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December 10, 1999

MEMORANDUM TO: Edwin M. Hackett, Acting Chief
Materials Engineering Branch
Division of Engineering Technology
Office of Nuclear Regulatory Research

FROM: Joseph Muscara
Materials Engineering Branch
Division of Engineering Technology
Office of Nuclear Regulatory Research

SUBJECT: EXPERTS' MEETING ON JET IMPINGEMENT EFFECTS AND LEAK RATES FROM STEAM GENERATOR TUBES DURING SEVERE ACCIDENTS

Attached are minutes for the subject meeting held at Argonne National Laboratory (ANL) on November 19, 1999. The minutes were prepared by ANL staff. I have reviewed the minutes, and my comments were incorporated. The minutes accurately reflect the discussions held at the meeting.

Attachment: As stated

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UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

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## Meeting Minutes

### Experts' Meeting on Jet Impingement Effects and Leak Rates from Steam Generator Tubes During Severe Accidents held at Argonne National Laboratory, November 19, 1999

An Experts' Meeting on Jet Impingement Effects and Leak Rates from Steam Generator Tubes During Severe Accidents was held in Building 212, Room B-201 of Argonne National Laboratory on November 19, 1999. Attached are the agenda for the meeting and a list of attendees. Also attached are copies of the presentation materials for the presentations by Schaperow, Majumdar, and Diercks listed in the agenda.

Joe Muscara (NRC) opened with introductory remarks on the purpose of the meeting. He stated that the NRC is interested in evaluating the possibility that the jet of superheated steam, hydrogen and entrained particles emanating from a cracked tube may penetrate the neighboring tube during severe-accident transients. This requires a determination of the leak rate from tubes with throughwall cracks of various lengths under severe-accident conditions. In the absence of data on leak rates under the conditions of interest, one would need to calculate the crack opening areas under these conditions to estimate the leak rates. Besides information on the mechanical properties of Alloy 600 tubes at the temperatures of interest, we need to know if (and how) creep and creep crack growth play a role in the crack opening areas developed under the time/temperature/pressure exposures during severe accidents. Also, information is needed on whether the fluid escaping the crack will cause erosion of the crack walls, thereby increasing the crack opening areas.

Following this, Jason Schaperow (NRC) made a presentation entitled "Thermal Hydraulic Conditions in the Reactor Coolant System for Evaluating Steam Generator Tube Integrity." In this presentation, he described the temperature, pressure, and flow conditions anticipated in a nuclear steam generator during a severe accident with station blackout and loss of feedwater. During Shaperow's presentation, Mati Merilo (EPRI) raised a number of points. He first noted the EPRI and NRC analyses of the postulated severe-accident scenario differ somewhat in that EPRI assumes that the water level in the reactor pressure vessel drops rather slowly once it has fallen below the level of the hot fuel, whereas the NRC analysis assumes that the water level continues to drop more rapidly. Schaperow responded that radiative heating and thermal conduction through the structures would be expected to cause a significant boil-off of coolant even after it is no longer in contact with the fuel. Despite these differences in the analyses, it was noted that the temperature history predictions calculated by the EPRI codes and the NRC seem to be in reasonably close agreement at this time.

Merilo then raised a question on the event-tree analysis example given in Schaperow's presentation. He noted that if the core damage frequency (CDF) due to station blackout with loss of turbine-driven auxiliary feedwater (SBO-TDAFW) is assumed to be $1 \times 10^{-5}$, then the probability of containment bypass by a subsequent series of events (e.g., outcome R4 in Shaperow's figure) should be substantially lower and presumably below the $1 \times 10^{-6}$ threshold level. Schaperow responded that the initial SBO-TDAFW CDF was plant specific, and for some plants the probability of containment bypass would not be below the threshold level for outcome R4.

Mike Mayfield (NRC) observed that the rapid fluctuations indicated in the plot of reactor cooling system pressure vs. time for Surry Case 6 in Schaperow's presentation were associated with the continuous opening and closing of the pressure-operated relief valve. He noted that one might expect the relief valve to eventually fail under such rapid cycling, probably in the open or partly open position. Mayfield also stated that while a great deal of attention has been given to the steam generator tubes in a severe accident, there is now a growing feeling that the overall analysis must take more account of potential failures of other pressure-boundary components, e.g., the hot leg, the surge line, etc. It was noted that typically we do not expect cracking in these components as we do in the steam generator tubes. However, the surge line is typically fabricated of cast stainless steel, and its inspection by conventional NDE techniques is inherently more difficult than for the steam generator tubes or other wrought pressure-boundary components.

Saurin Majumdar (ANL) followed with a presentation entitled "High-Temperature Behavior of Flawed Steam Generator Tubing" in which he described work conducted at ANL on the pressure testing and analysis of flawed and unflawed steam generator tubes under simulated severe-accident conditions. Most of the presentation focused on the previous work used to develop a high-temperature failure model for the tubes, although he also presented the results of a test to determine the time-dependent crack opening displacement and creep-crack growth in steam generator tubing at 700°C. Ashok Saxena (Georgia Tech) commented that the loss of constraint during high plasticity deformation would lead to larger crack openings than would be predicted from the ANL analysis, which was based on the deformation plasticity solutions in the EPRI Fracture Mechanics Handbook.

Dwight Diercks (ANL) then followed with a short presentation entitled "Assumptions and Uncertainties in Analyzing Possible Erosion/Ablation Damage of Steam Generator Tubes." In addition to summarizing the principal assumptions and uncertainties in the analysis, he described experiments initiated at ANL on creep crack opening in Alloy 600 and described proposed experiments on the erosion of steam generator tubes under severe-accident conditions using a facility at the University of Cincinnati. During this presentation, he stated that the jet escaping a leaking tube is predicted to contain entrained Ag particles from the control rods, as well as lesser quantities of $In_2O_3$, $CsMoO_4$, $SnO_2$, CsI, and other constituents. This is based on the assumption that the primary source of any particulate loading are the aerosol particles which form from the volatile species generated by the melting core. Because the velocities due to the natural circulation flows are low, there was agreement that any larger debris type particles would be unlikely to escape from the core region or would settle out before they reached the steam generator. Peter Nelson (ABB-CE) noted that CE-design PWRs use $B_4C$ rather than Ag in the control rods, and so no Ag would be expected in the jet for a CE plant. Merilo noted that other analyses had predicted the presence of CsH in the jet, but its presence was not indicated in the NRC analysis. He suggested that we may want to look at the results of the LOFT tests to get more information on the type and nature of particles present in the superheated steam. Schaperow and Merilo agreed that the particles would form irregular agglomerations, but they would be very smal,l with most less than 2–3 µm.

The possible erosion/ablation damage in steam generator tubes under the postulated severe-accident conditions described was then discussed. John Stringer (EPRI) offered several "rules of thumb" regarding erosion. He first stated that particles below ≈5 µm in size tend to be considerably less damaging in erosion than larger particles. Such small particles tend to follow streamlines and thus are turned away as they approach the solid surface. Particles between 5 and 20 µm in size can produce significant erosion in thousands of hours, and larger particles can produce damage in shorter times. Wright agreed that this was the case, and Stringer agreed to prcvide references for this size effect. Stringer added that these smaller particles also would not be expected to erode the crack walls and thereby enlarge the crack opening.

Stringer observed that there were several mechanisms for erosion: cutting erosion in which particles cut material from the surface, including "droplet" erosion in which even soft particles can remove material by cumulative damage processes (fatigue), and erosion-corrosion in which a protective corrosion film is removed by mechanical damage so that additional erosion could occur. Cutting erosion is the most rapid of the processes.

Stringer noted that cutting erosion in metals is more favorable at lower temperatures, typically <250°C for steels, than at higher temperatures. This observation was confirmed by Wright, who added that, for classical cutting erosion in the absence of corrosion, the erosion rate did not vary greatly for different alloys of similar hardnesses. Finally, Stringer stated that the rate of material loss due to erosion is typically of the order of 0.1% of the mass flux of erosive particles striking the surface. He observed that the 100 $g/m^3$ of Ag particles predicted to be present in the jet represented a rather low concentration, even if the Ag particles were assumed to be effective erodents.

Stringer said that he would not expect significant cutting erosion from the Ag particles or from most of the other particles predicted to be present in the escaping jet. The calculated median particle size of 1.5 μm for the present scenario also indicates low erosion, but Stringer noted that it would be desirable to know the expected size distribution, since larger particles (particularly those >5 μm) control the erosion rate. He also questioned the assumption of chemical equilibrium that was used in calculating the nature and sizes of the particles in the stream. Schaperow responded that because of the relatively high temperatures and long transit times for the particles to be transported to the crack, chemical equilibrium would be expected.

Stringer stated that there were special circumstances where erosive failures could occur in very short times. He cited the example of a fluidized-bed coal combustor in which tube failure occurred in as little as 5-10 minutes of operation in contact with hard abrasive particles ≈800 μm in size moving at velocities that were probably similar to those predicted for the steam generator severe-accident scenario.

Stringer also noted that water droplet erosion would not likely be a problem. First of all, he doubted that there would be any condensation in the escaping jet from the leaking steam generator tube. Even if there were, the small droplets that formed would be unlikely to cause significant erosion. Stringer stated that water droplet erosion in steam turbines occurs primarily from the coalescence of the fine droplets entering the turbine into larger drops, which are then struck by the rotating blades ("baseball bat erosion"). Ian Wright (ORNL) added that water droplet erosion had been thoroughly studied by the Air Force, but primarily on polymeric materials. He was aware of some limited work that had been conducted on Al alloys. Also since droplet erosion (whether water or soft Ag particles) is a cumulative damage process, neither Wright nor Stringer felt that it could be significant for the time scales and mass flows of interest.

The possible contribution of corrosion to the failure of steam generator tubes was also considered. It was agreed that CsI was probably the most corrosive species predicted to be present in the jet. However, Stringer and others argued that times of the order of days or more would be required to produce significant corrosive effects, while the severe-accident scenario was predicted to run its course in an hour or less.

The discussion then turned to the possibility of other more erosive particles being somehow entrained in the jet. In Canadian reactors with ferritic steel primary piping, magnetite is commonly present on the primary side of the steam generator tubes and is a cause for significant wear in eddy current probes. In U.S. reactors, significant quantities of magnetite are typically present on the secondary side of the steam generators, primarily as sludge piles atop the tubesheet and tube support plates. Some participants speculated that an escaping steam jet blowing through such a region might entrain enough magnetite to produce significant erosion, although magnetite was not regarded as a particularly abrasive erodent. Others felt that the sludge was sufficiently "sticky" that the jet would simply cut a hole through the sludge and no further entrainment would occur. Stringer noted that particle entrainment in a jet takes place in a distance of ≈3 times the diameter of the hole through which the jet is escaping. Thus, for example, a steam jet exiting through a 2-mm-diameter hole would entrain particles up to essentially the gas jet velocity within a distance of ≈6 mm.

The possibility of the leaking crack plugging with time was also discussed. It was agreed that the likelihood of crack plugging was dependent on the crack size, the particle size, the rate of crack opening, etc. Several participants questioned whether it was reasonable to expect a crack with an opening width of the order of hundreds of μm or more to be plugged by particles with a median size of 1.5 μm. Stringer stated that David Rosner of Yale University was an authority on the condensation and deposition of small particles and might be able to help with that question.

The details of the proposed erosion experiments to be conducted at the University of Cincinnati were also discussed. Stringer and Wright were not sure if the particle feeding system for that erosion rig could handle particles with a median size as small as 1.5 μm. Others felt that conducting the tests with somewhat larger particles might be more desirable in any case, since 1.5 μm was the predicted median particle size, and larger (and therefore more erosive) particles were likely to be present in the size distribution. It was also suggested that bounding experiments could be conducted using particles more abrasive than Ag, particularly if suitable Ag particles could not be obtained. If no significant erosion was observed in such experiments, then erosion with Ag particles could be ruled out. Stringer noted that Joe Drenner at ABB-Combustion Engineering in Windsor, CN had an erosion rig that was set up to inject steam into the erosive stream. However, he was not sure if the gas stream and particle velocities were high enough to simulate the steam generator scenario. Wright suggested rotating-arm erosion rigs as another possibility for conducting the proposed tests.

The discussion then turned to the question of the effects of plasticity and creep on the crack opening area in steam generator tubes during a severe accident. Majumdar discussed the first creep crack opening rate test, which had just been completed at ANL. The test specimen was a 7/8-in.-diameter, 0.050-in.thick Alloy 600 steam generator tube containing two symmetric circumferential EDM notches each extending 45° around the circumference. The specimen was loaded in axial tension at 27 ksi, and two notches were used rather than one to avoid bending moments on the specimen during the test. The EDM notches, which had initial widths of ≈0.007 in., grew to widths of ≈0.072 in. after 1 h,, with the opening rate being most rapid in the initial stages of the test and then leveling off. However, no increase in crack length was observed, which is consistent with results reported in the literature by Sadananda and Shahinian (Met. Trans. A, 14A, 1983, p. 1467). After about 1 h, the specimen began to neck down and the test was terminated.

Saxena commented that the initial cracks in the present specimen were probably sufficiently long that they "saw" each other, so that they did not behave like small cracks in an infinite plate. Instead, the test simulated the behavior of two large ligaments in a cracked specimen. He suggested that a metallographic examination of this first specimen be carried out to determine if crack tunneling was present at the ends of the flaw. He stated that a test on a specimen containing a single short circumferential notch would better simulate the situation we are dealing with and could be more readily analyzed. Overall, Saxena commented that ANL's current approach to the analysis of the failure of flawed tubes under internal pressurization and creep was sound, but he suggested that more use be made of modern finite-element analysis techniques.

The question of determining the velocity of the jet exiting a cracked steam generator tube in a severe accident was also considered. Merilo felt that the problem was not as complicated as some made it out to be, and he doubted that the exiting jet attained supersonic velocity at any point. His suggested approach to the calculation of the jet velocity differed somewhat from that previously performed by the NRC (NUREC-1570), where a shock is assumed to form at the exit. After the shock, the jet expands with the angle of expansion on the order of 10–15° (NRR analysis used 15°). However, both approaches agreed that the jet was subsonic at the point of impact. Merilo suggested that the simple calculation of jet velocity based on classical gas dynamics could be confirmed experimentally using a prototype setup and a hot-wire anemometer. He expressed doubts that the results from the proposed experiments at the University of Cincinnati could be easily translated to the present problem, since the velocity of the jet escaping from a cracked steam generator tube probably varied over the spread of the jet.

Tom Wei and Yong Shin (ANL) proposed to determine the jet velocity by using an existing three-dimensional gas-dynamics computer code utilized at ANL. They estimated that ≈2 months would be required to adapt the code to the present problem and perform the analysis. Shin noted that 0.25 to 0.40-in. spacing between the tubes is tight and is likely to produce an "obstructing" effect that will significantly influence the jet flow. Merilo agreed that this was likely to be the case, but there was a general consensus that the simplified jet analysis used would give conservative results and it would be better to get some preliminary results from erosion tests to determine whether erosion really is a significant problem before embarking on more elaborate calculations.

The experts agreed that in any erosion experiment, the proper simulation of the particles in the stream in terms of size, chemistry, and particle loading was the most crucial element in conducting a meaningful experiment. Wright suggested that the particles used in the experiment should be the worst-case particles selected from the spectrum of particles predicted to be in the stream. He stated that the angle of attack strongly influenced the erosion rate, and it was noted that the angle of attack in the real erosion situation would be variable along the contour of the eroded hole as the jet cut through the wall. Muscara and Diercks noted that it was intended to include the "worst case" angle of attack in the proposed experiments.

**Recommendations and Action Items**

The following recommendations and action items resulted from the meeting:

1. The existing literature on particle erosion should be reviewed to determine if erosion is plausible for the conditions defined, in particular the small size of the particles. Particular attention should be given to particle size and temperature effects. Wright stated that Peter Blau at ORNL had possession of a large collection of papers on erosion, and Wright could assist ANL in getting access to these papers.

2. The physical and chemical nature of the sludge should be reviewed to determine if its entrainment in the escaping jet is likely.

3. The literature on aerosol sizes observed in severe-accident experiments (e.g., LOFT) should be reviewed to determine if the particle sizes predicted for the present situation are reasonable. Schaperow has access to this body of literature.

4. A limited number of creep crack opening rate experiments should be conducted using a single crack. The experiment should be designed to validate the model that is to be applied to it.

5. More use should be made of modern finite-element analysis techniques in the analysis of the failure of flawed tubes under internal pressurization and the behavior of flaws under creep.

6. A simple analysis of jet velocity using classical gas dynamic theory should be carried out. It was suggested that expertise existed within the NRC to perform this analysis.

## AGENDA

## Experts' Meeting on Jet Impingement Effects and Leak Rates from Steam Generator Tubes During Severe Accidents

**November 19, 1999**

| Time | Topic | Presenter |
|---|---|---|
| 8:30 - 8:45 | Introductory Remarks | J. Muscara, NRC |
| 8:45 - 9:30 | Thermal Hydraulic Conditions in the Reactor Coolant System for Evaluating Steam Generator Tube Integrity | J. Schaperow, NRC |
| 9:30 - 10:20 | High-Temperature Behavior of Flawed Steam Generator Tubing | S. Majumdar, ANL |
| 10:20 - 10:30 | Break | |
| 10:30 - 10:40 | Assumptions and Uncertainties in Analyzing Possible Erosion/Ablation Damage of Steam Generator Tubes | D. R. Diercks, ANL |
| 10:40 - 12:00 | Discussion of Possible Erosion/Ablation Damage | All |
| 12:00 - 1:00 | Lunch | |
| 1:00 - 2:00 | Discussion of Plasticity and Creep Effects on Crack Opening Area during Severe Accident | All |
| 2:00 - 3:00 | Discussion of Gas Dynamics, Expected Jet Velocities, and Particle Loadings | All |
| 3:00 - 3:30 | Summary | All |

**Experts' Meeting on Jet Impingement Effects and Leak Rates from Steam Generator Tubes During Severe Accidents**
**Argonne National Laboratory**
**November 19, 1999**

**List of Attendees**

| Name | Affiliation | Phone/Fax/e-mail |
|---|---|---|
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*United States*
*Nuclear Regulatory Commission*

# Thermal Hydraulic Conditions in the Reactor Coolant System for Evaluating Steam Generator Tube Integrity

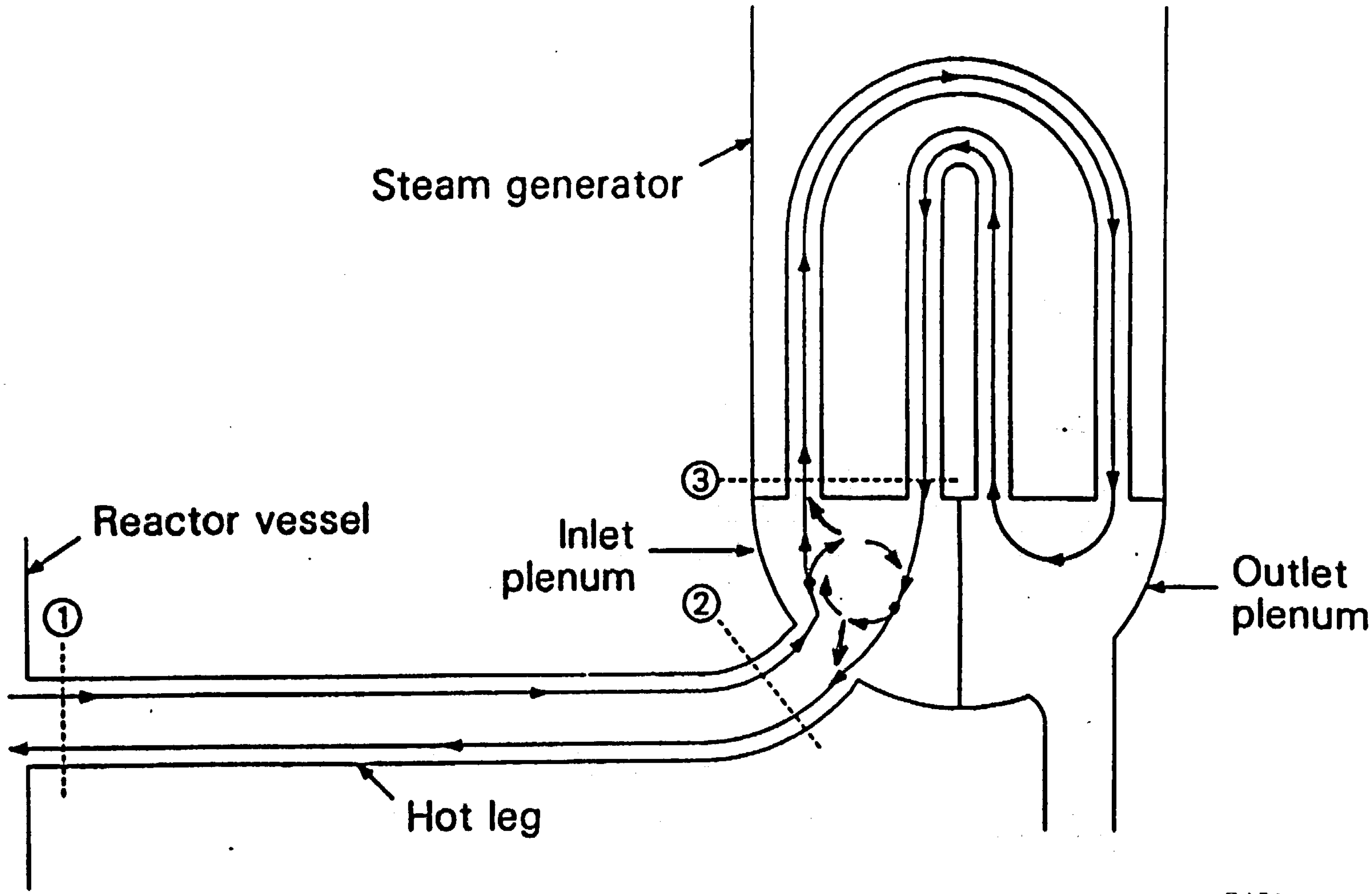
**Presentation at Public Meeting on Steam Generator Tube Integrity**

**Jason H. Schaperow**
**Safety Margins and Systems Analysis Branch**
**Division of Systems Analysis and Regulatory Effectiveness**
**Office of Nuclear Regulatory Research**

**November 19, 1999**

## BACKGROUND (continued)

- Integral experiments were conduced by W at 1/7 scale under an EPRI/NRC cooperative program to investigate severe accident natural circulation in PWRs with U-tube steam generators
  - Several series of tests conducted, using water, low pressure $SF_6$ and high pressure $SF_6$
- Low pressure tests showed (by using dye in the fluid), that a stable countercurrent flow was present in the hot legs. Flow patterns were consistent over a wide range of conditions.
- High pressure $SF_6$ tests provided data for validation of codes. Five series of experiments with high pressure $SF_6$ were conducted. Temperature measurements in the steam generator inlet plenum and tube inlets indicated that the fluid in the inlet plenum was well mixed.

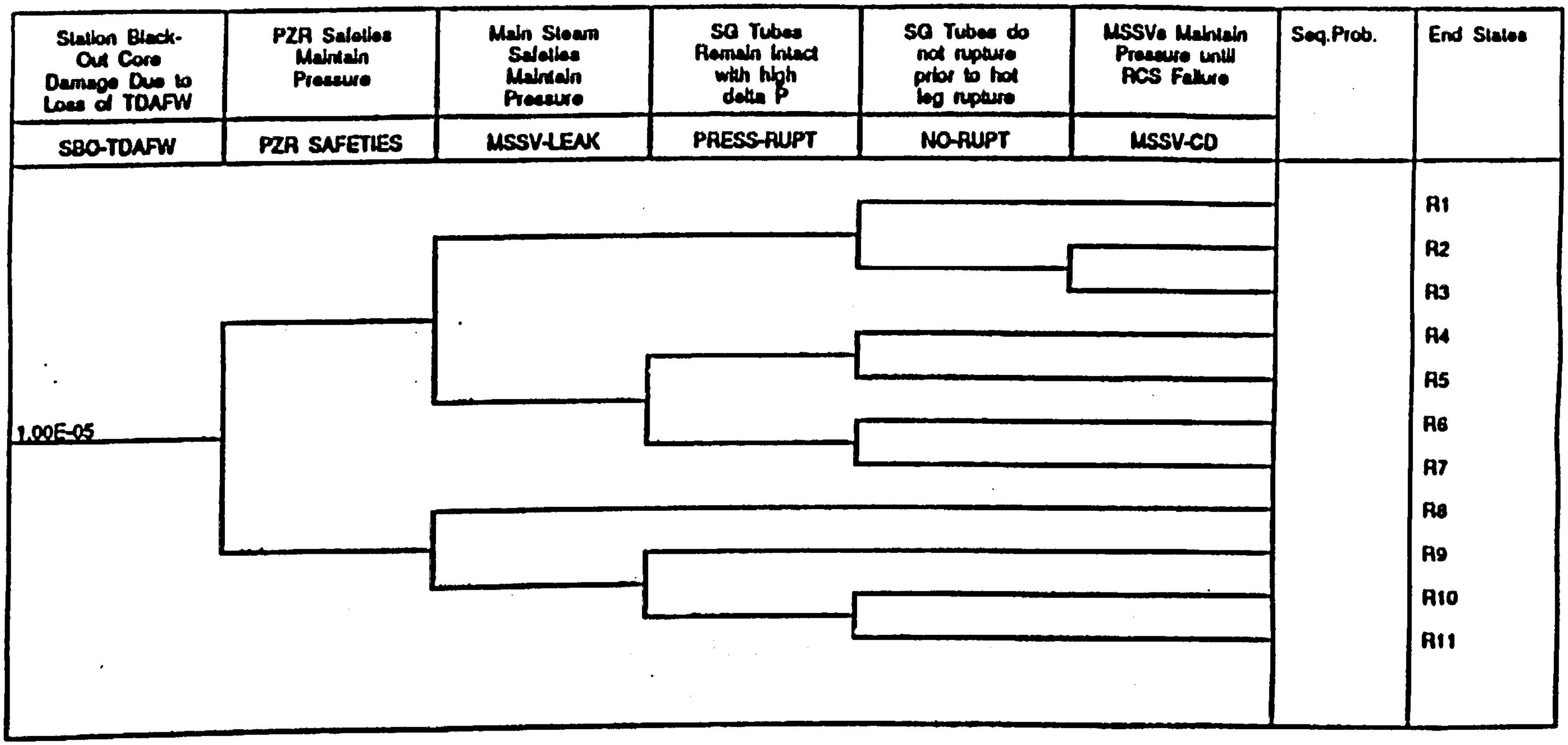



P431-LN87031-3

**Figure 2.** Hot leg natural circulation stream flows.

# SUMMARY (continued)

- Analyses using SCDAP/RELAP5 have been performed for representative plants for scenarios of interest (high pressure TMLB' sequences with depressurized secondary side) to estimate effects of high temperature gas circulation
  - SCDAP/RELAP5 analyses predict failure of hot leg or surge line before unflawed SG tubes
  - Sensitivities on thermal hydraulic modeling did not alter conclusion on tube integrity

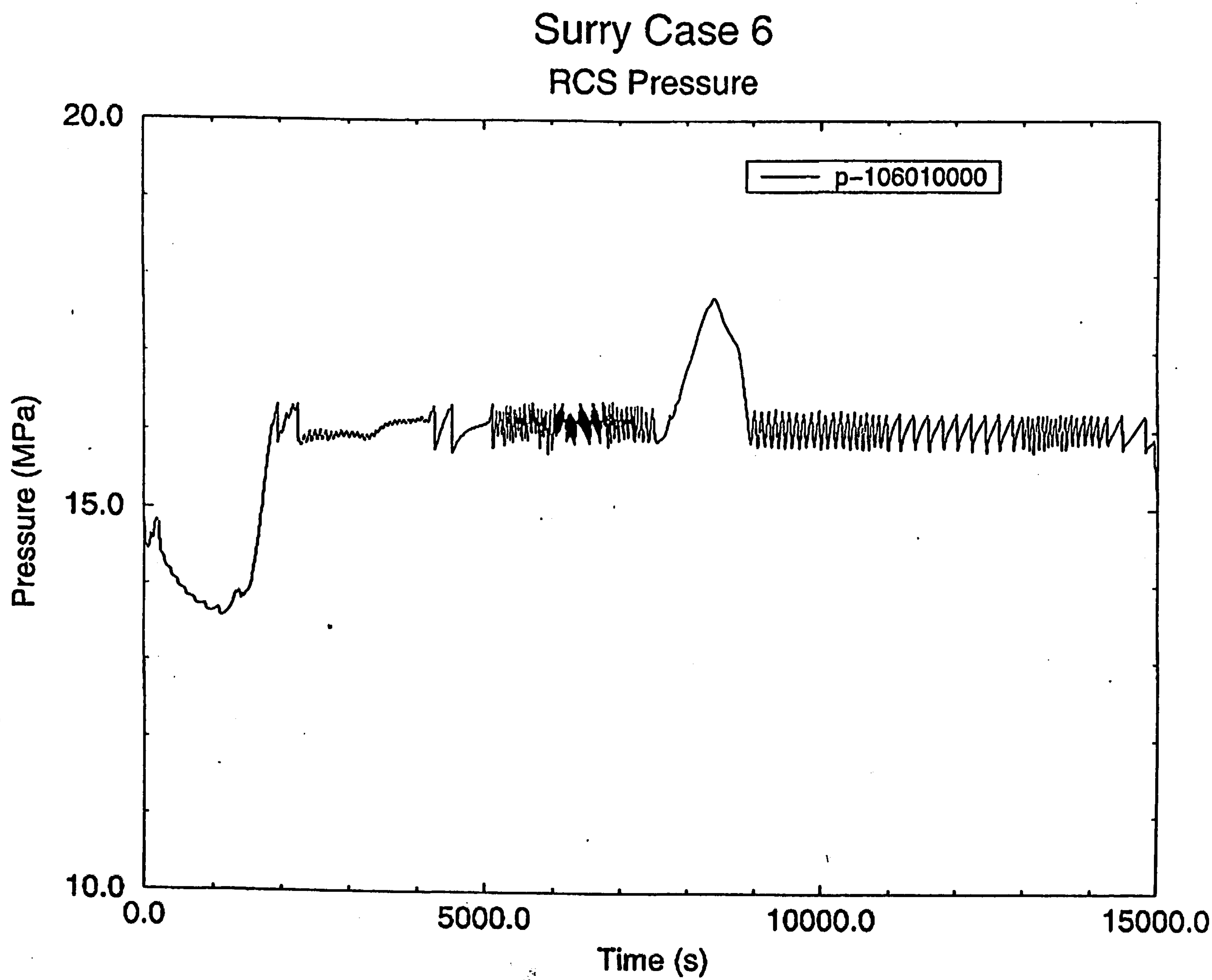


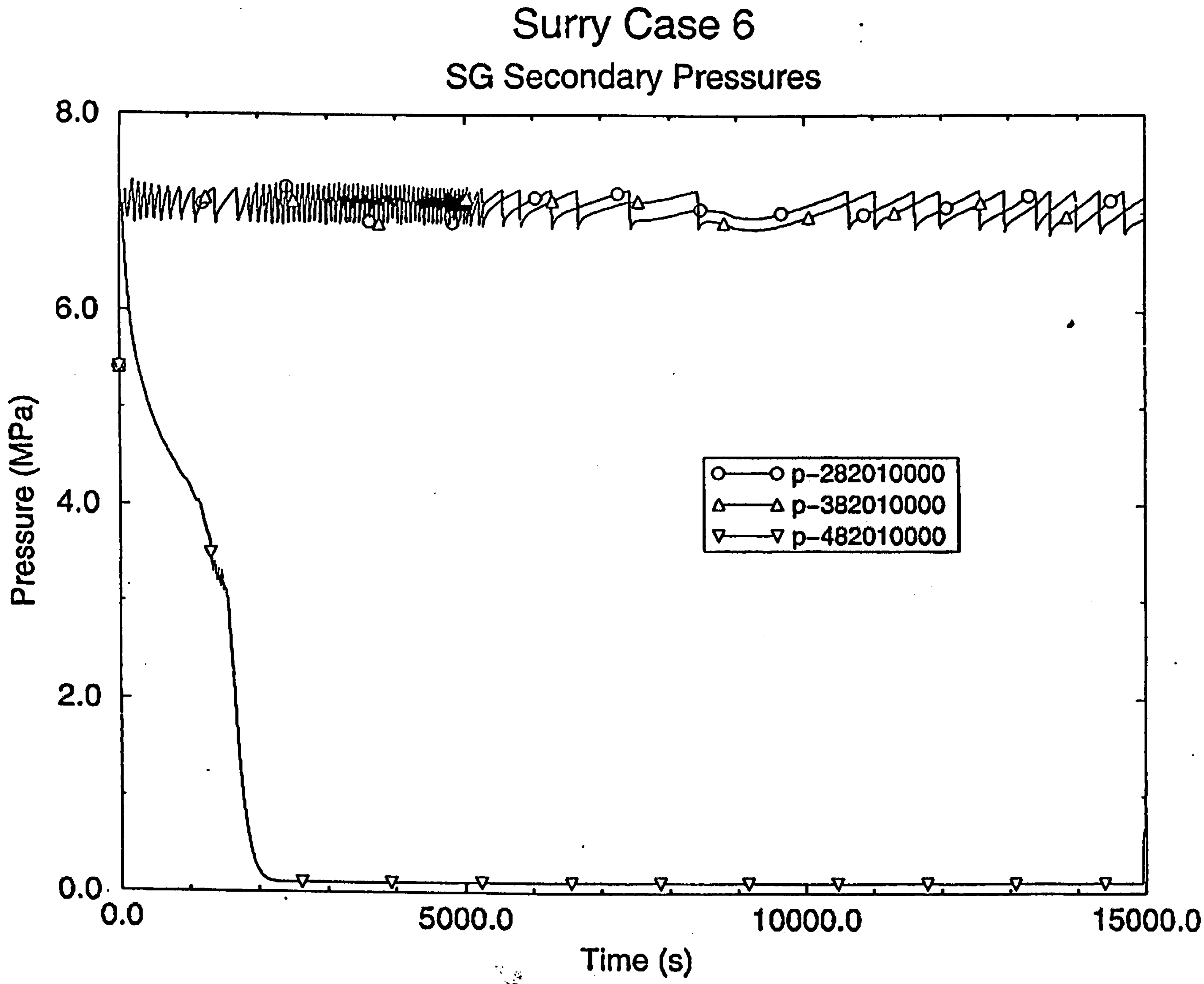

**Event Tree for High-Pressure Station Blackout**

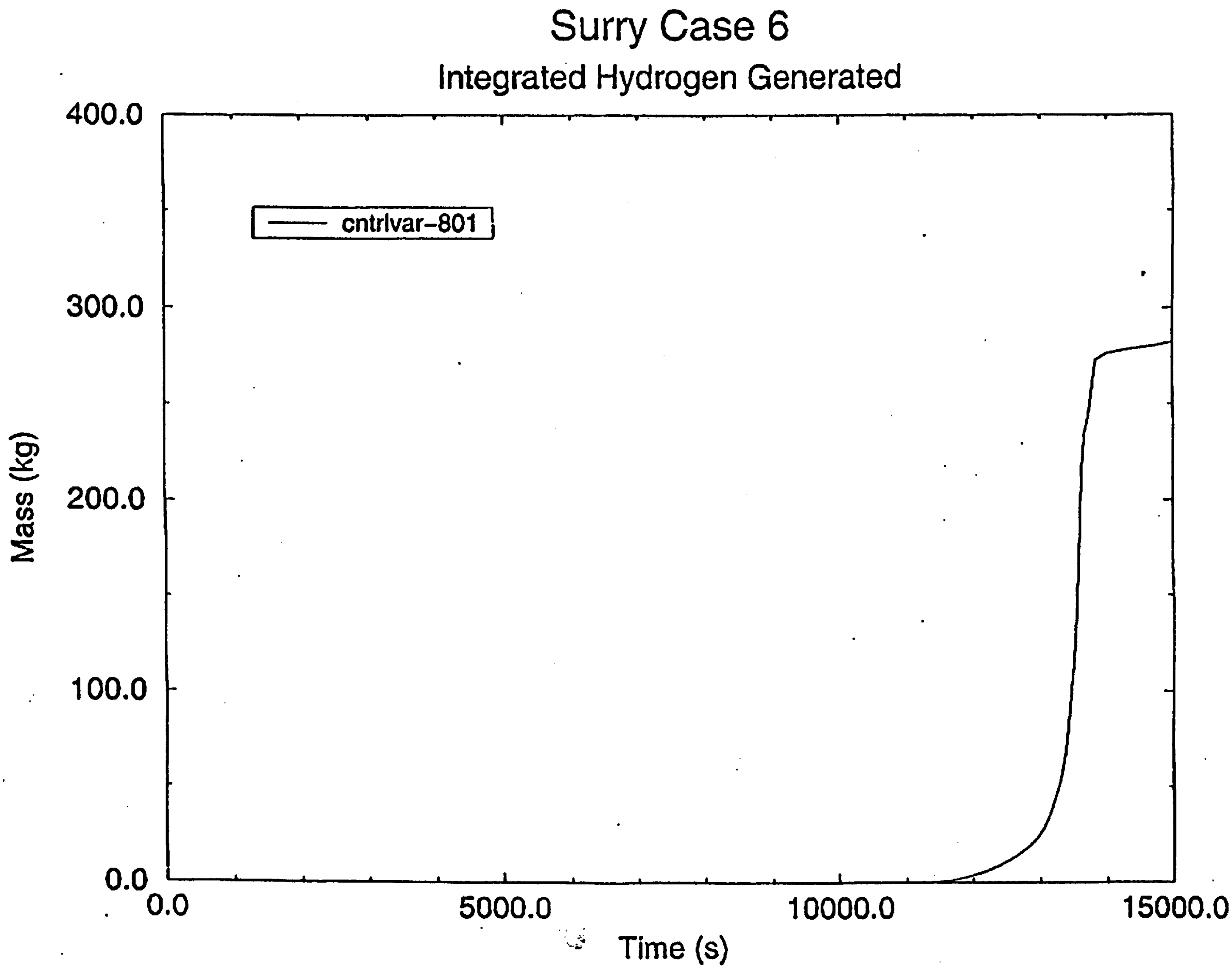
# SURRY PLANT CALCULATION

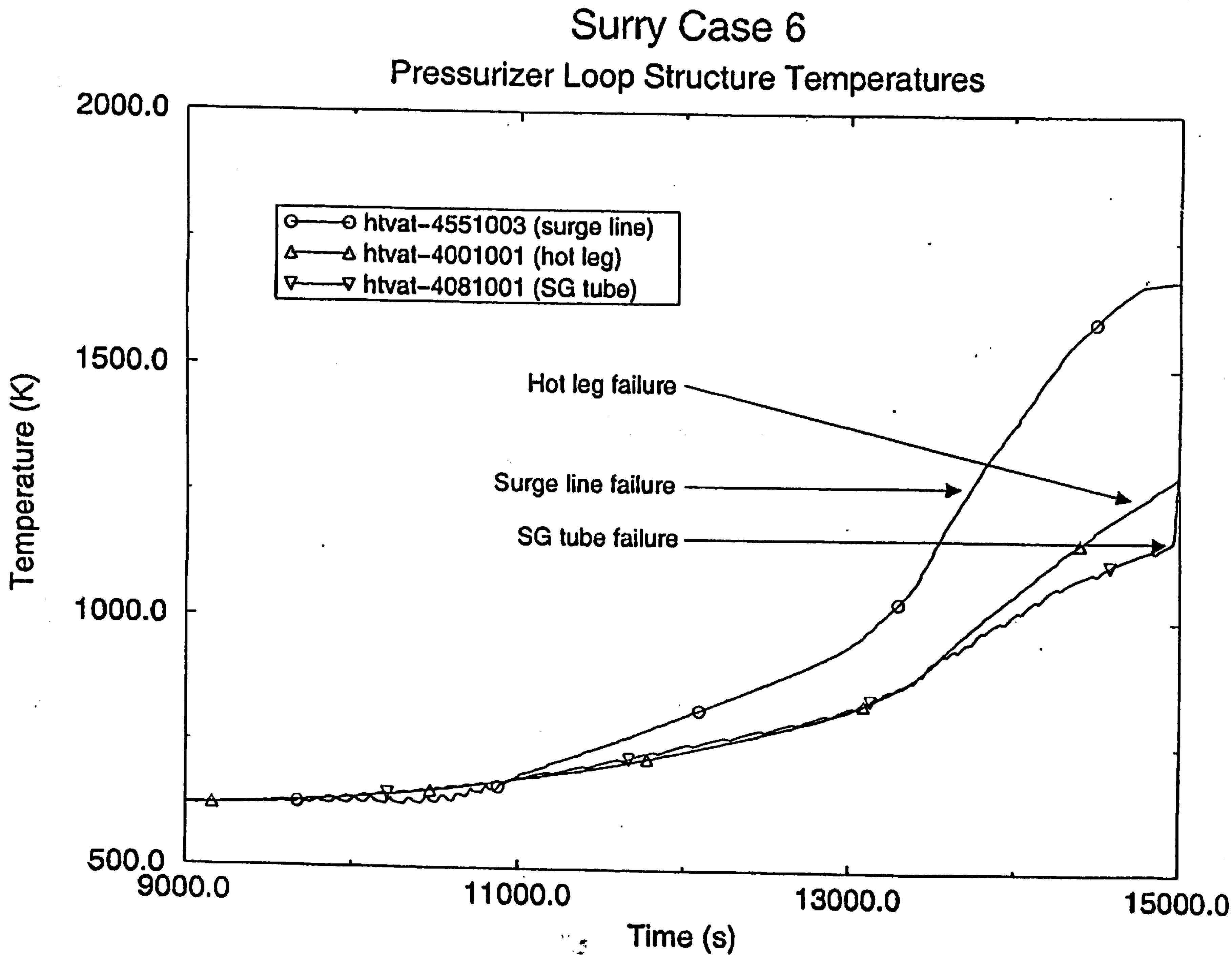
## Recent Application of SCDAP/RELAP5

- Surry Plant calculation
  - TMLB' transient with SG secondary side depressurization
  - Base case: # SG tubes participating in forward flow → 53%
    mixing fraction = 0.87
    recirculation ratio = 1.9
- Sensitivity analysis was performed to address inlet plenum mixing, hot/cold tubes split


Surry Case 6
RCS Pressure
p-106010000
Pressure (MPa)
20.0
15.0
10.0
0.0
5000.0
10000.0
15000.0
Time (s)


Surry Case 6
SG Secondary Pressures
8.0
6.0
4.0
2.0
0.0
Pressure (MPa)
0.0
5000.0
10000.0
15000.0
Time (s)
p-282010000
p-382010000
p-482010000


Surry Case 6
Integrated Hydrogen Generated
cntrlvar-801
Mass (kg)
400.0
300.0
200.0
100.0
0.0
0.0
5000.0
10000.0
15000.0
Time (s)



Surry Case 6
Pressurizer Loop Structure Temperatures
2000.0
1500.0
1000.0
500.0
Temperature (K)
9000.0
11000.0
13000.0
15000.0
Time (s)
htvat-4551003 (surge line)
htvat-4001001 (hot leg)
htvat-4081001 (SG tube)
Hot leg failure
Surge line failure
SG tube failure

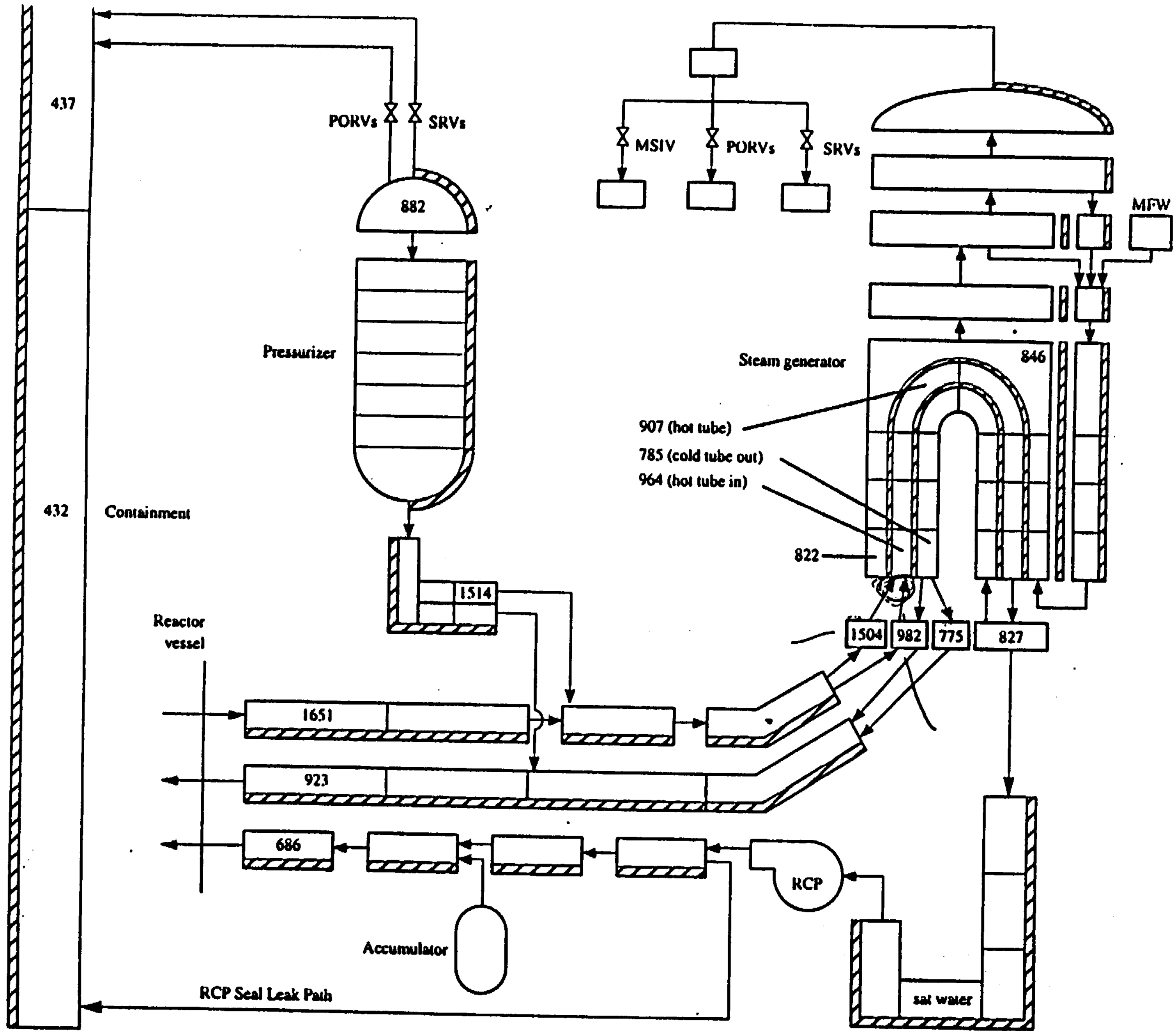



Figure 1. Surry Case 6 vapor temperatures (K) near the time of surge line failure (13,730 s).

# High Temperature Behavior of Flawed Steam Generator Tubing

by

Saurin Majumdar
Energy Technology Division
Argonne National Laboratory

Presented at the experts meeting on jet impingement effects and leak rates for steam generator tubes during severe accidents on Nov. 19, 1999

# Objectives

- Determine at what temperature (and time) during a severe accident the ligament at the tip of a part-throughwall crack will rupture
  - This problem has been addressed previously
- Determine the leak rate after crack becomes throughwall
  - how does the crack opening area vary with time ?

    - creep effect

    - is there any creep crack growth ?
- Determine the erosion rate of neighboring tubes due to jet impingement
  - jet impact velocity, particle loading, etc.

# Flow Stress Failure Models

- Single part-through-wall axial crack

$$p_{sc} = \frac{\bar{\sigma} h}{m_p R_m} = \frac{p_b}{m_p}$$

where $m_p$ = ligament stress magnification factor, $\bar{\sigma}$= flow stress

– BCL Equation [Eiber et al. (1967), Kiefner et al. (1972)]

$$m_p = \frac{1-\frac{a}{mh}}{1-\frac{a}{h}}$$, where m = bulging factor (function of R, h and 2c)

– ANL Equation (1996) - modified BCL equation based on PNNL tests

$$m_p = \frac{1-\alpha\left(\frac{a}{h}\right)\frac{a}{mh}}{1-\frac{a}{h}} \text{ where } \alpha\left(\frac{a}{h}\right) = 1+0.9\left(\frac{a}{h}\right)^2\left(1-\frac{1}{m}\right)$$

# Creep Rupture Model for High-Temperature Failure

- Linear Damage Rule

$$\int_0^{t_f} \frac{dt}{t_R(T, m_p\sigma)} = 1$$

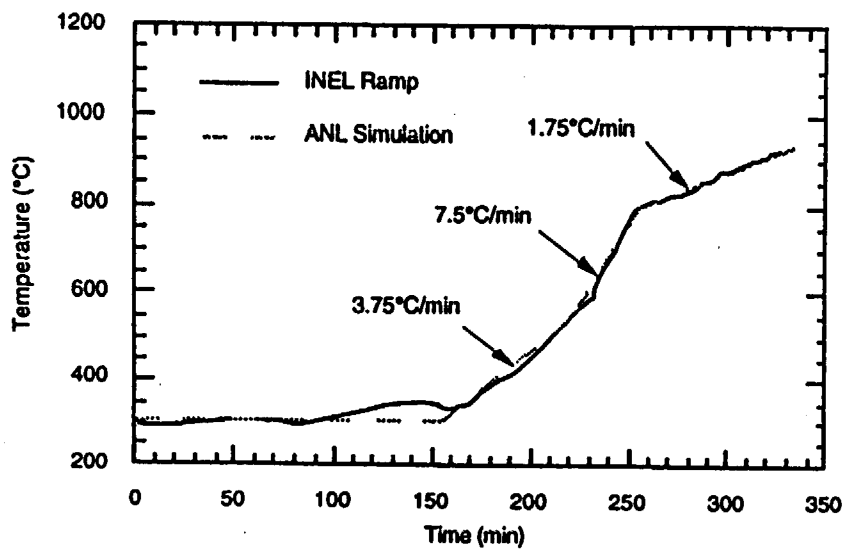
where $t_R$ = time to creep rupture at temperature T and stress $m_p\sigma$

- Unlike flow stress model, the time to failure $t_f$ is dependent on the history of loading.

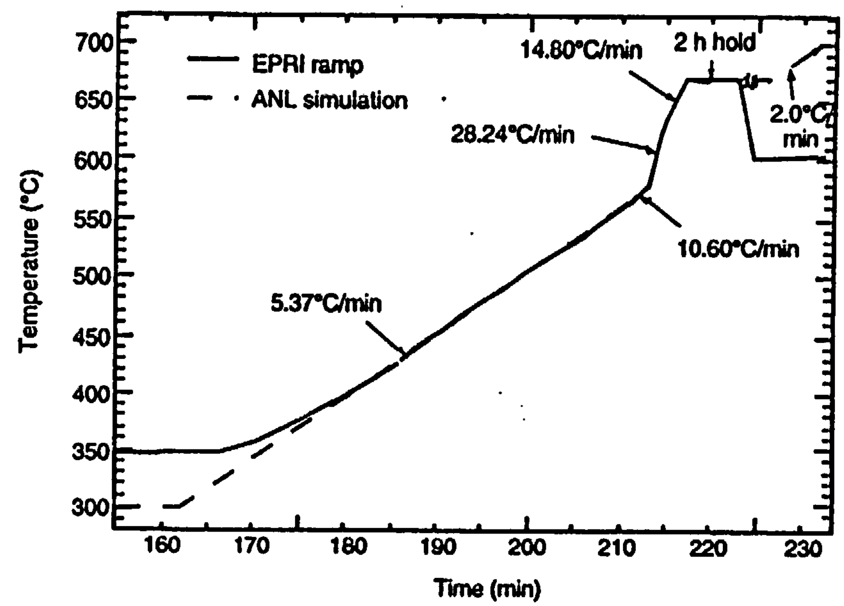
# Validation Tests on Specimens with Machined Flaws

- Isothermal, constant pressure creep failure tests
  - Tests with deep axial flaws (≥90%)
- Ramp tests
  - Constant-pressure temperature ramp tests (axial and circumferential flaws)
  - Isothermal pressure ramp (axial flaws)
- Tests under varying temperature history (axial flaws)

# Tests under Simulated Severe Accident Transients




INEL ramp




EPRI ramp

- Pressure held constant at 2350 psi for all tests.
- Flaw length 0.25- 2.0 in. with depth between 20-65%

# Tests on Throughwall Notches

- Two specimens with 0.5" throughwall EDM notches were tested
- 3" long thin sheet rolled, seam-welded and welded to the ID surface of tube
  - 0.010" thick Ni liner, pressurized @1 ksi/min at 850°C ($S_y$=17 ksi),
    - liner failed (pin hole) at 1.5 ksi (cf. $p_f$=2.3 ksi)
  - 0.008" thick 304SS liner pressurized to 2.35 ksi ($\sigma_h$ = 19 ksi) at 750°C ($S_y$ = 34 ksi) and held
    - liner failed (pin hole) after 1 min, final notch opening = 0.043"
    - incremental opening due to creep = 0.035"

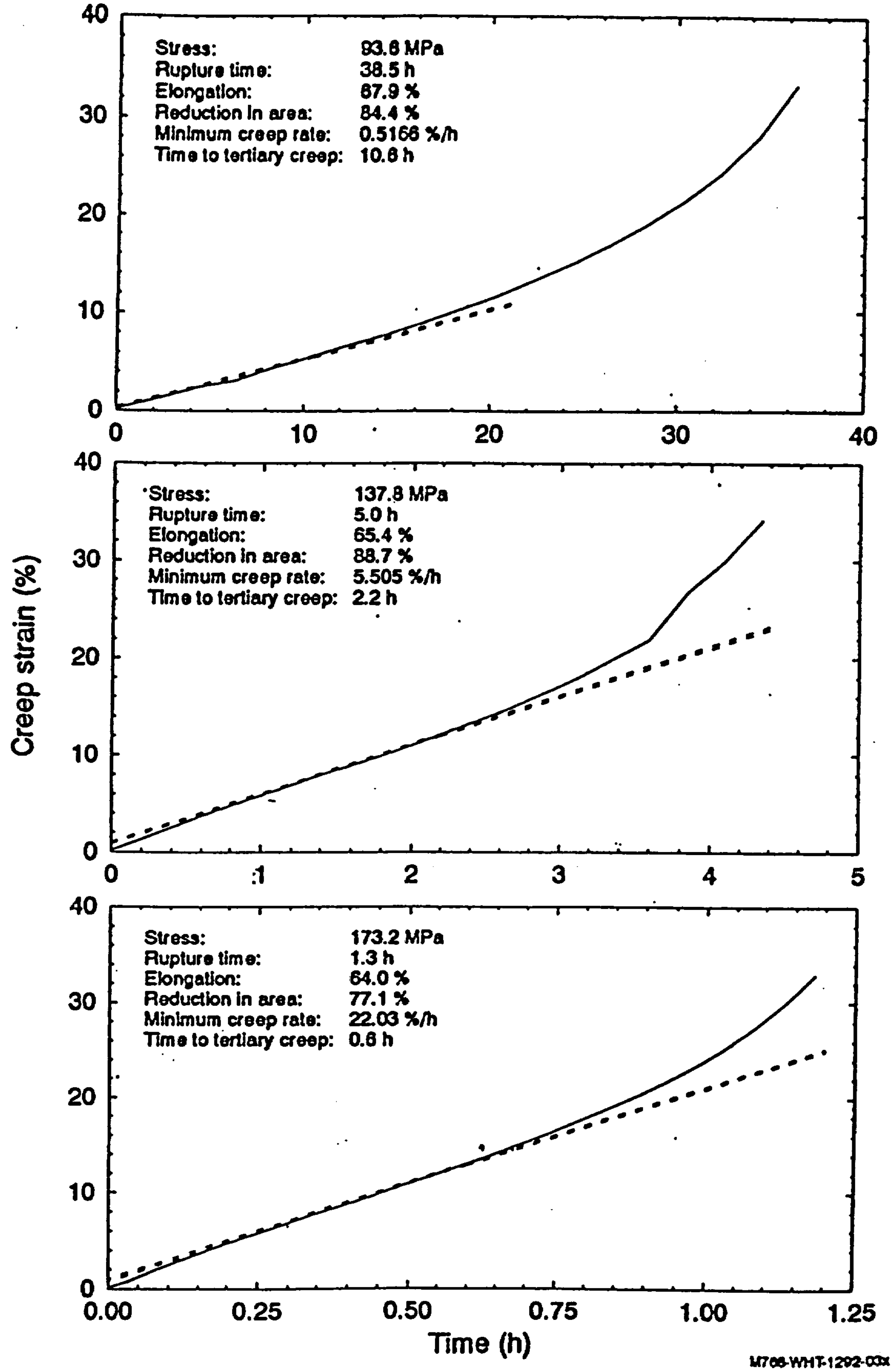
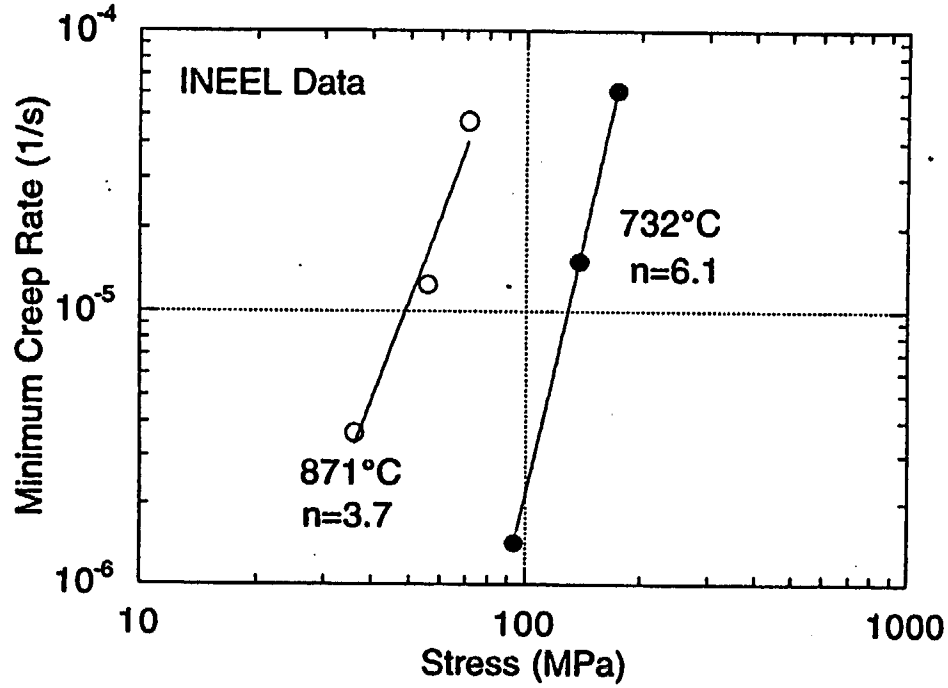


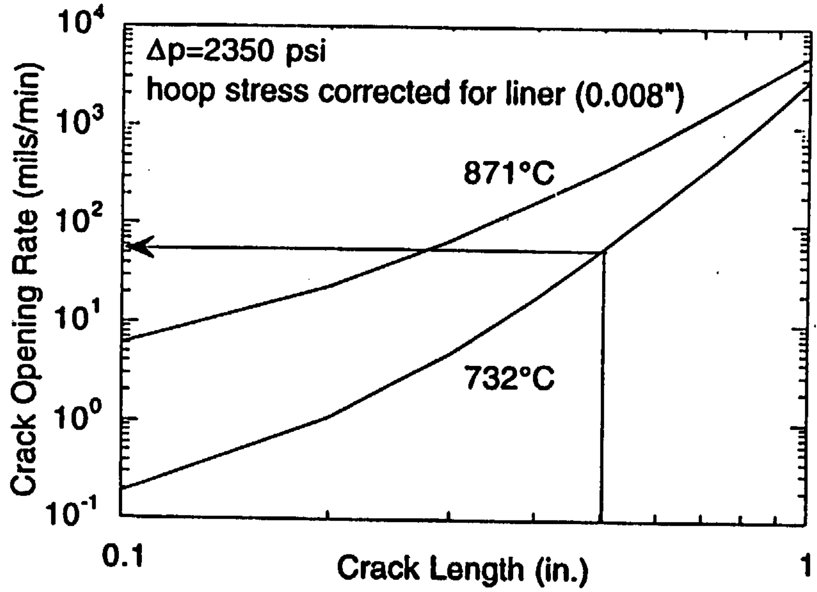

Figure B-32. Inconel 600 creep strain versus time at 1005 K—INEL results.

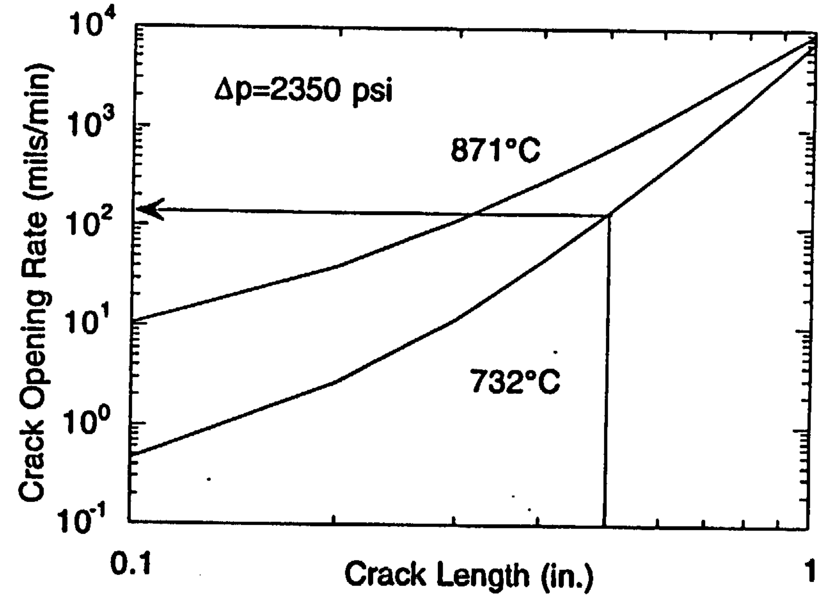
# Creep Rate Data for Alloy 600 (NUREG/CR-5642)




- No primary creep
- A =1.36 x $10^{-18}$ and n = 6.1 at 732°C
- A = 6.14 x $10^{-12}$ and n = 3.7 at 871°C

# Crack Opening Rate

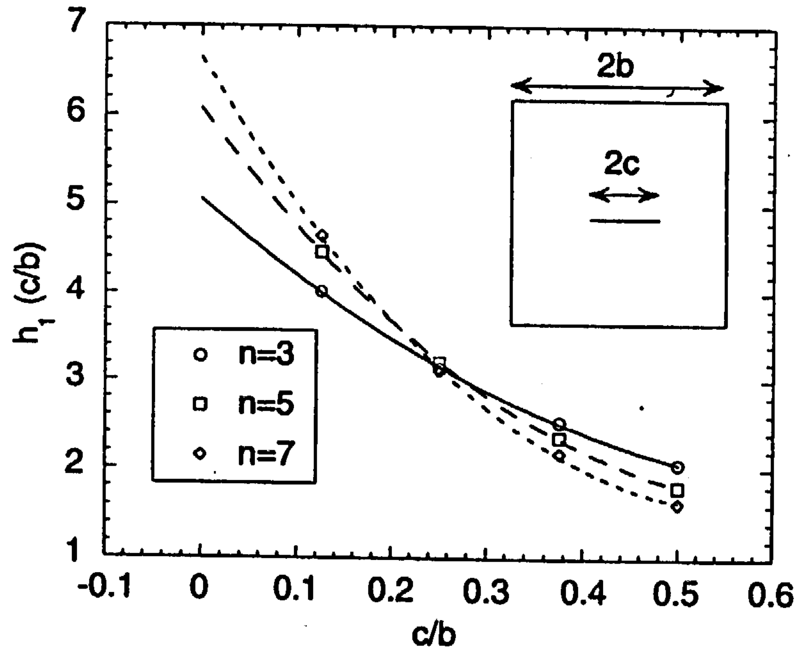


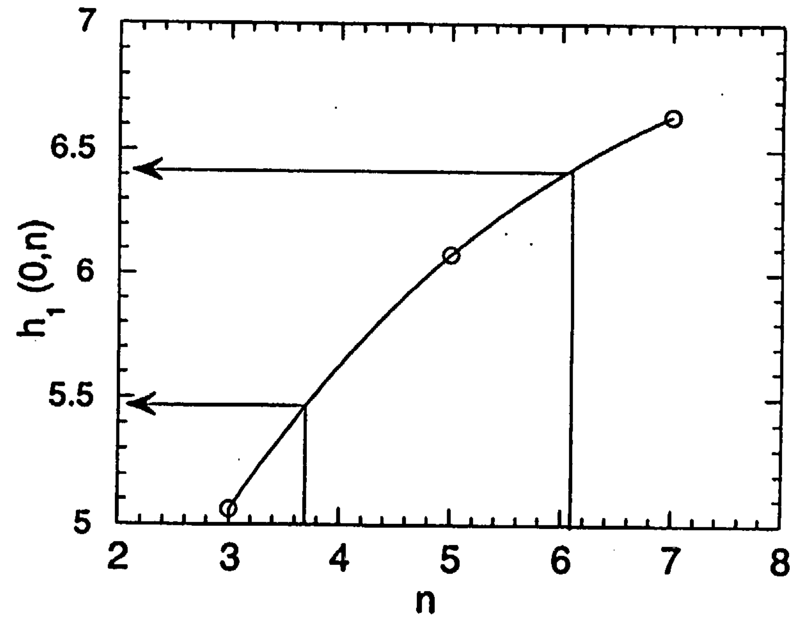




- For 0.008" thick 304 SS liner (750°C), crack opening in 1 min =0.057" (cf. 0.035")
- Crack opening rate is very sensitive to liner thickness, 0.14"/min w/o liner
- Notch opening rate < crack opening rate?

# Determination of C*

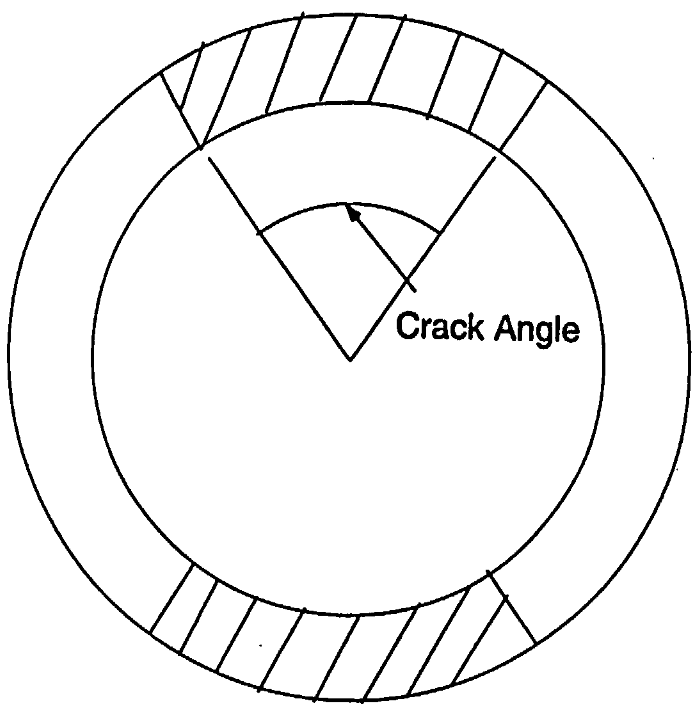
- $J = \alpha\sigma_o\varepsilon_o c h_1(0,m)\left(\frac{P}{P_o}\right)^{m+1}$ , By analogy, $C^* = A c h_1(0,n)\sigma^{n+1}$

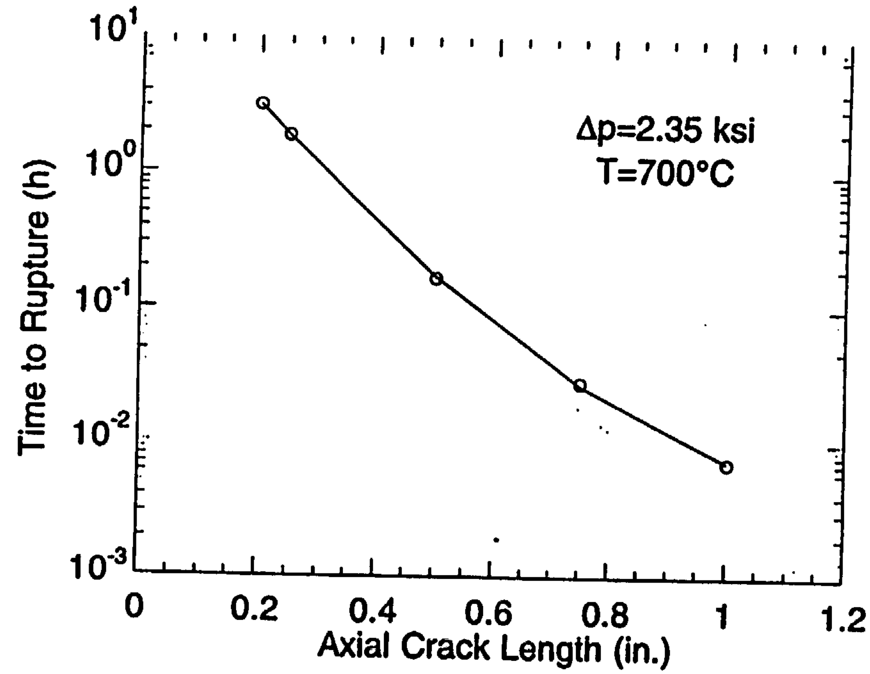



- $h_1$ values are 6.4 and 5.48 at 732 and 871°C, respectively.

# Tests on Specimens with Circ. Cracks




- Simulate axial crack in pressurized tube – net axial stress = $m\sigma_{hoop}$
- Measure crack opening area periodically

# Assumptions and Uncertainties in Analyzing Possible Erosion/Ablation Damage of Steam Generator Tubes

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November 19, 1999

## Erosion/Ablation Damage and Leak Rate of Steam Generator Tubes Under Severe-Accident Conditions

Assumptions:

- Maximum temperature is ≈700°C (1292°F).
- Maximum Δp across tube wall is ≈15.9 MPa (2300 psi).
- Tube spacing (OD surface to OD surface) is ≈6.4-10.2 mm (0.25-0.40 in.).
- Jet consists of superheated steam + 10-20% $H_2$.
- Particulate in jet consists primarily of Ag (≈100 g/$m^3$) plus lesser amounts of $In_2O_3$ (7.4 g/$m^3$), $CsMoO_4$ (2.5 g/$m^3$), $SnO_2$ (2.2 g/$m^3$), CsI (1.1 g/$m^3$), and other species.
- Median particle diameter is ≈1.5 μm.

# Erosion/Ablation Damage and Leak Rate of Steam Generator Tubes Under Severe-Accident Conditions

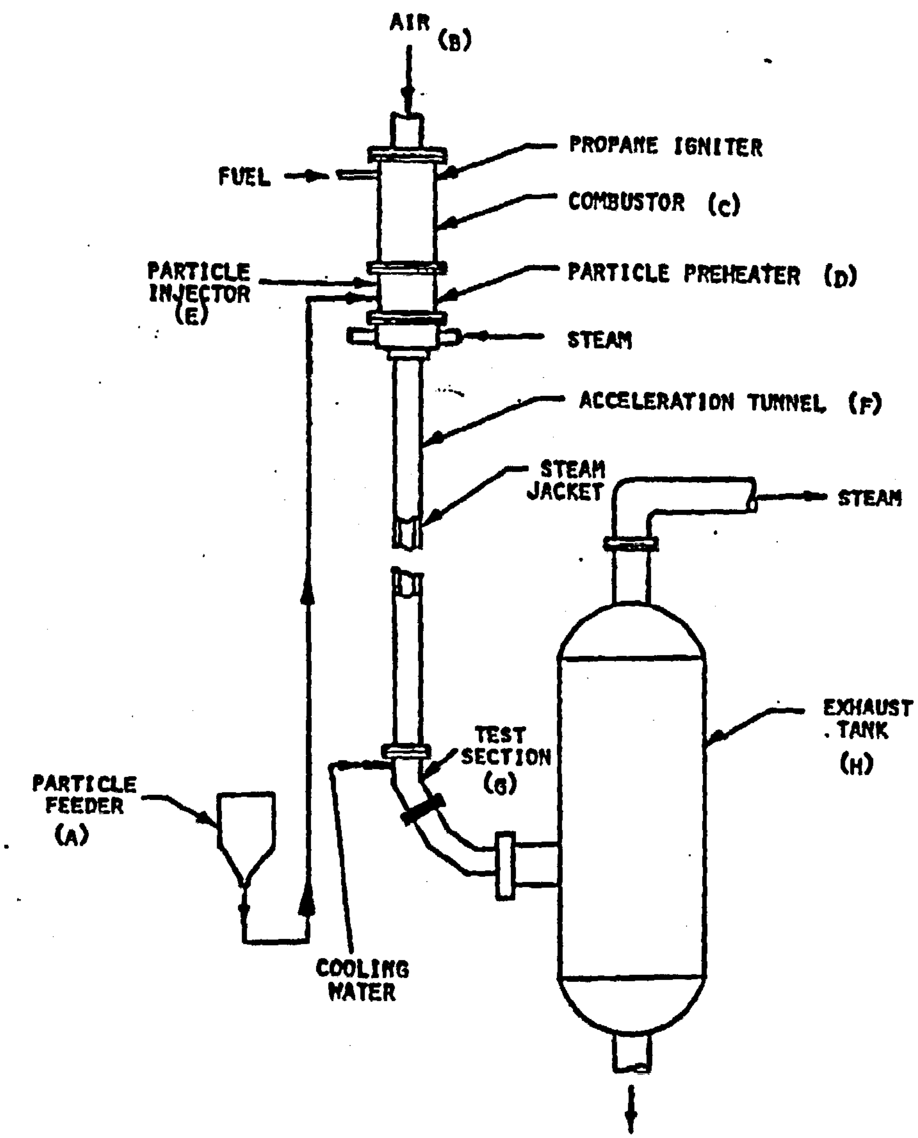
## Uncertainties:

- Extent of growth of crack opening area due to plasticity and creep.
- Jet velocity at adjacent tube surface.
- Maximum temperature.
- Type, amount, and size of particles entrained in jet.
- Erosion rate as a function of velocity, particle loading, angle of impingement, temperature, ...

# Creep Crack Opening Area Tests at Argonne

- Test specimens are Alloy 600 steam generator tubes with a diameter of 22.2 mm(0.875-in.) and a wall thickness of 1.27 mm ( 0.050-in.).
- Test temperature = 700°C (1292°F).
- Axially loaded specimens have two symmetric circumferential EDM notches, each extending 45° around the circumference.
- Tests are interrupted periodically to observe crack opening area as a function of time.
- Test times are of the order of a few hours.

# High-Temperature Erosion Apparatus (U. of Cincinnati)



# High-Temperature Erosion Tests (U. of Cincinnati)

- Test specimens are Alloy 600 plate ≈25 x 13 x 4 mm thick (1 x 0.5 x 0.156 in. thick).
- Test temperature = 700°C (1292°F).
- Impingement angles range from 0-90°.
- Gas stream is kerosene combustion products plus ≈50% injected steam.
- Erosion rates are determined by weight loss after exposures of ≈1 h or less.
- Particle loadings and jet velocities correspond to those calculated for the severe-accident scenario.