ASSESSMENT OF RELAP5/MOD3.2.2Gamma for PTS APPLICATIONS

Contributors

USNRC: David Bessette, Gene Rhee

ISL, Inc.: Bill Arcieri, Robert Beaton, Mark Bolander, Don Fletcher, Ben Gitnick, Diane Mlynarczyk, Dan Prelewicz, Len Ward

Applied Analysis Corp: Ron Anderson, Juan Cajigas

ITS Corp.: Jack Dallman, K.C. Wagner

ACRS T/H Subcommittee Meeting

December 11, 2002

OBJECTIVES

- Establish applicability of RELAP5 for PTS analysis
- Perform requisite PTS-specific RELAP5 validation and assessment making maximum use of available experimental data and input models
- Demonstrate how limitations of RELAP5, e.g., one-dimensional nature of code and numerical issues, are addressed

MAJOR POINTS

- PTS risk significant transients primarily involve relatively rapid energy removal from the primary system by some combination of:
  - loss of high energy coolant (through break or valve)
  - excessive heat removal by the secondary
  - injection of low temperature coolant
- RELAP5 is used to perform a transient energy balance and pressurization analysis
- Important parameters are downcomer pressure, temperature and heat transfer coefficient
- Some phenomena are shown to be modeled in a reasonable manner (e.g., loop flow stagnation)
- Some phenomena cannot be modeled by a one-dimensional code (e.g., cold leg thermal stratification) but have minimal effect on the important response parameters

MAJOR POINTS (continued)

- Many events have single-phase flow in primary loops throughout the event (complex two-phase flow phenomena play no role)
- Some flow behavior was predicted that is unphysical (cold leg recirculation; downcomer recirculation). Steps were taken (Hi reverse flow K, selectively disabling the momentum flux model) to compensate for potential unphysical behavior.
- Modeling practices were followed that are consistent with past experience, e.g., AP600
- Consistency was maintained between the plant analyses and the assessments against experimental data
- Comparison of RELAP5 predictions against experimental data from integral tests are in reasonable agreement for PTS significant pressure and downcomer fluid temperatures

CONCLUSION: RELAP5 is applicable for PTS analysis

Important Phenomena for PTS

- Phenomena of primary or secondary importance for the PTS figures of merit (reactor vessel downcomer fluid temperature, pressure and wall heat transfer coefficient).
- Three main phenomena:
  - "Natural Circulation/Flow Stagnation" - if loop flow continues, warm fluid is flushed through the reactor vessel downcomer, while if flow stagnates, the effects of cold ECCS water are seen more rapidly and directly in the downcomer.
  - "Integral System Response" - ECCS injection behavior (flow rates, timings, and to some extent temperatures) are functions of the overall system behavior (mainly pressure, but also various levels and temperatures).
  - "Pressurization" is itself a primary figure of merit in the PTS analyses.
- Other phenomena influence the main phenomena or represent potentially significant downcomer localized effects, e.g. critical flow at break.

PTS Phenomena (continued)

- RELAP5 cannot predict a number of PTS relevant phenomena: reflux condensation, mixing and stratification in the cold leg, downcomer plumes and dissipation
- Assessments were performed where these phenomena were known to occur to establish impact on RELAP5 PTS calculation results

PTS RISK SIGNIFICANT EVENT CATEGORIES

- Primary side valve opens and re-closes later with operator failure to control HPI flow
- Primary side breach in which HPI flow rate cannot compensate for the break flow rate
- Small primary side breach (HPI can compensate break flow) plus failure and recovery of HPI (causing late repressurization)
- Multiple system failure (e.g.,, small primary side breach + secondary side depressurization)
- Large secondary side depressurization

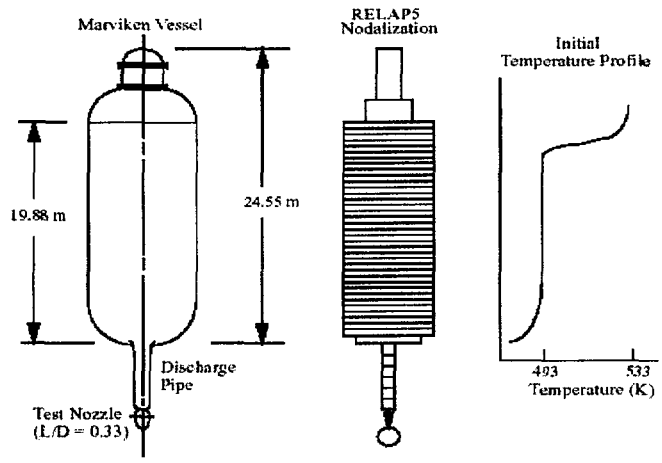
PTS ASSESSMENTS

- Maximum use of existing experimental data
  - relevant RELAP5 DA cases: Marviken, MIT Pressurizer, Semiscale Natural Circulation, UPTF downcomer condensation
  - relevant integral test data: MIST (Feed and Bleed, SBLOCA), LOFT (SBLOCA), ROSA-IV (SBLOCA, Natural Circulation) data
  - used relevant AP600 facility data: APEX and ROSA
- NRC identified additional data needs: APEX-CE PTS Testing Program
  - Assessment cases run by OSU and ISL (APEX-CE-13)

Marviken Experiments - Critical Flow

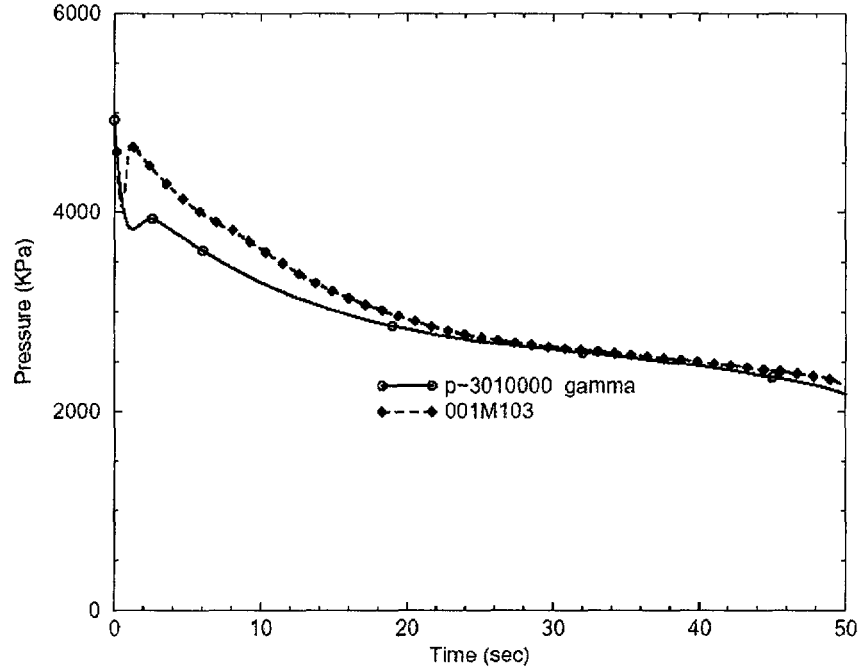
- Two-phase cases (Runs 22 and 24)
- Henry-Fauske Critical Flow model (used for PTS cases)
- Full scale vessel and piping at power station:
  - Vessel ID 5.22 m, height 24.55 m
  - discharge connection piece 752 mm ID
  - blowdown nozzle: 500 mm ID, L/D = 0.33 (test 24), L/D = 1.5 (test 22)
  - initial water level: 19.88 m (test 24), 19.64 m (test 22)
  - initial pressure: 4.96 MPa (test 24), 4.93 MPa (test 22)
- For PTS analysis, large number of runs (break spectrum) reduces uncertainties related to break flow model

Marviken Experiments - Schematics (Test 24)



Pressure in top of vessel

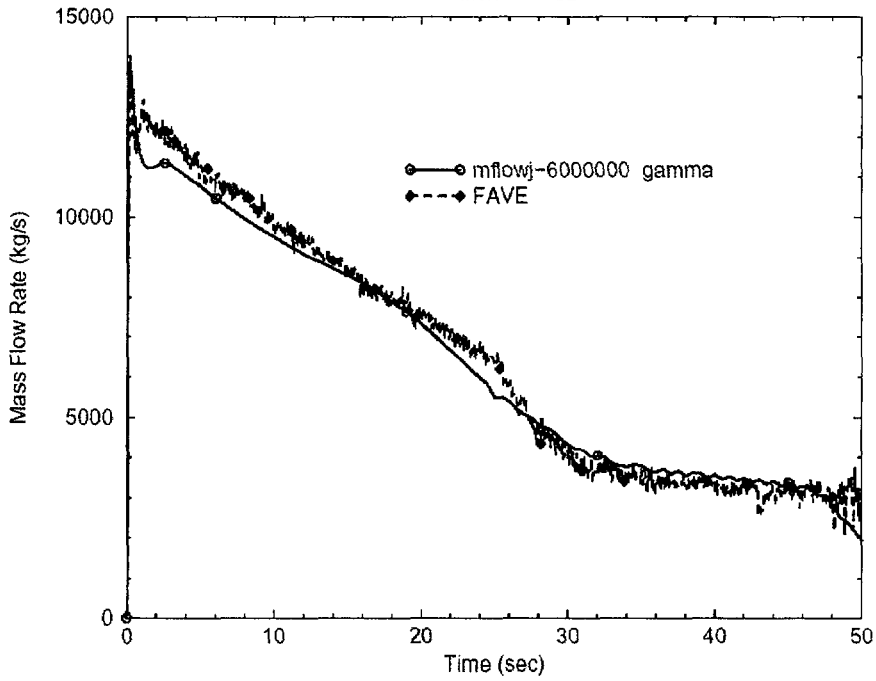
Marviken Test 22



Information Systems Laboratories

Mass flow rate at nozzle outlet

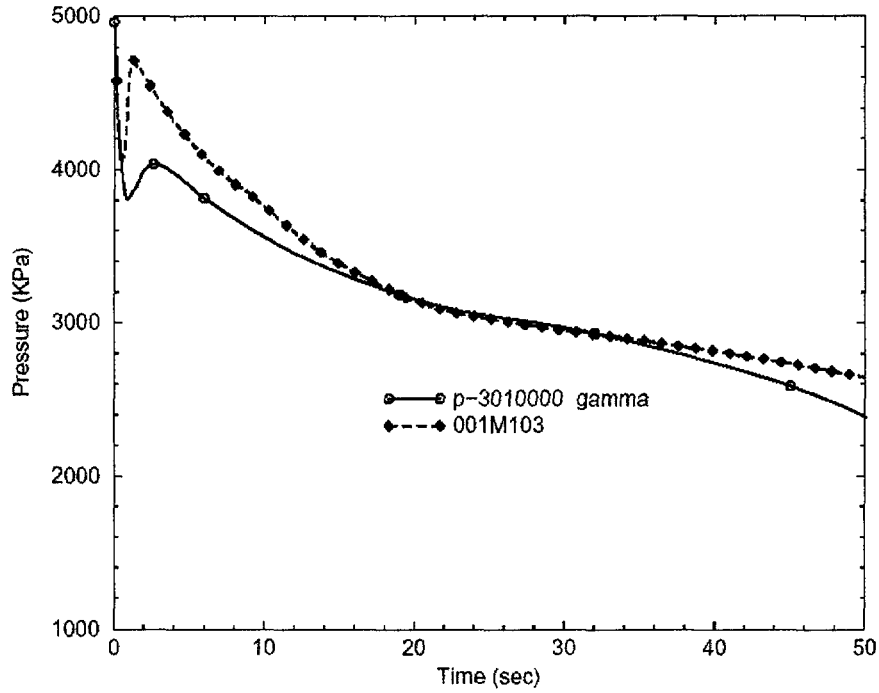
Marviken Test 22



Information Systems Laboratories

Pressure in top of vessel

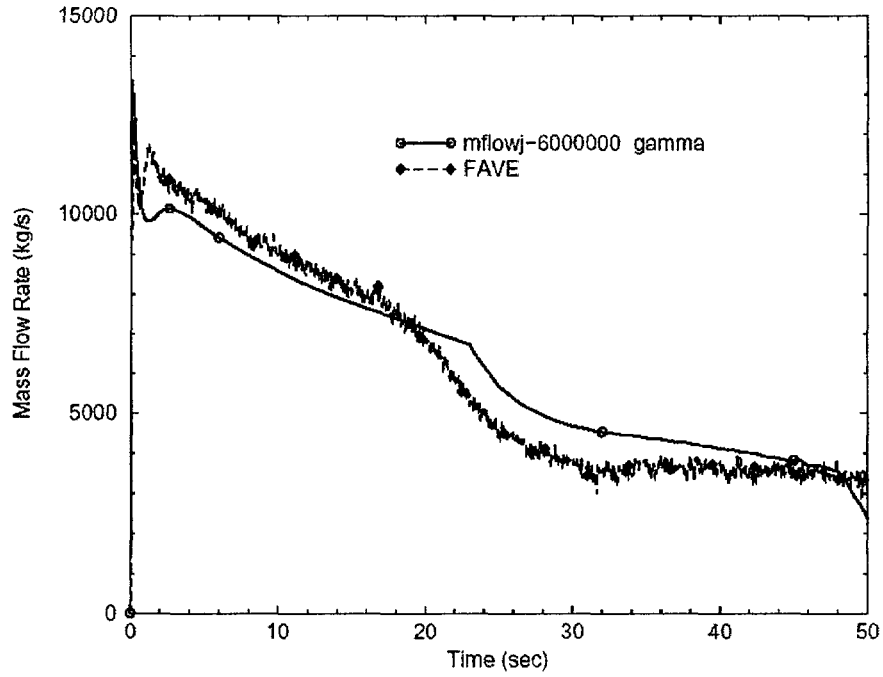
Marviken Test 24



Information Systems Laboratories

Mass flow rate at nozzle outlet

Marviken Test 24



Information Systems Laboratories

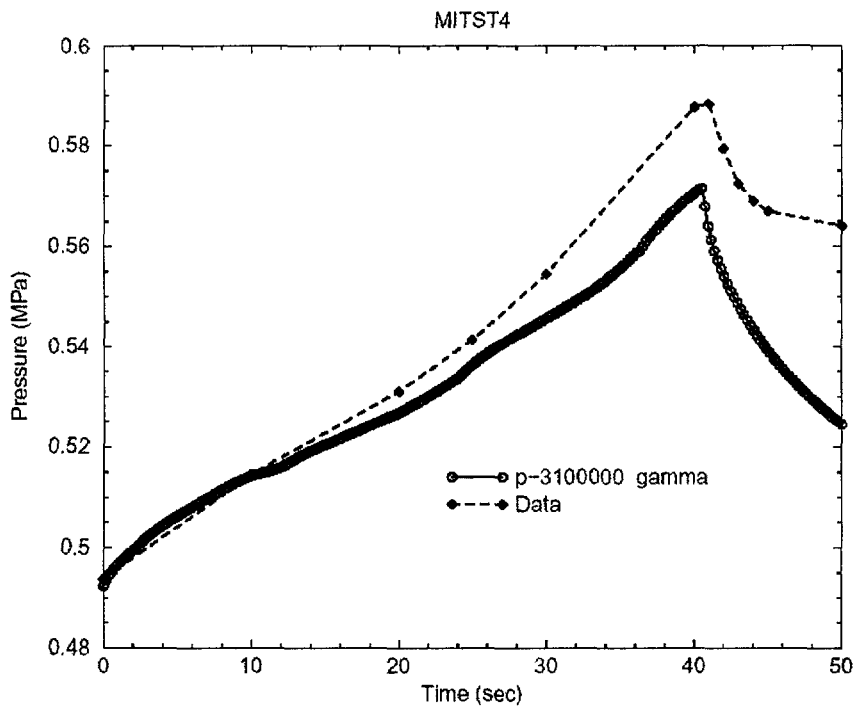
MIT Pressurizer ST4 Test - Pressurization

- ST4 test is an insurge under quiescent conditions
- As water is injected into the bottom of the pressurizer the steam pressure in the top of the pressurizer rises.
- Potential important phenomena include:
  - wall condensation,
  - mixing of incoming cold water with already present hot water in the vessel, and
  - free surface heat transfer
- RELAP5 tends top over-predict wall condensation
- In this small test facility, environmental heat loss is a significant factor

MIT Pressurizer ST4 Test - Pressurization

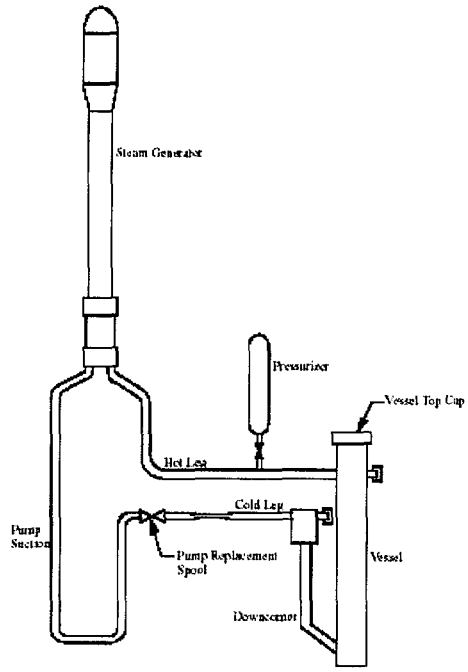
- ST4 test is an insurge under quiescent conditions
- As water is injected into the bottom of the pressurizer the steam pressure in the top of the pressurizer rises.
- Potential important phenomena include:
  - wall condensation,
  - mixing of incoming cold water with already present hot water in the vessel, and
  - free surface heat transfer
- RELAP5 tends top over-predict wall condensation
- In this small test facility, environmental heat loss is a significant factor

MIT Pressurizer Test

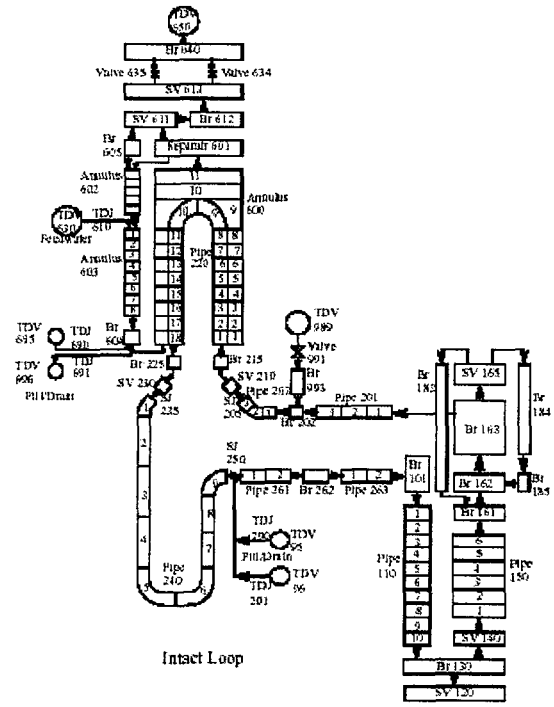


Semiscale MOD-2A

- Semiscale models the primary system of a four-loop PWR (scaling factor 1/1705).
- Natural circulation experiments were performed in the Semiscale Mod-2A test facility
- A single-loop configuration was used; the intact loop pump was replaced with a spool piece containing an orifice that simulated the hydraulic resistance of a locked pump rotor
- The vessel was modified from the normal Mod-2 configuration by removing the low flow upper head region and replacing it with a cap. This ensured uniform heatup of the entire system (no cold trapped fluid in upper head) and avoided condensation in cold upper-head structures



Semiscale MOD-2A Single-Loop Configuration



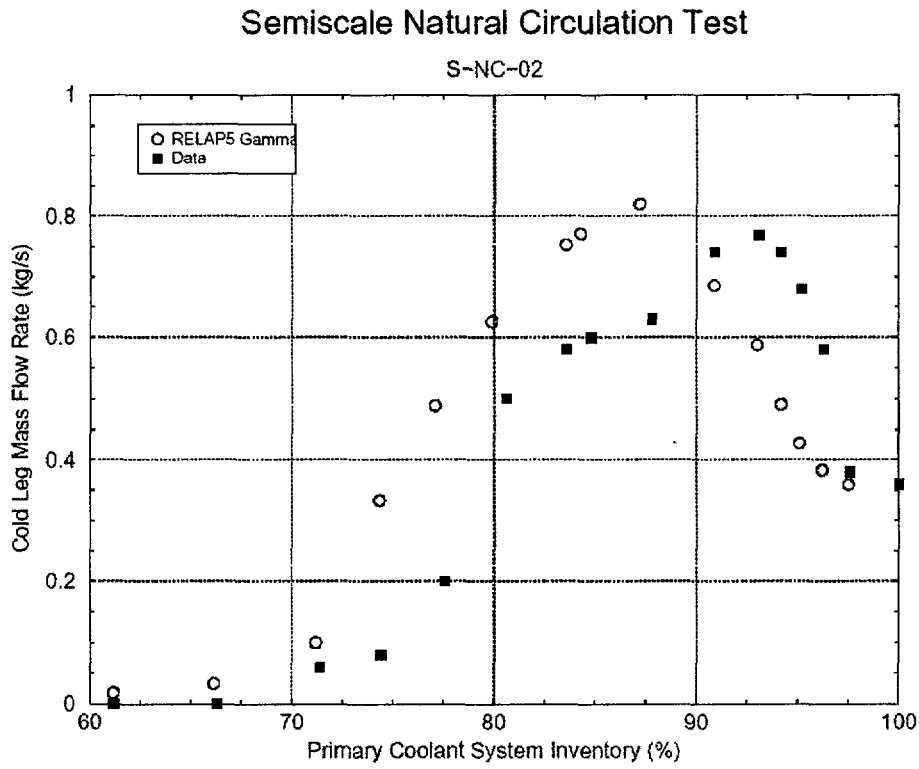
Semiscale MOD-2A RELAP5 Noding Diagram

Semiscale Natural Circulation Tests

Test S-NC-2

- Examined single-phase, two-phase, and reflux steady-state modes by varying the primary side system mass with a constant steam generator secondary side condition. Measured steady-state loop natural circulation flow rate as a function of primary side mass inventory.
- Reflux boiling occurs at low values of total primary mass - RELAP5 predicts oscillatory hot leg flow.

Information Systems Laboratories



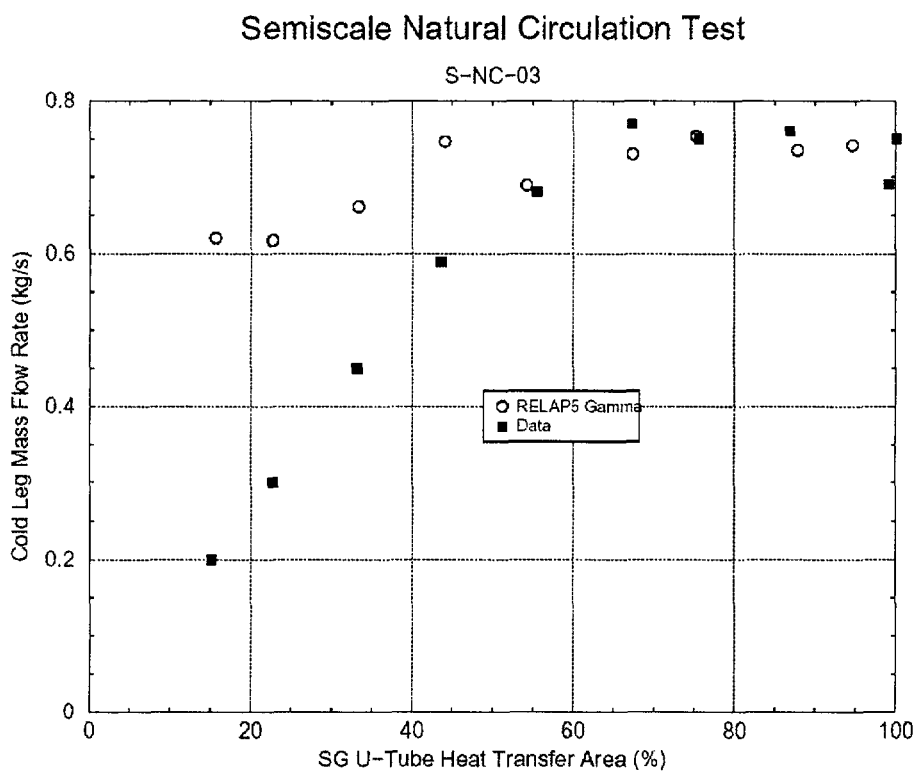
Information Systems Laboratories

Semiscale Natural Circulation Tests

Test S-NC-3

- **Test S-NC-03 examined primary side two-phase natural circulation behavior under varying steam generator secondary side mass inventory at a core power of 62 kW. Measured steady-state loop natural circulation flow rate as a function of steam generator heat transfer area.**

Information Systems Laboratories

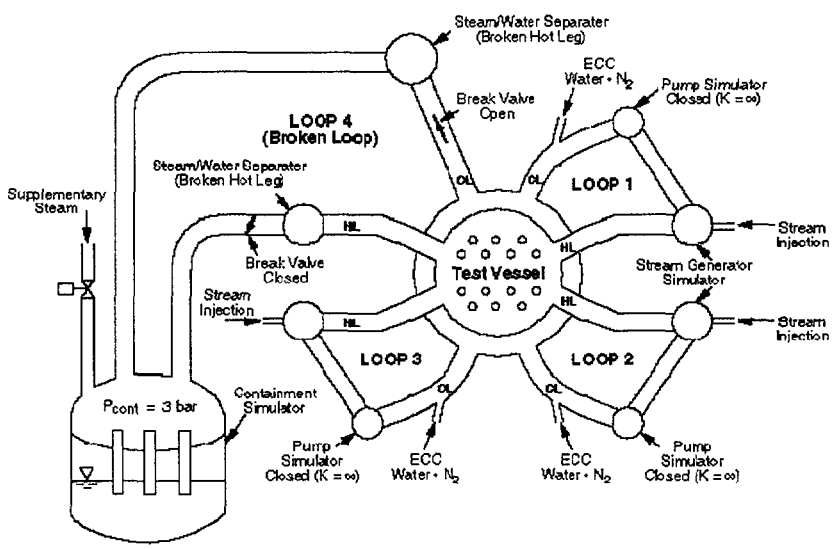


Information Systems Laboratories

Upper Plenum Test Facility (UPTF)

- Full-scale model of a four-loop 1300 MWe PWR.
- Components included are the reactor vessel, downcomer, lower plenum, core simulation, upper plenum, and four loops with pump and steam generator simulation.
- Four full-scale hot and cold legs simulating three intact loops and a broken loop.
- Investigated the steam/water CCFL behavior in the full-scale downcomer of a PWR. Facility was designed and operated to obtain LBLOCA downcomer penetration data during late blowdown and refill (PTS not considered).
- Test are of interest for PTS due to condensation of superheated steam by slightly subcooled injection water

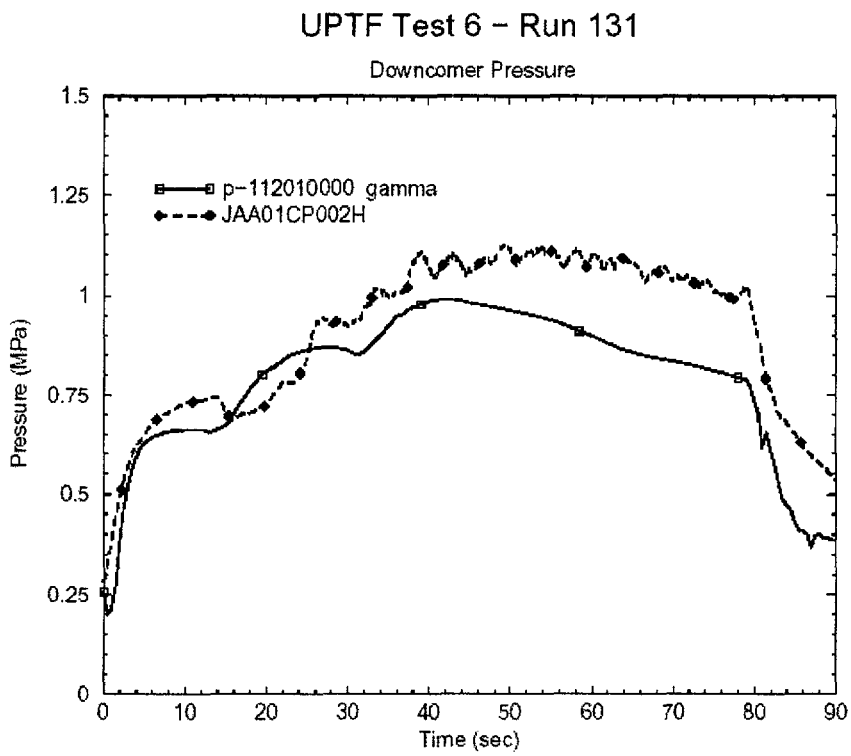
UPTF Test 6 Configuration



UPTF Downcomer Test 6 Run 131

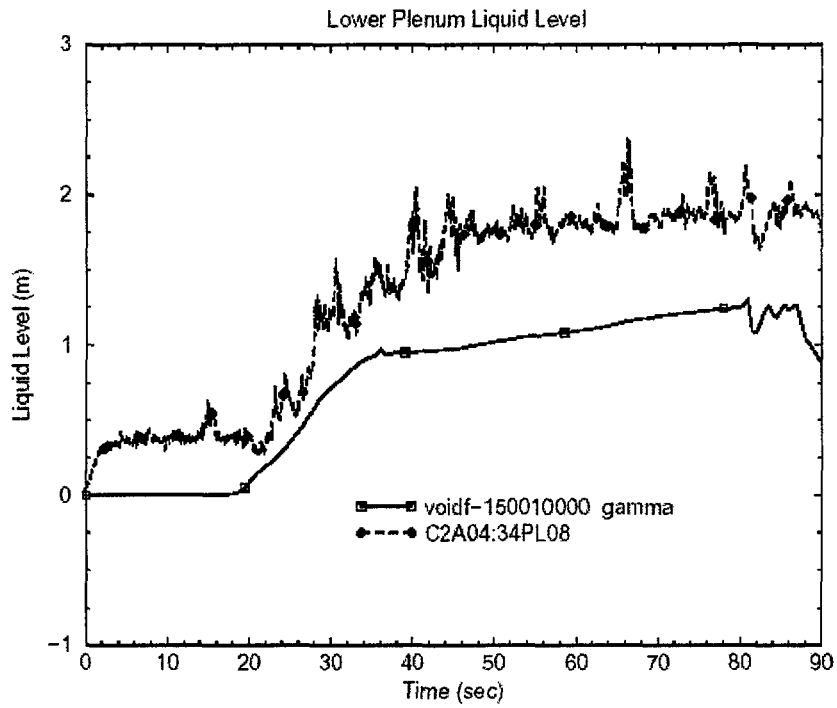
- Steam injection from core and steam generators at 477 K (400 F). ECC injected from accumulators in 3 intact loops at 392 K (246 F)
- For Test 6, Run 131: Initial pressure 2.58E+5 MPa (37.4 psia). At this pressure, T_{sat} = 400 K (263 F)
- RELAP5 predictions fairly close to experimental data.
- Pressure prediction somewhat low due to "expected" overcondensation by RELAP5.
- Downcomer penetration prediction is reasonable.

Information Systems Laboratories



Information Systems Laboratories

UPTF Test 6 – Run 131



MIST Facility

- MIST (**M**ulti-loop **I**ntegral **S**ystem **T**est) is a scaled, full-pressure, experimental facility arranged to represent the B&W lowered-loop plant design with two hot legs and four cold legs.
- MIST's major components include two once-through steam generators with full length tubes, two hot leg pipe segments, four cold leg pipe segments, four coolant pumps, a reactor vessel with an external downcomer, a pressurizer with spray and PORV connections, and one core flood tank (CFT). Boundary systems provided simulation of the HPI, Auxiliary Feedwater (AFW), vents, controlled leaks, and steam generator tube ruptures.
- The plant-to-MIST power scaling factor is 817. The plant-to-MIST volume scaling factor is 620 for the total primary system volume (CFT excluded).

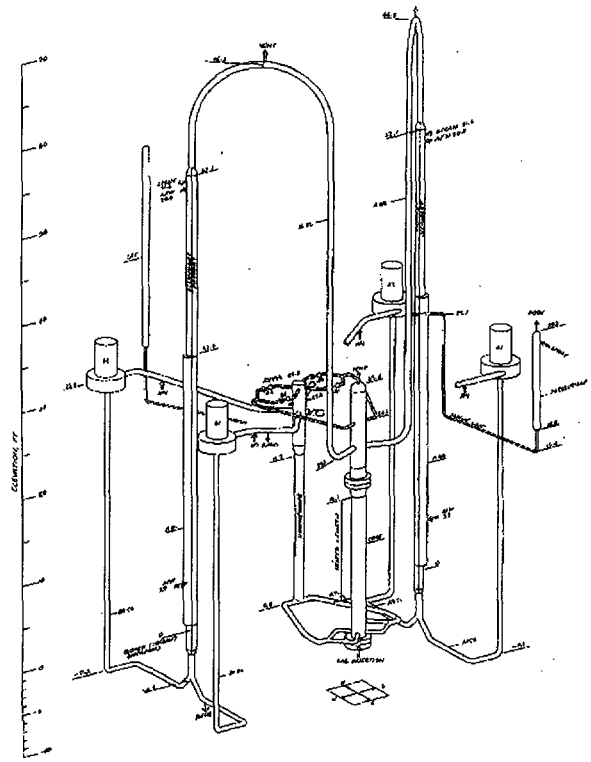
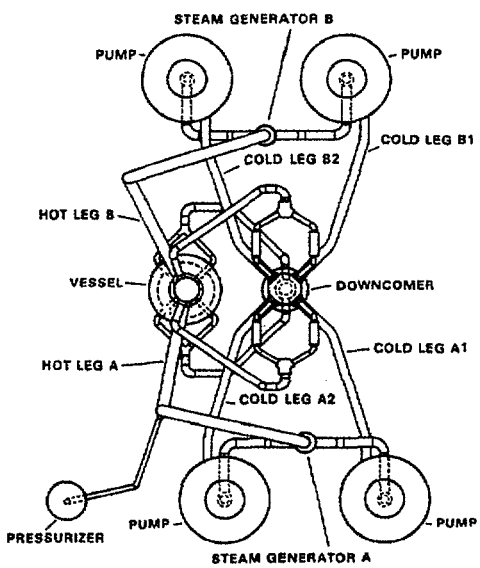
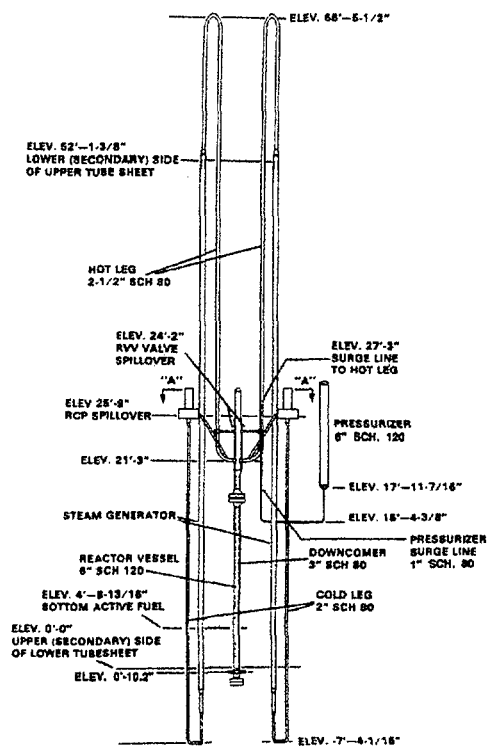


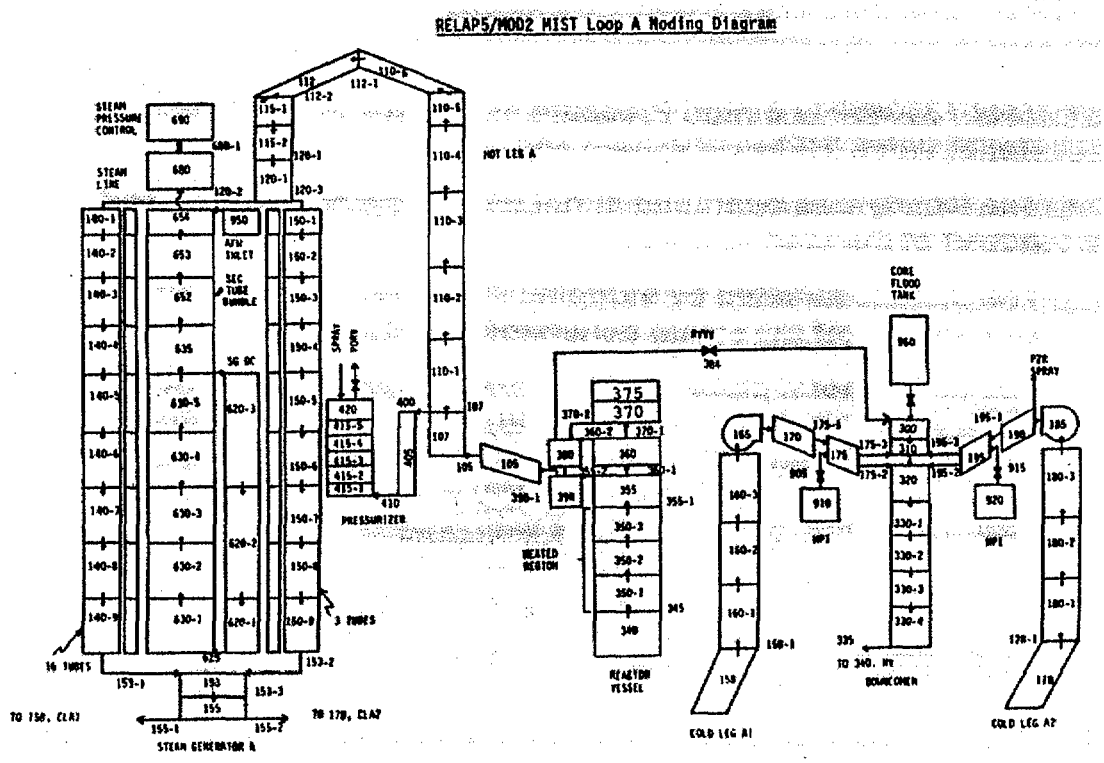
Figure 2.1 MIST Arrangement



Reactor Coolant System Layout



Reactor Coolant System Arrangement



Information Systems Laboratories

MIST Assessment Cases

- Test 360499A - Feed and Bleed - similar to pressurizer PORV stuck open PTS cases
- Test 3109AA - 10 cm^2 Cold Leg LOCA (1.4 inch equivalent - HPI can compensate for break flow)
- Test 4100B - 100 cm^2 Cold Leg LOCA (4.4 inch equivalent - HPI cannot compensate for break flow)

Information Systems Laboratories

MIST Test 360499A

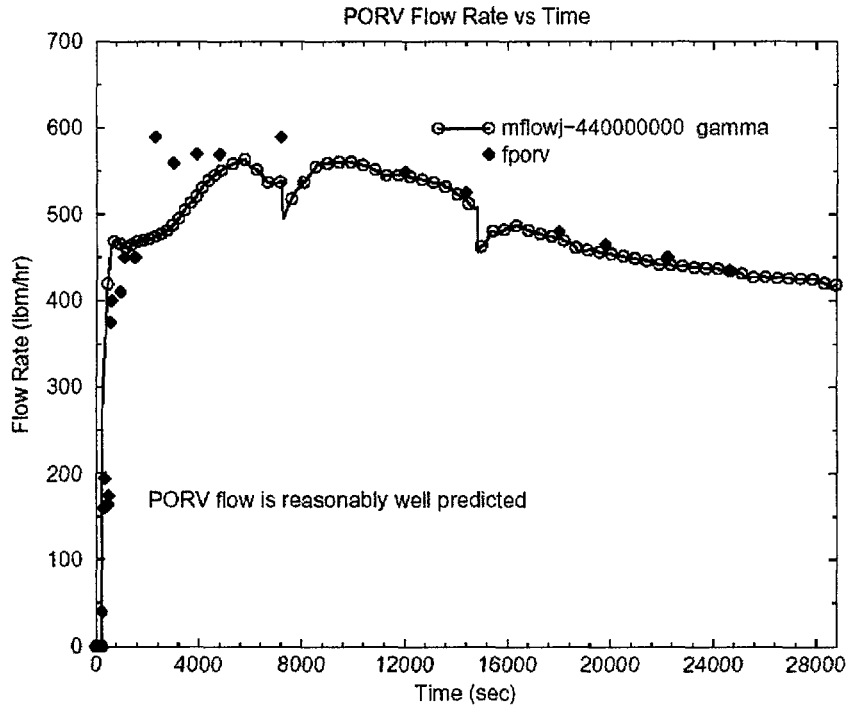
- Test T360499 is a High Pressure Injection – Power Operated Relief Valve (HPI-PORV) feed and bleed.
- The facility was operating at full pump flow and 10% scaled power at the start of the test.
- Transient is initiated by stopping the AFW pumps followed by isolation of the steam generators (SGs).
- Key parameters, pressure and downcomer temperature predictions agree well with the data in spite of differences in predictions of loop flow stagnation. Basic energy and mass system inflows and outflows (PORV flow, HPI flow, SG secondary side conditions) are well predicted.

MIST 360499A Feed and Bleed

Measured and Calculated Sequences of Events

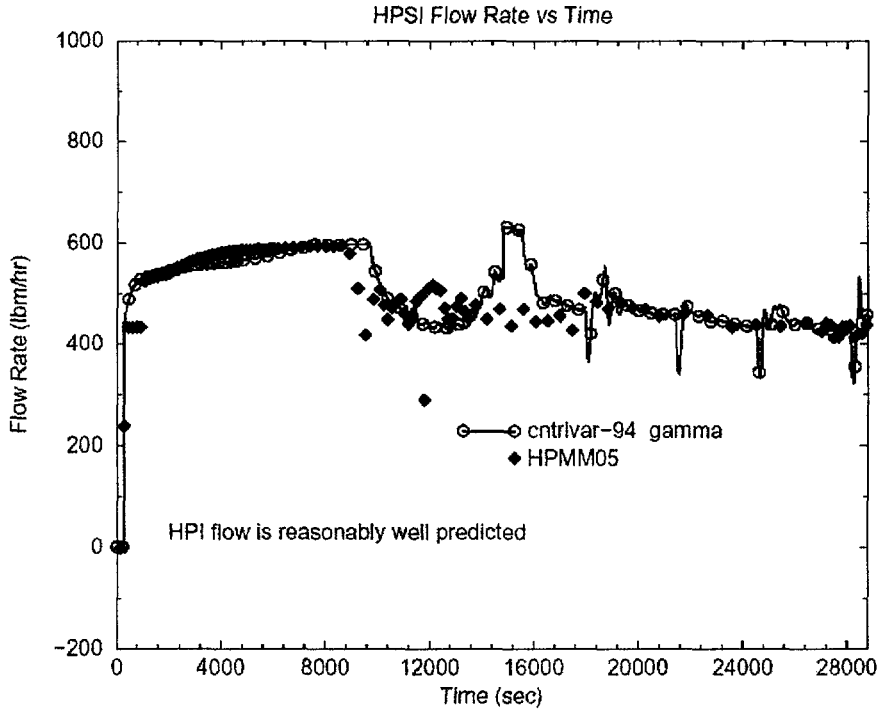
Event Description	Event Time (s) Measured	RELAP5
Stop AFW pumps and isolate SGs	0	0
Scram signal (core power decay)	9	9
Pressurizer sprays actuated	48	141
PORV locked open	282	240
HPI flow begins	286	286
Reactor coolant pumps tripped	338	280
Liquid flow at PORV begins	516	251
Flow stagnation in loop A	6,963	N/A
Flow stagnation in loop B	4,285	6,232
HPI flow throttled	8,728	9,701
High point vents opened (simulation ended)	28,800	28,800

MIST Test 360499 – Feed and Bleed



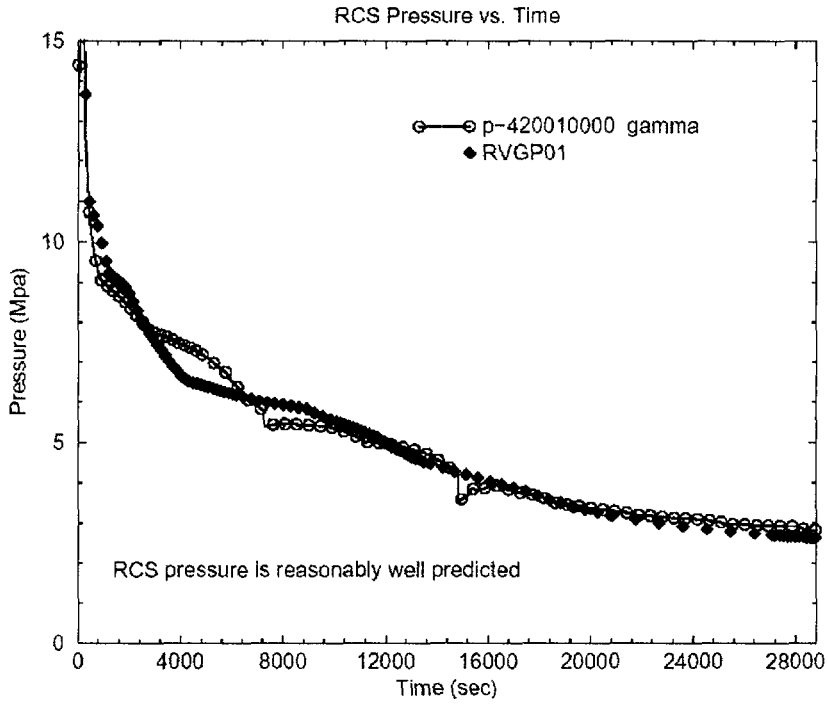
Information Systems Laboratories

MIST Test 360499 – Feed and Bleed



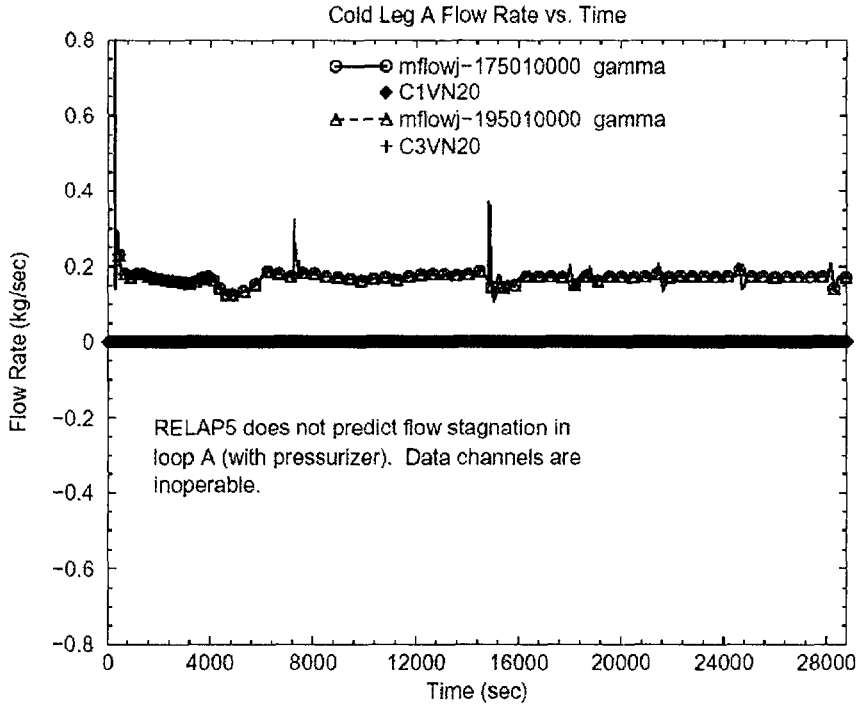
Information Systems Laboratories

MIST Test 360499 – Feed and Bleed



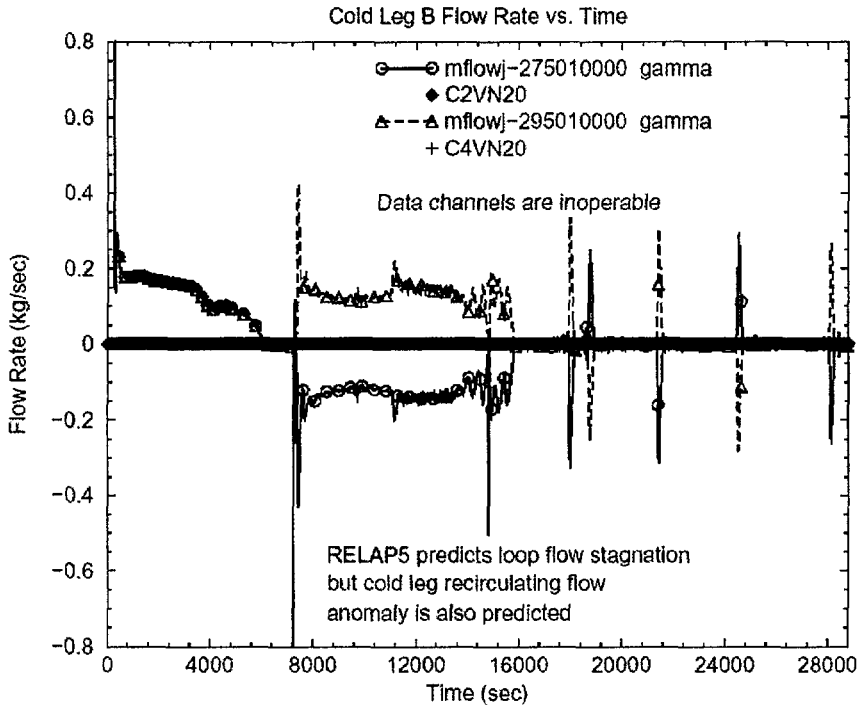
Information Systems Laboratories

MIST Test 360499 – Feed and Bleed



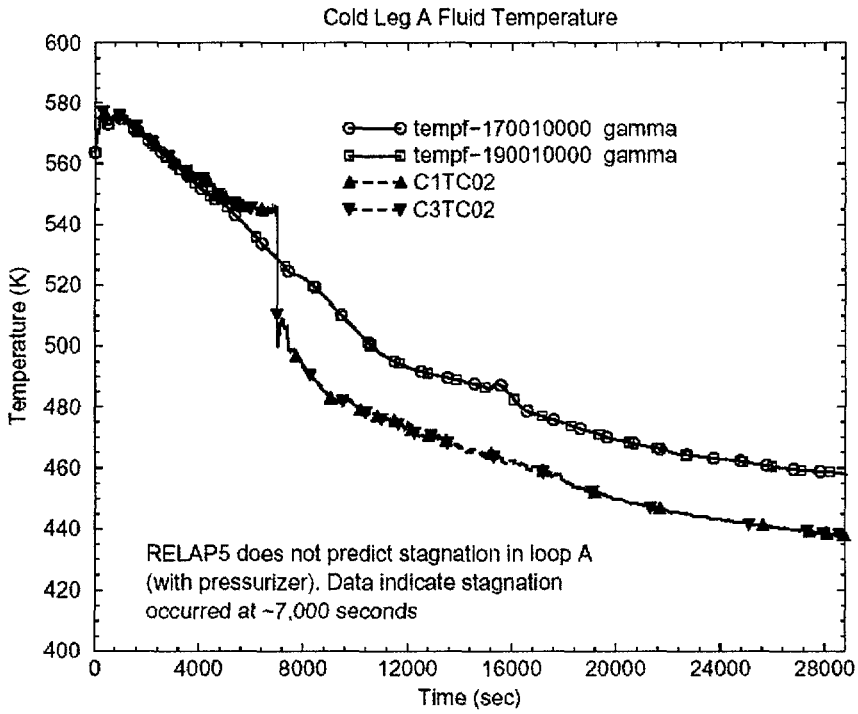
Information Systems Laboratories

MIST Test 360499 – Feed and Bleed



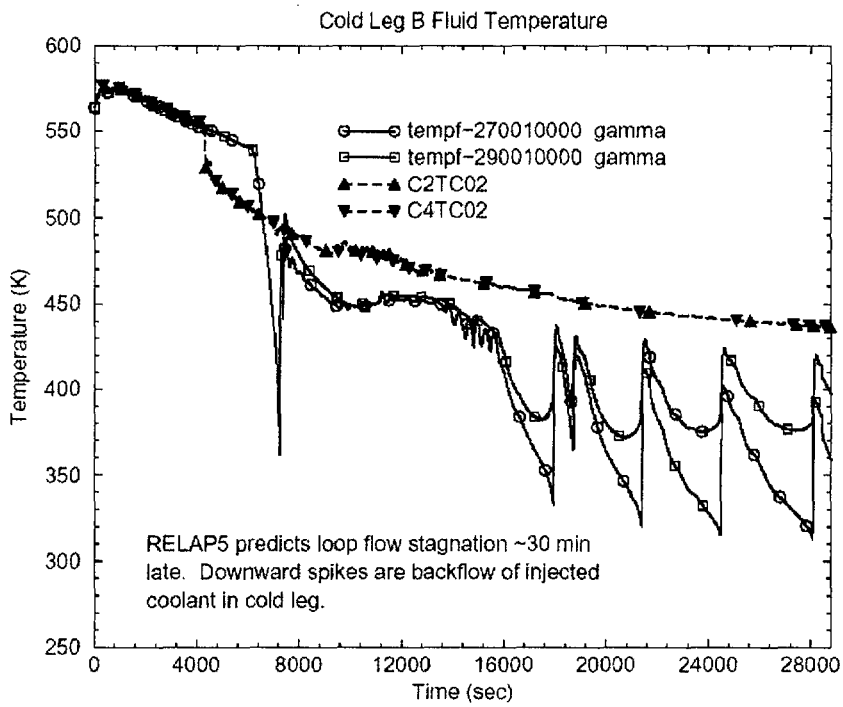
Information Systems Laboratories

MIST Test 360499 – Feed and Bleed



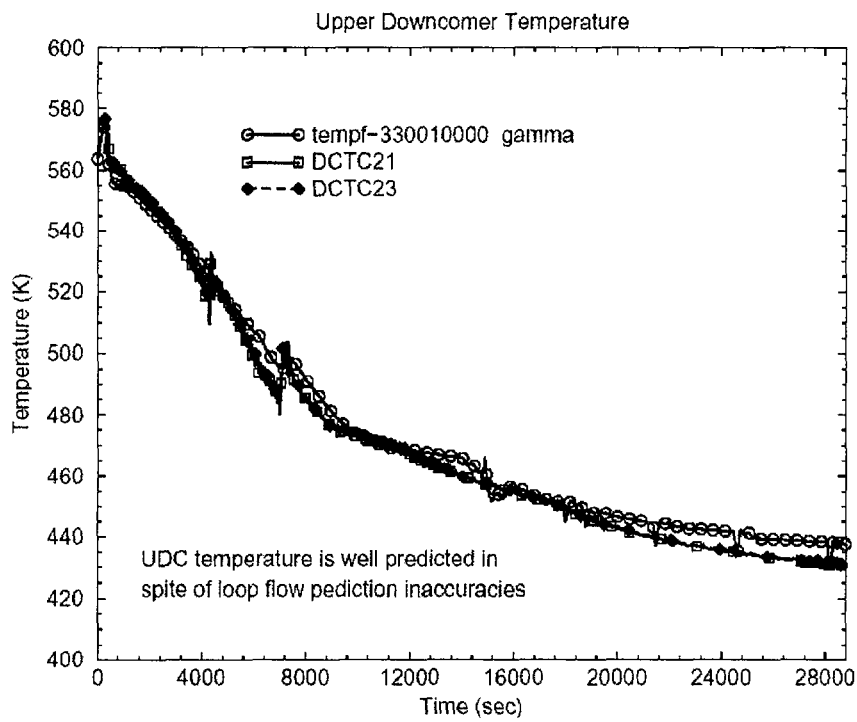
Information Systems Laboratories

MIST Test 360499 – Feed and Bleed



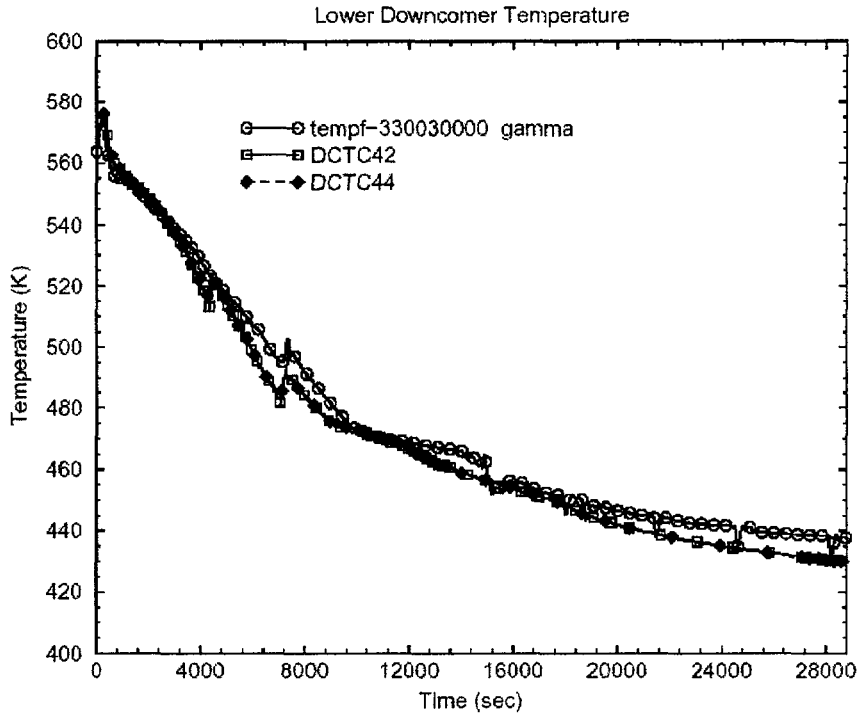
Information Systems Laboratories

MIST Test 360499 – Feed and Bleed



Information Systems Laboratories

MIST Test 360499 – Feed and Bleed



MIST Test 3109AA

- **Test 3009AA is a 10 cm^2 cold leg break in the pump discharge leg. This break size scales to a 1.4 inch break in the plant.**
- **At the start of the test the facility was operating at natural circulation conditions with the reactor coolant pumps in a locked rotor position.**
- **When pressurizer level dropped 1 foot (~ 1 minute) the following actions were initiated:**
  - **SG level setpoint increased from 9.63 to 31.6 feet**
  - **HPSI actuated**
  - **Core decay power curve initiated**
- **During the test, natural circulation is interrupted (loop flow stagnation)**
- **No core uncovery occurs**

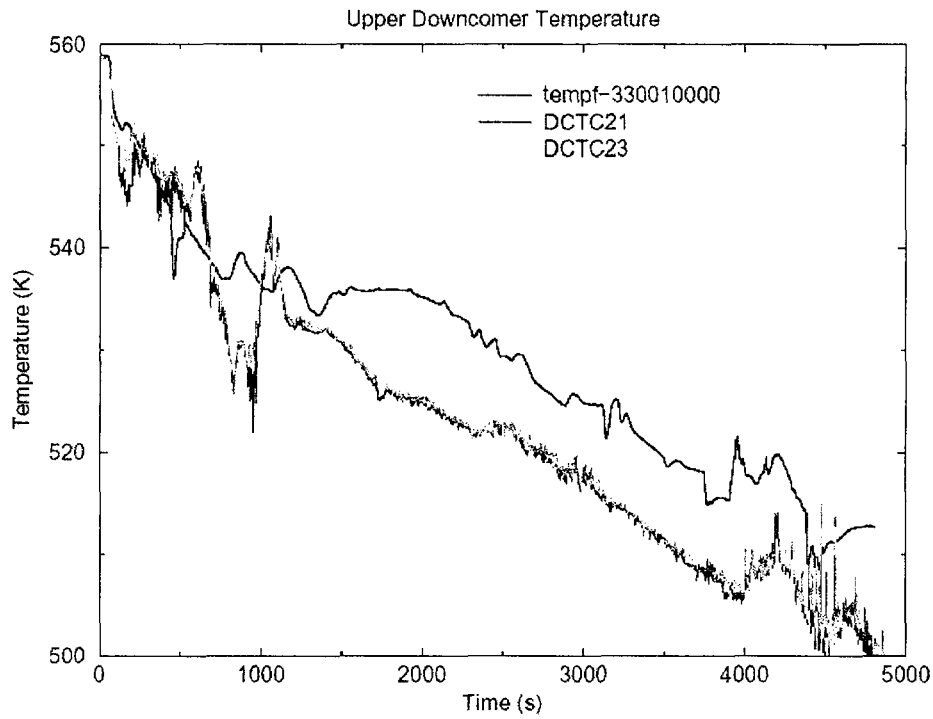
MIST 3109AA SBLOCA Test

Measured and Calculated Sequences of Events

Event Description	Event Time (s) Measured	RELAP5
Break opened	0	0
Low pressurizer level - initiate hpi and power decay	126	55
Hot leg A flow interruption	228	143
SG level reaches 31.6 ft setpoint level	552	532
Hot leg B flow interruption	1,020	1,362
Complete loss of loop natural circulation flow	1,560	1,373
Flow reversal in loop B	1,606	1,515
Flow reversal in loop A	2,662	4,447
Simulation ended	4,800	4,800

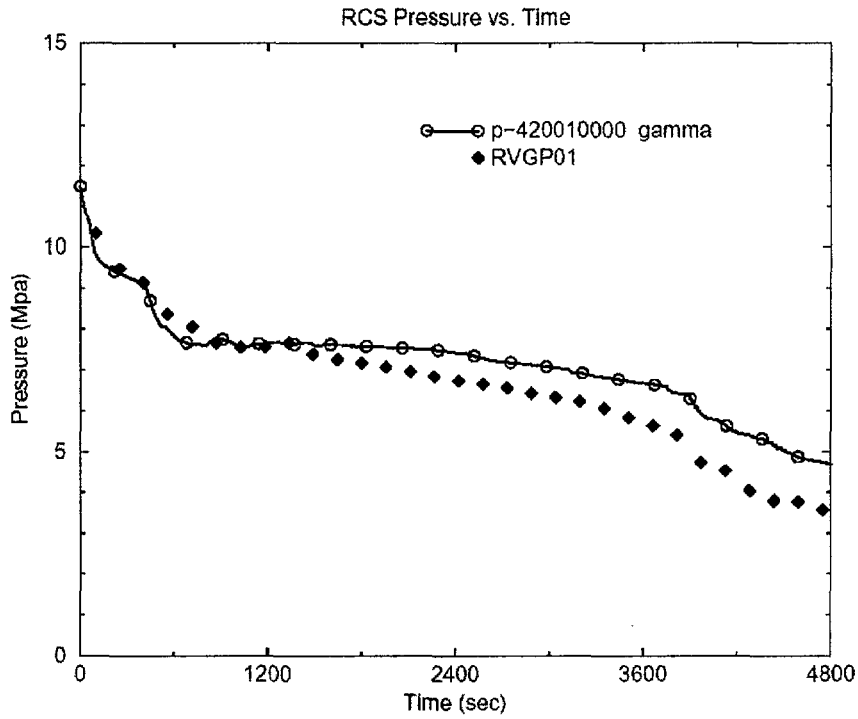
Information Systems Laboratories

MIST Test 3109AA – 10 cm2 CLB



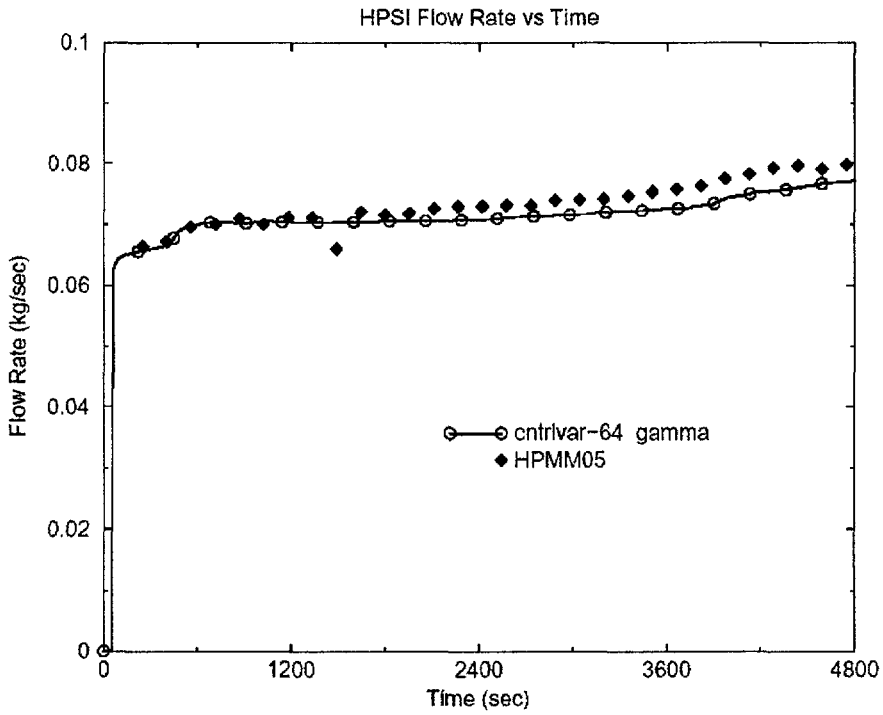
Information Systems Laboratories

MIST Test 3109AA – 10 cm2 CLB



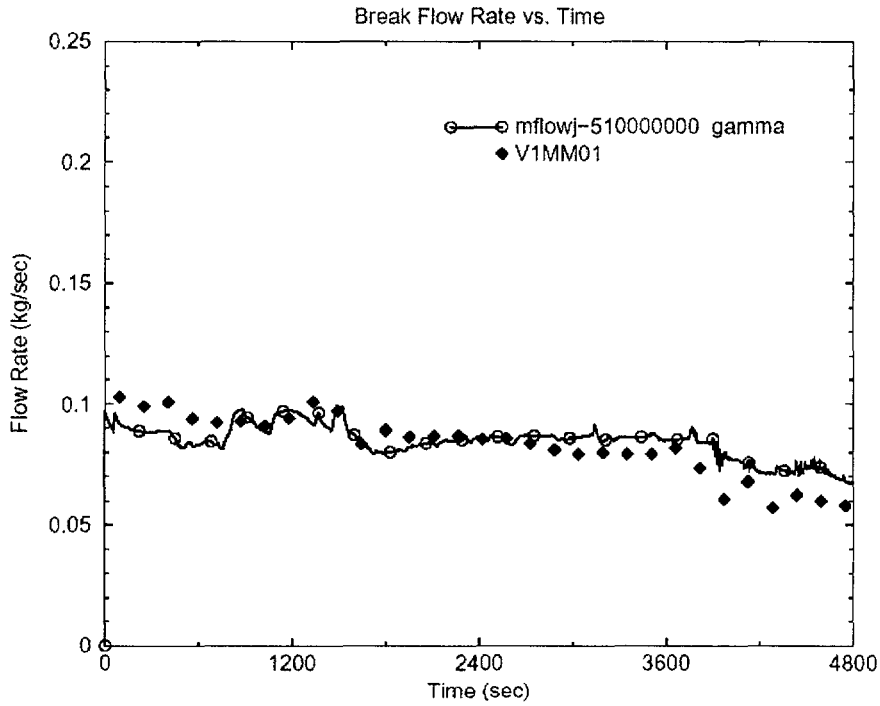
Information Systems Laboratories

MIST Test 3109AA – 10 cm2 CLB



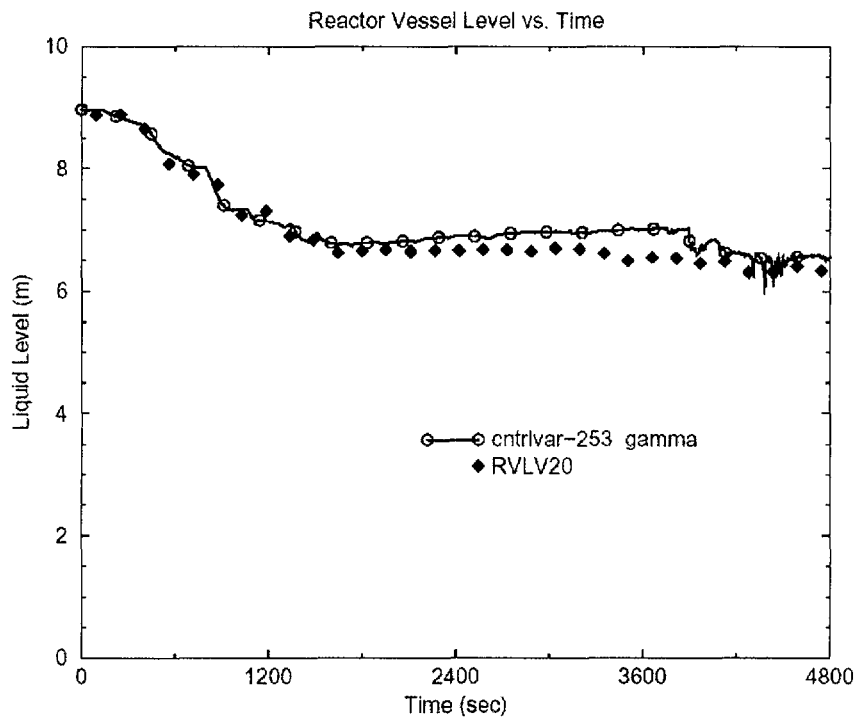
Information Systems Laboratories

MIST Test 3109AA – 10 cm2 CLB



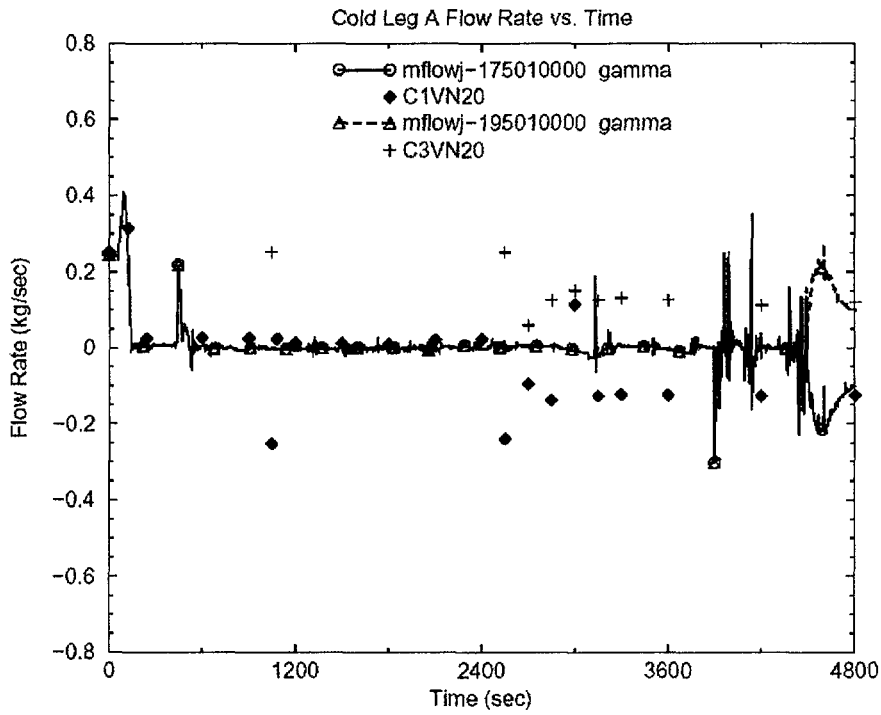
Information Systems Laboratories

MIST Test 3109AA – 10 cm2 CLB



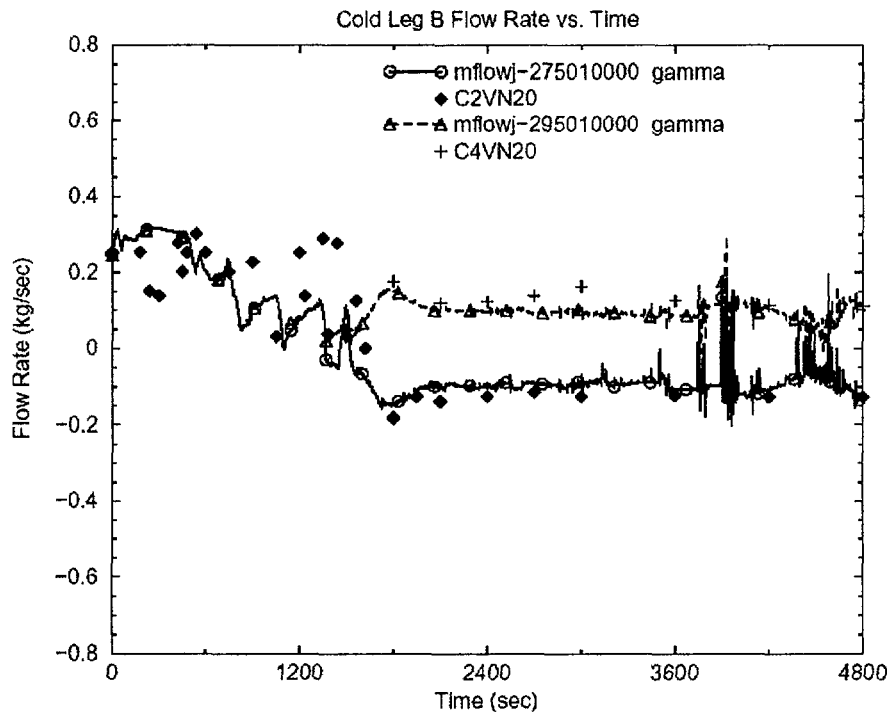
Information Systems Laboratories

MIST Test 3109AA – 10 cm2 CLB

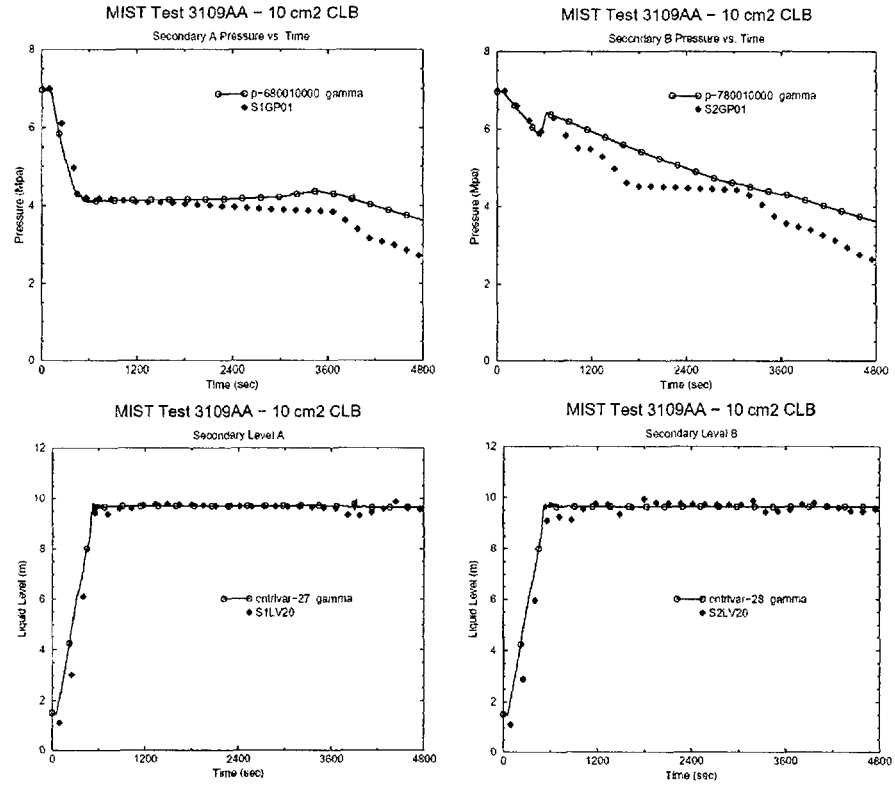


Information Systems Laboratories

MIST Test 3109AA – 10 cm2 CLB



Information Systems Laboratories



Information Systems Laboratories

MIST Test 4100B2

- Transient is initiated by opening the large 100 cm^2 break in cold leg B1.
- Core power decay is initiated after the pressurizer drains.
- HPI and AFW are actuated increasing the steam generator's secondary side levels to the "constant level control" setpoint of 31.6 ft.
- Cold legs voided at around 2 minutes interrupting the primary loop flow.
- As the primary system depressurized, the hot leg risers flashed and completely voided at approximately 15 minutes.
- LPI initiates at approximately 34 minutes. Together with CFT discharge and HPI flow, primary system inventory is increased.

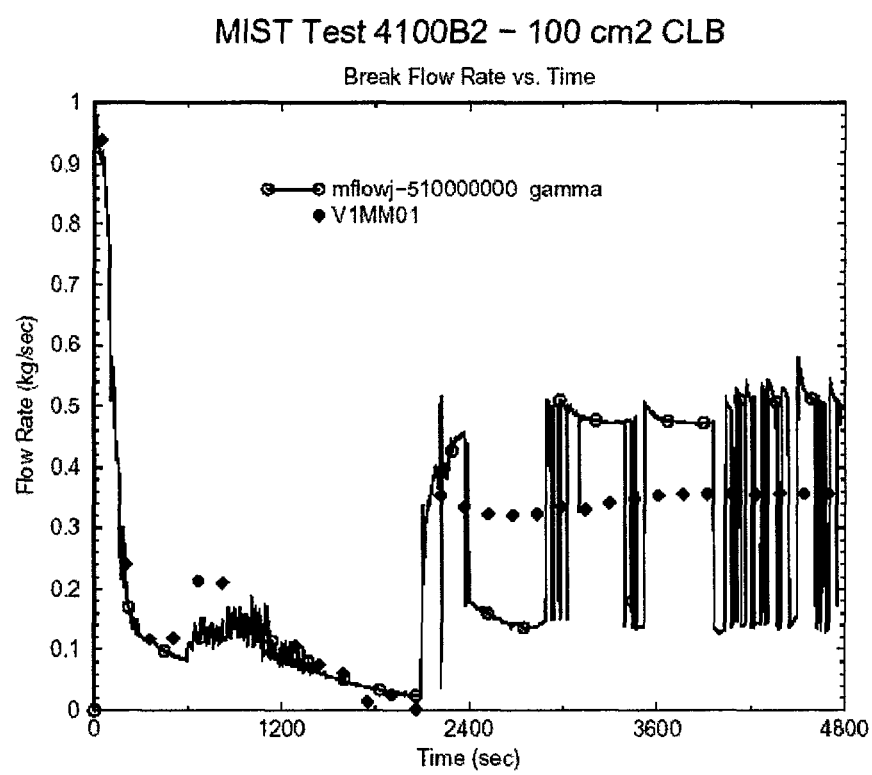
Information Systems Laboratories

MIST 4100B2 Larger Cold Leg Break LOCA

Measured and Calculated Sequences of Events

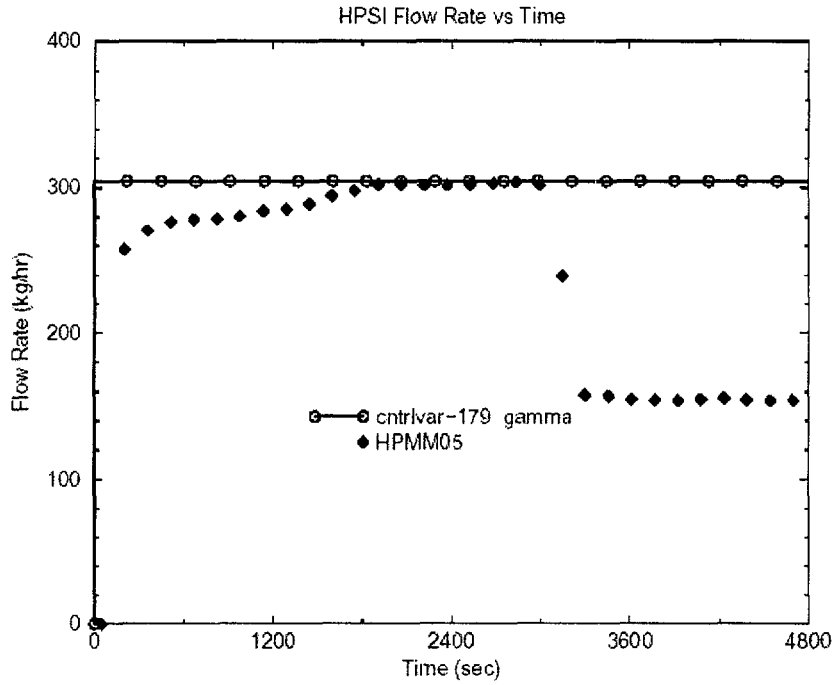
Event Description	Event Time (s) Measured	RELAP5
Break opened	0	0
Initiate power decay and hpi	manual (within 20 s)	0
Loss of loop natural circulation flow	~120	114
SG level reaches 31.6 ft setpoint level	~530	532
accumulator injection begins	~1,000	991
lpi flow begins	2,043	2,093
hpi flow throttled on high subcooling	2,986	N/A
Simulation ended	4,800	4,800

Information Systems Laboratories



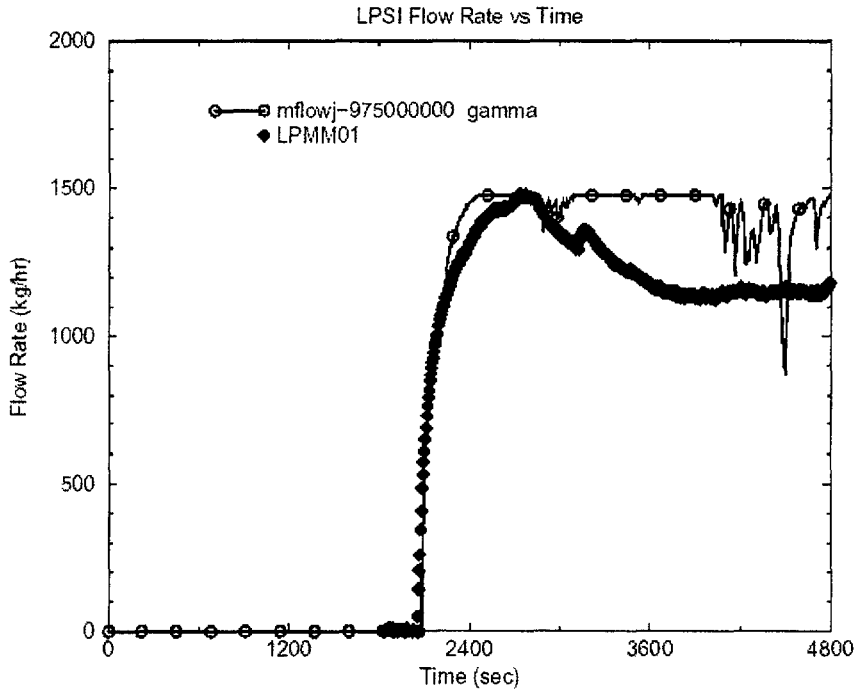
Information Systems Laboratories

MIST Test 4100B2 - 100 cm2 CLB



Information Systems Laboratories

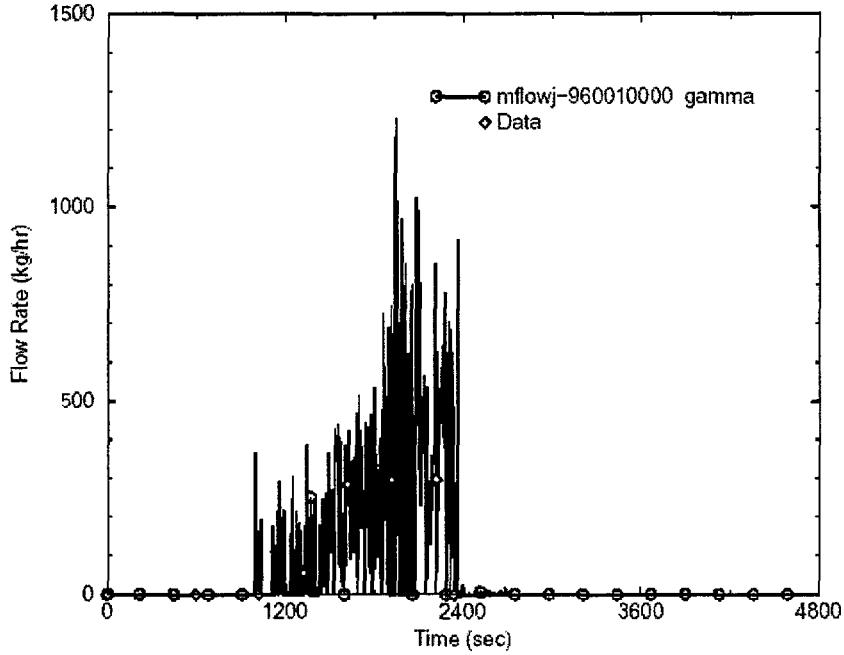
MIST Test 4100B2 - 100 cm2 CLB



Information Systems Laboratories

MIST Test 4100B2 – 100 cm2 CLB

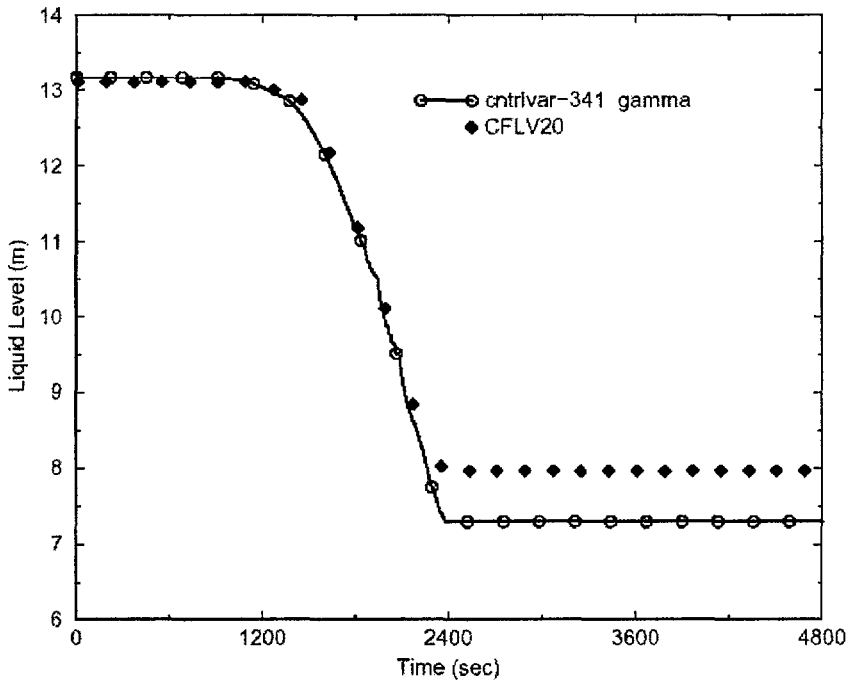
Accumulator Flow Rate vs Time



Information Systems Laboratories

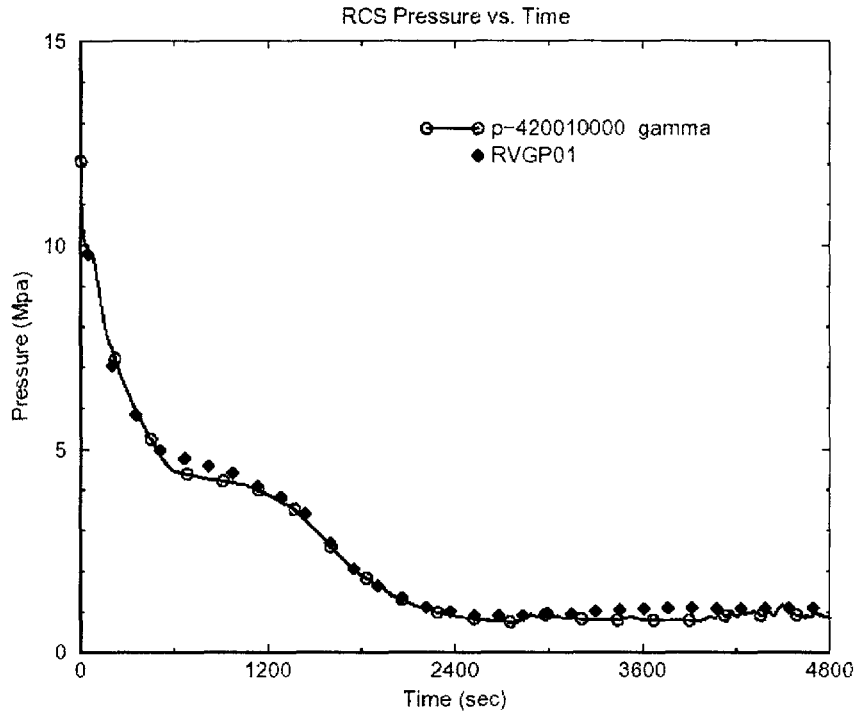
MIST Test 4100B2 – 100 cm2 CLB

Accumulator Level vs Time



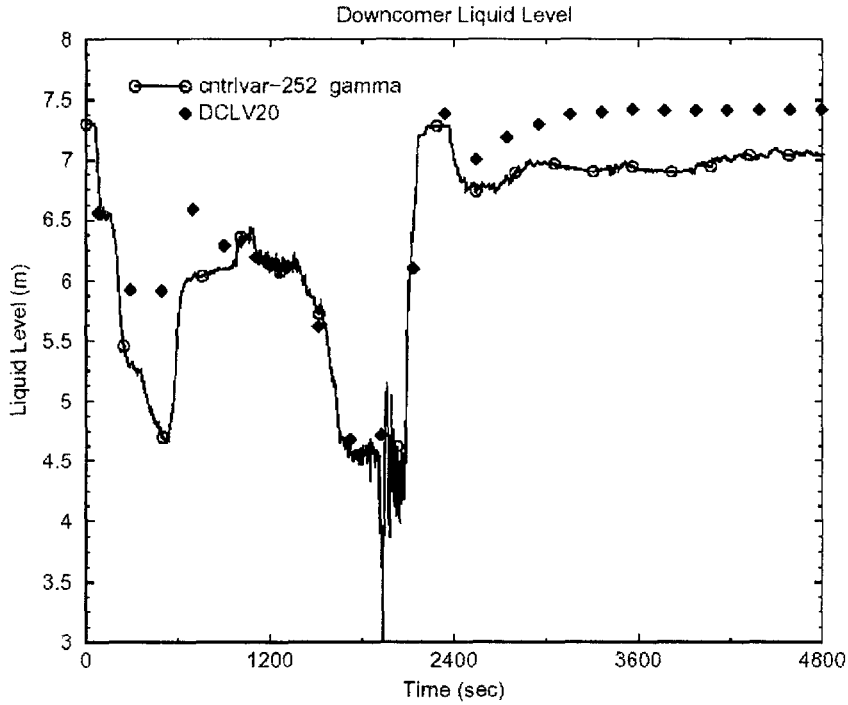
Information Systems Laboratories

MIST Test 4100B2 – 100 cm2 CLB



Information Systems Laboratories

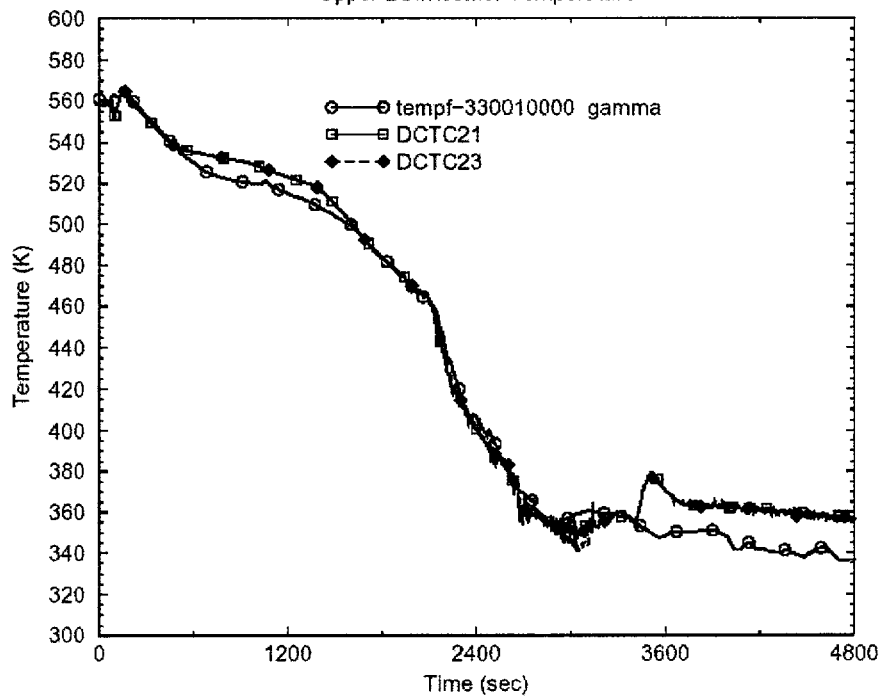
MIST Test 4100B2 – 100 cm2 CLB



Information Systems Laboratories

MIST Test 4100B2 – 100 cm2 CLB

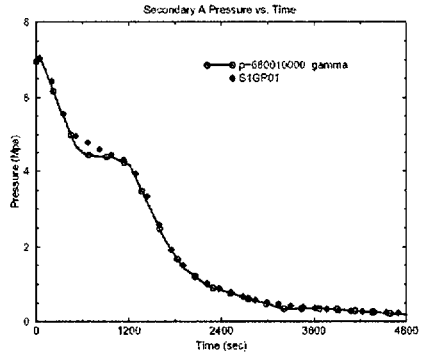
Upper Downcomer Temperature



Information Systems Laboratories

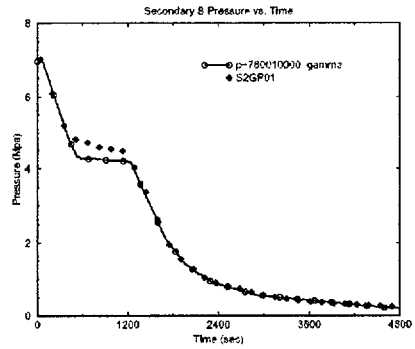
MIST Test 4100B2 – 100 cm2 CLB

Secondary A Pressure vs. Time



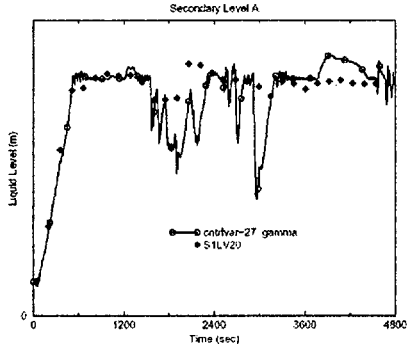
MIST Test 4100B2 – 100 cm2 CLB

Secondary B Pressure vs. Time



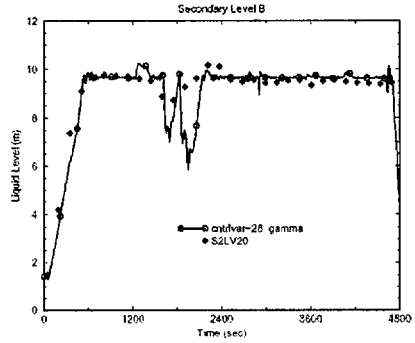
MIST Test 4100B2 – 100 cm2 CLB

Secondary Level A



MIST Test 4100B2 – 100 cm2 CLB

Secondary Level B



Information Systems Laboratories

LOFT L3-7 SBLOCA Test

- 1-inch scaled cold leg break
- Pumps were manually tripped and coasted down. Pump coastdown was followed by the inception of loop natural circulation
- Break flow approximately equal to HPIS flow with primary pressure of about 6.9 Mpa (1,000 psia); establish conditions for steam generator reflux cooling
- HPIS was turned off to hasten the loss of fluid inventory
- Operator-controlled steam bleeding and steam generator feeding to decrease primary system pressure. Steam generator secondary feed and bleed maintained an effective heat sink throughout the experiment
- RELAP5 predictions fairly close to experimental data

LOFT L3-7 Schematic

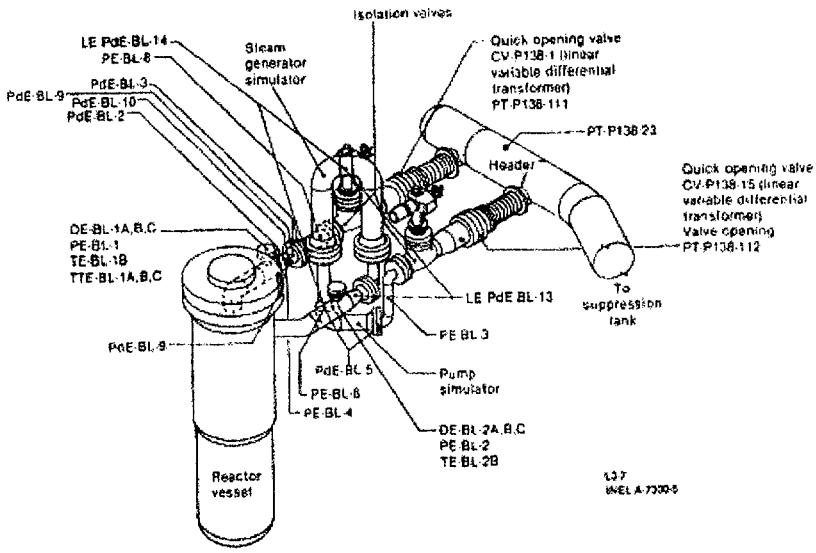
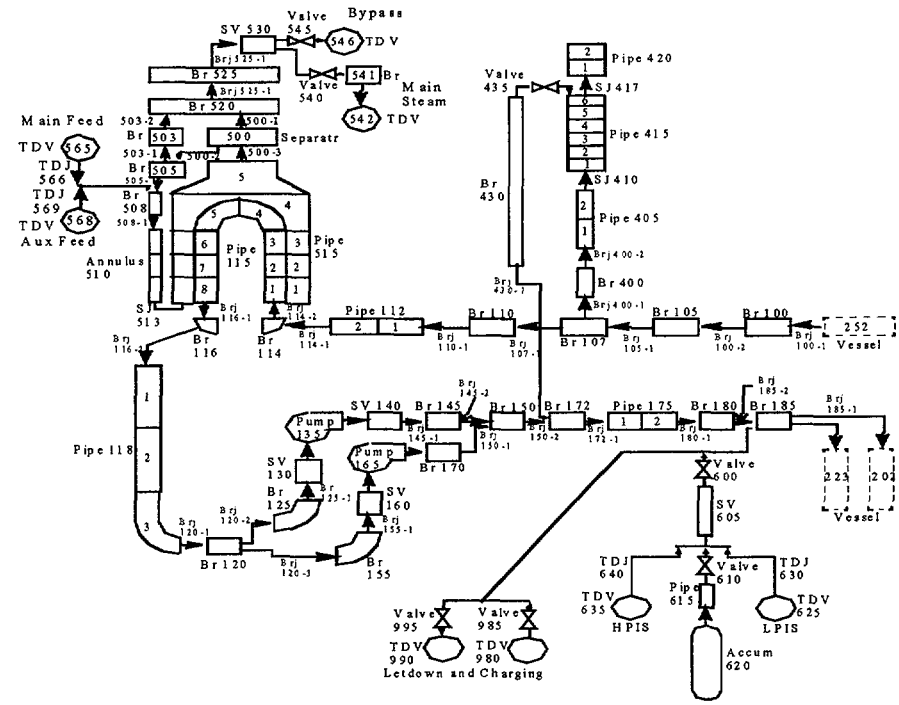


Figure 3-5. LOFT thermal-hydraulic instrumentation for broken loop.



RELAP5 nodalization for LOFT Test L3-7: Intact Loop.

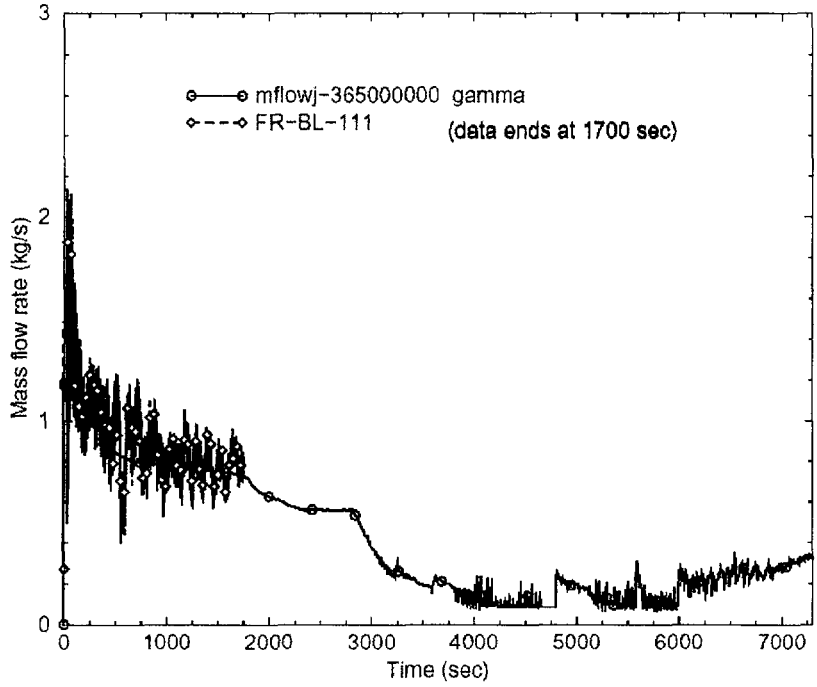
LOFT L3-7 SBLOCA Test

Measured and Calculated Sequences of Events

Event Description	Event Time (s) Measured	RELAP5
Break valve opened	0	0
Scram signal (p<14.193 MPa)	36	28
Reactor coolant pumps tripped manually at scram	39	28
HPI flow begins (p<13.159 MPa)	65.4	80.1
HPI flow turned off	1800	1800
HPI flow turned back on	5974	5974
Break valve closed (simulation ended)	7,302	7,300

LOFT Test L3-7

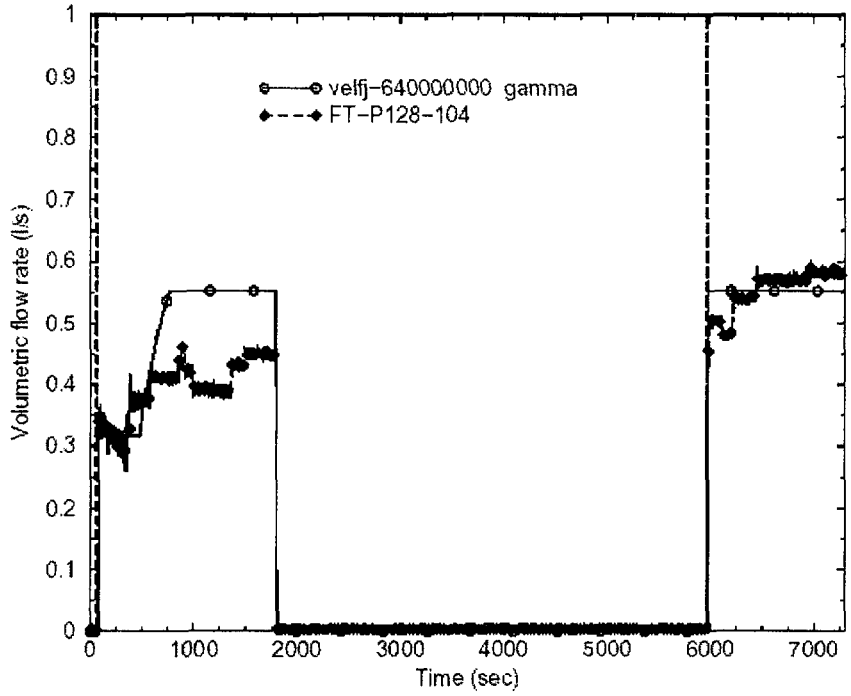
Break mass flow rate



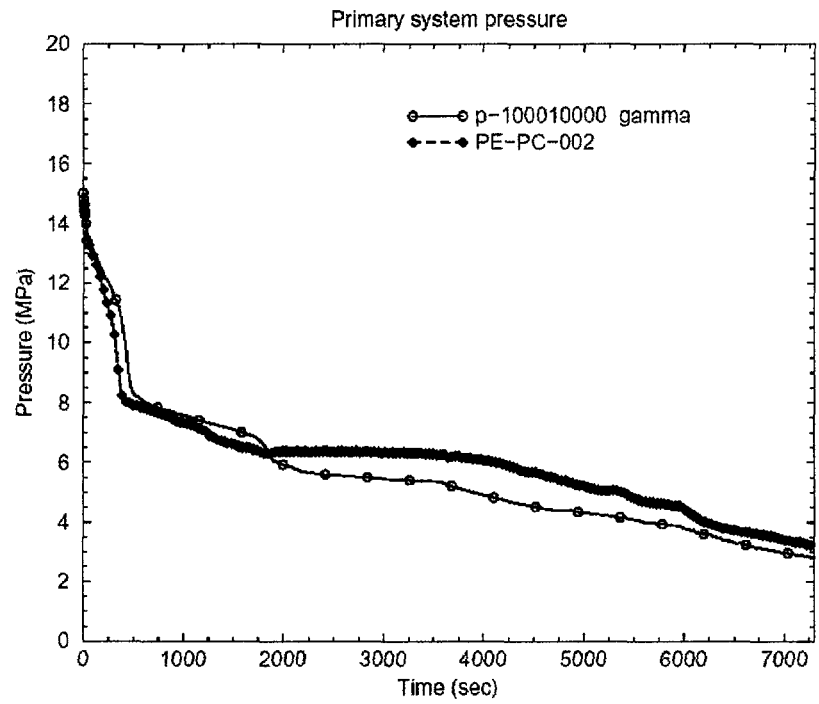
Information Systems Laboratories

LOFT Test L3-7

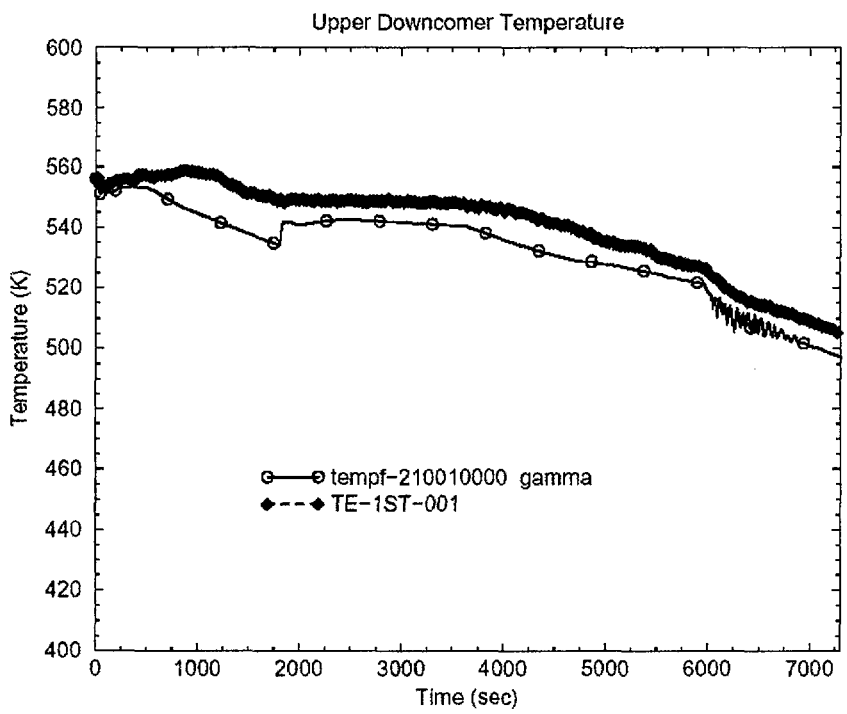
HPI Volumetric Flow Rate



Information Systems Laboratories



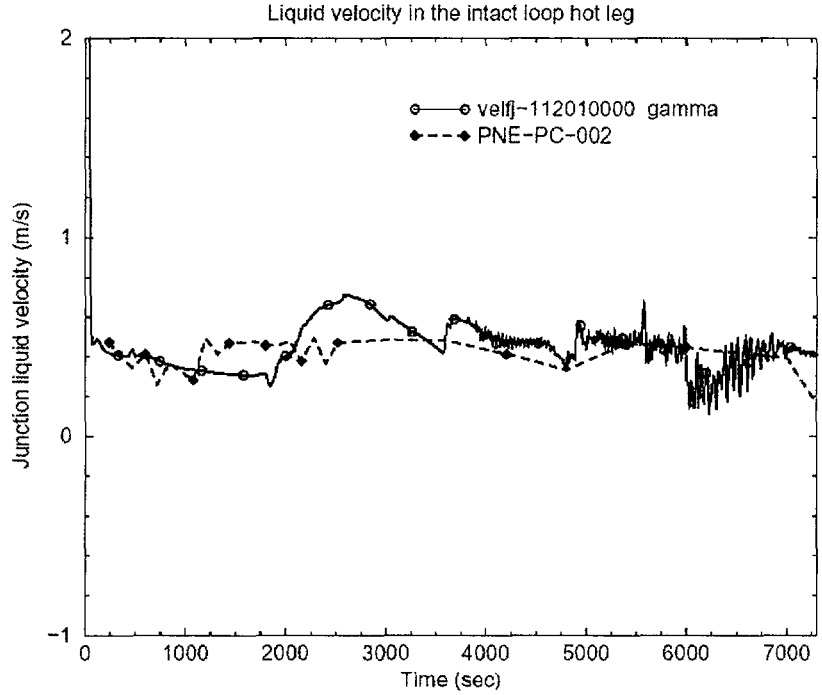
Information Systems Laboratories



Information Systems Laboratories

LOFT Test L3-7

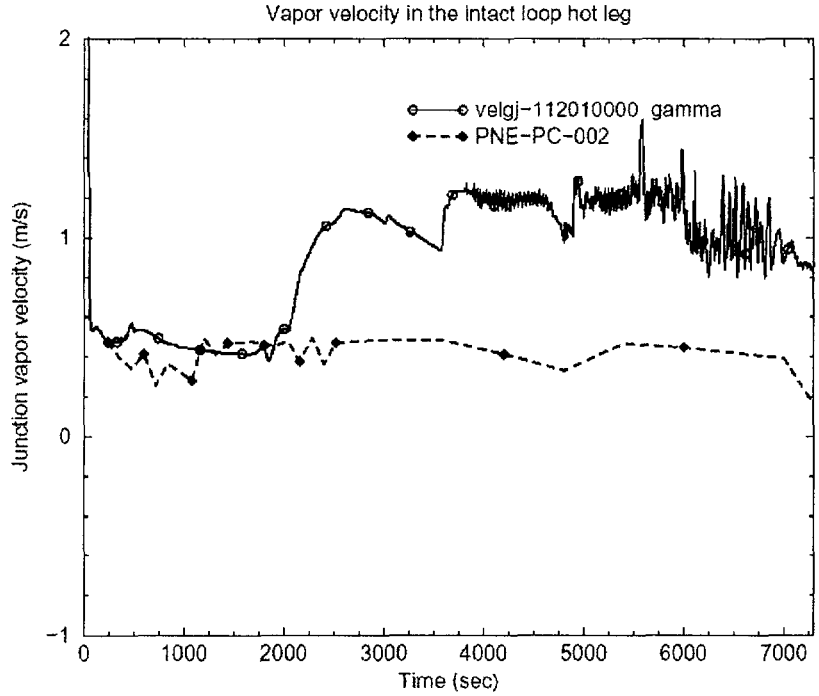
Liquid velocity in the intact loop hot leg



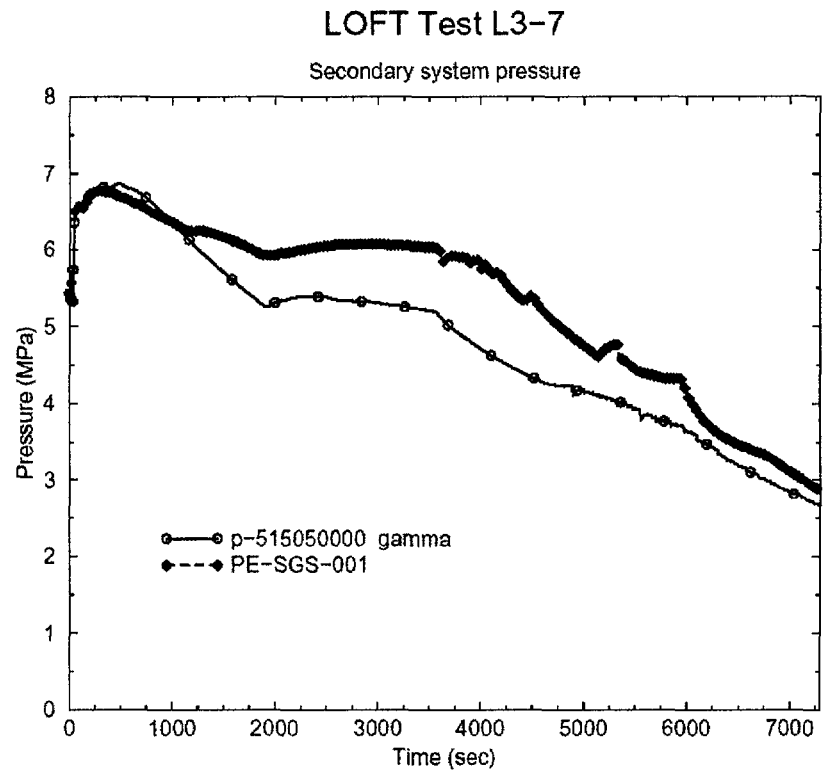
Information Systems Laboratories

LOFT Test L3-7

Vapor velocity in the intact loop hot leg



Information Systems Laboratories



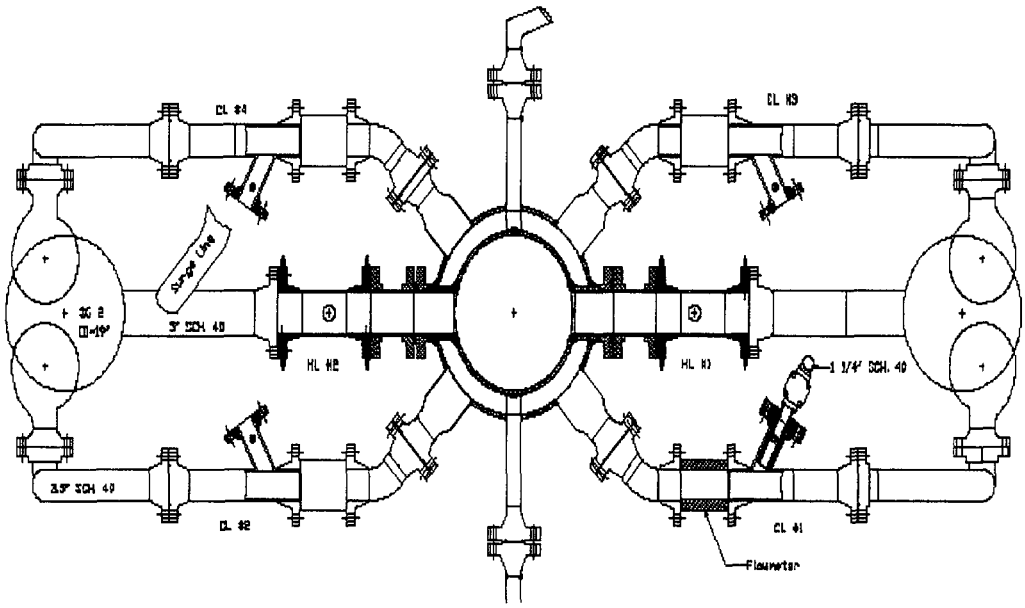
Information Systems Laboratories

APEX-CE PTS TEST OBJECTIVES

- **To investigate mixing of the HPI in the cold leg and downcomer. In particular, it was necessary to ensure that strong plumes did not persist into the downcomer region adjacent to the core in order to support the adequacy of the 1-D treatment of the temperature boundary condition in the code FAVOR;**
- **To provide data to validate and assess RELAP5 for PTS-significant transients**

Information Systems Laboratories

APEX-CE SCHEMATIC



APEX-CE 13 TEST

- Stuck Open Safety Relief Valve from Full Power with Subsequent Reclosure - typical PTS event
- Initiated from full power steady-state conditions.
- ADS-2 valve was opened at the start of the transient to simulate a stuck open pressurizer safety relief valve (SRV).
- Simultaneously, two of the reactor coolant pumps (RCPs) were tripped, the high-pressure injection (HPI) was actuated, and the reactor core power was shifted into decay heat mode.
- ADS-2 valve remained open for an hour and then was closed.
- The test was completed approximately 20 minutes later after the system had refilled

APEX-CE-13 Initial Conditions Comparison

Parameter	Test Specification	Test Condition	Calculated Value
RCS Pressure	2.65±0.03 MPa (370±5 psig)	2.65 MPa (370 psig)	2.65 MPa (370 psig)
Cold Leg Temperature	n/a	480 K (403°F)	480 K (403°F)
Core Power	610 kW	610 kW	610 kW
SG 1 Pressure	1.70±0.01 MPa (232±2 psig)	1.71 MPa (234 psig)	1.70 MPa (232 psig)
SG 2 Pressure	1.70±0.01 MPa (232±2 psig)	1.71 MPa (234 psig)	1.70 MPa (232 psig)
SG 1 Level	38±3 cm H_2O (15±1 inches H_2O)	38.6 cm (15.2 inches H_2O)	32.8 cm (12.8 inches H_2O)
SG 2 Level	38±3 cm H_2O (15±1 inches H_2O)	38.6 cm 15.2 inches H_2O	32.8 cm (12.8 inches H_2O)
Pressurizer Level	51±5 cm H_2O (20±2 inches H_2O)	53.8 cm H_2O (21.2 inches H_2O)	50.5 cm H_2O (19.9 inches H_2O)

Information Systems Laboratories

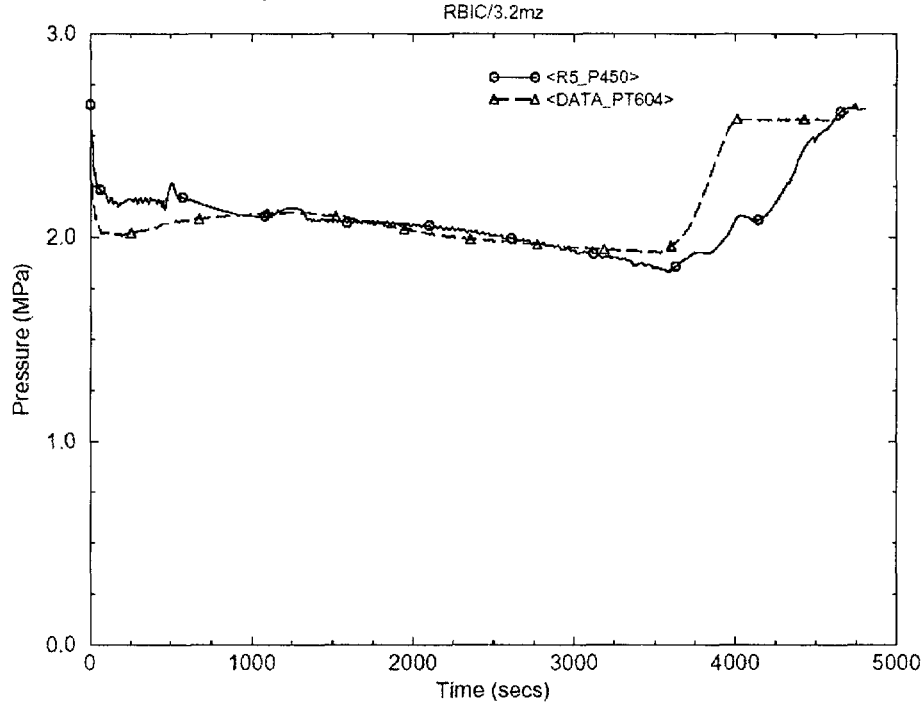
APEC-CE-13 Test

Measured and Calculated Sequences of Events

Event Description	Event Time (s) Measured	RELAP5
Pressurizer SRV opened	0	0
Scram signal (core power decay)	0	0
HPI flow starts	0	0
RCP #1 and #4 tripped	4.2	4.2
RCP #2 and #3 tripped	20.8	20.8
Turbine stop valves closed	18.0	18.0
Pressurizer SRV closed	3589.1	3589.1
Simulation ended	4,800	4,800

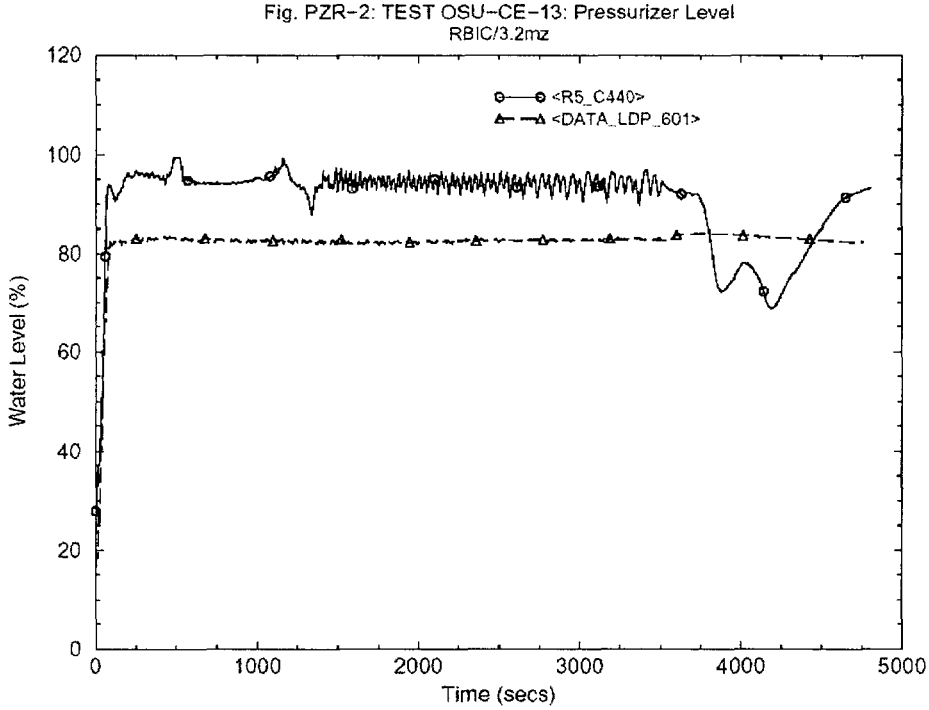
Information Systems Laboratories

Fig. PZR-1: TEST OSU-CE-13: Pressurizer Pressure
RBIC/3.2mz



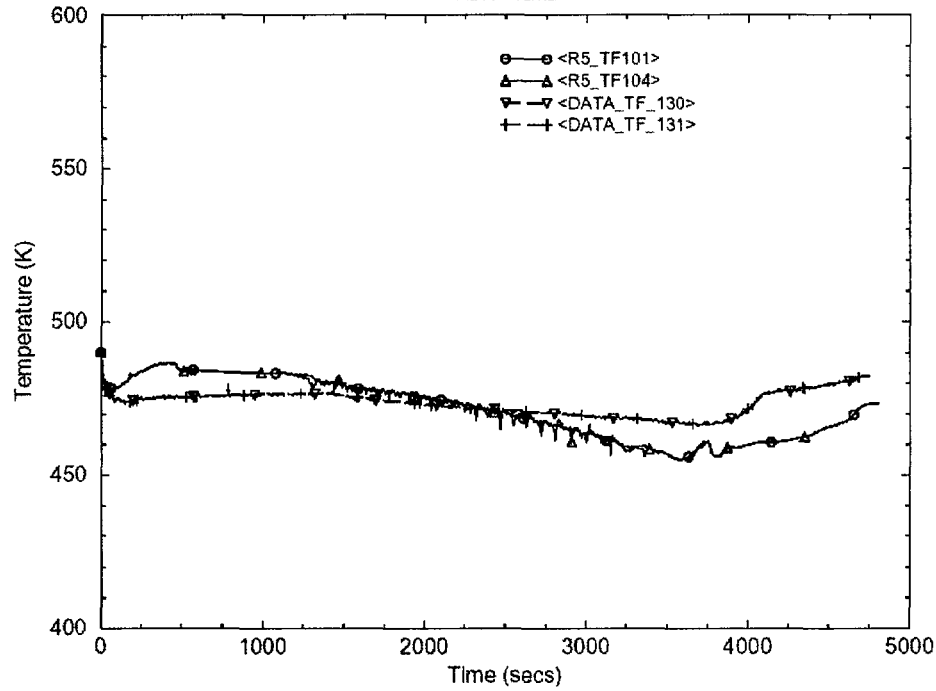
Information Systems Laboratories

Fig. PZR-2: TEST OSU-CE-13: Pressurizer Level
RBIC/3.2mz



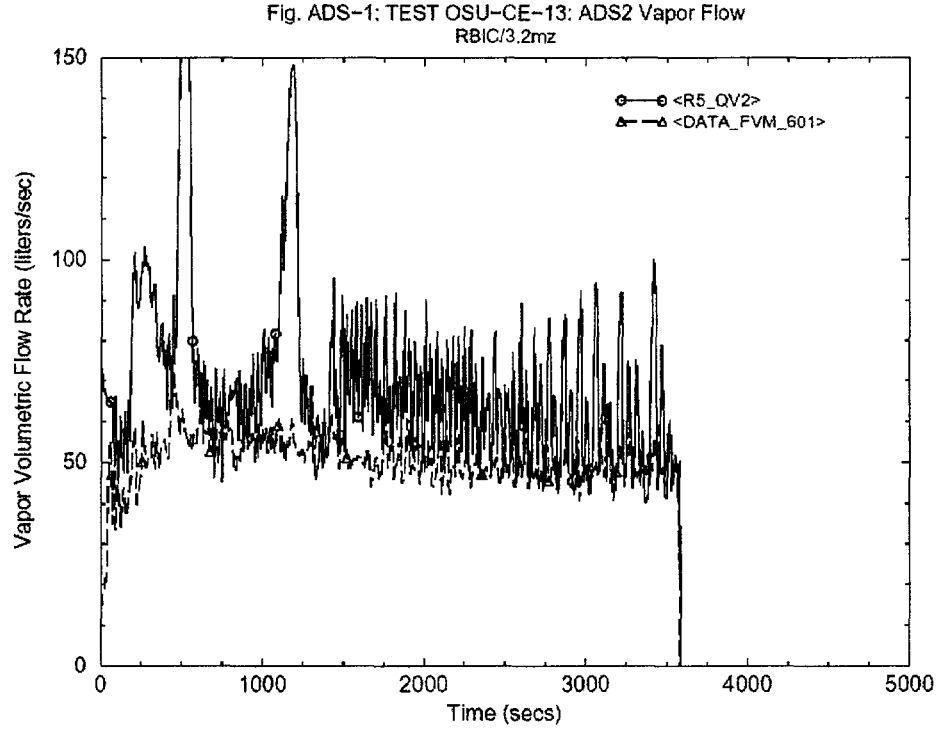
Information Systems Laboratories

Fig. DC-1: TEST OSU-CE-13: Downcomer Fluid Temperatures
RBIC/3.2mz



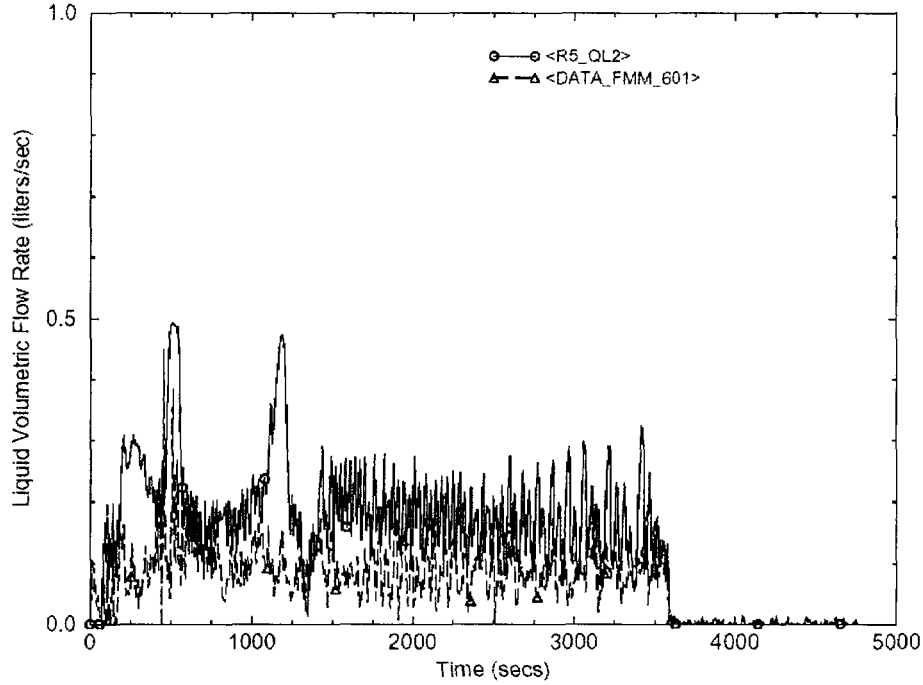
Information Systems Laboratories

Fig. ADS-1: TEST OSU-CE-13: ADS2 Vapor Flow
RBIC/3.2mz



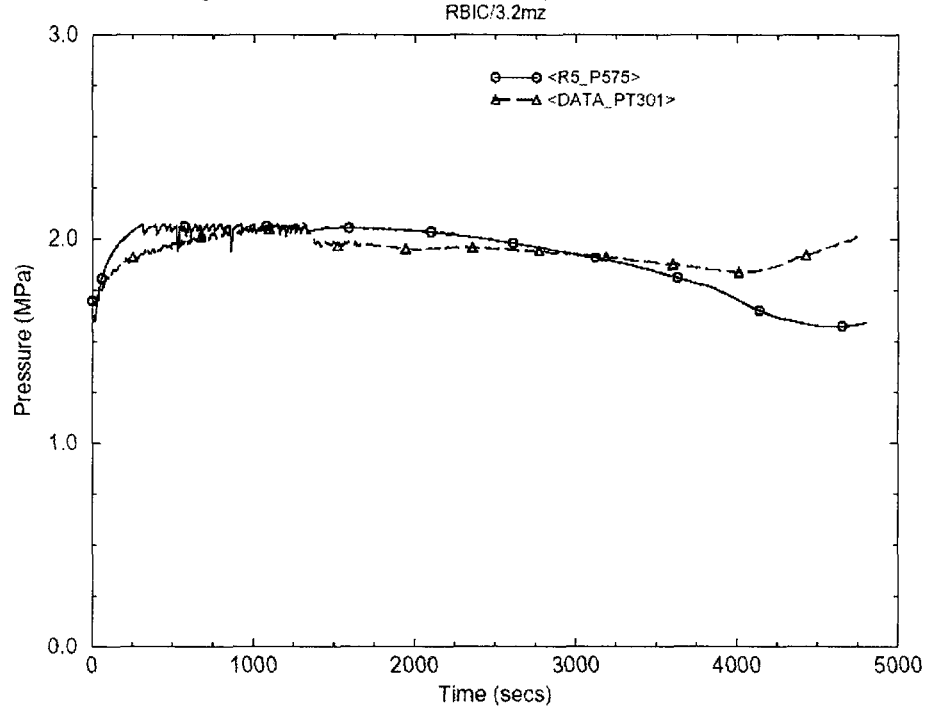
Information Systems Laboratories

Fig. ADS-2: TEST OSU-CE-13: ADS2 Liquid Flow
RBIC/3.2mz



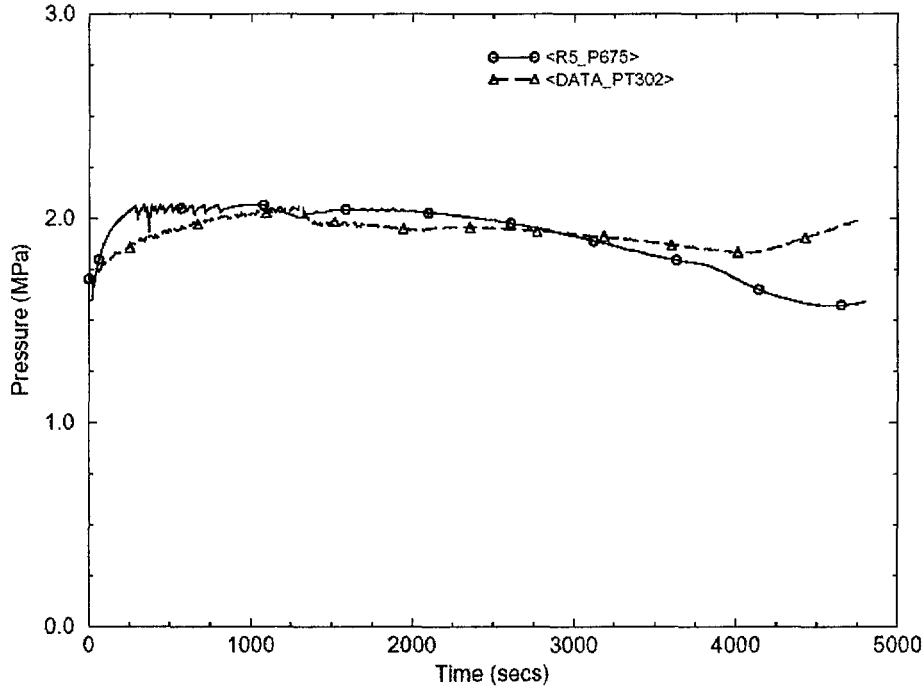
Information Systems Laboratories

Fig. SG-1: TEST OSU-CE-13: C-Loop Steam Generator Pressure
RBIC/3.2mz



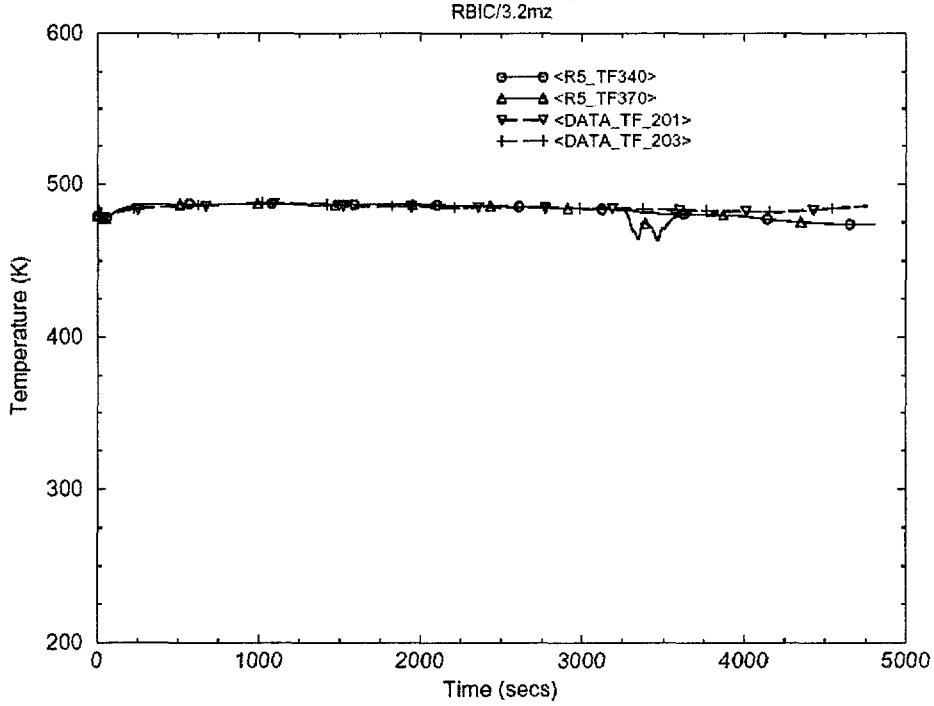
Information Systems Laboratories

Fig. SG-2: TEST OSU-CE-13: P-Loop Steam Generator Pressure
RBIC/3.2mz



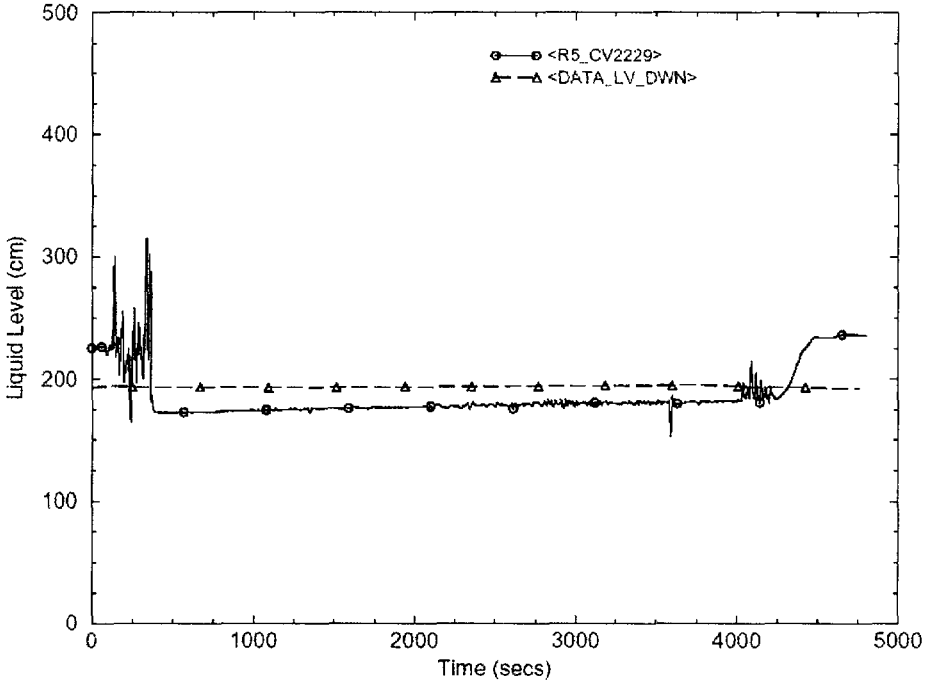
Information Systems Laboratories

Fig. RCP-1: TEST OSU-CE-13: C-Loop RCP Inlet Temperatures
RBIC/3.2mz



Information Systems Laboratories

Fig. VES-5: TEST OSU-CE-13: Downcomer Collapsed Liquid Level
RBIC/3.2mz



APEX-CE-13 TEST SUMMARY

- **Test APEX-CE-13 simulates a stuck open pressurizer safety relief valve from full power with subsequent reclosure, a PTS significant event.**
- **Downcomer fluid temperature is predicted with reasonable accuracy. Temperature shows little dependence on azimuthal position in both the RELAP5 results and the APEX measurements.**
- **RELAP5 result shows repressurization at a somewhat lower rate than the measured data, but the eventual peak pressure is slightly higher.**
- **Overall, the RELAP5 prediction is a reasonable simulation of the test data.**

ROSA EXPERIMENTS USED FOR ASSESSMENT

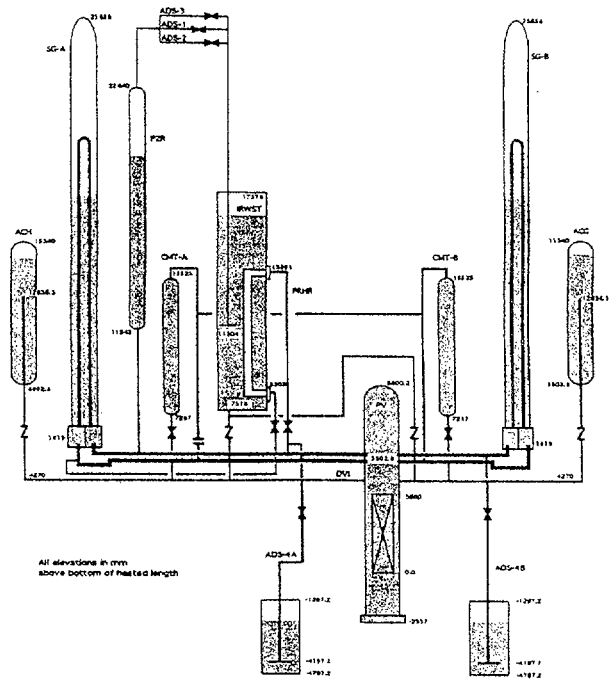
- ROSA-AP600 AP-CL-03 1" Cold Leg LOCA
- ROSA-AP600 AP-CL-09 1" Cold Leg LOCA with Multiple Passive Safety System Failures
- ROSA-IV SB-CL-18 6" Cold Leg LOCA with Failure of HPI
- ROSA-IV SB-HL-06 2" Hot Leg LOCA with Failure of HPI
- ROSA-IV ST-NC-09 Natural Circulation/Reflux Cooling

ROSA-AP600 FACILITY DESCRIPTION

- 1/30 volume-scaled, full-pressure representation of a Westinghouse AP600 passive-safety PWR
- Full-height electrically-heated core
- The two AP600 PWR loops represented with two equal-volume loops

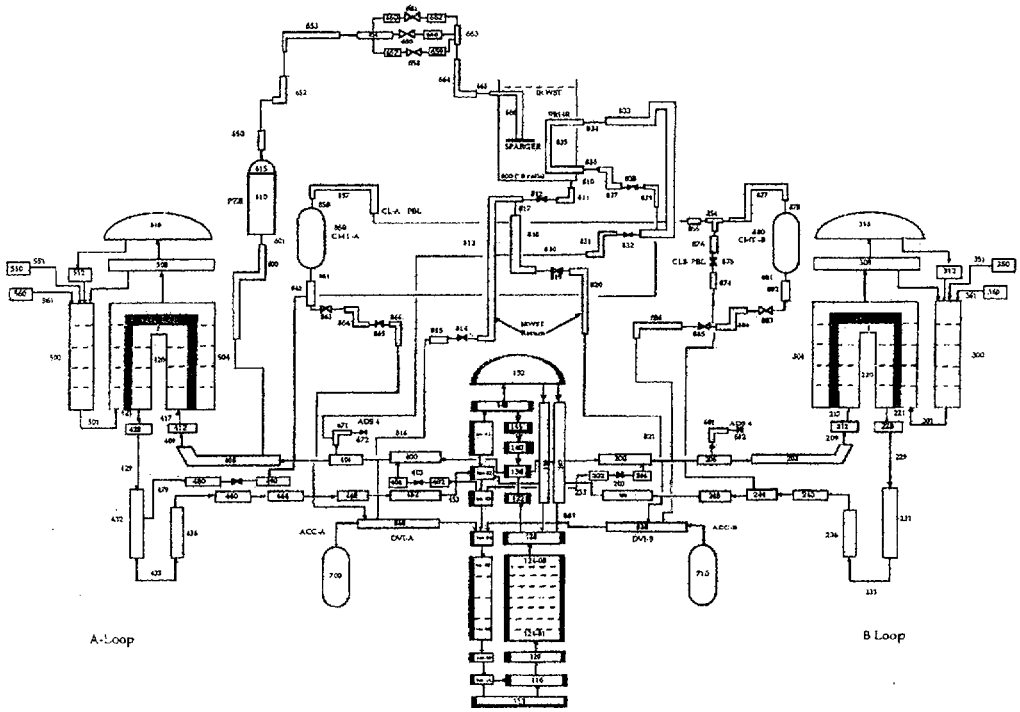
  Hot leg
  Steam generator
  One reactor coolant pump (vs. two in AP600)
  One cold leg (vs. two in AP600)
  Pressurizer on one loop
  CMTs on the other loop
  PRHR
  ADS
  IRWST

ROSA-AP600 Facility Layout



Information Systems Laboratories

ROSA-AP600 RELAP5 Nodalization



Information Systems Laboratories

ROSA-AP600 AP-CL-03

Test Description

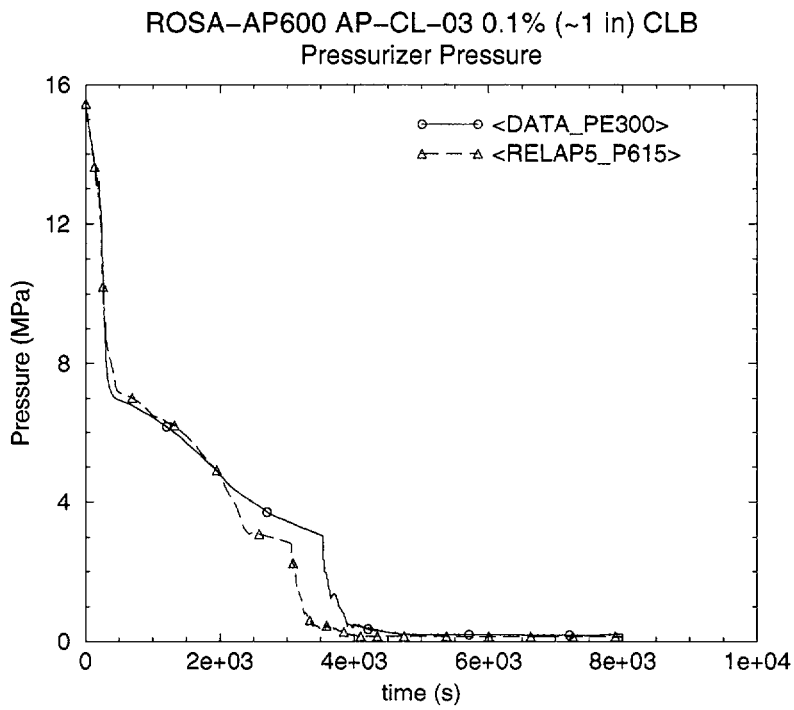
0.1%, 1-inch equivalent diameter scaled break on bottom of cold leg in CMT-loop with reactor in full-power operation

Single failure: one of the two ADS-4 valves on the CMT-loop hot leg fails to open

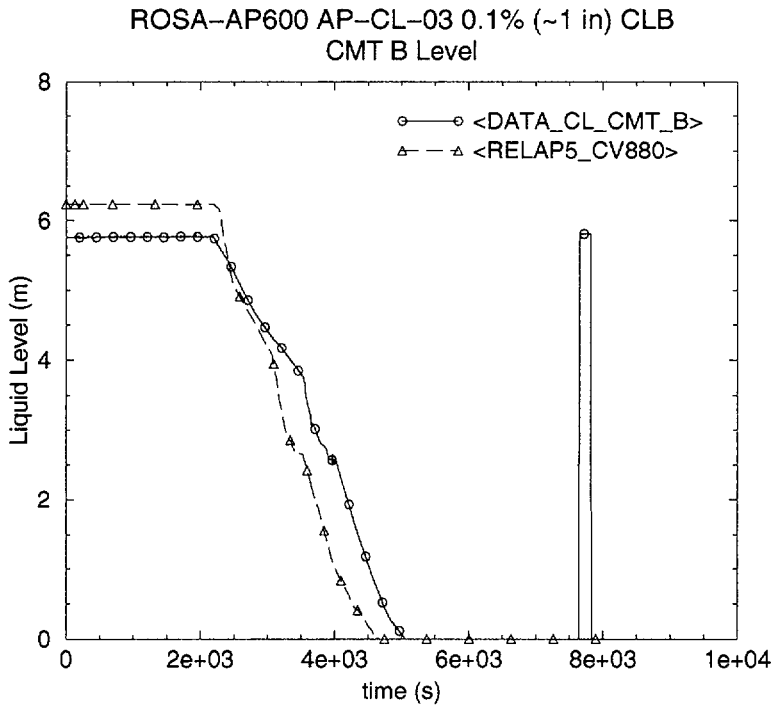
ROSA-AP600 AP-CL-03

Measured and Calculated Sequences of Events

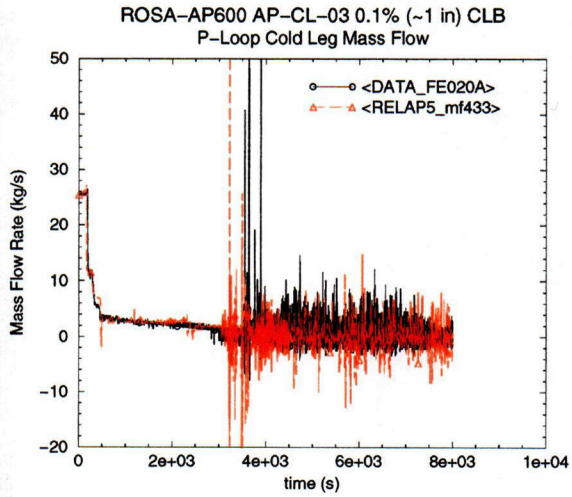
Event Description	Event Time (s) Measured	RELAP5
Break opens	0	0
CMT recirculation begins	158	137
PRHR flow begins	159	137
Reactor scram, reactor coolant pumps tripped	178	152
S signal	203	163
Loss of natural circulation in pressurizer loop	463	470
Loss of natural circulation in CMT loop	1115	1080
Accumulator injection begins	1934	1900
CMT draining begins	2198	2196
ADS-1 valve opened	3533	3055
ADS-4 valves opened	4450	3853
IRWST injection begins	4978	4246

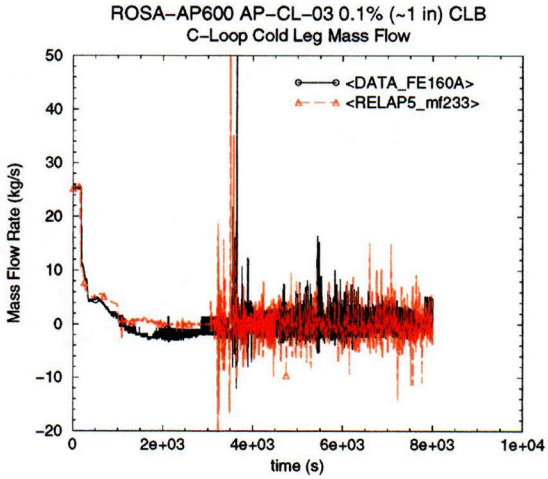


Information Systems Laboratories

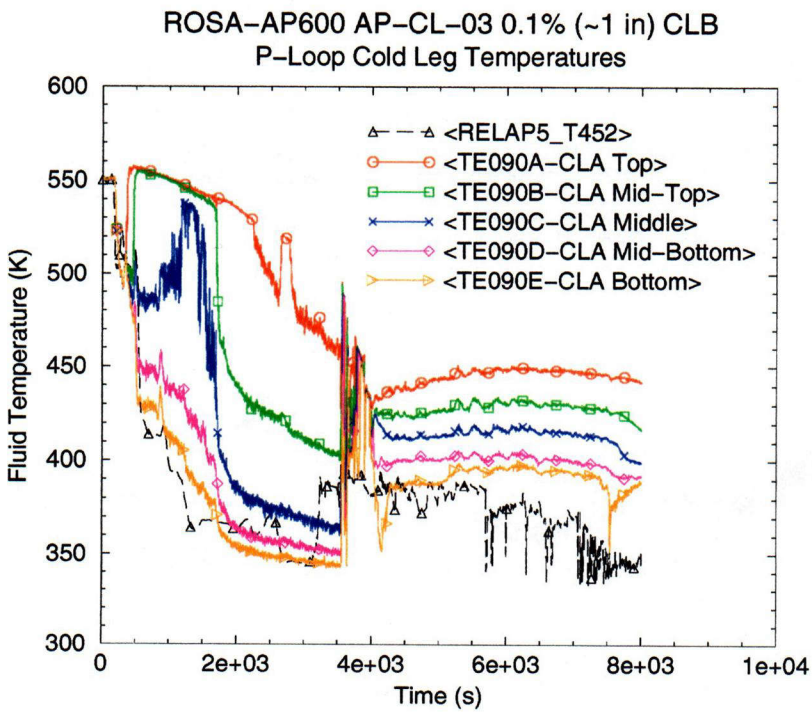


Information Systems Laboratories



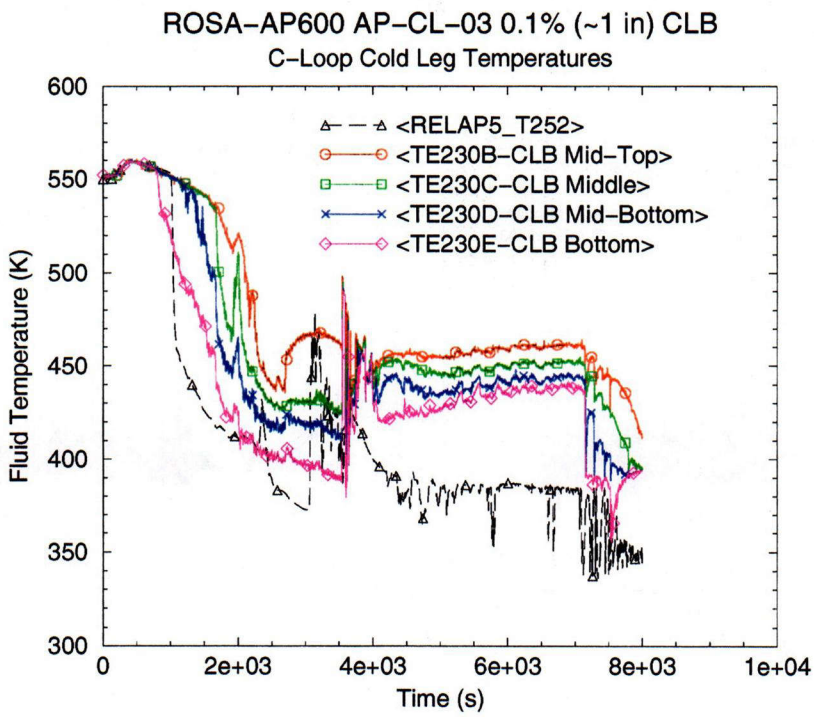


Information Systems Laboratories

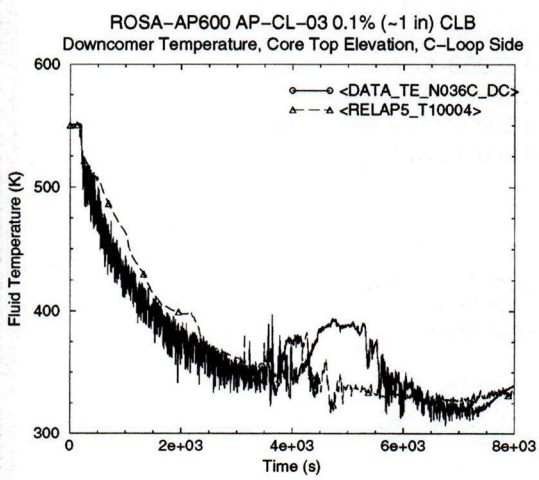


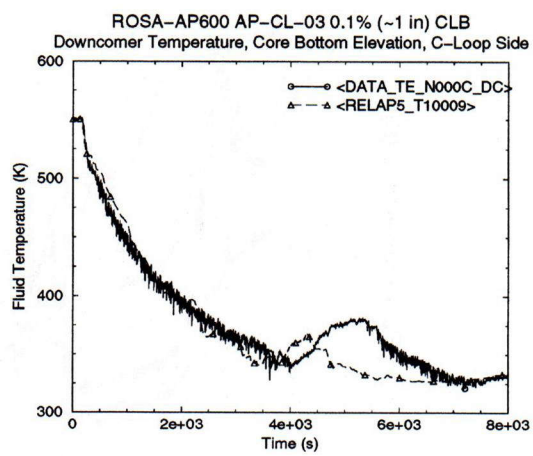
Information Systems Laboratories

C01



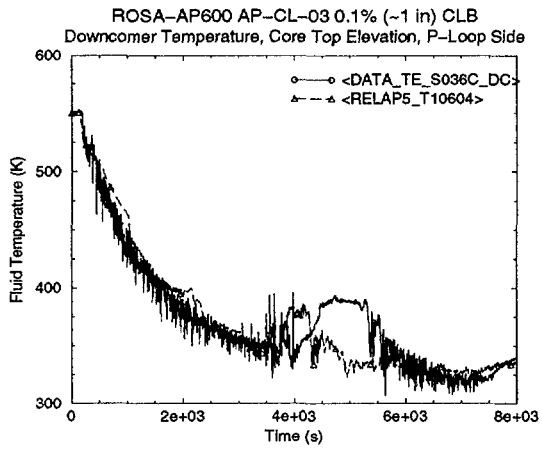
Information Systems Laboratories

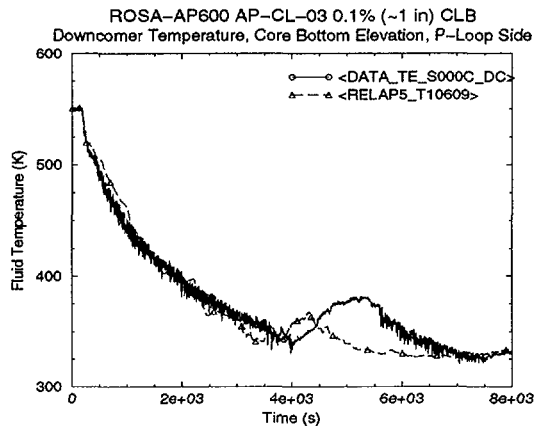




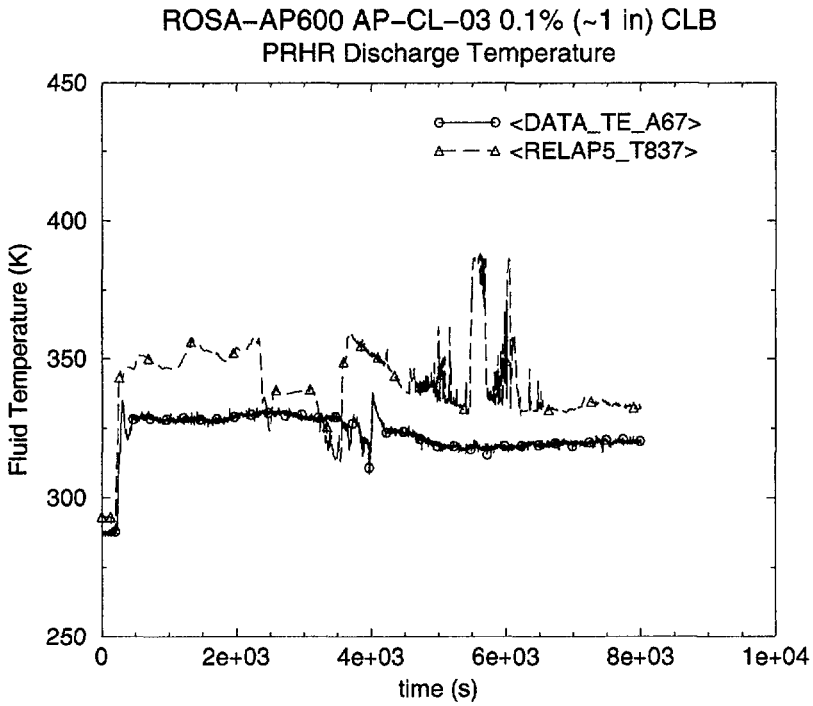
Information Systems Laboratories

C02

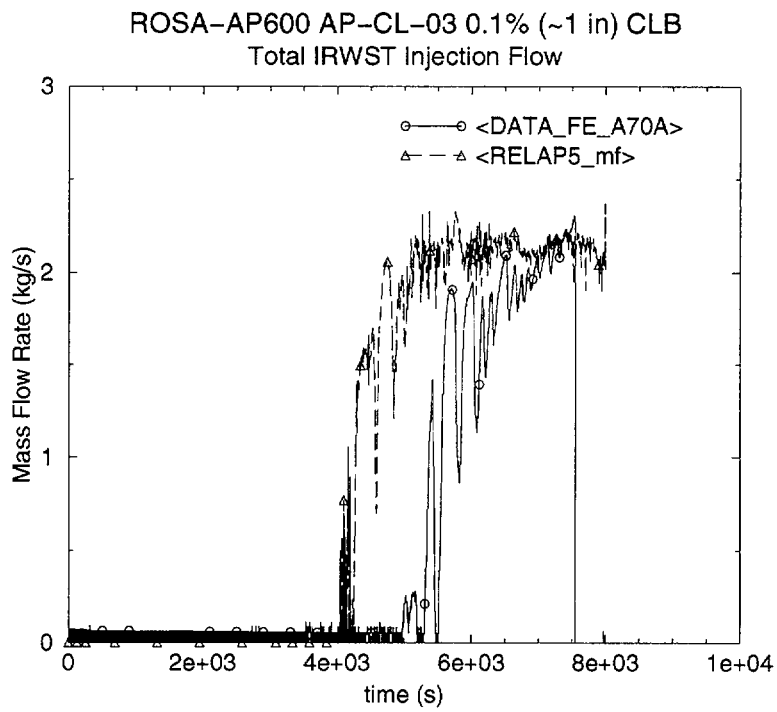




Information Systems Laboratories



Information Systems Laboratories



Information Systems Laboratories

ROSA-AP600 AP-CL-03

Summary of Assessment Comparison Results Pertinent for PTS

Complex system behavior and timing are well predicted with RELAP5

Coolant loop flow stagnation is excellently predicted

The experiment exhibits thermal stratification in liquid-filled cold legs and RELAP5 models cannot simulate this phenomenon

Code-to-data comparisons show that the effect on downcomer liquid temperatures is minimal

Information Systems Laboratories

ROSA-AP600 AP-CL-03

Summary of Assessment Comparison Results Pertinent for PTS (continued)

<u>Downcomer liquid temperatures are shown to be well predicted</u>

Differences between the measured and calculated downcomer temperature responses reflect differences in the timing and/or discharge temperature responses for the systems which inject into the primary coolant system (PRHR, CMT and IRWST)

ROSA-AP600 AP-CL-09

Test Description

0.1%, 1-inch equivalent diameter scaled break on bottom of cold leg in CMT-loop with reactor in full-power operation

Same as Test AP-CL-03, except with multiple passive safety feature failures to demonstrate the robustness of the AP600 design for safe shutdown

Test indicated no core uncovery or heatup

ROSA-AP600 AP-CL-09

Test Description (continued)

Multiple passive safety system failures simulated:

- Both CMT discharge valves fail closed
- Half of the valves in each ADS stage fail closed
- ADS (normally activated on low CMT level) activated 30 minutes after low-low pressurizer pressure signal

ROSA-AP600 AP-CL-09

Test Description (continued)

Multiple passive safety system failures simulated (continued)

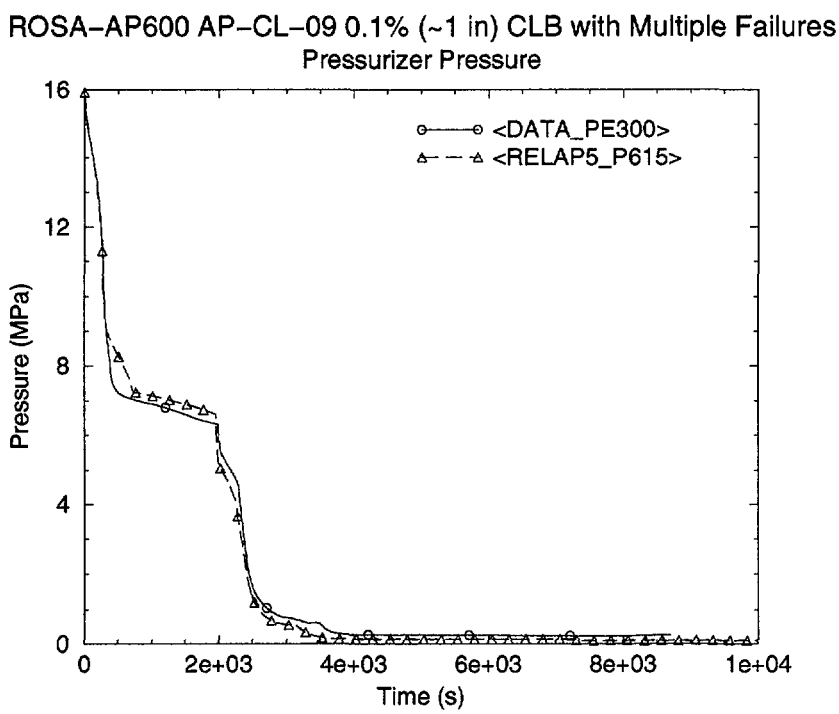
- Check valve in accumulator discharge line on the CMT loop assumed to fail closed
- Check valve in IRWST discharge line on the CMT loop assumed to fail closed
- Only one-half of the PRHR heat exchanger tubes used

ROSA-AP600 AP-CL-09

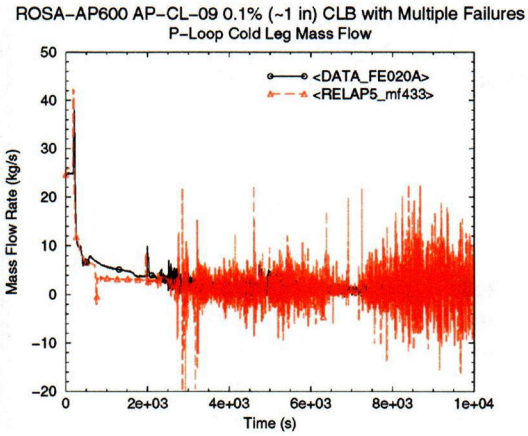
Measured and Calculated Sequences of Events

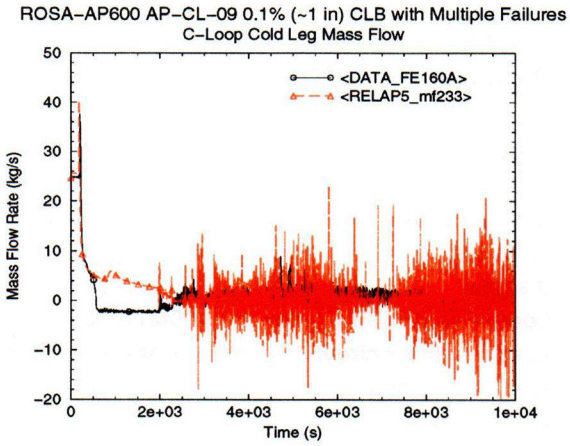
Event Description	Event Time (s) Measured	RELAP5
Break opens	0	0
Reactor scram, steam line valve closes, reactor coolant pumps tripped, PRHR activated, CVCS pump injection begins	183	173
S signal	203	173
Loss of natural circulation in the CMT loop	500	1972
Loss of natural circulation in the pressurizer loop	1650	740
ADS-1 valve opened	1985	1950
Accumulator injection begins	2190	2056
ADS-4 valves opened	3486	3150
IRWST injection begins	3990	4000

Information Systems Laboratories

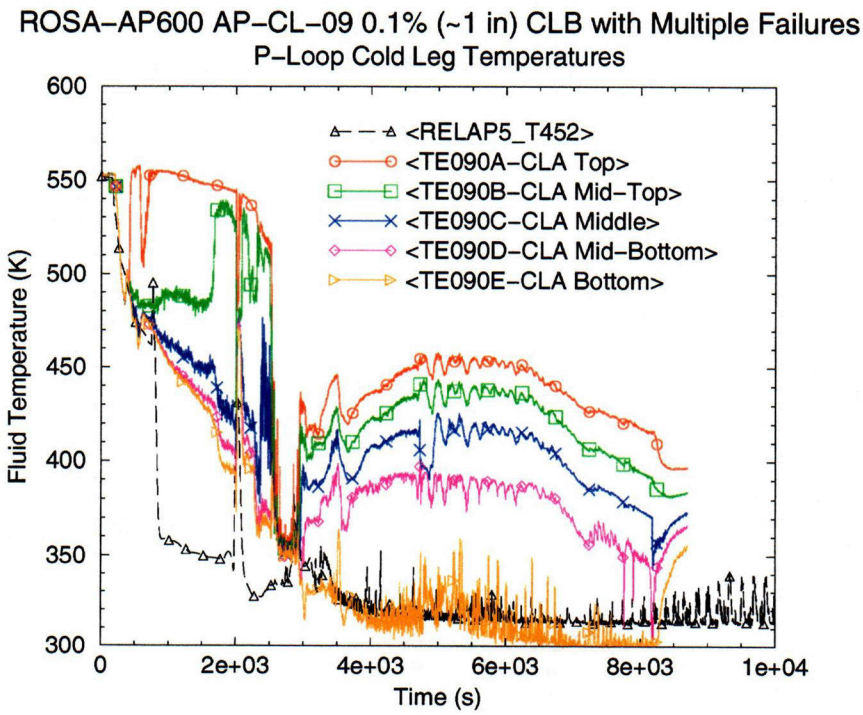


Information Systems Laboratories





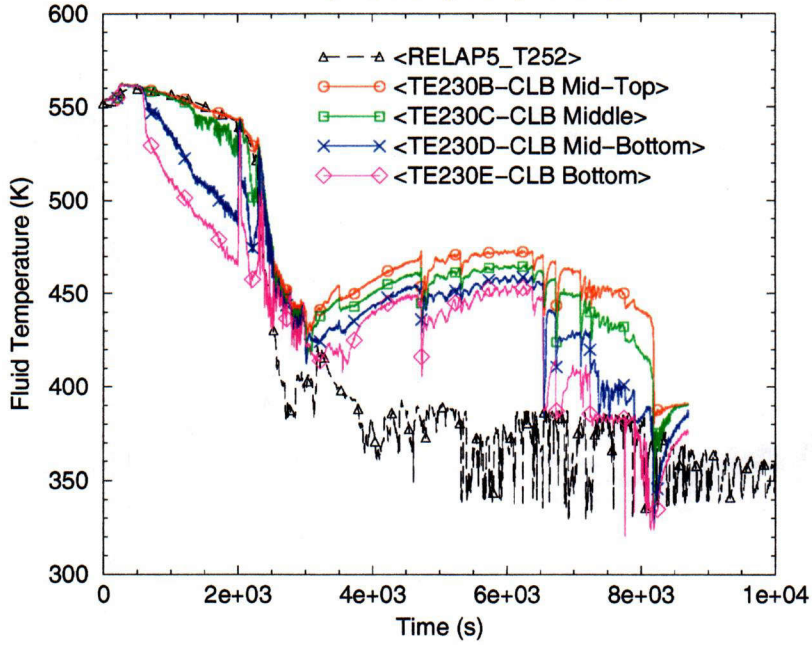
Information Systems Laboratories



Information Systems Laboratories

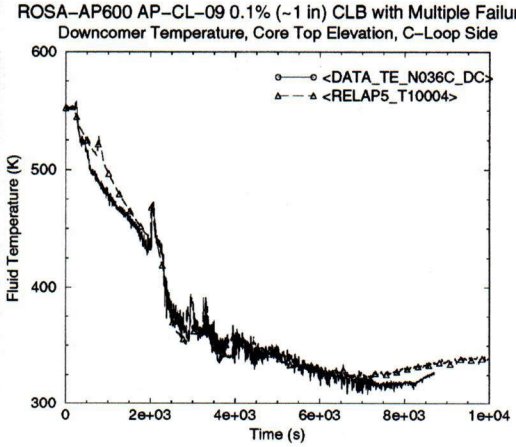
C03

ROSA–AP600 AP–CL–09 0.1% (~1 in) CLB with Multiple Failures
C–Loop Cold Leg Temperatures

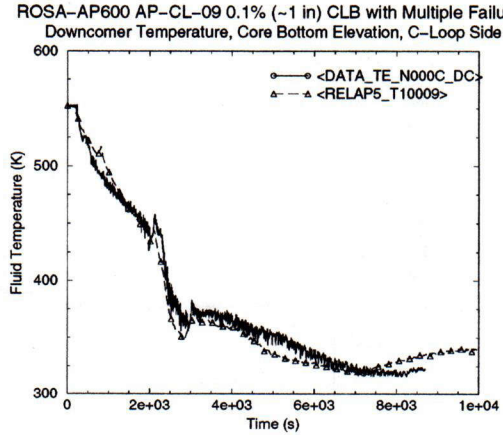


Information Systems Laboratories

ROSA–AP600 AP–CL–09 0.1% (~1 in) CLB with Multiple Failures
Downcomer Temperature, Core Top Elevation, C–Loop Side

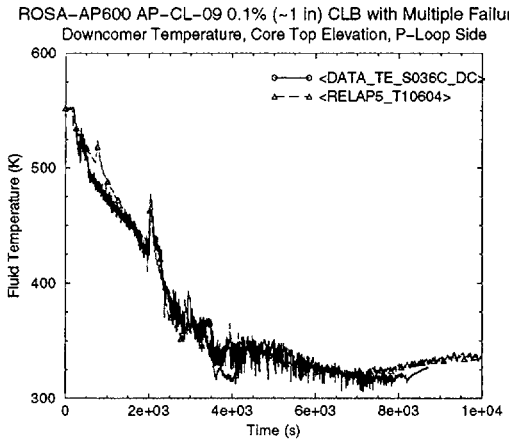


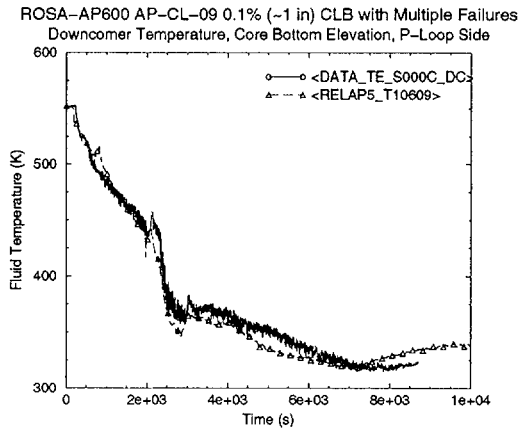
ROSA–AP600 AP–CL–09 0.1% (~1 in) CLB with Multiple Failures
Downcomer Temperature, Core Bottom Elevation, C–Loop Side



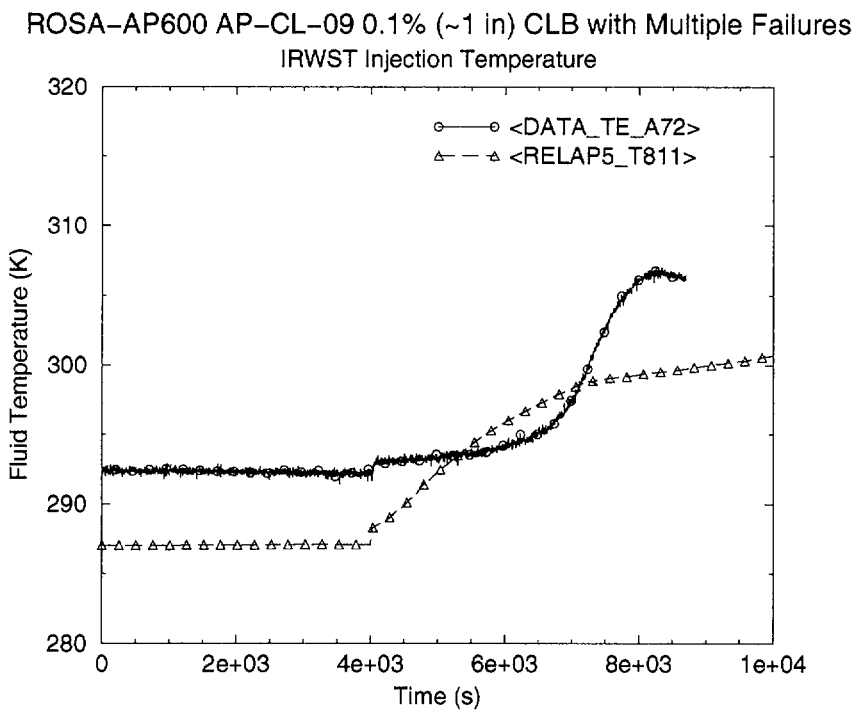
Information Systems Laboratories

C04





Information Systems Laboratories



Information Systems Laboratories

ROSA-AP600 AP-CL-09

Summary of Assessment Comparison Results Pertinent for PTS

Complex system behavior and timing are well predicted with RELAP5

The order in which the coolant loops stagnate is reversed between the test and calculation

In the CMT loop, the test shows abrupt stagnation while flow continues in the calculation for another 1500 s

In the pressurizer loop, the calculation shows abrupt stagnation while flow continues in the test for another 900 s

ROSA-AP600 AP-CL-09

Summary of Assessment Comparison Results Pertinent for PTS (continued)

The test exhibits thermal stratification in liquid-filled cold legs leading to loop flow stagnation behavior that cannot be simulated with RELAP5

Stagnation of the CMT loop in the test is caused by reverse flow of cold water from the vessel to the break, along the bottom of the cold leg

This behavior cannot be simulated with RELAP5, resulting in continuation of flow in the CMT loop and stagnation of the pressurizer loop in the calculation

ROSA-AP600 AP-CL-09

Summary of Assessment Comparison Results Pertinent for PTS (continued)

<u>Downcomer liquid temperatures are shown to be well predicted</u>

Over the first 3000 s, the differences in loop flow stagnation behavior cause the differences in the calculated and measured downcomer temperatures (peak local instantaneous difference is about 25 K and average difference is about 5 K)

After 4000 s, differences in the IRWST injection temperature are the main cause of differences in calculated and measured downcomer temperatures

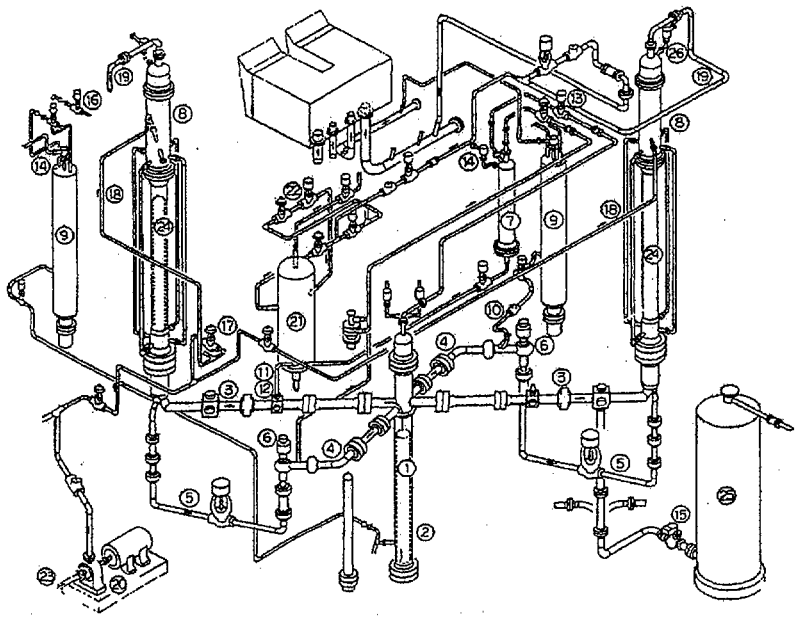
ROSA-IV ASSESSMENTS

ROSA-IV FACILITY DESCRIPTION

- o 1/48 volume-scaled, full-pressure representation of a Westinghouse 3423-MW four-loop PWR
- o Full-height electrically-heated core
- o Four PWR coolant loops represented with two equal-volume loops

  Hot leg
  Steam generator
  Reactor coolant pump
  Cold leg
  Pressurizer on unbroken loop
  ECCS systems (HPI, LPI, Accumulators)

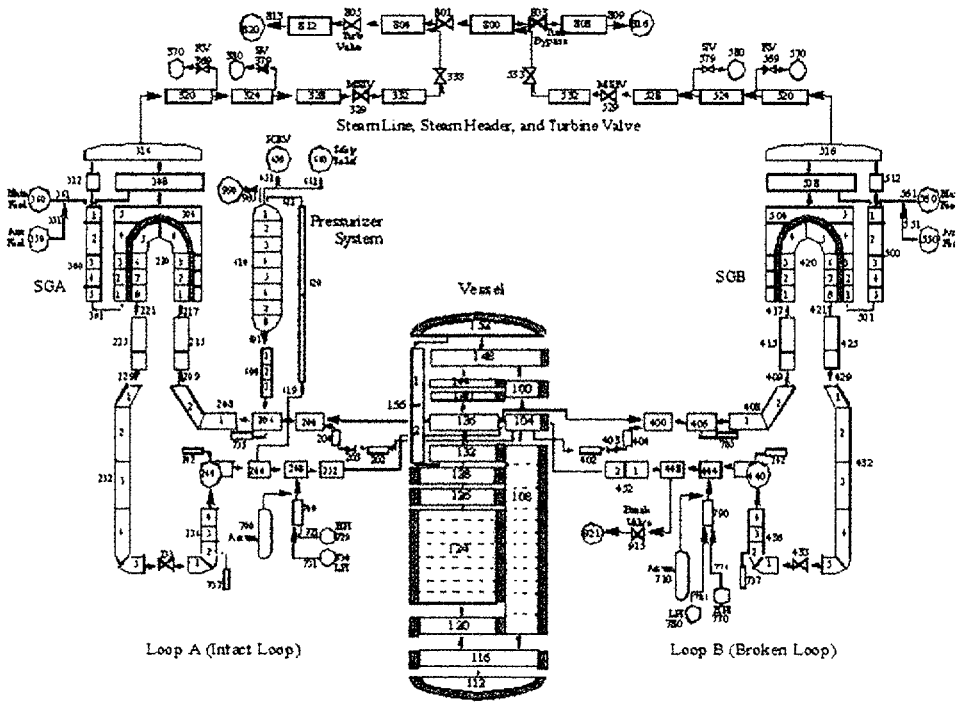
ROSA-IV Facility Layout



1. Simulated core
2. Reactor pressure vessel
3. Hot leg
4. Cold leg
5. Crossover leg
6. RCS pump
7. Pressurizer
8. Steam generator
9. Accumulator
10. ACC piping
11. HPIS piping
12. RHR piping
13. Pressure control vent valve
14. Relief valve
15. Break initiation valve
16. N2 supply valve
17. Feed water control valve
18. Feed water line
19. Main steam line
20. Feed water pump
21. Jet condenser
22. Main steam valve
23. Cooling tower line
24. Steam generator tubes
25. Break flow storage tank
26. Safety valve

General View of LSTF

ROSA-IV RELAP5 Nodalization



ROSA-IV SB-CL-18

Test Description

5%, 6-inch equivalent diameter scaled break on side of cold leg with reactor in full-power operation

This experiment used as International Standard Problem 26

HPI and AFW assumed to fail

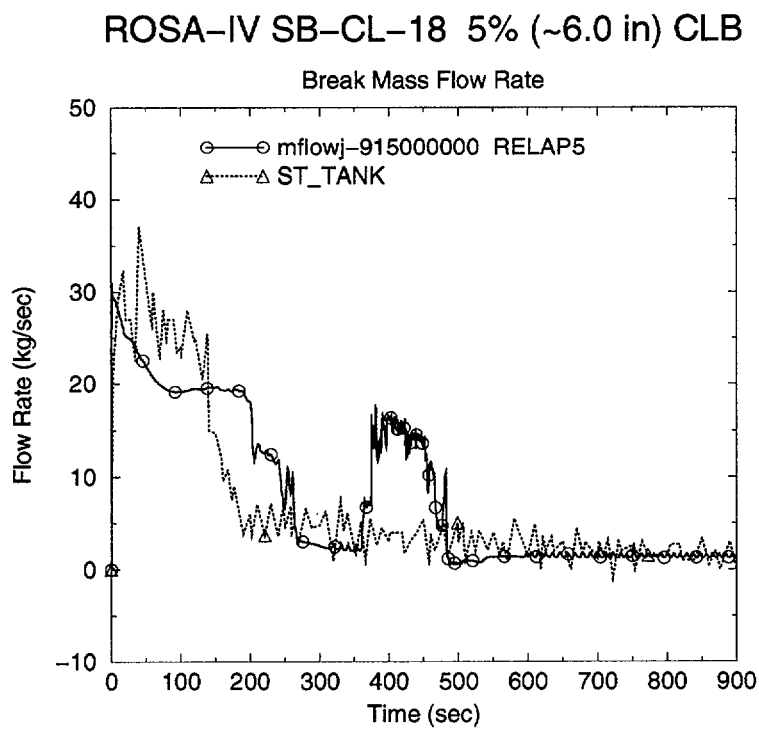
Loss of offsite power assumed at the time of reactor scram

ROSA-IV SB-CL-18

Measured and Calculated Sequences of Events

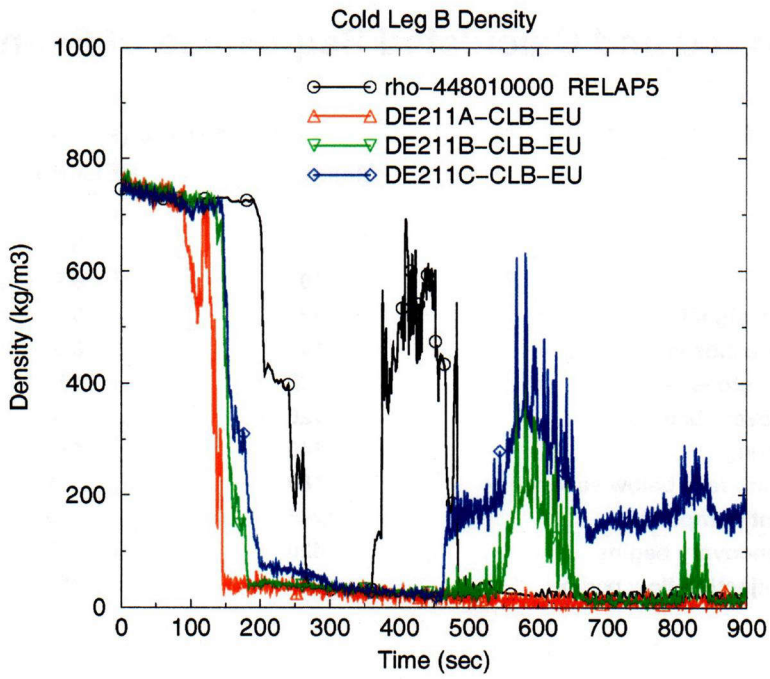
Event Description	Event Time (s) Measured	RELAP5
Break opens	0	0
Scram signal	10	8.9
Safety injection signal	12	9.6
Steam line valve closes	14	8.9
Feedwater flow stops	16	10
First core uncovery begins	120	186
Loop seal clearing	140	180
Primary pressure falls below secondary	180	221
Reactor coolant pumps stop	265	270
Second core uncovery begins	420	239
Accumulator injection flow begins	455	355

Information Systems Laboratories



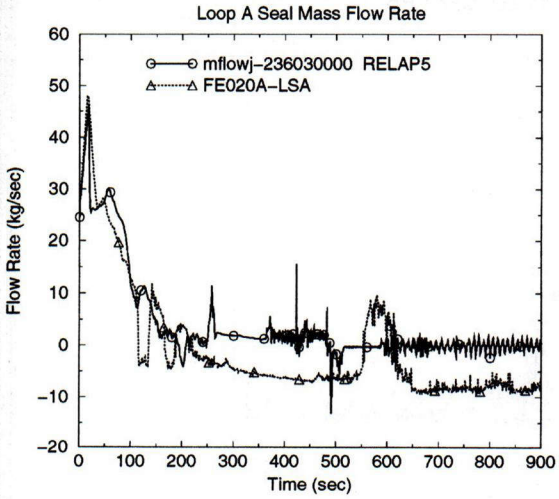
Information Systems Laboratories

ROSA–IV SB–CL–18 5% (~6.0 in) CLB

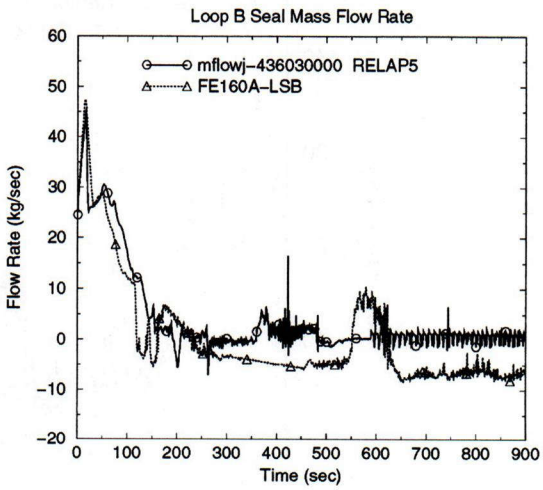


Information Systems Laboratories

ROSA–IV SB–CL–18 5% (~6.0 in) CLB



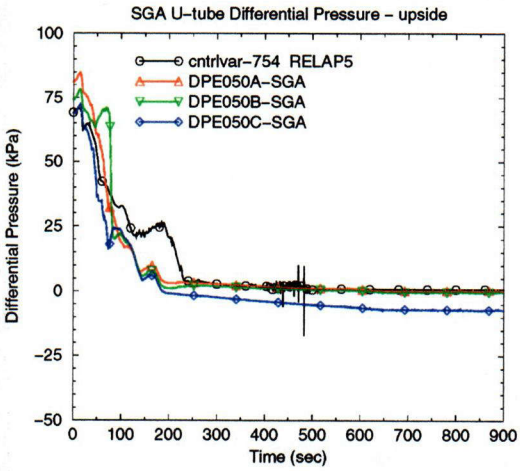
ROSA–IV SB–CL–18 5% (~6.0 in) CLB



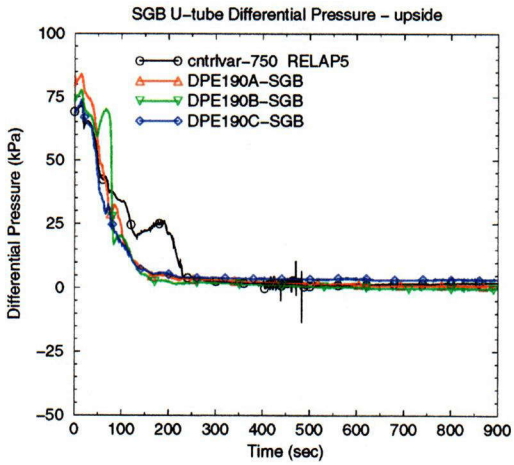
Information Systems Laboratories

C05

ROSA–IV SB–CL–18 5% (~6.0 in) CLB

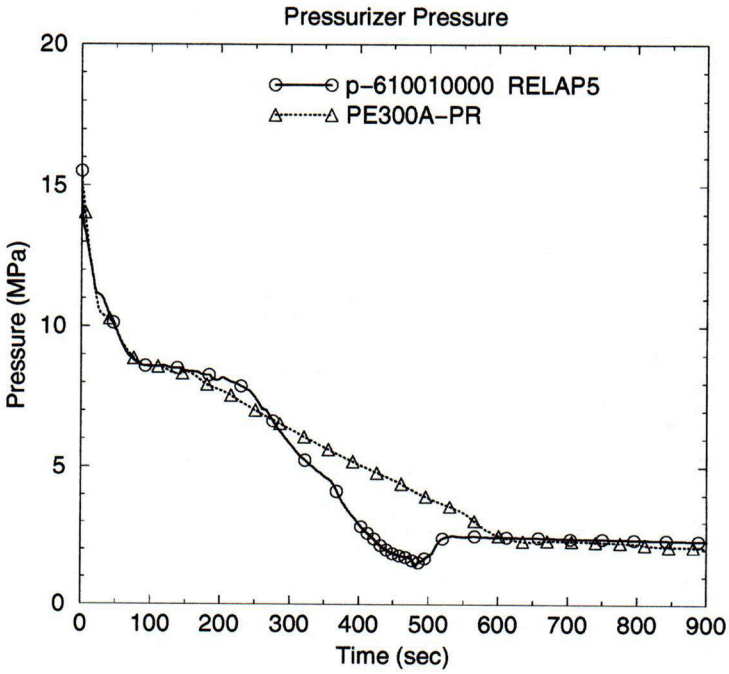


ROSA–IV SB–CL–18 5% (~6.0 in) CLB



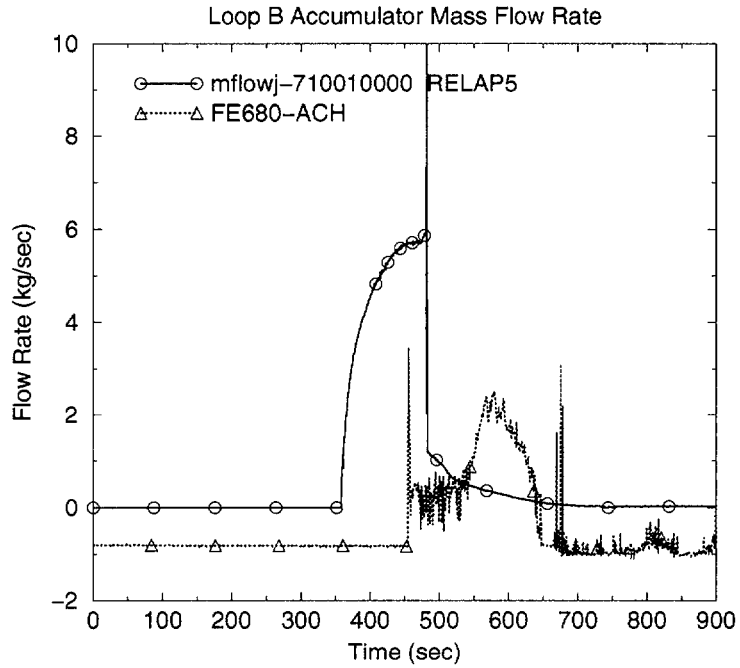
Information Systems Laboratories

ROSA–IV SB–CL–18 5% (~6.0 in) CLB



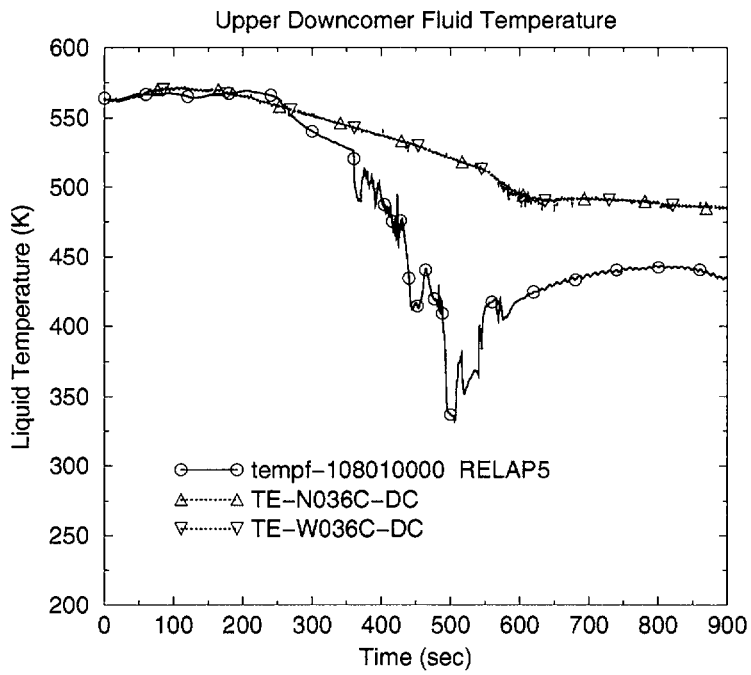
Information Systems Laboratories

ROSA–IV SB–CL–18 5% (~6.0 in) CLB



Information Systems Laboratories

ROSA–IV SB–CL–18 5% (~6.0 in) CLB



Information Systems Laboratories

ROSA-IV SB-CL-18

Summary of Assessment Comparison Results Pertinent for PTS

Calculated cold leg density and break mass flow greatly exceed the measured values from 150 to 250 s

RELAP5 overpredicts the holdup of water in the SG tubes during the period of tube draining, causing core level depression and flooding of the break with water

Measured RCS depressurization is steady but the calculated depressurization is slower than in the experiment before the break clears of liquid and then faster afterward

Faster RCS depressurization in the calculation leads to both earlier and faster accumulator injection

ROSA-IV SB-CL-18

Summary of Assessment Comparison Results Pertinent for PTS (continued)

The higher accumulator injection rate in the calculation leads to still more RCS depressurization and yet-higher accumulator injection flow (RELAP5 overpredicts interphase condensation effects)

<u>The timing of coolant loop flow stagnation is adequately predicted by RELAP5</u>

<u>Although the comparison with the test data is poor, RELAP5 conservatively predicts the downcomer fluid temperature</u>

ROSA-IV SB-HL-06

Test Description

0.5%, 2-inch equivalent diameter scaled break on top of hot leg with reactor in full-power operation

HPI and AFW assumed to fail

Loss of offsite power assumed at the time of reactor scram

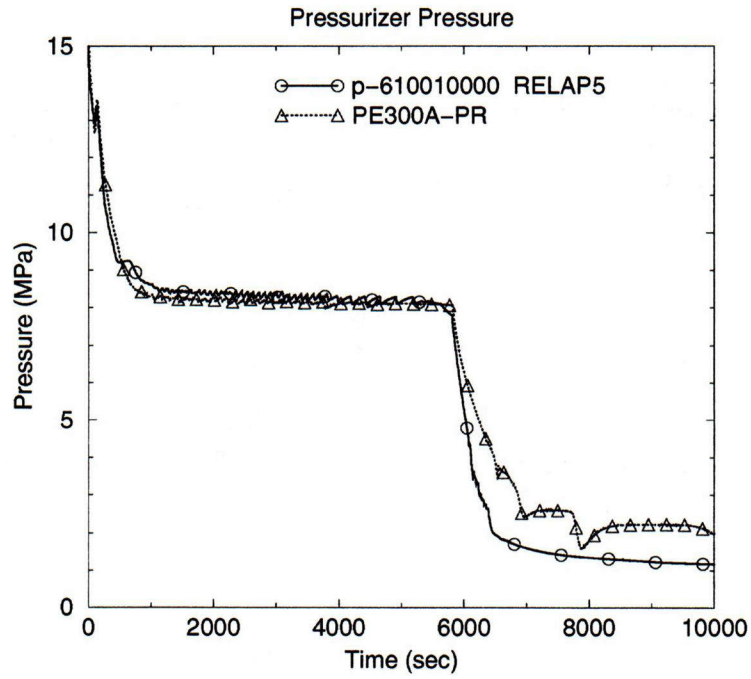
Once core uncovering and heatup started, the pressurizer PORV was opened to depressurize the primary system and initiate accumulator injection

ROSA-IV SB-HL-06

Measured and Calculated Sequences of Events

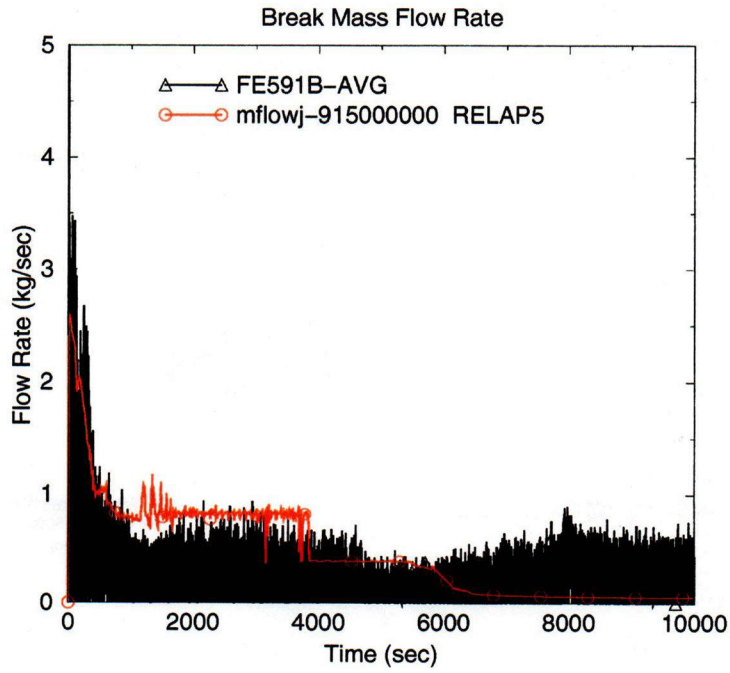
Event Description	Event Time (s) Measured	RELAP5
Break opens	0	0
Scram signal	87	94
Steam line valve closes	90	94
Feedwater flow stops	92	95
Initiation of core power decay	110	110
Vapor appears in hot legs	200	150
Reactor coolant pumps stop	341	350
Vapor appears in cold legs	800	840
Loop A natural circulation stops	1200	1700
Loop B natural circulation stops	1900	1700
Core heatup begins	5680	5200
Pressurizer PORV opened	5806	5806
Accumulator injection begins	6425	6070

ROSA–IV SB–HL–06 0.5% (~2.0 in) HLB



Information Systems Laboratories

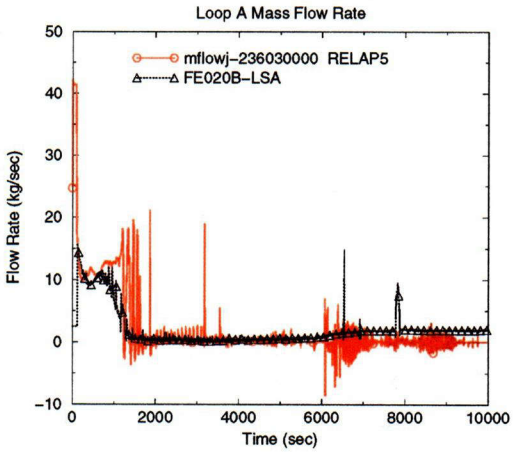
ROSA–IV SB–HL–06 0.5% (~2.0 in) HLB



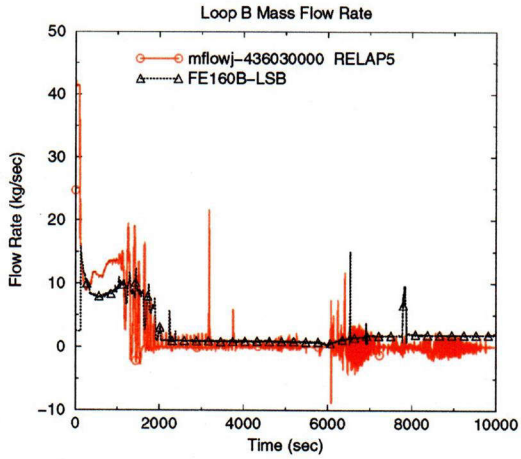
Information Systems Laboratories

C07

ROSA–IV SB–HL–06 0.5% (~2.0 in) HLB

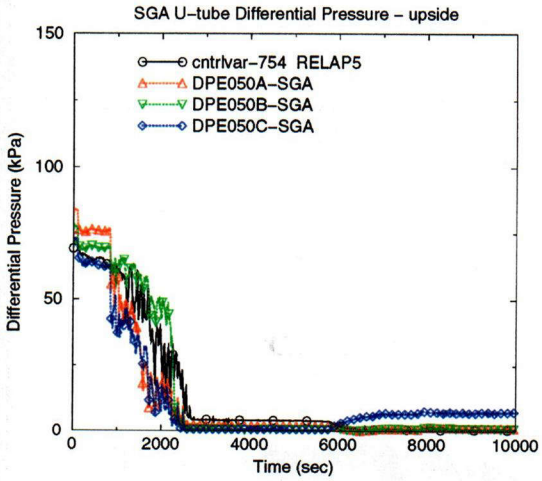


ROSA–IV SB–HL–06 0.5% (~2.0 in) HLB

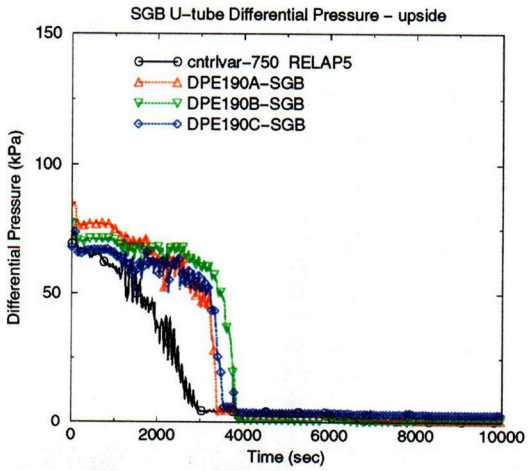


Information Systems Laboratories

ROSA–IV SB–HL–06 0.5% (~2.0 in) HLB



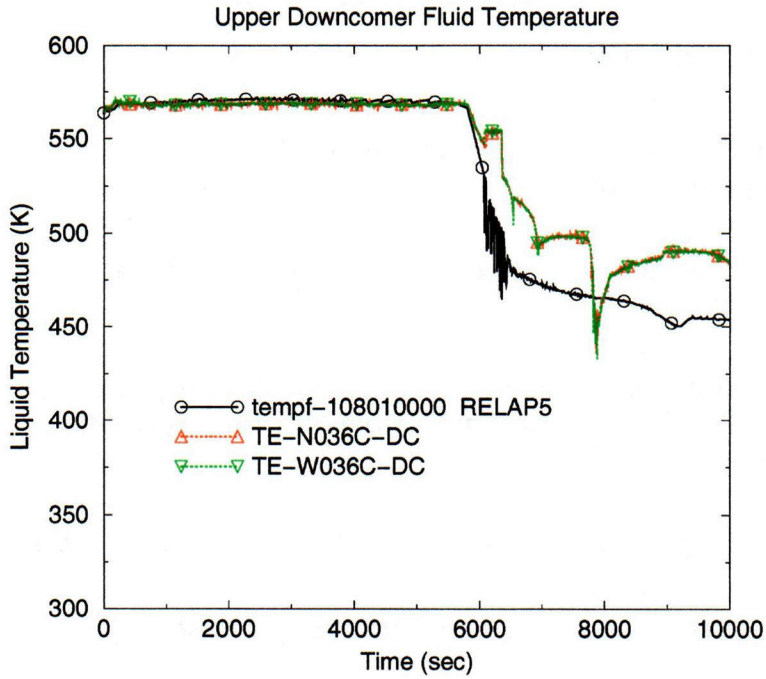
ROSA–IV SB–HL–06 0.5% (~2.0 in) HLB



Information Systems Laboratories

C08

ROSA–IV SB–HL–06 0.5% (~2.0 in) HLB



ROSA-IV SB-HL-06

Summary of Assessment Comparison Results Pertinent for PTS

Overall, calculated system parameters compare well with test data, but calculated break mass flow is higher than the measured

Break flow difference leads to faster depressurization when the PORV is opened and earlier accumulator injection in the calculation

<u>Timing of the loss of coolant loop natural circulation flow is well predicted with RELAP5</u>

<u>Downcomer fluid temperature is conservatively predicted by RELAP5</u>

C09

ROSA-IV ST-NC-09

Test Description

Natural circulation experiment under reflux condensation cooling conditions

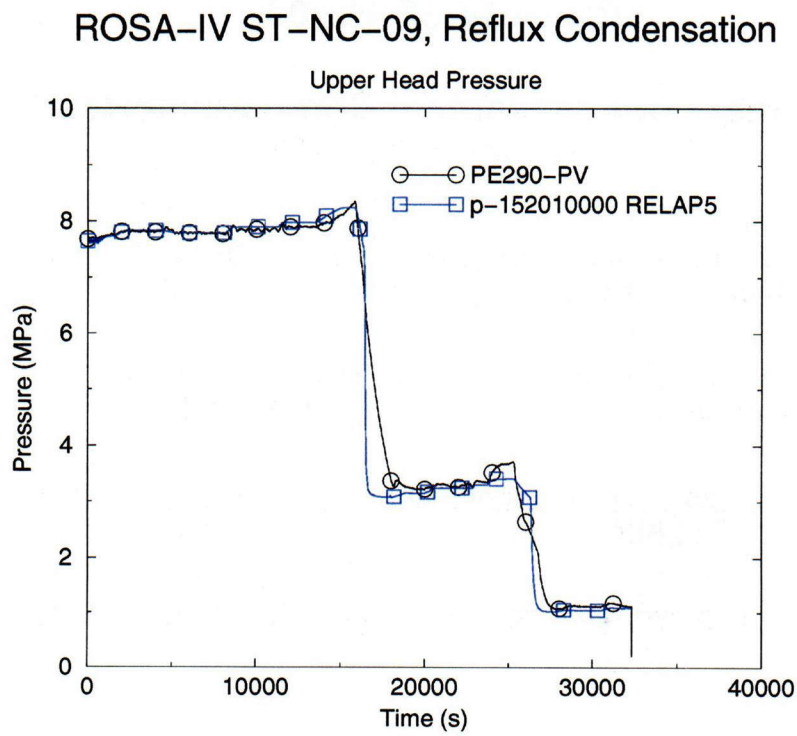
Both coolant loops (but not pressurizer) used in the experiment

Experiment consisted of a series of quasi-steady tests at 7, 3, and 1 MPa SG secondary pressures and with a closed primary system

Primary coolant discharged to induce reflux cooling mode

At each SG pressure, core power is raised in steps

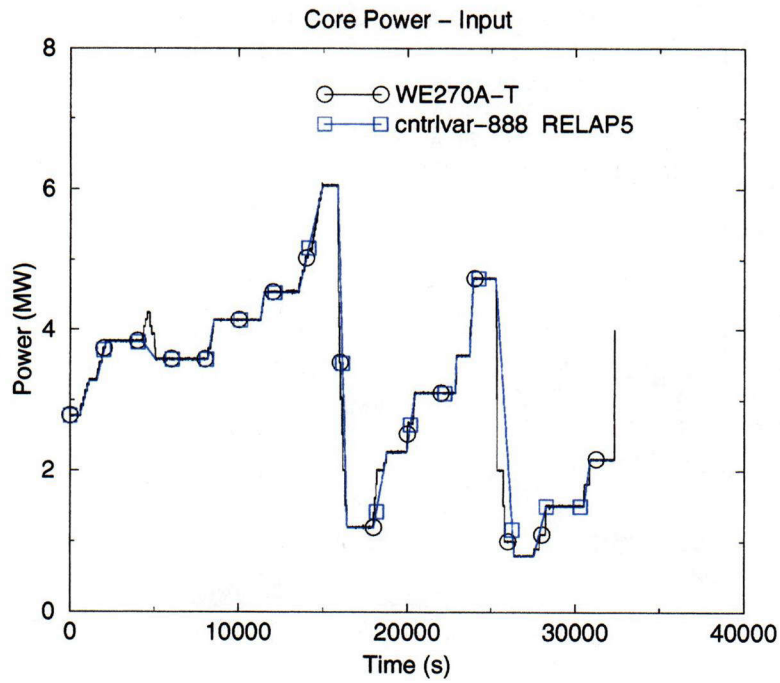
Information Systems Laboratories



Information Systems Laboratories

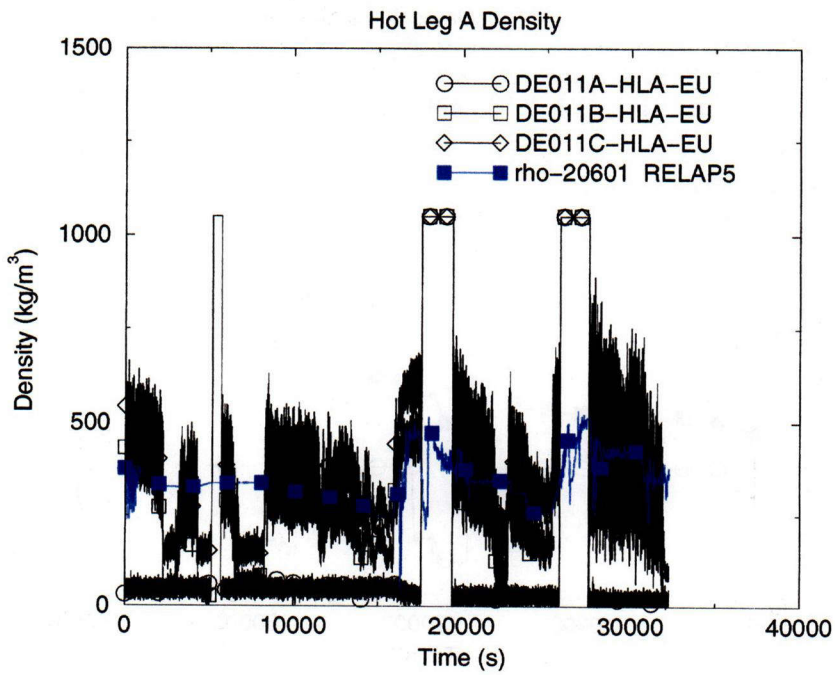
C10

ROSA–IV ST–NC–09, Reflux Condensation



Information Systems Laboratories

ROSA–IV ST–NC–09, Reflux Condensation

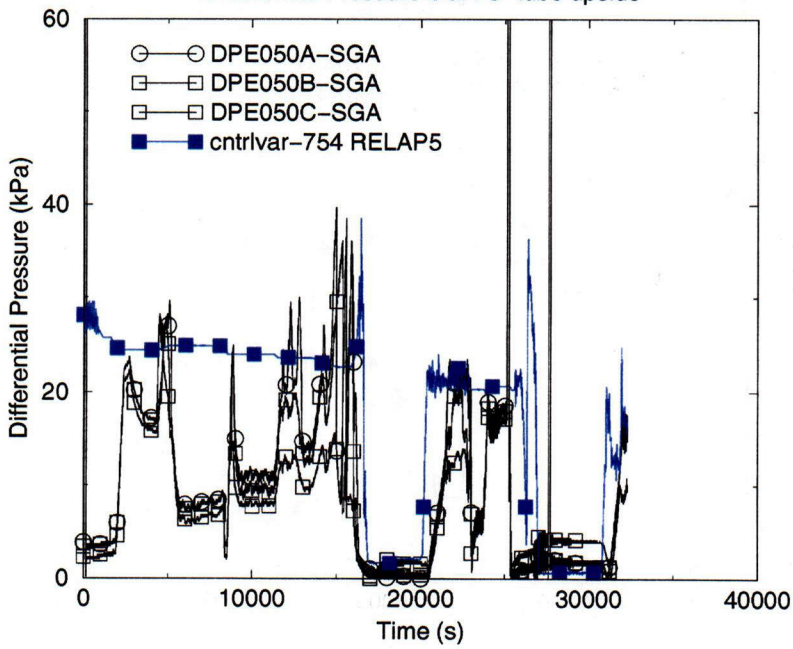


Information Systems Laboratories

C11

ROSA–IV ST–NC–09, Reflux Condensation

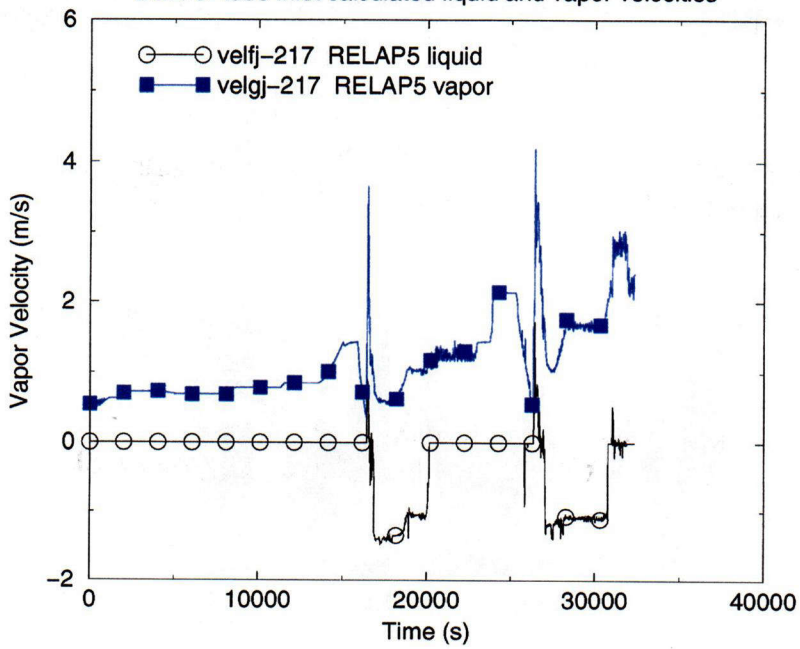
Differential Pressure SGA U–tube upside



Information Systems Laboratories

ROSA–IV ST–NC–09, Reflux Condensation

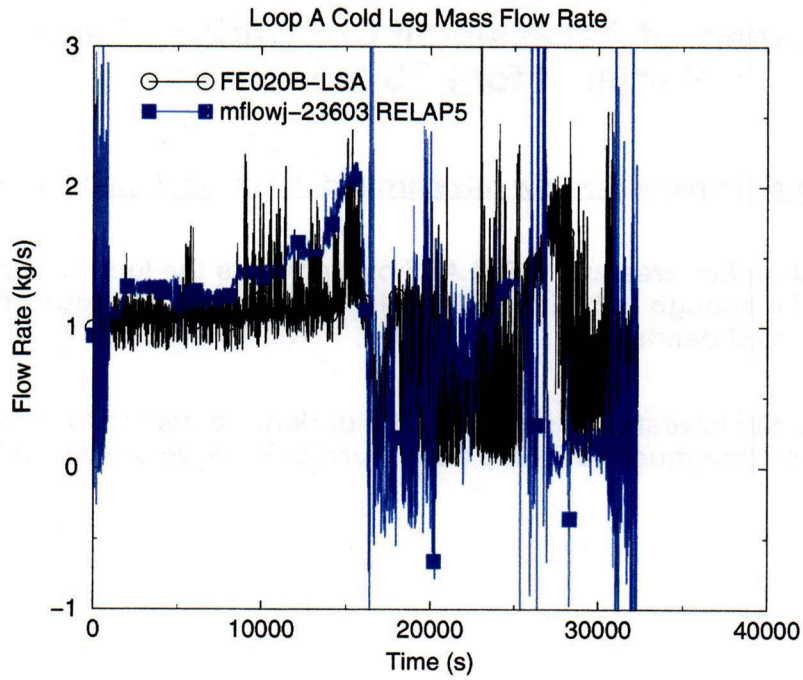
SGA U–tube inlet calculated liquid and vapor velocities



Information Systems Laboratories

C12

ROSA–IV ST–NC–09, Reflux Condensation



ROSA-IV SB-NC-09

Summary of Assessment Comparison Results Pertinent for PTS

<u>RELAP5 acceptably predicts the primary system pressure but does not predict well the countercurrent flow in the hot legs and steam generator tubes</u>

At higher pressures (and especially at lower core powers), RELAP5 holds up too much water in the SG tubes

Only at the lowest pressure does RELAP5 exhibit prediction of countercurrent flow at the steam generator tube inlet

C13

ROSA-IV SB-NC-09

Summary of Assessment Comparison Results Pertinent for PTS (continued)

<u>RELAP5 prediction of the flow rates around the coolant loops is fair</u>

At higher pressures, RELAP5 overpredicts the loop flow rate (not enough refluxing, with water spilling over the tops of SG tube U-bends)

At the lowest pressure, RELAP5 underpredicts the loop flow rate (too much refluxing and return of liquid to the vessel)

ASSESSMENT CONCLUSIONS

RELAP5/MOD3.2.2Gamma has been assessed against data from separate effects and integral effects experiments relevant to the risk-dominant PTS accident sequences

The code is shown to provide acceptable predictions for the important PTS parameters, the reactor vessel downcomer fluid temperature and pressure

RELAP5/MOD3.2.2Gamma is applicable for PTS analysis

PTS Analysis

ACRS Thermal Hydraulic Subcommittee
Rockville, MD

December 11, 2002

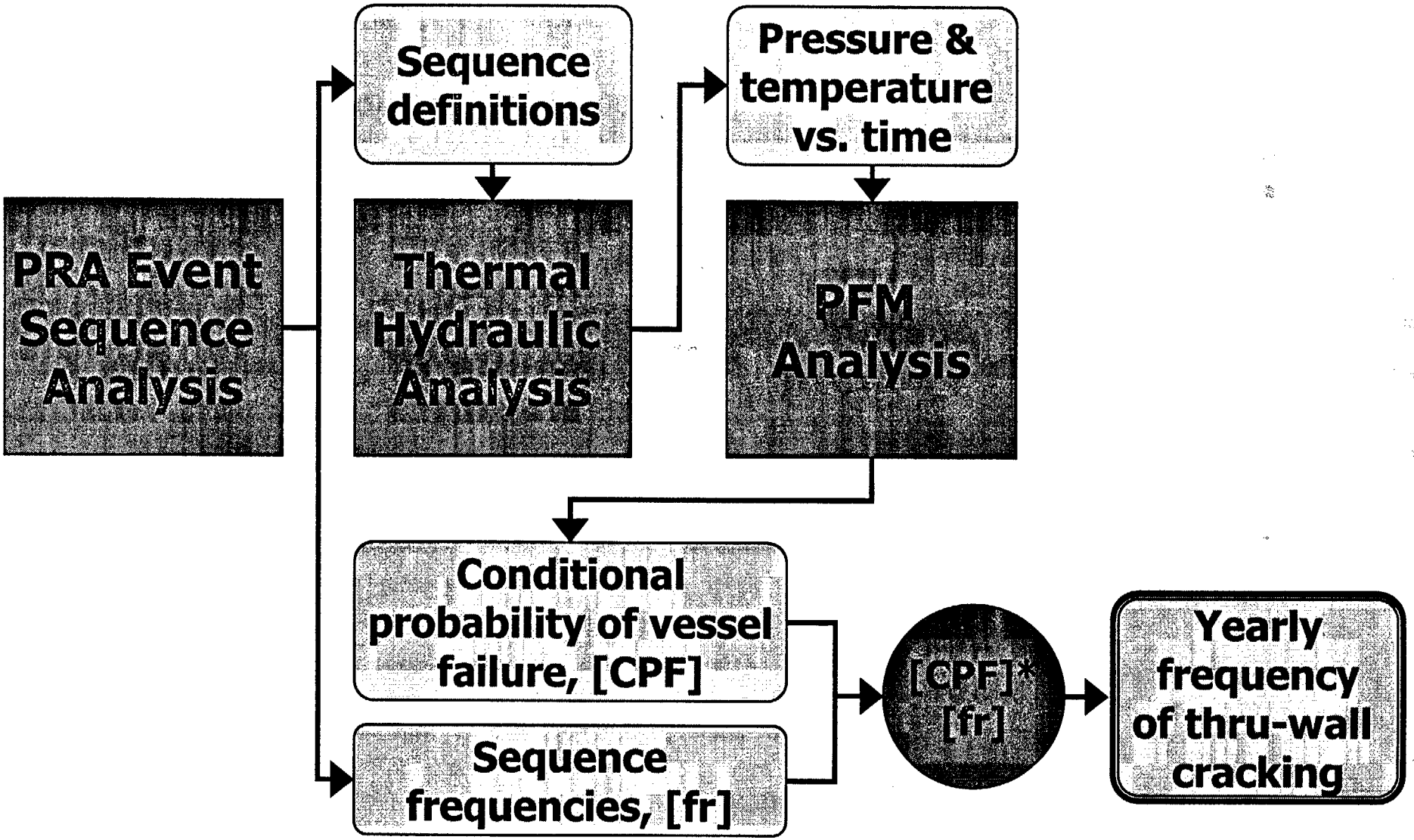
Introduction and Overview

David Bessette
deb@nrc.gov
Safety Margins and Systems Analysis Branch
Office of Nuclear Regulator Research

Purpose of Today's Meeting

- Introduction and background
- APEX-CE experimental program results
- RELAP5 assessment carried out in support of RELAP5 PTS analysis
- Show that the important phenomena are identified, RELAP assessment is adequate, phenomena not treated by RELAP have been treated separately through experiments and analysis
- Will not cover: Specific results of RELAP5 PTS analyses or results of TH uncertainty studies (to be included in February 5, 2003 PTS meeting)

Analysis Procedure



PTS Reanalysis - Unusual Feature

- Involves three RES divisions
  1. Division of Engineering Technology
     Principal Contractor: ORNL

  2. Division of Risk Analysis and Applications
     Principal Contractors: SNL, SAIC, University of Maryland

  3. Division of Systems Analysis and Regulatory Effectiveness
     RELAP5 PTS transients, ISL, Inc., William Arcieri, Robert Beaton, Don Fletcher,

     RELAP5 Assessment, ISL, Inc, Dan Prelewicz, Don Fletcher

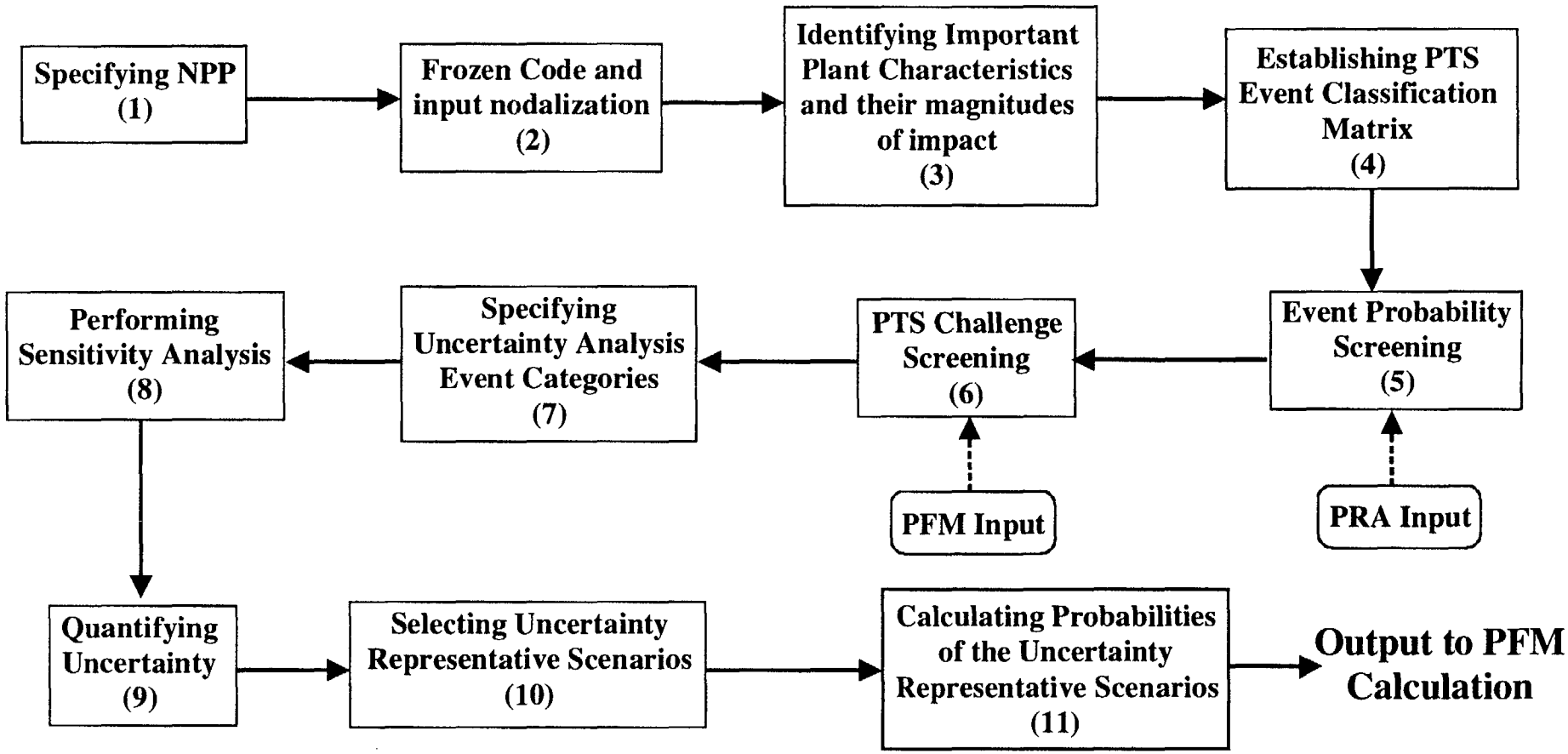
     TH Uncertainty, University of Maryland, Prof. Ali Mosleh, Dr James Chang, Prof. Kazys Almenas

     TH experiments and phenomena, Oregon State University, Prof. Jose Reyes, John Groome, graduate students

The PTS T-H Analysis Problem

- PTS effort is broader and more extensive than any prior transient investigation
- ISL has calculated ~400 transients of 4 hours duration and University of Maryland has performed an additional ~200 sensitivity calculations
- Oconee scenario list grew from initially ~20 to 177 as refinement of bins was recognized as important to reducing unnecessary conservatism
- A profile was developed that would in the end be generalized to all PWRs of PTS risk significance
- It was necessary to treat uncertainties. CSAU was developed specifically to treat a single specified transient in a single plant

T/H Uncertainty Assessment Process



VG 83

Plant Selection Rationale

- Started with the three plants from the IPTS study of 1983-85. Rationale was to select one plant from each of the three PWR vendors
- Oconee-1, Calvert Cliffs, H.B. Robinson
- For the current study, substituted another higher power Westinghouse 3-loop plant, Beaver Valley-1, for H.B Robinson
- Added Palisades for life extension considerations

Transient Classification

- Started by classifying events into three broad categories

  1. Increase in heat removal by secondary system - steam line break, stuck open steam generator safety valve(s), stuck open turbine bypass valve(s), stuck open atmospheric dump valve

  2. Increase in feedwater flow to the steam generator - failure of automatic level control, feedwater run on

  3. Loss-of-coolant accident - either isolated at some time into the event (pressurizer PORV or safety valve that recloses) or not

- Within these broad categories, specific transients to be analyzed determined through interactions between PRA, TH, and PFM

PTS PIRT

- PIRT process was used to determine the thermal hydraulic phenomena that have the most impact on the figures of merit for PTS, namely the time-histories of pressure, temperature, and heat transfer in the downcomer adjacent to the core.

- PIRT provides the guiding rationale for experiments, RELAP5 assessment, and uncertainty study

- PIRT was used to guide the APEX-CE scaling studies, the University of Maryland uncertainty studies, and the RELAP5 assessment

Thermal Hydraulic Issues: Phenomenological and Modeling

- Single and two phase loop natural circulation.
- Criteria for interruption of loop flow (flow stagnation).
- Number of cold legs which must be flowing to assure mixing in the downcomer.
- Local fluid mixing and onset of thermal stratification in the cold leg.
- Plume mixing in the downcomer:

  Plumes are seen to have dissipated (mixed) before reaching the beltline region, based on experimental data, as well as associated CFD calculations
- RELAP assessment

APEX-CE Experimental Program

- To investigate these issues, and to provide integral system test results focused on PTS risk-dominant transient scenarios, the APEX-CE experimental program was specifically conceived and carried out
- APEX-CE test matrix revised and expanded from 12 to 20 experiments as program evolved, to ensure adequate scope
- Scaling study performed to relate APEX-CE to Palisades (other CE plants notably Calvert Cliffs and Fort Calhoun are similar)
- APEX configured to represent CE design - loop seal and safety injection flow
- Downcomer was instrumented with thermocouples to measure temperature distribution

RELAP Application

- Current application used the principle that thermal hydraulic code applications should be supported by relevant experiments and assessment

- RELAP application built on the recent six-year work carried out integrating code, experiments and scaling for AP-600 resulting in improvements to RELAP

- The phenomena are quite similar between the current PTS calculations and the AP-600, involving relatively large breaks off the hot leg.

- RELAP validation for PTS combined APEX-CE test results with other available experiments to cover the key thermal hydraulic phenomena

Up-to-Date PTS Results for Oconee, Palisades, and Beaver Valley

- Dominant scenarios are all primary system LOCAs. Some of these LOCAs include closing of the break (pressurizer PORV or SRV) at some time (50 minutes or 100 minutes) into the transient
- The University of Maryland TH uncertainty studies focused on these events
- Small residual contribution from Main Steam Line Breaks

Most Important Changes in the TH Analysis from IPTS study (1985) to now

- Orders-of-magnitude improvements in computers
- Greatly improved input and output processing
- RELAP5 is more robust and faster running
- Permits for the first time an adequate range of transient scenarios to be calculated
- Revolutionary change in transient analyses (AP600 analysis centered on 12 calculations)
- Code still requires expertise/experience in evaluating results
- Input preparation is still time consuming. The possibility of input errors remains a concern. During the course of ~400 calculations we found approximately 6 input problems which were corrected and the affected calculations rerun.

Results from H.B. Robinson PTS PIRT

- H.B. Robinson PIRT panel consisted of

Cliff Davis,	Idaho National Engineering Laboratory
Prof. Marino di Marzo	University of Maryland
Prof. Peter Griffith	Massachusetts Institute of Technology
Prof. Yassin Hassan	Texas A&M University
Prof. Barklay Jones	University of Illinois
Marcos Ortiz	Idaho National Engineering Laboratory
Donald Palmrose	Idaho National Engineering Laboratory

- Considered the four transients that were calculated for the H.B. Robinson reanalysis: (1) main steam line break from hot standby; (2) steam generator overfeed, (3) 2-inch cold leg break LOCA; and (4) 2-inch hot leg break LOCA.

- Of these four transients, the small hot leg break was the most limiting PTS event.

- The other transients did not pose a concern, therefore, the small hot leg break LOCA was selected for the PIRT

H.B. Robinson PIRT Rankings

Rank	Phenomena/boundary condition	Ranking (1 to 10)
1	*Accumulator injection rate (boundary condition)*	10.0
2	Reactor vessel wall heat conduction (phenomena/process)	9.0
3	*HPI injection flow (boundary condition)*	8.9
4	**Flow distribution in downcomer (phenomena/process)**[1]	6.0
5	*Accumulator liquid temperature (boundary condition)*	5.6
6	*Break flow/break size (boundary condition)*	5.3
7	*HPI injection temperature (boundary condition)*	5.2
8	**Jet behavior entering cold leg and downcomer (phenomena/process)**[1]	4.4
9	*Decay heat (boundary condition)*	4.4
10	Wall-fluid heat transfer (thermal shield and vessel wall) (phenomena/process)	3.2

11	Flow stagnation (phenomena/process)[1]	2.8
12	**Mixing in cold leg (phenomena/process)[1]**	2.8
13	Cold leg temperature upstream of HPI (phenomena/process)	2.7
14	Bypass; in-vessel circulation (phenomena/process)	1.2
15	Upper head heat transfer (phenomena/process)	1.2
16	Liquid/vapor interface in upper downcomer (phenomena/process)	1.1
17	*Feedwater temperature (boundary condition)*	1.0
18	*Feedwater control (boundary condition)*	1.0
19	*Steam generator heat transfer (boundary condition)*	1.0
20	*Timing of reactor coolant pump trip (boundary condition)*	1.0
21	Loop flow resistance (facility characteristic/phenomena/process)	1.0

1. Phenomena/process studied in APEX-CE testing (also Creare, IVO)

Bold: not calculated by RELAP

Italics: boundary condition: input parameter to RELAP

Uncertainty Sources Treated and their Types

Parametric (Boundary Condition) Uncertainty

- Primary side breach size
- Primary system breach location
- Decay heat
- Season
- HPI state
- HPI flow rate
- Core flood tank pressure

RELAP5 Code Model Uncertainty

- RPV vent valves state
- Component heat transfer coefficient
- Flow resistance
- Break flow rate
- Numerical "mixing" (removed by conservatively using a high cold leg reverse flow resistance)

Conclusions

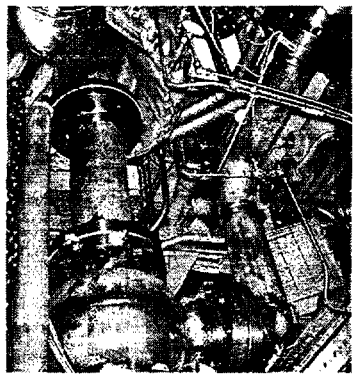
- We used an integrated experimental, scaling, code assessment approach to support code applications
- The risk dominant PTS sequences for the three plants analyzed thus far are LOCAs
- We have 30 years of experience calculating LOCAs

NRC Pressurized Thermal Shock Research at OSU (Experiments)

Presentation to the T/H Subcommittee
Advisory Committee on Reactor Safeguards

December 11, 2002

José N. Reyes, Jr. Professor
Department of Nuclear Engineering
Oregon State University



OREGON STATE UNIVERSITY
Open minds. Open doors.

1

Outline

1. Introduction
2. OSU PTS Research Plan
3. Test Facilities
4. APEX-CE Test Procedures
5. Test Matrix
6. Test Program Key Observations
7. Impact on PTS PIRTs
8. Conclusions

OREGON STATE UNIVERSITY
Open minds. Open doors.

2

1. Introduction

OREGON STATE UNIVERSITY
Open minds. Open doors.

3

Program Objectives

- Remove some of the limitations of the previous PTS Thermal Hydraulic Study.
- Revise the SBLOCA and MSLB PTS Phenomena and Identification Ranking Tables (PIRTs)
- Propose an improved PTS Thermal Hydraulic Assessment Methodology.

OREGON STATE UNIVERSITY
Open minds. Open doors.

4

Limitations of Prior PTS Integral System T/H Research

- **Integral System overcooling transient tests were not available to benchmark the TRAC and RELAP5 calculations.**
  - **Onset of loop stagnation**
  - **Asymmetric loop stagnation.**
  - **Benchmarks for downcomer cooling rates, temperatures and system pressures.**

OREGON STATE UNIVERSITY
Open minds. Open doors.

5

Limitations of Prior PTS Separate Effects T/H Research

- **Results of Separate Effects tests could not be adequately integrated with system behavior**
  - **Effect of downcomer plume behavior in a co-flowing stream was not assessed for low HPSI flows.**
  - **Effect of loop seal cooling on primary loop stagnation was not assessed.**
  - **Effect of downcomer driven loop natural circulation was not assessed.**
  - **Tests did not include effect of core decay heat.**

OREGON STATE UNIVERSITY
Open minds. Open doors.

6

Limitations of Prior PTS Separate Effects T/H Research

- **Computer speeds were not adequate for extensive CFD code calculations.**
  - **Multi-dimensional aspects of cold leg and downcomer mixing behavior were not modeled.**
  - **Effect of multiple plume interactions on wall heat transfer and downcomer temperature were not assessed.**

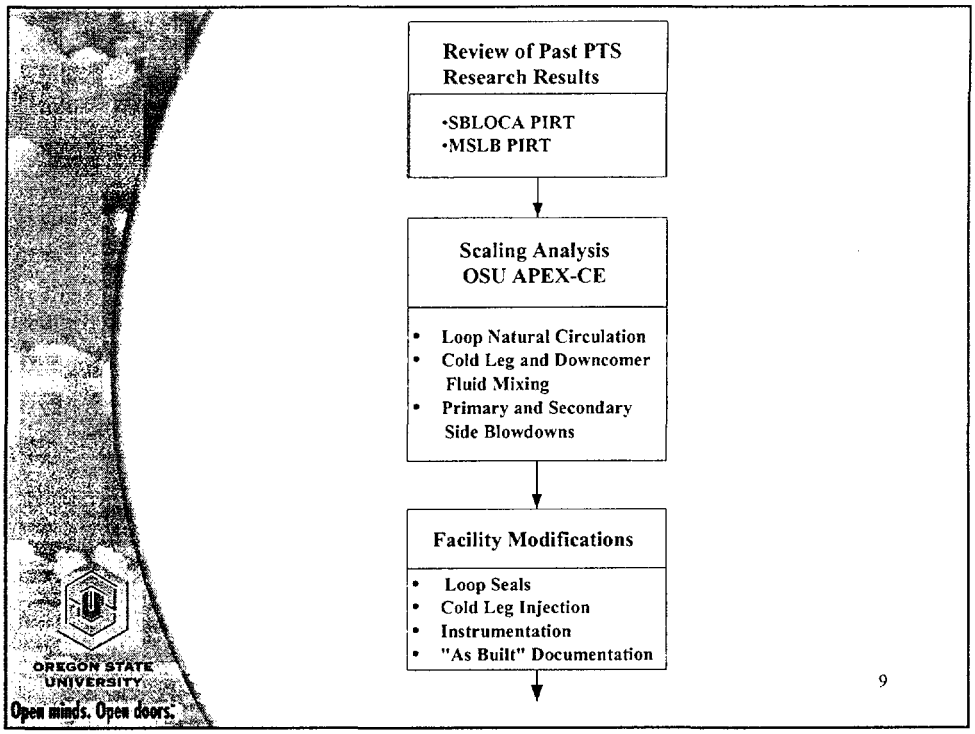
OREGON STATE UNIVERSITY
Open minds. Open doors.

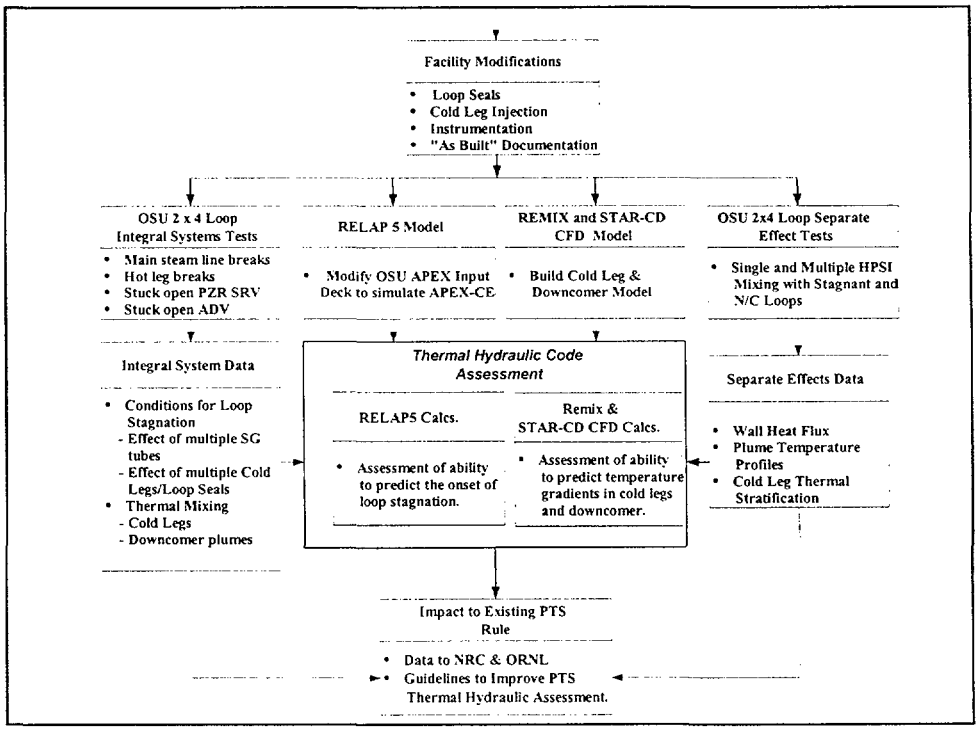
7

2. OSU PTS Research Plan

OREGON STATE UNIVERSITY
Open minds. Open doors.

8


Review of Past PTS Research Results
•SBLOCA PIRT
•MSLB PIRT
Scaling Analysis OSU APEX-CE
• Loop Natural Circulation
• Cold Leg and Downcomer Fluid Mixing
• Primary and Secondary Side Blowdowns
Facility Modifications
• Loop Seals
• Cold Leg Injection
• Instrumentation
• "As Built" Documentation
9
OREGON STATE UNIVERSITY
Open minds. Open doors.


Facility Modifications
• Loop Seals
• Cold Leg Injection
• Instrumentation
• "As Built" Documentation
OSU 2 x 4 Loop Integral Systems Tests
• Main steam line breaks
• Hot leg breaks
• Stuck open PZR SRV
• Stuck open ADV
RELAP 5 Model
• Modify OSU APEX Input Deck to simulate APEX-CE
REMIX and STAR-CD CFD Model
• Build Cold Leg & Downcomer Model
OSU 2x4 Loop Separate Effect Tests
• Single and Multiple HPSI Mixing with Stagnant and N/C Loops
Integral System Data
• Conditions for Loop Stagnation
- Effect of multiple SG tubes
- Effect of multiple Cold Legs/Loop Seals
• Thermal Mixing
- Cold Legs
- Downcomer plumes
Thermal Hydraulic Code Assessment
RELAP5 Calcs.
• Assessment of ability to predict the onset of loop stagnation.
Remix & STAR-CD CFD Calcs.
• Assessment of ability to predict temperature gradients in cold legs and downcomer.
Separate Effects Data
• Wall Heat Flux
• Plume Temperature Profiles
• Cold Leg Thermal Stratification
Impact to Existing PTS Rule
• Data to NRC & ORNL
• Guidelines to Improve PTS Thermal Hydraulic Assessment.

3. Test Facilities

OREGON STATE UNIVERSITY
Open minds. Open doors.

11

APEX-CE Test Facility

- OSU modified APEX to simulate T/H overcooling transients in the Palisades 2x4 PWR. The following was added:
  - Four Cold Leg HPSI Lines
  - Four Cold Leg Loop Seals
  - Weir-Wall in each Cold Leg to Simulate Lip of Palisades PCP Housing
  - Approximately 50 Additional Downcomer and 12 Loop Seal Thermocouples
  - 4 HPSI Mass Flow Meters

OREGON STATE UNIVERSITY
Open minds. Open doors.

12

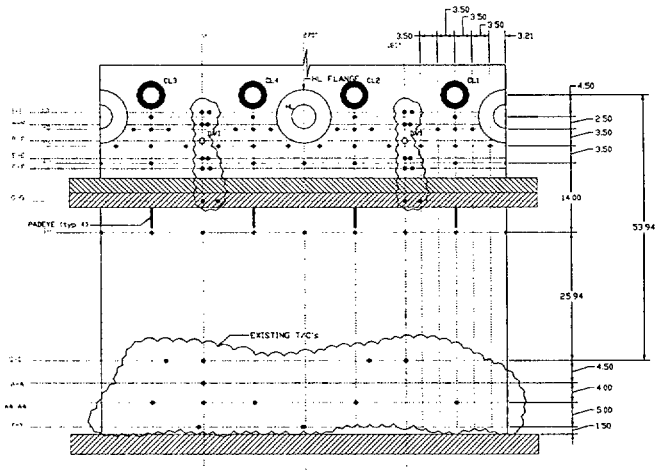
APEX-CE Facility Instrumentation

- Thermocouples, 450 used to measure fluid, wall and heater rod temperatures
- Differential pressures - 50 total
- Pressure Transducers - 41 total
- Magnetic Flowmeters - 28 total
- Vortex Flow Meters - 17 total
- Load Cells - 3 sets
- Coriolis Flow Meters - 4 total

OREGON STATE UNIVERSITY
Open minds. Open doors.

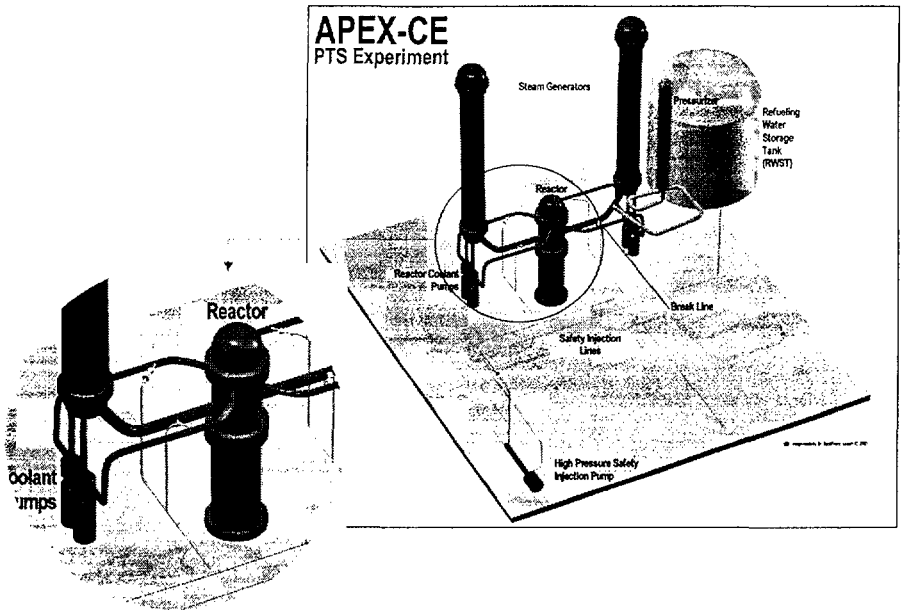
13

APEX-CE Downcomer Fluid Thermocouples



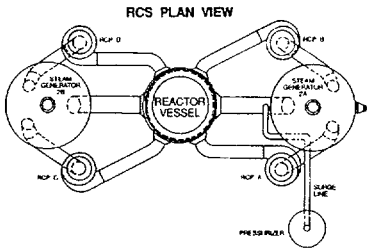
EXISTING THERMOCOUPLES

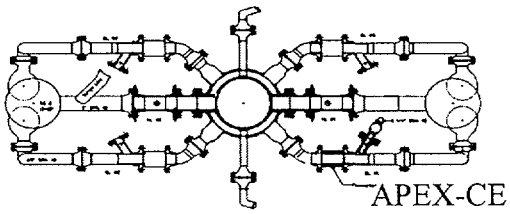
Layer	Tag #	Degree
E-E	TF-151	186.2
	TF-152	180
	TF-134	0
	TF-135	6.2
F-F	TF-153	180
	TF-154	180
	TF-132	0
	TF-133	0
H-H	TF-149	180
	TF-150	186.2
	TF-164	0
	TF-165	6.2
I-I	TF-147	180
	TF-148	180
	TF-166	0
	TF-167	0
G-G'	TF-155	180
	TF-156	193.3
	TF-130	0
	TF-131	11.3
C-C	TF-157	212
	TF-158	180
	TF-128	0
	TF-129	32
A-A	TF-126	225
	TF-127	213
	TF-162	45
	TF-163	135
AA-AA	TF-172	0
	TF-173	270
Y-Y	TF-118	225



Geometric Similarity Between APEX-CE and Typical CE 2x4

Palisades

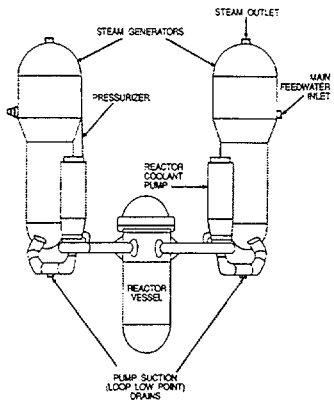




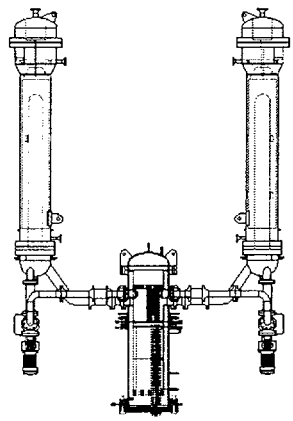
APEX-CE

Geometric Similarity Between APEX-CE and Typical CE 2x4

Palisades



APEX-CE



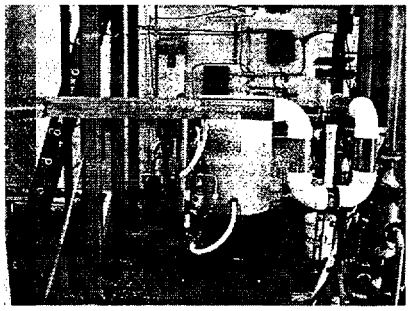
Separate Effects Test Loop (SETL)

- **OSU built a transparent flow visualization loop to study mixing in the cold leg, loop seal and HPSI Line.**
- **Test Loop includes:**
  - **Clear PVC piping**
  - **Single Cold Leg Piping geometry representing APEX-CE**
  - **HPSI nozzle with check valve**
  - **Weir-Wall in Cold Leg**
  - **50 gallon salt water mixing tank**
  - **20 gpm HPI pump**
  - **500 gpm Cold Leg pump**

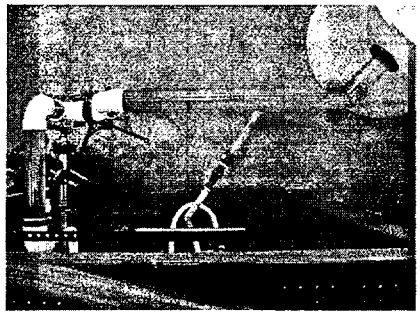
OREGON STATE UNIVERSITY
Open minds. Open doors.

18

SETL Flow Visualization Loop



Side View



Top View

4. APEX-CE Test Procedures

OREGON STATE UNIVERSITY
Open minds. Open doors.

20

Input from Palisades Operators

- NRC meeting held at the Palisades Nuclear Plant in Covert, Michigan on March 19, 2001.
  - Forum for valuable discussions with the Palisades plant control room operators.
  - Palisades plant operators demonstrated how they would respond to a small MSLB and a SBLOCA using the plant simulator.
  - Based on our discussions with the Palisades operators, our observations of their simulator scenarios and a review of the APEX-CE scaling limitations, a set of test procedures were developed for APEX-CE.

OREGON STATE UNIVERSITY
Open minds. Open doors.

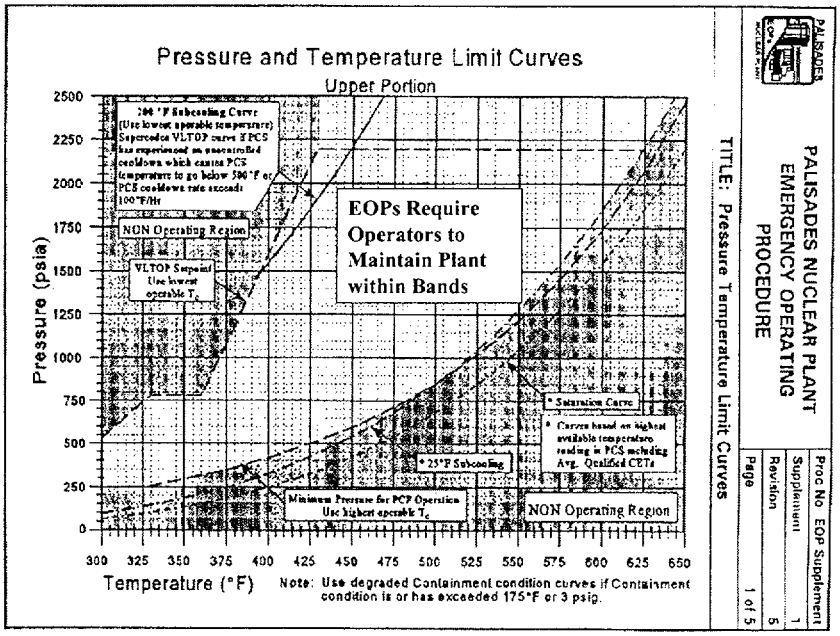
21

Palisades EOPs

- The following Palisades Emergency Operating Procedures (EOP)were examined as part of the effort to develop test procedures for APEX-CE:
  - "Standard Post Trip Actions," EOP-1.0
  - "Loss of Coolant Accident Recovery," EOP-4.0
  - "Excess Steam Demand Event," EOP-6.0
  - "Functional Recovery Procedure," EOP-9.0
  - "EOP Supplements."

OREGON STATE UNIVERSITY
Open minds. Open doors.

22



APEX-CE Operator Actions

- **APEX-CE operator and plant actions were generally realistic with the following *very important* exceptions:**
  - **Throttling of the HPSI was not permitted.**
  - **Isolation of Feedwater flow to a Broken Steam Generator was assumed to take 10 minutes.**
  - **No effort was made to keep the plant within a Pressure/Temperature Band (scaled) as required by EOPs.**

OREGON STATE UNIVERSITY
Open minds. Open doors.

24

5. APEX-CE Test Matrix

OREGON STATE UNIVERSITY
Open minds. Open doors.

25

APEX-CE Test Matrix

Test Number	Title
OSU-CE-0001	Natural Circulation Flow Benchmark Test
OSU-CE-0002	Natural Circulation Stepped-Inventory Test
OSU-CE-0003	N/C Fluid Mixing Test - (8 Parametric)
OSU-CE-0004	Stagnant Loop Fluid Mixing Tests - 1 HPSI
OSU-CE-0005	Stagnant Loop Fluid Mixing Tests - 4 HPSI
OSU-CE-0006	Stagnant Loop Fluid Mixing Tests - 4 HPSI
OSU-CE-0007	1.4-Inch Hot Leg Break from Full Power
OSU-CE-0008	1.4-Inch Hot Leg Break from HZP
OSU-CE-0009	Stuck-Open PZR PORV from Full Power
OSU-CE-0010	Stuck-Open PZR PORV from HZP

APEX-CE Test Matrix

Test Number	Title
OSU-CE-0011	1.0 ft^2 MSLB Hot Zero Power w/ failure to isolate AFW
OSU-CE-0012	1.0 ft^2 MSLB Full Power w/ failure to isolate AFW
OSU-CE-0013	Stuck open Primary SRV with Subsequent Re-closure
OSU-CE-0014	Stagnant Loop Fluid Mixing Test - 2 Adjacent HPSI
OSU-CE-0015	Stagnant Loop Fluid Mixing Test - 2 Opposite HPSI
OSU-CE-0016	Stagnant Loop Fluid Mixing Test - 3 HPSI
OSU-CE-0017	Stagnant Loop Fluid Mixing Test - 1 HPSI with Upper Plenum/Downcomer bypass
OSU-CE-0018	Stagnant Loop Fluid Mixing Test - 4 HPSI with Upper Plenum/Downcomer bypass
OSU-CE-0019	2.0-Inch Hot Leg Break from Full Power with Upper Plenum/Downcomer bypass
OSU-CE-0020	2.0 Inch Hot Leg Break Separate Effects Test

6. Key Observations

OREGON STATE UNIVERSITY
Open minds. Open doors.

28

A. Integral System Cooling Transients

- Eight MSLB and SBLOCA transients were performed to determine the primary-side pressures and downcomer fluid temperatures. Primary focus was 2.4D to 6.8D into downcomer along the active core region.
  - The SBLOCA transients resulted in lower downcomer fluid temperatures but did not re-pressurize.
  - The 1.0 ft^2MSLB from Hot Zero Power, OSU-CE-0011, resulted in the lowest downcomer fluid temperatures while at re-pressurized conditions.
  - Same result was obtained in original Calvert Cliffs TRAC-PF1 calculations (NUREG/CR-4109).

OREGON STATE UNIVERSITY
Open minds. Open doors.

29

Downcomer Fluid Temperatures and Pressures

Test Number	Description	Minimum Downcomer Temperature	Pressure at Minimum Temperature
OSU-CE-0007	1.4-Inch Hot Leg Break from Full Power	397 °K (255 °F)	1.0 MPa (145.7 psia)
OSU-CE-0008	1.4-Inch Hot Leg Break from HZP	354 °K (177 °F)	0.59 MPa (86.3 psia)
OSU-CE-0009	Stuck-Open PZR SRV from Full Power	422 °K (300 °F)	1.5 MPa (217.7 psia)
OSU-CE-0010	Stuck-Open PZR SRV and Steam Line ADV from HZP	370 °K (207 °F)	0.63 MPa (91.6 psia)
OSU-CE-0011	1.0 ft^2 MSLB Hot Zero Power with failure to isolate AFW	388 °K (238 °F)	2.5 MPa (363.7 psia)
OSU-CE-0012	1.0 ft^2 MSLB Full Power with failure to isolate AFW	404 °K (268 °F)	2.4 MPa (347.7 psia)
OSU-CE-0013	Stuck-Open Primary SRV with Subsequent Re-closure	465 °K (378 °F)	2.1 MPa (297.7 psia)
OSU-CE-0019	2.0-Inch Hot Leg Break from Full Power with Upper Plenum/Downcomer Bypass	348 °K (167 °F)	0.55 MPa (80.3 psia)

B. Mechanisms for Primary Loop Stagnation

- **Primary loop stagnation during HPSI operation results in thermal stratification in the cold legs and downcomer plumes.**
- **Three mechanisms were observed for loop stagnation:**
  - **Steam Generator Reverse Heat Transfer**
  - **Steam Generator Tube Draining**
  - **Cold Liquid Intrusion into the Loop Seal**

OREGON STATE UNIVERSITY
Open minds. Open doors.

31

Loop Stagnation Behavior

Test Number	Description	Stagnation Phenomena
OSU-CE-0002	Stepped Inventory Reduction	Cold Legs 1,2,3,4 due to SG#1 and SG#2 Tube Draining
OSU-CE-0007	1.4-Inch Hot Leg Break from Full Power	Cold Legs 2,3,4 due to SG#1 and SG#2 Reverse Heat Transfer and Negatively Buoyant Loop Seals
OSU-CE-0008	1.4-Inch Hot Leg Break from HZP	Cold Legs 1 and 2 due to SG#1 and SG#2 Tube Draining and 3 and 4 due to Negatively Buoyant Loop Seals
OSU-CE-0009	Stuck-Open PZR SRV from Full Power	Cold Legs 2 and 4 due to SG#2 Reverse Heat Transfer and Negatively Buoyant Loop Seals
OSU-CE-0010	Stuck-Open PZR SRV and Steam Line ADV from HZP	Cold Legs 2 and 4 due to SG#2 Reverse Heat Transfer
OSU-CE-0011	1.0 ft^2 MSLB Hot Zero Power with failure to isolate AFW	Cold Legs 2 and 4 due to SG#2 Reverse Heat Transfer
OSU-CE-0012	1.0 ft^2 MSLB Full Power with failure to isolate AFW	Cold Legs 1 and 3 due to SG#1 Reverse Heat Transfer
OSU-CE-0013	Stuck-Open Primary SRV with Subsequent Re-closure	None
OSU-CE-0019	2.0-Inch Hot Leg Break from Full Power with Upper Plenum/Downcomer Bypass	Cold Legs 1 and 2 due to SG#1 and SG#2 Draining and Cold Legs 3 and 4 due to Negatively Buoyant Loop Seals

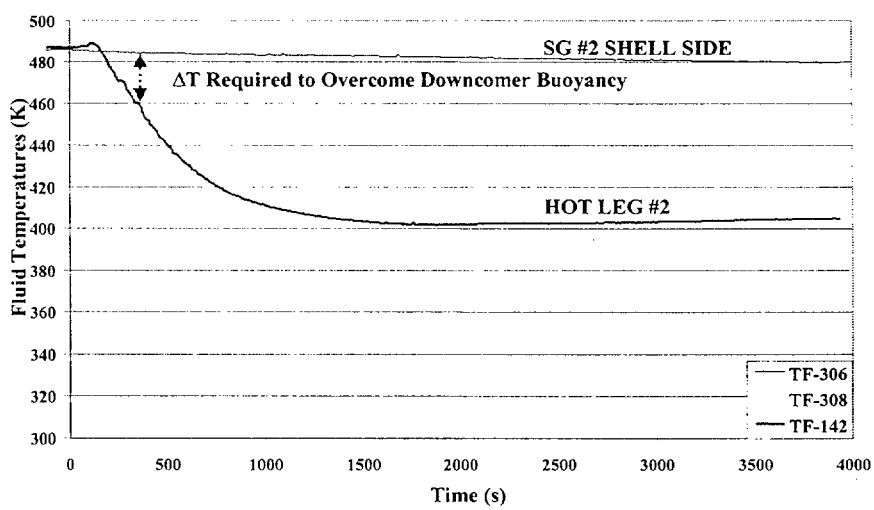
Steam Generator Reverse Heat Transfer

- During the MSLB tests, stagnation occurred in the cold legs attached to the unaffected steam generator after the unaffected steam generator became a heat source for the primary system.
- For the Stuck-Open SRV and the 1.4 inch SBLOCA tests, the isolated steam generators became a heat source for the primary loop. This caused primary loop stagnation.
- Cold HPSI flow into the downcomer provided a positive driving head for N/C flow even after a Steam Generator became a heat source.

OREGON STATE UNIVERSITY
Open minds. Open doors.

33

Steam Generator #2 Fluid Temperatures (MSLB OSU-CE-0011)



Steam Generator Tube Draining

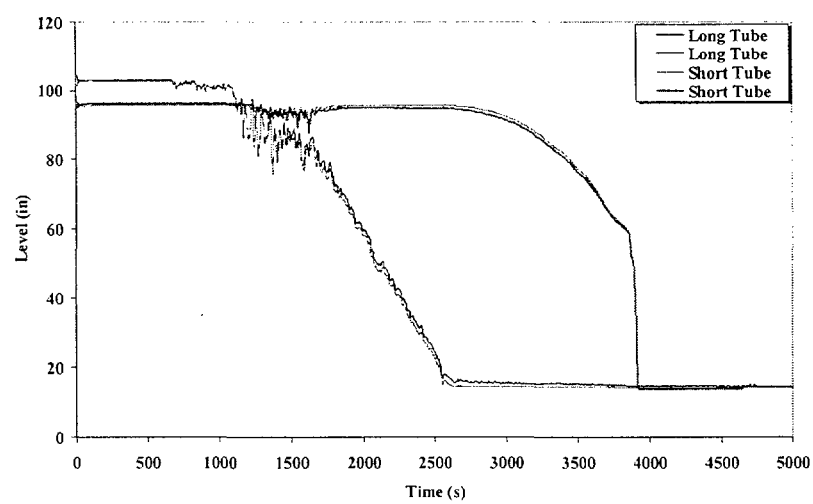
- For the SBLOCA Tests (> 5.0 cm), stagnation was determined to be caused by steam generator tube draining.
- Long tubes drained much earlier than short tubes. Primary loop natural circulation continued until the short tubes drained.
- RELAP5 models typically use one tube to simulate the steam generator. This can create difficulties in predicting the onset of loop stagnation.

OREGON STATE UNIVERSITY
Open minds. Open doors.

35

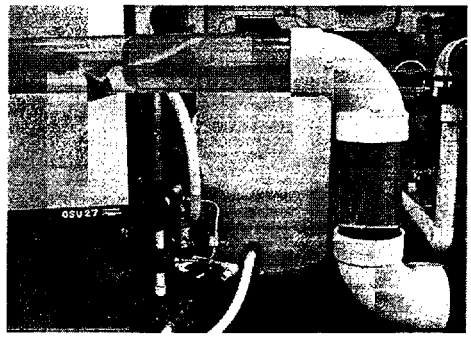
Steam Generator Tube Draining

Liquid Level in Long and Short Tubes,
Steam Generator #2 (OSU-CE-0008)



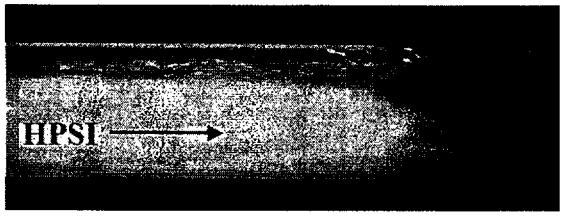
Cold Liquid Intrusion into the Loop Seals

- Cold HPSI fluid backflow into the cold leg loop seals produced negatively buoyant liquid columns that resisted loop natural circulation.
- Produced asymmetric loop stagnation.
- Only effective in conjunction with one of the other stagnation mechanisms.
- Example of a local phenomenon affecting integral system behavior.



C. HPSI Plume Mixing Behavior

- Buoyant fluid backflow into the HPSI line resulted in significant heating of the cold HPSI fluid before entering the cold leg, reducing cold leg fluid thermal stratification.
- Backflow entrainment rates ranged from 1 to 3 times the HPSI Flow Rate.



OREGON STATE UNIVERSITY
Open minds. Open doors.

38

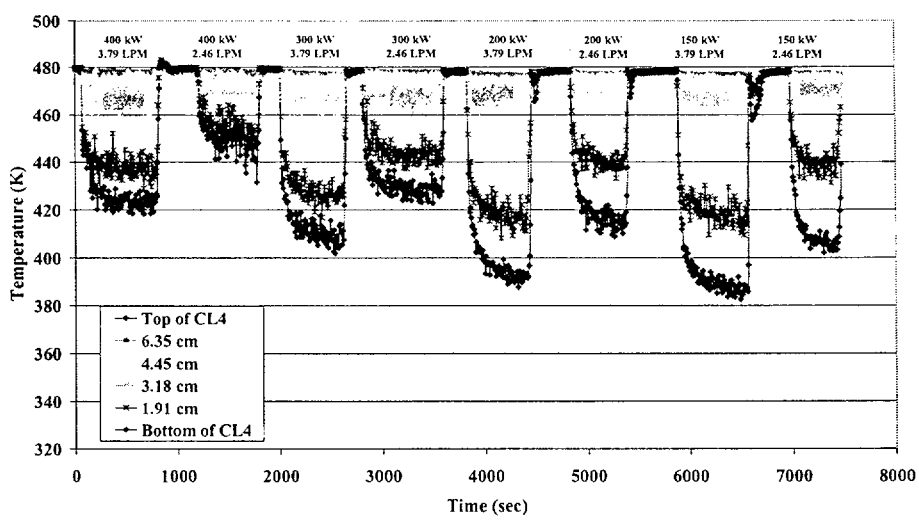
D. Cold Leg Fluid Thermal Stratification

- Thermal stratification was observed for primary loop natural circulation flows associated with core decay powers ranging from 1.5 % to 4% and HPSI flow rates ranging from 30% to 100%.
- As N/C flow increased, the degree of Cold Leg thermal stratification decreased.
- Presence of Lip located at the Reactor Coolant Pump discharge enhanced thermal stratification.
- Screening Criterion for the onset of thermal stratification did not predict the onset for this geometry.
  - Significantly affects the PTS T/H Assessment Methodology used in the past.

OREGON STATE UNIVERSITY
Open minds. Open doors.

39

Cold Leg Fluid Thermal Stratification with Natural Circulation (OSU-CE-0003)



E. Downcomer Plume Behavior

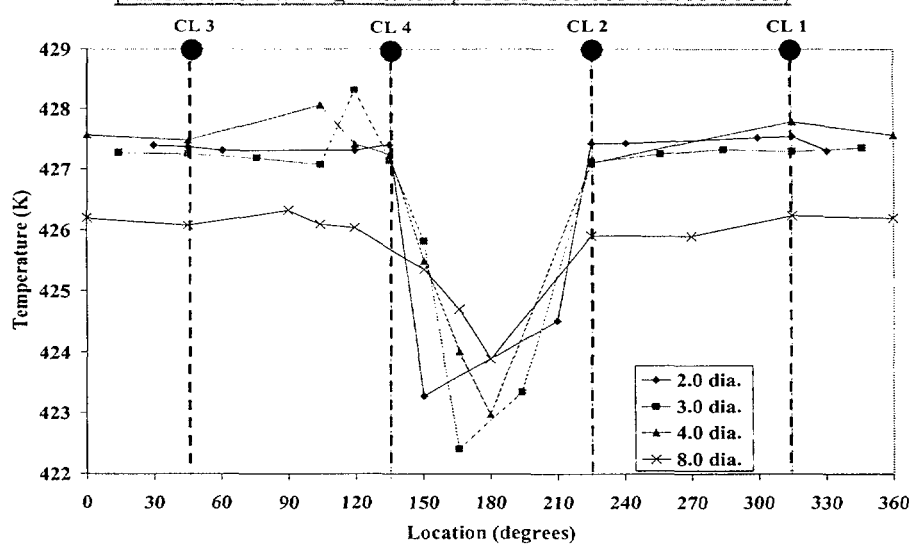
- **HPSI flow into stagnant cold legs produced relatively weak plumes that could be detected 8 cold leg diameters into the downcomer.**
  - **Maximum APEX-CE HPSI flow corresponding to 150% Palisades HPSI flow, into a single stagnant cold leg produced a plume having a temperature ~ 4 °K less than the surrounding ambient fluid.**
  - **Maximum HPSI Flow into two adjacent, stagnant cold legs resulted in plume merger to form a slightly stronger plume (~5 °K less than the surrounding ambient fluid.)**
  - **Maximum HPSI Flow into three or four stagnant cold legs resulted in a very flat, well-mixed, temperature profile in the downcomer.**

OREGON STATE UNIVERSITY
Open minds. Open doors.

41

Merging of Two Adjacent Plumes in the Downcomer

(HPSI #2 & #4, Stagnant Loop, OSU-CE-0014, 2000-3000s)



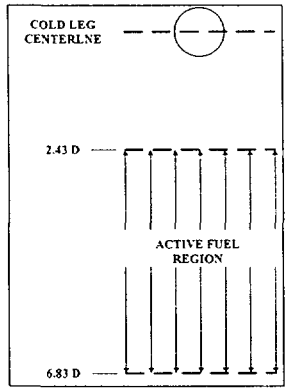
E. Downcomer Plume Behavior

- **HPSI operation during <u>loop natural circulation</u> produced plumes that were weaker than those observed for the stagnant flow case.**
  - **In theory, a plume "co-flowing" with the ambient fluid in the downcomer can remain intact longer if the relative velocity is small.**
  - **In practice, co-flow in the downcomer is caused by cold leg flow. The presence of flow in the cold leg produced fluid mixing that overwhelmed the potential co-flow effect.**

OREGON STATE UNIVERSITY
Open minds. Open doors.

43

F. Downcomer Fluid Thermal Stratification



High Injection Flow Rate with Cold Leg Flow in IVO Tests

OREGON STATE UNIVERSITY
Open minds. Open doors.

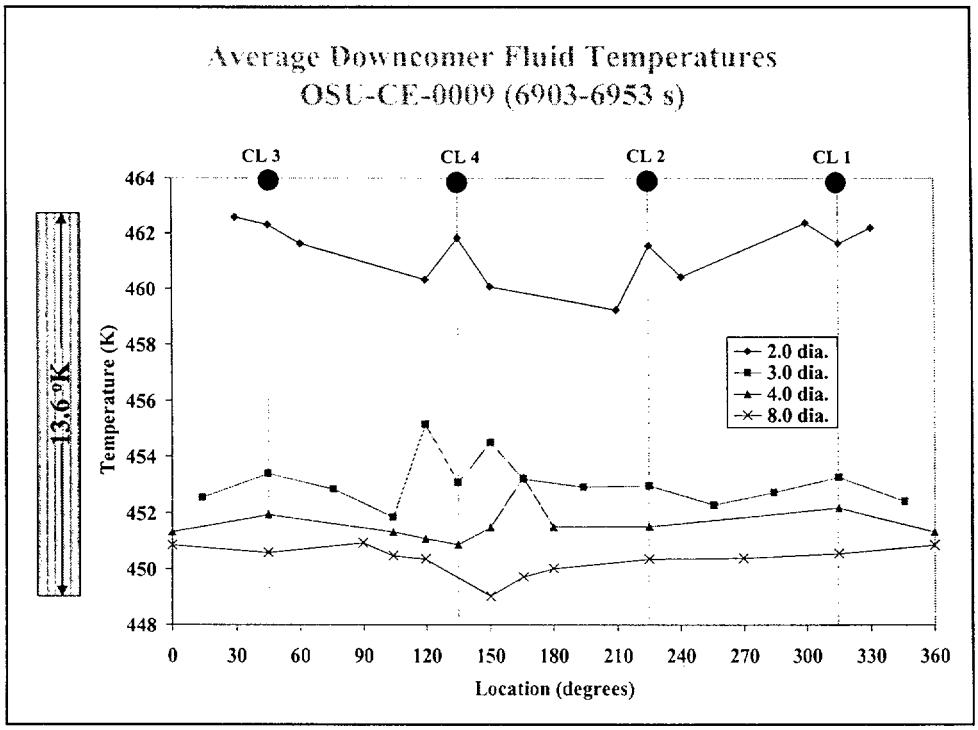
44

F. Downcomer Fluid Thermal Stratification

- **The maximum fluid temperature difference observed from the 2D elevation to the 8D elevation, based on a 50 second average, was ~13.6 °K for OSU-CE-0009, the Stuck-Open Pressurizer Safety Relief Valve.**
- **The temperature difference was due to the presence of saturated steam at the 2D elevation.**

OREGON STATE UNIVERSITY
Open minds. Open doors.

45



G. Dimensionless Temperature and Time Scales

- **APEX-CE Scaling Analysis Report NUREG/CR-6731 provides dimensionless groups to collapse and extend applicability of transient data.**

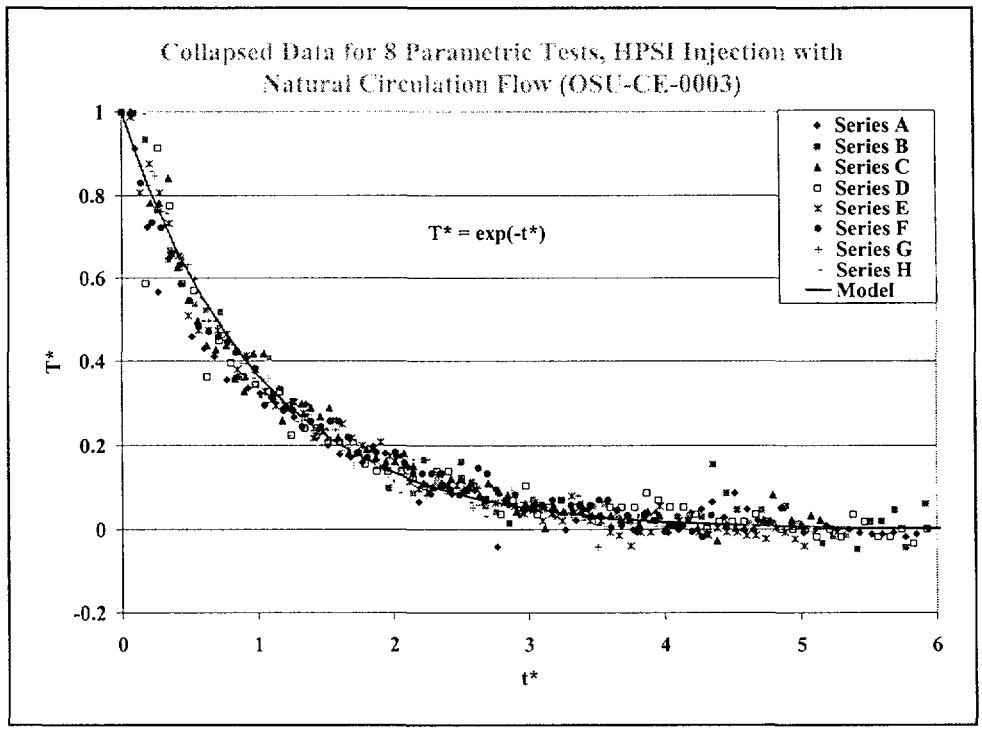
$$T_m^* = e^{-t^*}$$

- **Where :**

$$t^* = \frac{t}{\tau_m} \qquad T_m^* = \frac{(T_m - T_I)}{(T_L - T_I)}$$

OREGON STATE UNIVERSITY
Open minds. Open doors.

47



7. Impact on PTS PIRTs

OREGON STATE UNIVERSITY
Open minds. Open doors.

49

PTS Phenomena Identification and Ranking Tables

- **MSLB and SBLOCA PTS PIRTs have been developed for the H.B. Robinson Unit 2 Plant (NUREG/CR-5452) and the Yankee Rowe Plant (INEL Letter Report, SAN-12-92)**
- **The present study suggests that the ranking of some phenomena should be re-assessed.**

OREGON STATE UNIVERSITY
Open minds. Open doors.

50

SBLOCA PIRT (High Ranked PTS Phenomena)

Phenomena	Significant Impact on Minimum Downcomer Fluid Temperature and/or System Pressure	Phenomena Dependencies
Break Mass Flow Rate	·Primary system pressure. ·Primary system saturation temperature.	·Primary System Pressure ·Break Geometry ·Break Location
HPSI Flow Rate and Number	·Degree of cold leg thermal stratification ·Downcomer plume strength ·Plume merging and location of the coldest plumes ·Primary system re-pressurization	·Primary System Pressure
HPSI Buoyant Fluid Backflow	·Degree of cold leg thermal stratification ·Downcomer plume strength	·HPSI Flow Rate ·HPSI Line Geometry
HPSI Water Source Temperature	·Degree of cold leg thermal stratification ·Downcomer plume strength	·RWST Location
Cold Leg Fluid Thermal Stratification	·Downcomer plume strength	·HPSI Flow Rate ·Primary Loop Flow Rate ·Cold Leg Geometry ·RCP Discharge Geometry
Core Decay Heat	·Primary system pressure ·Primary loop natural circulation flow rate ·Primary loop fluid temperatures	·Core Operating History ·Time since scram

SBLOCA PIRT (High Ranked PTS Phenomena)

Phenomena	Significant Impact on Minimum Downcomer Fluid Temperature and/or System Pressure	Phenomena Dependencies
Reactor Wall Conduction Heat Transfer	·Downcomer fluid temperature	·Wall Thickness ·Wall Temperature Profile ·Wall Thermal Conductivity
Downcomer Plume Merging and Mixing	·Minimum downcomer fluid temperature and location	·Number of HPSI ·Cold Leg Flow Rate ·Plume Temperature ·Ambient Fluid Temperature
Primary Loop Natural Circulation Flow Rate and Stagnation	·Cold leg thermal stratification ·Downcomer plume strength	·Loop Resistance ·Core Decay Power ·Distance between Thermal Centers ·HPSI Flow Rate and Orientation (Loop Seal Backflow) ·Steam Generator Heat Transfer (< ~5.0 cm breaks) ·Steam Generator Tube Draining (>~5.0 cm breaks)

MSLB PIRT (High Ranked PTS Phenomena)

Phenomena	Significant Impact on Minimum Downcomer Fluid Temperature and/or System Pressure	Phenomena Dependencies
Steam Line Break Mass Flow Rate	·Primary system pressure. ·Primary system temperature.	·Break Geometry ·Break Location
HPSI Flow Rate and Number	·Degree of cold leg thermal stratification ·Downcomer plume strength ·Plume merging and location of the coldest plumes ·Primary system re-pressurization	·Primary System Pressure
HPSI Buoyant Fluid Backflow	·Degree of cold leg thermal stratification ·Downcomer plume strength	·HPSI Flow Rate ·HPSI Line Geometry
HPSI Water Source Temperature	·Degree of cold leg thermal stratification ·Downcomer plume strength	·RWST Location
Cold Leg Fluid Thermal Stratification	·Downcomer plume strength	·HPSI Flow Rate ·Primary Loop Flow Rate ·Cold Leg Geometry ·RCP Discharge Geometry
Core Decay Heat	·Primary system pressure ·Primary loop natural circulation flow rate ·Primary loop fluid temperatures	·Core Operating History ·Time since scram

MSLB PIRT (High Ranked PTS Phenomena)

Phenomena	Significant Impact on Minimum Downcomer Fluid Temperature and/or System Pressure	Phenomena Dependencies
Reactor Wall Conduction Heat Transfer	·Downcomer fluid temperature	·Wall Thickness ·Wall Temperature Profile ·Wall Thermal Conductivity
Downcomer Plume Merging and Mixing	·Minimum downcomer fluid temperature and location	·Number of HPSI ·Cold Leg Flow Rate ·Plume Temperature ·Ambient Fluid Temperature
Primary Loop Natural Circulation Flow Rate and Stagnation	·Cold leg thermal stratification ·Downcomer plume strength	·Loop Resistance ·Core Decay Power ·Distance between Thermal Centers ·HPSI Flow Rate and Orientation (Loop Seal Backflow) ·Steam Generator Heat Transfer

Reduced Rank of PTS Phenomena for the MSLB and SBLOCA PIRTs

- **RPV Convective Heat Transfer Coefficient.**
  - The Reactor Pressure Vessel wall is conduction limited.
- **Upper Head/Downcomer Flow**
  - For the APEX-CE design tested, the upper head/downcomer bypass connections produced some warming of the downcomer fluid over time. However, this flow path was very small. Therefore, the impact was not significant.
- **Downcomer to Core Inlet Bypass Flow**
  - For the APEX-CE design tested, the core bypass flow under natural circulation conditions was very small. Therefore, the impact was not significant.

OREGON STATE UNIVERSITY
Open minds. Open doors.

55

Reduced Rank of PTS Phenomena for the MSLB and SBLOCA PIRTs

- **Timing of RCP Trips.**
  - SBLOCA: RCPs tripped on low subcooling temperature which occurs very early for the SBLOCA transients.
  - MSLB inside Containment: Containment isolation results in a loss of component cooling water and reactor coolant pump (RCP)seal cooling. This results in tripping all four RCPs. Thus the RCPs were tripped at the beginning of the transient.
- **Steam Generator Energy Exchange, Feedwater Control and Feedwater Temperature.**
  - SBLOCA Breaks > 5 cm: Secondary side temperature and pressure did affect primary side conditions until the steam generator tubes drained causing loop stagnation. After tube voiding, the primary loop was decoupled from the secondary loop.

OREGON STATE UNIVERSITY
Open minds. Open doors.

56

Reduced Rank of PTS Phenomena for the MSLB and SBLOCA PIRTs

- **Liquid/Steam Interface in the Upper Downcomer.**
  - **This region in the upper downcomer is filled with saturated steam and liquid. It was found to be thermally decoupled from the rest of the downcomer fluid.**
- **Upper Head Heat Transfer Coefficient Under Voided Conditions.**
  - **This phenomenon did impact primary side pressure to some extent. However, the energy associated with the break flow and the core decay power dominated the pressure behavior.**

OREGON STATE UNIVERSITY
Open minds. Open doors.

57

8. Conclusions

- **A total of 20 APEX-CE tests have been performed for NRC's PTS Research Program.**
- **The APEX-CE tests will help guide the revision to the PTS SBLOCA and MSLB PIRTs.**
- **Tests have provided insights into:**
  - Integral System Cool-down Behavior
  - Loop Stagnation Mechanisms
  - HPSI Plume Behavior
  - Cold Leg Fluid Thermal Stratification
  - Downcomer Plume Behavior
  - RPV Heat Transfer

OREGON STATE UNIVERSITY
Open minds. Open doors.

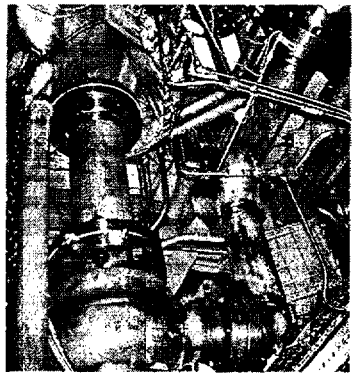
58

NRC Pressurized Thermal Shock Research at OSU (Code Comparisons)

Presentation to the T/H Subcommittee
Advisory Committee on Reactor Safeguards

December 11, 2002

José N. Reyes, Jr. Professor
Department of Nuclear Engineering
Oregon State University



OREGON STATE UNIVERSITY
Open minds. Open doors.

Outline

1. Introduction
2. RELAP-5 Calculations
   - Sensitivity to Transport Rate Model Uncertainties
3. STAR-CD Calculations
4. Comparison of REMIX, RELAP-5 and STAR-CD Downcomer Fluid Temperatures
5. Revised PTS T/H Assessment Methodology
6. Conclusions

OREGON STATE UNIVERSITY
Open minds. Open doors.

1. Introduction

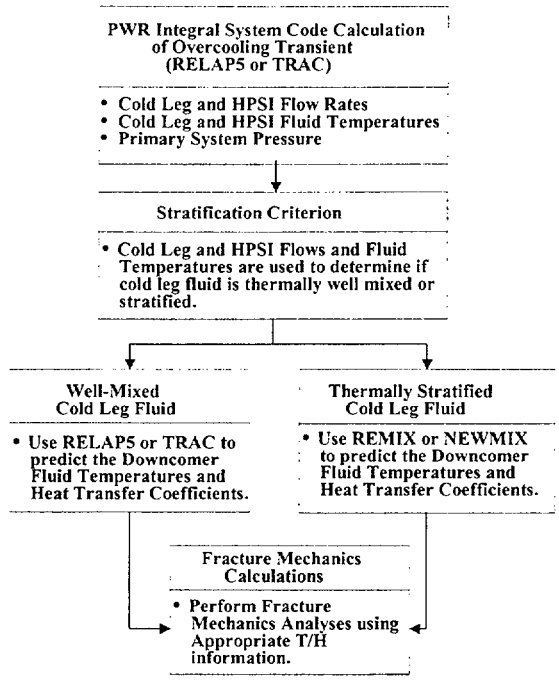
OREGON STATE UNIVERSITY
Open minds. Open doors.

Code Comparison Objectives

- Objective was to assess certain aspects of RELAP5, STAR-CD and REMIX that are important to the PTS Thermal Hydraulic Assessment Methodology.
- The PTS T/H Assessment Methodology provides the detailed information needed for the Fracture Mechanics Assessment for a wide range of overcooling transients, (>200 in earlier study) including:
  - Downcomer Fluid Temperature Profiles
  - Convective Heat Transfer Coefficients at the inside wall of the RPV
  - System Pressures

OREGON STATE UNIVERSITY
Open minds. Open doors.

PTS Thermal Hydraulic Assessment Methodology



OREGON STATE UNIVERSITY
Open minds. Open doors.

Assessment Scope

- RELAP-5 (System Code)
  - Ability to predict the downcomer fluid temperatures and the onset of loop stagnation.
- STAR-CD (CFD Code)
  - Ability to predict the downcomer fluid temperatures, Cold Leg fluid temperature gradients, HPSI backflow behavior, downcomer plume temperatures and motion.
- REMIX (Regional Mixing Model)
  - Ability to predict the downcomer fluid temperatures.

OREGON STATE UNIVERSITY
Open minds. Open doors.

Code Analyses Matrix

Test Number	Title	Analyses
OSU-CE-0001	N/C Flow Benchmark Test	
OSU-CE-0002	N/C Stepped-Inventory Test	RELAP5
OSU-CE-0003	N/C Fluid Mixing Test - (8 Parametric)	STAR-CD
OSU-CE-0004	Stagnant Loop Fluid Mixing Tests - 1 HPSI	STAR-CD, REMIX
OSU-CE-0005	Stagnant Loop Fluid Mixing Tests - 4 HPSI	STAR-CD, REMIX
OSU-CE-0006	Stagnant Loop Fluid Mixing Tests - 4 HPSI	STAR-CD, REMIX,RELAP5
OSU-CE-0007	1.4-Inch Hot Leg Break from Full Power	
OSU-CE-0008	1.4-Inch Hot Leg Break from HZP	RELAP5
OSU-CE-0009	Stuck-Open PZR PORV from Full Power	
OSU-CE-0010	Stuck-Open PZR PORV from HZP	RELAP5

Code Analyses Matrix

Test Number	Title	Analyses
OSU-CE-0011	1.0 ft^2 MSLB Hot Zero Power w/ failure to isolate AFW	RELAP5
OSU-CE-0012	1.0 ft^2 MSLB Full Power w/ failure to isolate AFW	RELAP5
OSU-CE-0013	Stuck open Primary SRV with Subsequent Re-closure	
OSU-CE-0014	Stagnant Loop Fluid Mixing Test - 2 Adjacent HPSI	
OSU-CE-0015	Stagnant Loop Fluid Mixing Test - 2 Opposite HPSI	
OSU-CE-0016	Stagnant Loop Fluid Mixing Test - 3 HPSI	
OSU-CE-0017	Stagnant Loop Fluid Mixing Test - 1 HPSI with Upper Plenum/Downcomer bypass	
OSU-CE-0018	Stagnant Loop Fluid Mixing Test - 4 HPSI with Upper Plenum/Downcomer bypass	
OSU-CE-0019	2.0-Inch Hot Leg Break from Full Power with Upper Plenum/Downcomer bypass	
OSU-CE-0020	2.0 Inch Hot Leg Break Separate Effects Test	

2. RELAP5 3.2.2 γ Calculation of a 1.0ft^2 MSLB Simulation (OSU-CE-0011)

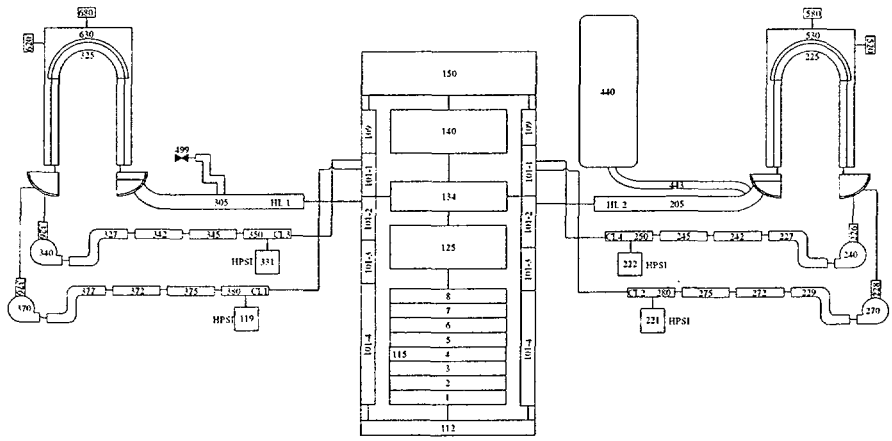
OREGON STATE UNIVERSITY
Open minds. Open doors.

APEX-CE 1ft^2 Main Steam Line Break From Hot Zero Power

- **OSU-CE-0011 was successfully performed on May 4, 2001.**
- **The test simulated a 0.092 m^2 (1.0 ft^2) main steam line break initiated from hot zero power (100 hours after shutdown).**
- **For an inside Containment MSLB, Containment isolation results in trip of all Reactor Coolant Pumps.**
- **HPSI systems actuates on low primary pressure setpoint.**
- **Auxiliary Feedwater flow to the broken steam generator (SG#1) was isolated after 10 minutes.**

OREGON STATE UNIVERSITY
Open minds. Open doors.

RELAP5 APEX-CE Model Nodalization



Measured and RELAP5 Calculated Initial Conditions for OSU-CE-0011

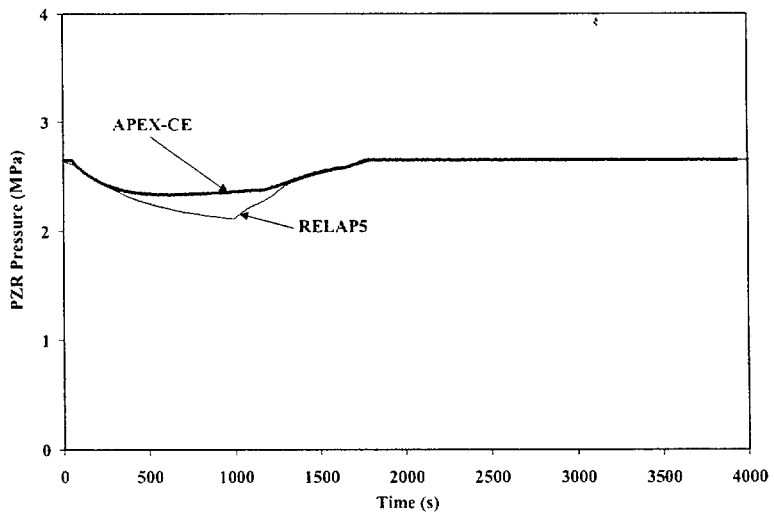
Parameter	APEX-CE MEASURED		RELAP5 CALCULATED	
Core Power	94.78 Btu/s	100 kW	94.78 Btu/s	100 kW
Core Mass Flow Rate	92 lbm/s	41.7 kg/s	92 lbm/s	41.7 kg/s
Pressurizer Pressure	384.7 psia	2.65 MPa	384.7 psia	2.65 MPa
Pressurizer Level	20 in.	50.8 cm	20 in.	50.8 cm
Hot Leg Temperature	415 °F	485.7 °K	415.7 °F	486.2 °K
Cold Leg Temperature	414 °F	485.2 °K	414.4 °F	485.44 °K
Steam Generator #1 Pressure	286.7 psia	1.975 MPa	286.7 psia	1.975 MPa
Steam Generator #2 Pressure	286.7 psia	1.975 MPa	286.7 psia	1.975 MPa
Steam Generator #1 Water Level (NR)	24 in.	60.96 cm	24.2 in.	61.46 cm
Steam Generator #2 Water Level (NR)	24 in.	60.96 cm	24.2 in.	461.46 cm
Steam Generator 1& 2 Feedwater Temperatures	68.7 °F	293.4. °K	68.7 °F	293.4 °K
Steam Generator 1& 2 Mass Flow Rates (per SG)	0.04 lbm/s	0.0181 kg/s	0.04lbm/s	0.0181 kg/s

Comparison of APEX-CE and RELAP5 Sequence of Events for OSU-CE-0011

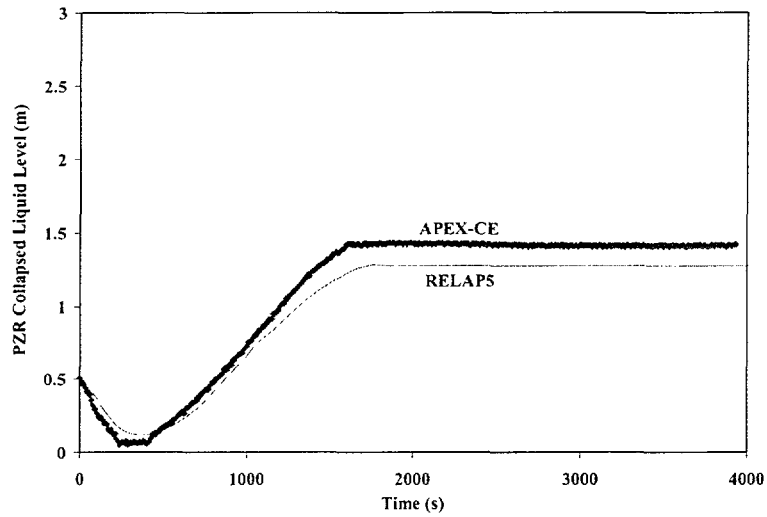
	APEX-CE	RELAP5
Event Description	Time (s)	Time (s)
Opened Steam Generator #1 PORV ; Drop Power to 45.8 kW	0	0
Manually Tripped RCP-1, RCP-2, RCP-3 and RCP-4 as per Logic	4	0
HPSI Flow begins automatically at pressure setpoint	91	92
Steam Generator #2 becomes a Heat Source	171	171
Cold Leg #2 Stagnated	383	600*
Cold Leg #4 Stagnated	383	820*
Feedwater flow to Steam Generator #1 was secured	619	600
HPSI Flow automatically stops on pressure setpoint	1616	1641
Test Ends	3937	4000

* Onset of oscillation about zero flow, complete stagnation at 1756 seconds.

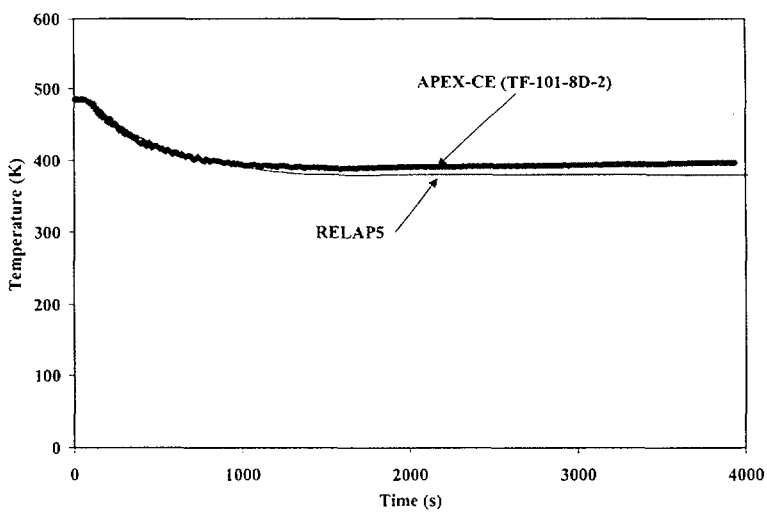
Primary Side Pressure Comparison (OSU-CE-0011)



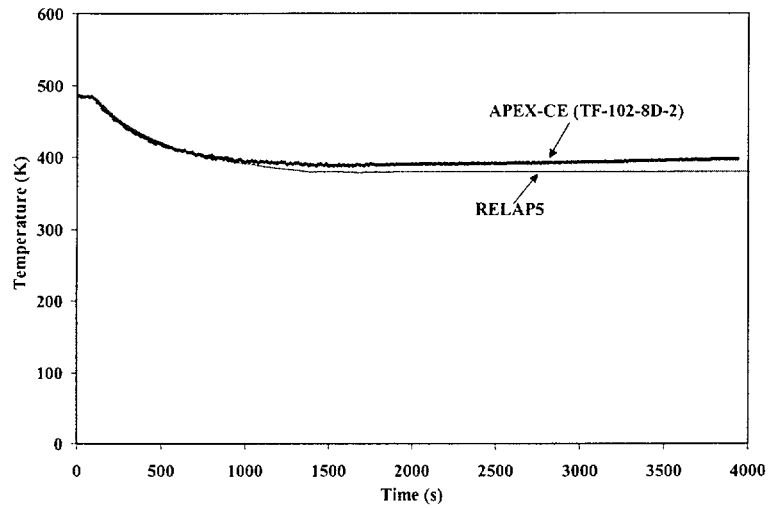
Pressurizer Liquid Level (OSU-CE-0011)



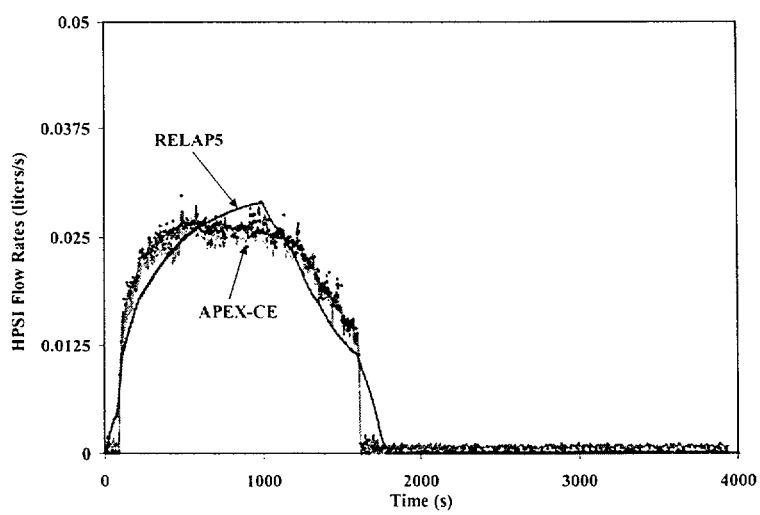
Downcomer Fluid Temperature at 8D Location Under Cold Leg #1 (OSU-CE-0011)



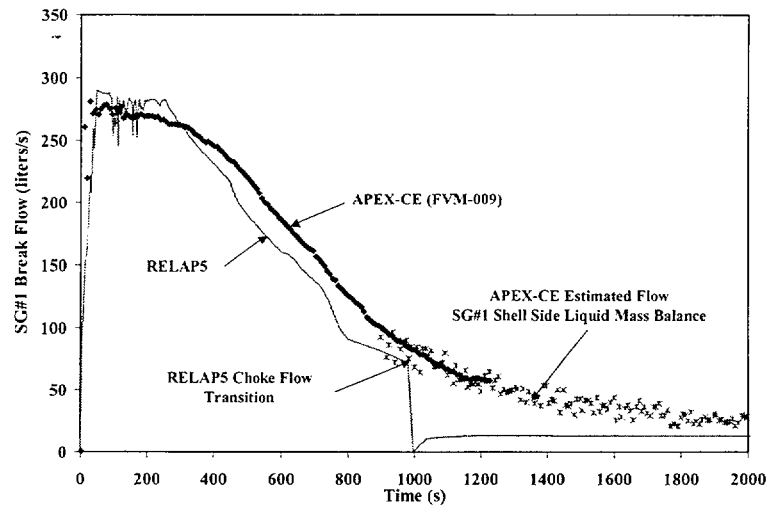
Downcomer Fluid Temperature at 8D Location Under Cold Leg #2 (OSU-CE-0011)



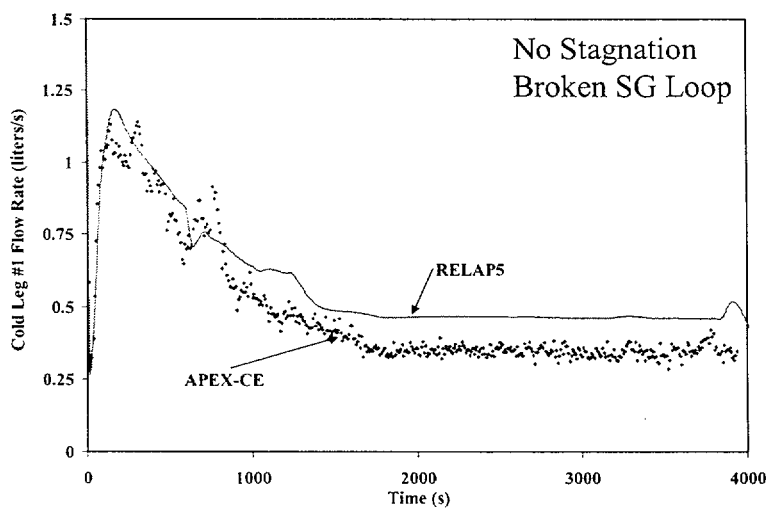
HPSI Flow Rate Comparison (OSU-CE-0011)



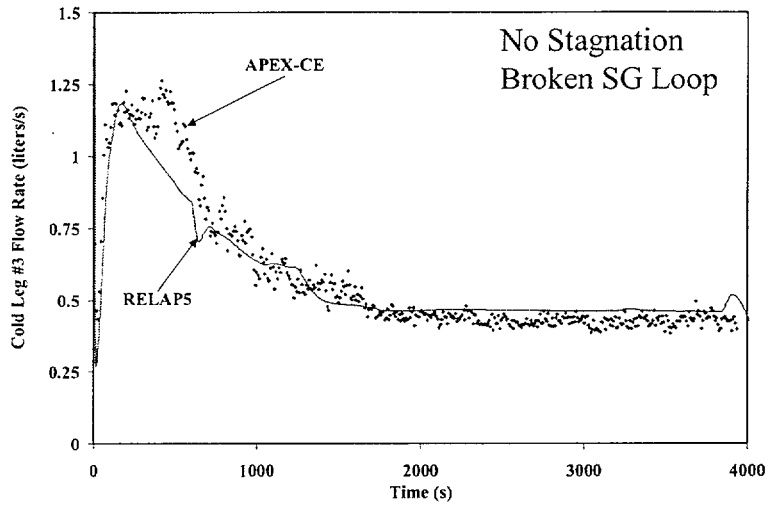
SG#1 Break Flow Rate Comparison (OSU-CE-0011)



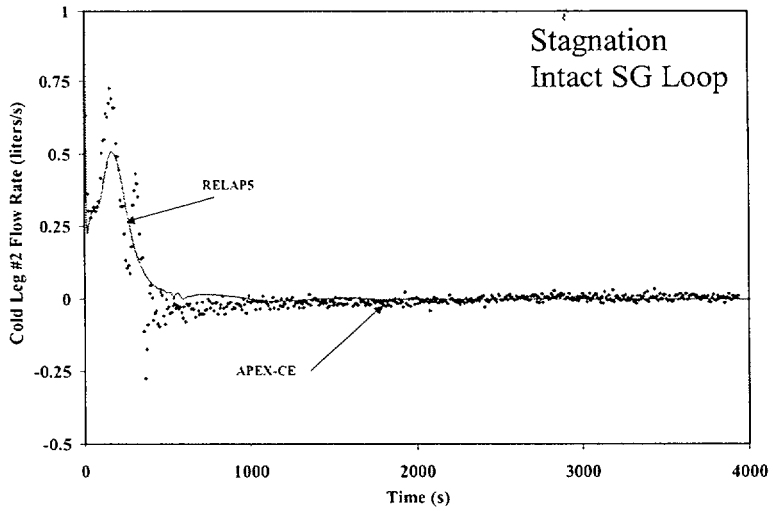
Cold Leg #1 Flow Rate (OSU-CE-0011)



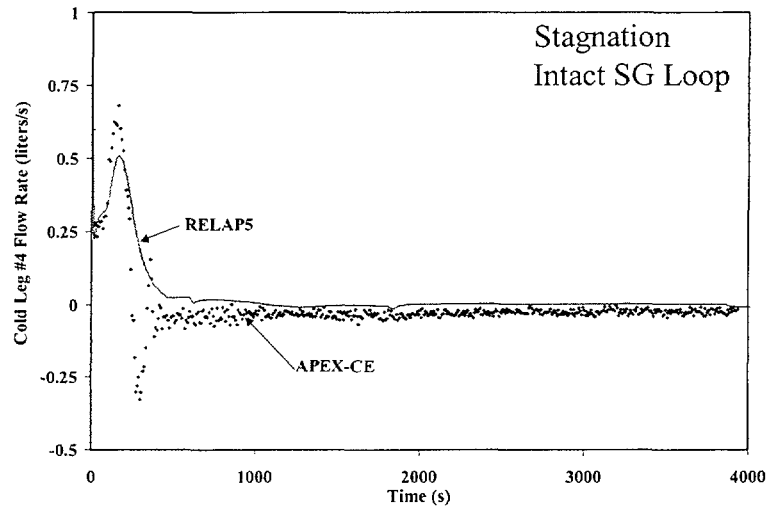
Cold Leg #3 Flow Rate (OSU-CE-0011)



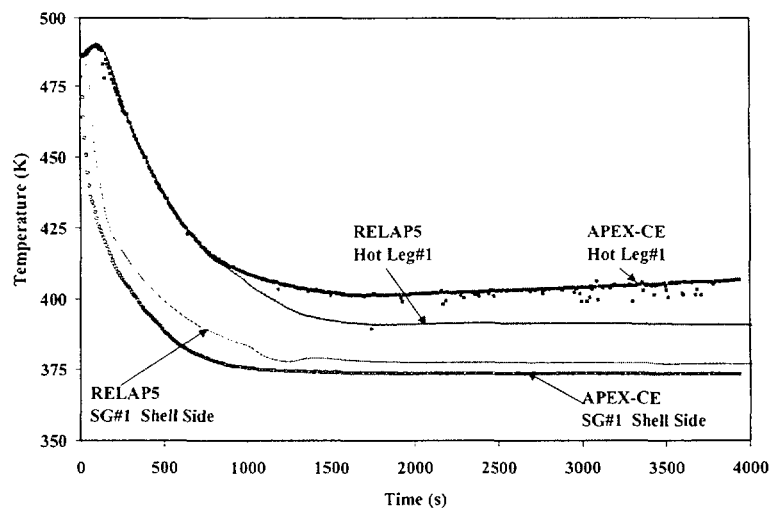
Cold Leg #2 Flow Rate (OSU-CE-0011)



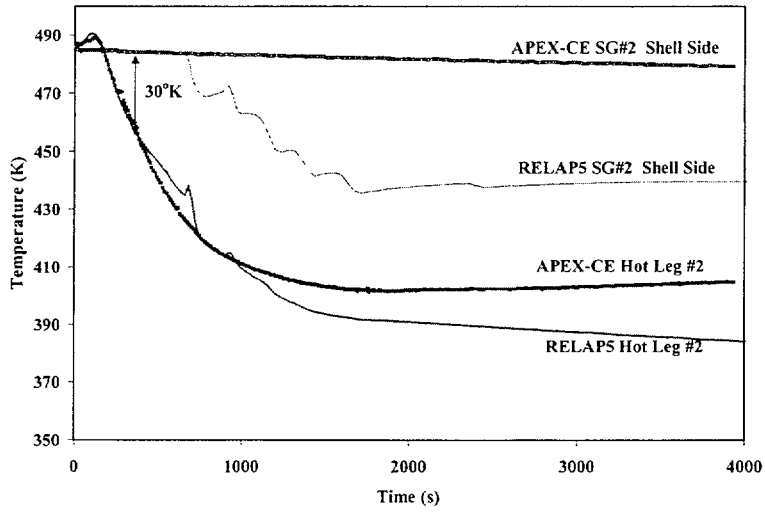
Cold Leg #4 Flow Rate (OSU-CE-0011)



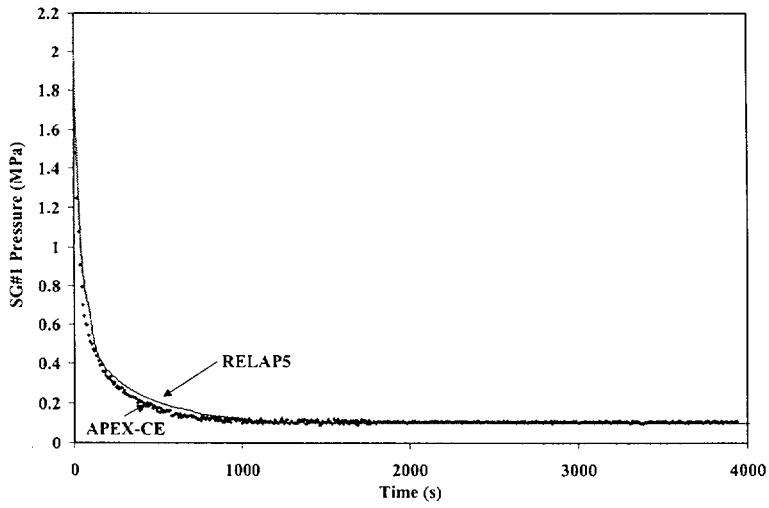
SG#1 Shell Side and Tube Side Fluid Temperature Comparisons (OSU-CE-0011)



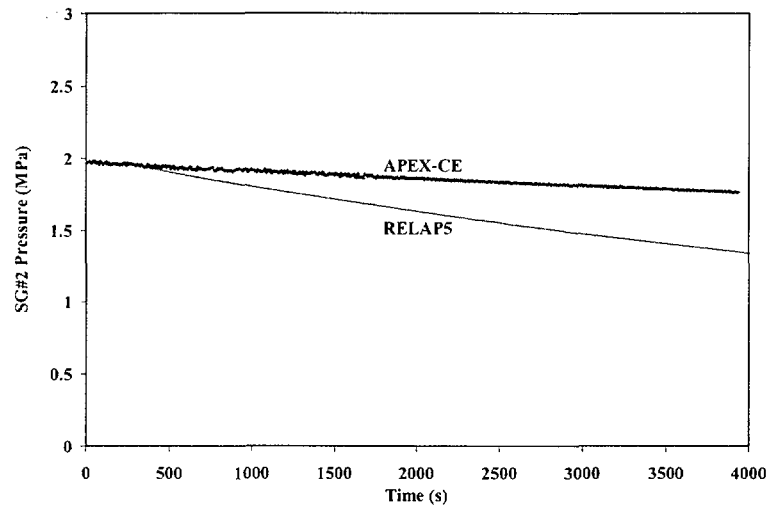
SG#2 Shell Side and Tube Side Fluid Temperature Comparisons (OSU-CE-0011)



SG#1 Broken Steam Generator Shell Side Pressure Comparisons (OSU-CE-0011)



SG#2 Intact Steam Generator
Shell Side Pressure Comparisons (OSU-CE-0011)



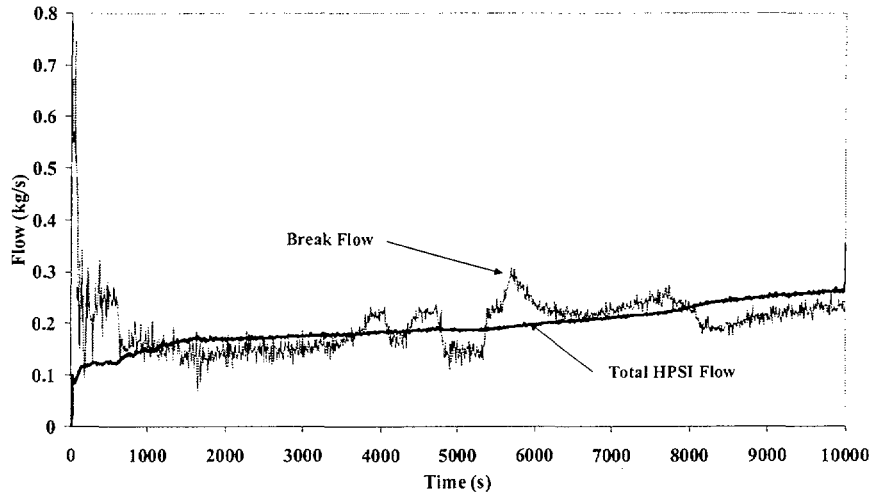
Sensitivity to Transport Rate Model Uncertainties

- **There exists a class of transients that exhibit a significant departure in plant behavior when a critical set-point is exceeded.**
- **For example:**
  - **A minimum core mass below which a fuel temperature excursion must occur.**
  - **A maximum primary system liquid volume above which the HPSI pumps will rapidly pressurize the system.**
- **Code predictions of the outcome of these transients must be considered "indeterminate" when the sum of the uncertainties in the transport rate models are on the same order as the net difference among the transport rates.**

OREGON STATE UNIVERSITY
Open minds. Open doors.

Small Differences Between HPSI Flow and Break Flow can Lead to a Large Departure in Plant Behavior

(2-inch Hot Leg Break, OSU-CE-0008)



Sensitivity to Transport Rate Model Uncertainties

Integrated Mass Balance in Code:

$$M(t) = M_o + \int (w_{in} \pm n\sigma_{in})dt - \int (w_{out} \pm n\sigma_{out})dt$$

Where:

- **w is an inlet or exit mass flow rate (kg/s)**
- **$n\sigma$ is the mass flow rate model uncertainty (kg/s)**
- **M_0 is the initial system mass (kg)**

Simple Illustration:

- **Assume $n\sigma$ is very small relative to its respective mass flow rate.**

OREGON STATE UNIVERSITY
Open minds. Open doors.

Sensitivity to Transport Rate Model Uncertainties

Rewrite:

$$M(t) = M_o + \int (w_{in} - w_{out})\, dt \pm \int n\sigma_{in}\, dt \pm \int n\sigma_{out}\, dt$$

- **The model uncertainties significantly impact the mass predictions when $(w_{in} - w_{out})$ is on the order of $\pm (n\sigma_{in} + n\sigma_{out})$.**
- **An accurate estimate of when, <u>or if</u>, the system becomes liquid filled and re-pressurizes is strongly influenced by the magnitudes of the time dependent model uncertainties.**
- **Important to designers seeking to fine-tune their designs.**

OREGON STATE UNIVERSITY
Open minds. Open doors.

RELAP5 Conclusions

- **The RELAP5/MOD 3.2.2 (gamma) code was used to predict thermal hydraulic behavior of an APEX-CE MSLB from Hot Zero Power.**
- **The RELAP5 calculations of primary system pressure and downcomer fluid temperature were in excellent agreement with the measured data.**
  - **The maximum deviation in primary system pressure was 10.6% (0.25 MPa) for a short portion of the transient. Otherwise the difference was on the order of 1%.**
  - **The maximum deviation in the well-mixed downcomer fluid temperature was 4% (16°K).**
- **The RELAP5 predictions of HPSI flow rate, pressurizer collapsed liquid level, feedwater flow rate were all in excellent agreement with the measured data.**

OREGON STATE UNIVERSITY
Open minds. Open doors.

RELAP5 Conclusions

- The maximum break flow rate predicted by RELAP5 was 289.4 liters/s. This value was within 3% of the measured value of 281.3 liters/s and fell within the uncertainty of the vortex flow meter measurements.
- RELAP5 predicted that the break flow experiences a sharp drop at 980 seconds. This was a transition from choked to non-choked flow conditions.
- RELAP5 predicted stagnation in cold legs #2 and #4 as a result of steam generator #2 becoming a heat source. The time at which steam generator #2 became a heat source was accurately predicted by RELAP5.

OREGON STATE UNIVERSITY
Open minds. Open doors.

RELAP5 Conclusions

- The trends in the cold leg flow rates were very similar and the numerical values were in reasonable agreement with the measured values with the exception of the data for cold leg#1.
- Caution must be exercised when analyzing transients that involve small differences in the transport terms because model uncertainties become important.
  - The outcome of transients that exhibit a significant departure in plant behavior when a critical set-point is exceeded may be predicted incorrectly.

OREGON STATE UNIVERSITY
Open minds. Open doors.

3. STAR-CD Calculations

OREGON STATE UNIVERSITY
Open minds. Open doors.

STAR-CD Calculations

- STAR-CD was used to predict two stagnant loop cases (OSU-CE-0005 and OSU-CE-0006). The following Phenomena were observed:
  - HPSI Line Backflow
  - Cold Leg Thermal Stratification
  - Cold Leg Counter-Current Flow
  - Downcomer Plumes Merging
- STAR-CD was also used to calculate a transient MSLB case (OSU-CE-0012).

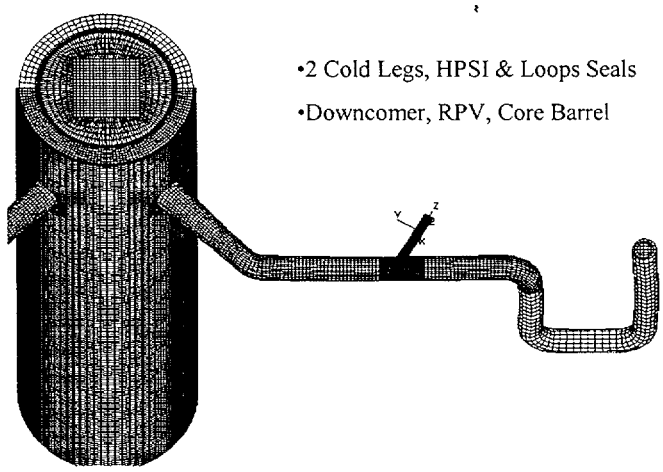
OREGON STATE UNIVERSITY
Open minds. Open doors.

Star-CD Model

- The model consists of 768,784 cells and 2,038,300 vertices that construct the fluid domain to be solved.
- The solution of the problem was completed in parallel on four SUN Fire 240R servers. Each machine has dual SUN Spark III 750 MHz 64 bit processors and 1 Gigabit of RAM.
- The problem was run for approximately 2200 seconds for OSU-CE-0005 with a constant time step of 0.1 seconds for both of the calculations, requiring approximately 33 days of real time.

OREGON STATE UNIVERSITY
Open minds. Open doors.

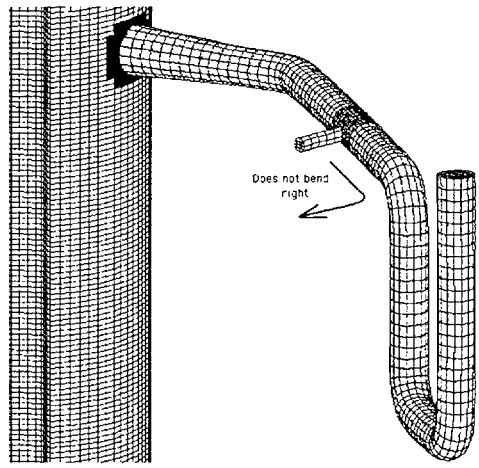
STAR-CD APEX-CE Model



- 2 Cold Legs, HPSI & Loops Seals
- Downcomer, RPV, Core Barrel

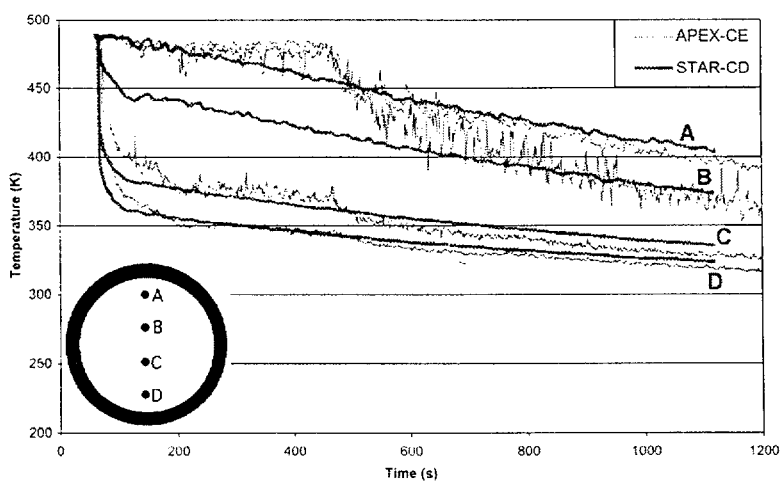
OREGON STATE UNIVERSITY
Open minds. Open doors.

STAR-CD APEX-CE Cold Leg and Loop Seal Bends

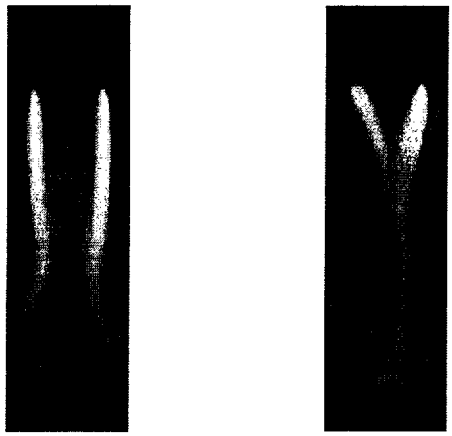


OREGON STATE UNIVERSITY
Open minds. Open doors.

Cold Leg Thermal Stratification (Stagnant Loop OSU-CE-0005)



STAR-CD Calculation Showing Plumes Merging



OREGON STATE UNIVERSITY
Open minds. Open doors.

Reactor Pressure Vessel Transient Convection and Conduction Heat Transfer

- **STAR-CD was used to solve the inverse conduction problem for a MSLB test using the following <u>Measured Boundary Conditions</u>:**
  - **RPV Outside Wall Heat Flux**
  - **Cold Leg Flows**
  - **Cold Leg Fluid Temperatures**
- **STAR-CD <u>Calculated</u> the:**
  - **Local convective heat transfer coefficient**
  - **RPV Inside surface temperature**
  - **Temperature profile inside the RPV wall**
  - **RPV Outside Wall Temperature**

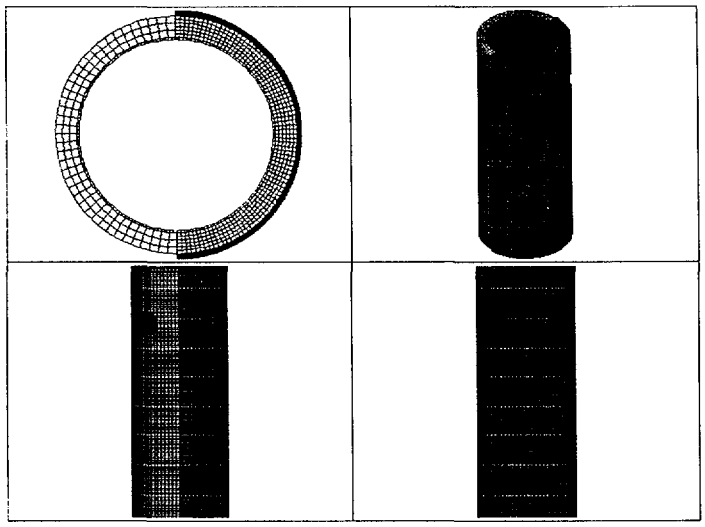
OREGON STATE UNIVERSITY
Open minds. Open doors.

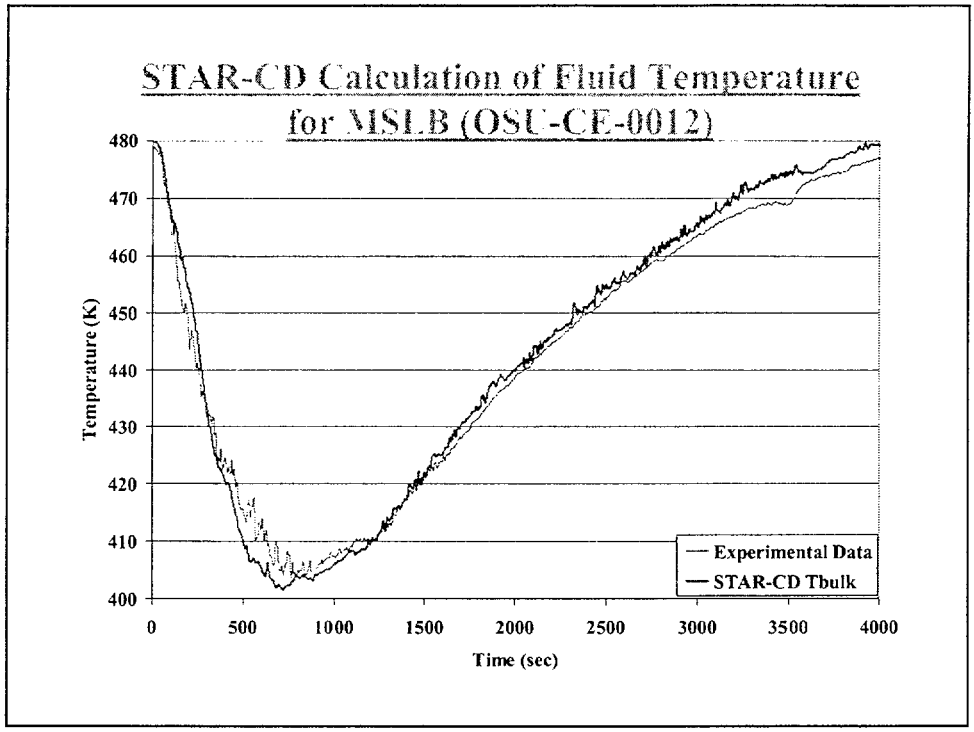
Simplified STAR-CD Model

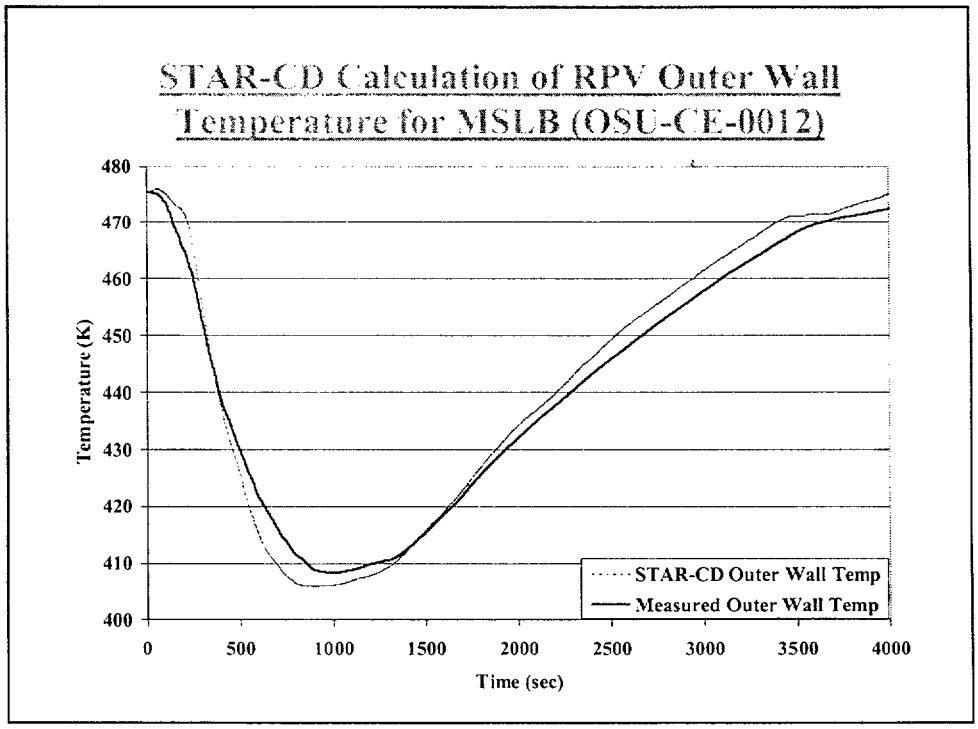
- The CFD model is comprised of 41,132 solid cells and 185,097 fluid cells with a total cell count of 226,229 cells.
- This simplified model incorporates the stainless steel vessel and the fluid within the downcomer.
- The calculation was performed using 0.25-second time and was run to obtain 4000 seconds of transient data.
- The full transient took about 20 days to complete on a dual 750 MHz processor Sun Blade 1000 computer.

OREGON STATE UNIVERSITY
Open minds. Open doors.

STAR-CD Model Used to Calculate RPV Wall Temperature Profile




STAR-CD Calculation of Fluid Temperature for MSLB (OSU-CE-0012)
Temperature (K)
480
470
460
450
440
430
420
410
400
0
500
1000
1500
2000
2500
3000
3500
4000
Time (sec)
Experimental Data
STAR-CD Tbulk


STAR-CD Calculation of RPV Outer Wall Temperature for MSLB (OSU-CE-0012)
Temperature (K)
480
470
460
450
440
430
420
410
400
0
500
1000
1500
2000
2500
3000
3500
4000
Time (sec)
STAR-CD Outer Wall Temp
Measured Outer Wall Temp

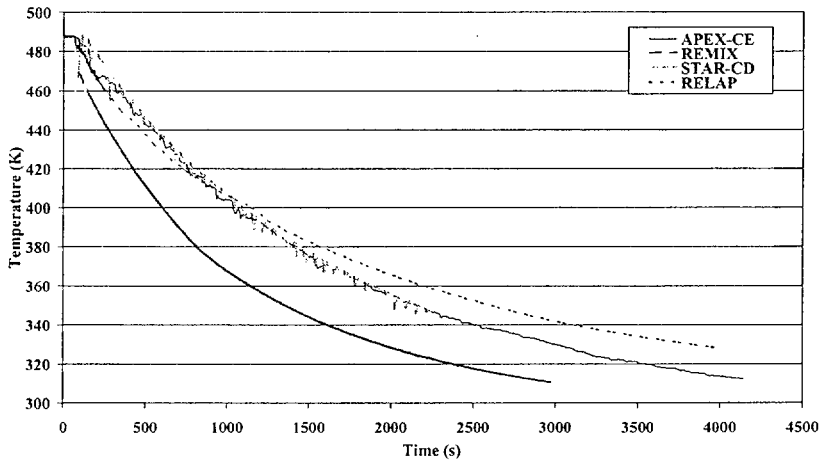
4. Comparison of RELAP5, STAR-CD and REMIX Calculations

OREGON STATE UNIVERSITY
Open minds. Open doors.

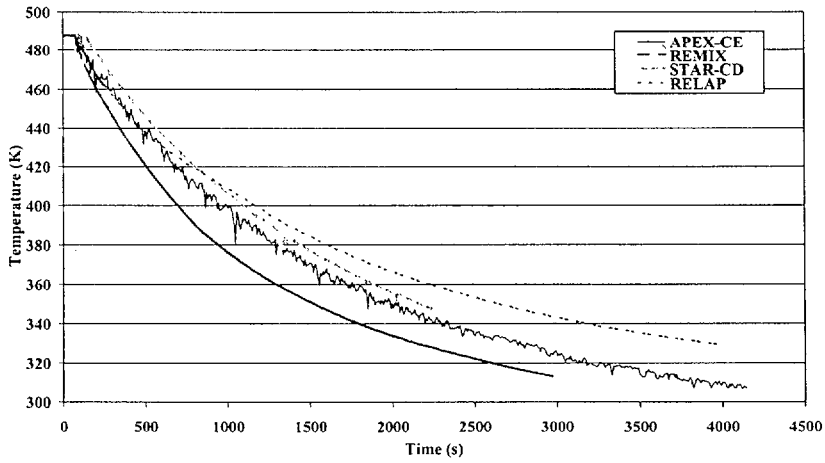
Overview of STAR-CD, REMIX and RELAP5

	STAR-CD	REMIX	RELAP5
Turbulence Models	5 Models	Simple Functions fitted to κ-ε-θ' Model	None
Conservation of Mass	3-D	Regional & System	1-D
Conservation of Momentum	3-D	Lock Exchange Model for Closure	1-D
Conservation of Energy	3-D	Regional & System	1-D
Geometries Modeled	Any	One Set of Reactor Components	Many, Pre-defined components
Boiling and Condensation	No	No	1-D
Heat of Structures	3-D	1-D	1-D
Variable Boundary Conditions	Yes	HPSI Flow Rate	Yes
Computation Expense	Significant	Negligible	Little

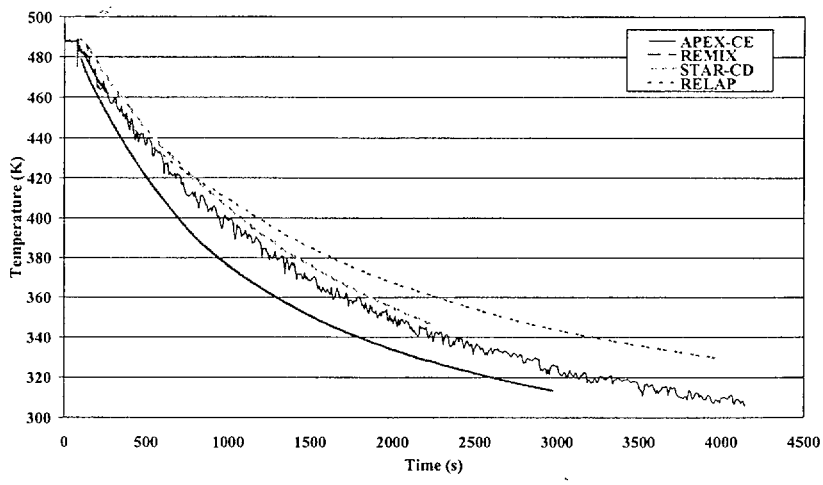
Downcomer Fluid Temperature at 1.3D (Stagnant Loop OSU-CE-0005)



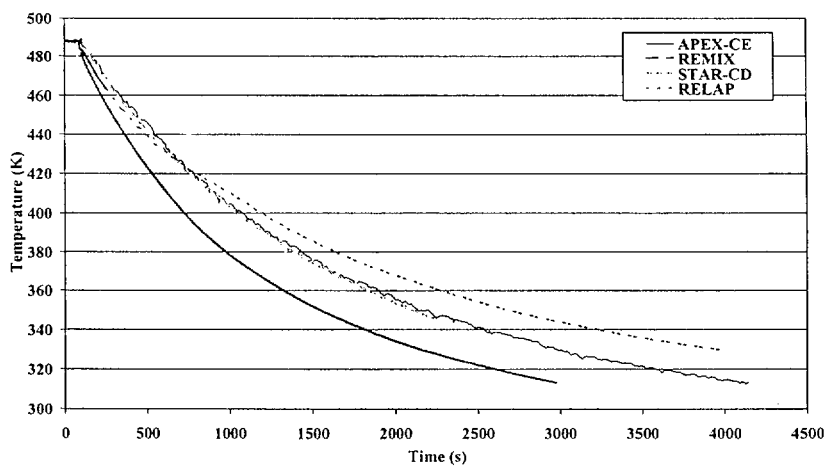
Downcomer Fluid Temperature at 2.0D (Stagnant Loop OSU-CE-0005)



Downcomer Fluid Temperature at 4.0D (Stagnant Loop OSU-CE-0005)



Downcomer Fluid Temperature at 8.0D (Stagnant Loop OSU-CE-0005)



OSU-CE-0005 Downcomer Cold Stream Temperature Change Comparisons

Comparison	200 Seconds			600 Seconds			900 Seconds		
Position	APEX-CE	STAR-CD	% Diff	APEX-CE	STAR-CD	% Diff	APEX-CE	STAR-CD	% Diff
1.3 D	179.6	165.7	7.7	150.1	152.5	1.6	124.7	130.7	4.7
2.0 D	172.0	165.7	3.6	141.4	153.6	8.6	116.0	124.6	7.4
4.0 D	178.4	165.8	7.1	142.9	152.1	6.4	117.1	130.5	11.5
8.0 D	189.9	163.7	13.8	149.4	151.8	1.6	124.7	128.7	3.2

Comparison	200 Seconds			600 Seconds			900 Seconds		
Position	APEX-CE	REMIX	% Diff	APEX-CE	REMIX	% Diff	APEX-CE	REMIX	% Diff
1.3 D	179.6	164.9	8.2	150.1	114.4	23.8	124.7	87.9	29.5
2.0 D	172.0	174.6	1.5	141.4	123.7	12.5	116.0	96.8	16.6
4.0 D	178.4	177.3	0.6	142.9	126.3	11.6	117.1	99.3	15.2
8.0 D	189.9	180.5	5.0	149.4	129.6	13.2	124.7	102.5	17.8

Comparison	200 Seconds			600 Seconds			900 Seconds		
Position	APEX-CE	RELAP	% Diff	APEX-CE	RELAP	% Diff	APEX-CE	RELAP	% Diff
1.3 D	179.6	181.0	0.8	150.1	143.1	4.7	124.7	125.1	0.3
2.0 D	172.0	181.5	5.5	141.4	144.7	2.3	116.0	128.4	10.7
4.0 D	178.4	182.7	2.4	142.9	145.4	1.7	117.1	128.6	9.8
8.0 D	189.9	183.3	3.5	149.4	145.8	2.4	124.7	129.4	3.7

5. Revised PTS T/H Assessment Methodology

OREGON STATE UNIVERSITY
Open minds. Open doors.

Improved PTS T/H Assessment Methodology

PWR Integral System Code Calculation of Overcooling Transient (RELAP5 or TRAC)

- Cold Leg and HPSI Flow Rates
- Cold Leg and HPSI Fluid Temperatures
- Primary System Pressure

↓

CFD Code Model

Using Integral System Boundary Conditions, a CFD Subsystem Model is used to predict:

- HPSI Backflow Rate
- Cold Leg Fluid Temperature Gradients
- Loop Seal Spillover
- Downcomer Plume Interactions
- RPV Heat Transfer

↓

Fracture Mechanics Calculations

- Perform Fracture Mechanics Analyses using Appropriate T/H information.

OREGON STATE UNIVERSITY
Open minds. Open doors.

Conclusions

- RELAP5 3.2.2 γ predictions have been compared to six APEX-CE transients.
  - Predictions are in good agreement with the measured well-mixed downcomer fluid temperatures, the stagnation mechanisms, and the system pressure.
- REMIX tended to conservatively under-estimate the downcomer fluid temperatures.

OREGON STATE UNIVERSITY
Open minds. Open doors.

Conclusions

- There exists a class of transients that exhibit a significant departure in plant behavior when a critical set-point is exceeded.
- Code predictions of the outcome of these transients must be considered "indeterminate" when the sum of the uncertainties in the transport rate models are on the same order as the net difference among the transport rates.

OREGON STATE UNIVERSITY
Open minds. Open doors.

Conclusions

- STAR-CD predictions have been compared to two loop stagnation tests and one transient test in APEX-CE.
  - STAR-CD predicted all of the HPSI, Cold and Downcomer fluid mixing phenomena observed in the tests.
    - HPSI Line Backflow
    - Cold Leg Fluid Thermal Stratification
    - Downcomer plumes merging
  - Predictions are in good agreement with the measured cold leg fluid temperatures and downcomer plume temperatures.

OREGON STATE UNIVERSITY
Open minds. Open doors.

Conclusions

- **CFD codes offer a significant improvement to the existing PTS Thermal Hydraulic Assessment Methodology**

OREGON STATE UNIVERSITY
Open minds. Open doors.