - Modeling of thermal radiation heat transfer processes
  - CCFL modeling at the pressurizer-to-surge line connection
  - Reactor vessel internal circulation rate
  - Reactor coolant system heat loss to containment
  - Pressurizer PORV function and operator intervention strategy
  - SG tube leakage rate
  - Reactor vessel bypass flow at the hot leg nozzle penetrations
  - Recirculation ratio (results not yet available)
  - Hot and cold mixing fractions (results not yet available)

Sensitivity of Results to SG Power Fraction

The SG power fraction is defined as the ratio of the integral of heat removed to the four SGs to the integral of the core neutronic and oxidation heat

This parameter was observed to range from 25% to 40% in the Westinghouse 1/7-scale test data; a value of 30.2% was used in the SCDAP/RELAP5 base case

Sensitivity calculations were performed for 25% and 40% SG power fractions

Results were found to be moderately sensitive to this parameter, with less SG tube failure margin at 40% and more at 25% (at higher power fractions, by definition, more heat is deposited into the SG tubes)

Stress multipliers required for SG tube failure to precede surge line failure:

SG Power Fraction	Average Tube	Hottest Tube
25%	>7.5	2.5
30.2% (base case)	5.0	2.0
40%	2.5	1.5

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Sensitivity of Results to RC Pump Shaft Seal Leakage Assumption

A loss of all AC power results in loss of reactor coolant pump shaft seal injection cooling flow, which promotes leakage of reactor coolant from the pumps into containment

Westinghouse and other evaluations based on experiments indicate a virtual certainty that leakage will begin shortly after the loss of seal cooling flow

The SCDAP/RELAP5 updated base case assumed a 21 gpm per pump leakage rate starting at the initiation of the station blackout transient

The pump seal shaft leakage paths are modeled using constant flow area junctions that initially produce a 21-gpm volumetric water flow rate; the flow rates during the transient calculations vary based upon the pressures and fluid conditions in the pumps

Sensitivity of Results to RC Pump Shaft Seal Leakage Assumption (Continued)

Sensitivity calculations were performed for four additional RC pump shaft seal leakage assumptions:

21 gpm per pump at all times (base case)

21 gpm per pump prior to 2 hours, 61 gpm per pump after 2 hours

21 gpm per pump prior to 2 hours, 172 gpm per pump after 2 hours

21 gpm per pump prior to 13 minutes, 182 gpm per pump after 13 minutes

21 gpm per pump prior to 2 hours, 300 gpm per pump after 2 hours

Results were found to be sensitive to this parameter, with the effect varying as a function of the leakage rate

A higher leakage rate leads to less PORV flow, lower surge line temperatures and delayed or no surge line failure; however it also leads to lower RCS pressure, which also delays or eliminates the hot leg and SG tube failures

Sensitivity of Results to RC Pump Shaft Seal Leakage Assumption (Continued)

Stress multipliers required for SG tube failure to precede pressurizer surge line or hot leg failure:

RC Pump Leakage Assumption	Average Tube	Hottest Tube	Notes
21 gpm at all times (base case)	5.0	2.0	----
61 gpm after 2 hours	3.5	1.5	SL failure delayed
172 gpm after 2 hours	Did not fail	3.5	SL did not fail
182 gpm after 13 minutes	Did not fail	3.0	SL did not fail
300 gpm after 2 hours	Did not fail	Did not fail	SL did not fail, HLs did not fail, Early core melt

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Sensitivity of Results to the Extent of SG Tube Plugging

The SCDAP/RELAP5 updated base case calculation was performed assuming 10% tube plugging in each SG

Sensitivity calculations were performed for 0% and 20% SG tube plugging, which represent the practical limits for variations in this parameter

Results were found to be insensitive to this parameter, with only slightly reduced SG tube failure margins at 20%tube plugging (for which the active tube heat structure is smaller, causing the tube temperatures to be higher)

Stress multipliers required for SG tube failure to precede pressurizer surge line failure:

SG Tube Plugging	Average Tube	Hottest Tube
0%	5.0	2.0
10% (base case)	5.0	2.0
20%	4.5	2.0

Sensitivity of Results to SG Tube Outer-Wall HT Coefficient

The updated base case calculation was performed using the standard SCDAP/RELAP5 heat transfer models on the exterior of the SG tubes

During the heatup period, heat transfer is by single-phase vapor convection (SCDAP/RELAP5 Mode 9), which is based on the maximum of:

Forced convection (Dittus-Boelter, multiplied by the pitch/diameter ratio, per Inyatov for vertical bundle configurations)

Laminar convection (Kays, Sellars)

Natural convection (Churchill-Chu)

The Zion SCDAP/RELAP5 updated base case model thus effectively represents a minimum heat transfer coefficient on the exterior surfaces of the SG tubes

Sensitivity calculations were performed with the heat transfer coefficient on the exterior surfaces of the SG tubes increased by factors of 5.0 and 10.0

Sensitivity of Results to SG Tube Outer-Wall HT Coefficient (Continued)

Results were found to be sensitive to this parameter, with the runs performed at the higher heat transfer coefficients indicating more SG tube failure margin than the base case (higher tube outer-surface HTC more tightly couples the tube wall to the cooler steam in the SG secondary)

Stress multipliers required for SG tube failure to precede pressurizer surge line failure:

Tube Outer Wall HTC Multiplier	Average Tube	Hottest Tube
1.0 (base case)	5.0	2.0
5.0	>7.5	3.0
10.0	>7.5	4.0

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Sensitivity of Results to Thermal Radiation Modeling

The Zion SCDAP/RELAP5 updated base case calculation was performed using best estimate wall-to-wall radiation modeling between the upper and lower hot leg piping walls and steam-to-wall radiation modeling on the interior surfaces of the primary and secondary coolant systems

Sensitivity calculations were performed assuming thermal radiation heat transfer at 50% and 200% of that in the base case

Results were found to be insensitive to this parameter, with little change in SG tube failure margins among the sensitivity and base cases

Stress multipliers required for SG tube failure to precede pressurizer surge line failure:

Thermal Radiation Multiplier	Average Tube	Hottest Tube
50%	5.0	2.0
100% (base case)	5.0	2.0
200%	5.5	2.0

Sensitivity of Results to Pressurizer-to-Surge Line CCFL Modeling

The Zion SCDAP/RELAP5 base case model assumes a simple tank-to-pipe connection configuration between the bottom of the pressurizer and the surge line

The base case modeling employed the Kutateladze form for the countercurrent flow limiting correlation using the flow area of the 11.5-inch diameter surge line

A sensitivity calculation was performed in which a sparger configuration (based on the AP600 sparger design) was instead assumed at this junction

The sensitivity case modeling employed the Wallis form for the countercurrent flow limiting correlation using a flow area based on the sum of the hole flow areas (which totals 1.695 times the surge line cross-sectional flow area) and a hydraulic diameter equal to the hole diameter (0.375 inches)

Sensitivity of Results to Pressurizer-to-Surge Line CCFL Modeling (Continued)

Results were found to be insensitive to the change in countercurrent flow limit modeling, with little change in SG tube failure margins between the sensitivity and base cases

In both cases, the pressurizer drained before the steam temperatures became highly superheated so liquid draining from the pressurizer did not significantly affect the surge line thermal response during the heatup period

Stress multipliers required for SG tube failure to precede pressurizer surge line failure:

Pressurizer-Surge Line CCFL Model	Average Tube	Hottest Tube
Open Pipe / Kutateladze (base case)	5.0	2.0
Sparger / Wallis	5.0	2.0

Sensitivity of Results to Reactor Vessel Internal Circulation

The plant behavior during the heatup period includes three major, buoyancy-induced steam circulations: (1) within the SG tubes, (2) within the hot legs and (3) within the reactor vessel

In the Zion SCDAP/RELAP5 updated base case calculation, buoyancy-induced circulations are observed within the reactor vessel:

- Upward through the higher power core channels and downward through the lower power core channels, and
- Within the upper plenum region with steam flowing toward the upper hot leg sections and away from from the lower hot leg sections

The flow loss coefficients in the base case model represent the physical configuration of the reactor vessel

The base case solution for the vessel internal circulations was reviewed and found to represent reasonable flow circulation patterns and flow rates based on steam-density buoyancy considerations

Sensitivity of Results to Reactor Vessel Internal Circulation (Continued)

Although the base case calculation well-represents the physical behavior, because RELAP5-based codes have a history of over-predicting circulating flows in certain applications, a sensitivity calculation was performed to evaluate the effects of variations in the vessel internal circulation rates on the SG tube failure margin results

In the sensitivity calculation, all lumped flow losses in the reactor vessel core and upper plenum regions (both axial and cross-flow) were arbitrarily increased by a factor of 8.0 in order to reduce the vessel internal circulation rates by about 50%

The slower vessel circulation results in an earlier and faster heatup within the reactor vessel and an acceleration of the core melting process

Sensitivity of Results to Reactor Vessel Internal Circulation (Continued)

The time constants associated with transfer of heat from the vessel, into the hot legs, surge line and SG tubes delay the spread of hot steam out into those components and the relative effect of this delay is more significant for the faster vessel heatup rate seen in the sensitivity calculation

SG tube failure margins are moderately larger at the reduced vessel internal circulation in the sensitivity case than in the base case

Stress multipliers required for SG tube failure to precede pressurizer surge line failure:

Internal Vessel Lumped Flow Losses	Average Tube	Hottest Tube
Physical (base case)	5.0	2.0
8.0 x Physical	>7.5	2.0

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Sensitivity of Results to Reactor Coolant System Heat Losses to Containment

The Zion SCDAP/RELAP5 updated base case calculation was performed assuming a best-estimate 4-MW total heat loss from the external surfaces of the primary and secondary coolant systems to the containment during normal full-power plant operation

Sensitivity calculations were performed assuming total normal-operation heat losses of 2 MW and 8 MW

Results were found to be moderately sensitive to this parameter, with more tube failure margin than the base case at 2 MW and less tube failure margin than the base case at 8 MW (this effect results because the heat loss directly cools the surge line and hot leg structures but not the SG tubes)

Stress multipliers required for SG tube failure to precede pressurizer surge line failure:

Coolant System Heat Loss to Containment	Average Tube	Hottest Tube
2 MW	5.5	2.0
4 MW (base case)	5.0	2.0
8 MW	3.5	1.5

Information Systems Laboratories

Sensitivity of Results to Pressurizer PORV Functioning and Operator Intervention

The Zion SCDAP/RELAP5 updated base case calculation was performed assuming normal functioning of the two pressurizer PORVs (opening and closing based on RCS pressure); a sensitivity calculation was performed to evaluate the effect of blocking closed both PORVs

Results were found to be insensitive to this assumption, with no change in SG tube failure margins between the sensitivity and base cases

With the PORVs blocked closed, the RCS pressure rises higher, but only by an additional 225 psi (1.55 MPa), to the opening setpoint pressure of the pressurizer SRVs

Stress multipliers required for SG tube failure to precede surge line failure:

Pressurizer PORV Functioning	Average Tube	Hottest Tube
Normal PORV Function (base case)	5.0	2.0
Both PORVs Blocked Closed	5.0	2.0

Sensitivity of Results to Pressurizer PORV Functioning and Operator Intervention (Continued)

A second sensitivity calculation was performed to evaluate the effect of the operators opening PORVs as a part of an accident mitigation strategy

The operators are assumed to open both pressurizer PORVs when the core exit steam temperature reaches 922 K (1200 °F); normal PORV functioning is assumed prior to that time and the PORVs are assumed to remain open after that time

The PORVs were opened at 10,798 seconds

Opening the PORVs rapidly depressurizes the RCS and causes discharging and emptying of the accumulators; the cooling this affords the RCS interrupts the core heatup process

Sensitivity of Results to Pressurizer PORV Functioning and Operator Intervention (Continued)

The core heatup resumes after the accumulators have emptied, with about 80% of the core melting and relocating to the reactor vessel lower head at 25,187 seconds

Because of the low RCS pressure and because the molten core remains in the reactor vessel, no structural failures of the hot legs, pressurizer surge line or SG tubes (average and hottest tubes, regardless of stress multiplier) are indicated

The calculation therefore indicates the success of the accident mitigation strategy for preventing fission product release due to SG tube failure

Sensitivity of Results to SG Tube Leakage Flow

The Zion SCDAP/RELAP5 updated base case calculation was performed assuming no SG tube leakage

Sensitivity calculations were performed to evaluate the effect on the results of assuming:

- 50 gpm tube leakage in SG 1
- 100 gpm tube leakage in SG 1
- 200 gpm tube leakage in SG 1

The leakage is assumed to be induced by the failing open of the SG1 secondary PORV, which occurs at 190 seconds in the base case calculation

Sensitivity of Results to SG Tube Leakage Flow (Continued)

Separate runs were made assuming a 50-gpm leakage located at the mid-tube elevations on the tube hot (up-flow) and cold (down-flow) sides

Results for the calculations for the two leakage locations were similar, but with slightly less SG tube failure margin for leakage from the tube hot (up-flow) side

The sensitivity runs were made with the more conservative assumption, leakage at the mid-elevation of the tube hot (up-flow) side

The tube leakage paths are modeled using junctions from the tube primary to SG boiler regions (with constant flow areas that initially produce the specified volumetric water flow rates); the flow rates during the transient calculations vary based upon the RCS and SG pressures and fluid conditions

Sensitivity of Results to SG Tube Leakage Flow (Continued)

Results were found to be sensitive to this parameter, with less SG tube failure margin for the cases with tube leakage than in the base case

The additional flow of hot steam directly into the SG 1 tubes caused by the leakage accelerates the tube heatup process

Stress multipliers required for SG tube failure to precede pressurizer surge line failure:

SG 1 Tube Leakage Assumption	Average Tube	Hottest Tube
None (base case)	5.0	2.0
50 gpm	4.0	1.5
100 gpm	3.0	1.5
200 gpm	3.0	1.5

Sensitivity of Results to Hot Leg Nozzle Core Bypass Flow

The Zion SCDAP/RELAP5 updated base case calculation was performed using nominal flow assumptions for the following core bypass flow paths

- Reactor vessel downcomer to upper head
- Barrel/baffle region
- Leakage between vessel and core barrel at the hot leg nozzles

Some early SCDAP/RELAP5 calculations indicated a possible sensitivity of results to variations in the hot leg nozzle bypass flow assumption

A sensitivity calculation was performed in which the hot leg nozzle bypass flow rate was reduced by 50%

Sensitivity of Results to Hot Leg Nozzle Core Bypass Flow (Continued)

Results were found to be insensitive to this parameter, with no change in SG tube failure margins between the sensitivity and base cases

Stress multipliers required for SG tube failure to precede pressurizer surge line failure:

Hot Leg Nozzle Bypass	Average Tube	Hottest Tube
Nominal (base case)	5.0	2.0
50% of Nominal	5.0	2.0

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Summary of Zion TMLB' Sensitivity Calculation Results

SG tube failure margin results were found to be <u>insensitive</u> to:

- Extent of SG tube plugging
- Thermal radiation modeling
- CCFL modeling at the pressurizer-to-surge line connection
- Blocked-closed pressurizer PORVs
- Core bypass flow at the hot leg nozzle penetrations

Summary of Zion TMLB' Sensitivity Calculation Results (Continued)

SG tube failure margin results were found to be <u>sensitive</u> to:

- SG power fraction
- Reactor coolant pump shaft seal leakage
- SG tube outer wall heat transfer coefficient
- Reactor vessel internal circulation rate
- Reactor coolant system heat loss to containment
- Opening of pressurizer PORVs as a part of an operator accident-mitigation strategy
- SG tube leakage

Conclusions

The updated SCDAP/RELAP5 Zion TMLB' base case provides a reference calculation upon which the remaining work can be based

The updated base case indicates Larsen-Miller creep rupture stress multipliers of 5.0 and 2.0, respectively, are required to fail average and hottest SG tubes prior to the time of pressurizer surge line failure

Only SG tubes with structural-strength degradations that are greater than represented by these stress multipliers are predicted to fail (and release fission products into the secondary coolant system) prior to the time when the pressurizer surge line fails

Conclusions (Continued)

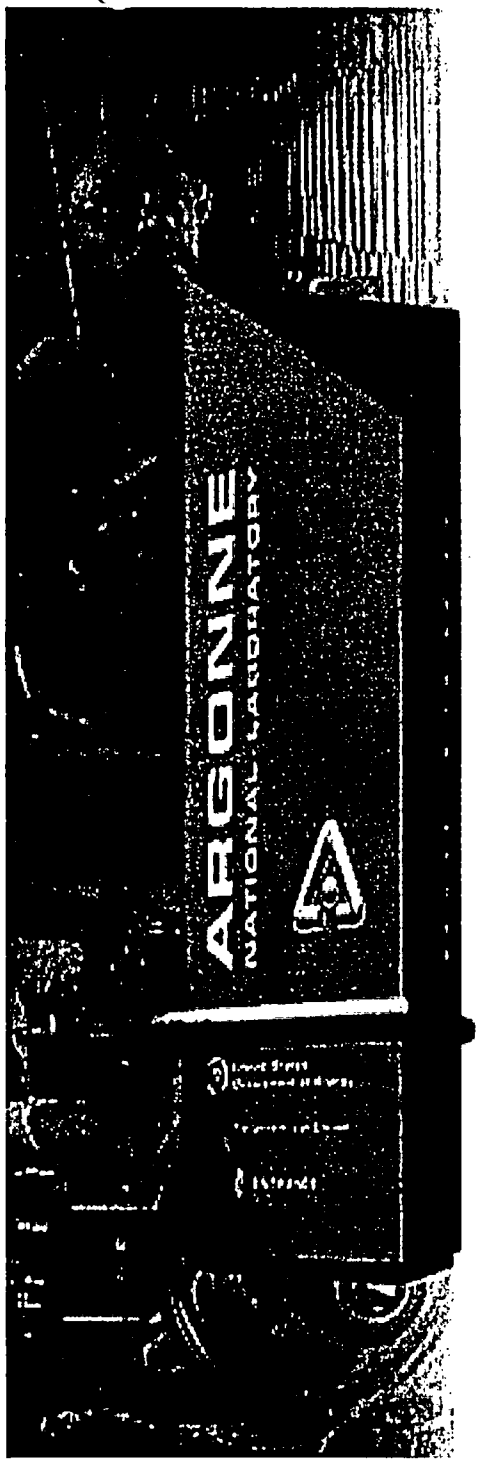
The flow patterns and rates of the SCDAP/RELAP5 reactor vessel internal circulations appear to be reasonable; increased SG tube failure margins were indicated in a calculation in which the circulation rates were artificially reduced

A calculation evaluating the opening of pressurizer PORVs (when core exit temperatures reach 1200 °F) as a TMLB' accident mitigation strategy indicates that strategy effectively eliminates the risk of fission product release due to SG tube failure

Sensitivity evaluations indicate that SG tube failure margin results are most affected by variations in the following parameters, which should be considered for evaluation in the uncertainty study:

- SG power fraction
- Reactor coolant pump shaft seal leakage
- SG tube outer wall heat transfer coefficient
- Reactor coolant system heat loss to containment
- SG tube leakage

PRIMARY SYSTEM COMPONENT RESPONSE



Behavior of PWR Reactor Coolant System Components under Severe Accidents

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Argonne National Laboratory

Office of Science
U.S. Department of Energy

A U.S. Department of Energy
Office of Science Laboratory
Operated by The University of Chicago

Introduction

- This presentation addresses Item No. (TAC No.) 3.4 h1-h3 of the SG Action Plan
  - Do other pressure boundary components fail before SG tubes depressurizing the system and avoiding bypass? Early failure is good!
- Addressed in NUREG-1570 (1998), but significant uncertainties in thermalhydraulics and structural behavior prompted further studies
- Follow–on program is a collaborative study between RES staff and several contractors
  - System response and problem definition–NRC staff
  - CFD studies to benchmark RELAP5 and provide more detailed TH information–NRC staff
  - RELAP5/SCDAP analyses of TH during accident–ISL
  - PRA studies to determine frequency of scenarios–Sandia
  - Structural behavior of pressure boundary under high temperature, pressure–ANL

Background & Objective

- In NUREG 1570, sequences in which the secondary side was depressurized while the primary system remain pressurized as the accident progressed and temperatures increased were identified as a potentially serious challenge to the structural integrity of the steam generator tubes (SGTs) and could lead to containment bypass.
- Although in the 1570 studies, failure of the pressurizer surge line (leading to depressurization of the reactor coolant system [RCS]) was predicted to occur before failure of the SGTs, the structural models for the RCS components were highly simplified and did not include the effects of local geometry, structural boundary conditions, thermal stresses, dead weight, and material variability.
- The objective of the ANL program is to improve predictions of the failure locations, failure modes and times-to-failure of reactor coolant system components (e.g., surge line, hot leg piping, steam generator manways, PORVs, and PSVs) under severe accident conditions.

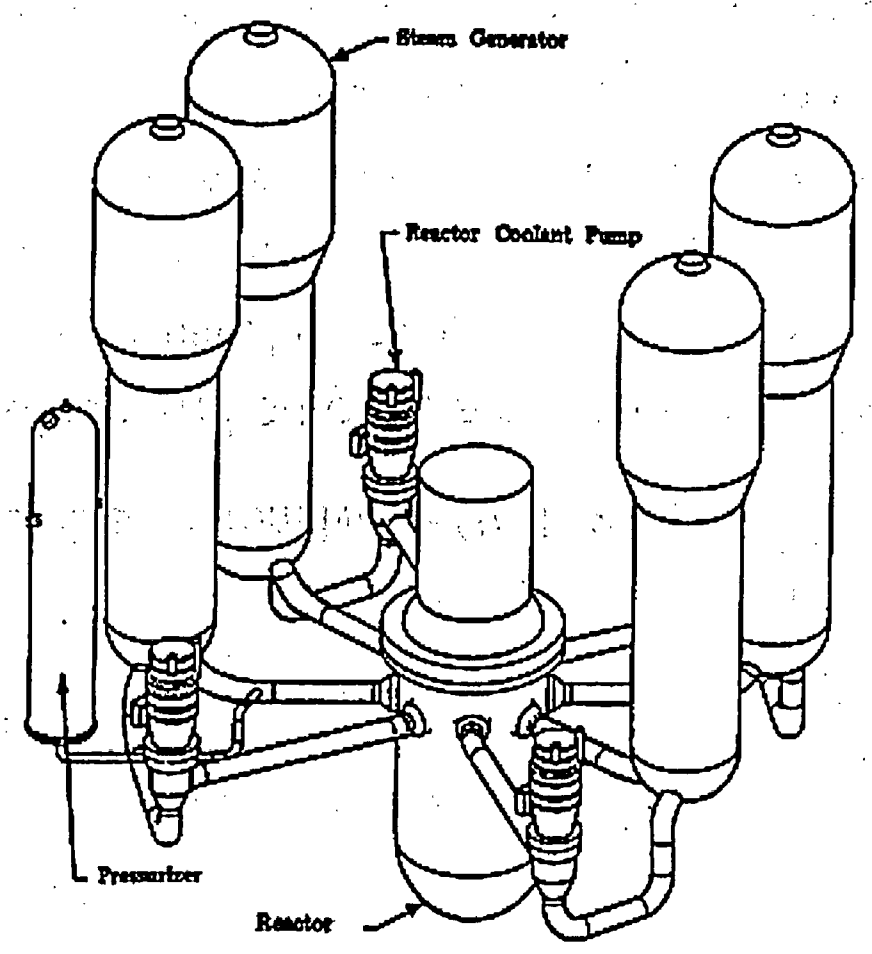
Technical Activities

- Based on NUREG-1570 studies and engineering review, failure of pressurizer safety valves (PSVs), power operated relief valves (PORVs), the manways, hot leg and surge line piping, including their intersection and their nozzles, were identified as the most likely to lead to depressurization of the RCS.
- Analyses of passive component failure is relatively straight-forward, analyses of the failure of active components was judged to be more challenging
- Reviewed literature of failure history of valves, bolted joints, and gaskets.
- To help determine whether detailed analysis of the active components (safety valves, relief valves, etc.) and bolted connections was a realistic goal, a workshop was held at ANL with participants from two valve manufacturers, a gasket manufacturer, NRC, EPRI, and ANL.
  - Participants concluded that detailed design information about the valve, including the tolerances between tightly fitting parts will be needed to carry out thermal-mechanical analyses (e.g., galling), and it was not likely that valve manufacturers would be willing to make such information available.
  - Participants were more optimistic about analysis of bolted joints.

Technical Activities (cont.)

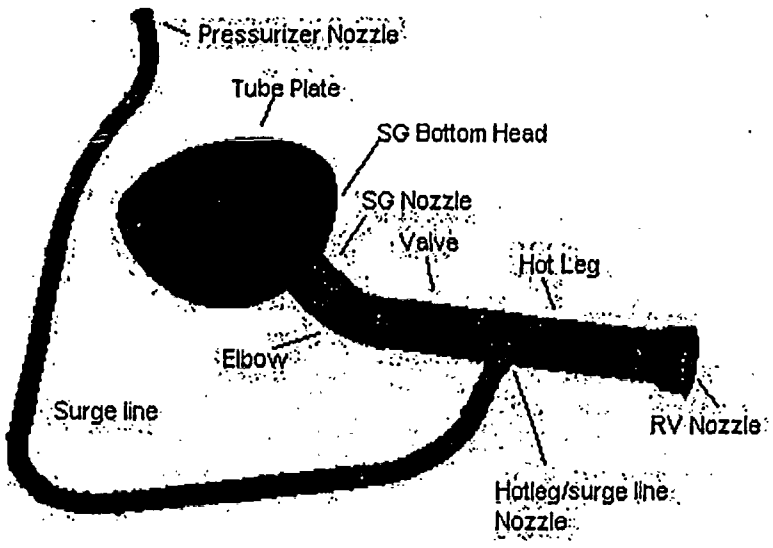
- Primary Efforts focused on analysis of passive component failure
  - Detailed mechanical and structural drawings of hot–leg and surge line piping of the Zion Nuclear Station were obtained.
- Finite element analyses (FEA) of the hot leg and surge line piping including the nozzles of Loop 4 of the Zion Plant were conducted
  - Analyses based on thermalhydraulic results provided by ISL and NRC RES
- Conducted FEA of other RCS passive components
  - Steam generator primary manway (loss of bolt pretension and opening of leakage area).
  - Resistance Temperature Detector (RTD) welds.
  - Socket weld connection of instrument line to the RTD flange.
- Conducted FEA of plug-to-seat impact for the PORV and PSV.
- Documents in NUREG/CR–6792 (May 2003) and NUREG/CR–xxxx (in peer review)

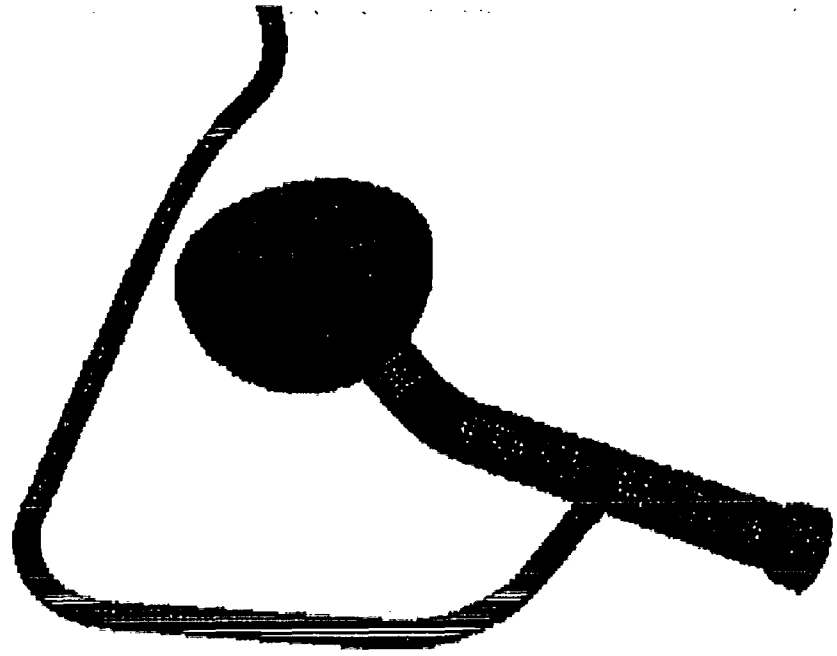
Simplified Diagram of Zion Plant



Schematic of four loop RCS at Zion

Finite Element Model of Hot Leg-Surge Line





CL coordinates from NUREG/CR-2189

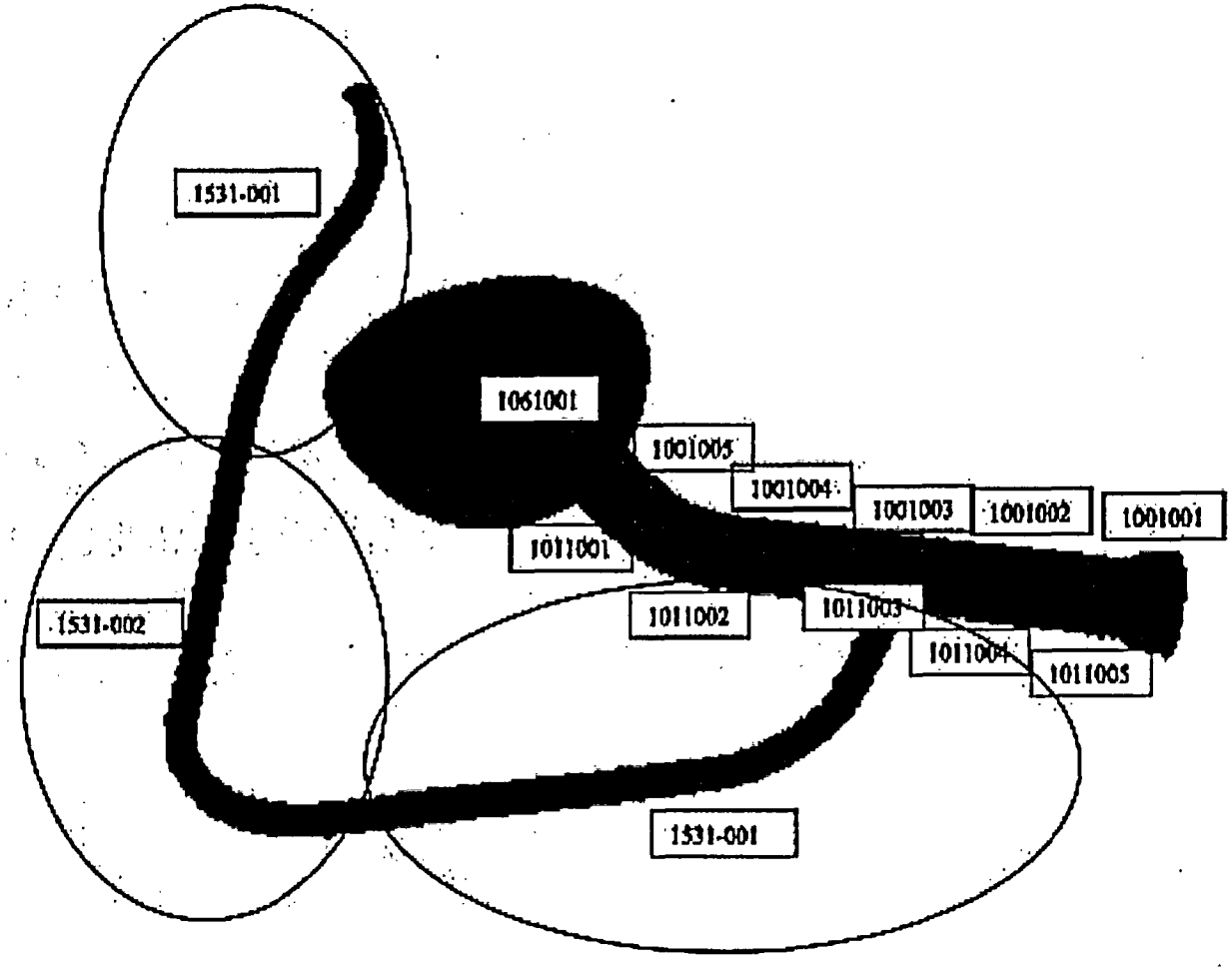
- Hot leg and surge line material is 316 stainless steel
  - Significant high temperature material properties database exists
- Nozzle materials is are either carbon or low alloy steel
  - High temperature mechanical properties are mostly unavailable
- High temperature weld (308 SS) properties database is incomplete
- Sensitivity analyses performed (uncertainty analyses planned)

Availability of Mechanical Properties Data

RCS Component	Material	Tensile Properties		Creep Properties	
		σ–ε Curve	Tensile Strength	Creep Rate	Rupture Time
Piping, RTD Body PORV plug	Type 316 SS	400–982°C	400–1093°C	538–816°C	427–1093°C
Hot Leg Elbow	A 35 1 CF8M	Not found	400–871°C	538–649°C	454–1000°C
Surge Line to Hot Leg Nozzle	SA 182 F316	Not found	400–538°C	Not found	549–699°C
Weld	308 SS	565°C	482–593°C	593°C	454–704°C
RV Nozzle	A–508 Class 2	Not found	400–727°C	627–752°C	627–954°C

RCS Component	Material	Tensile Properties		Creep Properties	
		σ–ε Curve	Tensile Strength	Creep Rate	Rupture Time
SG and PZR Nozzles	SA 216 WCC	Not found	400–538°C	Not found	Not found
Manway Cover	SA 533 A1 (SA 533 B1)	Not found (649–1200°C)	400–538°C (400–1200°C)	Not found (400–1100°C)	Not found (400–1100°C)
Manway Insert	304 SS	700–1100°C	400–1100°C	427–1077°C	538–1077°C
Manway Bolts	A 193 (B7)	Not found	427°C	Not found	Not found
PORV Cage	SA 564 (17–4PH) H1100	Not found	400–538°C	–	–

RELAP5 Model of the Zion Hot Leg/Surge Line

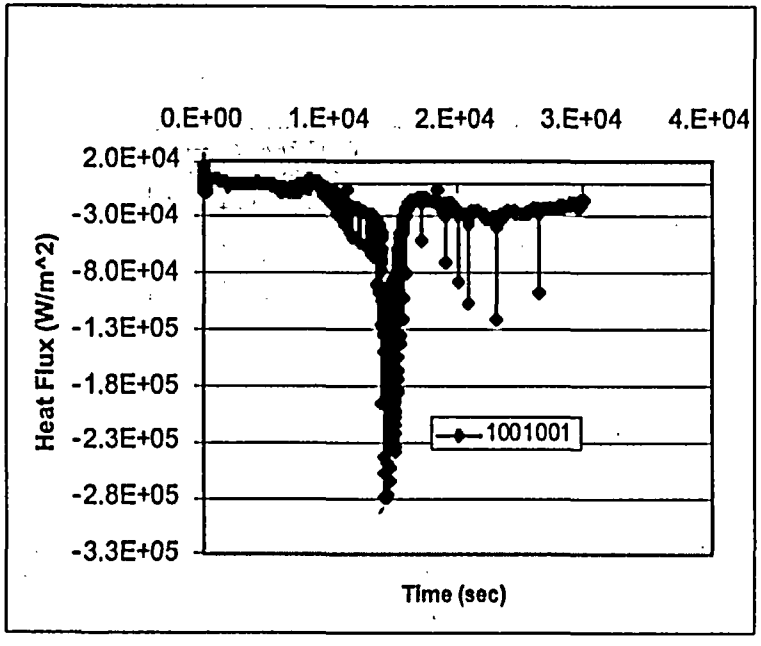


Baseline (Old) Case Assumptions for RELAP5 Analysis of the Zion Nuclear Station

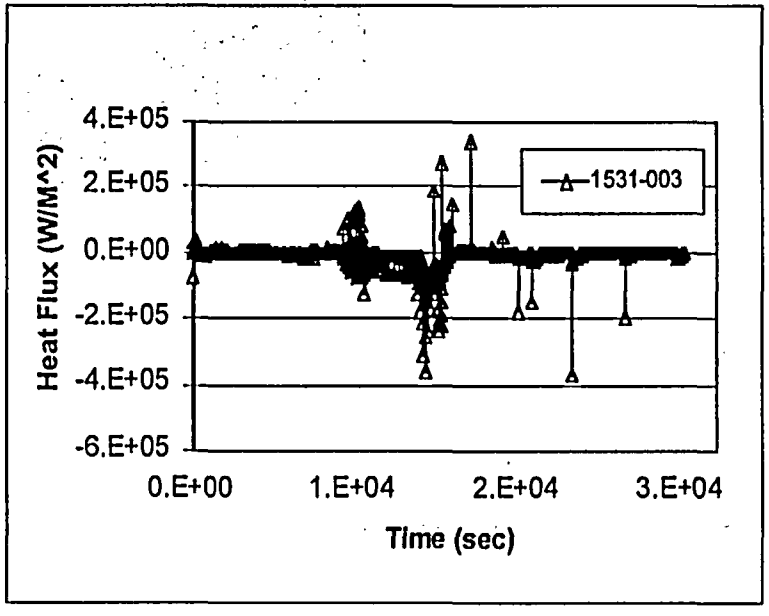
- SBO with "high-dry-low" sequence
  - High RCS pressure (constant 2350 psi)
  - Dry SGs
  - Low secondary side pressure in the pressurizer loop SG – a stuck open RV on the first challenge
- 15% (out of 3388) of the SGTs are plugged
- Cold leg loop seal is maintained
- Counter-current natural circulation flow in the hot leg (w/o radiation effects)
- No circumferential heat conduction or radiative heat transfer in the hot leg
- RCP seal leakage assumed zero
  - No significant increase in seal temperature

Hot leg & Surge line Transient Thermal Conduction Analysis With ABAQUS

- Internal surface heat fluxes obtained from RELAP5 analysis were input in the finite element model of the hot leg/surge line structure as functions of time [in graphs below, fluid-to-structure flux is negative (ABAQUS sign convention)]
- The structure temperatures calculated by ABAQUS were used in the stress analysis.

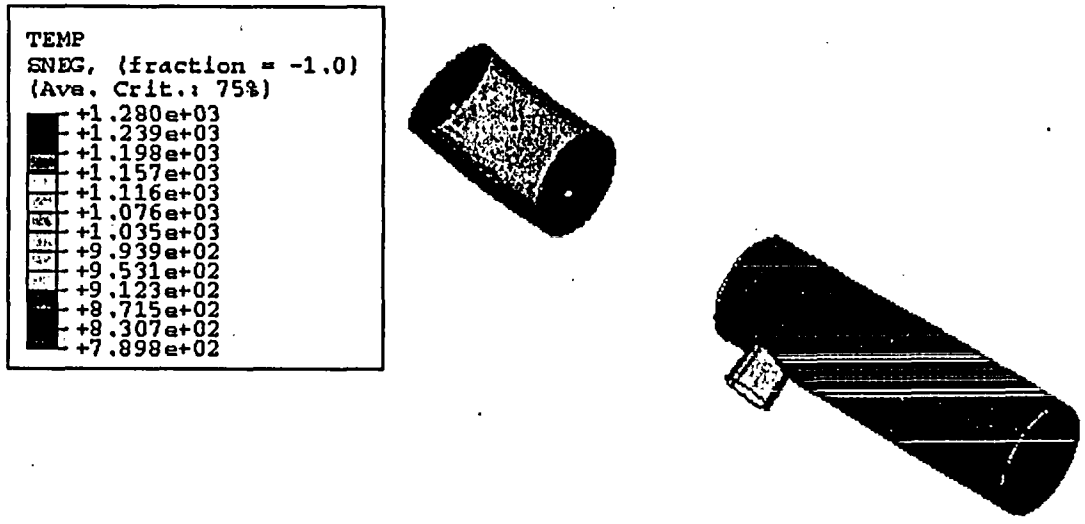


Hot leg



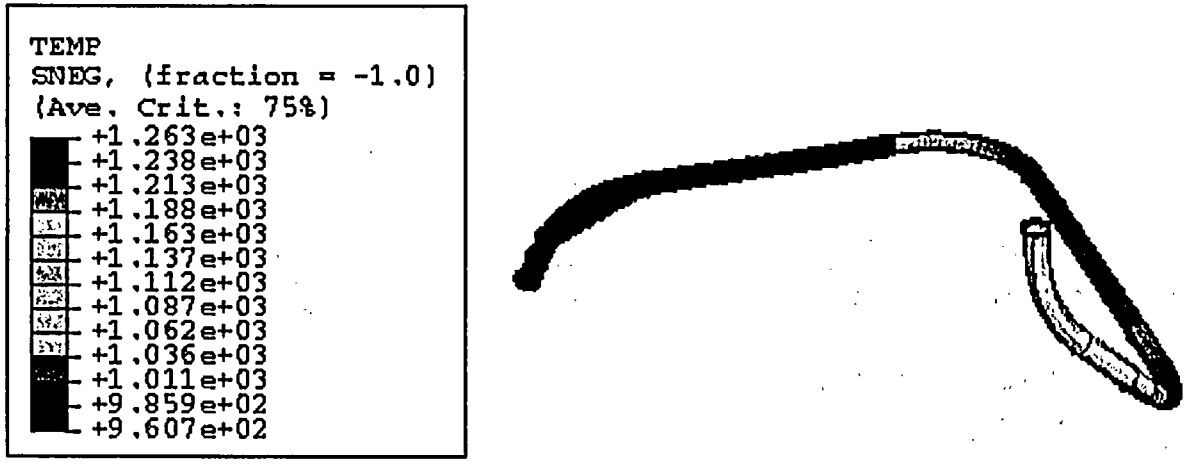
Surge line

Inner Surface Temperature (Deg K) Distribution in Hot Leg at 14,440 s



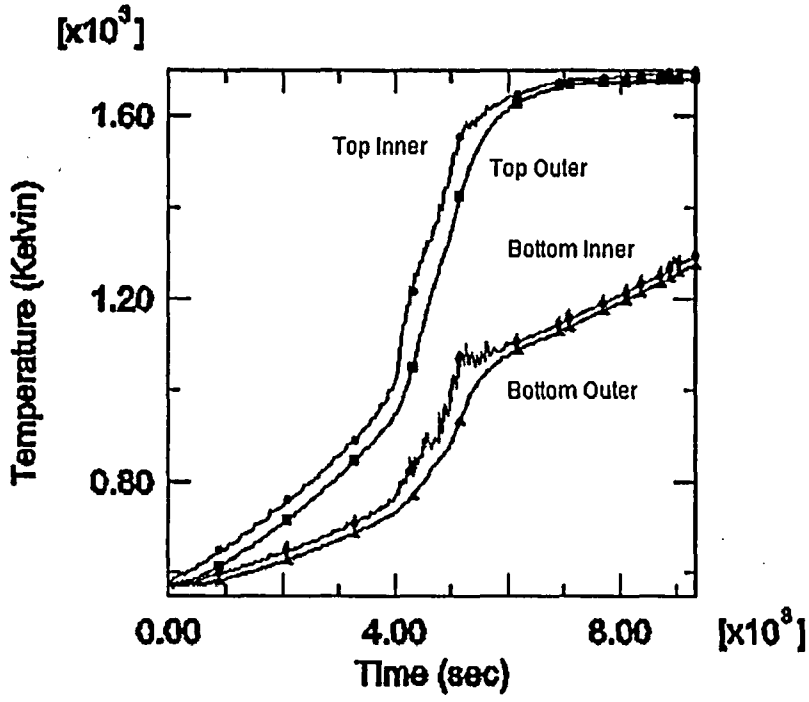
- Upper half of hot leg significantly hotter than lower half, as expected

Inner Surface Temperature (Deg K) Distribution in The Surge Line at 14,440 s



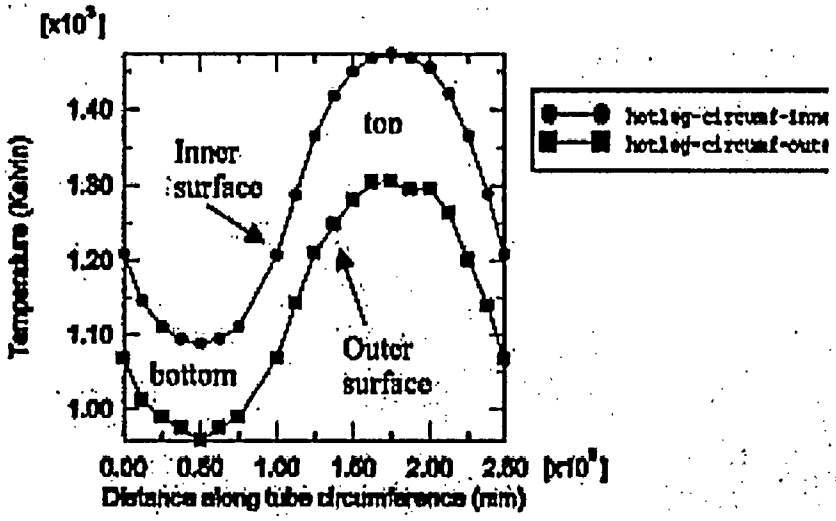
- Surge line piping is hot all around

Temperature Variation in Hot Leg with Time

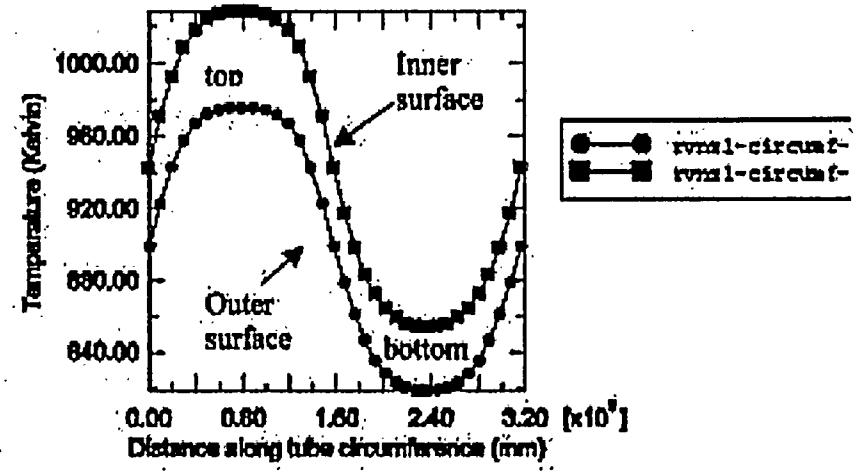


- Inner surface is 50-150°C hotter than outer surface
- Upper half is 100-500°C hotter than lower half
- Temperature ramp increases from 6°C/min to 24°C/min at 14,000s.

Circumferential Temperature Variation in The Hot Leg and RV Nozzle at 15,400 s



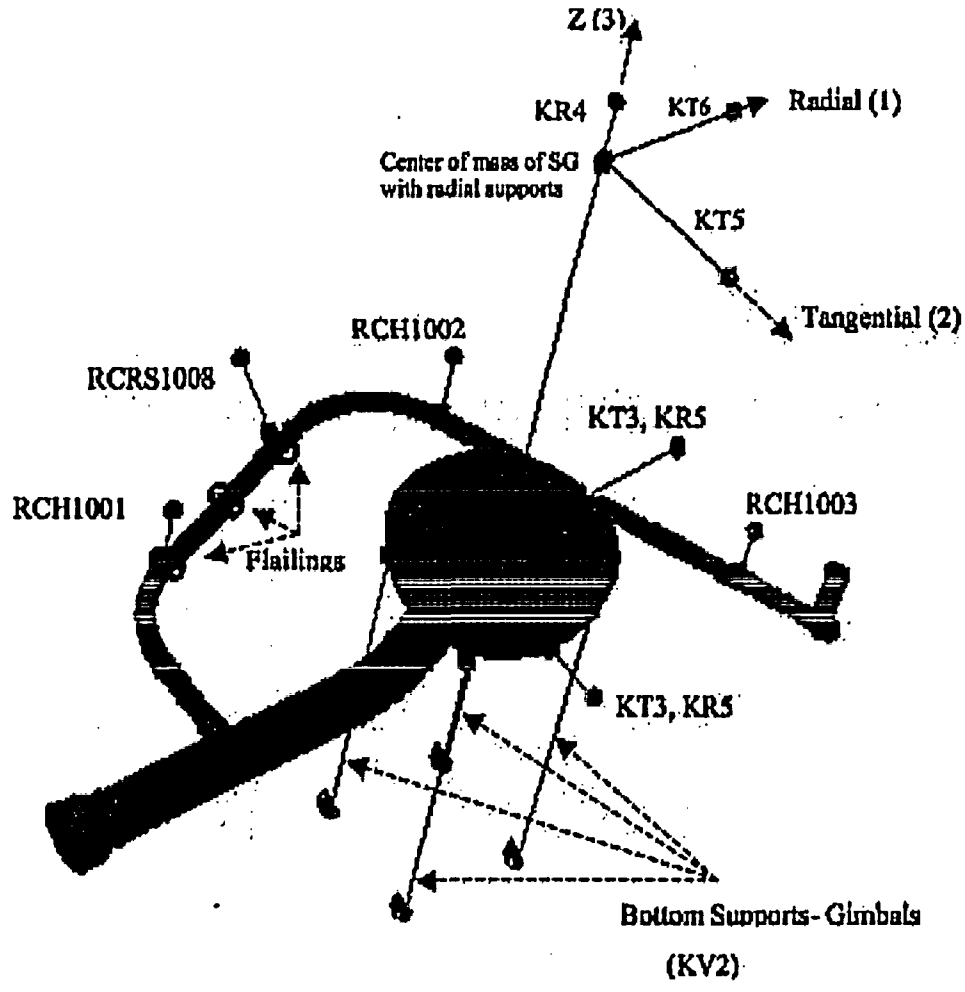
Hot leg



RV nozzle

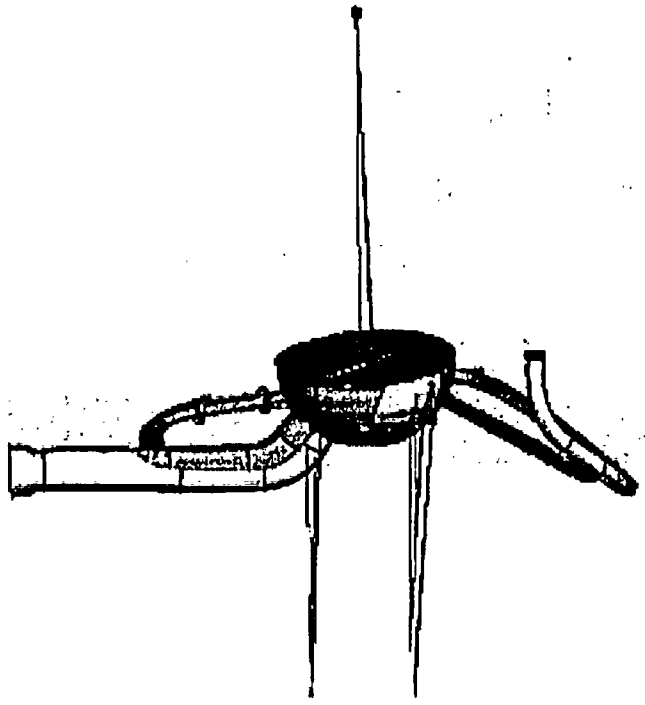
- Because of its large mass, the maximum temperature in the RV nozzle lags that in the hot leg by 450°C
- Thermal conduction makes the circumferential temperature variation much smoother than calculated by RELAP5.
  - Hot leg max. temp.=1200°C (1475 K), min. temp.=830°C (1100 K).
  - RELAP5-calculated hot-to-cold side wall temperature drop is 450°C

Structural Boundary Conditions

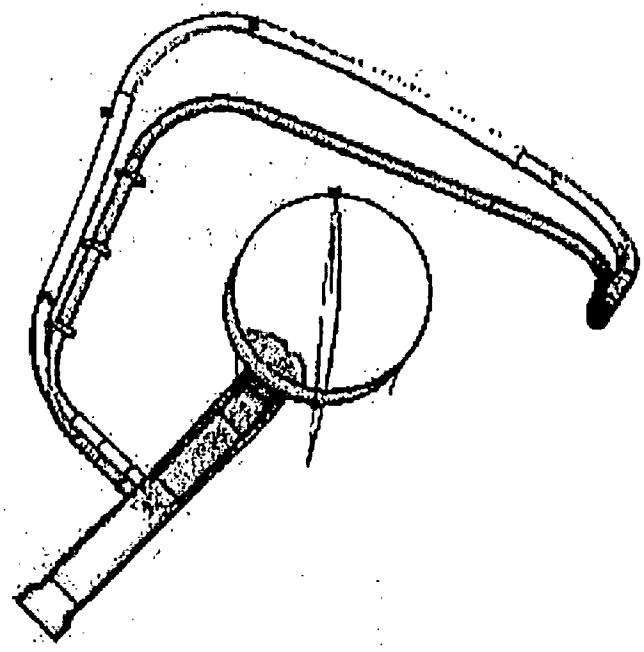


- All the supports and flailing restraints, except hydraulic snubbers were included in the model

Typical Deformation of Hot Leg-Surge Line (NO)



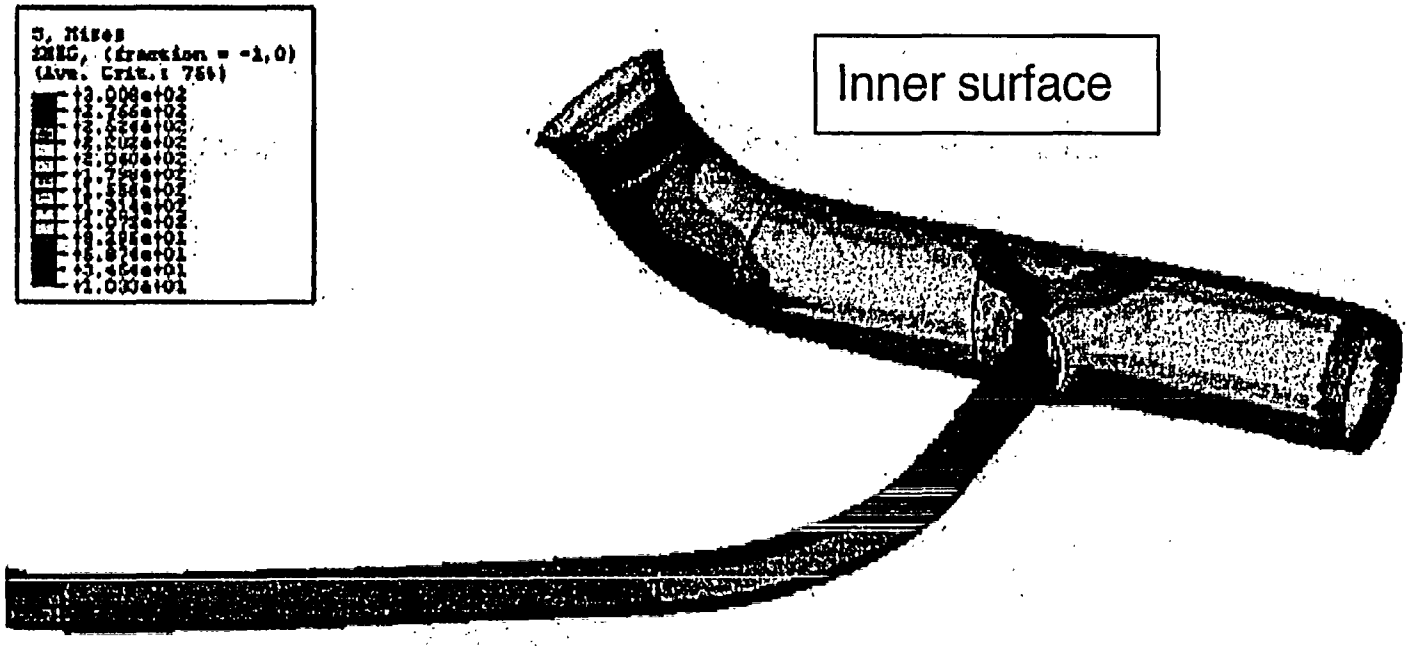
Side view



Top view

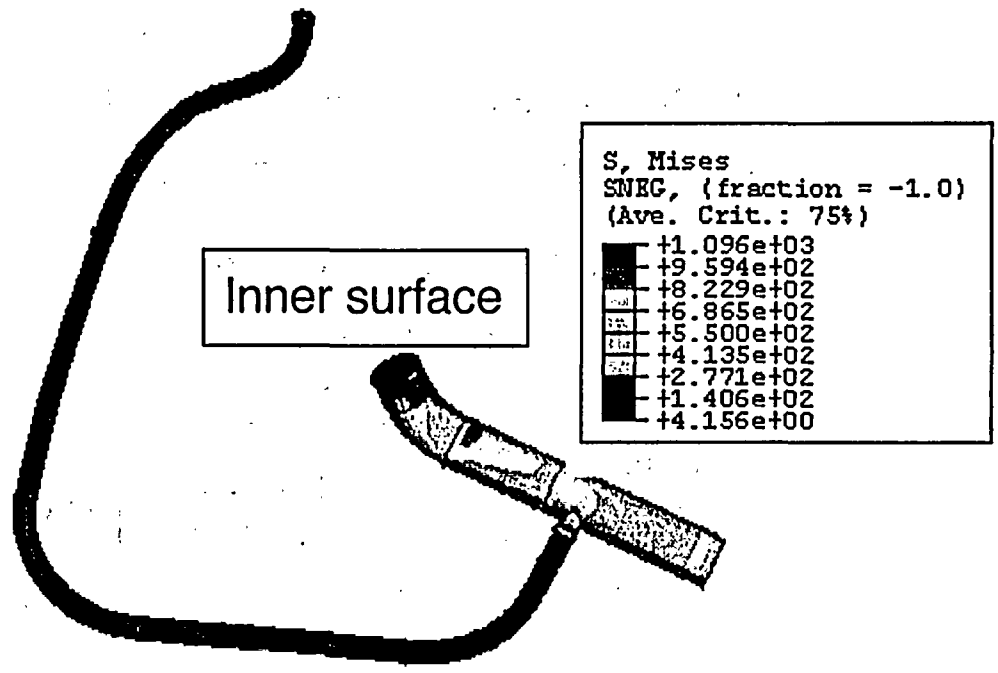
- Green shade denotes undeformed shape at RT
- Stresses due to this type of deformation were ignored in NUREG-1570.

Elastic Stresses at Normal Operation



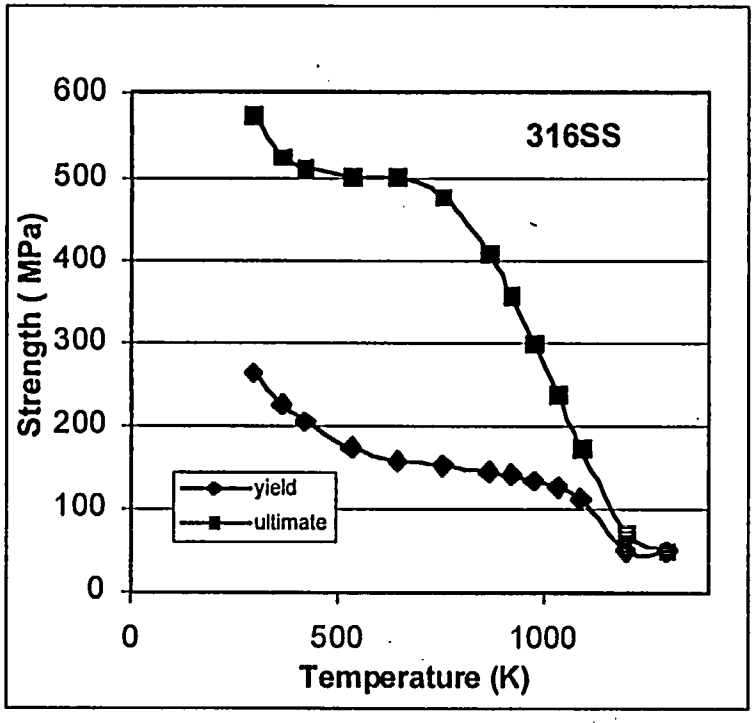
- Stresses are generally low, except at surge line to hot leg junction.
  - High local stresses will be relaxed by local plasticity (yield =172 MPa)
- Shell Model does not include 3-dimensional effect at junction.

Elastic Effective Stress Distribution at 14,400s



- Elbow and hot leg are highly stressed
- Plasticity and creep will play a significant role

Strength Properties of 316 SS at Temperature



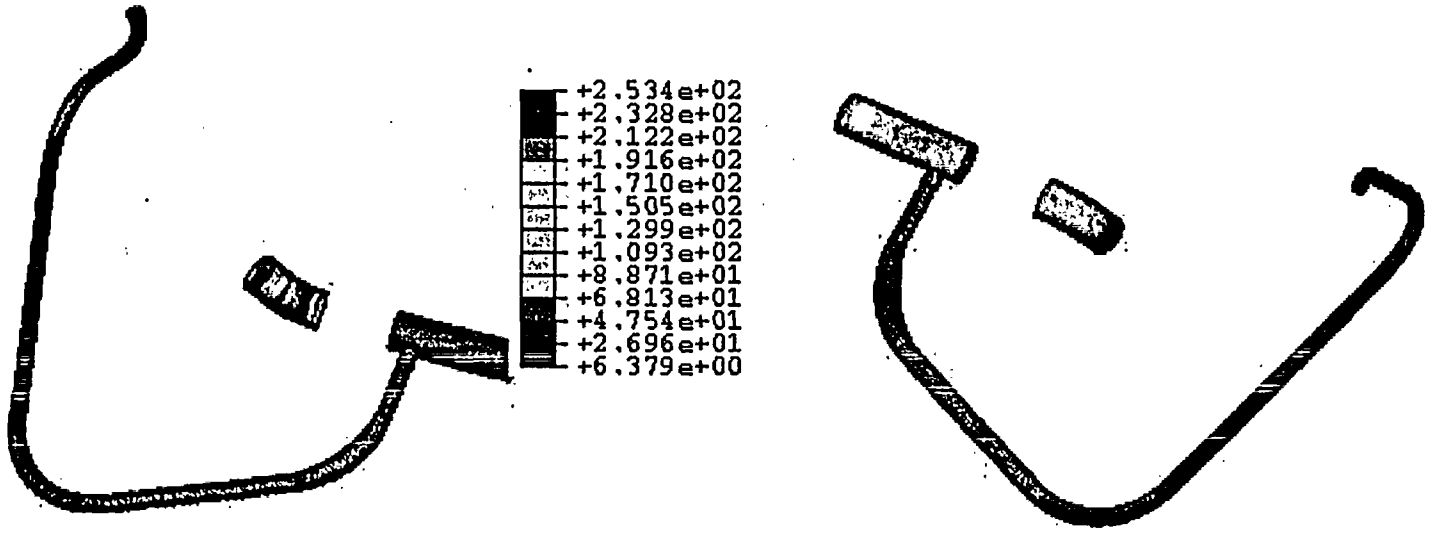
- Data not available beyond 1089 K (1500°F)
- Since yield and ultimate strengths approach each other, ε_u drops.
- NUREG/CR-5642 shows ε_u of 304 SS drops to 1 - 5% at ≥ 1200 K (1700°F) although ε_t stays high.

Creep Rate Data for 316 SS

- Creep rate equation $d\varepsilon/dt = A^*\sigma^m$
- $A = A_o \exp\left(-\frac{Q}{RT}\right)$ was used to extrapolate A beyond 1089 K (1500°F)

316SS				
A	Temp (K)	1/T	ln (A)	m
1.50E-31	866	1.15E-03	-70.9747	8.99
9.34E-29	922	1.08E-03	-64.5407	11.08
4.39E-25	977	1.02E-03	-56.0853	9.766
1.08E-18	1033	9.68E-04	-41.3733	9.33
1.03E-17	1089	9.18E-04	-39.1144	8.16
1.56241E-17	1100	9.09E-04	-38.6977	5.89
9.39132E-17	1150	8.70E-04	-36.9042	5.85
2.20621E-15	1250	8.00E-04	-33.7475	5.85
8.91283E-15	1300	7.69E-04	-32.3513	5.85
1.07849E-13	1400	7.14E-04	-29.858	5.85

Inelastic Stress Distribution at Inner Surface at 14,400s

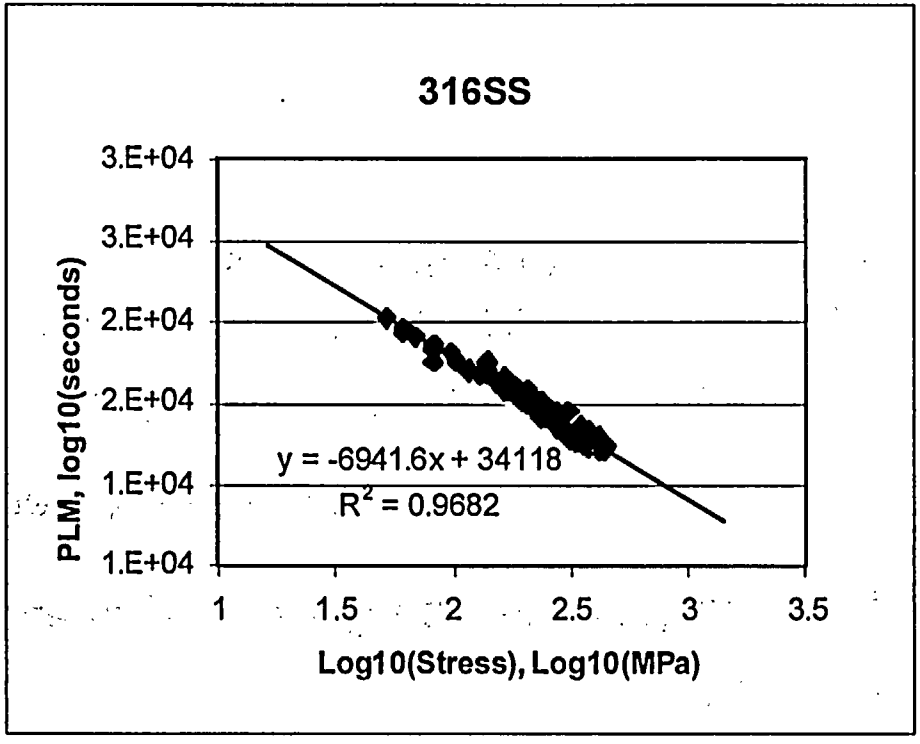


Top view

Bottom view

- Stresses are relaxed compared to elastic stresses
- Colder half (bottom) of hot leg has higher stresses than hotter half (top)

Creep Rupture Data for 316 SS



- Stress dependence of creep described by Larson Miller parameter $P_{LM} = -6941.6 * \log_{10}(\sigma) + 34118$ (best fit of data)
- Rupture time at given stress, temperature is $t_r = 10^{(P_{LM}/T+C)}$, where constant C=14 (best fit of data)
- Creep damage was considered only if the in–plane principal stress is tensile

Creep Rupture Failure Prediction

- Creep failure can be predicted either by the exhaustion of the material creep ductility or by the accumulation of creep damage.
  - Failure by exhaustion of creep ductility occurs when effective creep strain reaches a critical value $\varepsilon = \varepsilon_c$
    - *Time to failure is insensitive to the actual value of creep ductility (20%)*
  - Simplest creep damage rule is linear time fraction damage rule:

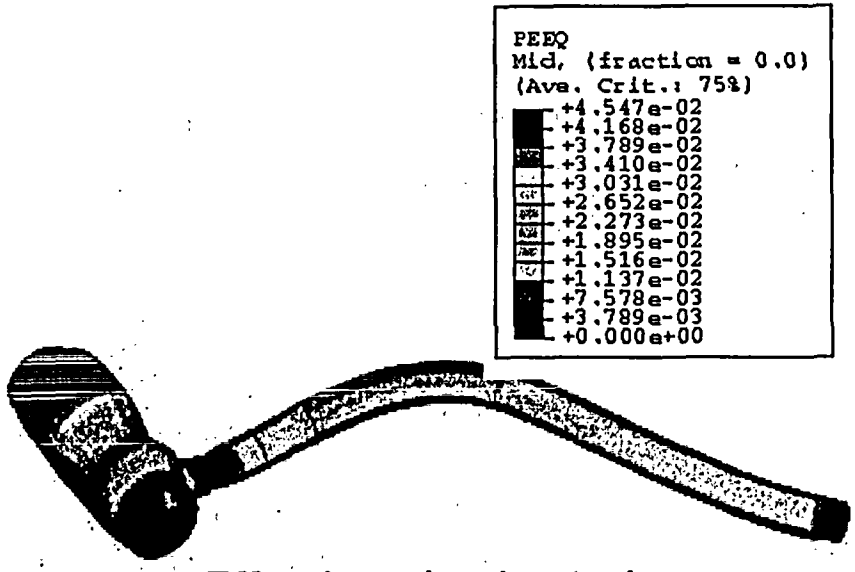
$$\text{Creep Damage} = \sum \frac{\Delta t}{t_r(T,\sigma)} = 1$$

- Times to failure predicted by either method are similar
- Failure is predicted if either of the above criteria is satisfied using average membrane stress that must be tensile over a significant portion of the structure.

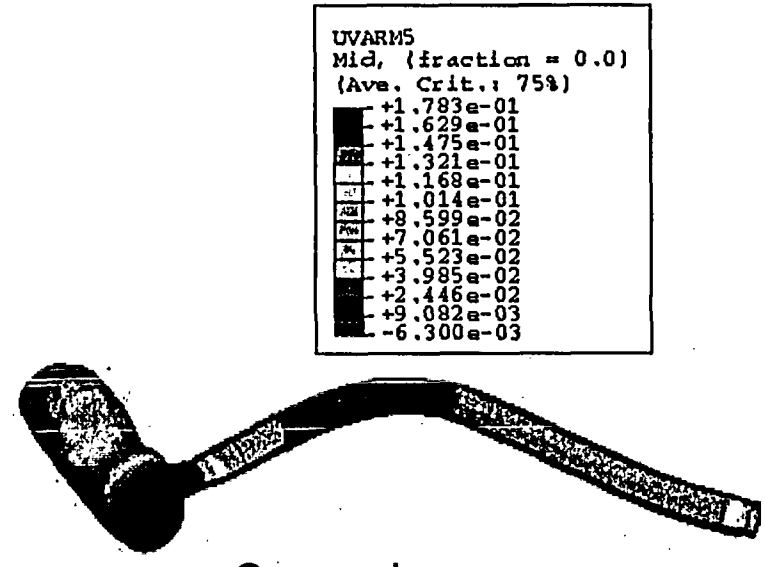
Tensile Rupture Failure Prediction

- If creep deformation is not fast enough to relax the stresses, failure can occur by tensile rupture
- At high temperatures, stainless steels and the ferritic steels have a uniform elongation of the order of 2% beyond which necking and plastic strain localization occur
  - If through–thickness average (i.e., membrane) tensile plastic strain reaches a value of 2% or more before creep damage reaches a value of 1, then the section is considered to have failed by tensile rupture

Tensile and Creep Damage Accumulation at Mid Surface (14,580 s)



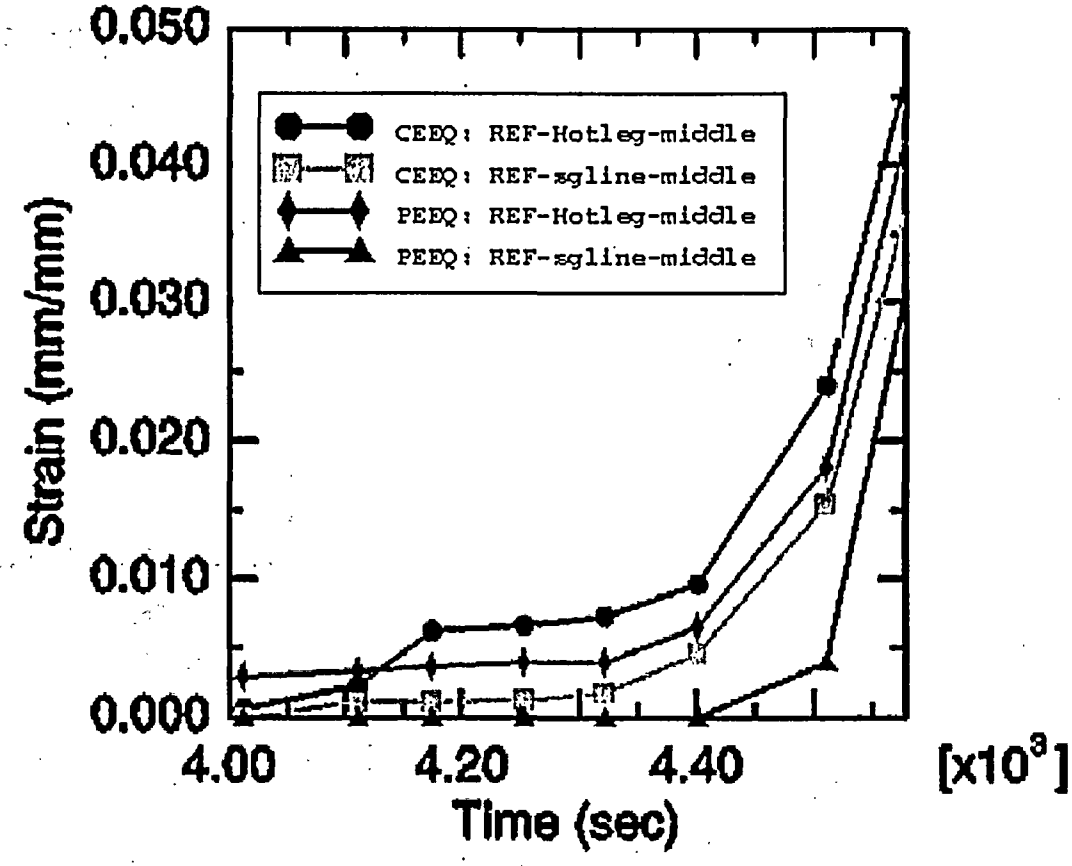
Effective plastic strain



Creep damage

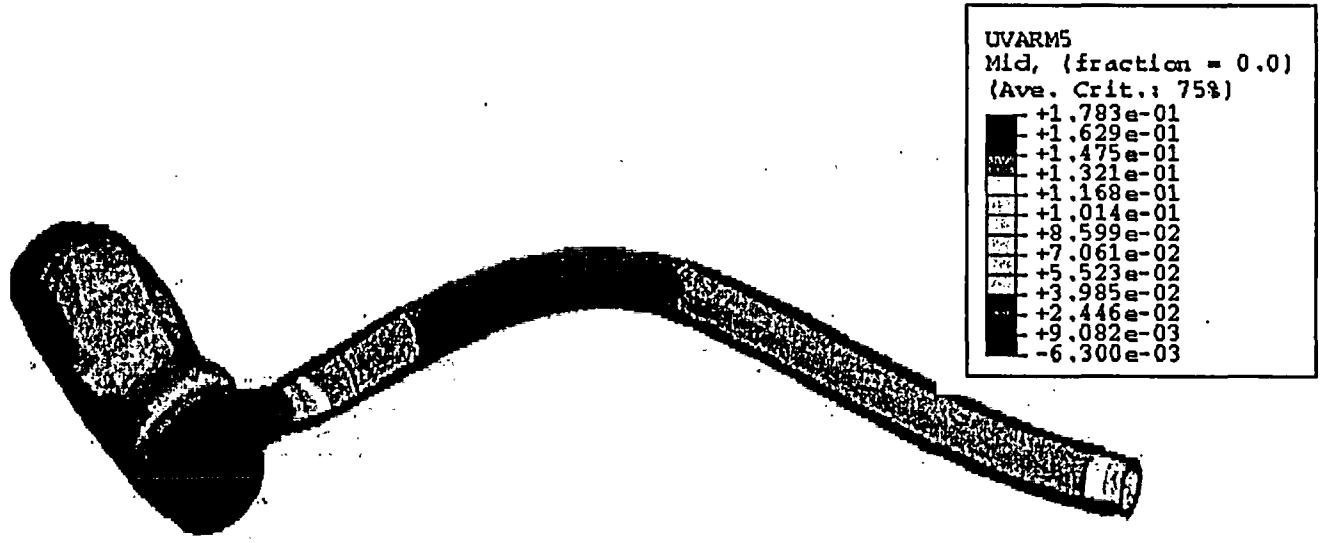
- Tensile damage is highest in the hot leg near RV nozzle
- Creep damage is highest in the surge line bend area.

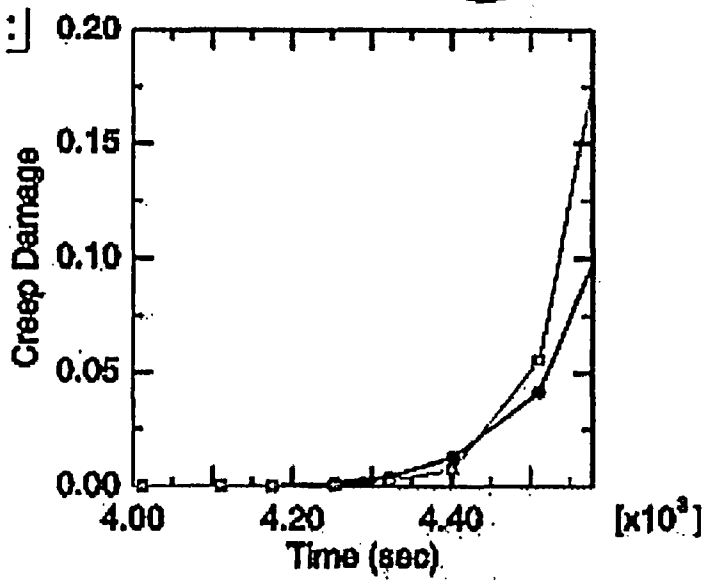
Inelastic Strain Accumulation



- 2% tensile membrane stress is accumulated in hot leg at 14,500 s
- 2% tensile membrane stress is accumulated in surge line at 14,550 s

Creep Damage Accumulation at 14,580 s

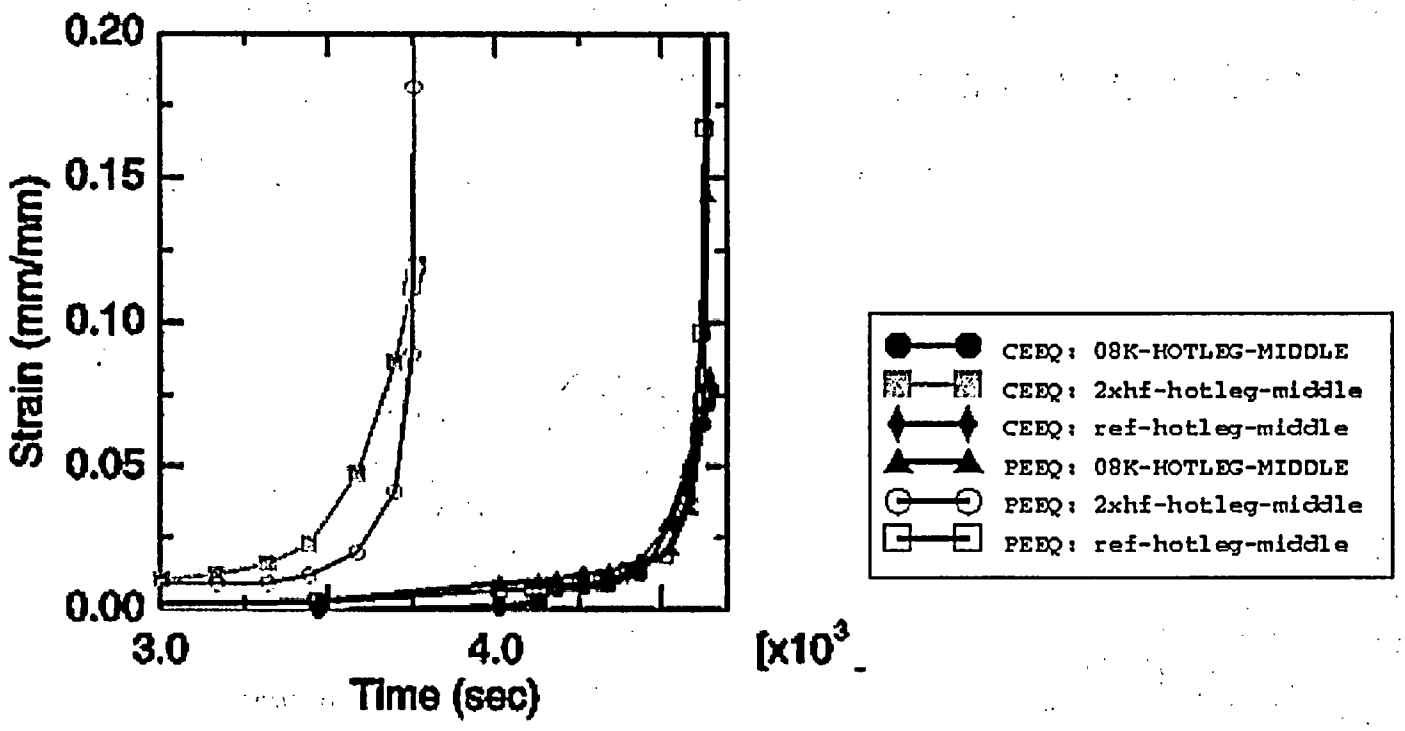




Creep Damage: REF-Hotleg-middle

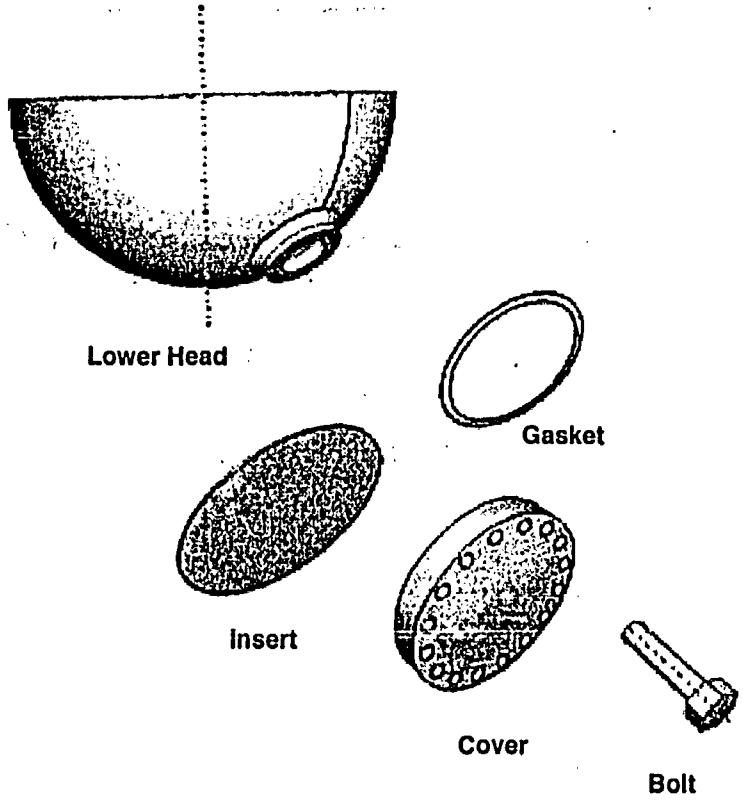
Creep Damage: REF-sgline-middle

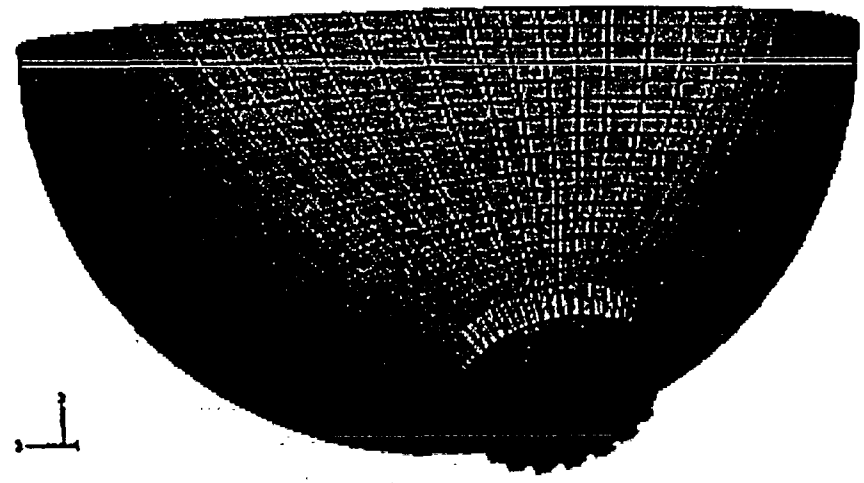
Sensitivity Analyses



- Reducing thermal conductivity by 20% has minimal effect
- Increasing surface heat flux by a factor of 2 has large effect.

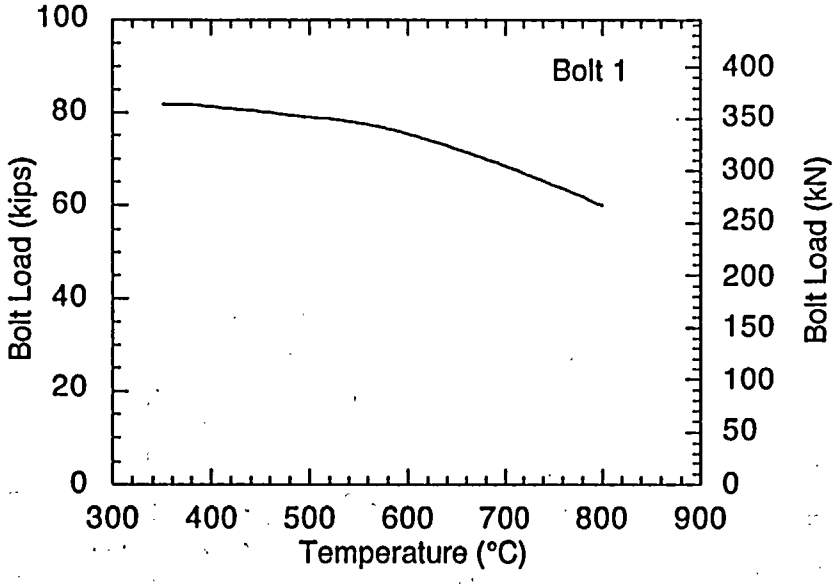
Steam Generator Primary Manway



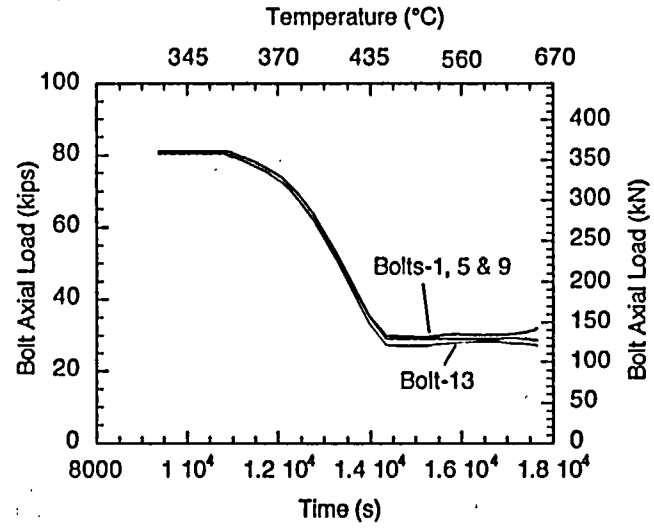


- Bolts pretensioned at room temperature. Manway uniformly heated.
- Gasket effect on stress and deformation is negligible
- Failure was defined as the creation of a flow area equivalent to a 2 in. dia. hole due to lifting of cover plate.

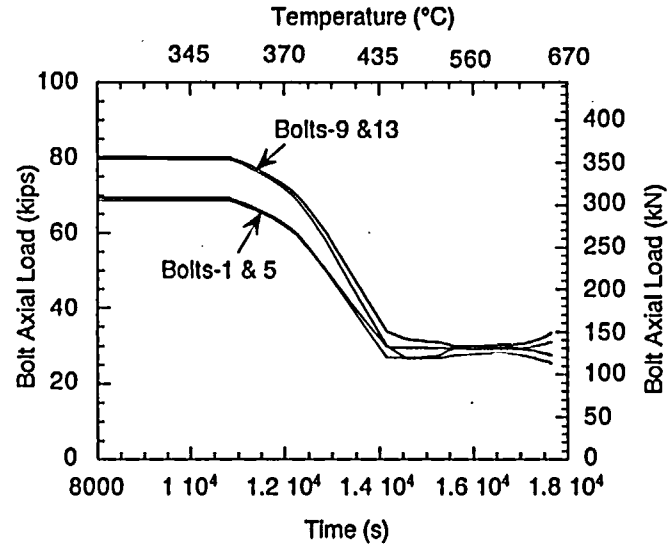
Bolt Load Relaxation



Without creep

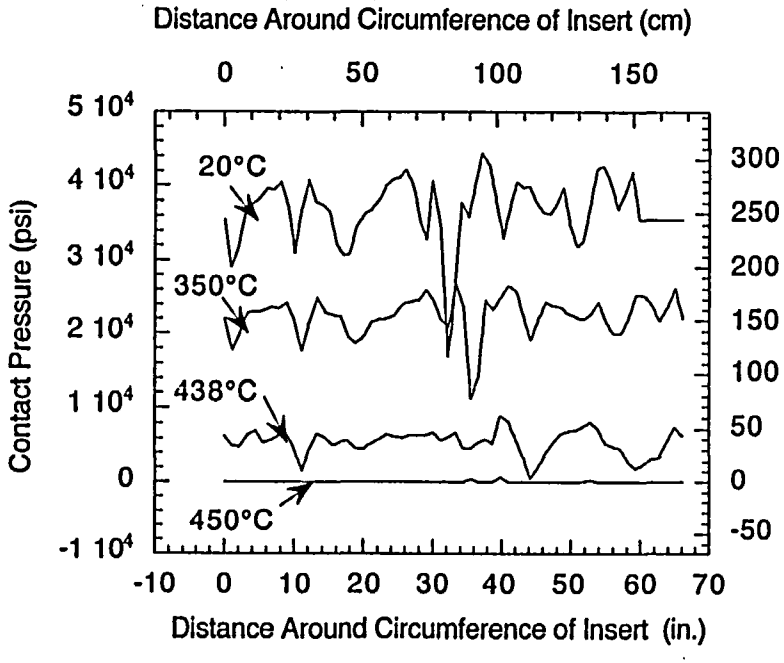


Half the bolts preloaded to 85% design preload ⇒

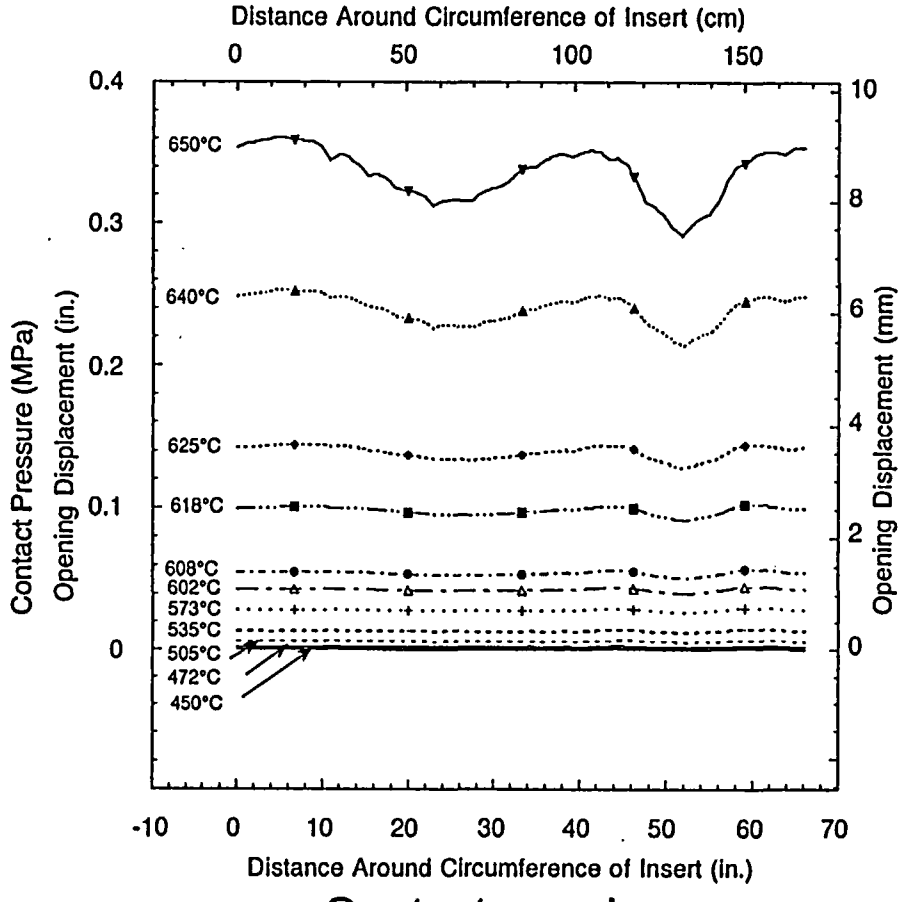


With creep

Contact Pressure and Contact Opening Between Cover Plate and Insert

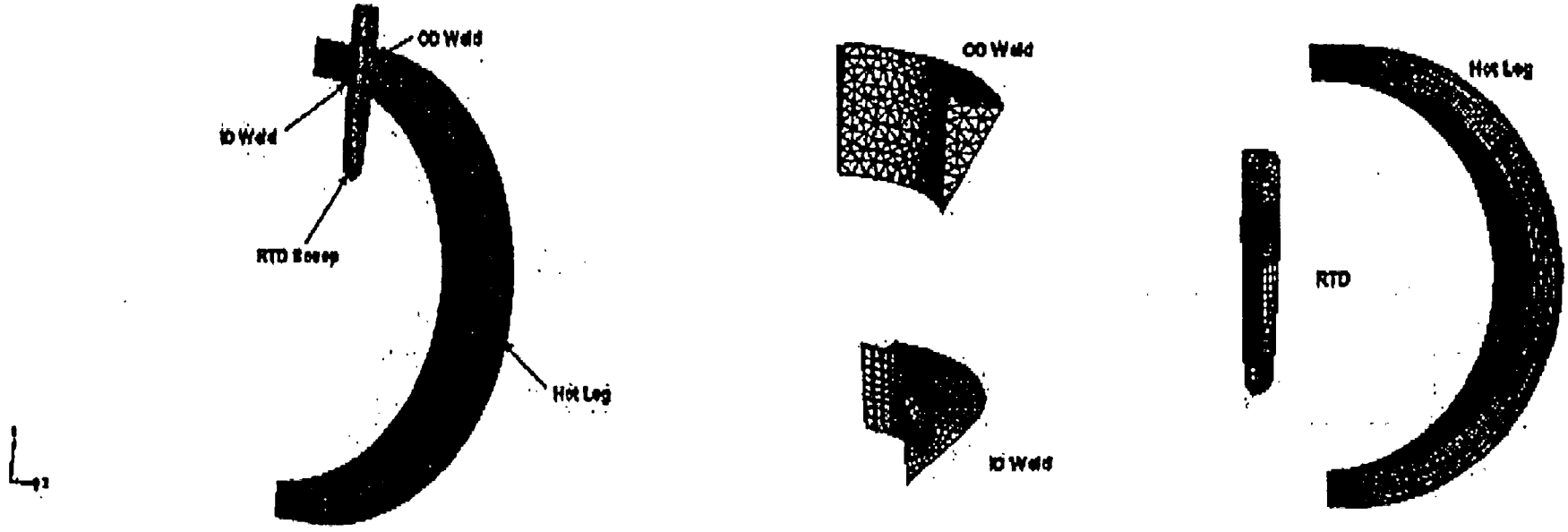


Contact Pressure



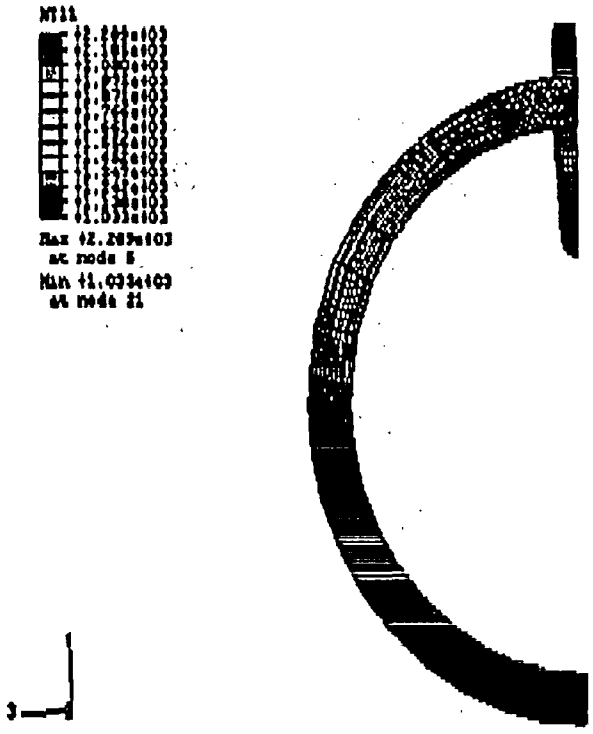
Contact opening

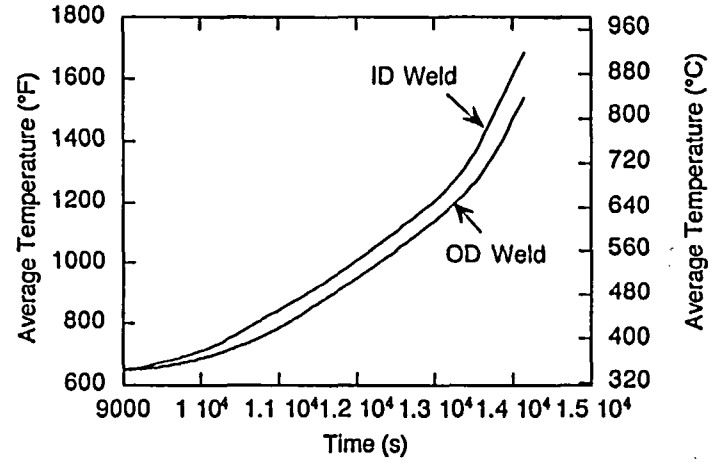
Resistance Temperature Detector (RTD) Welds



- Thermal analysis conducted first.
- Temperature and pressure fed into stress analysis.
- Failure defined as 2% average plastic strain or 20% average creep strain at the weld interface, whichever occurs first.

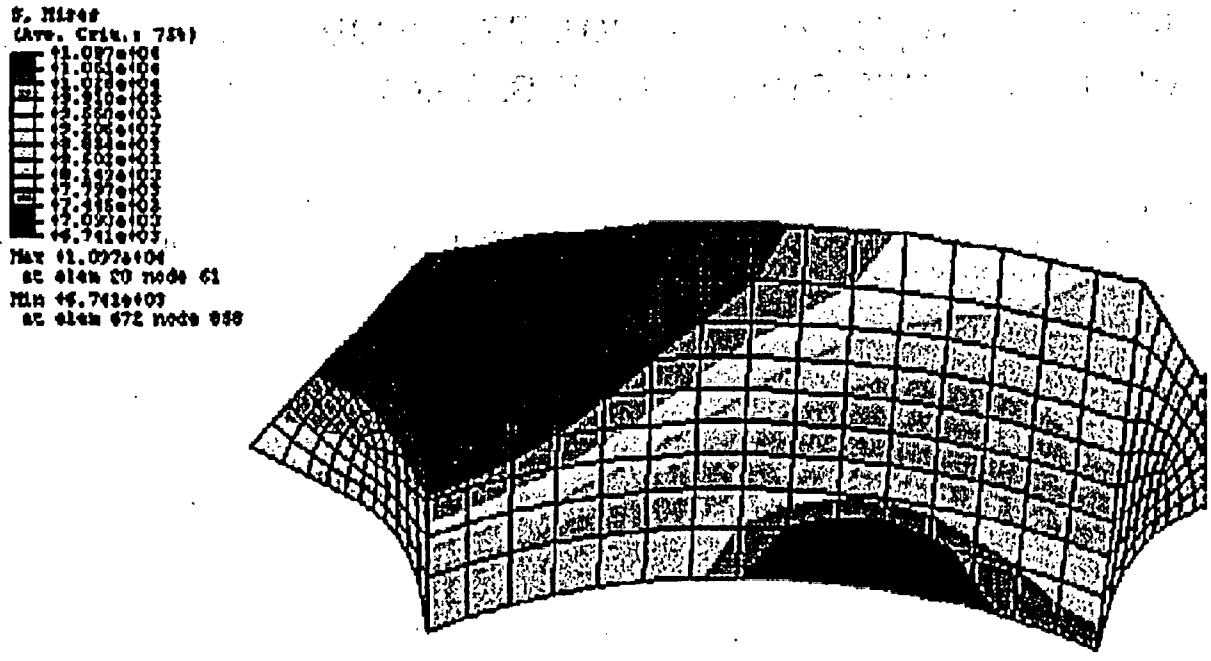
Temperature (in °F) in RTD at 14,400 s





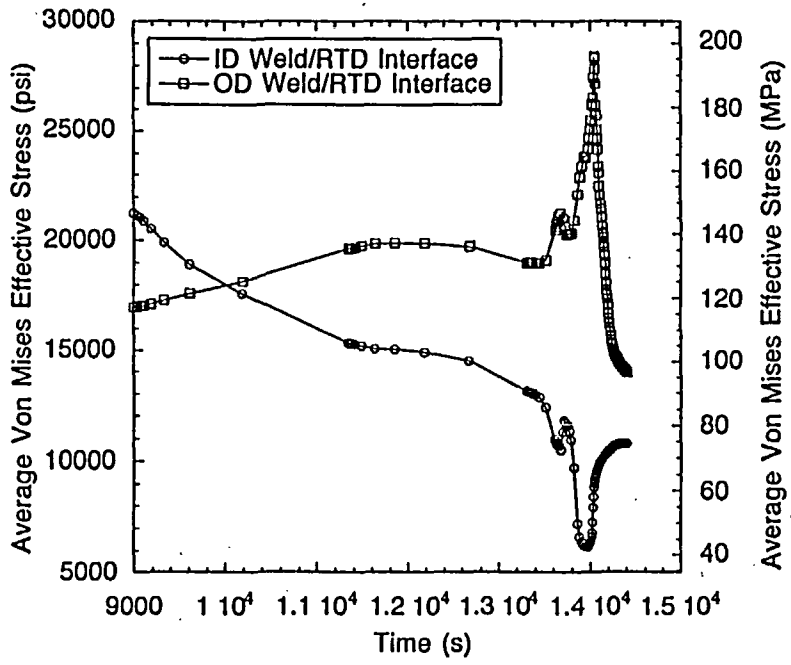
- RTD tip heats up fast
- Both welds heat up at approximately the same rate

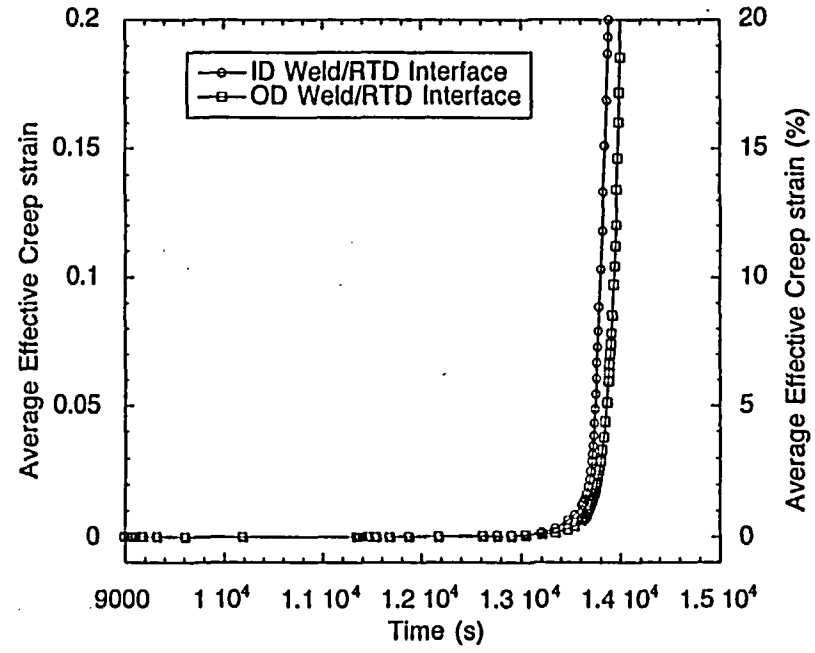
Stresses (in psi) at ID Weld/RTD Interface at 14,400 s



- No large scale plastic yielding is predicted

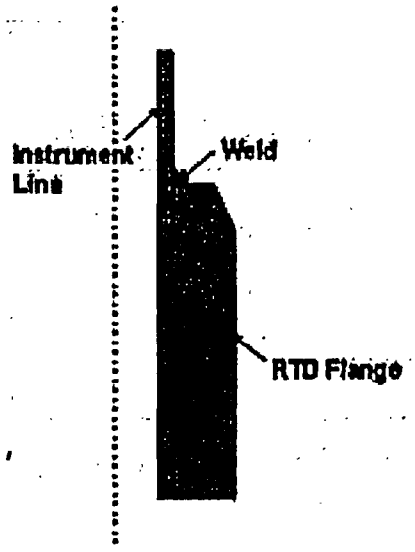
Time Variations of Average Interface Stress and Creep Strain

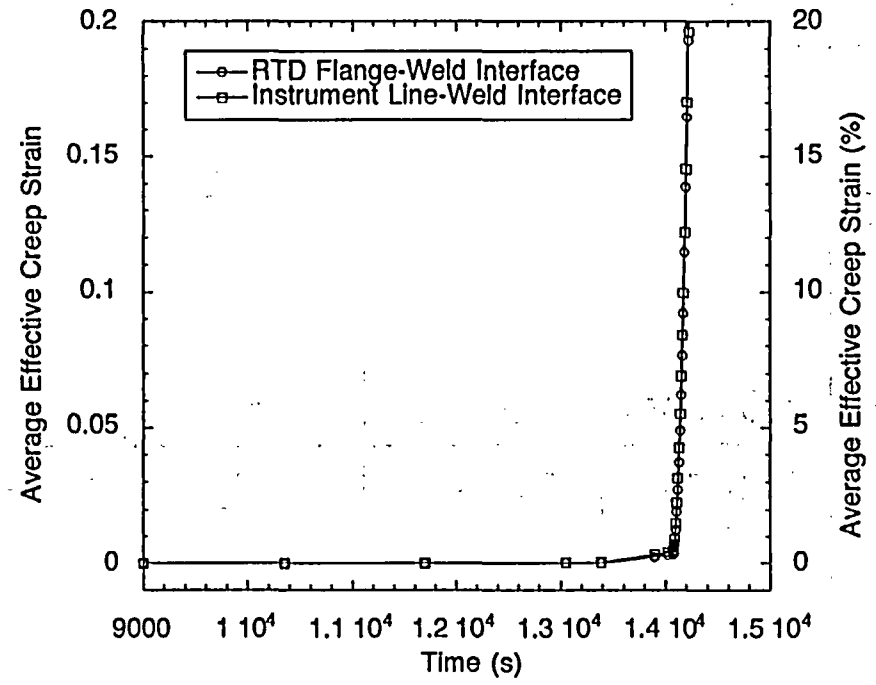




- Peaking of the stress occurs at about the same time (14,000 s) the hot leg temperature ramp increases from 6 to 24°C/min (see slide 14)

Instrument Line/RTD Flange Socket Weld



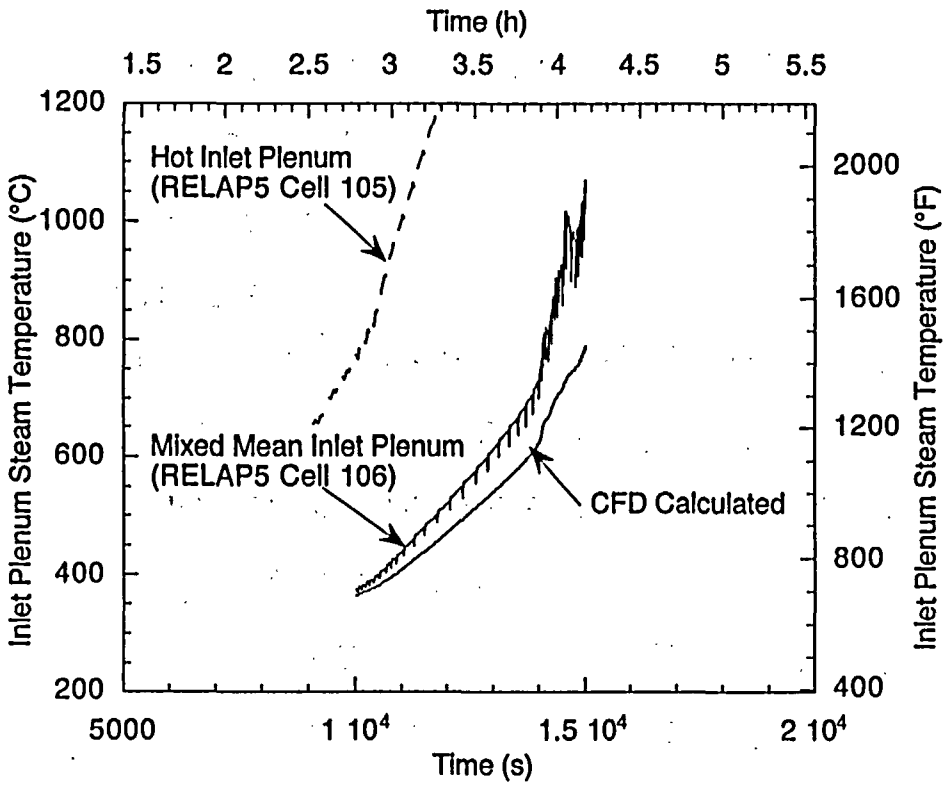


- Both weld interfaces undergo same creep strain history

Failure Times Summary

	Hot leg (HL) (near RV nozzle)	Surge line (SL) bend	HL / SL nozzle	HL elbow (at RTD hole)	RTD/HL weld	Instr. line socket weld	Manway
Ref. Case	14,500 s	14,550 s	14,250 s	No failure	13,890 s	14,230 s	16,726 s
$10x\dot{\varepsilon}_c$ reduced S_y (75 to 50 MPa)	14,380 s	14,350 s		–	13,710 s	14,110 s	15,600 s
2 x heat flux	13,200 s	14,500 s	12,750 s	13,750 s	13,706 s	–	15,200 s

Failure Times Discussion



- Failure times are close to 14,000 s in all cases
- Steam temperature ramp increases from 0.3 to 3°C/s at 14,000 s
- Failure times of components will always be close (< 15 min) no matter how detailed the analysis
- Better to focus on failure temperatures

Conclusions

- Predicted failure sequence for the reference case is:
  - RTD weld at 13,890 s (tensile or creep failure)
  - Instrument line socket weld at 14,230 s (creep failure)
  - Surge line to hot leg nozzle at 14,250 s (tensile failure)
  - Hot leg at 14,500 s (tensile failure)
  - Surge line bend at 14,550 s (tensile failure)
  - Manway (leakage) at 16,726 s (creep deformation)
  - Elbow – no failure predicted for reference conditions.
- Sensitivity analyses showed that the major factors controlling the failure times are
  - Surface heat flux
  - Creep rate equations
  - Tensile properties

Planned Future Work

- High temperature mechanical properties tests
  - bolt material (SA 193 B7)
  - gaskets
  - nozzle material (cast SA216 WCC)
- Analyses
  - Repeat the FEAs of hot leg-surge line, manway, and Westinghouse generic RTD welds for the new thermal-hydraulic base case
    - *More rigorous treatment of uncertainties*
    - *Estimate leak rate vs. time through manway*
  - Analyze RCP seal leakage
  - Evaluate CE RCS piping

Summary

- The following components of loop 4 (with pressurizer) of the Zion Nuclear Station were analyzed for SBO high/dry/low severe accident sequence ("old" base case) using detailed elastic-plastic-creep finite element analysis
  - The hot leg (including all nozzles and elbow)
  - SG primary manway
  - RTD and instrument line welds
- High temperature mechanical properties of carbon steel nozzle, manway cover bolts, and type 308 SS welds (HAZ) were identified as unavailable and needed to be developed.
- The predicted sequence of failure is RTD weld, followed by instrument line socket weld, surge-line-to-hot-leg nozzle, hot leg, surge line bend, and manway.
- Sensitivity analyses showed that the critical parameters that determine failure are surface heat flux, creep rate and tensile properties.

PRA SAI - SGCB

SGAP Project Briefing
Integrated SAI-SGCB PRA Methods

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David Bradley (Presenter)

Paul Amico

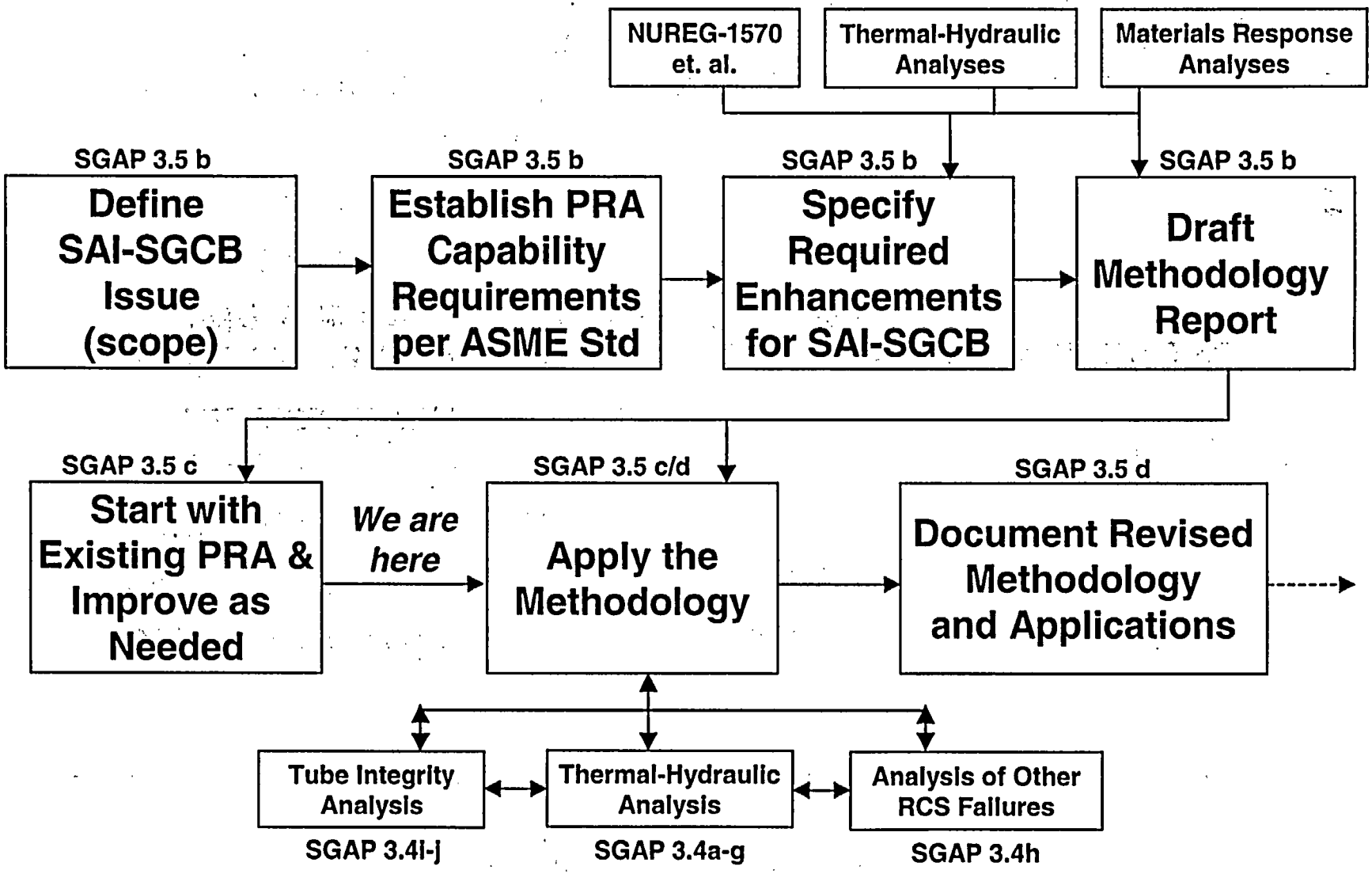
Science Applications International Corporation

ACRS Materials & Metallurgy and Thermal Hydraulic Subcommittees
Joint Meeting on SGAP and DPO Related Items
USNRC Headquarters • Rockville, MD • February 4, 2004

Scope of Study

- Severe accident-induced containment bypass scenarios only
  - No SGCB before core damage begins
- Initial efforts focused on developing methodology
  - Draft methodology report published June 2003
- Initial application to full power, internal events only
  - Sample plant: Westinghouse 4-loop
- Applications and extension to other plant types, external events, and low power and shutdown states to follow

Project Flow and Status



VG 3

Methodology

- Draft Methodology Report issued June 03
- Methodology based on SAI-SGCB being a risk-informed application
  - Define Capability Categories of PRA elements required for risk-informed SAI-SGCB
  - Enhance PRA Capability Category requirements to address unique SAI-SGCB needs
    - ✓ Partial failures
    - ✓ State changes
    - ✓ Errors of commission
  - Incorporate results from studies of unique phenomena associated with SAI-SGCB and other RCS failures (i.e., failures that would prevent containment bypass)

Overview of PRA Approach

- **Sequence definition**
- **Sequence binning**
- **Quantification**
- **Output from PRA are frequencies of scenarios that could lead to SAI-SGCB**
  - **Probability of SAI-SGCB for a given scenario determined in a separate analysis (also part of this effort)**

Sequence Definition

- **Starting point is a "capable" Level 1 PRA**
- **Use high-level tube integrity analysis to define P-T regimes of interest**
- **Use high-level thermal-hydraulic (T-H) analysis to determine how to get there**
- **Define combinations of events that can get you there**
- **To the extent possible, screen sequences with significant prior RCS failures within containment**

Sequence Binning

- Objective is to bin sequences that produce similar challenges to SG tube integrity
  - Reduce the size of the PRA model without adversely affecting model accuracy and completeness
- Use tube integrity analysis to assess sensitivity of tube failure to variations in T-H conditions
- Use T-H analysis to determine which sequences get to "similar" T-H conditions

Quantification

- Data for "typical" failures
- Data enhancements
  - Partial failures (e.g., valve leakage)
  - State changes (e.g., PORV reclosure)
- Human actions during severe accidents
  - Review procedures (including SAMGs)
  - Assess acts of commission and acts of omission
  - Apply elicitation process similar to that used successfully in PTS project
- Probabilistic analysis of SG tube failures and failures of other RCS components

Status of Ongoing PRA Activities

- **PRA model selected**
  - **Texas Utilities (TU) allowing us to use Comanche Peak (CP) PRA as the PRA generic model**
    - ✓ **Most "capable" of available PRAs**
  - **Only used to test the methodology; will not provide results applicable to Comanche Peak**
    - ✓ **Using generic Westinghouse information to incorporate SAI-SGCB into the CP model**
    - ✓ **Will simplify parts of the model not important to testing the methodology**
    - ✓ **T-H results and RCS component failure analysis will be based on Zion**

Status of Ongoing PRA Activities (con't.)

- **CP PRA model is running and the TU results can be duplicated**
- **Currently reviewing CP model against the ASME standard to see what enhancements will be needed**
- **Work on HRA-related enhancements has recently been initiated**

Overview of Probabilistic Analysis

Conceptual Approach

- **Use calculated P-T results for a given accident sequence**
- **Use assumed SG flaw characteristics for a given plant**
  - **Number of flaws of a given type, flaw locations, flaw size characteristics**
- **Perform Monte Carlo analysis to calculate probability distribution for time to reach leakage rate that would constitute a large release**
  - **Calculate failure time for each flaw**
    - ✓ **Assess both pop-through and burst failures**
  - **Calculate crack opening for each flaw and progressive leakage as additional tubes fail**
  - **Calculate time to reach large release leakage rate or time to reach leakage rate that would depressurize RCS and prevent further failures**

Overview of Probabilistic Analysis (cont.)

Conceptual Approach (cont.)

- **Combine with probability distributions for failure times of other RCS components (e.g., hot leg and surge line)**
  - **These failures assumed to prevent SGCB if they occur earlier**
- **Result is conditional probability of SAI-SGCB for the accident sequence**
- **Could repeat analysis with alternative P-T curves to determine uncertainty in the SAI-SGCB conditional probability due to uncertainty in T-H models**

Modeling of Tube Failure/Leakage

- Creep rupture is assumed failure mechanism for crack pop-through
- ANL creep rupture models will be used
  - Creep rupture models much more successful than flow stress models in predicting test results
- ANL tube leakage models will be used
  - Crack opening vs. time dependent on initial flaw size and P-T conditions
  - Models benchmarked against test data
- Limit-load analysis will be used to predict burst of tubes with through-wall cracks

Uncertainties To Be Considered

- **Flaw characteristics**
  - **Distributions for length and depth of flaws**
  - **Number and location of flaws**
- **Larson-Miller Creep Rupture Parameter**
  - **Distribution from ANL report**
- **Stress multiplier**
  - **Distribution from ANL report**
- **Tube Temperature**
  - **Radial variation between tubes (hot tube multiplier)**
  - **Axial distribution across tube length**
- **Uncertainties related to tube burst and leakage**
  - **TBD**

Uncertainties To Be Considered (cont.)

- **Pressure-Temperature history**
  - **Variations caused by T-H parameter uncertainty**
  - **Variations caused by model uncertainty (including use of different computer codes)**
- **Failure time of other RCS components**
  - **Subject to some of same uncertainties as tube failure**
  - **Examples: uncertainty in P-T history and in creep rupture parameters**

Status of Tube Failure Modeling

- **ANL creep rupture models coded into Excel**
- **Spreadsheet model benchmarked against ANL test results and published model predictions**
  - **Close match to published test results**
  - **Close match to published model predictions**
- **Crystal Ball Excel add-in being used for Monte Carlo analysis**
  - **Input uncertainty distributions for creep rupture model parameters, flaw size distributions**
  - **Sample calculations have used P-T histories based on SCDAP/RELAP runs**
- **Model calculates time of pop-through failure for each flaw**

Next Steps

- Incorporate burst failure and tube leakage models into spreadsheet model
- Build framework for aggregating leakage and identifying time that critical leakage level is reached
  - Critical leakage level to be established based on T-H and/or severe accident analyses
- Build framework for Monte Carlo analysis to calculate uncertainty distribution for this time
- Run series of calculations to determine sensitivity of results to P-T histories
  - Input to sequence binning process

Summary

- A probabilistic approach is being developed to assess SAI-SGCB
- Underlying assumption that SAI-SGCB analyses will be part of risk-informed application
- Starting point of PRA analysis is a "capable" PRA
  - Capabilities established based on SAI-SGCB requirements
  - Required enhancements in several areas have been identified
- Draft methodology has been prepared and application of the methodology is under way
- Methodology utilizes traditional PRA methods that have been adapted to the needs of the SAI-SGCB analysis

Summary (cont.)

- Updated Comanche Peak PRA being used in the initial application of the methodology
  - Will be enhanced as required to meet needs of the project
  - Will be used to determine frequency of conditions that could lead to SAI-SGCB
- Work also under way on approach to estimating the probability of SAI-SGCB for a given accident sequence
  - Perform Monte Carlo analysis to determine conditional probability of SAI-SGCB
    - ✓ Full spectrum of modeling uncertainties to be addressed
- Effort will require close interaction with other parts of the SG program
  - T-H analysis
  - Tube integrity analysis
  - Analysis of failure of other RCS components