Mechanisms for Primary Loop Stagnation

Jose N. Reyes, Jr.

Kent Welter

Presentation To

Advisory Committee On Reactor Safeguards

Thermal Hydraulic Phenomena Subcommittee Meeting

July 17-18, 2001

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Outline

- Introduction
- Loop Stagnation Mechanisms
  - OSU-CE-0002 Inventory Reduction Test
  - Steam Generator Tube Voiding
  - Steam Generator Reverse Heat Transfer
  - Loop Seal Cooling
- Downcomer Driven Loop Flow
- Conclusions

Stepped Inventory Reduction Test

- OSU-CE-0002 was a stepped reduction in inventory test.
  - Constant core power of 275 kW
  - Break on RPV opened to remove primary fluid in stepped intervals.
  - Break closed and cold leg flow rates measured at each step.
- Similar to tests performed at Semiscale.

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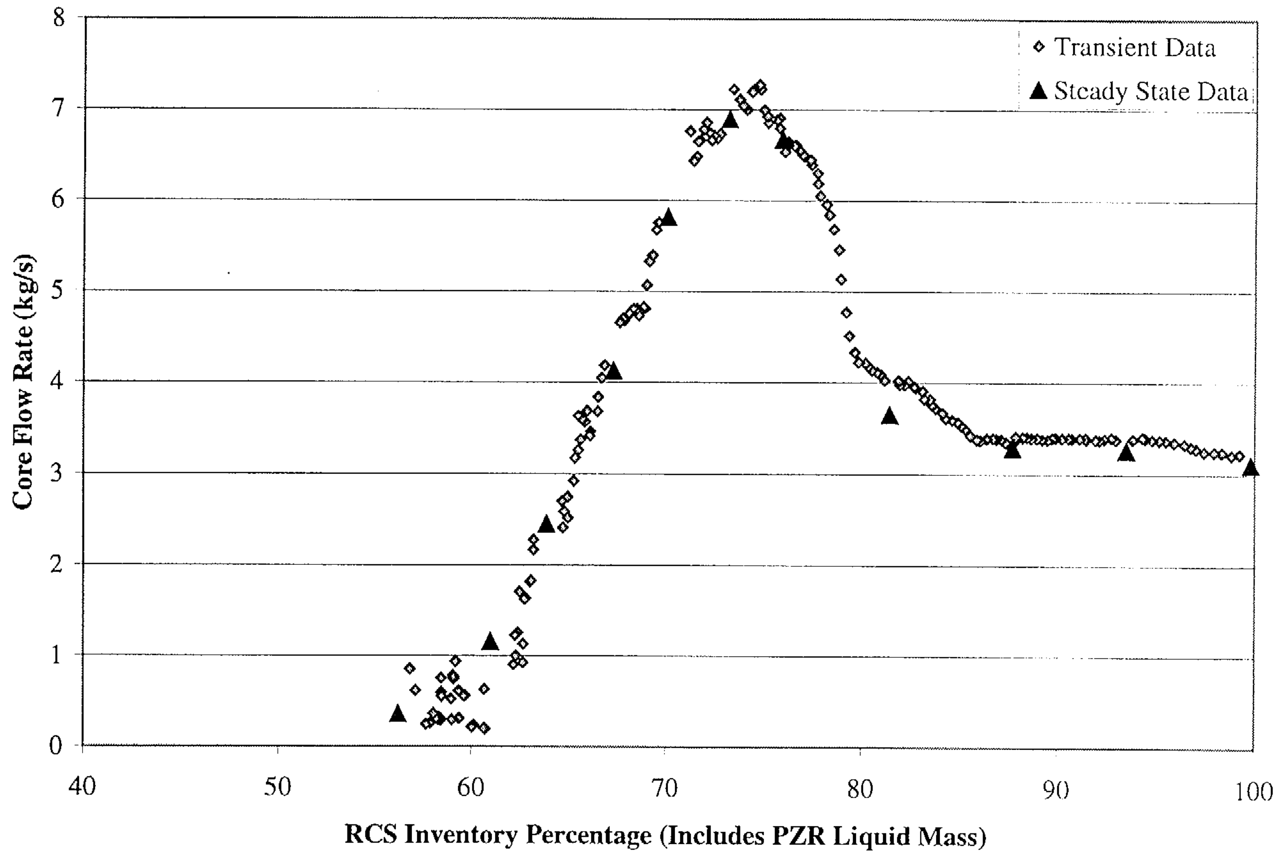
Core Flow Rates versus Percentage of Primary System Mass Inventory



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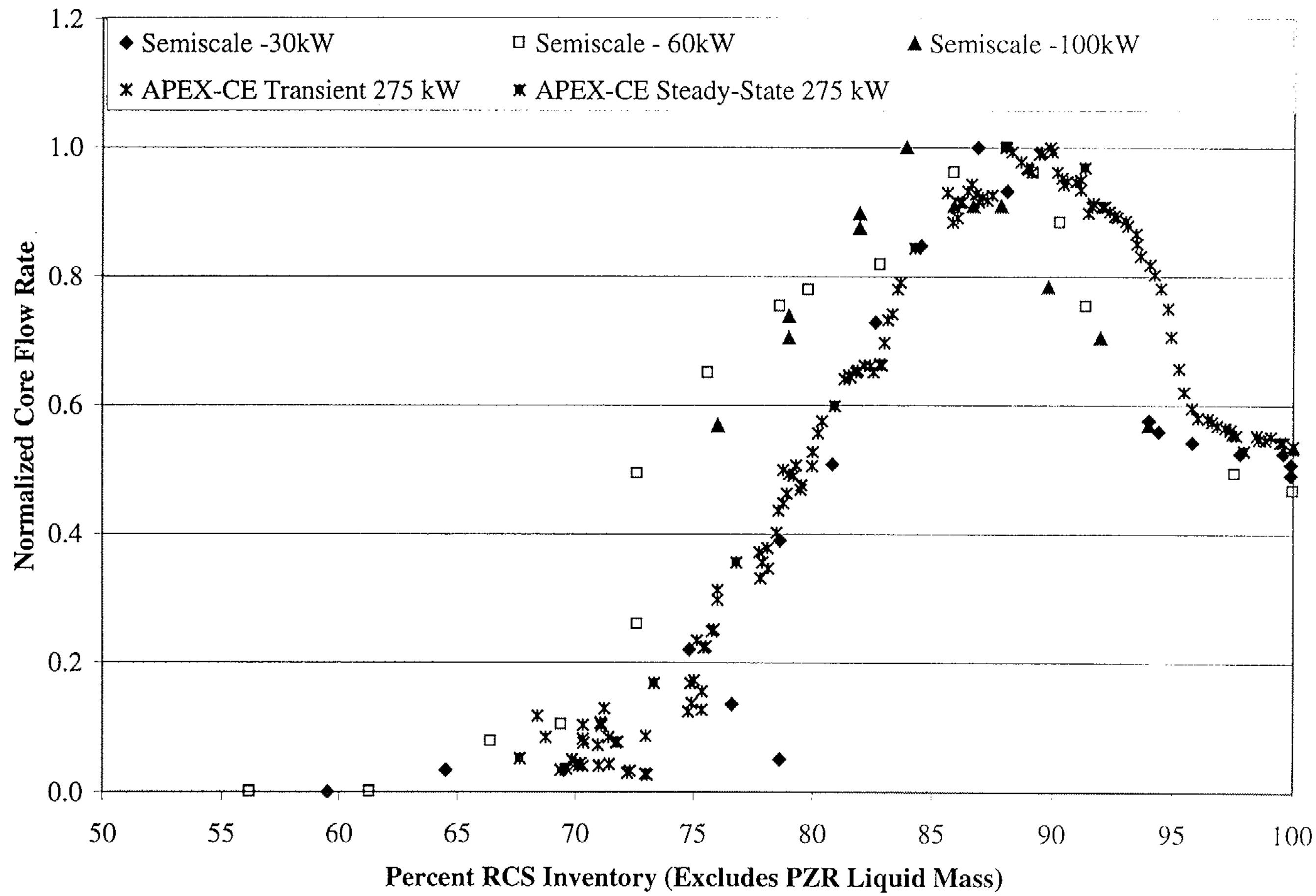
Comparison of OSU-CE-0002 and Semiscale Mod 2A Data



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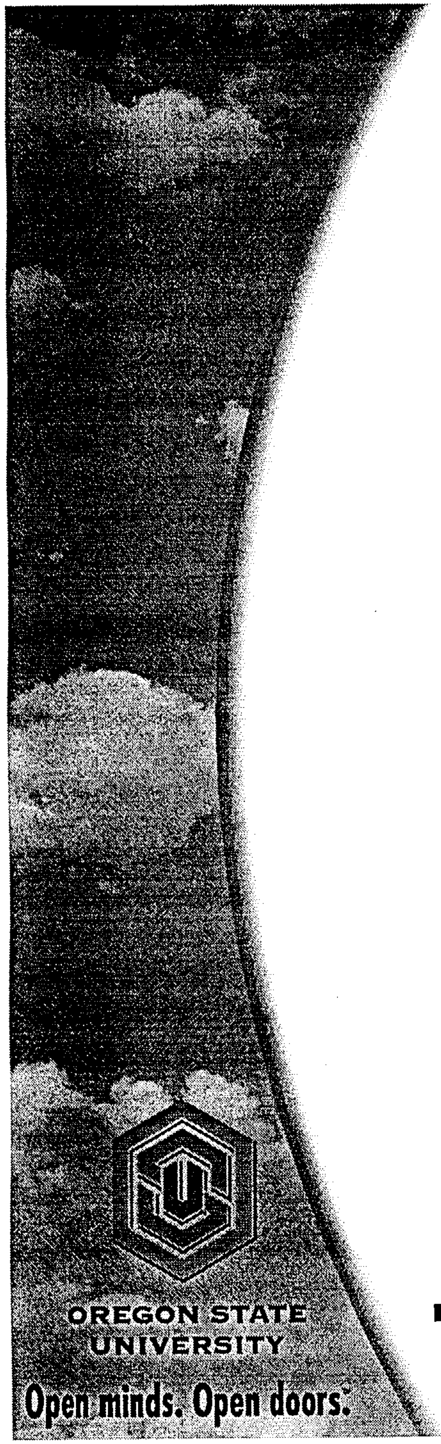
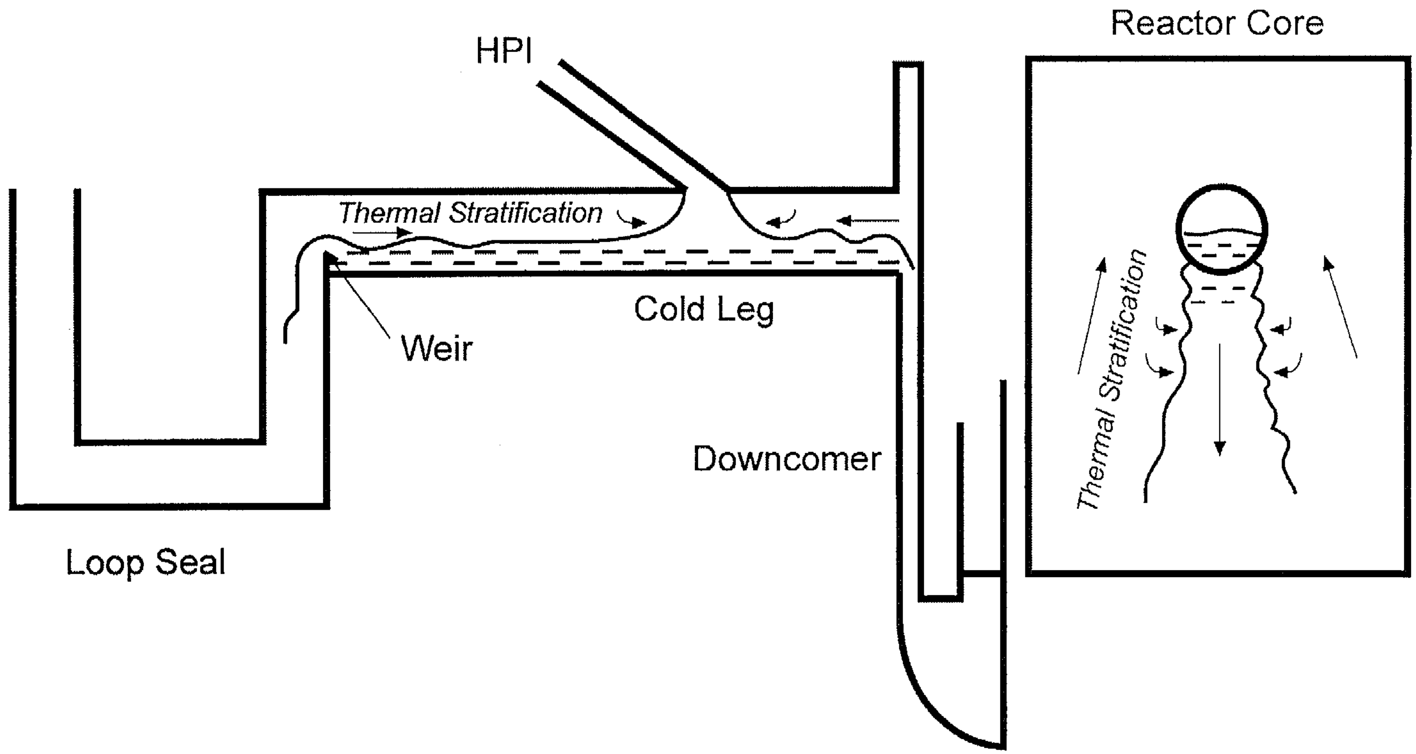


Stepped Inventory Reduction Test

- Test OSU-CE-0002 indicates that loop flow stagnation (Reflux Condensation) occurs when the primary side inventory drops below 60% of normal operating inventory.
- APEX-CE and Semiscale MOD2A trends are nearly identical.

Loop Stagnation Phenomena



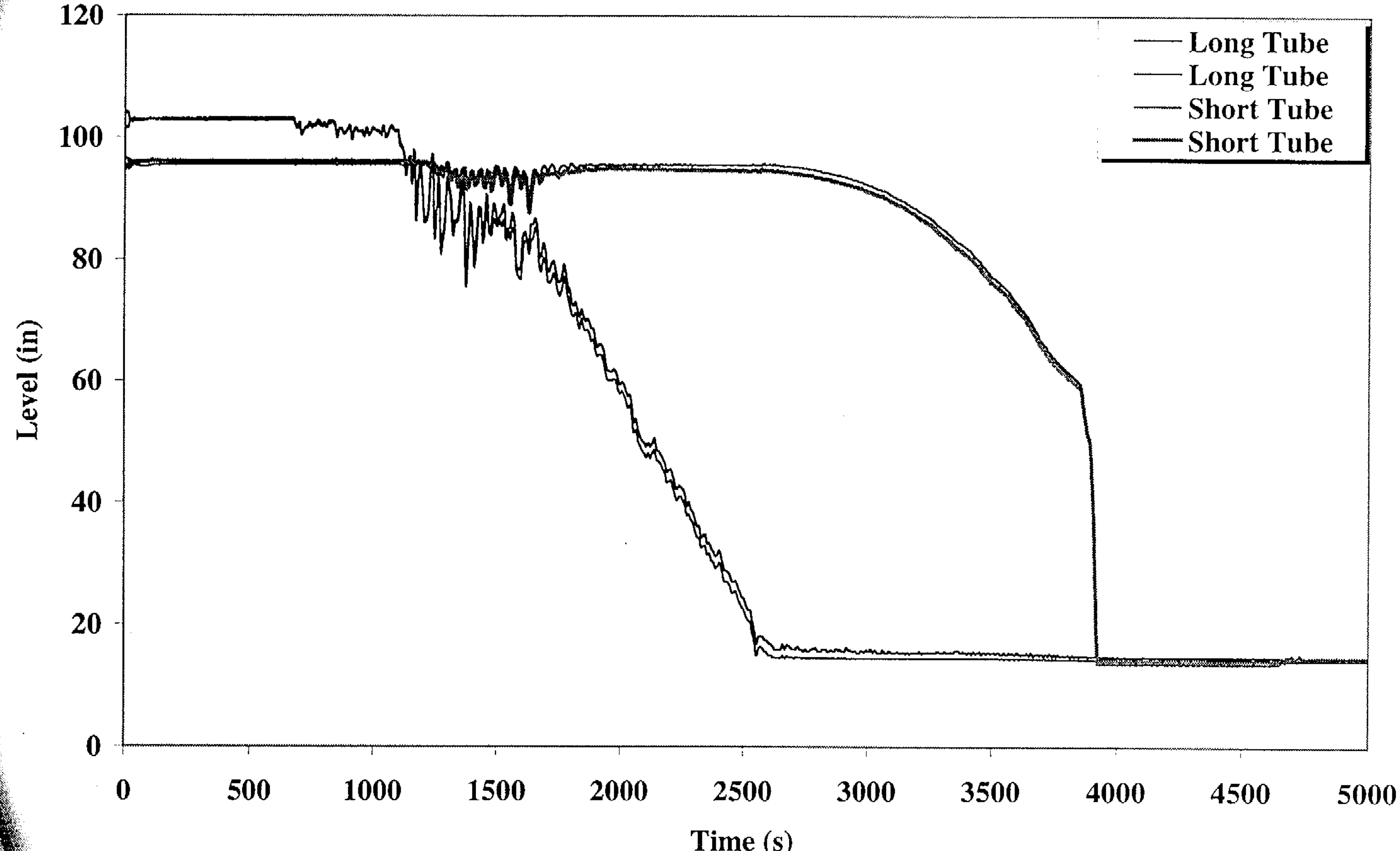
Loop Stagnation Test Summary

Test ID	Test Description	Stagnation Phenomena
OSU-CE-0007	1.4 " hot leg break from full power without charging	• CL 1, 2 and 3 stagnate due to presence of cold liquid plug in loop seals
OSU-CE-0008	2 " hot leg break from full power	• CL 1 and 2 stagnate due to steam generator voiding • CL 3 and 4 stagnate due to presence of cold liquid plug in loop seals
OSU-CE-0009	Stuck-open pressurizer SRV from full power	• CL 4 stagnates due to presence of cold liquid plug in loop seal
OSU-CE-0010	Stuck-open ADV and pressurizer SRV from full power	• CL 2 and 4 stagnate due to loss of SG 2 heat sink.
OSU-CE-0011	1 ft^2 main steam break inside containment from hot zero power with failure to isolate AFW	• CL 2 and 4 stagnate due to loss of SG 2 heat sink.
OSU-CE-0012	1 ft^2 main steam break inside containment from full power with failure to isolate AFW	• CL 1 and 3 stagnate due to loss of SG 1 heat sink.

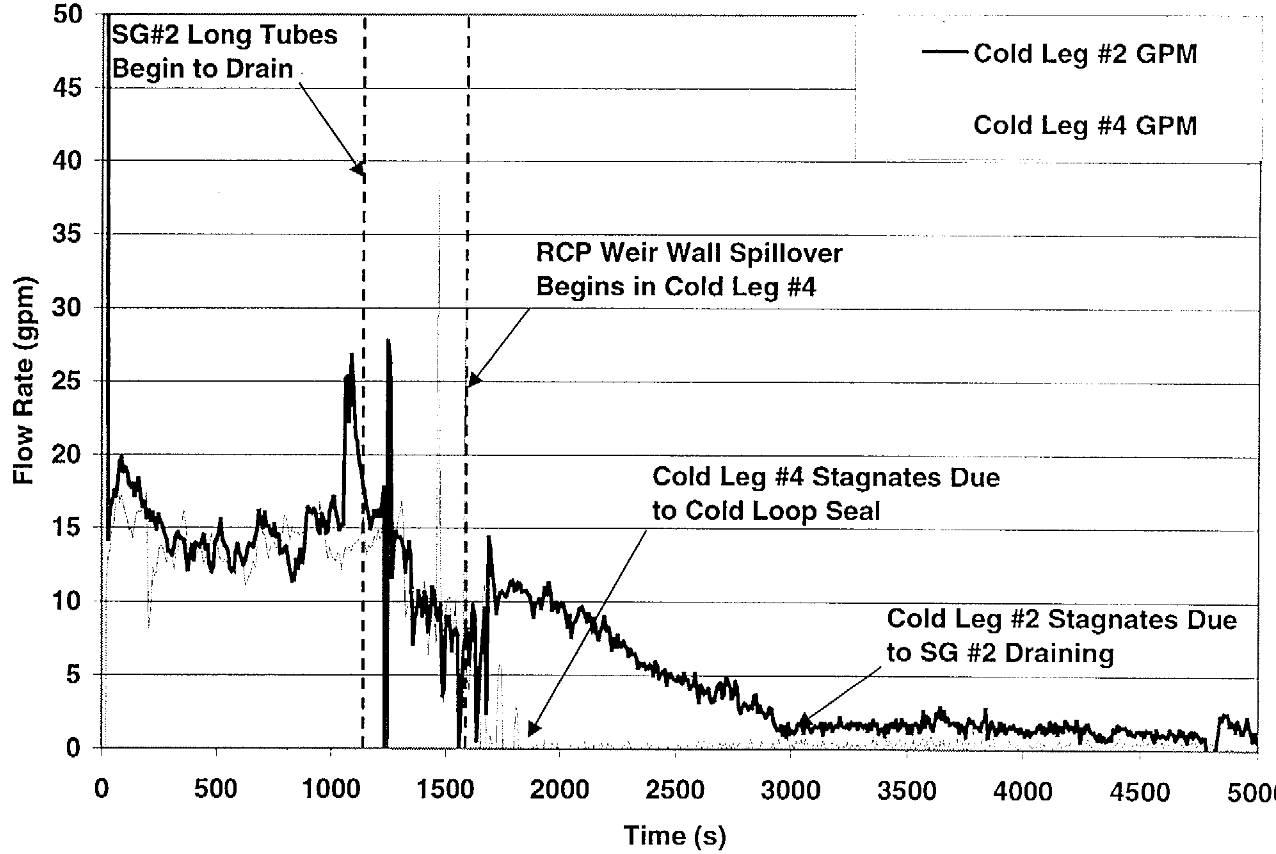
Steam Generator Tube Voiding and Loop Seal Cooling

- The 2-inch SBLOCA test experienced cold leg stagnation in all four cold legs.
  - Cold Legs #1 and #2 stagnate because of Steam Generator tube voiding.
  - Cold Legs #3 and #4 stagnate earlier because of loop seal cooling.

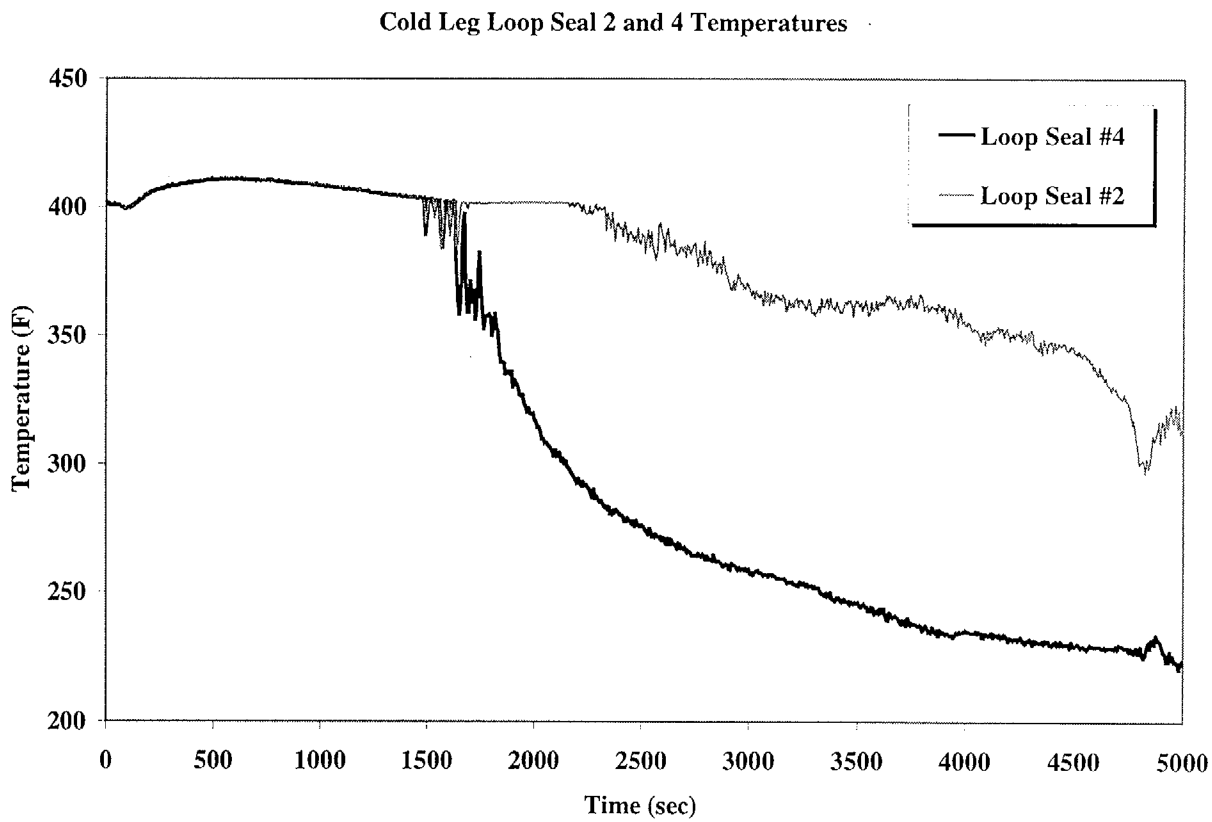
Steam Generator #2 Tube Voiding (OSU-CE-0008)



Loop Stagnation Due to SG Tube Voiding and Loop Seal Cooling



Loop Seal Cooling (OSU-CE-0008)



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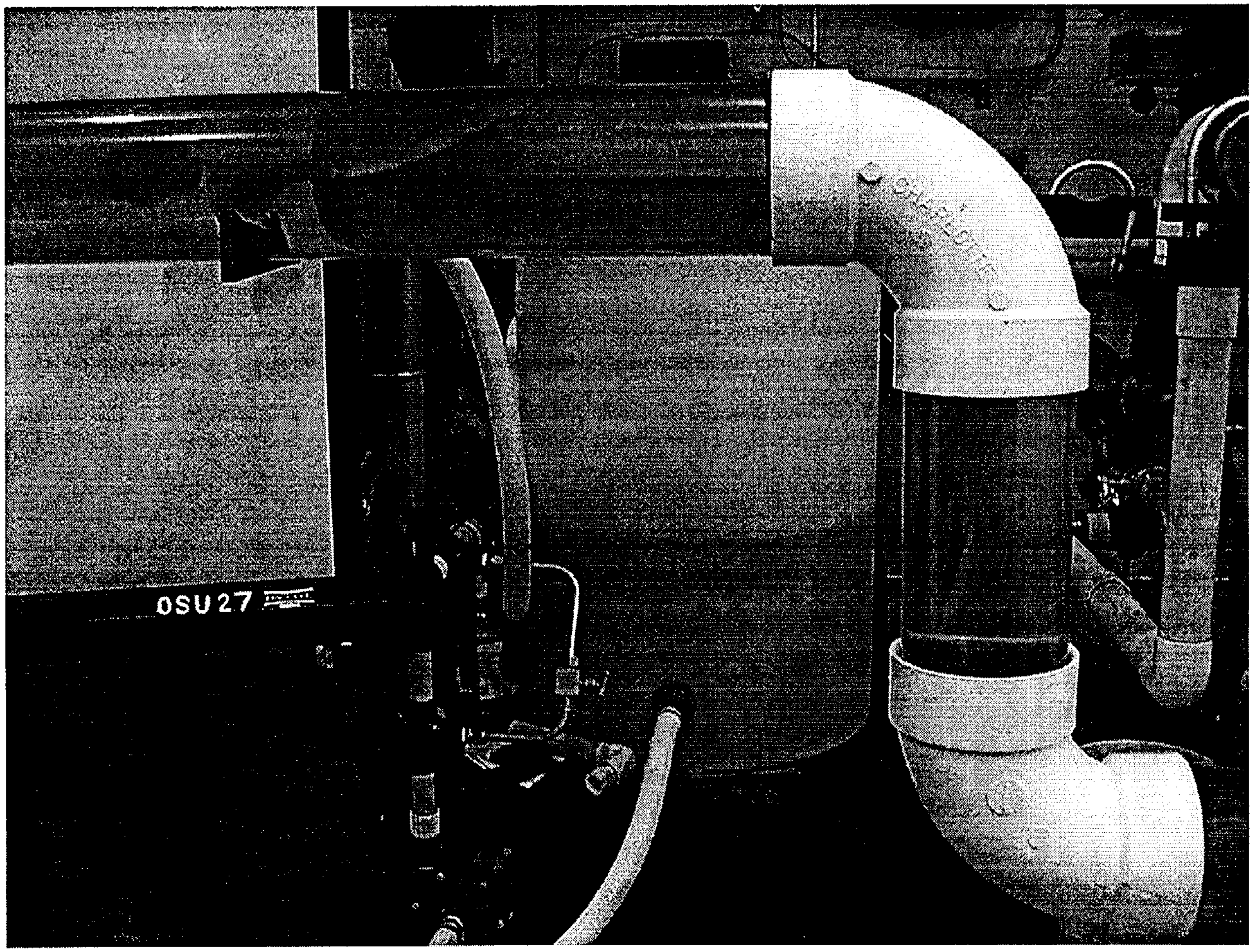
Stagnation Due to Loop Seal Cooling

- Cold water spill-over into the loop seal results in rapidly cooling down the loop seal volume.
- This creates a cold liquid "plug" with a gravity head that resists loop flow.
- The flow is preferentially diverted to the adjacent cold leg through the SG lower plenum.

Onset of Loop Seal Cooling



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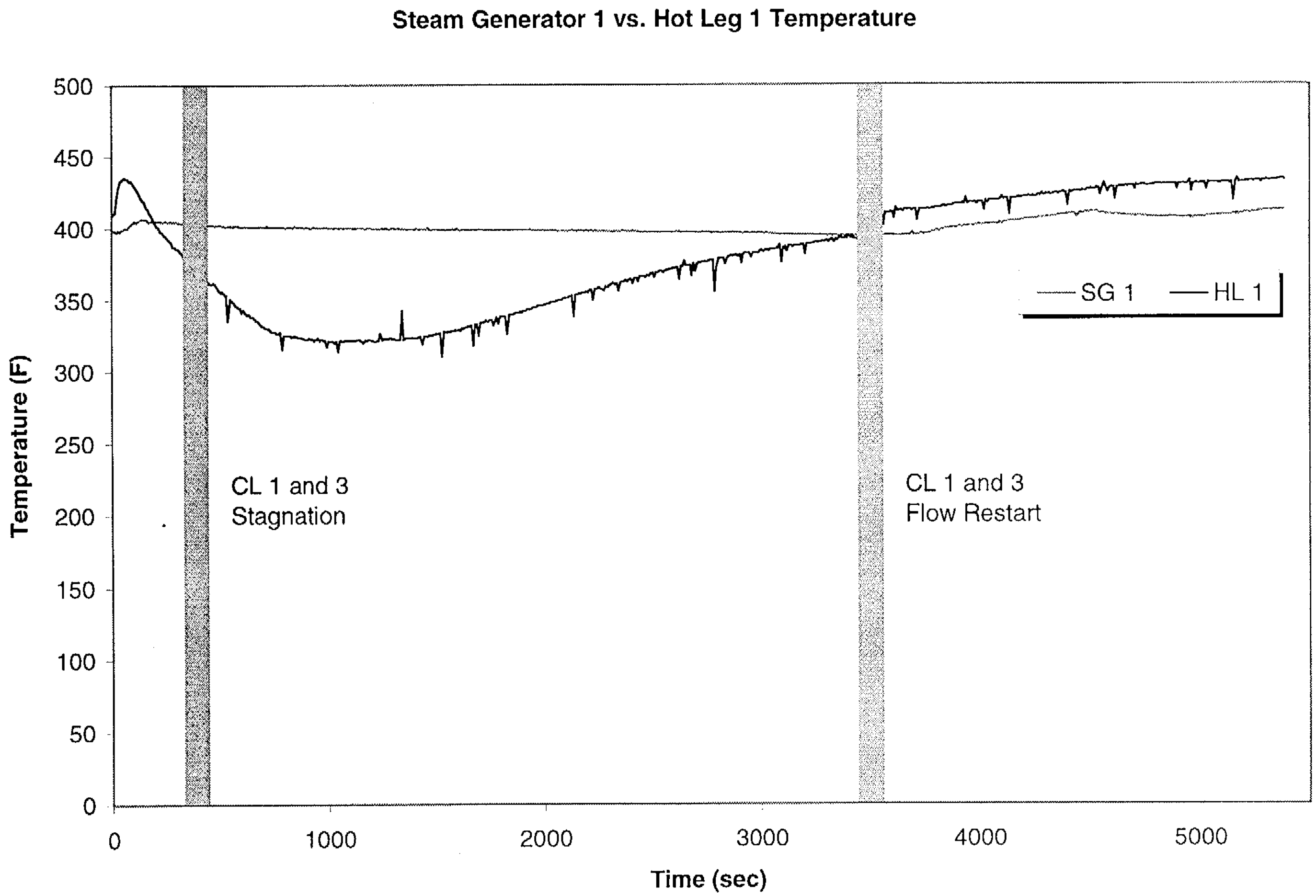
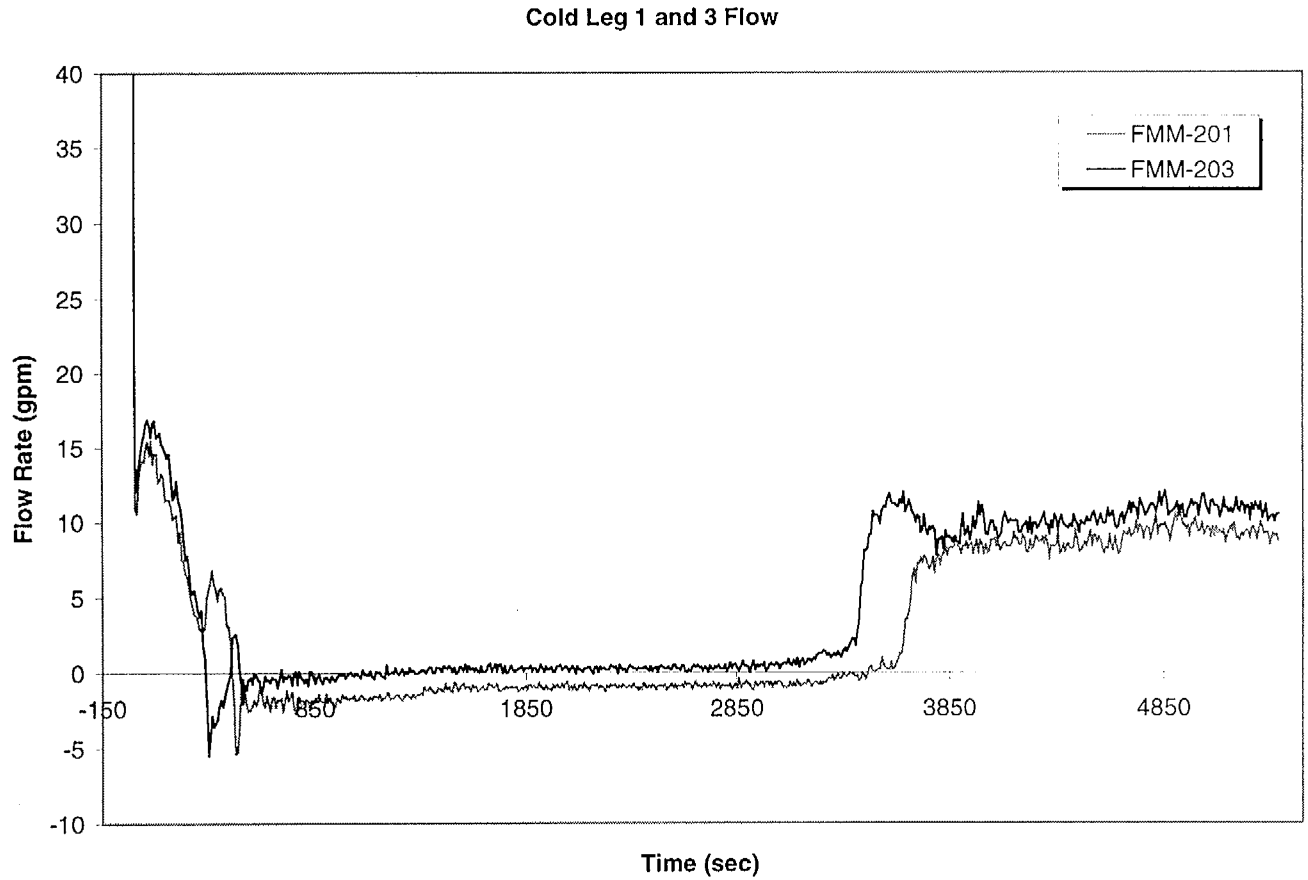
Steam Generator Reverse Heat Transfer (OSU-CE-0012)



Steam Generator Reverse Heat Transfer Cold Leg Stagnation



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Downcomer Driven Loop Flow

- It is noted that even in the presence of reverse heat transfer from the steam generators, positive loop natural circulation can occur because of HPSI injection into the downcomer.
- The buoyancy generated by the density difference between the cold downcomer fluid and the hot core fluid exceeds the resistance due to the SG acting as a heat source.
- The SG Reverse Heat Transfer can act as "brakes" that impede N/C loop flow.

Conclusions

- Three mechanisms for loop flow stagnation were observed in the APEX-CE tests.
  - Steam generator tube voiding
  - Loop Seal Cooling
  - Steam Generator Reverse Heat Transfer
- The presence of an RCP weir wall delays loop seal cooling and hence stagnation in the loops.
- SG Reverse Heat Transfer can reduce or stop primary loop N/C flow depending on the available downcomer fluid driving head.

Cold Leg Thermal Stratification and Plume Formation in APEX-CE

Jose N. Reyes, Jr.
Chris Linrud
Ian Davis

Presentation To
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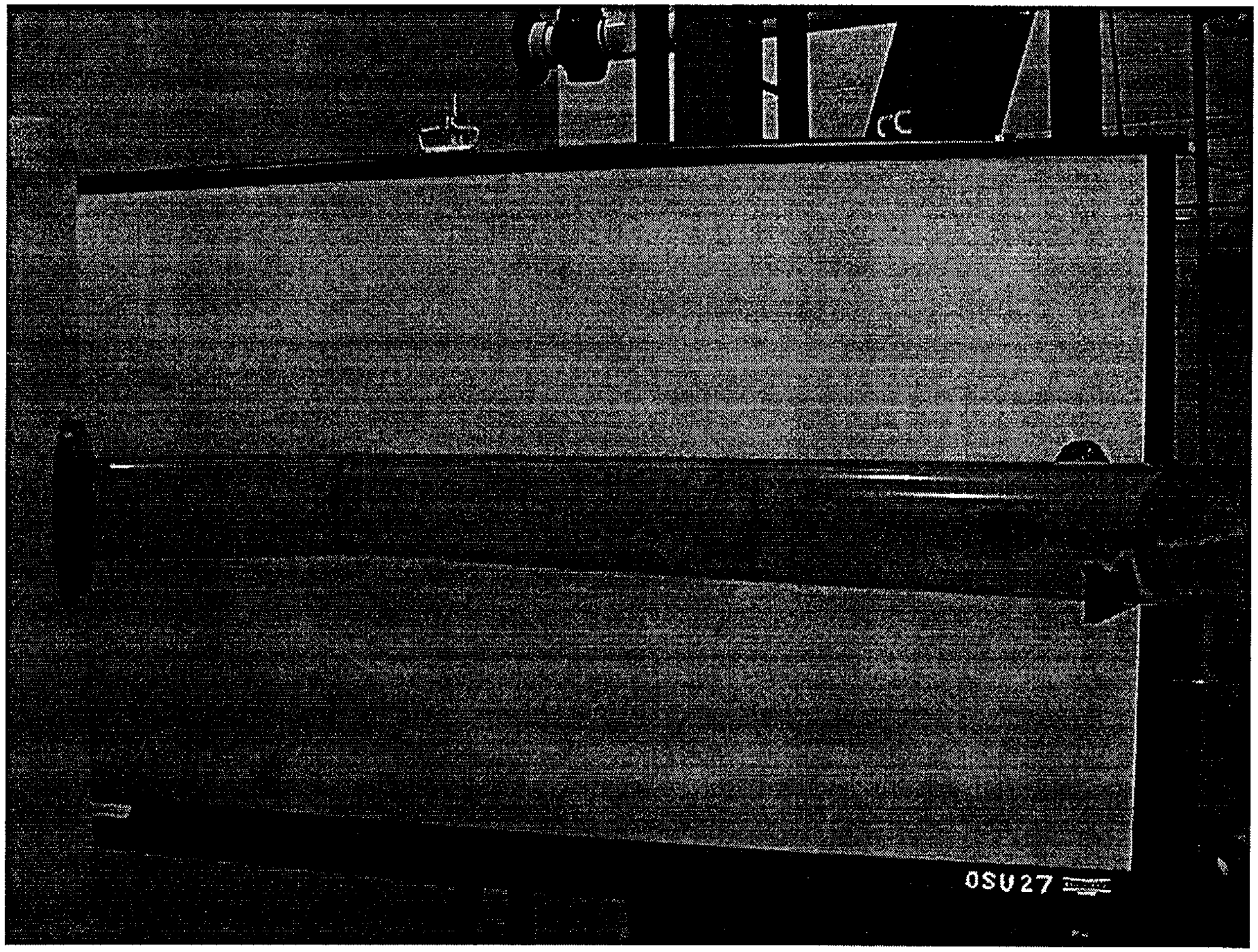
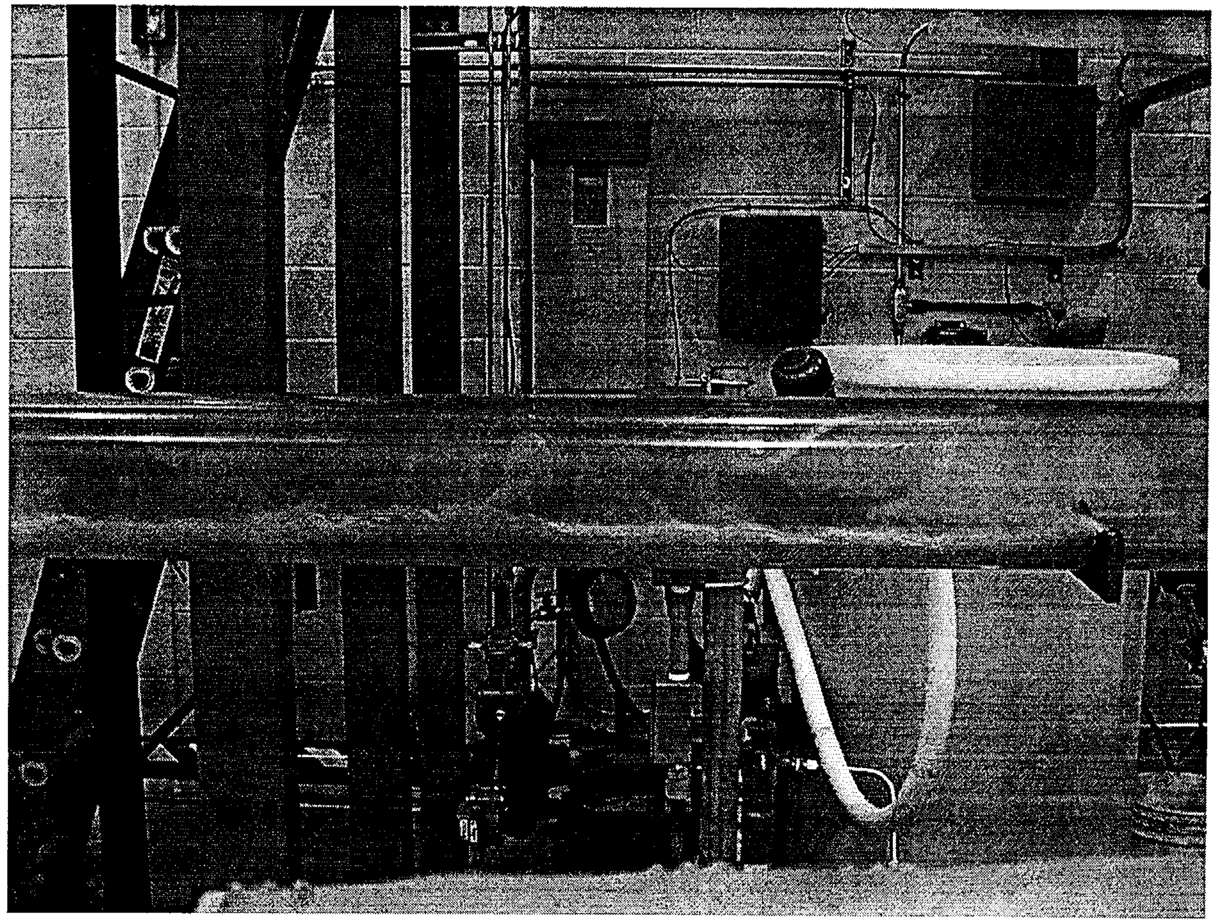
Outline

- **Introduction**
- **Cold Leg Thermal Stratification**
  - Flow Visualization
  - Effect of RCP Weir Wall
  - Onset of Weir Wall Spillover and Loop Seal Cooling
  - OSU-CE-0003 Test Results
- **Buoyant Plumes in the Downcomer**
  - Plumes in a Stagnant Downcomer
  - Plumes in a co-flow environment
  - Plume Interactions (Transient Temperature Map)
- **Conclusions**

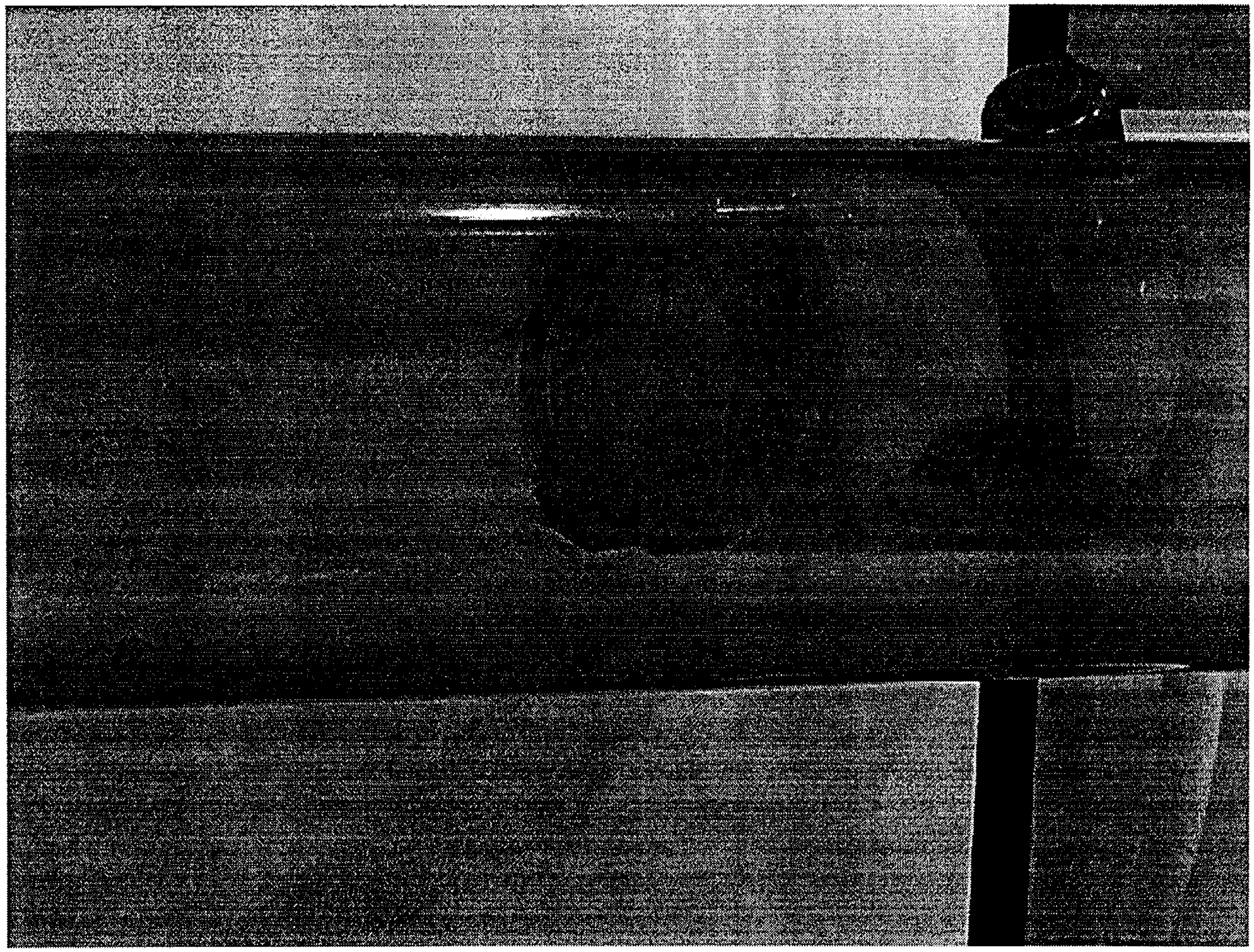
Cold Leg Thermal Stratification



Cold Leg Thermal Stratification



Side Entry HPSI



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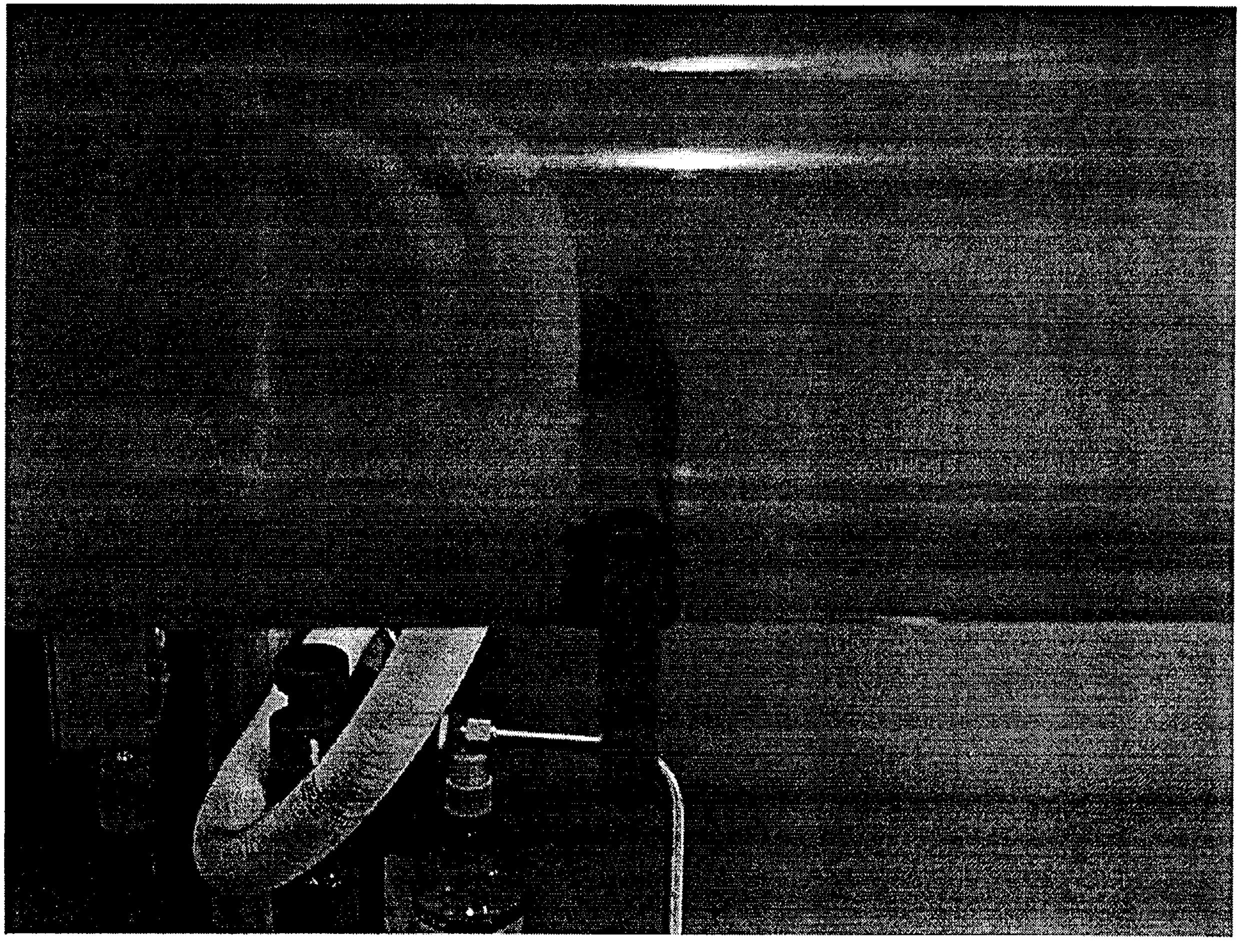
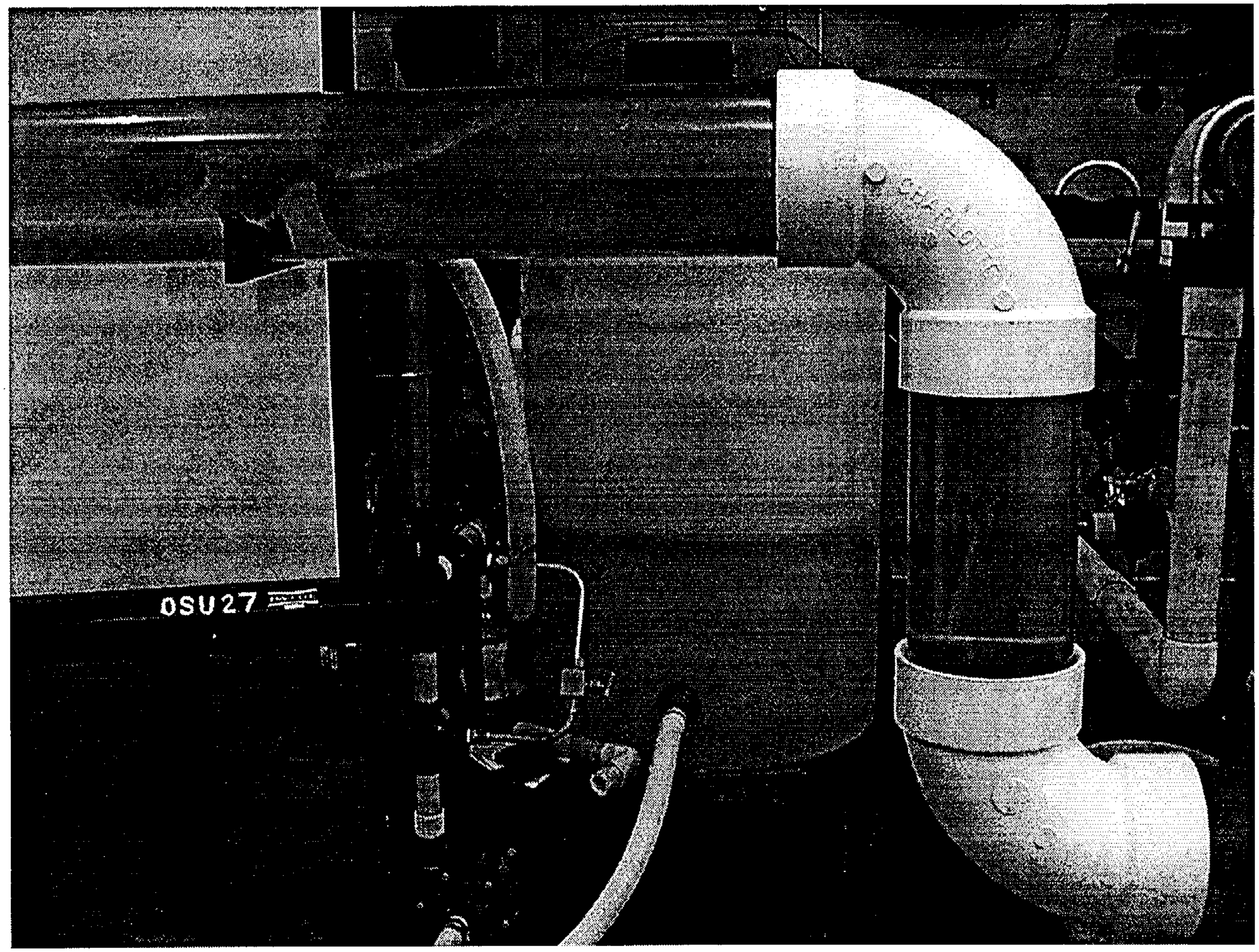
No Weir Wall Spill-Over

Onset of Weir Wall Spill-Over



Onset of Loop Seal Cooling



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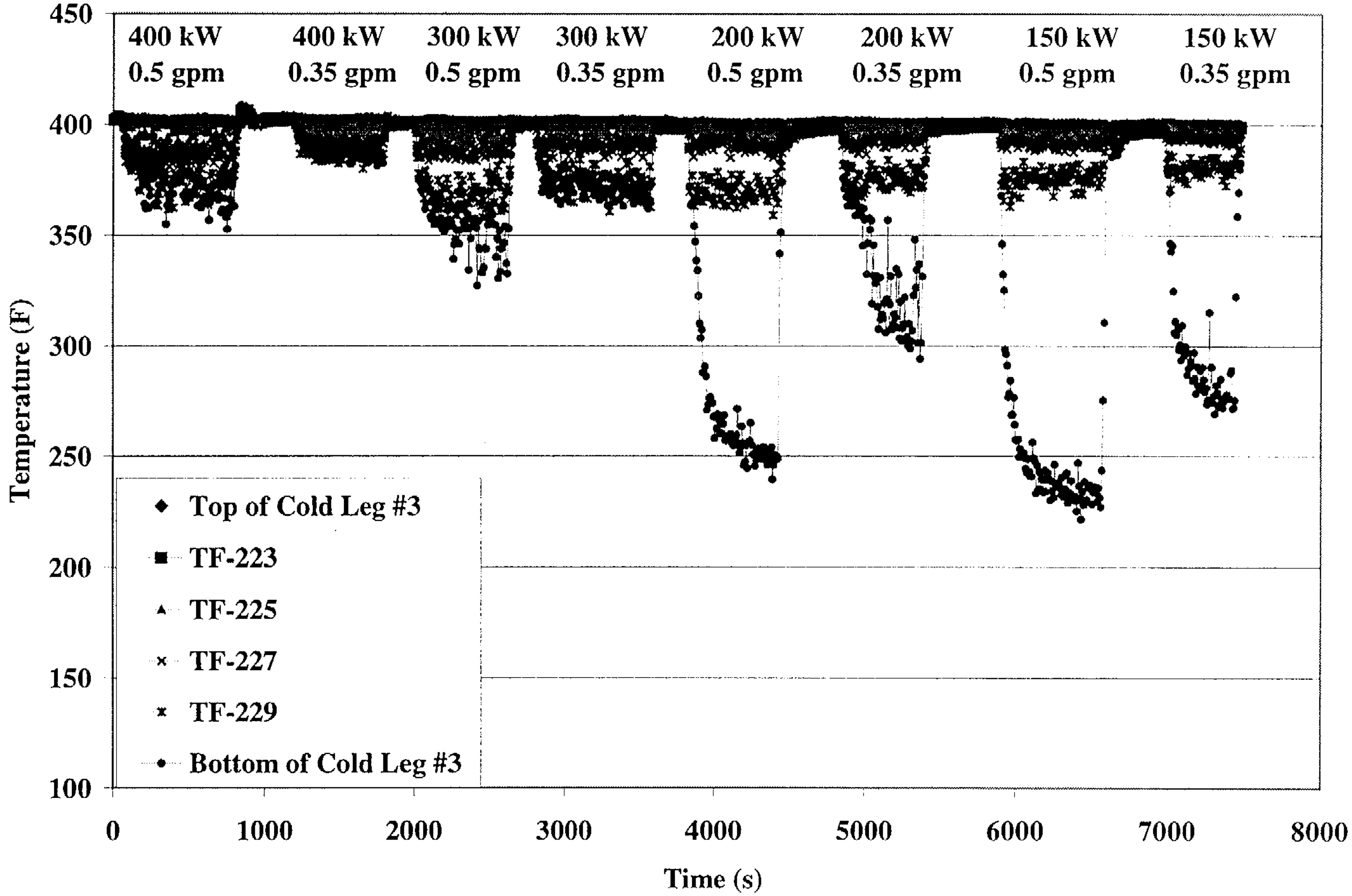
OSU-CE-0003 Parametric Study

- OSU-CE-0003 was a parametric study to examine the conditions for the onset of thermal stratification in the cold legs under natural circulation conditions.
- Presence of the RCP weir-wall results in some stratification for the full range of conditions studied. That is:
  - Natural circulation cold leg flow rates ranging from 1.5% to 4% decay power for 30% - 100% HPSI injections flow rates.
- RCP weir wall spill-over was not observed in these tests because natural circulation flow rates were always greater than 10 gpm per cold leg.

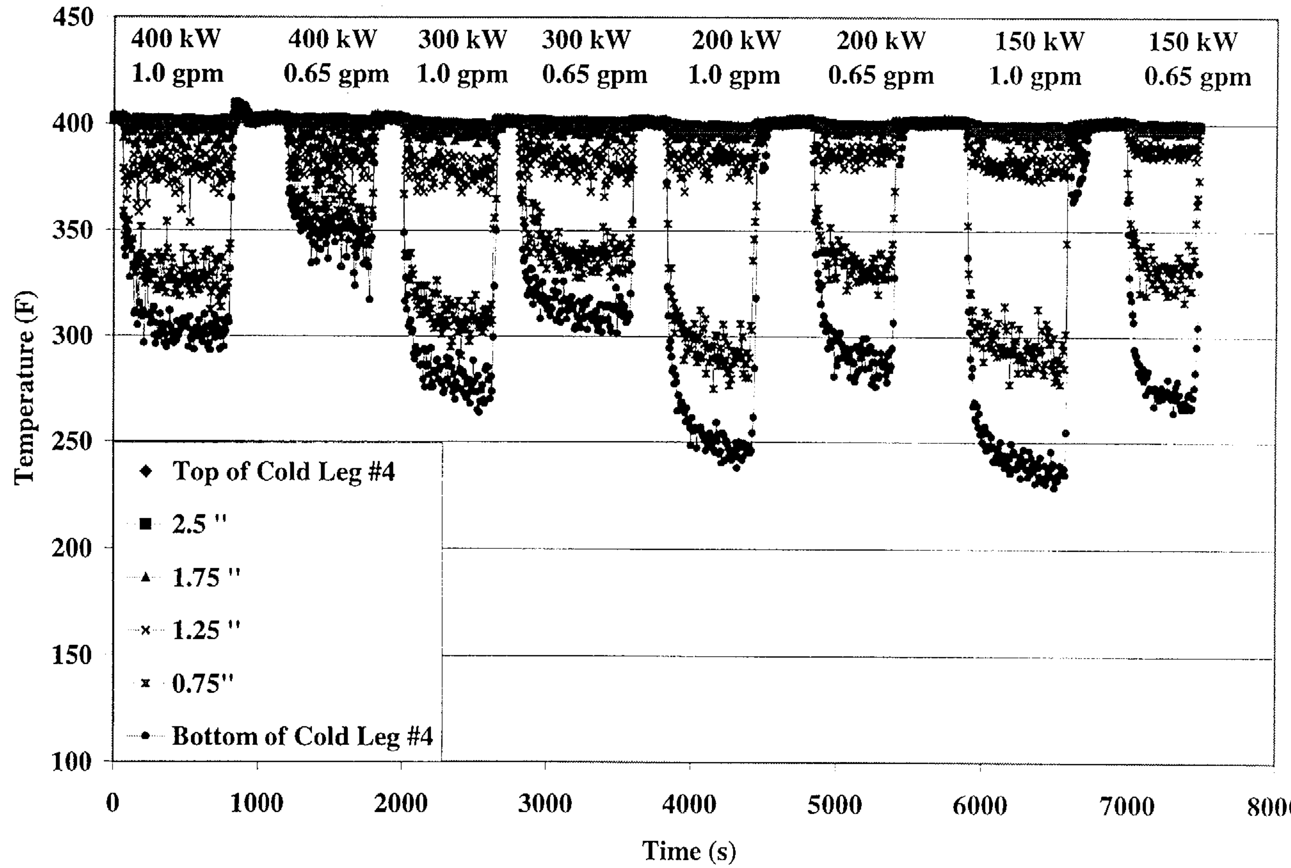
OSU-CE-0003 Parametric Study

Core Decay Power (kW)	Cold Leg #3 HPSI Flow Rate (gpm)	Cold Leg #4 HPSI Flow Rate (gpm)
400	0.50	1.00
400	0.35	0.65
300	0.50	1.00
300	0.35	0.65
200	0.50	1.00
200	0.35	0.65
150	0.50	1.00
150	0.35	0.65

Cold Leg #3 Thermal Stratification in OSU-CE-0003



Cold Leg #4 Thermal Stratification in OSU-CE-0003

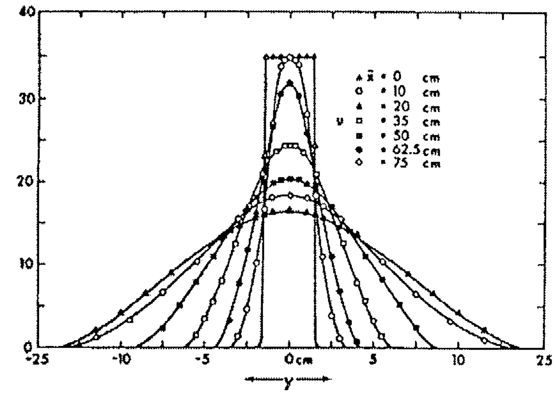


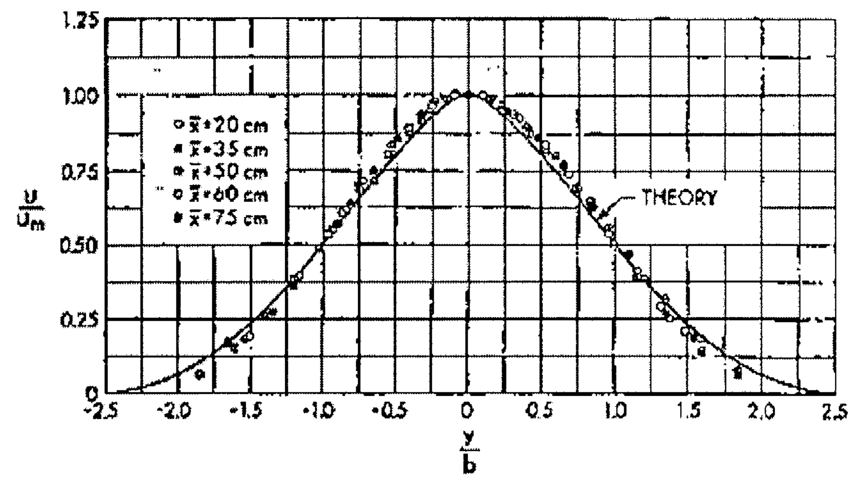
Buoyant Plumes in the Downcomer

- Typical analyses examine a single planar plume in a stagnant, uniform temperature, ambient fluid.
- Classic Assumptions:
  - G.I. Taylor's Entrainment Asssumption Linear spread of plume radius with axial position implies mean inflow velocity across the edge of the plume is proportional to the local mean downward velocity of the plume.
  - Similarity of Velocity and Buoyancy Profiles
  - Gaussian Shaped Profiles

Similarity of Velocity Profiles

- Velocities at different axial positions can collapse on a single Gaussian Profile (Foerthamnn 1934)





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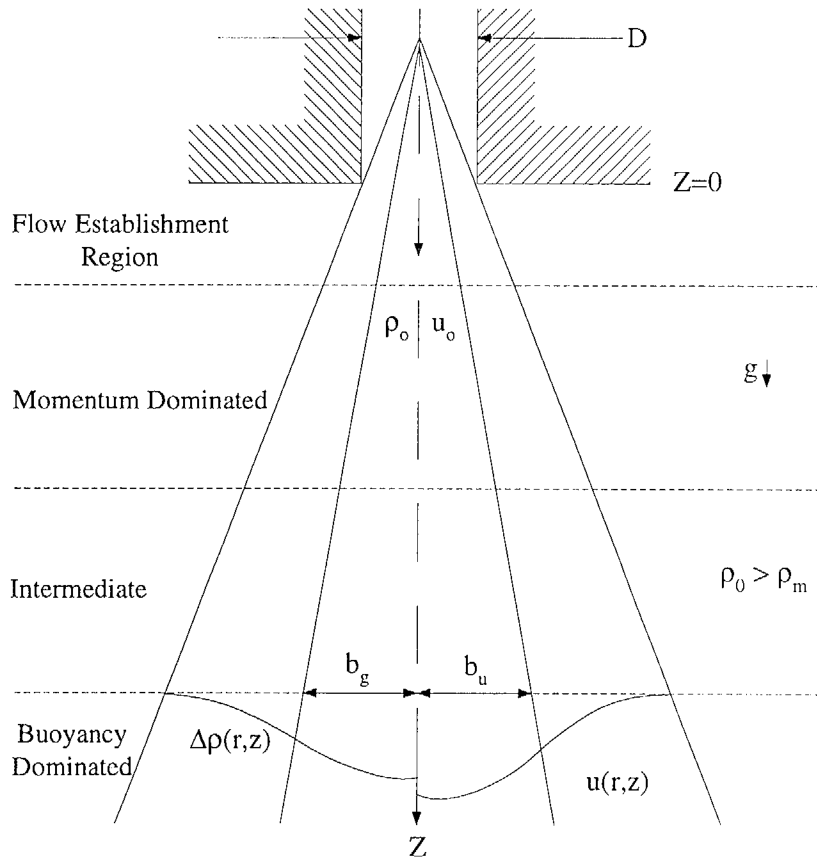
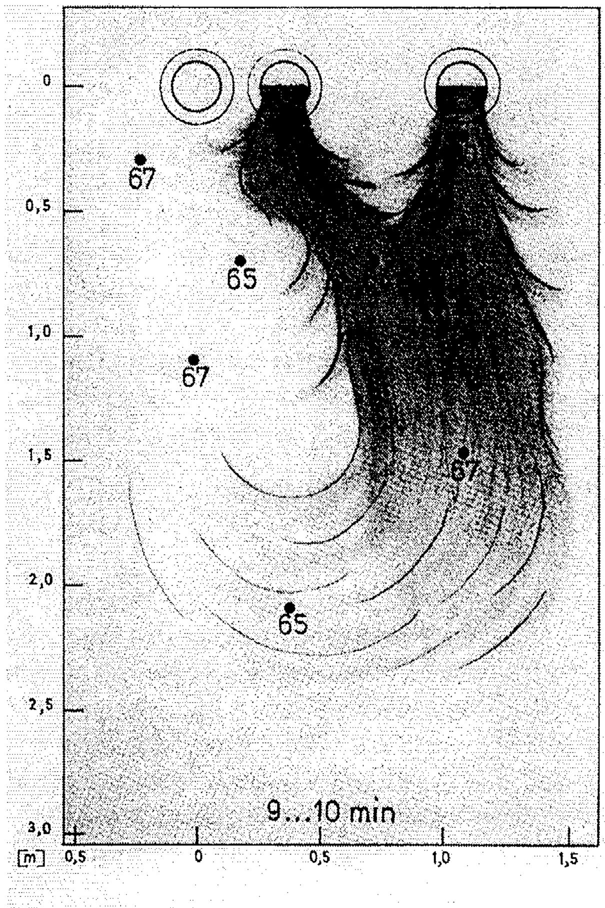
Buoyant Plume in a Uniform Stagnant Medium



Buoyant Plumes in the Downcomer

- Plume behavior in APEX-CE was significantly more complicated than typical analysis assumptions.
  - Some APEX-CE tests involved multiple asymmetric plume interactions with co-flow in a thermally stratified downcomer.

Merging of Downcomer Plumes



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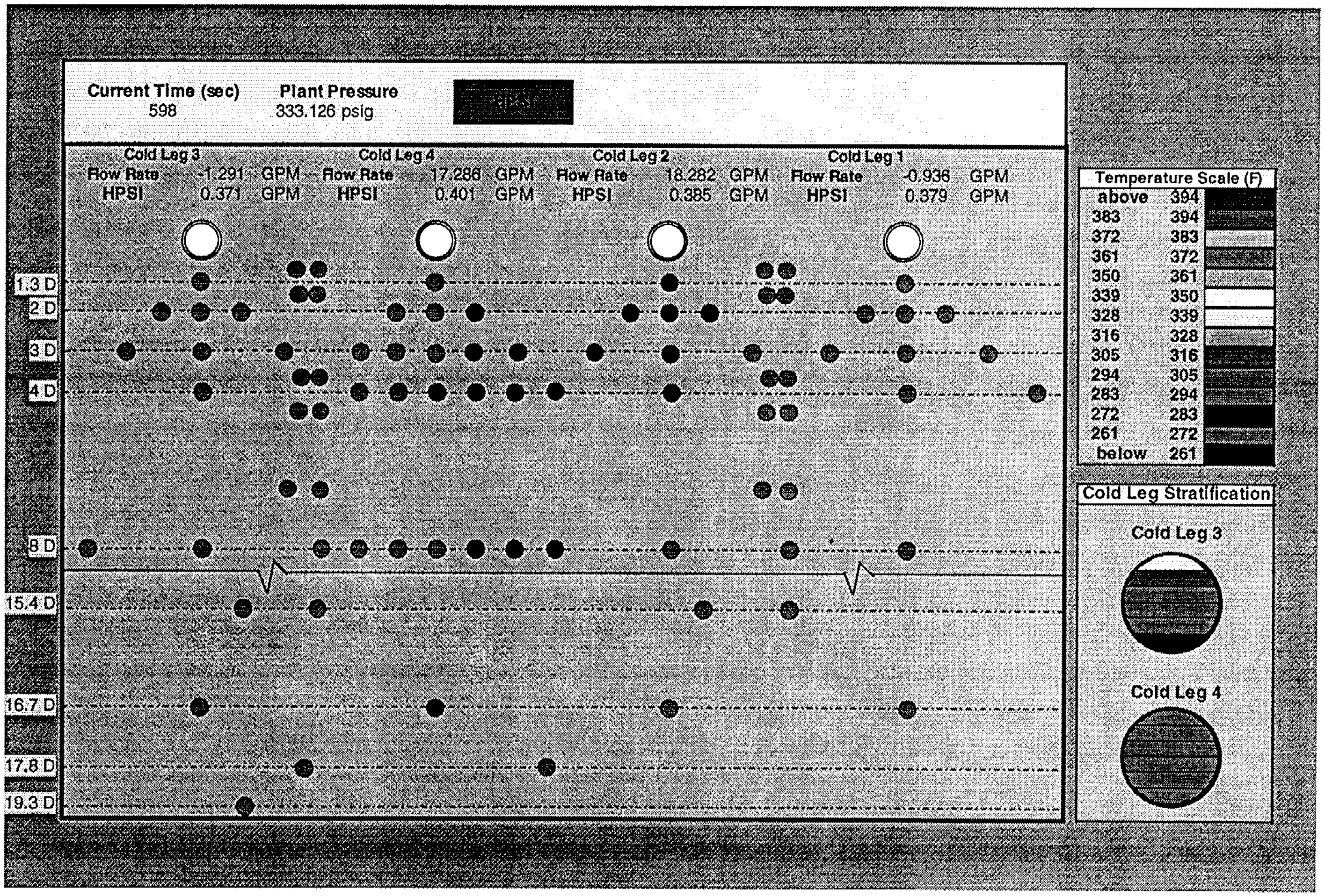
Plume Interaction During OSU-CE-0012 MSLB at Full Power



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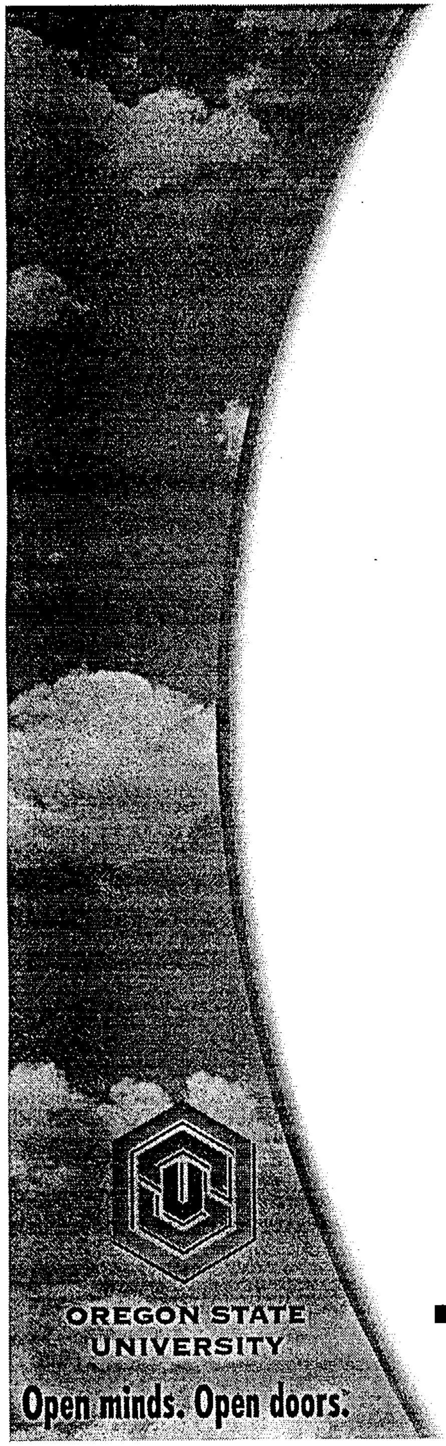

Transient Temperature Map Demonstration for OSU-CE-0012

Buoyant Plume Behavior in the Presence of a Co-flowing Stream

- I.R. Wood, "Asymptotic Solutions and Behavior of Outfall Plumes."
  - The presence of a co-flowing stream can reduce the spread of a falling plume because the relative velocity between the plume and the ambient fluid is reduced.

$$\frac{db}{dz} = \frac{k_s U_P}{\left[U_P + U_\infty \cos(\alpha)\right]}$$

  - Where k_s is the spread constant, b is the plume half width, U_∞ is the stream velocity, U_P is the plume centerline velocity and α is the angle between the flow direction and the plume direction.

Buoyant Plume Behavior in the Presence of a Co-flowing Stream

- In APEX-CE, thermal stratification in the cold leg permits significant flow of hot water into the downcomer. This sometimes produces a falling plume in the presence of co-flowing downcomer fluid stream.
- A positive value of U_∞ results in:

$$\left(\frac{db}{dz}\right)_{\text{Stagnant}} > \left(\frac{db}{dz}\right)_{\text{Coflow}}$$

- Downcomer thermal stratification has been observed to occur under these conditions.

Conclusions

- Cold Leg thermal stratification was observed to occur for all of the natural circulation flow rates and HPSI flow rates tested. (Range 1.5% to 4% Decay Power; Q_{HPI} flow to 30%-100%)
- Presence of an RCP weir-wall promotes thermal stratification.
- Plume merging was observed during the tests.
- Co-flow of downcomer fluid reduces plume spreading. This results in plume behavior similar to what was observed in the IVO facility.

Cold Leg Thermal Stratification and Plume Formation in APEX-CE (Appendix)

Jose N. Reyes, Jr.

Chris Linrud

Ian Davis

Presentation To

Advisory Committee On Reactor Safeguards

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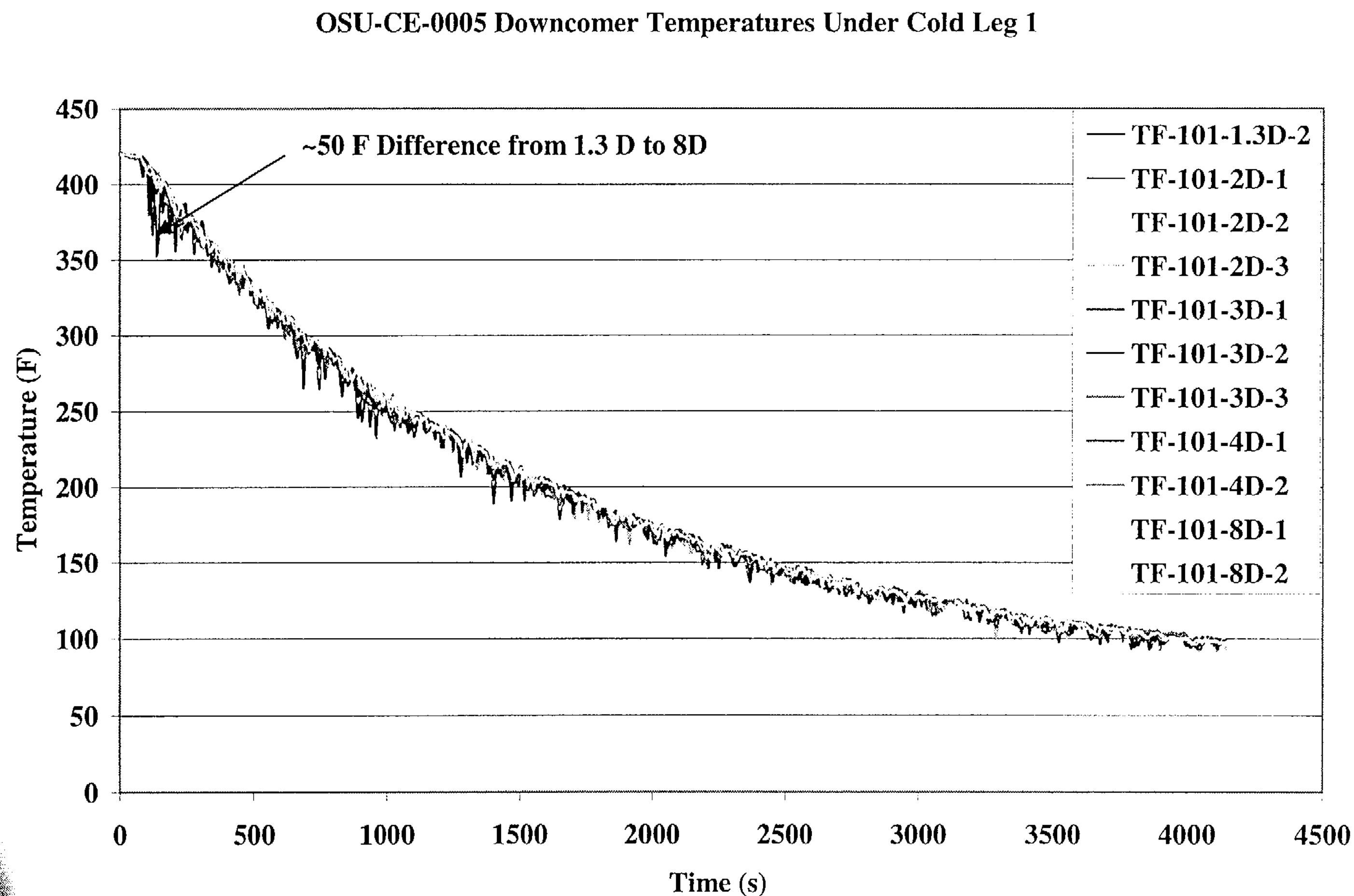
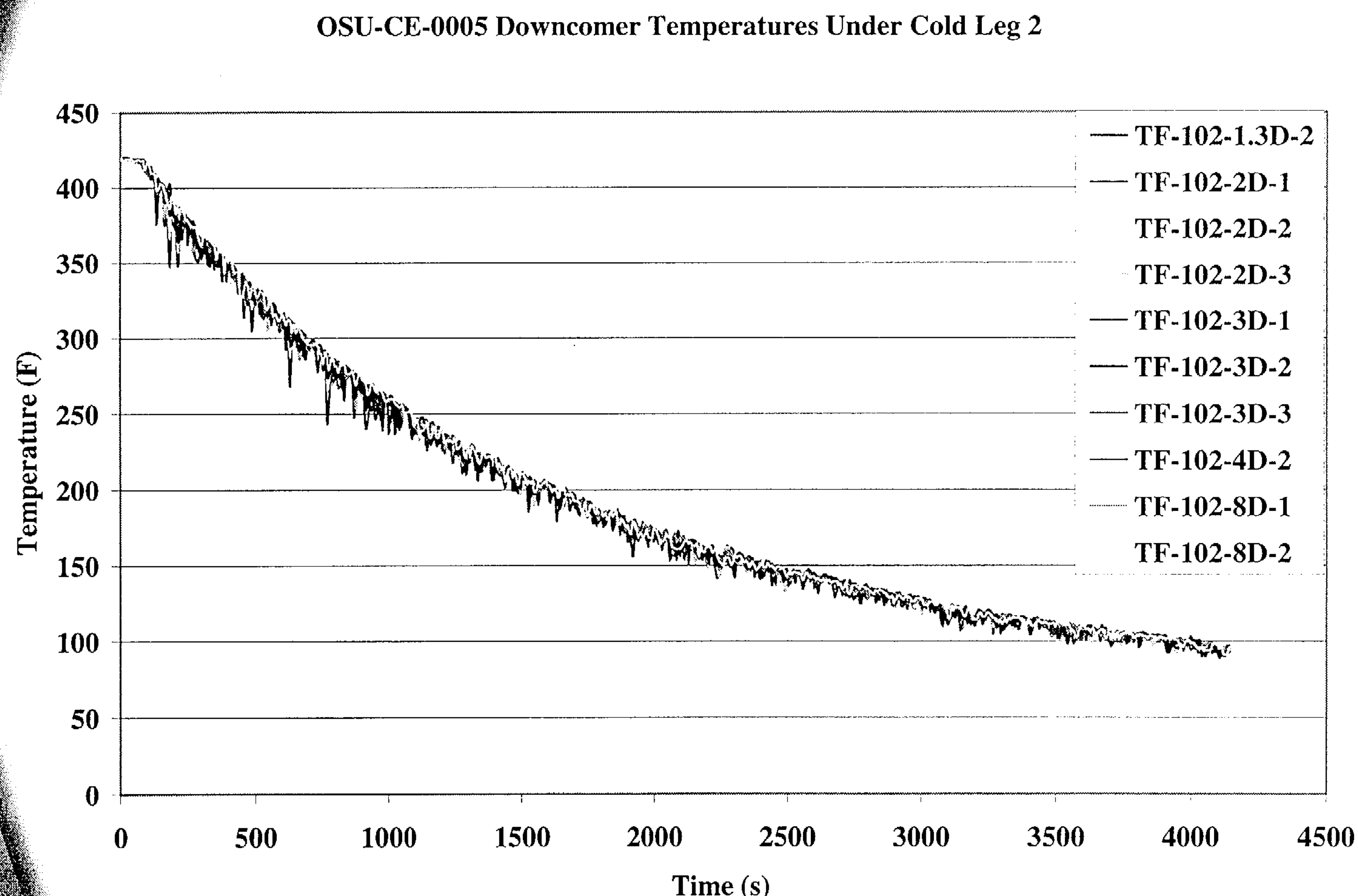
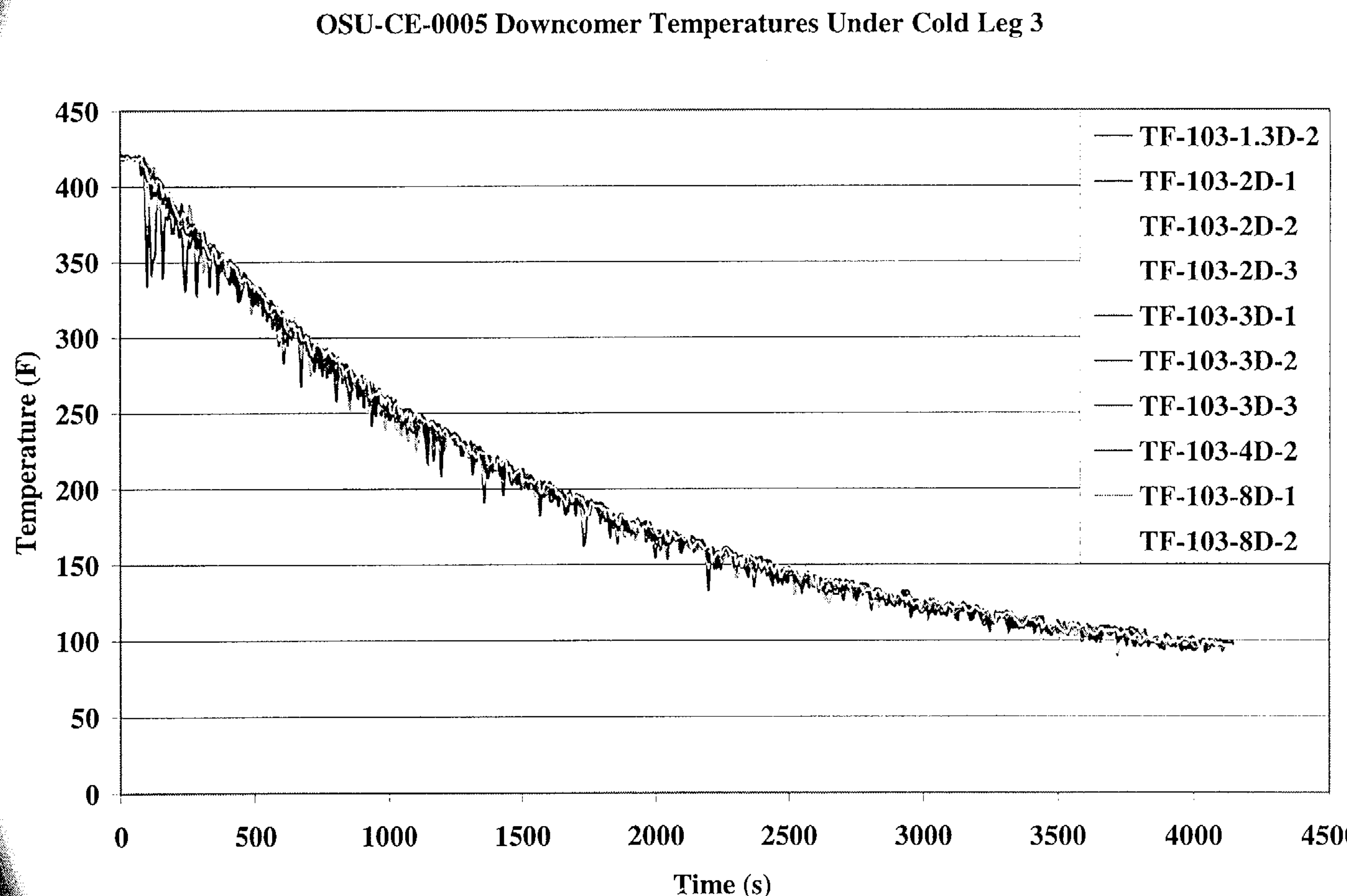
Stagnant Loop Case



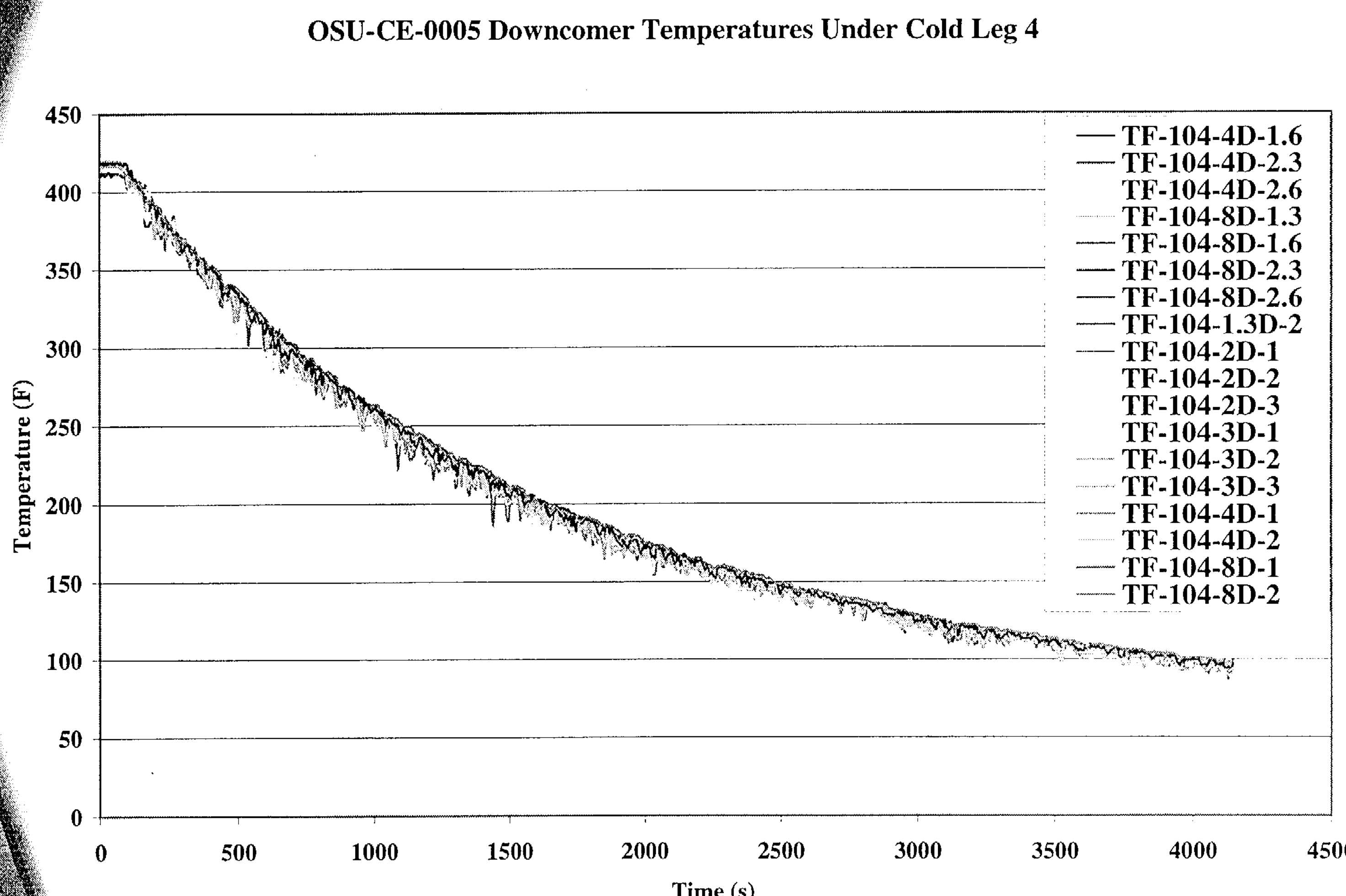
Stagnant Loop Case



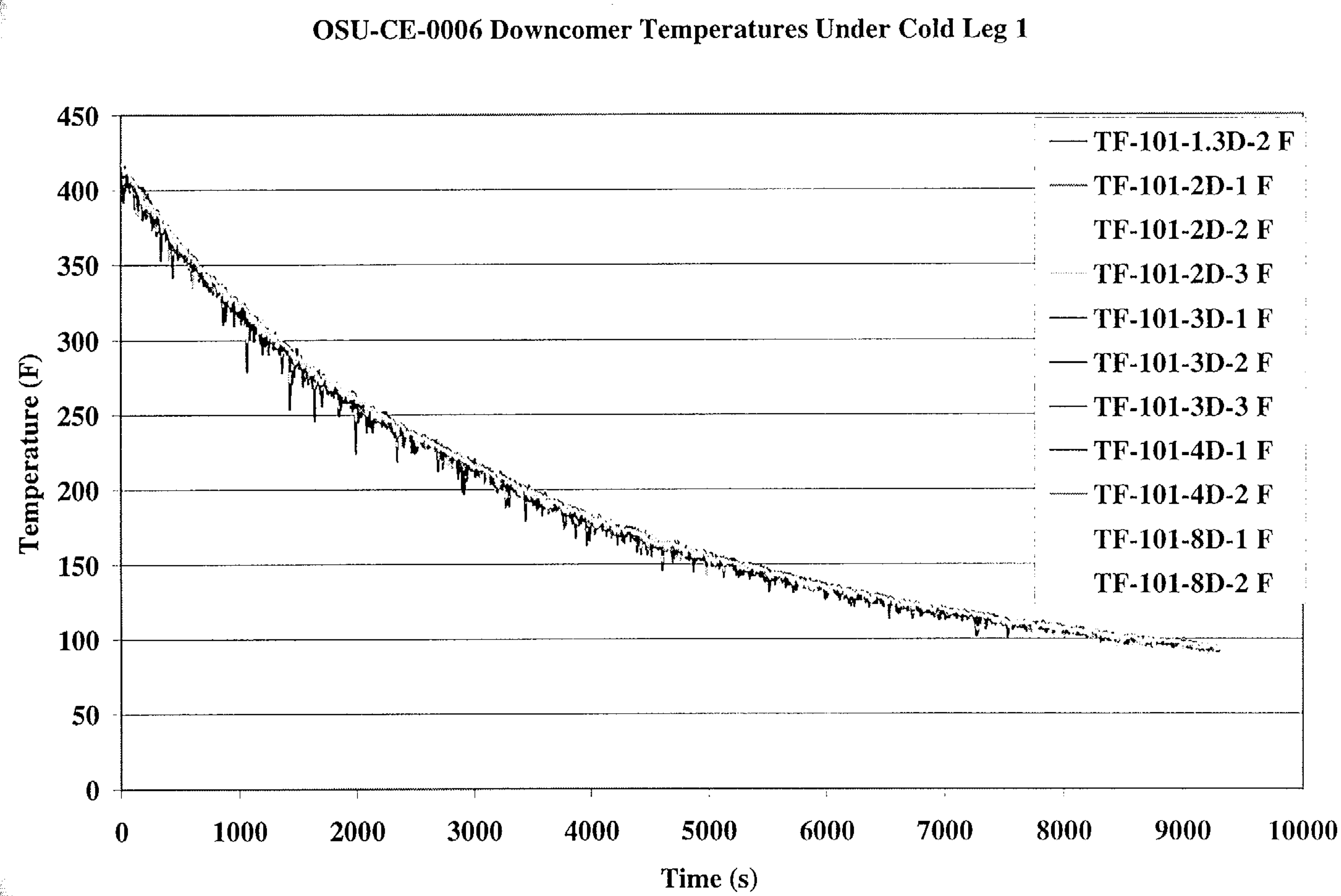
Stagnant Loop Case



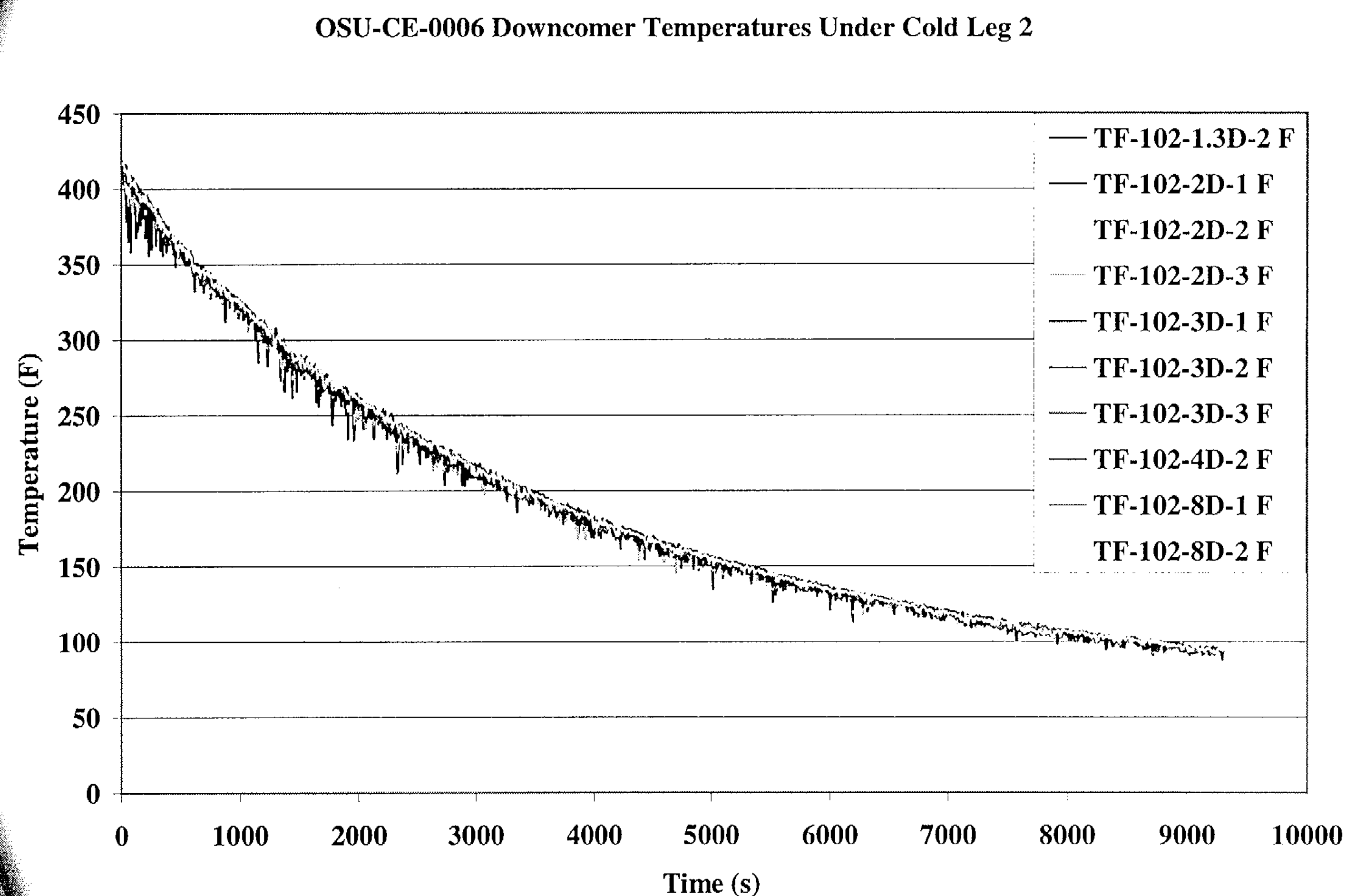
Stagnant Loop Case



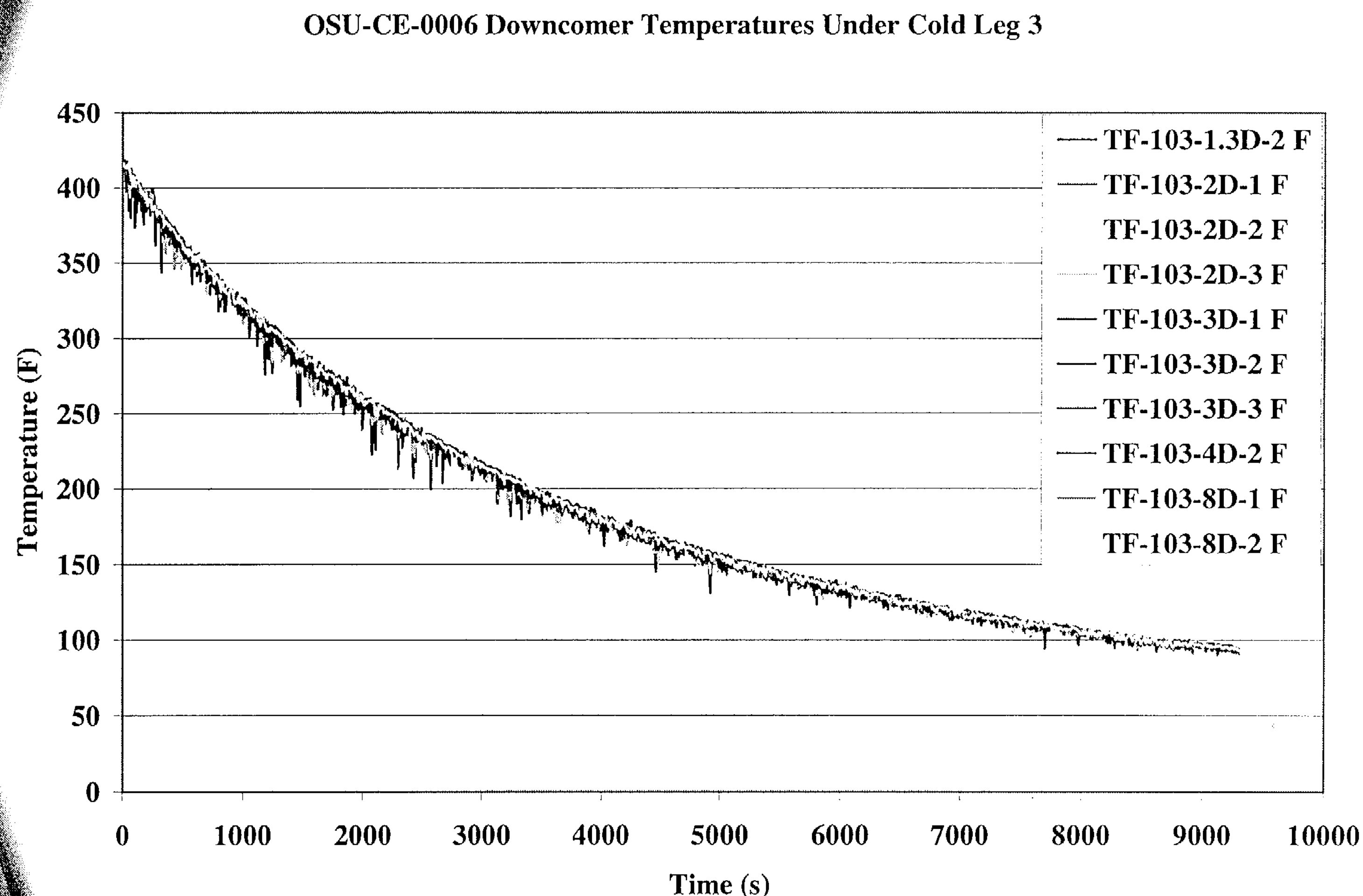
Stagnant Loop Case



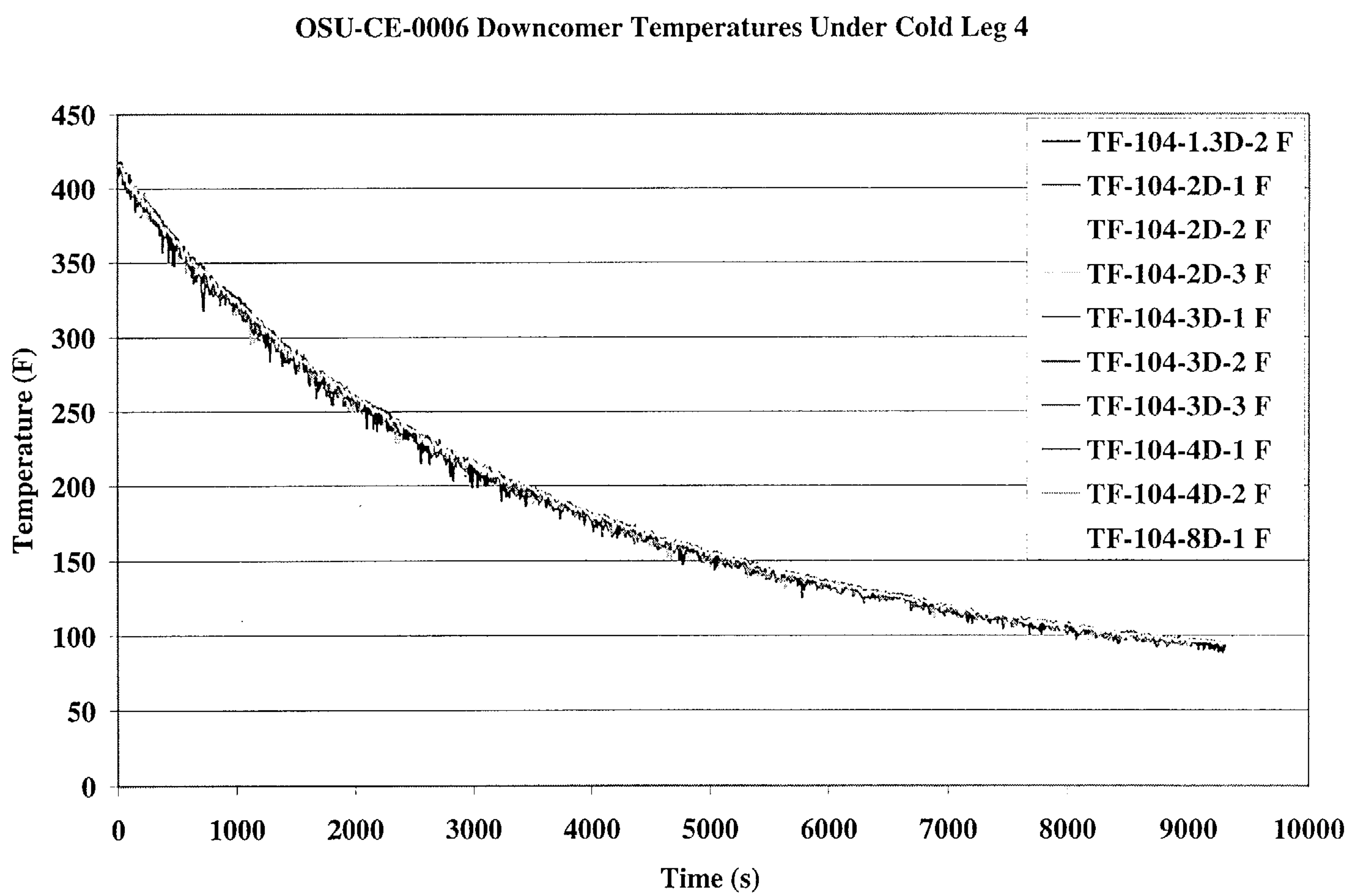
Stagnant Loop Case



Stagnant Loop Case



Stagnant Loop Case



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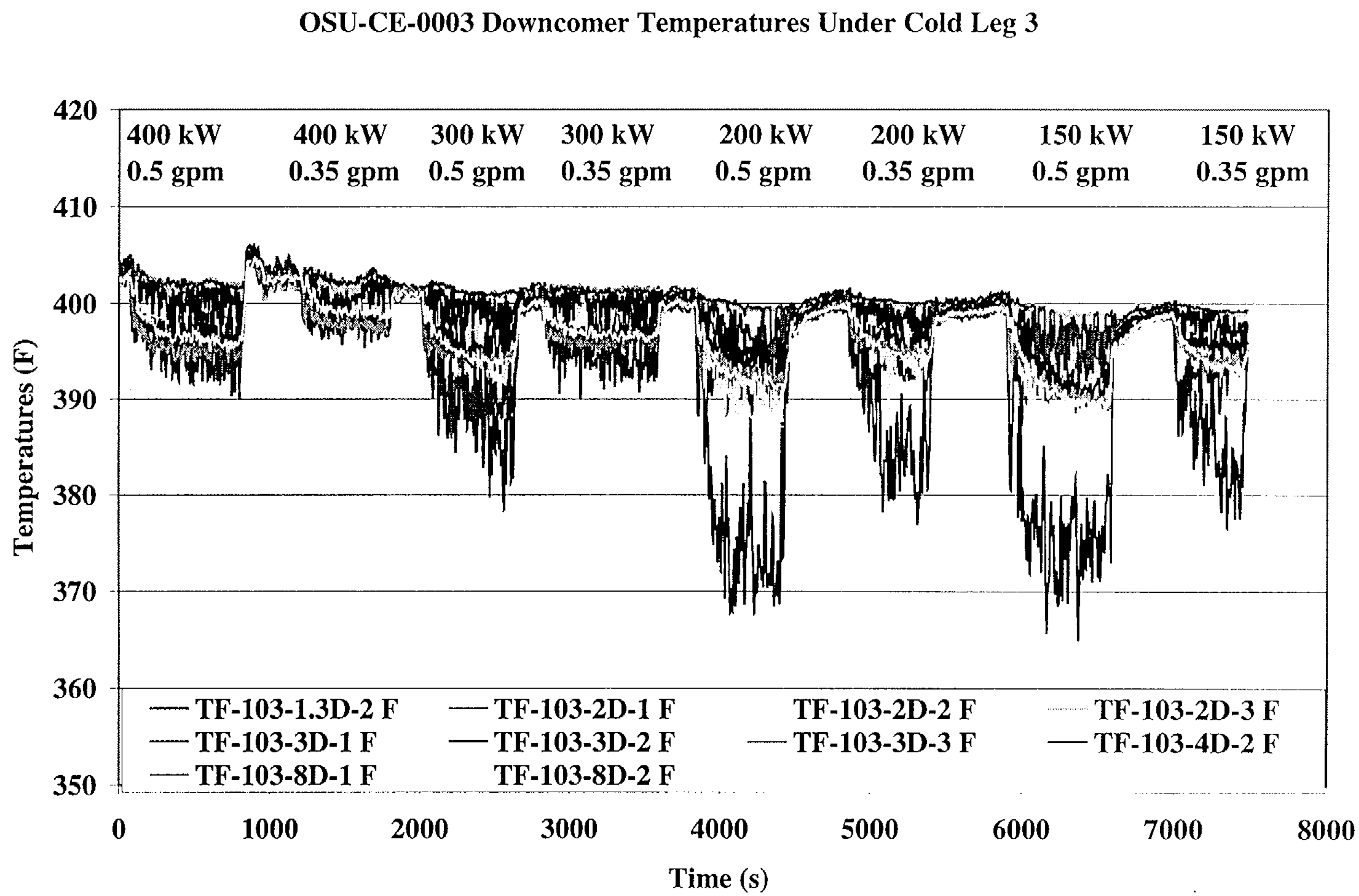
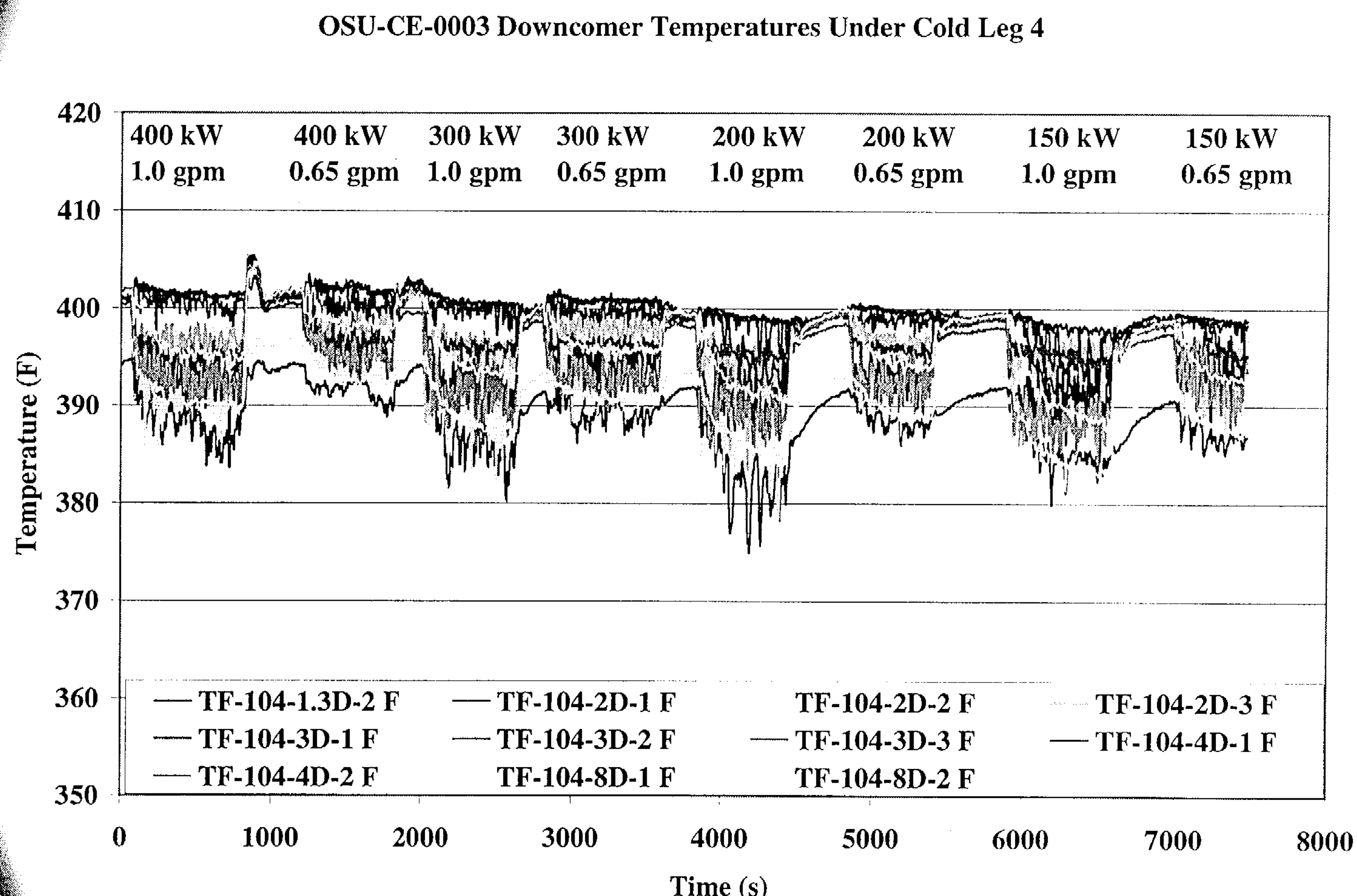
Natural Circulation Case



Natural Circulation Case



Conclusions

- Downcomer plumes are observed in both stagnant and natural circulation flow conditions.
- For range of natural circulation flows examined (~1.5% to 4% Decay Power and 30% -100% HPSI flows) the plumes were well-mixed by 4 cold leg diameters.

Downcomer Thermal Stratification in APEX-CE

Brandon Haugh and Kent Abel

Presentation To

Advisory Committee On Reactor Safeguards

Thermal Hydraulic Phenomena Subcommittee Meeting

July 17-18, 2001

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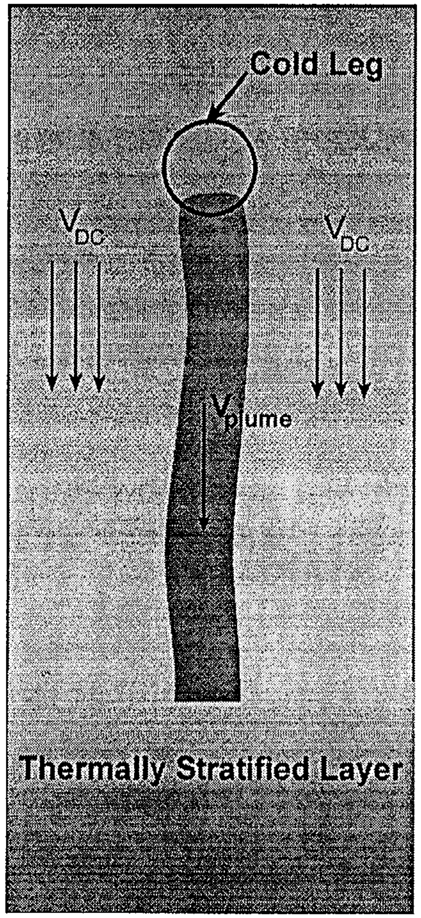
Outline

- Description of Downcomer Thermal Stratification
- Observations in APEX-CE
- Transient Temperature Map
- Conclusions

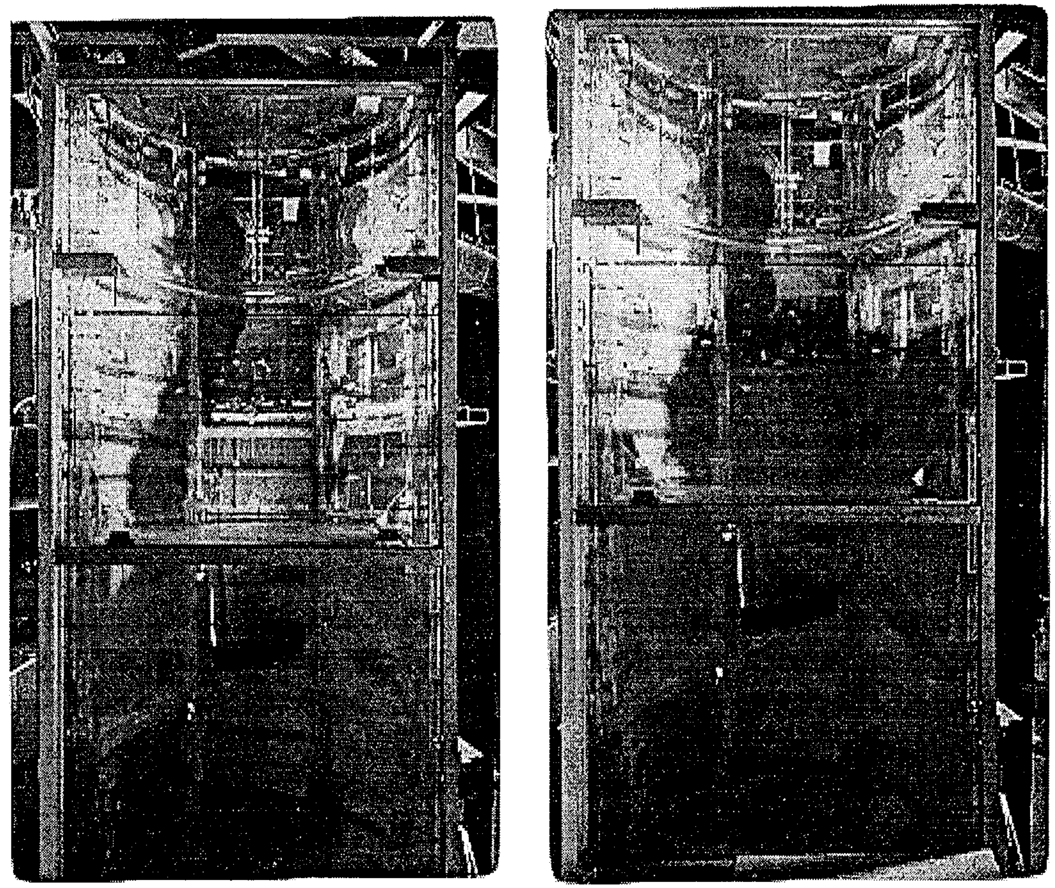
Downcomer Thermal Stratification Mechanism



- Thermal Stratification in the downcomer occurs in the presence of primary loop natural circulation and HPSI operation.
- Co-flow of the Downcomer fluid stream and the plume reduces mixing; thus permitting downcomer thermal stratification.

Downcomer Thermal Stratification

- Photos taken from the IVO facility in Finland
- Single HPI injection with flow in a Single Cold Leg
- Temperature Gradient observed in the Downcomer
- Similar Phenomenon Observed in APEX-CE



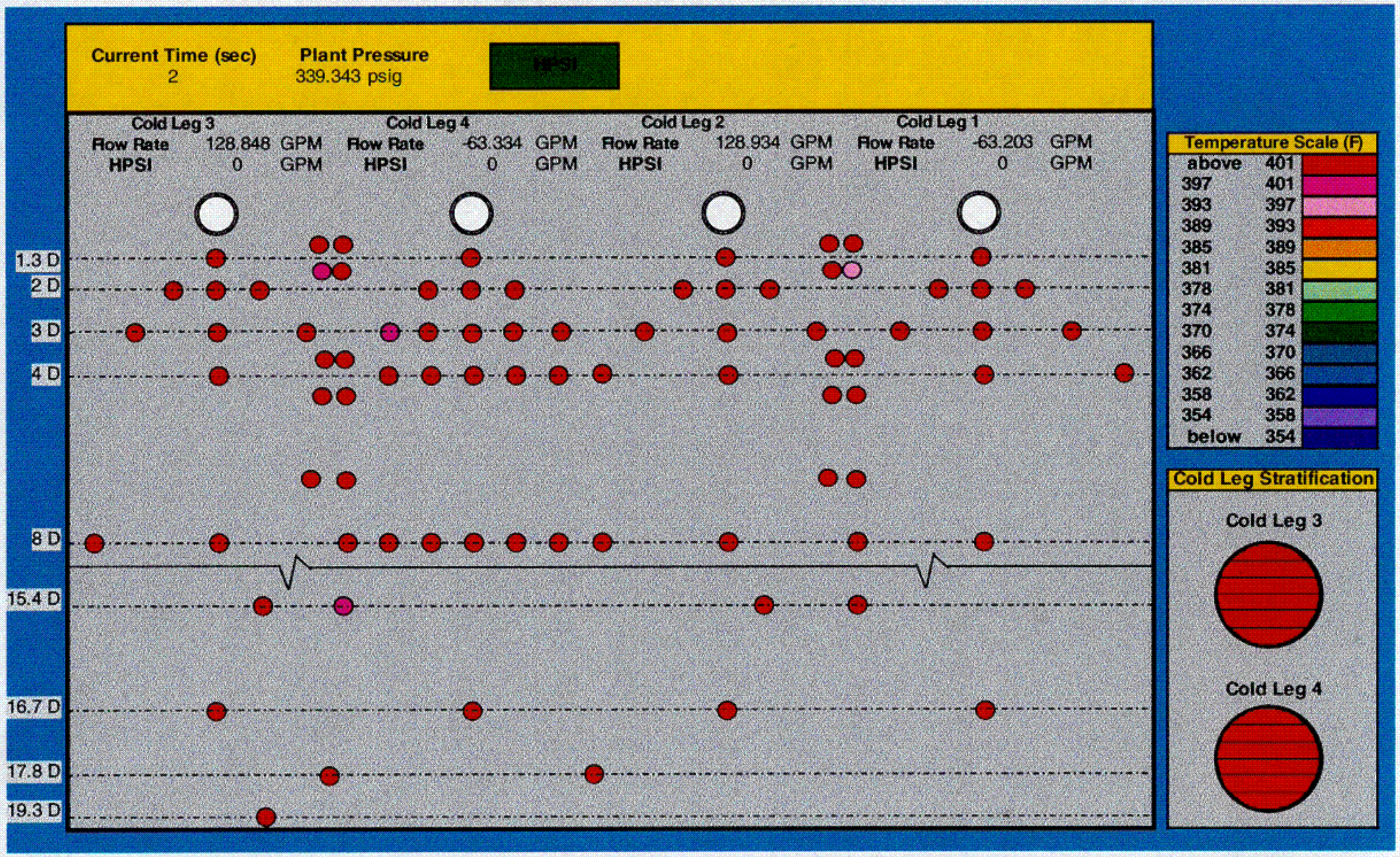
Test # 102 (66 GPM Cold Leg C, 6.6 GPM HPI Cold Leg B)

Observation in APEX-CE

Test #	Description	Downcomer T/S	Downcomer Max ΔT	Cold Leg Flow
OSU-CE-0004	Single HPSI	No		Stagnant
OSU-CE-0005	4 HPSI	No		Stagnant
OSU-CE-0006	4 HPSI	No		Stagnant
OSU-CE-0007	1.4"-SBLOCA	Yes	35.4 ^{0}F	Natural Circulation
OSU-CE-0008	2.0"-SBLOCA	Yes, only in the beginning of test.	40.3 ^{0}F	Natural Circulation
OSU-CE-0009	Stuck Open SRV	Yes	35.5 ^{0}F	Natural Circulation
OSU-CE-0010	Stuck Open SRV and Stuck Open ADV on SG-1	Yes, After SG-1 Emptied	28.2 ^{0}F	Natural Circulation
OSU-CE-0011	MSLB SG-1 Hot Zero Power	No		Natural Circulation
OSU-CE-0012	MSLB SG-2 Full Power	Minor, After SG-2 Emptied	12.1 ^{0}F	Natural Circulation

OSU-CE-0009

(Stuck-Open SRV Initial Conditions)



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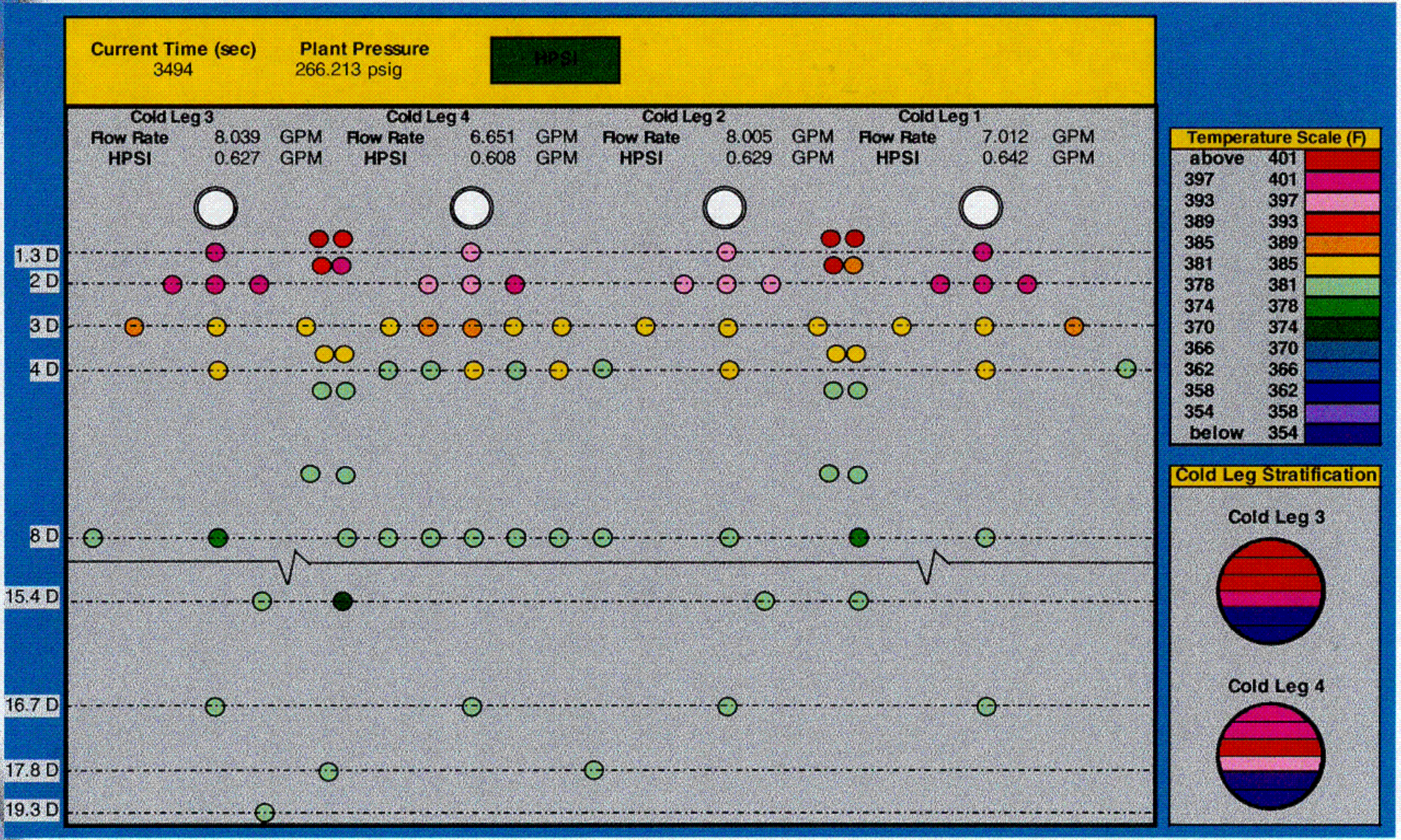
C01

OSU-CE-0009 (at 3494 seconds)



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C02

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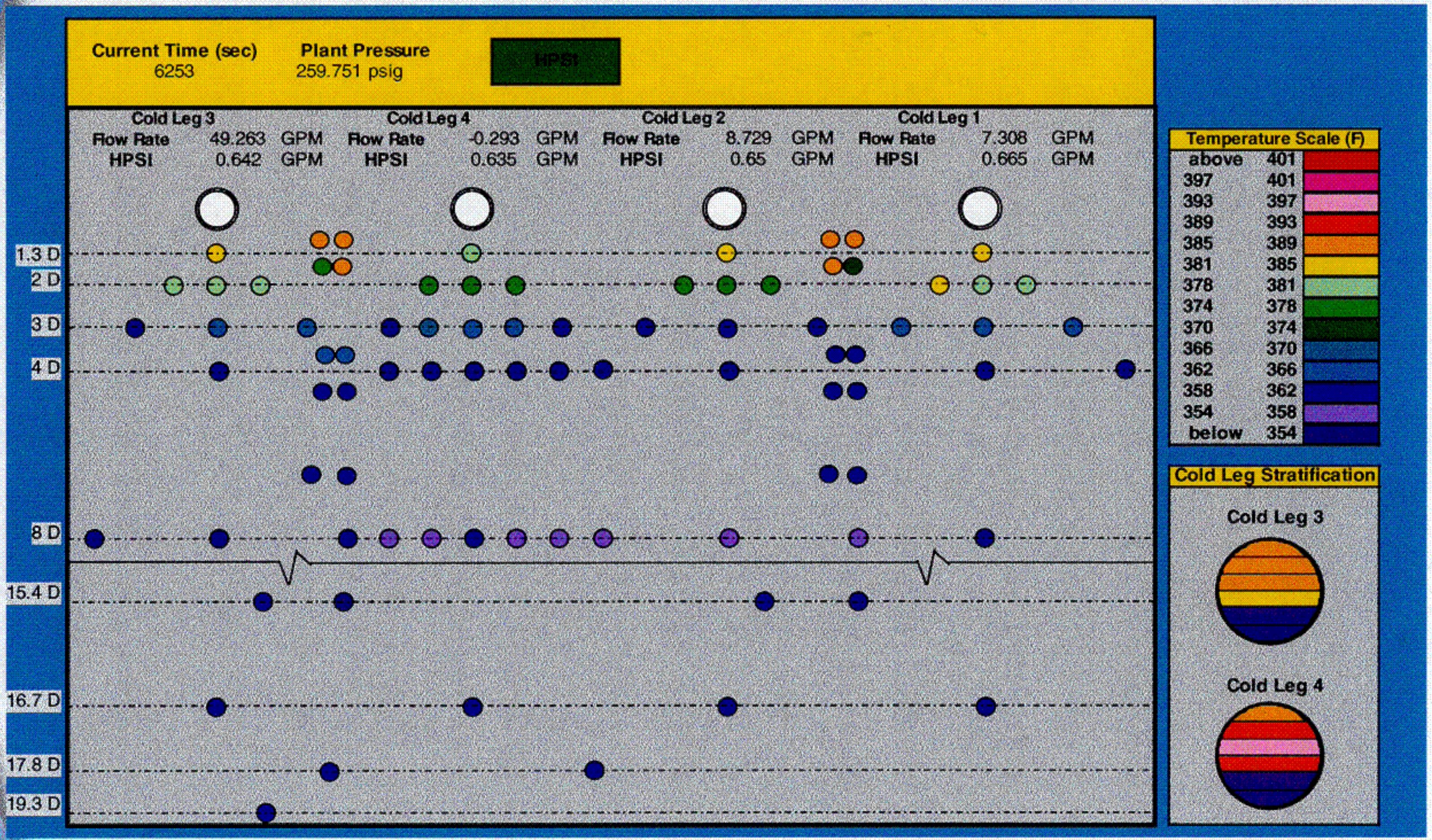

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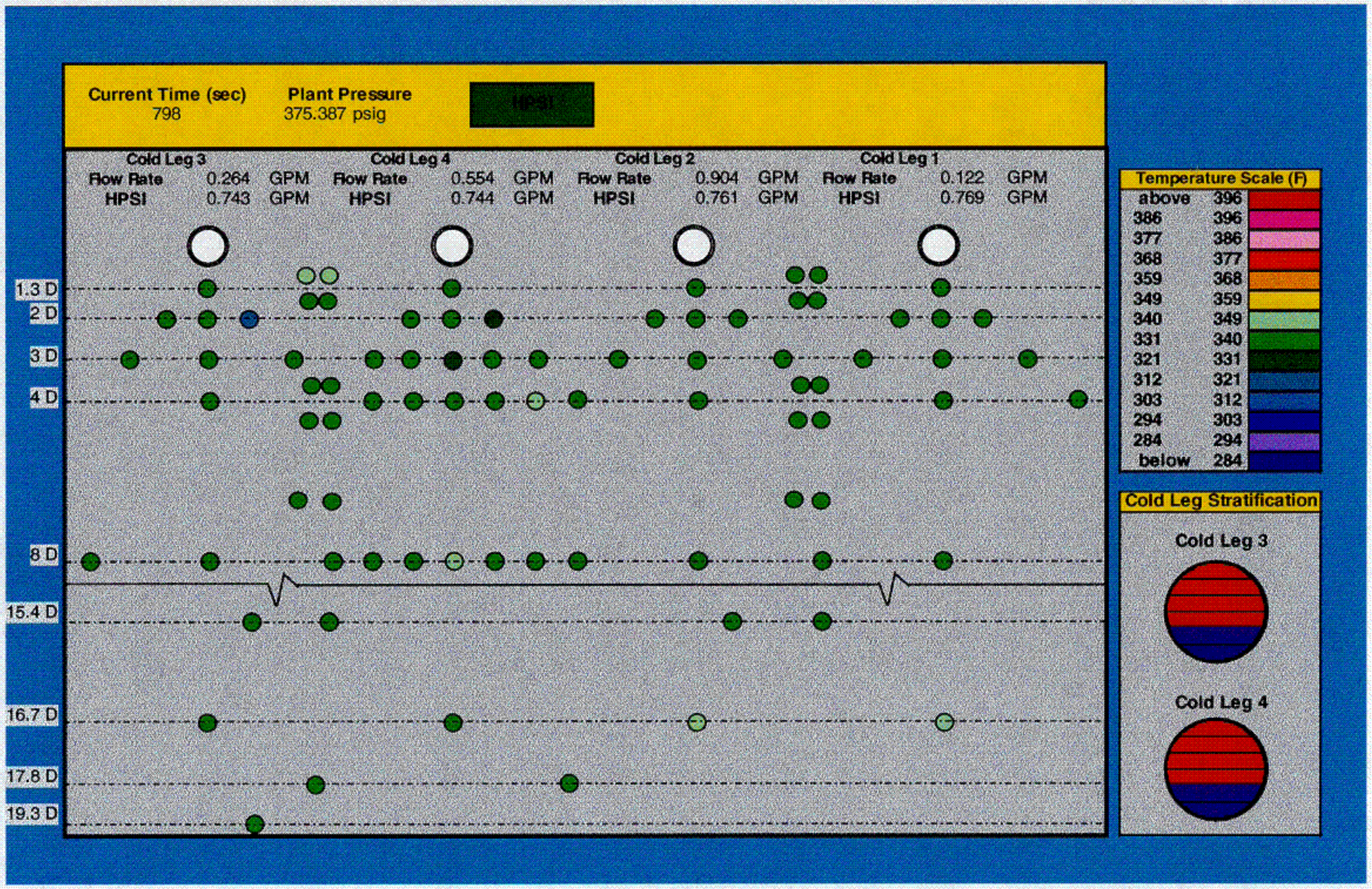
C03

OSU-CE-0006
(Stagnant Loop Injection Conditions)



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C04

Transient Temperature Map Demonstration

Conclusions

- The phenomenon of Downcomer Thermal Stratification (DTS) was observed in some of the APEX-CE tests.
- DTS did not occur under stagnant primary loop conditions or when the plant cool-down rate was very high. (e.g. MSLB)
- The tests where DTS occurred had primary loop natural circulation.
- The probable mechanism for DTS is the co-flow of the downcomer fluid stream and the plume. This tends to preserve the plume; thus permitting downcomer thermal stratification.

REMIX Calculations of APEX-CE Tests

Eric Young

Presentation to
Advisory Committee on Reactor Safeguards
Thermal Hydraulic Subcommittee Meeting
July 17-18, 2001

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Outline

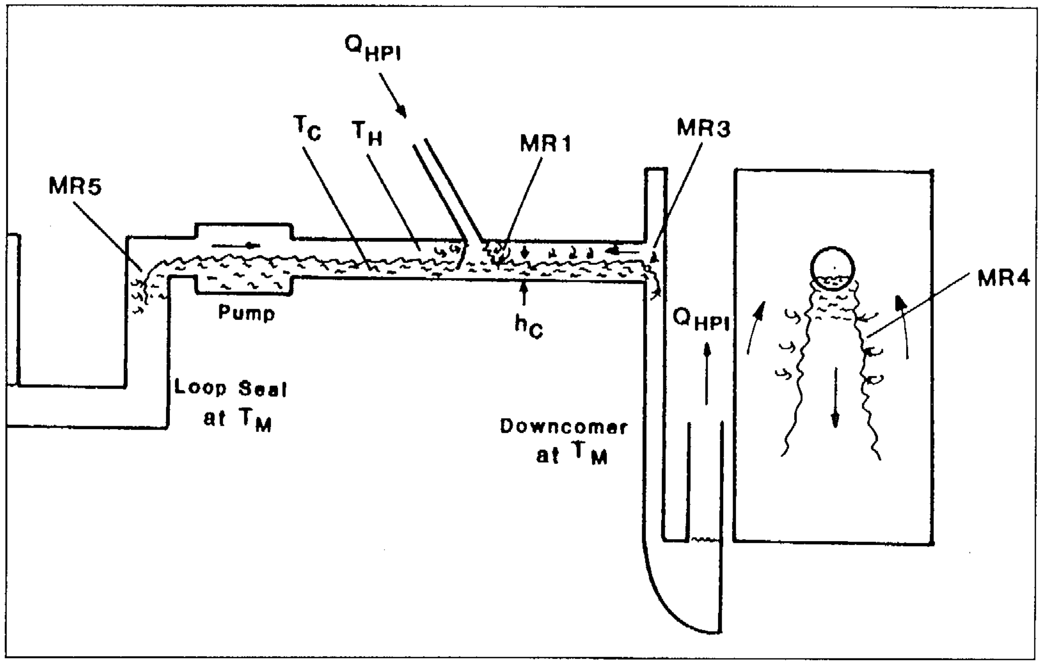
- Objectives
- Description of REMIX
- Description of APEX-CE Stagnation Tests
- REMIX Comparisons
  - OSU-CE-0004
  - OSU-CE-0005
  - OSU-CE-0006
- Effect of Core Barrel Heat Transfer
- Summary and Conclusions

Objectives

- Benchmark REMIX against APEX-CE stagnation tests
- Identify code limitations
- Assess the applicability of code for integral system geometries

Description of REMIX

- REMIX is based on the Regional Mixing Model. Global and Local calculations are carried out separately.



Description of REMIX

- Limitations
  - Not designed to predict the effect of multiple plume interactions on local downcomer temperatures.
  - Not designed to predict cold leg thermal stratification in presence of cold leg flow.
  - Only predicts plume centerline temperatures.
  - Does not predict plume velocities.
  - Uses a fixed surface heat transfer coefficient.
  - 1-D Conduction Heat Transfer

Test Descriptions

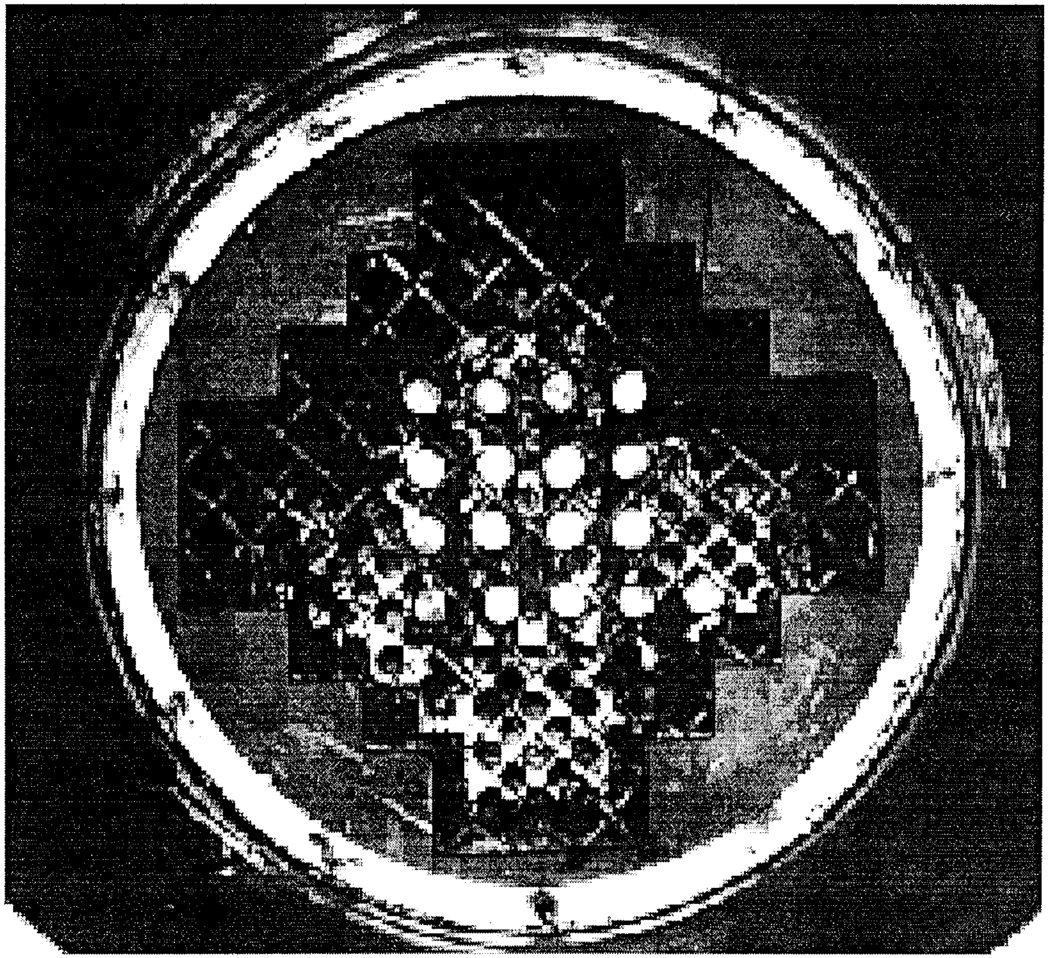
- Tests OSU-CE-0004, OSU-CE-0005 and OSU-CE-0006 were compared to REMIX predictions.

Test #	Fr #	$\Delta\rho/\rho$	Q_{HPSI} (ft^3/s)	# of HPSI Injection Sites
OSU-CE-0004	.0402	.18	.003315	1
OSU-CE-0005	.0350	.18	.002882	4
OSU-CE-0006	.0190	.18	.001652	4

REMIX Input for APEX-CE

- Fluid Volumes Included:
  - 1 HPSI Model
  - 4 HPSI Model
- Material Properties:
- HPSI Flow Rates, Fluid Temperatures
- Initial System Temperature
- Heat Transfer Areas
- Heat Transfer Coefficients

Core Barrel Reflector



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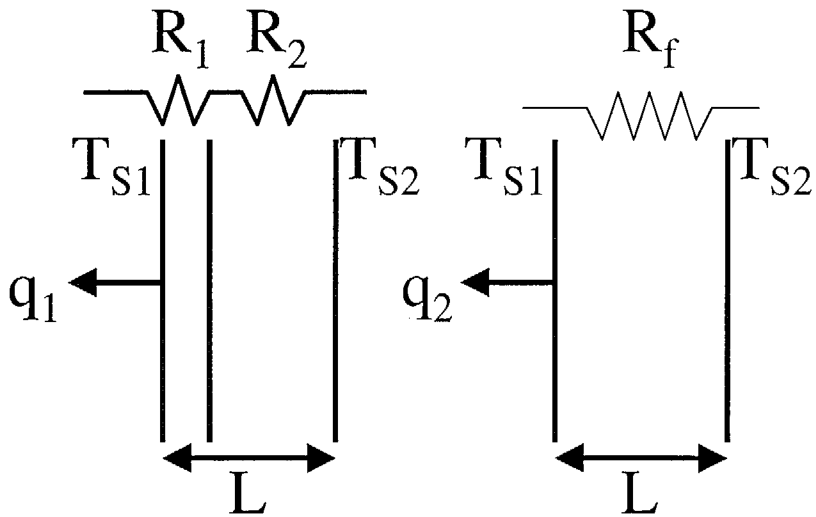
Thermal Circuit for Core Barrel/Reflector

- The mixed material must contribute equal heat as the composite, $q_1 = q_2$



Core Barrel and Reflector

Equivalent Material

$$q_1 = \frac{T_{S1} - T_{S2}}{R_1 + R_2}$$

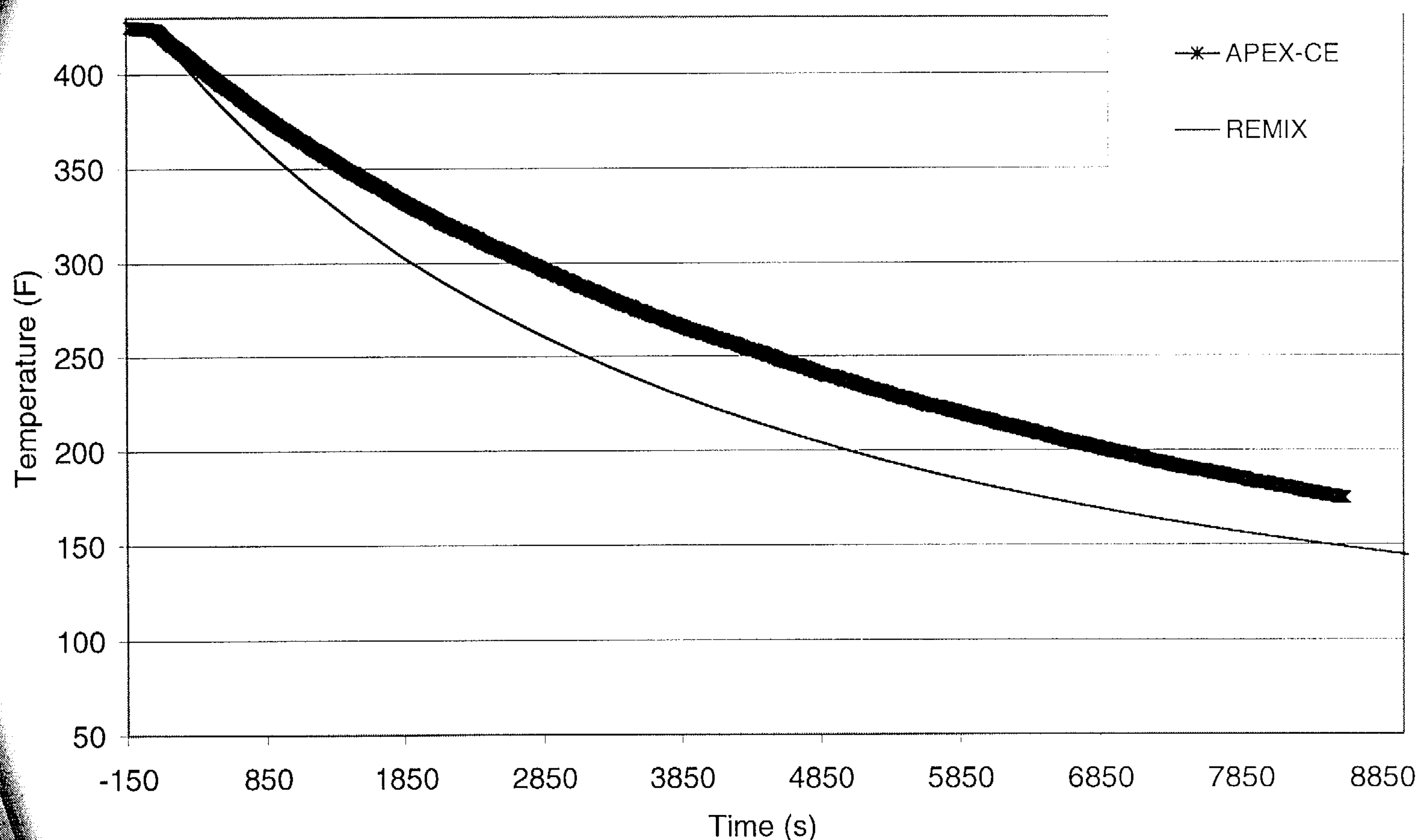
$$q_2 = \frac{T_{S1} - T_{S2}}{R_f}$$

$$R = \frac{L}{kA}$$

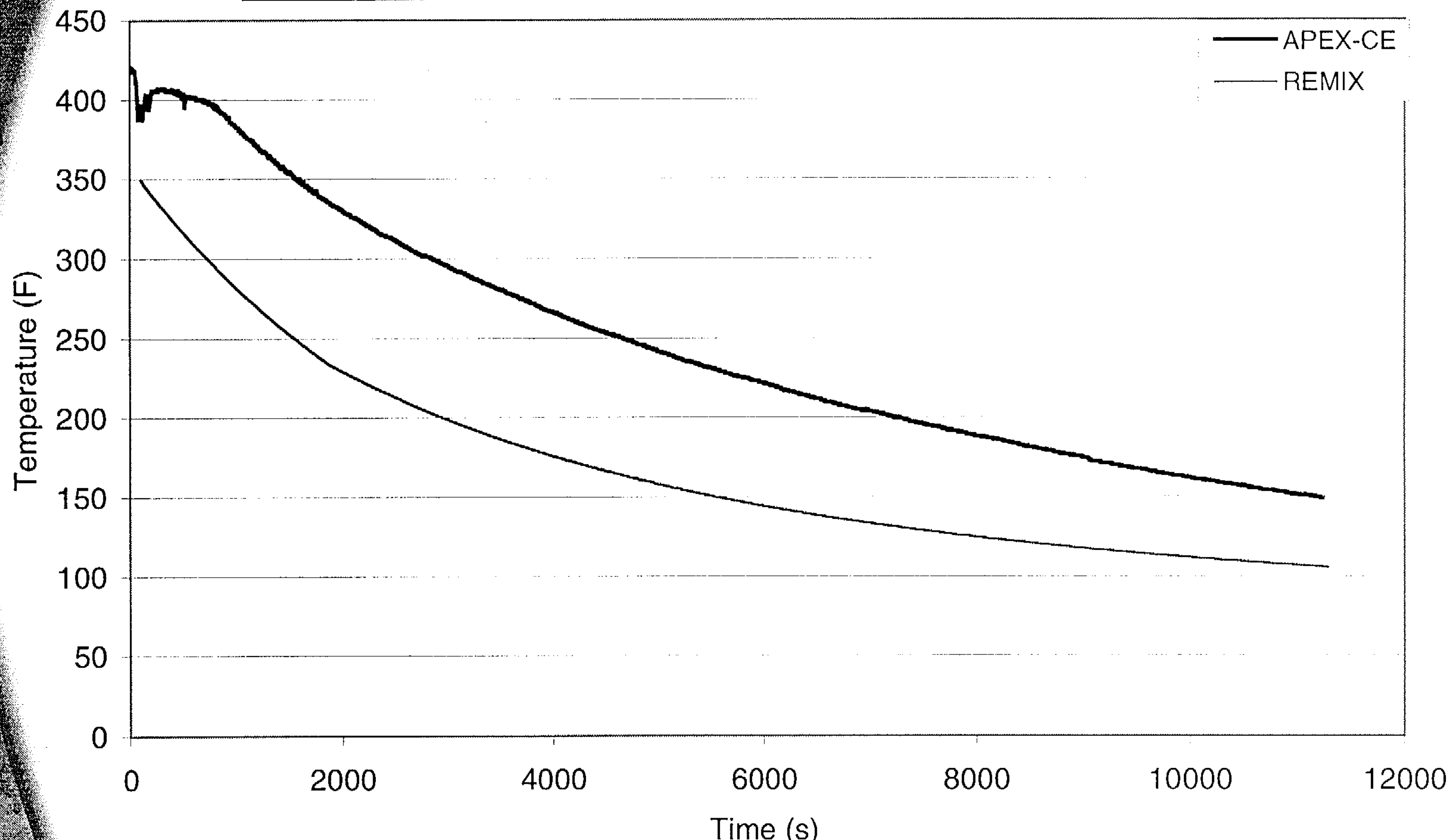
REMIX Comparisons

- Well-Mixed and DC Temperatures
  - OSU-CE-0004
  - OSU-CE-0005
  - OSU-CE-0006

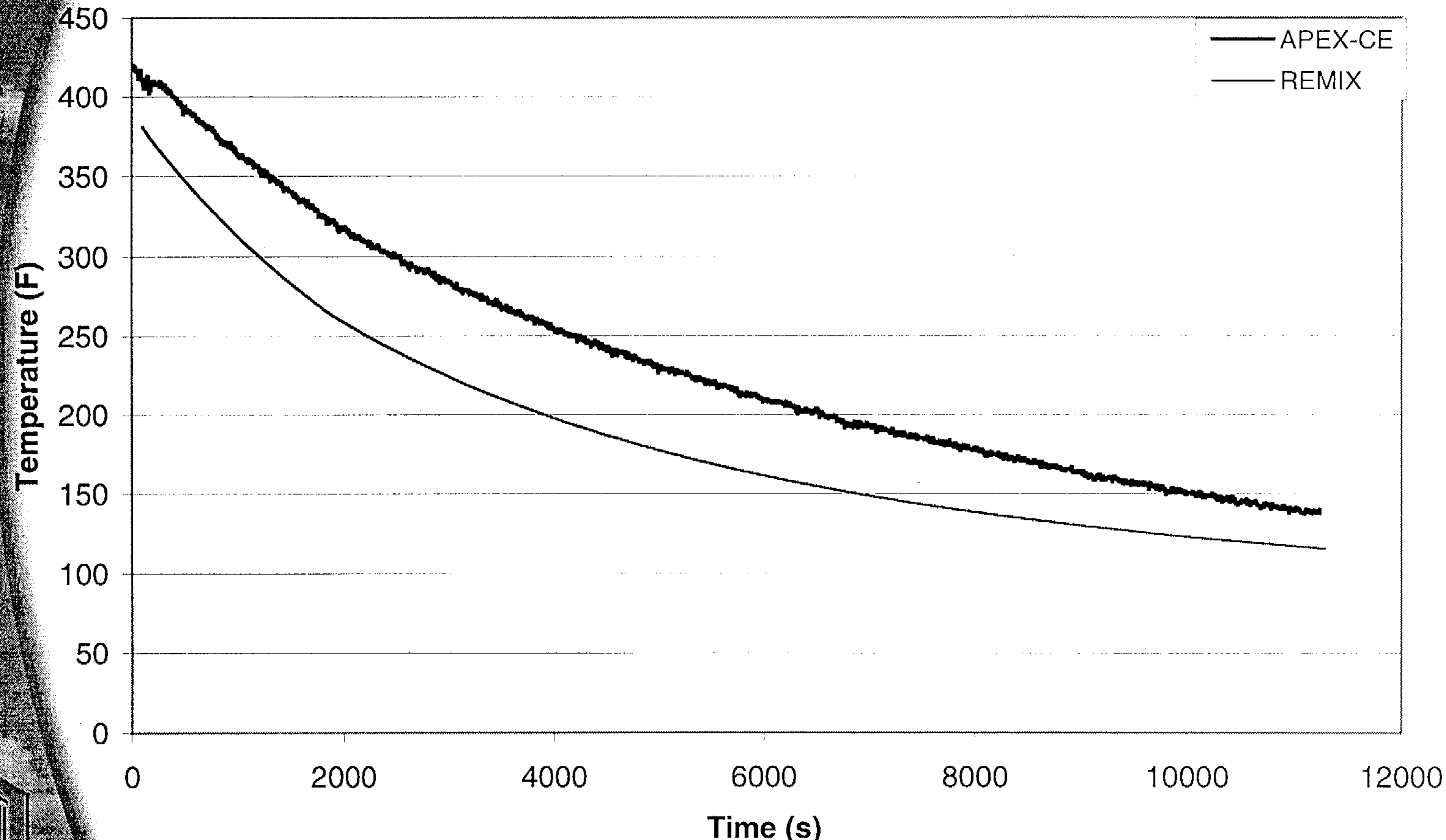
Core Inlet Well-Mixed Temperature, OSU-CE-0004 (1 HPSI)



DC Temperature 1.3 D, OSU-CE-0004 (1 HPSI)



DC Temperature 4.0 D, OSU-CE-0004 (1 HPSI)



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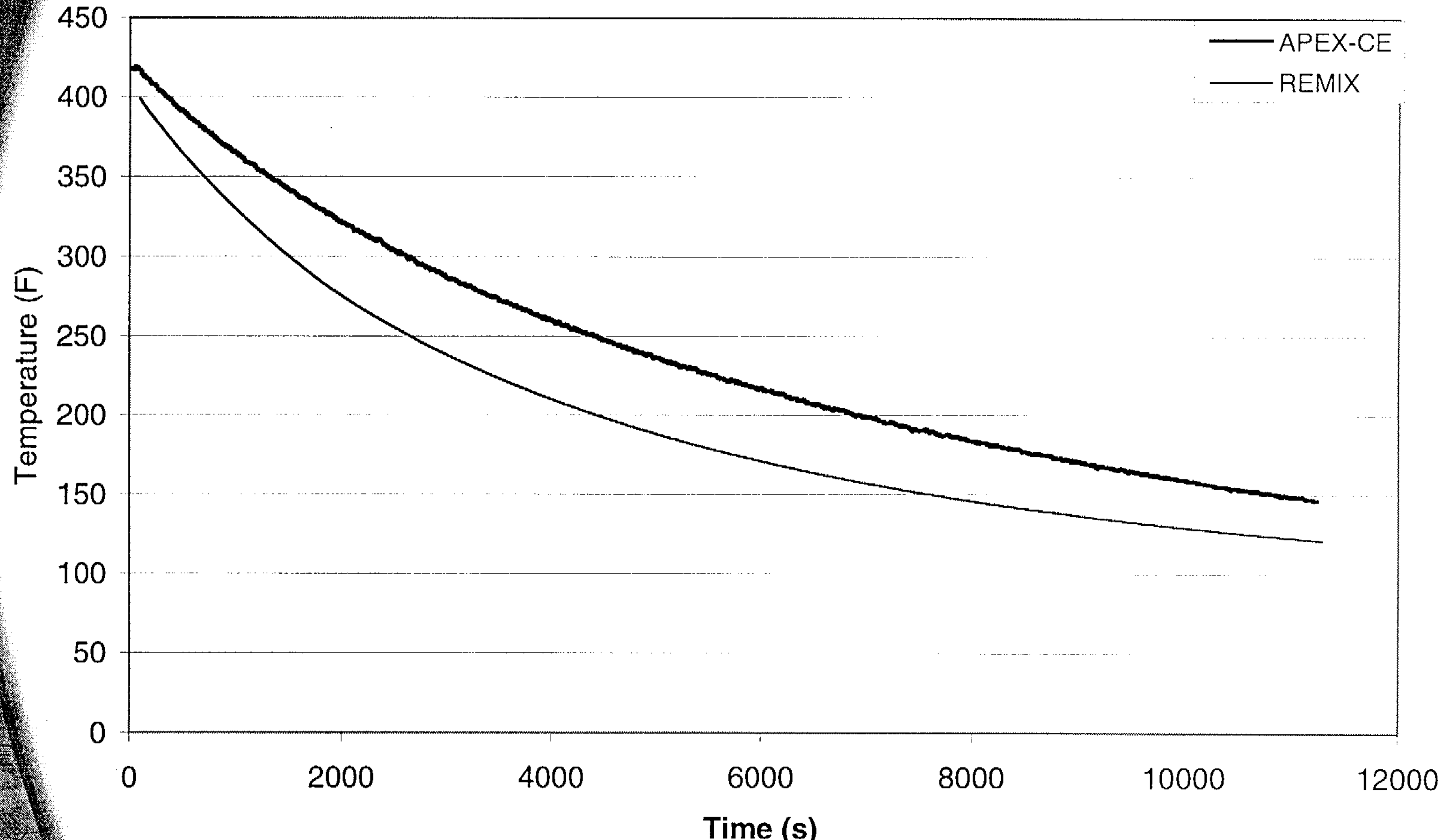
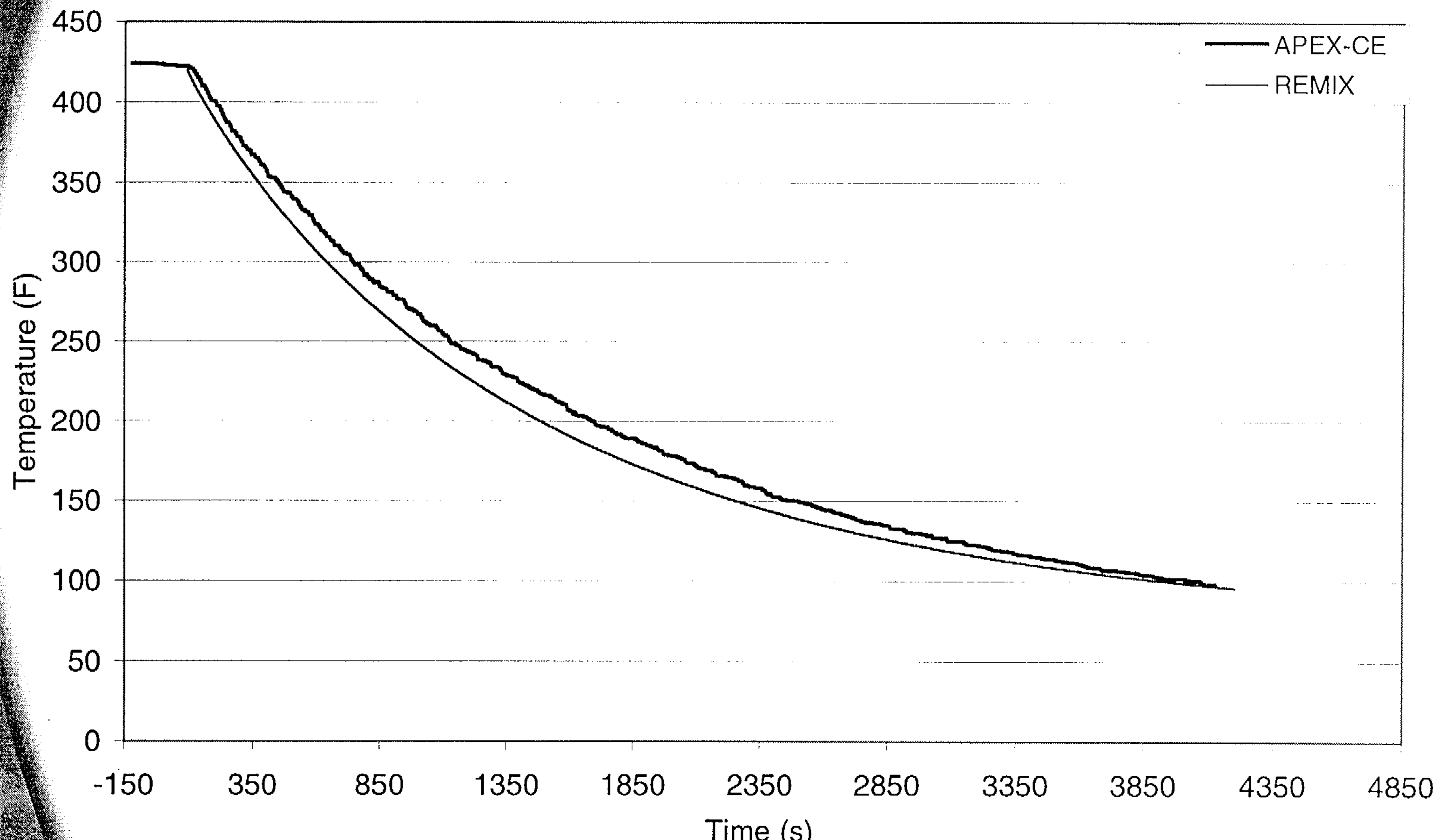
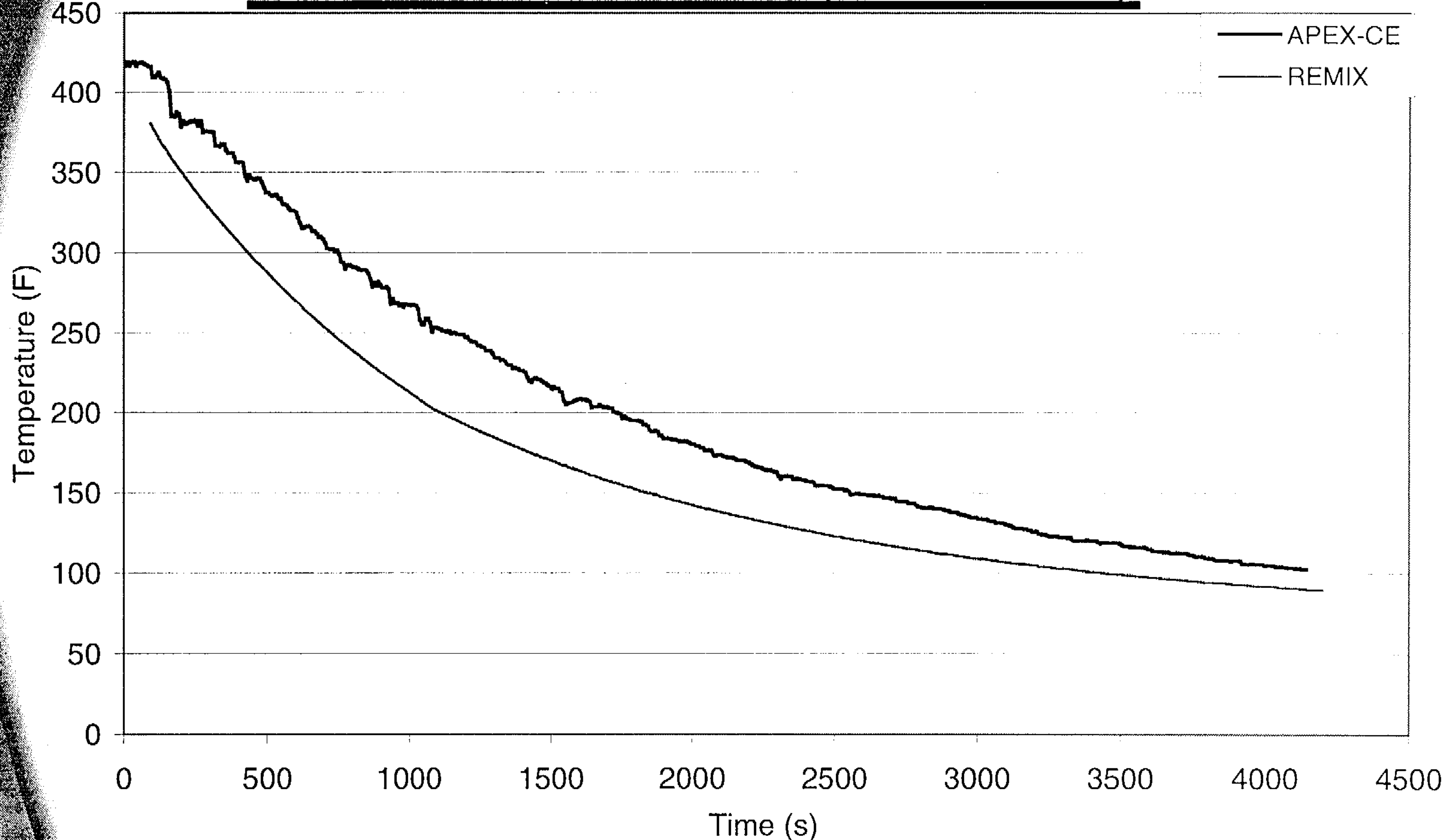
DC Temperature 8.0 D, OSU-CE-0004 (1 HPSI)



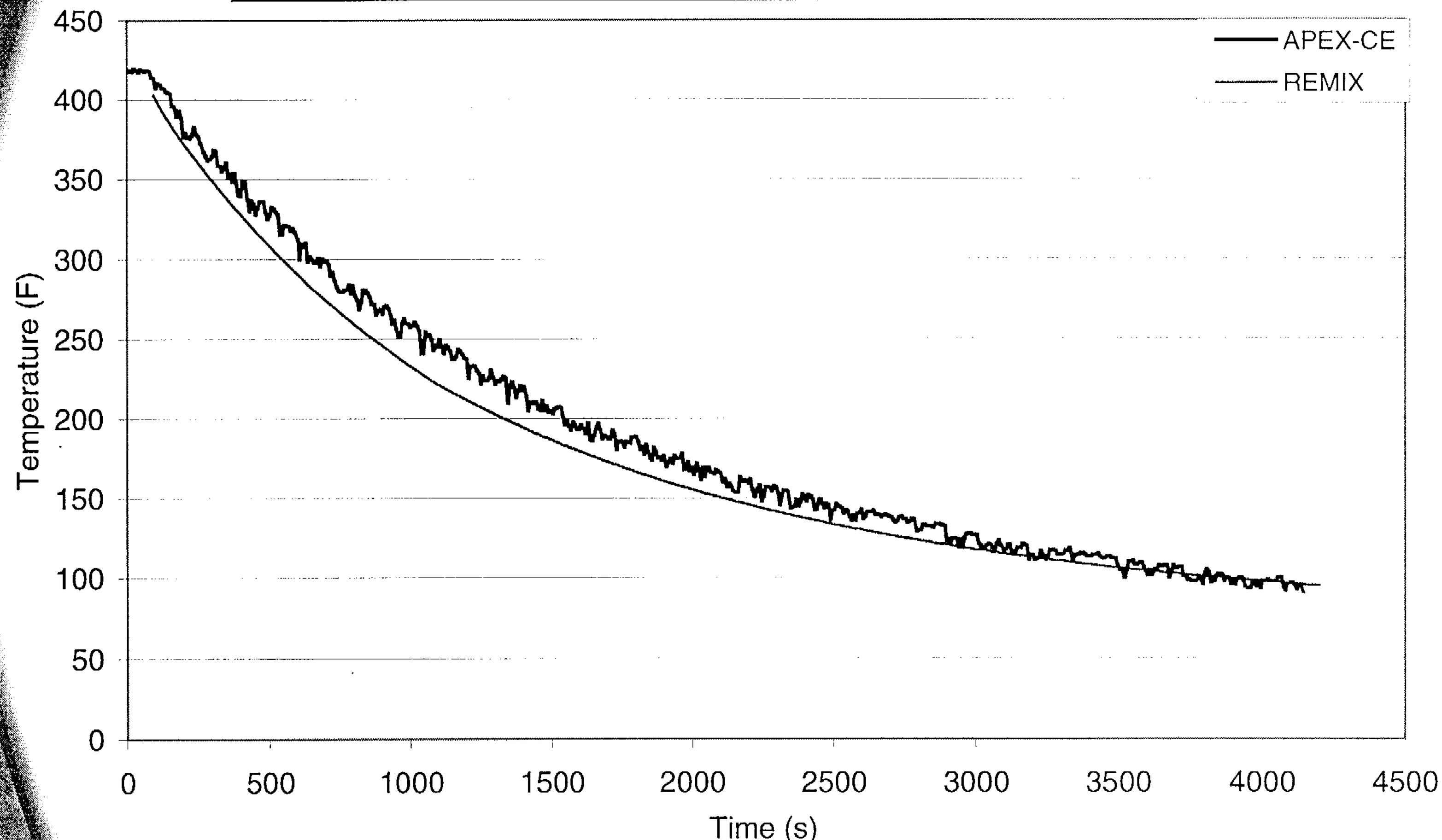
Core Inlet Well-Mixed Temperature, OSU-CE-0005 (4 HPSI)



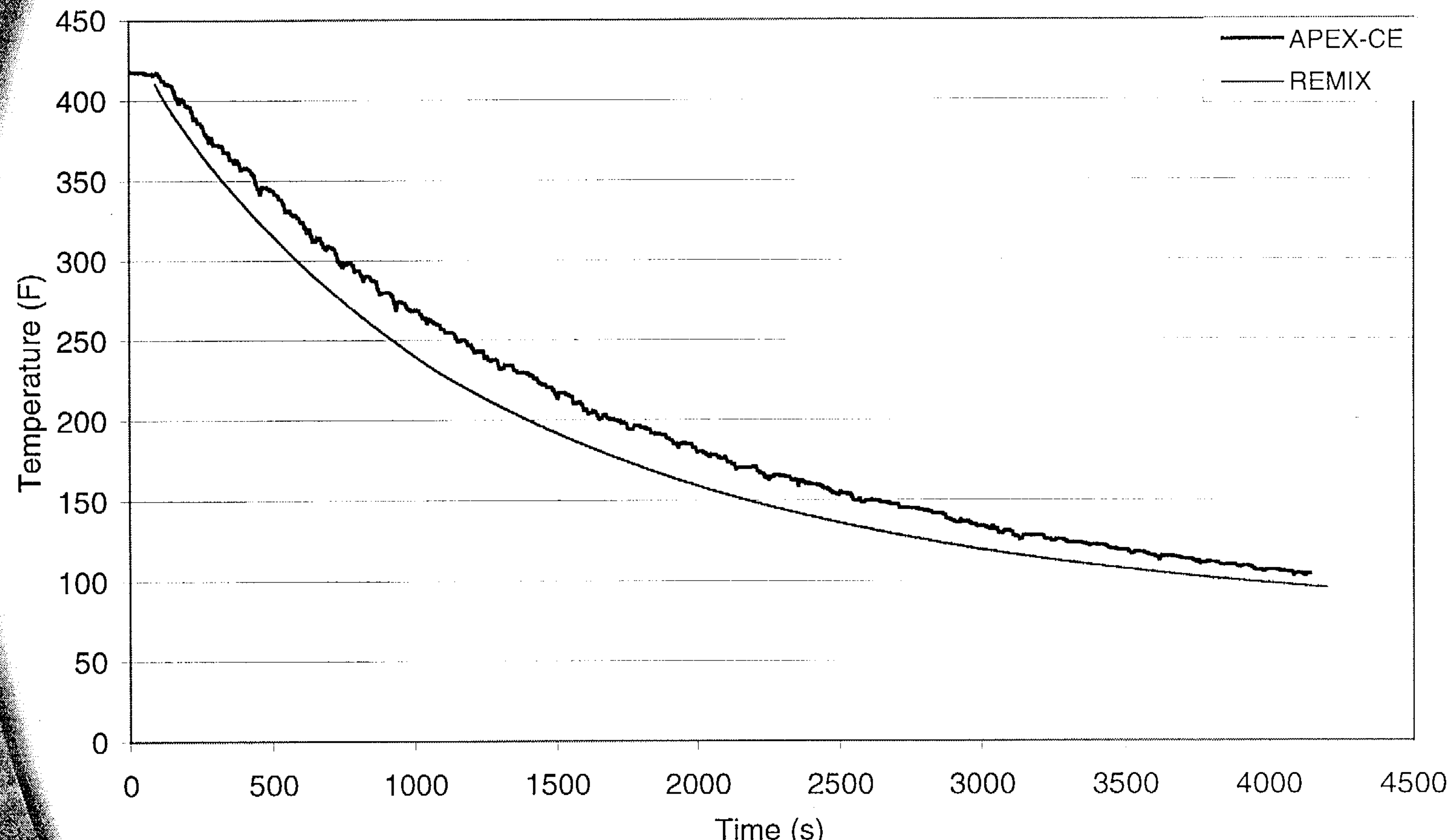
DC Temperature 1.3 D, OSU-CE-0005 (4 HPSI)



DC Temperature 4.0 D, OSU-CE-0005 (4 HPSI)



DC Temperature 8.0 D, OSU-CE-0005 (4 HPSI)



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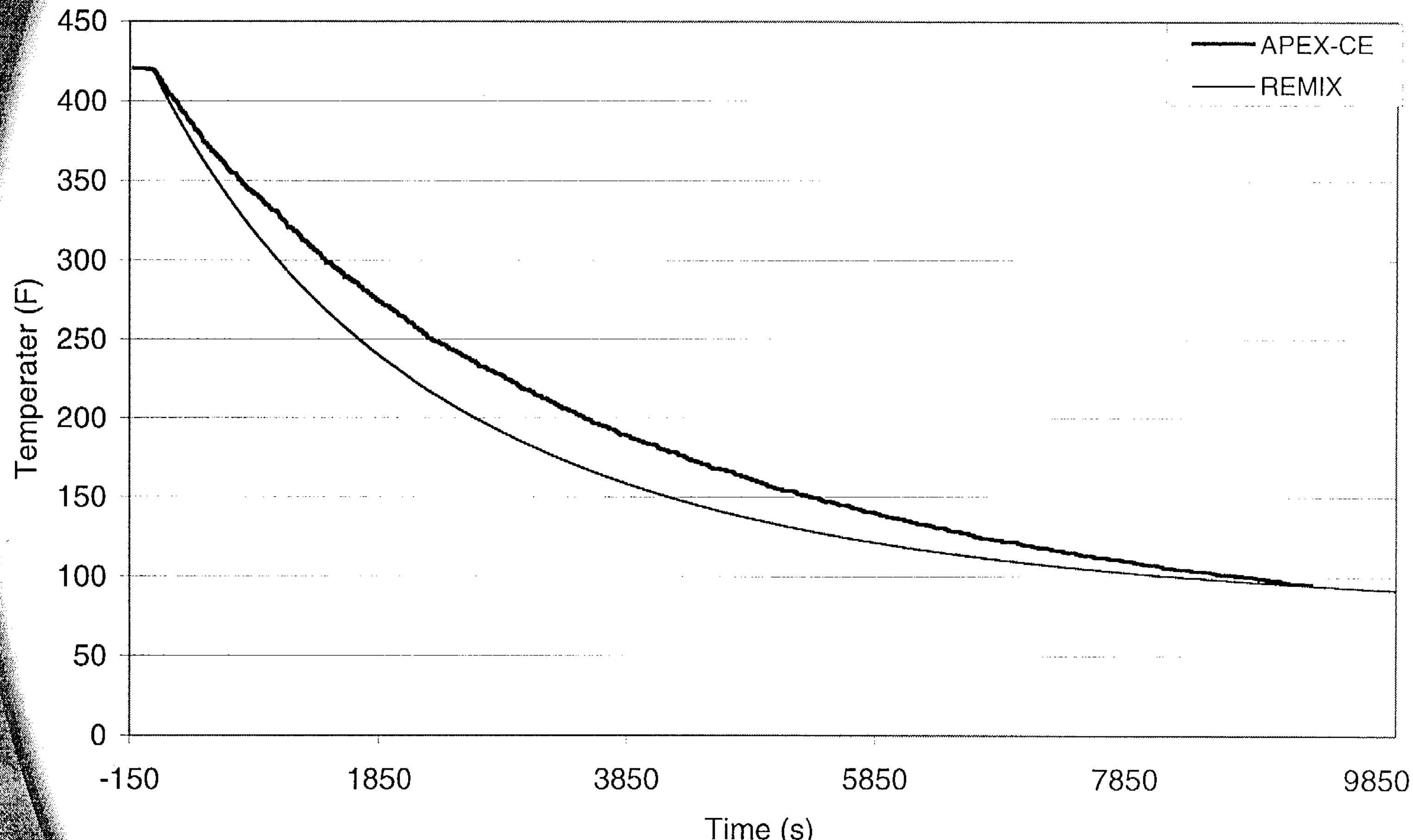
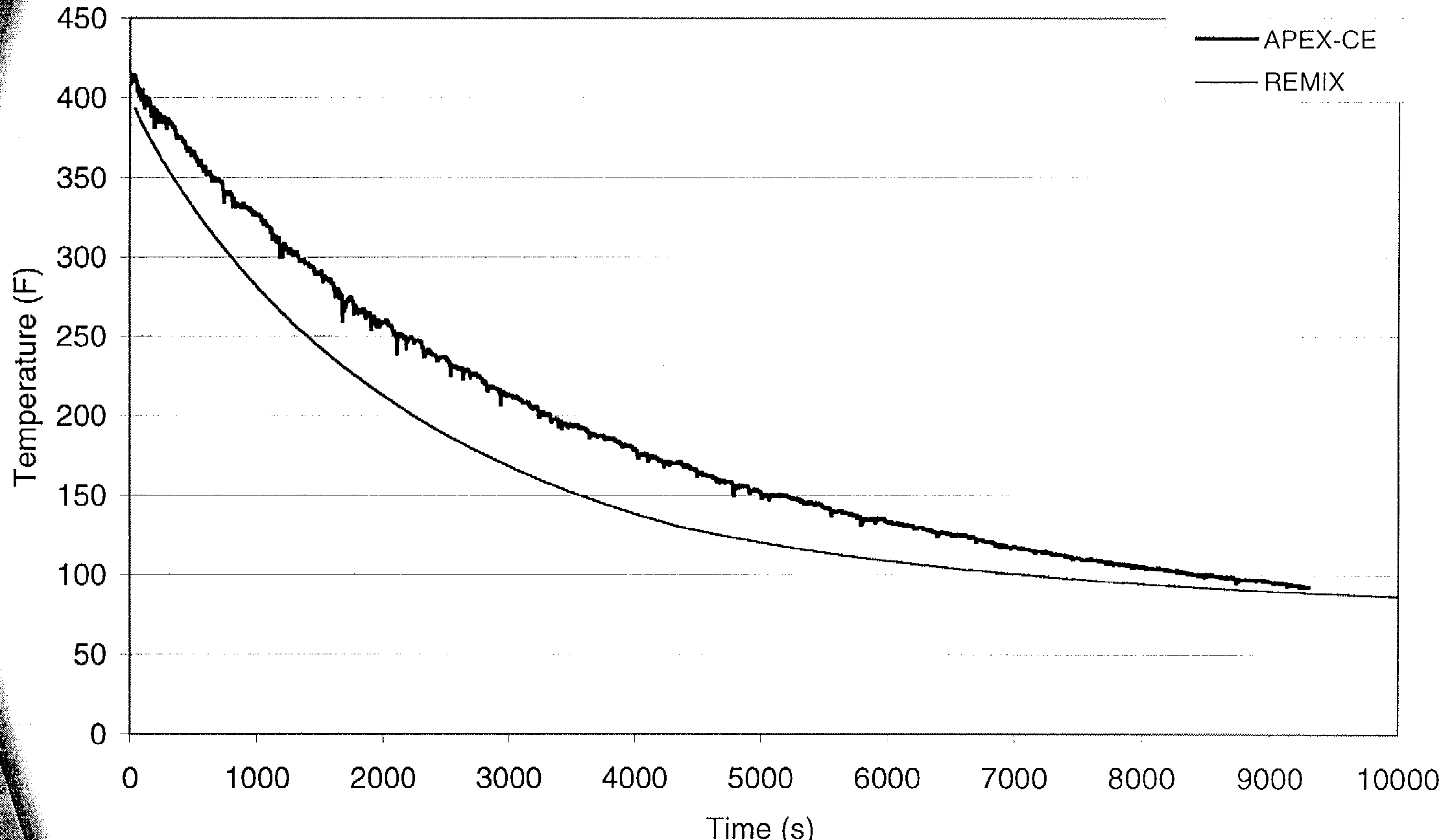
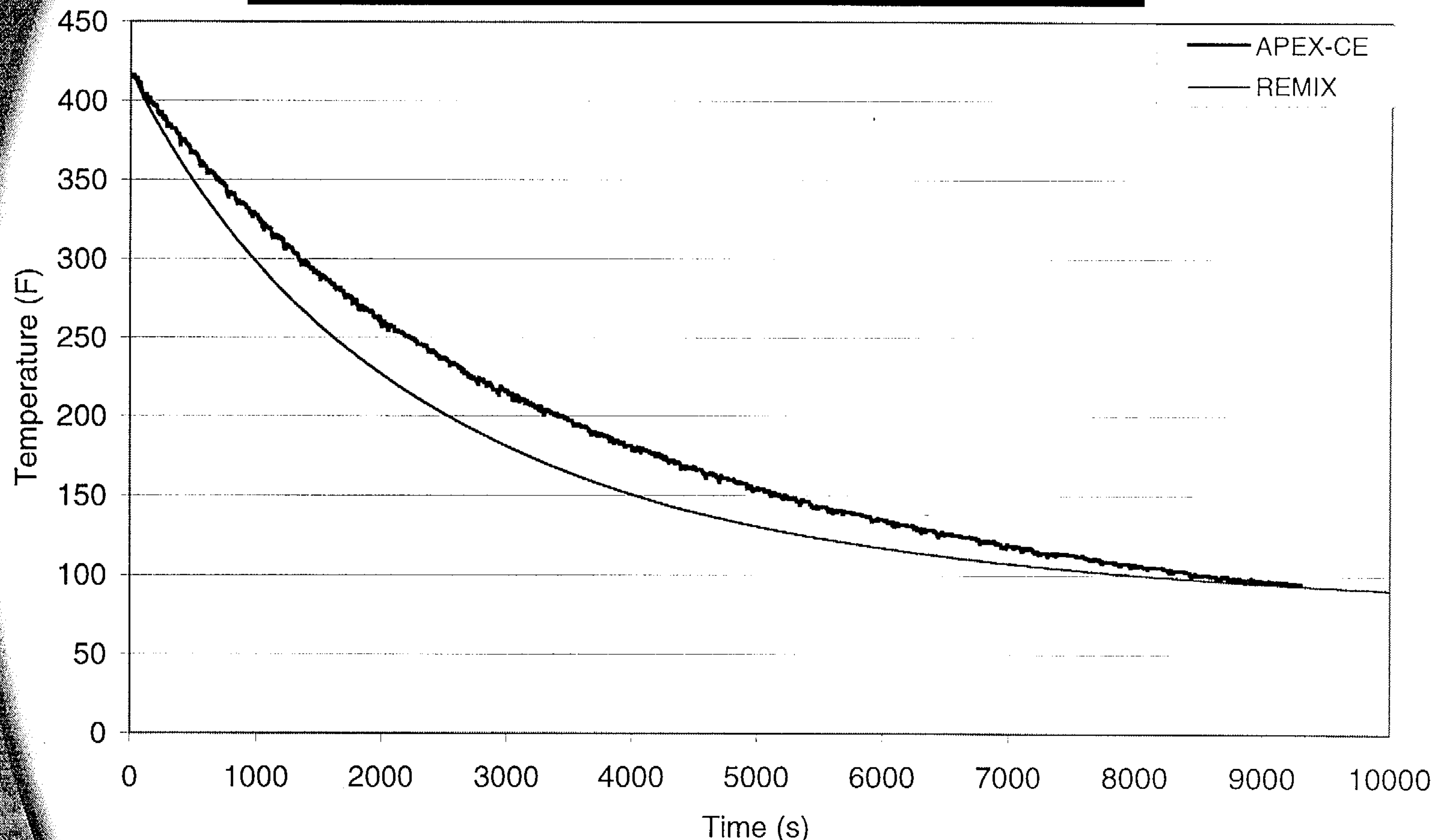
Core Inlet Well-Mixed Temperature, OSU-CE-0006 (4 HPSI)



DC Temperature 1.3 D, OSU-CE-0006 (4 HPSI)



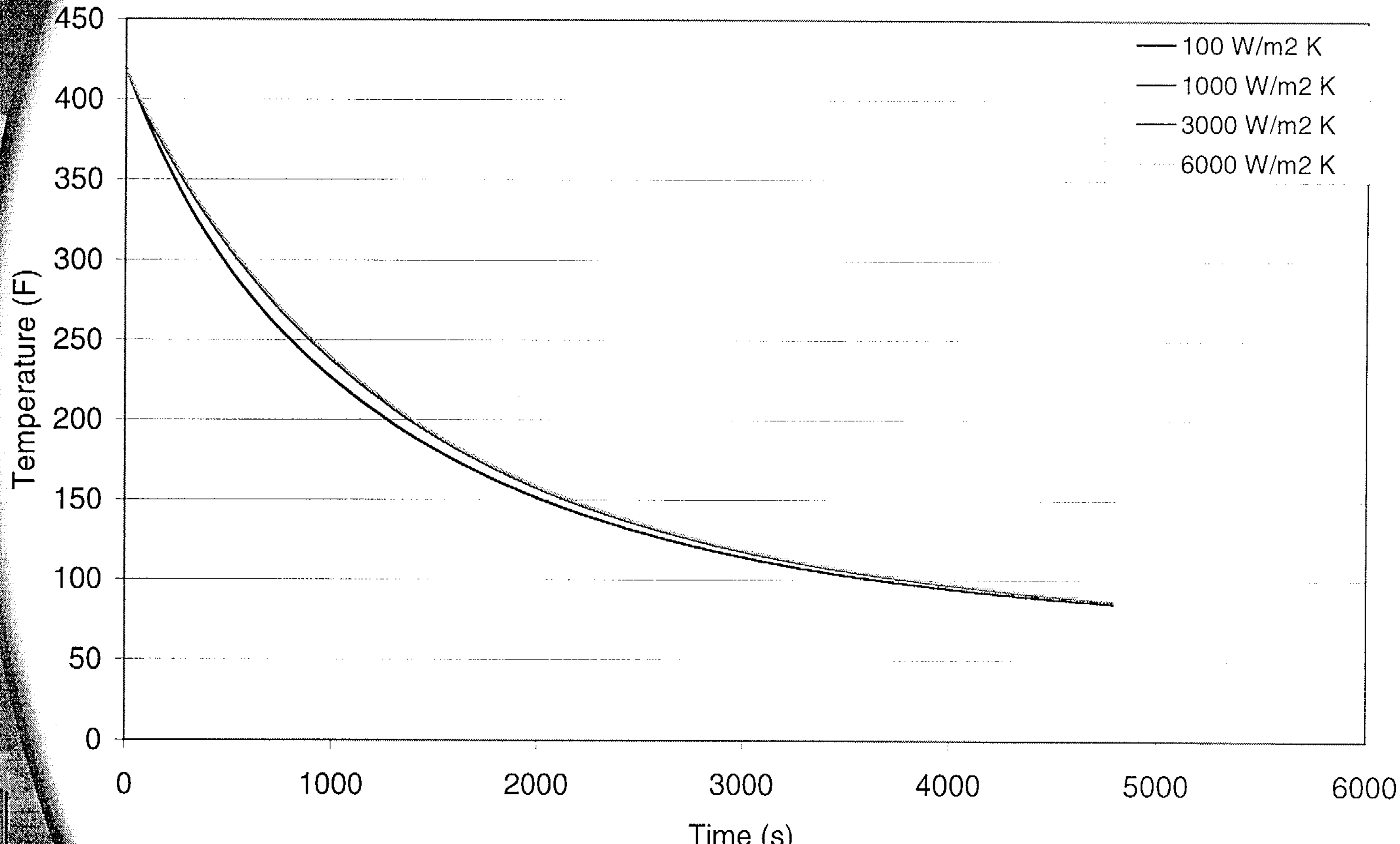
DC Temperature 8.0 D, OSU-CE-0006 (4 HPSI)



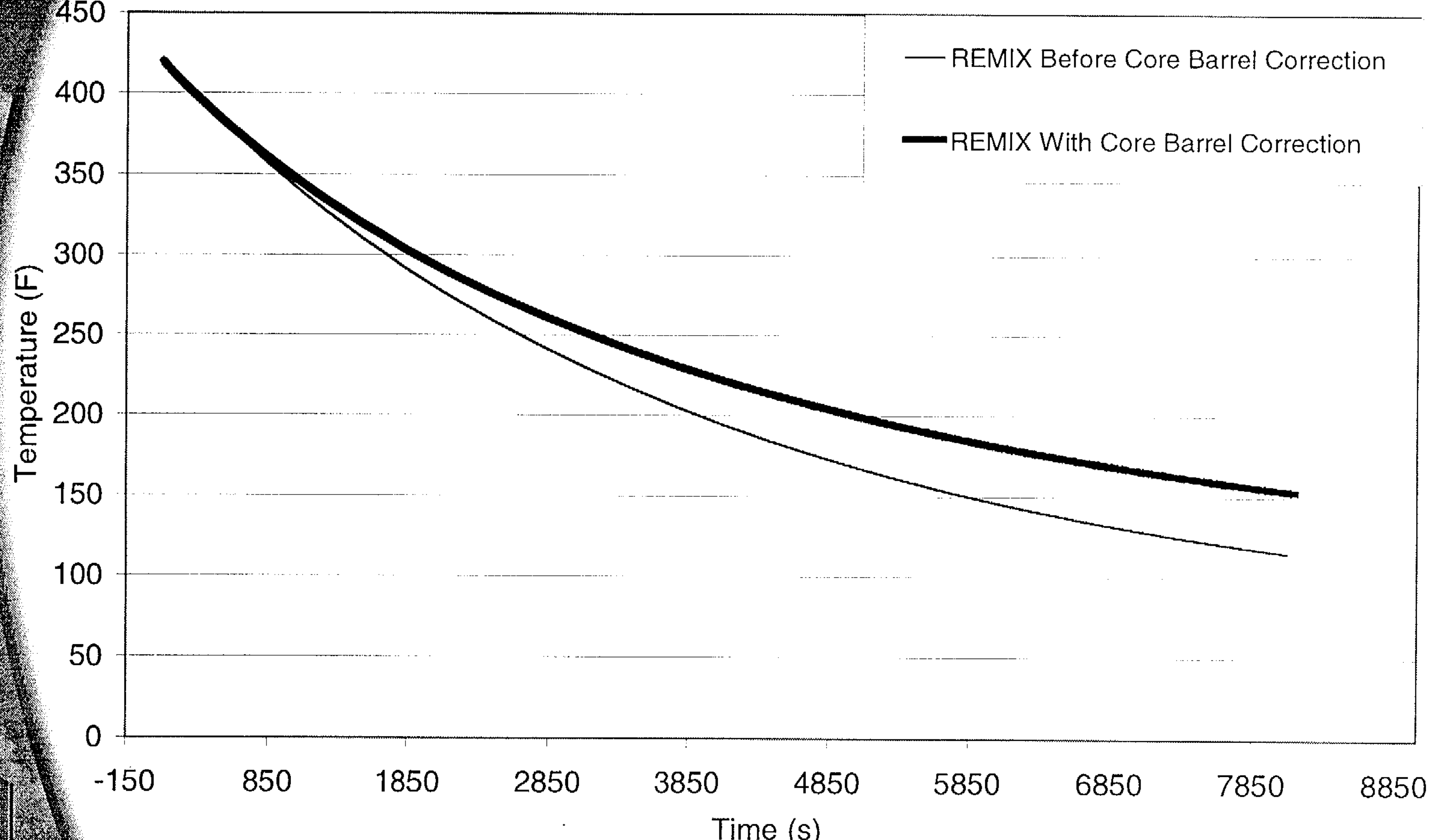
Effects of Heat Transfer Coefficient and Reflector/Core Barrel Stored Energy Release

- Varying the Heat Transfer Coefficient does not significantly impact the downcomer temperature.
- Not including the APEX-CE reflector has a significant impact on the downcomer temperatures.

REMIX Heat Transfer Coefficient Sensitivity



Effect of Reflector Stored Energy Release on Downcomer Fluid Temperatures

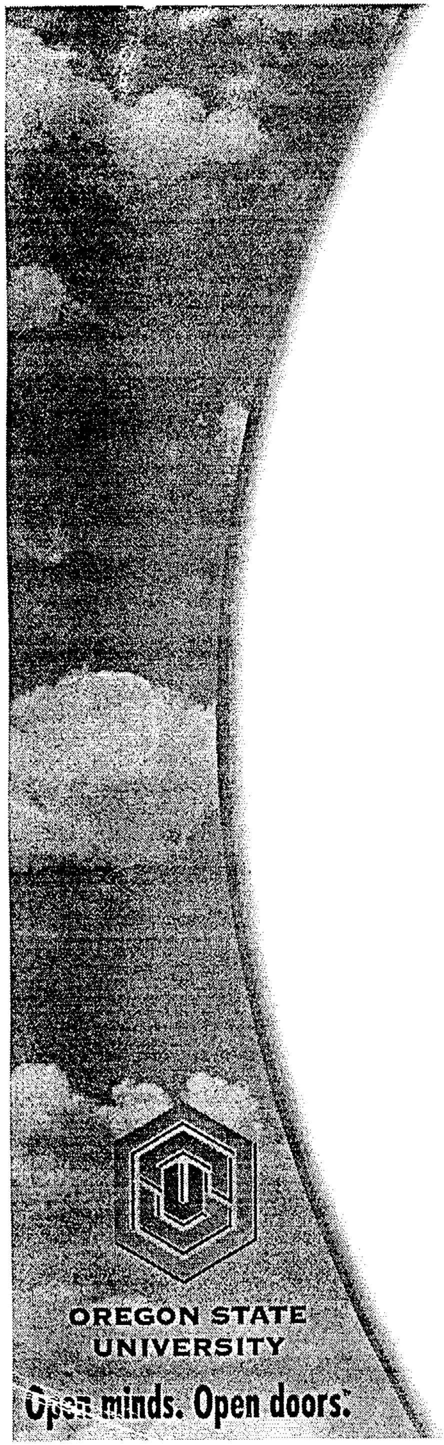


Summary and Conclusions

- A REMIX model has been developed for APEX-CE. It includes the core barrel and reflector.
- REMIX Comparisons
  - OSU-CE-0004
    - REMIX under predicted the core inlet (well-mixed) temperature and the DC temperatures.
  - OSU-CE-0005
    - REMIX was in good agreement with core inlet temperature
    - DC temperatures are under predicted
  - OSU-CE-0006
    - REMIX was in good agreement with the core inlet temperatures
    - DC temperatures are under predicted

Summary and Conclusions

- All of the 1.3 D fluid temperatures were significantly under predicted by REMIX. This was because the plume "jumps" the downcomer gap and impinges on the core barrel.
- REMIX generally under predicted the downcomer fluid temperatures. Multiple plume interactions may be one factor.



Star-CD and Creare ½ Scale Benchmark Calculations

Brandon Haugh

Presentation To

Advisory Committee On Reactor Safeguards

Thermal Hydraulic Phenomena Subcommittee Meeting

July 17-18, 2001

Outline

- Objectives
- Introduction to STAR-CD CFD Code.
- Description of the Creare 1/2-Scale Test Facility.
- Description of Creare MAY-105 Test.
- Description of STAR-CD Model.
- Comparison of STAR-CD Results with Creare Data.
- Conclusions

Objectives

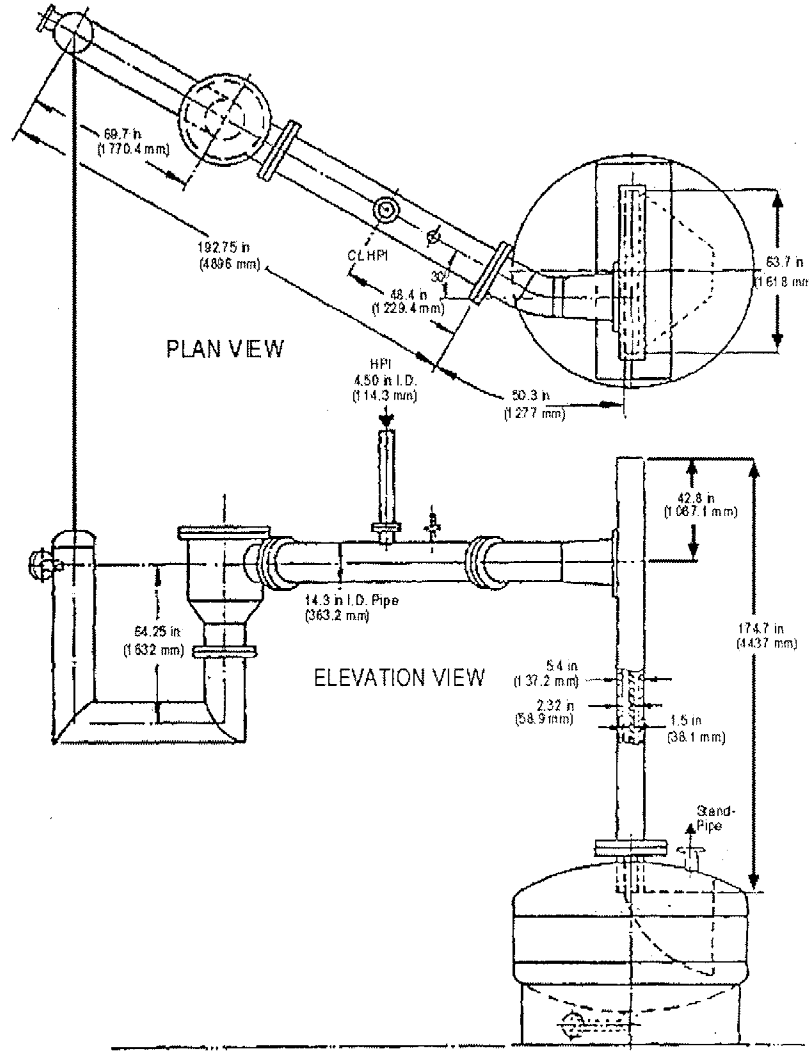
- Benchmark STAR-CD against an applicable data set.
- Provide insights into the code operation to support the APEX-CE Simulations.
- Establish the Learning Curve For STAR-CD.

STAR-CD CFD Code

- STAR-CD is a Computational Fluid Dynamics Code (CFD). The acronym STAR stands for Simulation of Turbulent flow in Arbitrary Regions.
- The Code Consists of:
  - A preprocessor/postprocessor called Prostar.
  - An analysis package called STAR.
  - A Parallel Computing Interface Called Pro-HPC.
- The code has the capability of handling many types of fluid flow, dispersed flow, and chemical reactions.

Creare 1/2-Scale Test Facility

- The Creare 1/2-Scale test facility is not a model of any particular PWR, but can simulate multiple types of PWR's.
- The configuration used in the MAY-105 test is shown to the right.



Creare 1/2-Scale Test Facility

- Some of the characteristic dimensions for the facility are:
  - Cold Leg *ID* – 14.3 inches (363.2 mm)
  - HPI *ID* – 4.5 inches (114.3 mm)
  - Downcomer Width – 63.7 inches (1618 mm)
  - Downcomer Gap – 5.4 inches (137.2 mm)
  - Thermal Shield Thickness – 1.5 inches (38.1 mm)
  - Vessel Wall Thickness – 2.75 inches (70 mm)

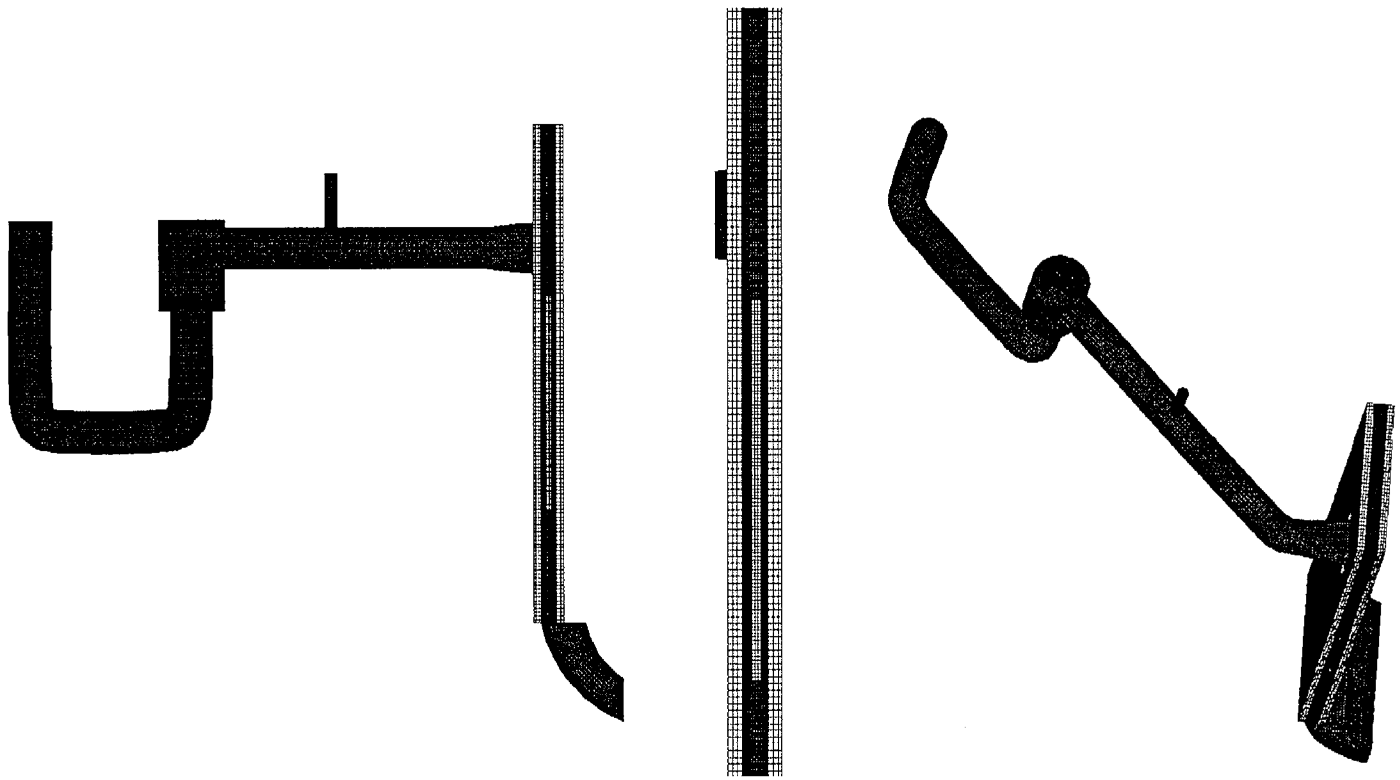
Creare MAY-105 Test

- The MAY-105 test initial conditions
  - Loop
    - Stagnant
    - 462.15 K (189 ^{0}C)
  - HPI
    - Constant Flow 5.17E-3 m^3/s
    - 287.35 K (14.2 ^{0}C)
- Test Duration
  - 2340 seconds

STAR-CD Model

- A computational grid was generated to represent the Creare test loop.
- The grid was generated using the meshing tool within STAR-CD
- The resulting grid consisted of
  - 214,308 Fluid Cells
  - 60,816 Solid Cells

STAR-CD Computational Grid



STAR-CD Model Vs. Creare

Component	Creare	STAR-CD	Difference
Loop Seal	17.72 ft^3	18.48 ft^3	0.76 ft^3
Pump Simulator	9.6 ft^3	4.19 ft^3	-5.41 ft^3
Cold Leg	14.35 ft^3	14.27 ft^3	-0.08 ft^3
Downcomer	29.45 ft^3	30.29 ft^3	0.84 ft^3
Lower Plenum	21.35 ft^3	19.07 ft^3	-2.28 ft^3
Total Volume	92.47 ft^3	86.3 ft^3	-6.17 ft^3

STAR-CD Model Inputs

- For the calculations to be run some parameters needed to be specified to establish the appropriate fluid conditions for the model.

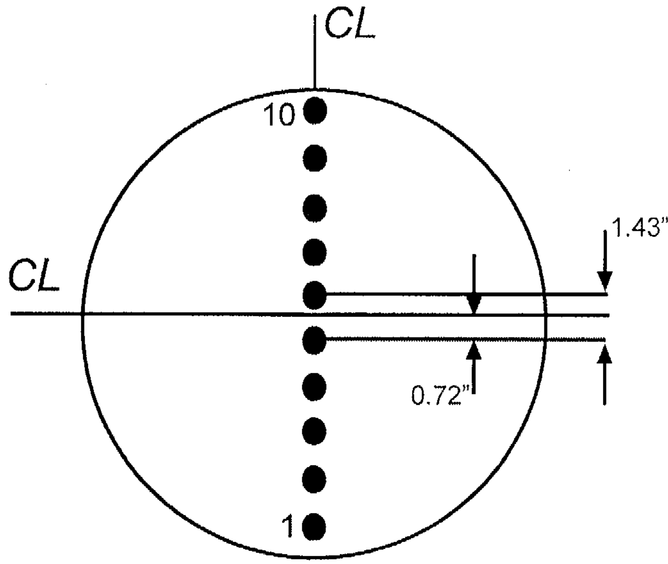
Turbulence Model	High Reynold's Number K-ε
Density is Isobaric	$\rho = \dfrac{\rho_0}{1+\beta_t(T-T_0)}$
Time Step	0.25 sec
Iterations	4280
Time of Transient	1070 sec

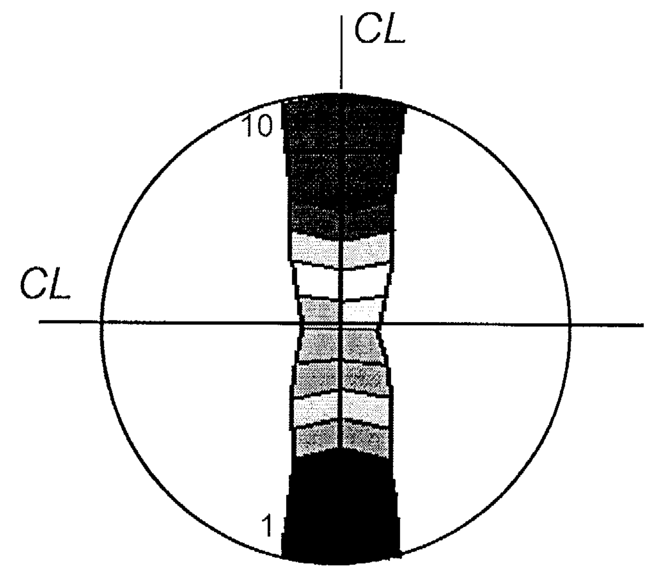
Results

- The model ran for a period of 7.7 days on a Sun Blade 1000 Dual 750 MHz Processor Unix machine.
- Results Presented
  - Cold Leg Stratification
    - Plots
  - Downcomer Temperatures
    - Animation of Plume activity in the downcomer
    - Plots
  - Velocities around the Thermal Shield
    - Snap Shots of Velocity Vectors

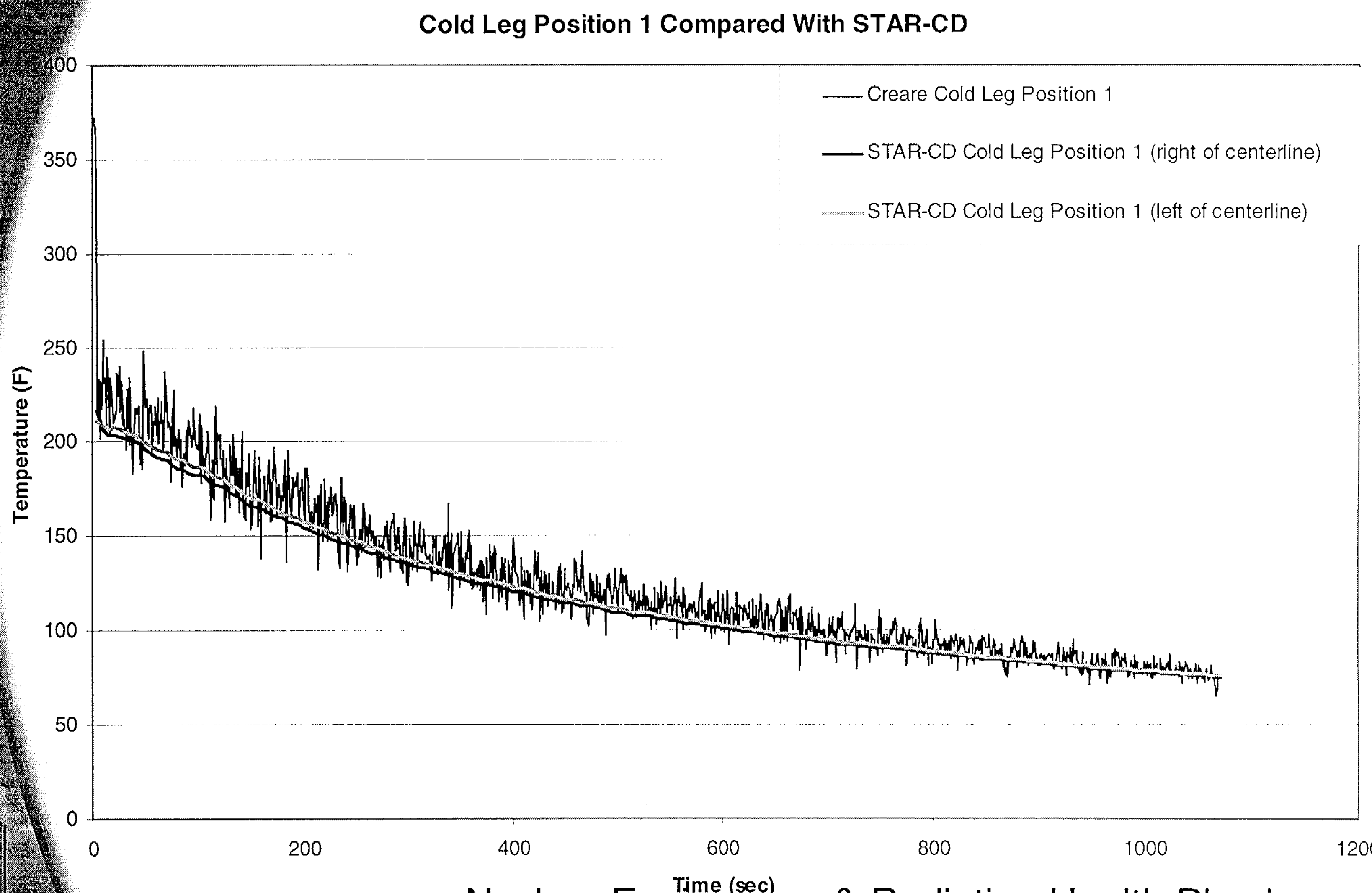
Cold Leg Stratification

- A cold leg rake in the Creare facility is located 9.1 inches (231.14 mm) after the HPI point towards the Downcomer.
- The thermocouples on this rake are compared with data from cells nearest or at the same location in the model.





Cold Leg Stratification (*continued*)



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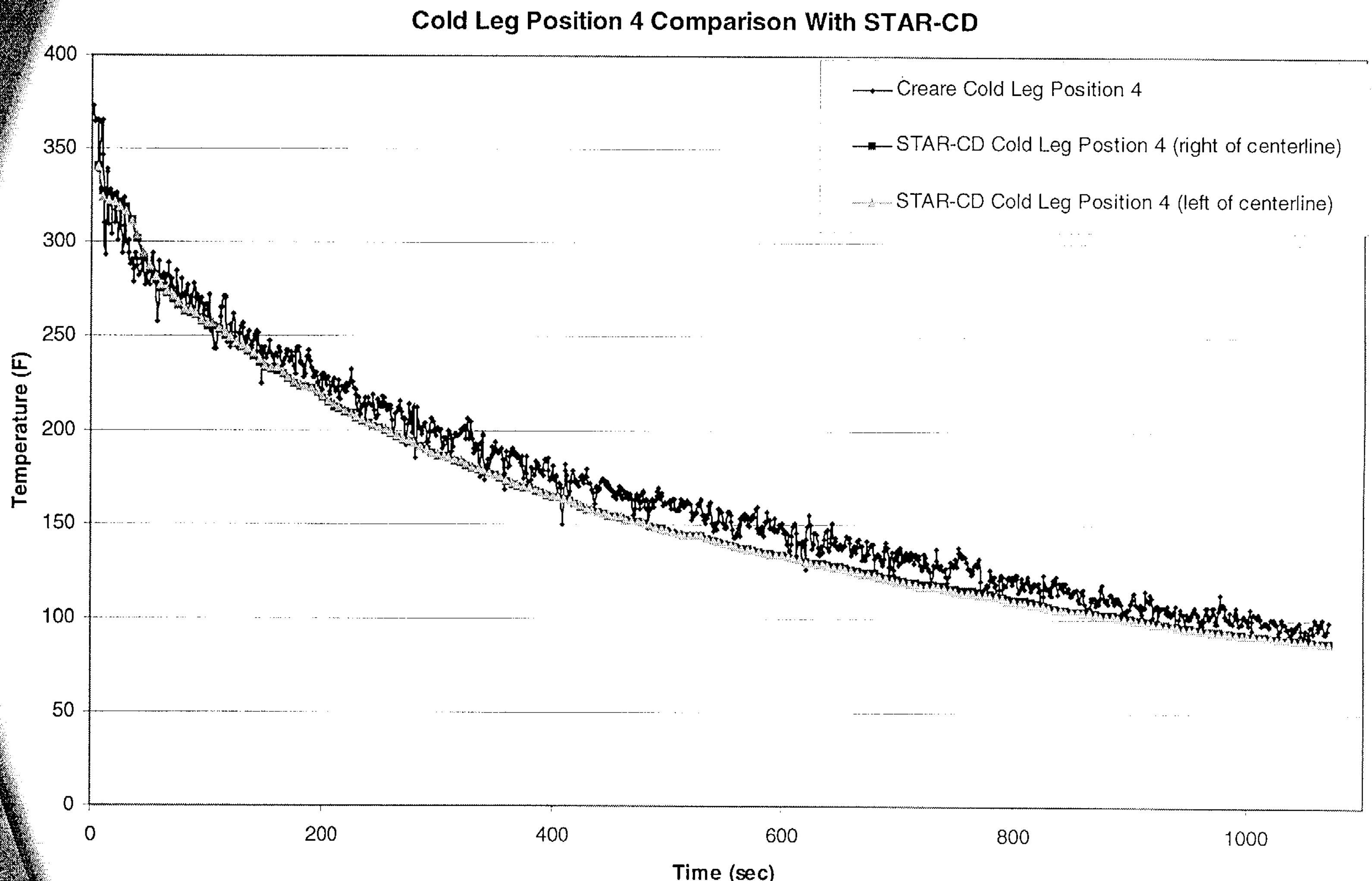
Cold Leg Stratification (*continued*)



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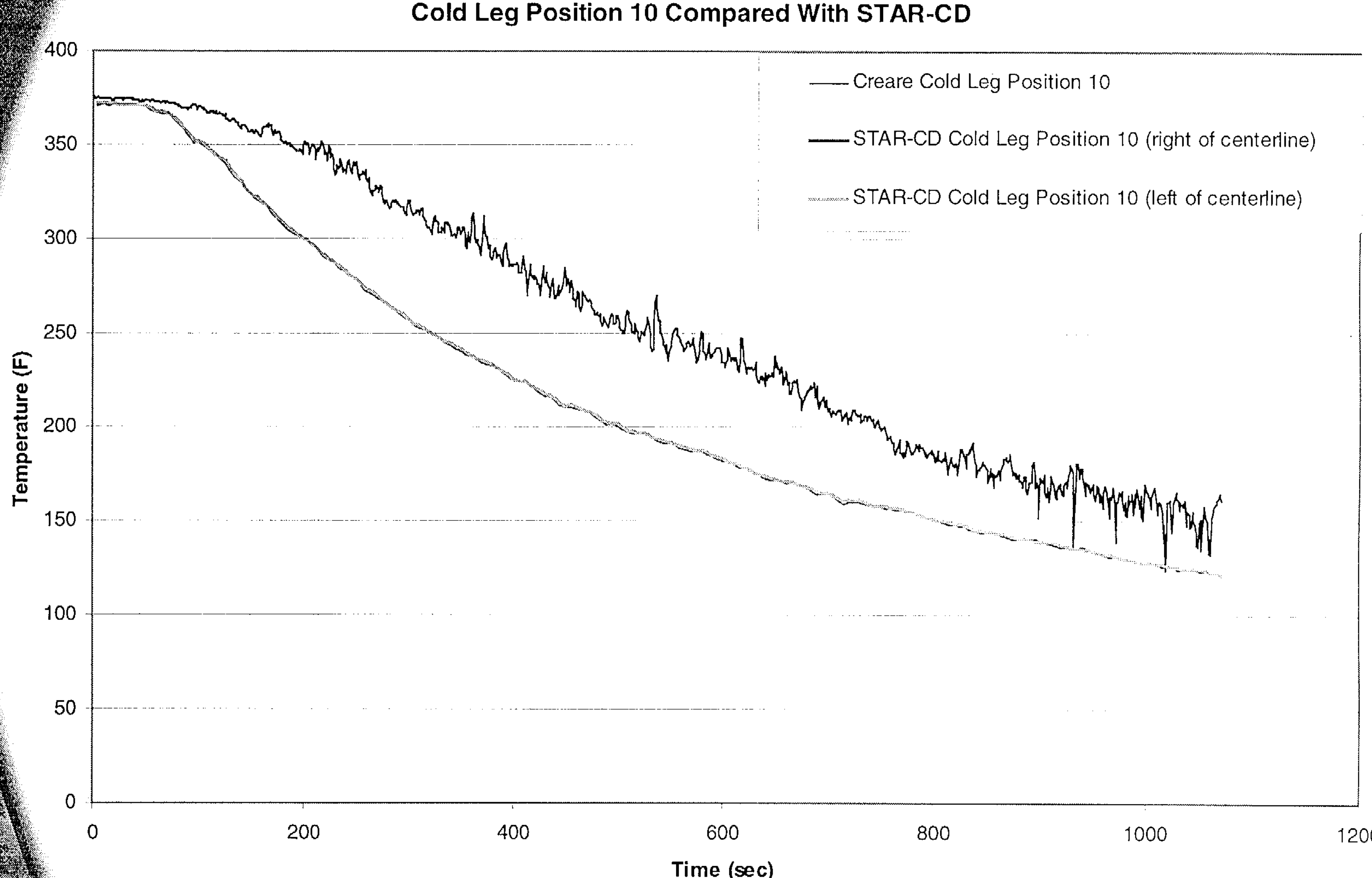
Cold Leg Stratification (*continued*)



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Downcomer Temperatures

- Animation of the model calculations to help visualize the plume development and mixing in the downcomer.
- The first animation is a view from the vessel side looking at the downcomer.
- The second is a view from the core side.

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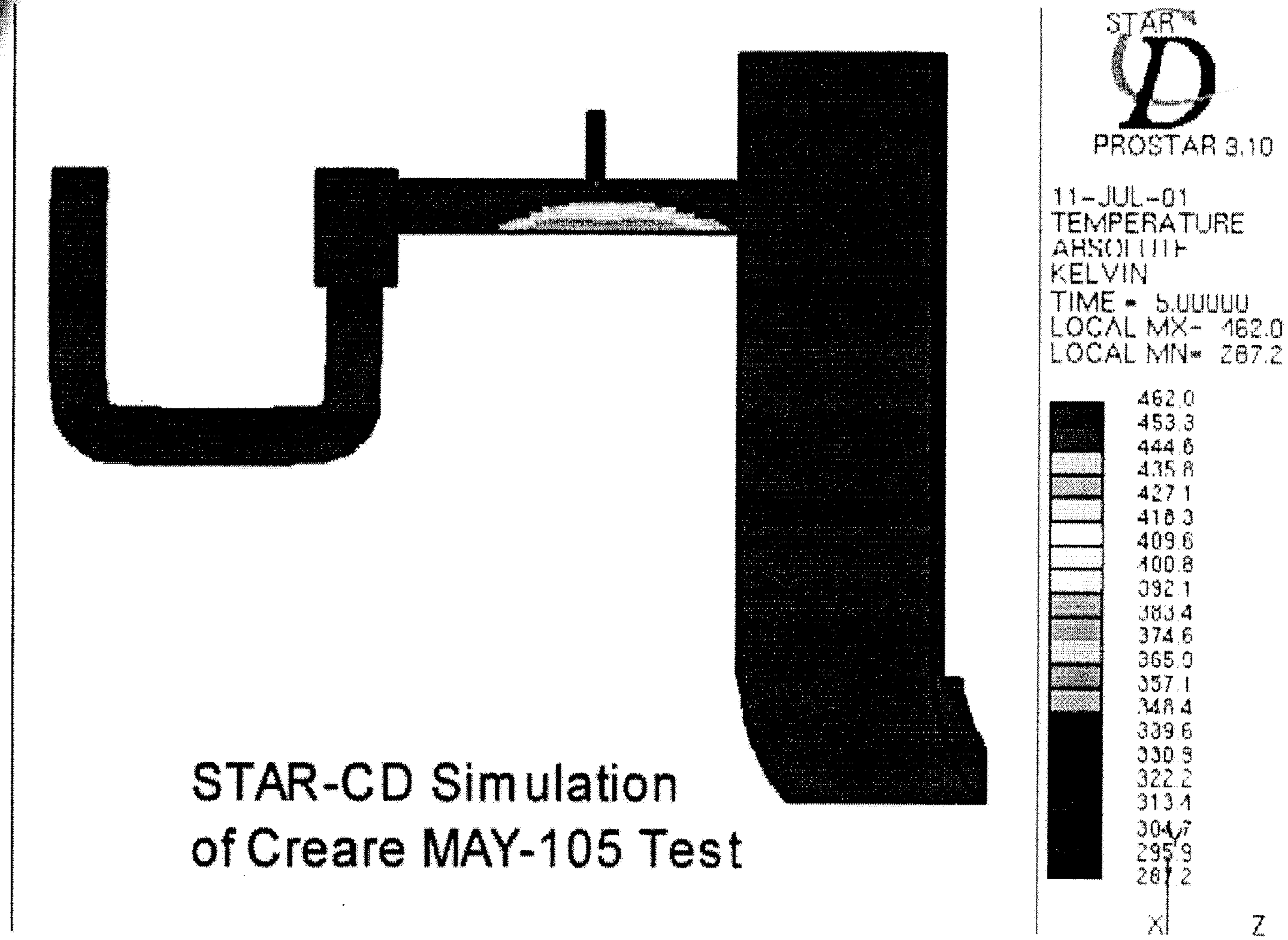
Downcomer Animation (Vessel Side)



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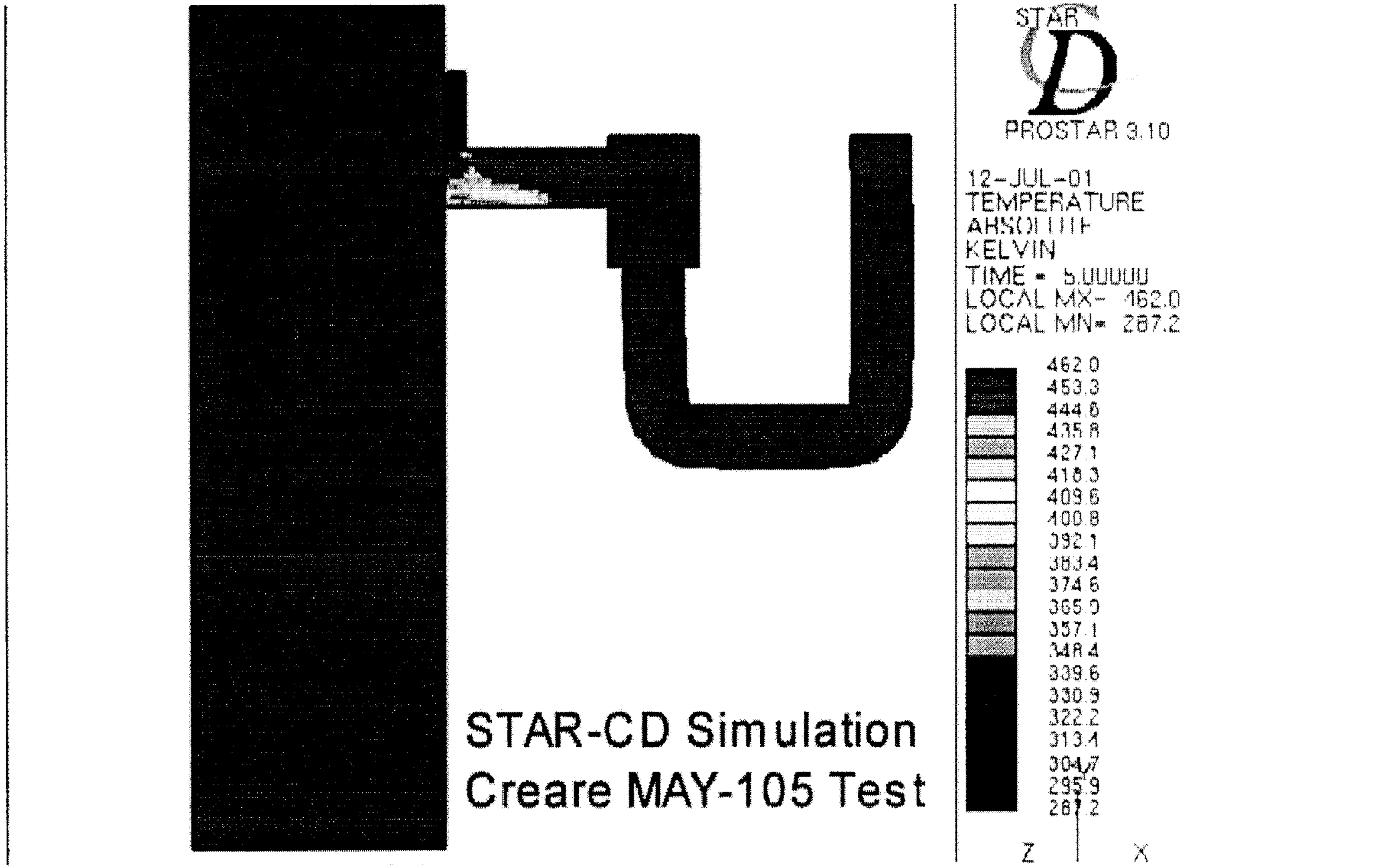
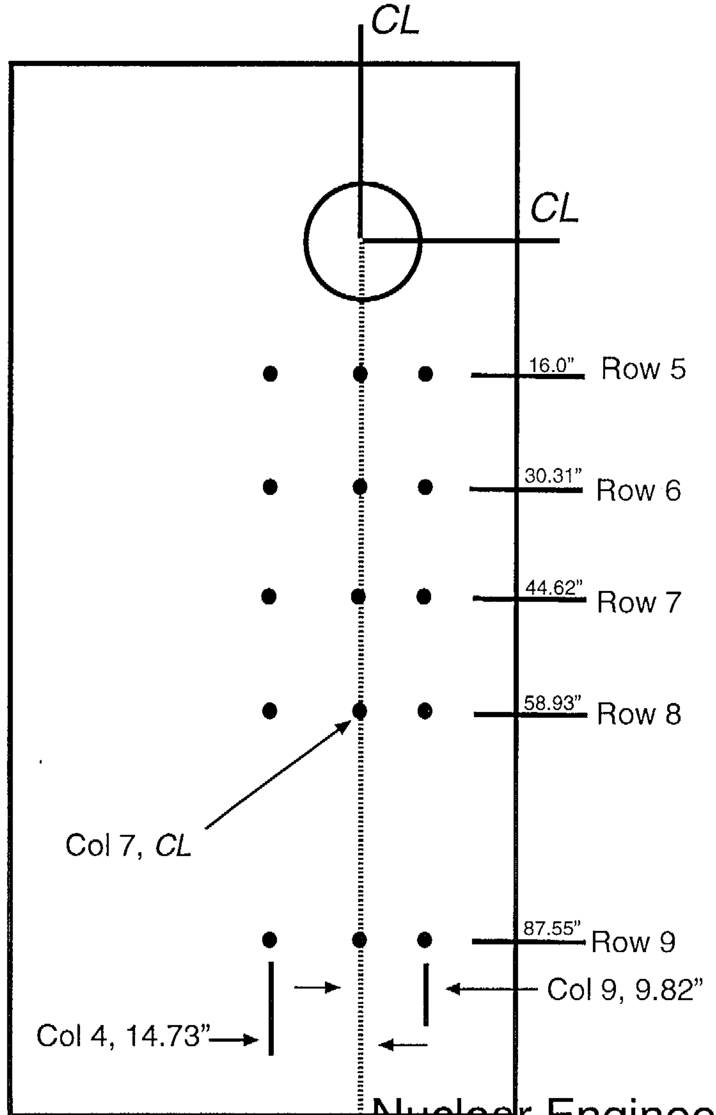
Downcomer Animation (Core) Side

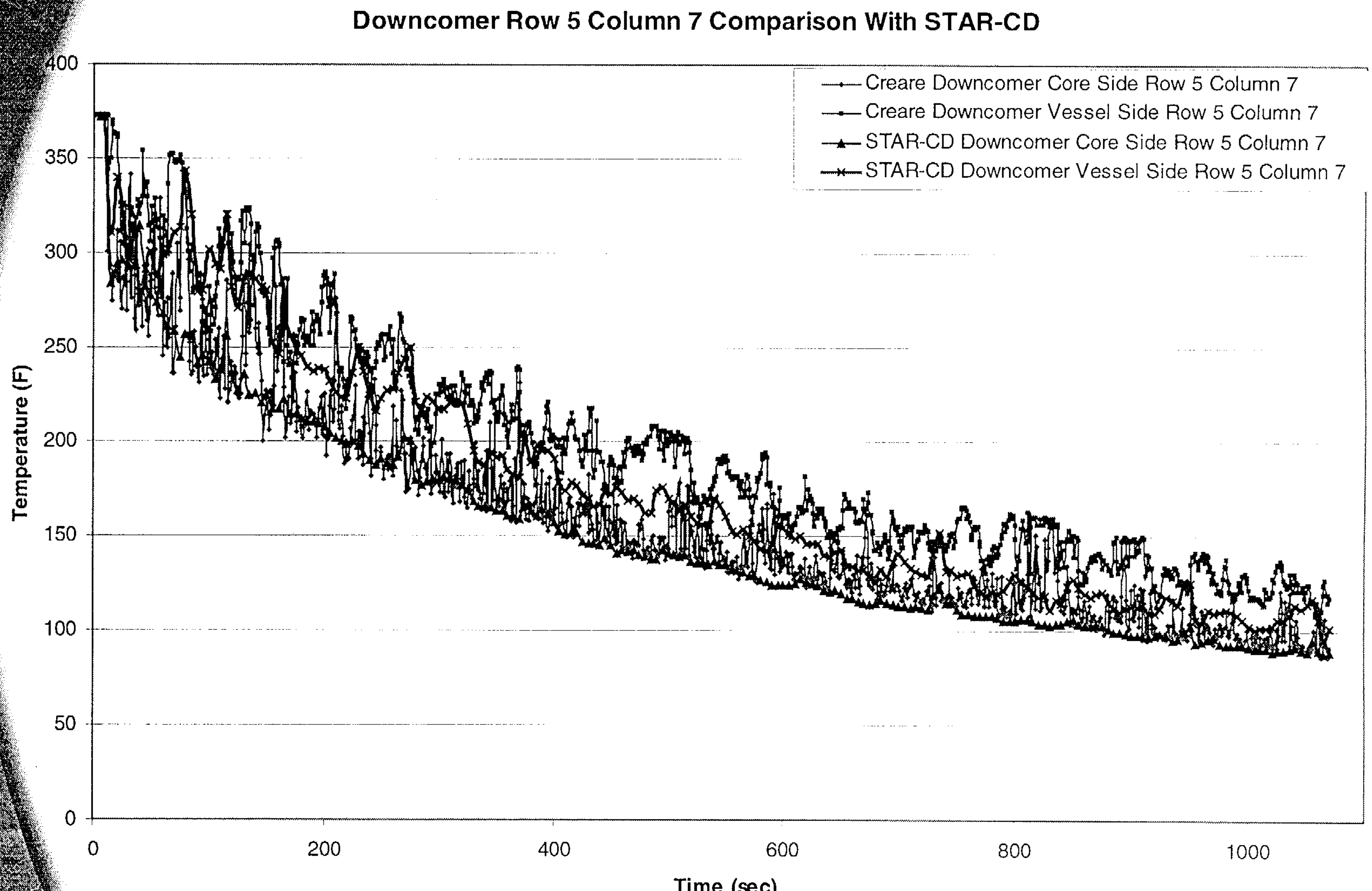


Downcomer Temperature Plots

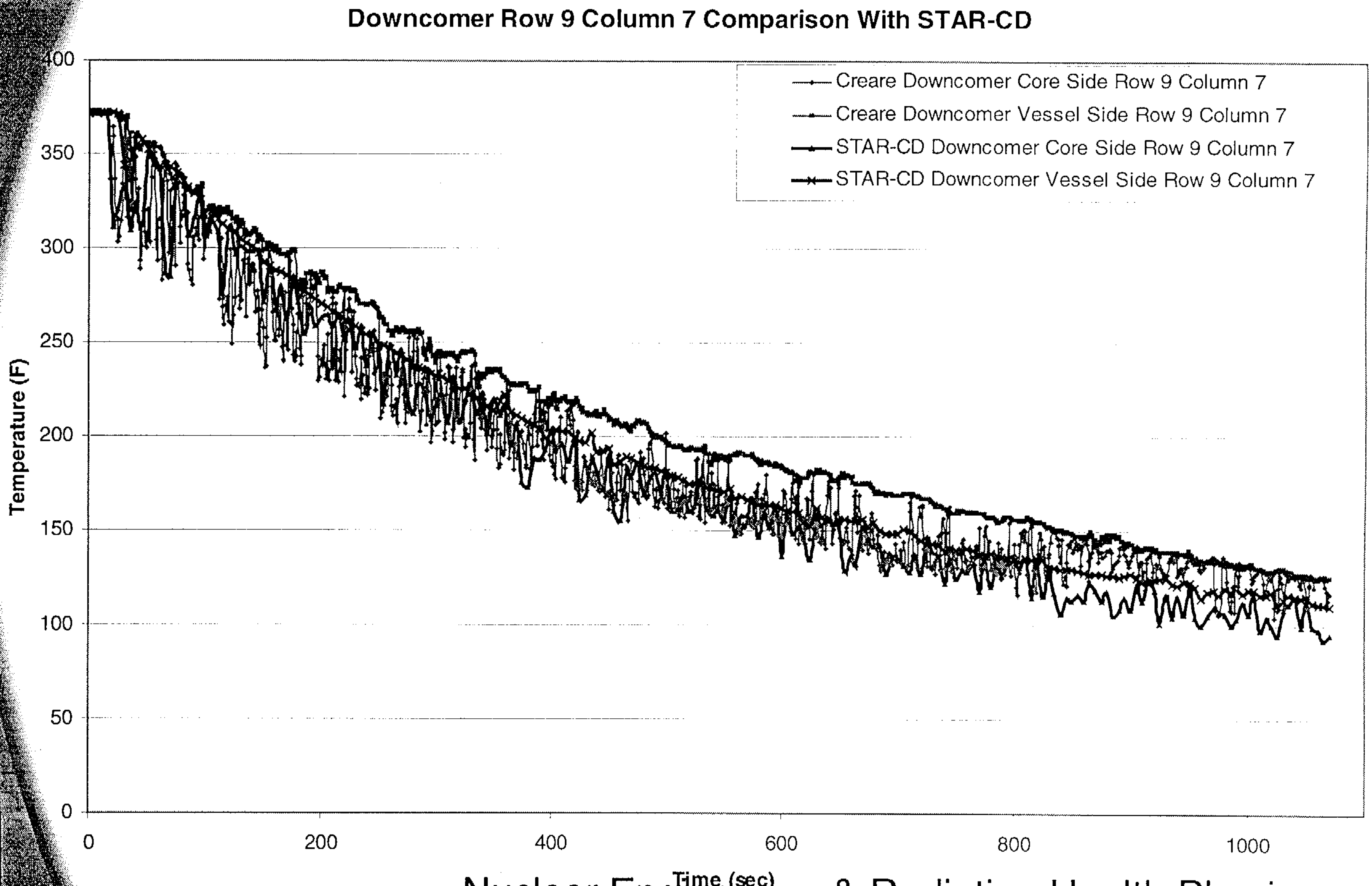


- Location of the thermocouples in the Creare facility.

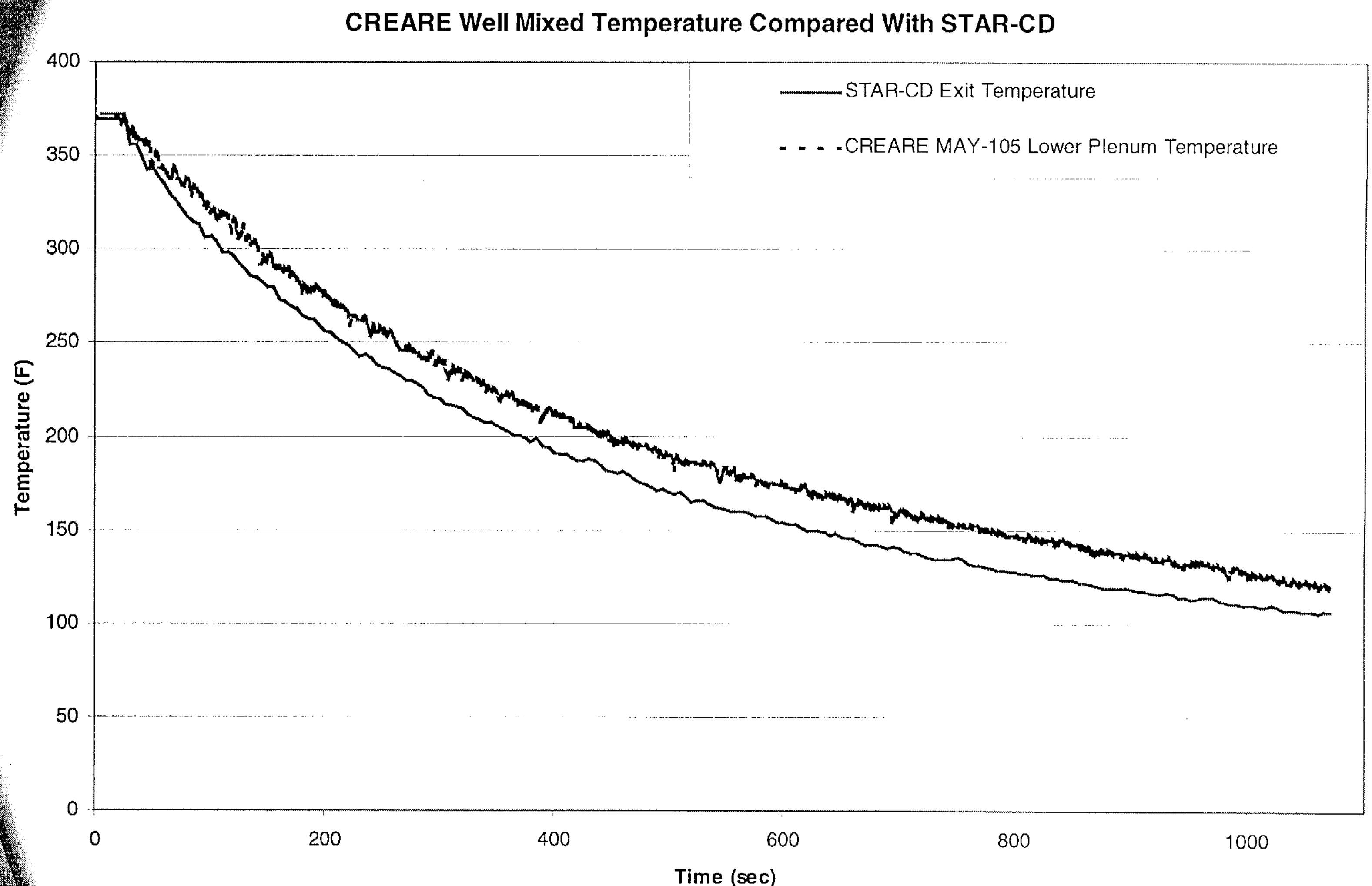
Downcomer Temperature Plots Cont.



Downcomer Temperature Plots Cont.



Well Mixed Temperature



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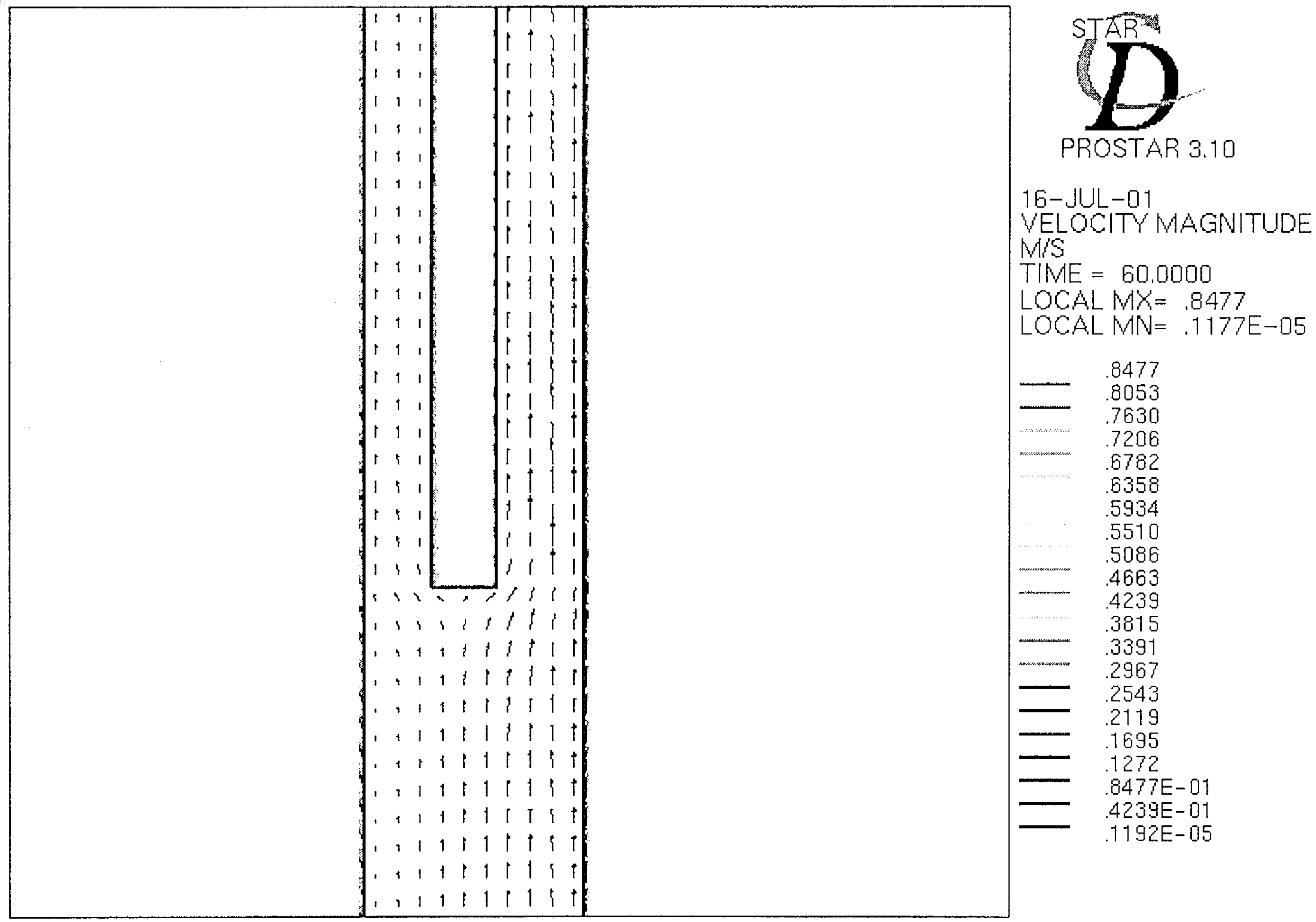
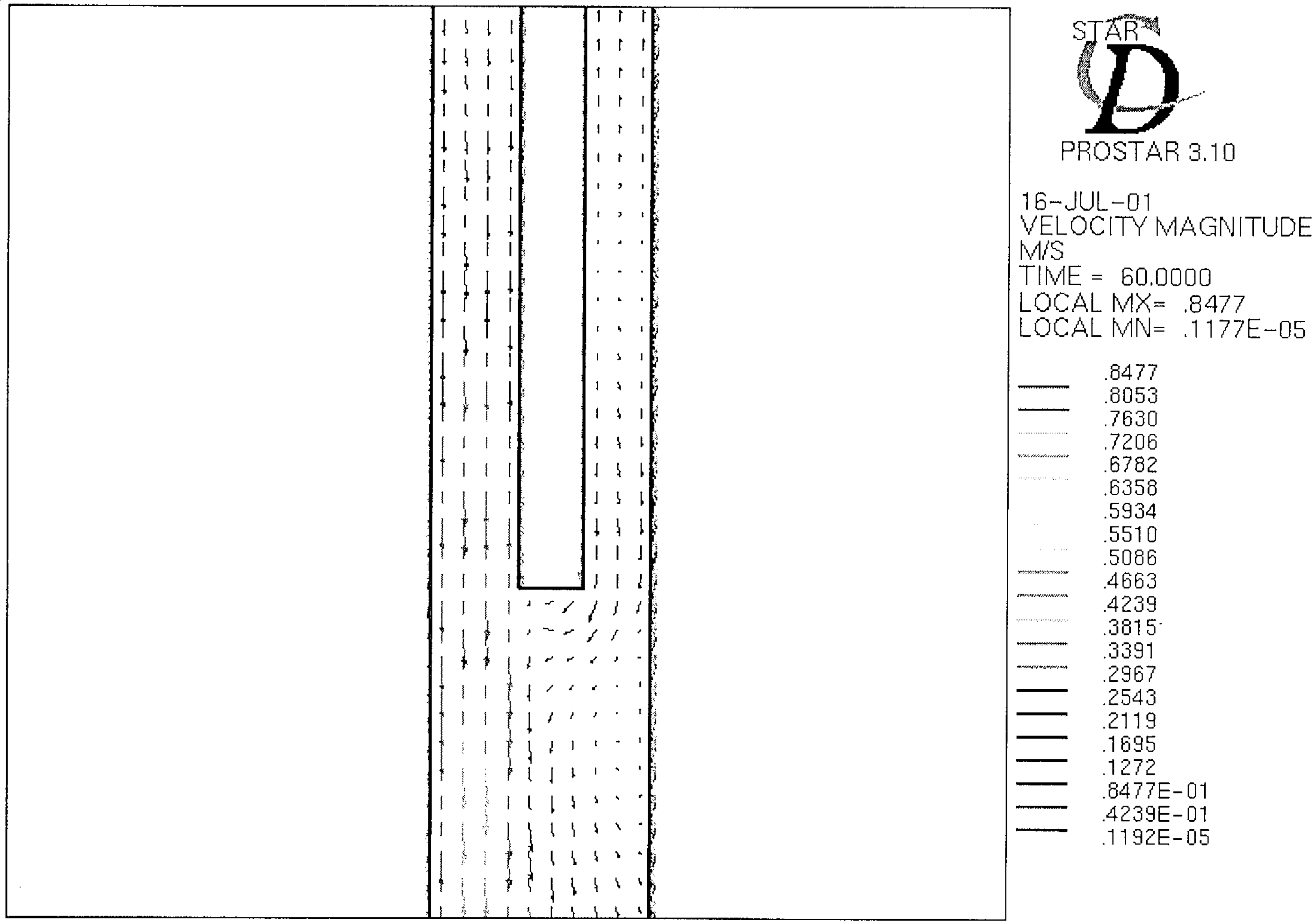
Velocities Around Thermal Shield



Base of the Thermal Shield (opposite side of plume entry)

Velocities Around Thermal Shield



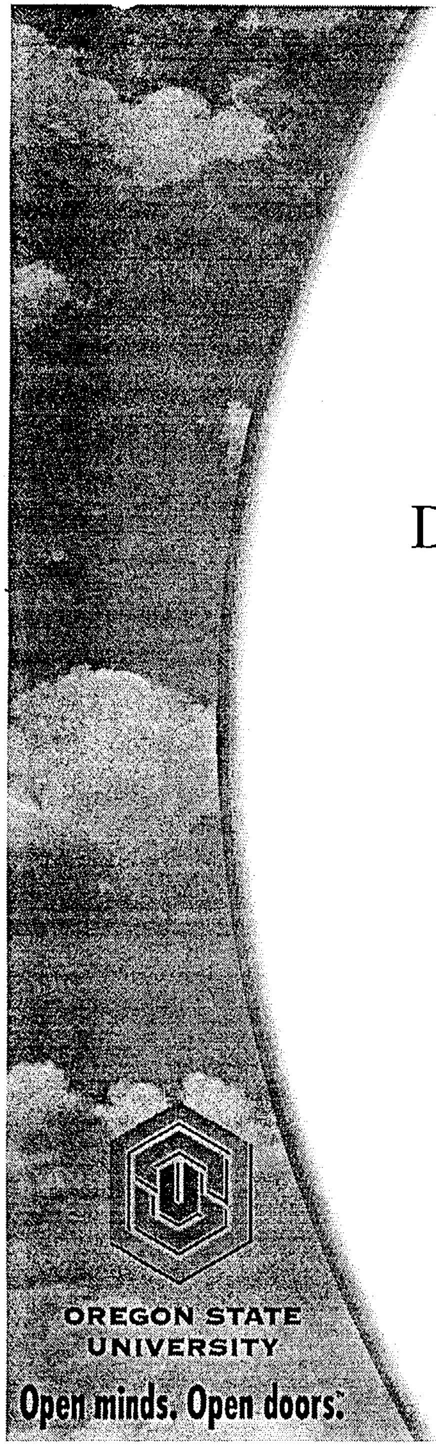
Base of the Thermal Shield (plume entry side)

Conclusions

- STAR-CD has been Benchmarked against the CREARE data:
  - Well-mixed temperatures were slightly under-predicted because model's total mixing volume was 6.7% less than the CREARE facility.
  - Predictions of plume temperatures in the downcomer compared reasonably well with the data.

Conclusions (*continued*)

- Learned to run STAR-CD using parallel processing to accelerate the computational process. This supported the APEX-CE calculations.
- Benchmark calculations aided in the selection of turbulence models.
  - Selection of diffusion lengths
  - Selection of turbulent intensity



3-D CFD Model of the APEX-CE Test Facility

Dan Wachs - Argonne National Laboratory – West
Eric Young - Oregon State University
John Rodgers - Adapco, Inc.

Presentation to
Advisory Committee on Reactor Safeguards
Thermal Hydraulic Subcommittee Meeting
July 17-18, 2001

Argonne National Laboratory

Outline

- OSU-CE-0003 Test Description
- Description of STAR-CD Model
- Cold leg stratification
- Core inlet temperature
- Downcomer temperature
- Downcomer plume velocity
- Downcomer heat transfer coefficient
- Summary

OSU-CE-0003 Test Description

- The objective of the test was to collect data on cold leg stratification and downcomer plume behavior during HPSI operation
- Reactor coolant pumps were tripped and cold leg flow was controlled with core power
- Data for four different HPSI injection rates was collected at each core power; 400 kW, 300 kW, 200 kW, 150 kW

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Description of Model

- Models the thermal hydraulic behavior within the Cold Legs and Downcomer
- Includes the HPSI, Loop Seal, and Lower Vessel Plenum
- Inlet conditions to Loop Seal and HPSI are specified
- Assumes adiabatic walls

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Initial and Boundary Conditions

- Constant initial temperature (~296°F/147°C)
- Moderate loop flow through the cold legs
  - $Q_{CL\#3}$~14.4 gpm
  - $Q_{CL\#4}$~12.3 gpm
- Constant injection flow rate from both HPSI lines
  - $Q_{HPI\#3}$~0.5206 gpm
  - $Q_{HPI\#4}$~0.9690 gpm

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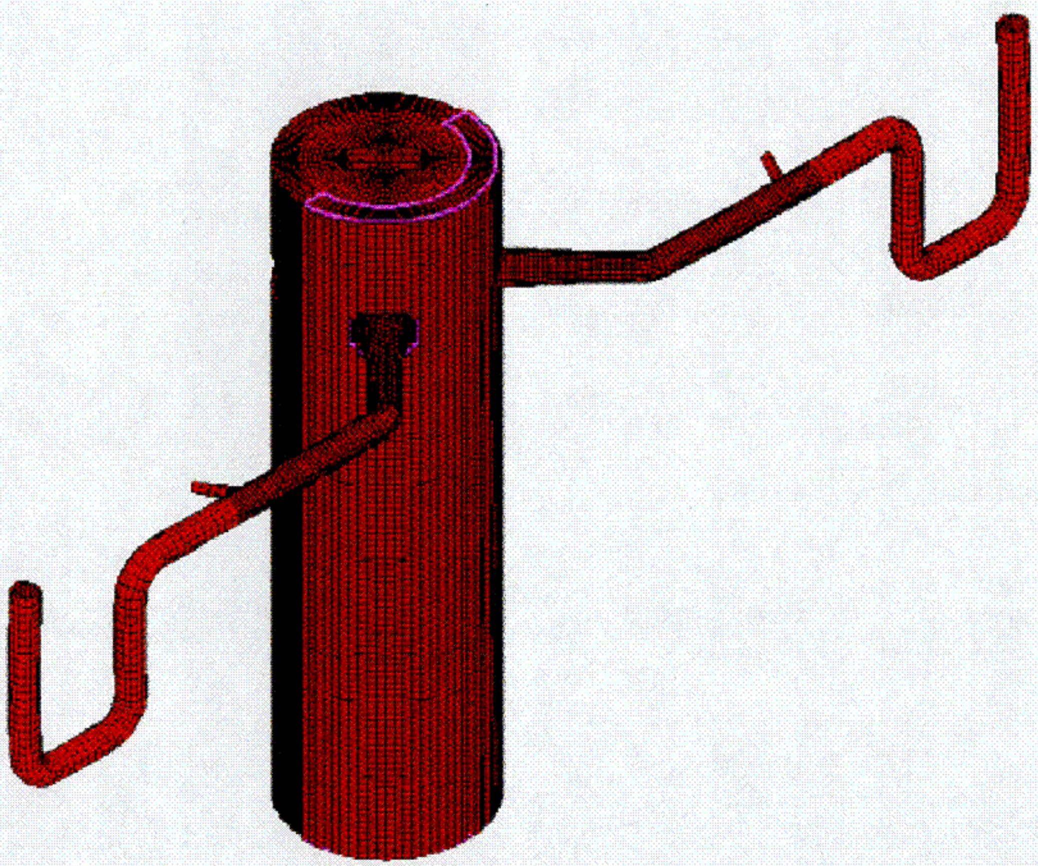
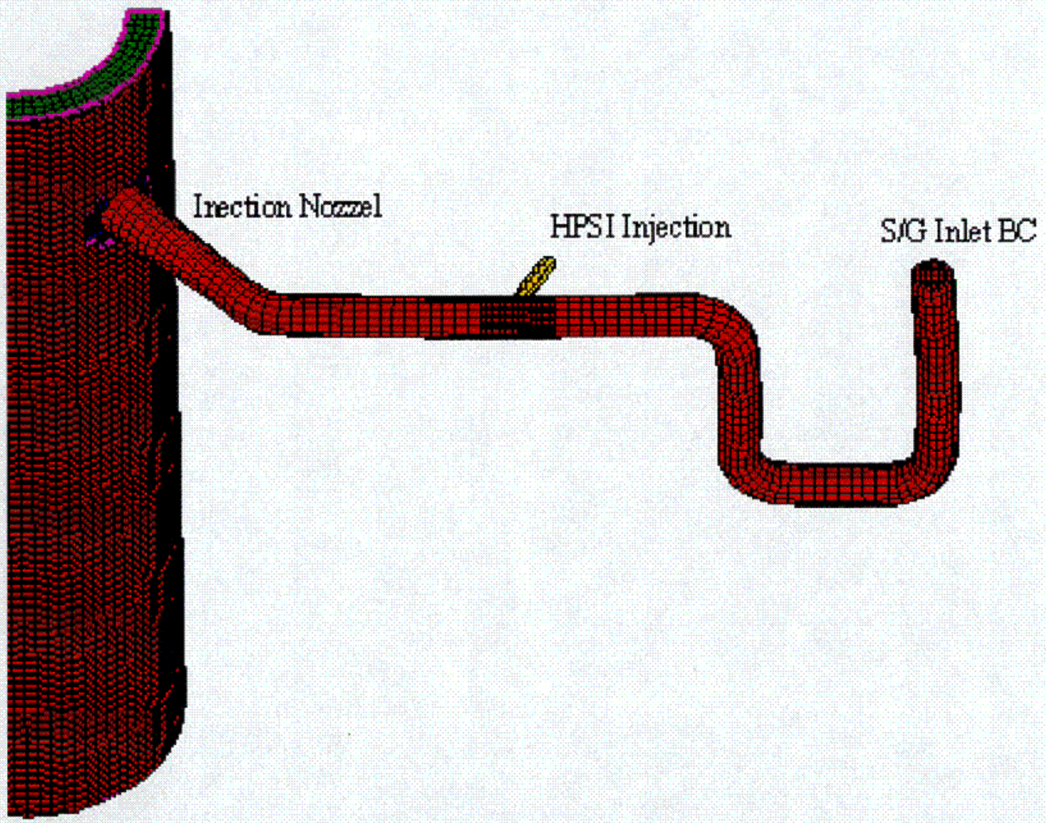
STAR-CD Model of APEX-CE



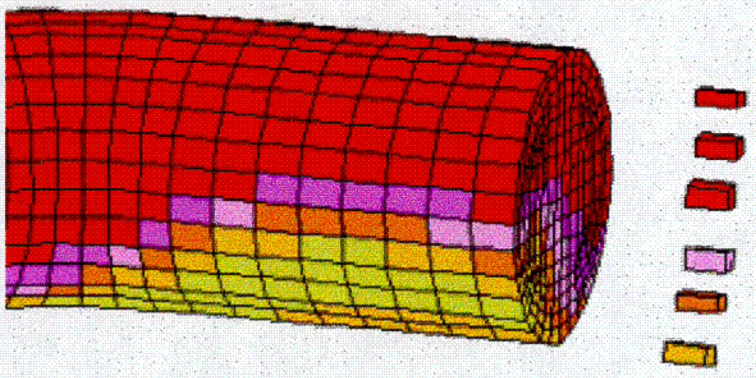
C05

Boundary Conditions



C06

Cell Location for CL TC Rake Comparison



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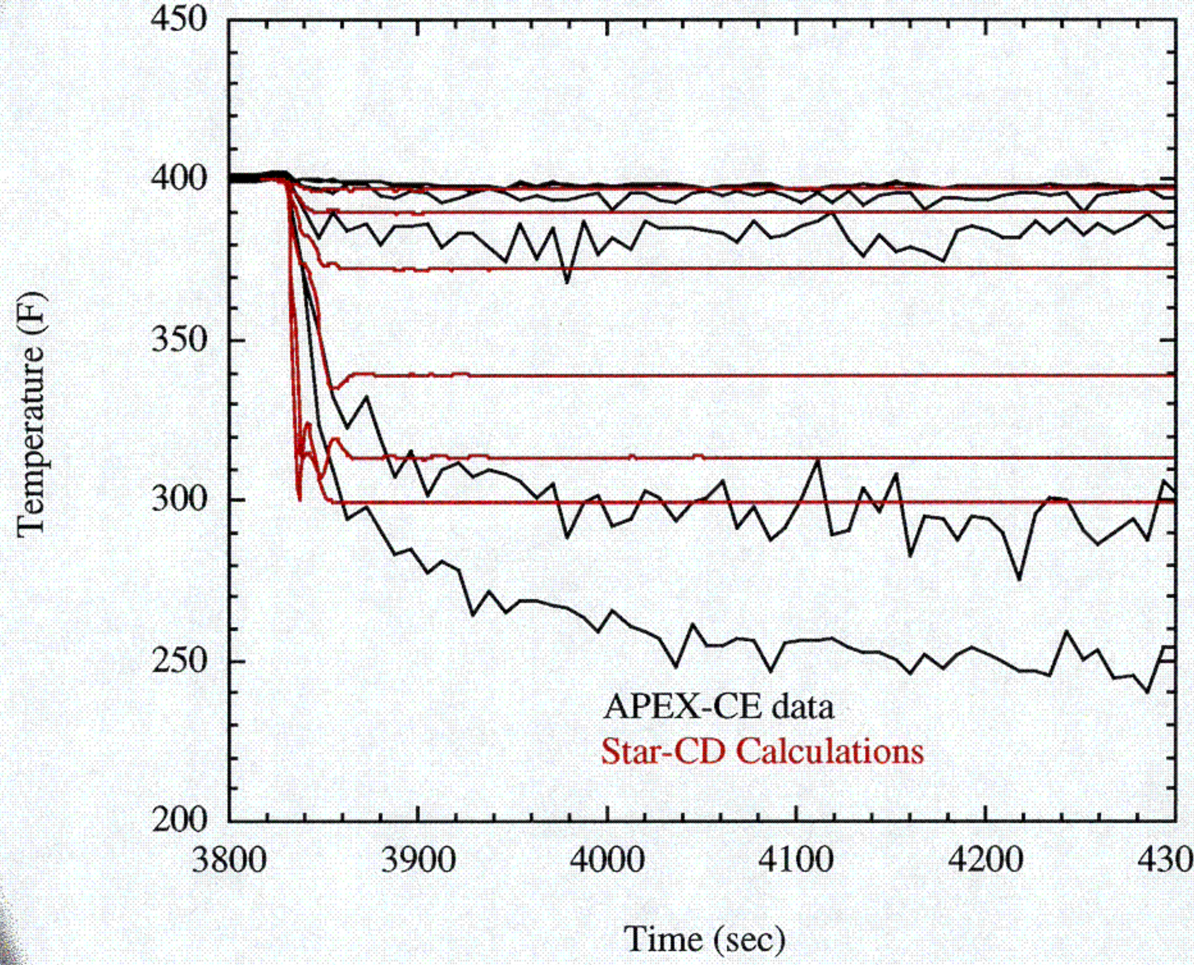
C07

Cold Leg Temperature Profile



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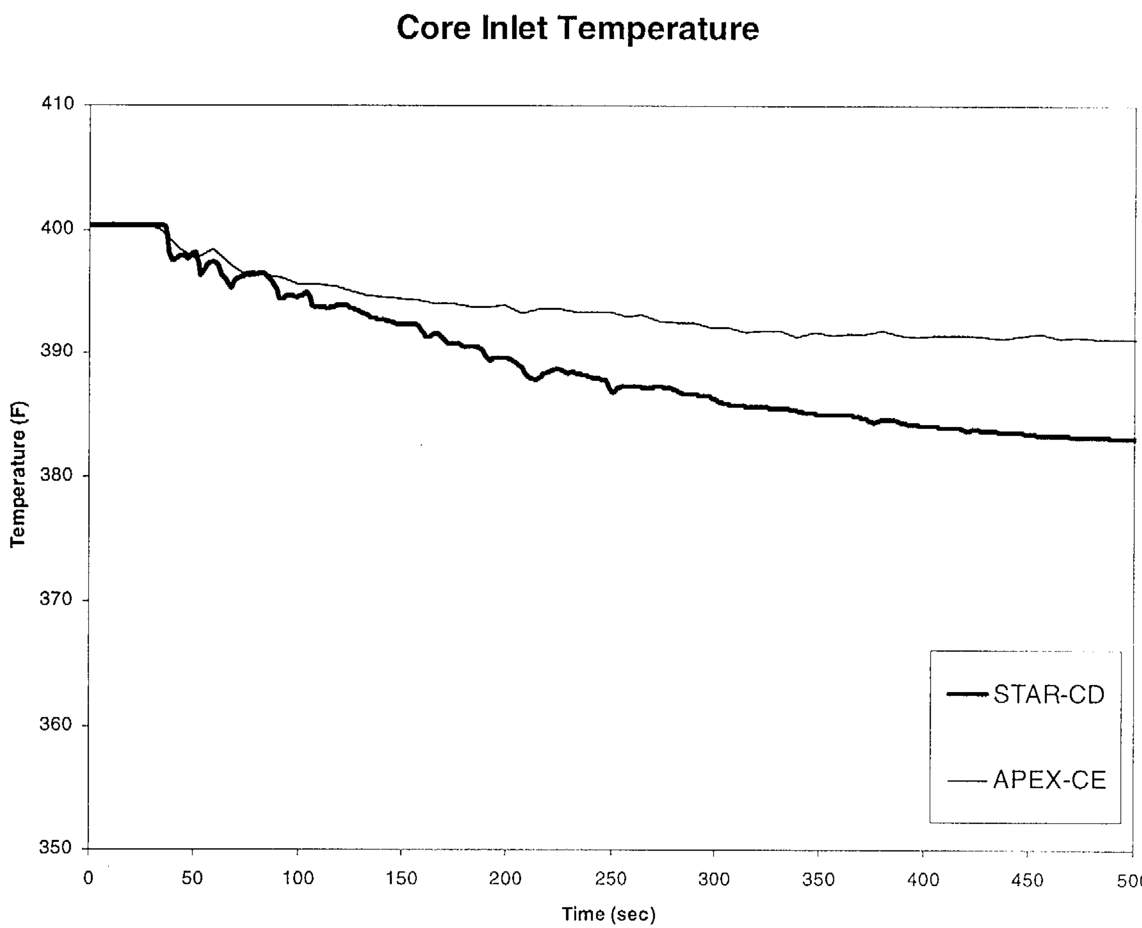
C08

Core Inlet Temperature



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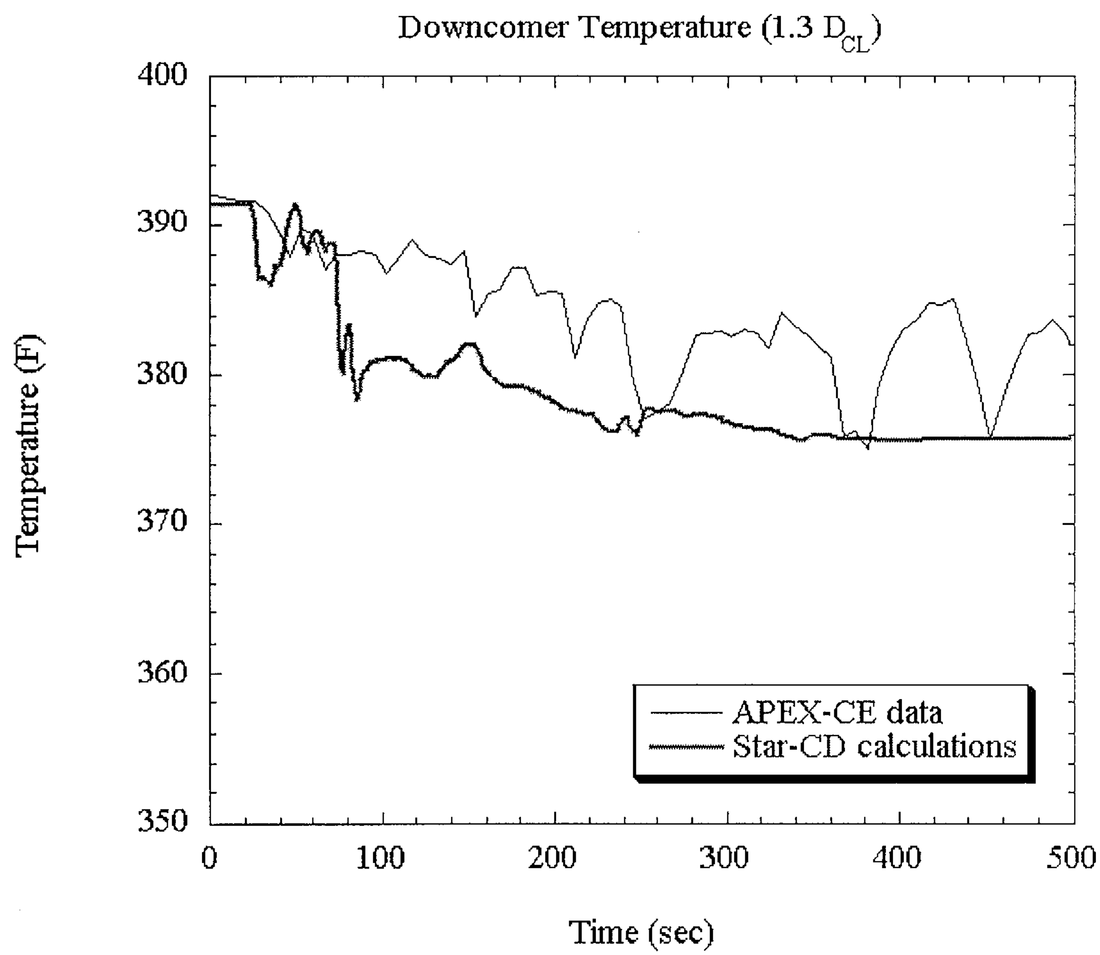
Downcomer Temperature (1.3 D_{CL})



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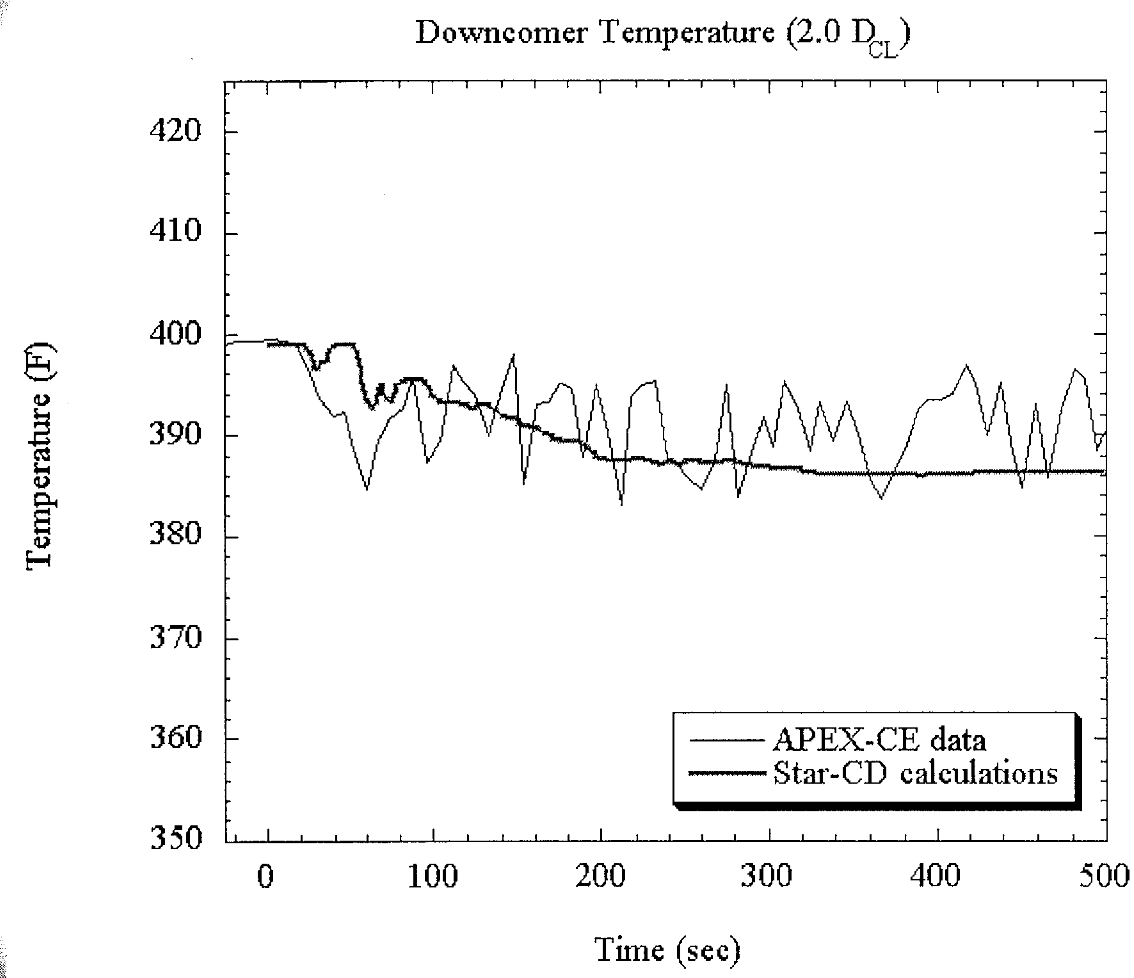
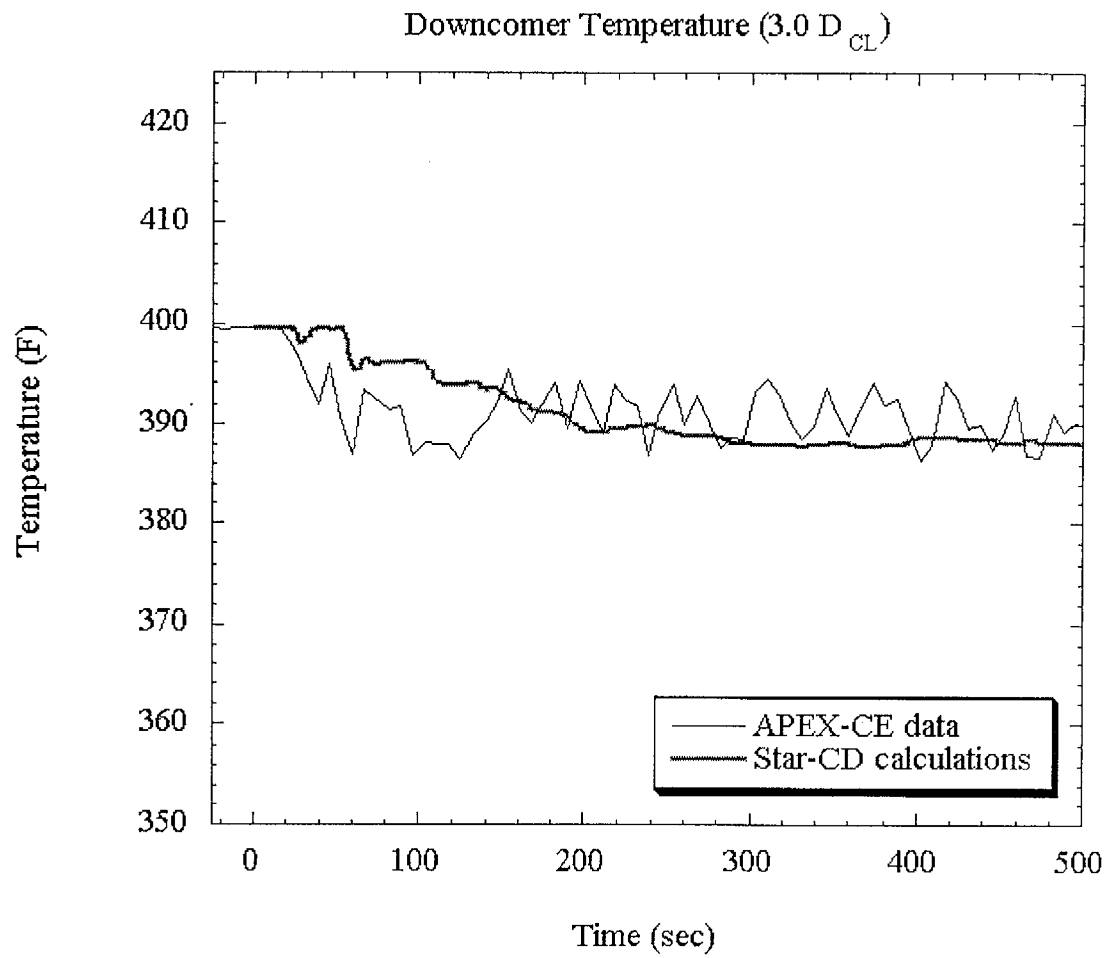
Downcomer Temperature (2.0 D_{CL})



Downcomer Temperature (3.0 D_{CL})



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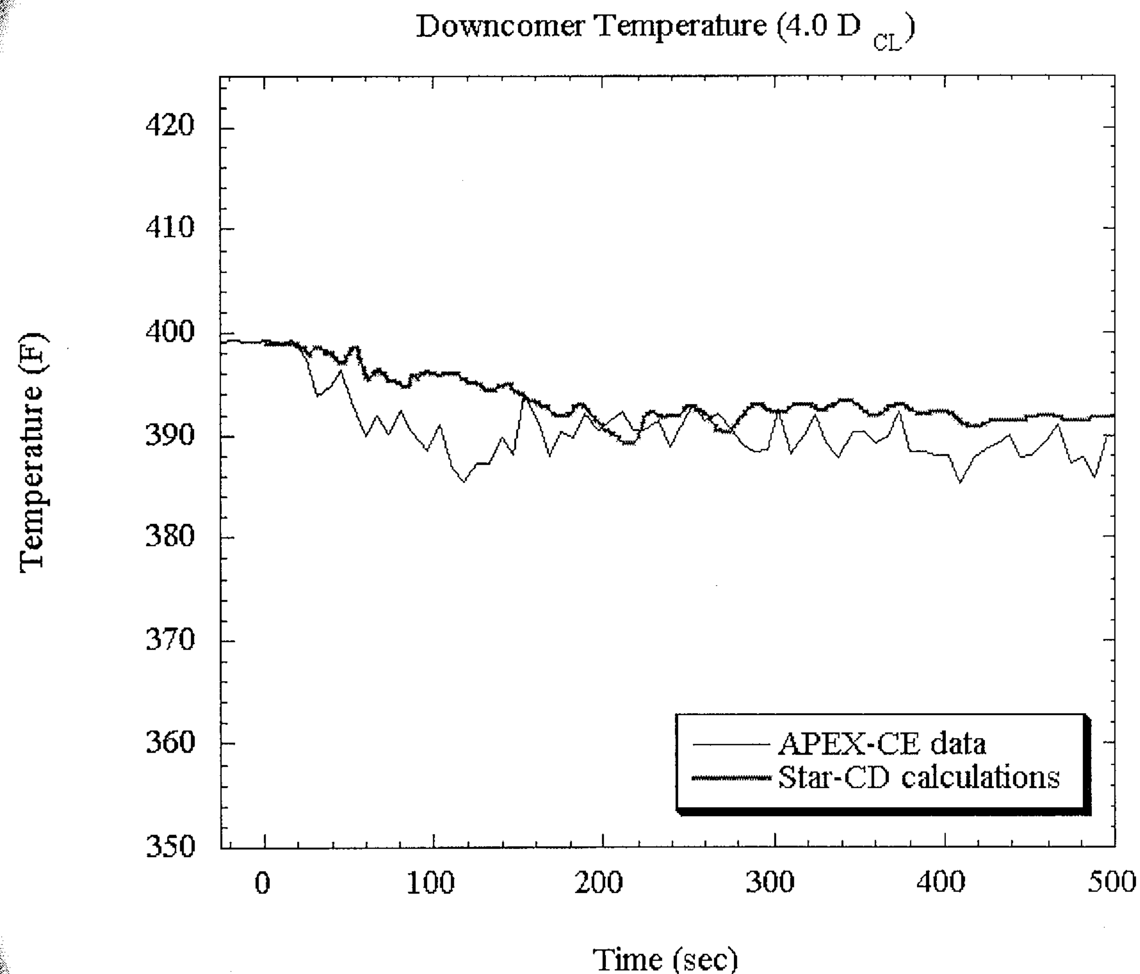
Downcomer Temperature (4.0 D_{CL})



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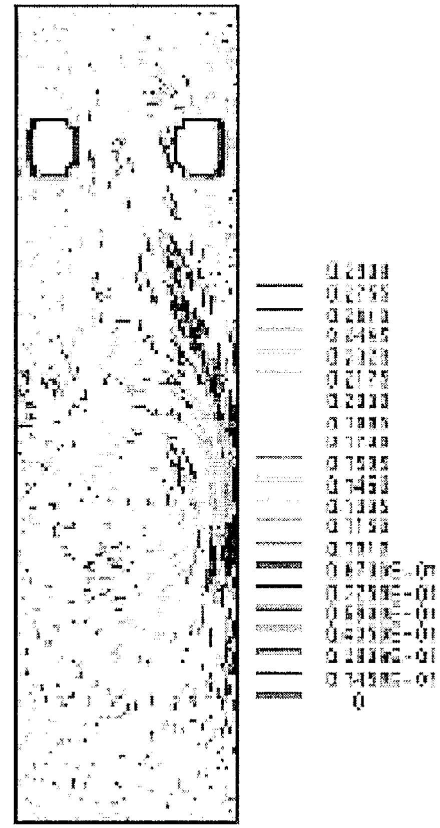
Plume Velocity



Plume Velocity

- The maximum plume velocity was extracted from the Star-CD model
- Plume Re

$$\mathrm{Re} = \frac{v_p D_H}{\upsilon} = \frac{v_p(2S)}{\upsilon}$$

where S is the downcomer gap and v_p is the plume velocity

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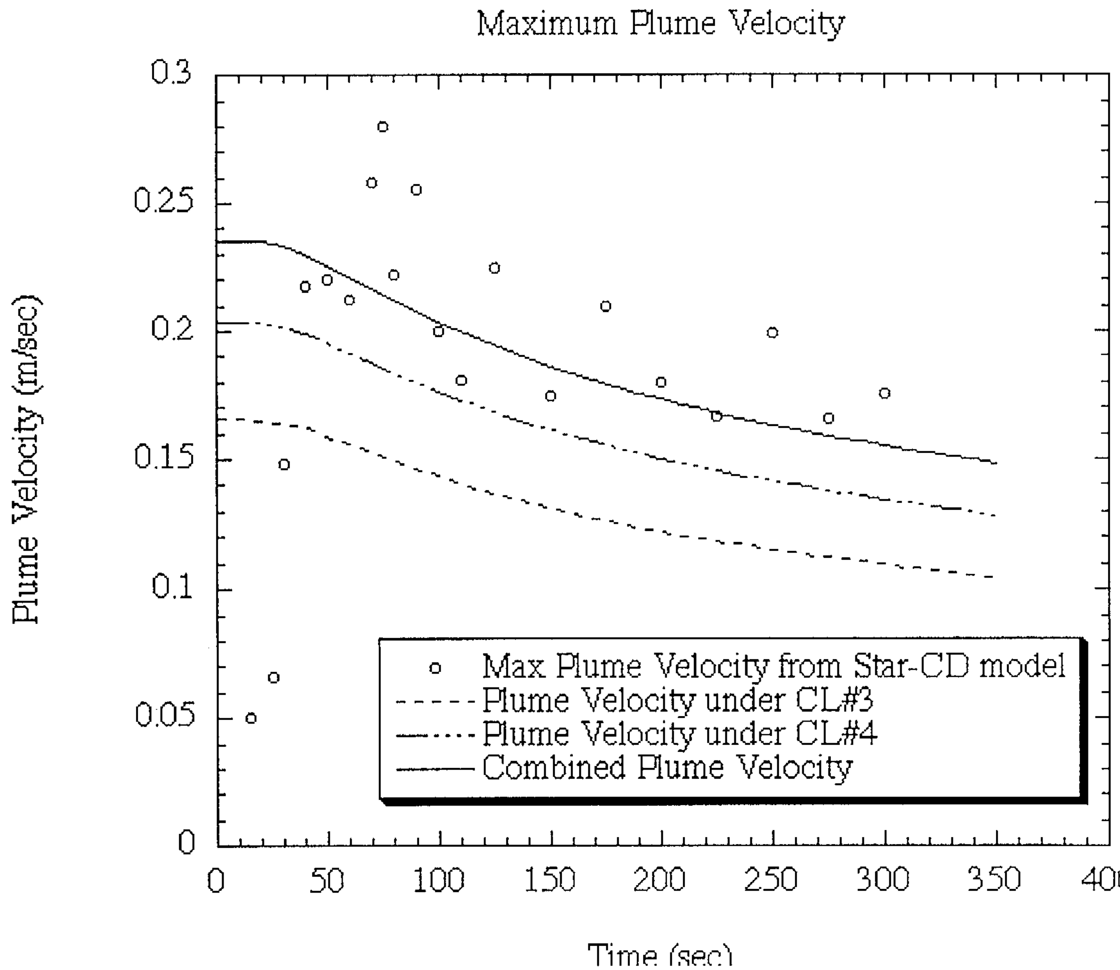
Kotsovinos Model for Plume Velocity

$$v_p = 1.66\, B^{1/3}$$

where B is the specific buoyancy flux defined as

$$B = g \frac{Q_{HPI}}{S} \frac{(\rho_{HPSI} - \rho_a)}{\rho_a}$$

Comparison with Model



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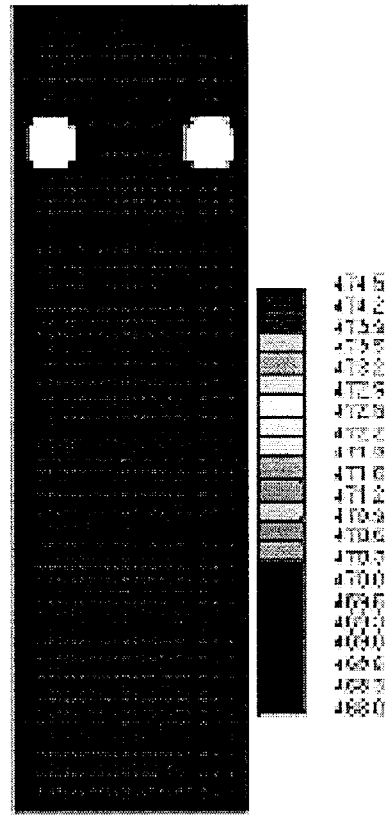
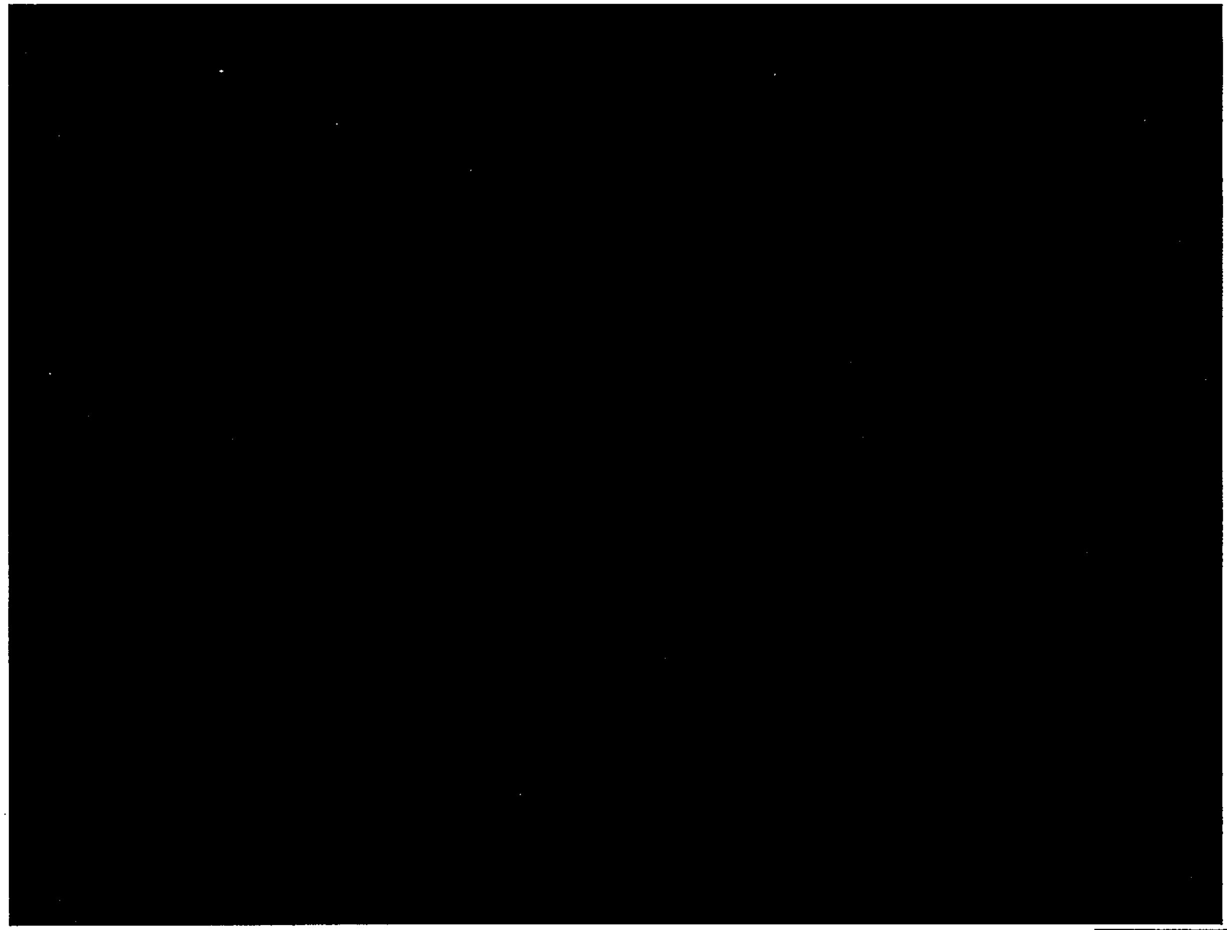
Downcomer Fluid Temperature



Vessel Temperature



Heat Transfer Coefficient

- Newton's Law of Cooling

$$q'' = h\,\Delta T$$

  - h contains all the hydrodynamic effects
  - ΔT contains most of the thermal effects

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Vessel Wall Heat Flux

- The radial temperature gradient in the wall can be extracted from the model (and thus the heat flux through it)

$$q'' = k\frac{dT}{dr}$$

Heat Transfer Coefficient

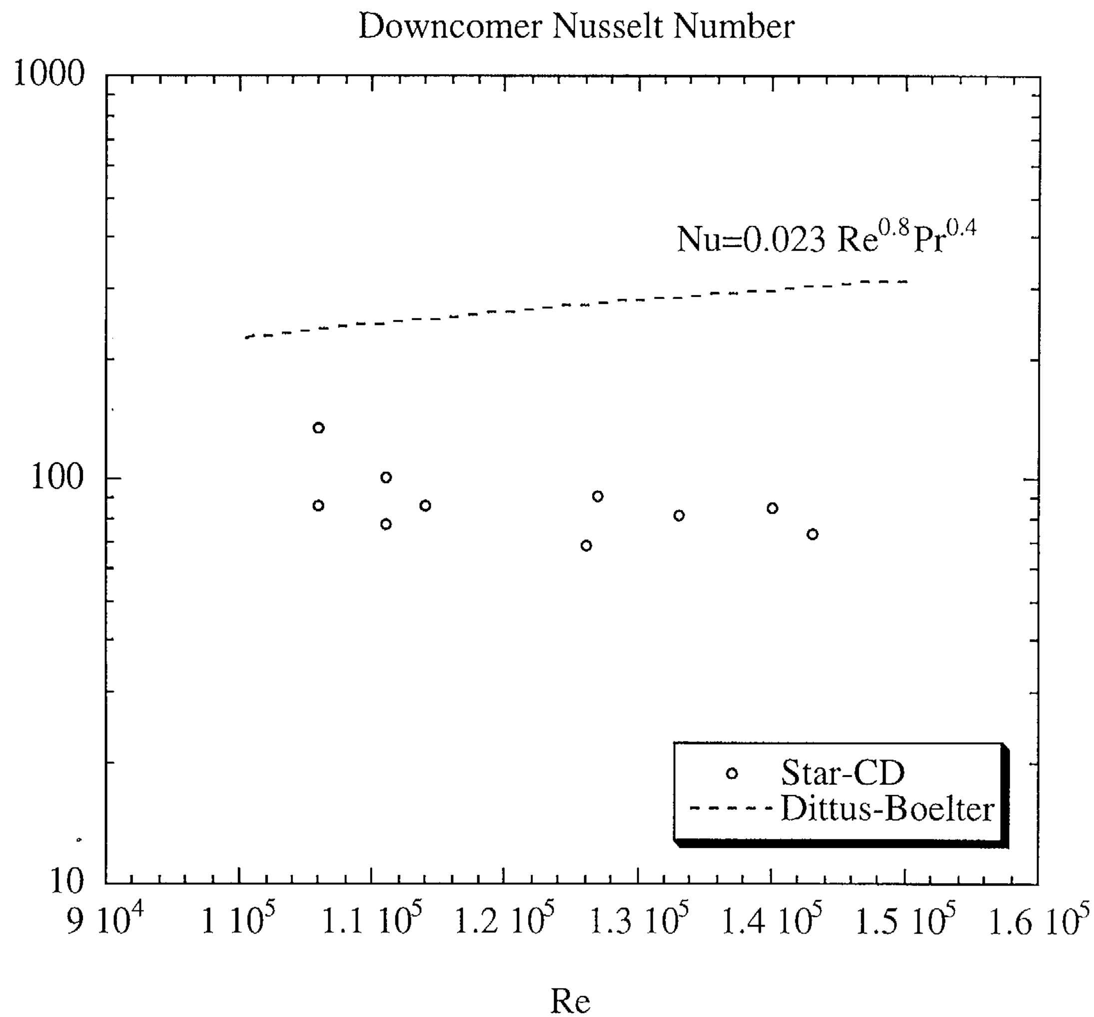
- The heat transfer coefficient can then be calculated

$$h = k\frac{dT}{dr}\frac{1}{(T - T_\infty)}$$

- Convert to a Nusselt number

$$Nu = h\frac{2S}{k_f}$$

Comparison with Model



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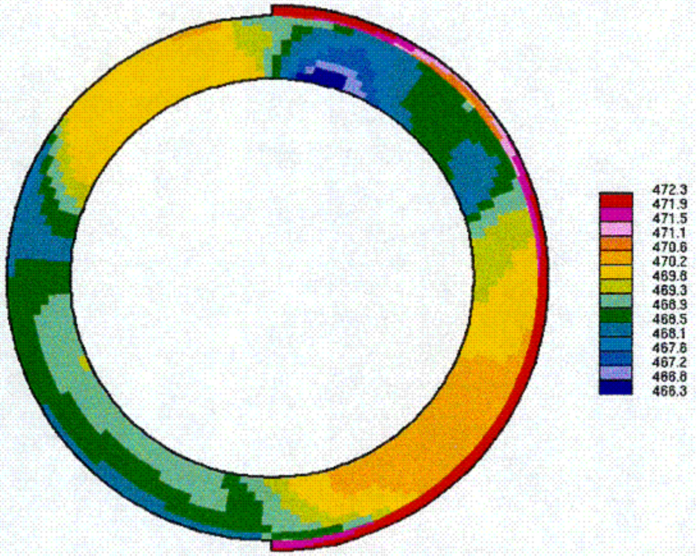
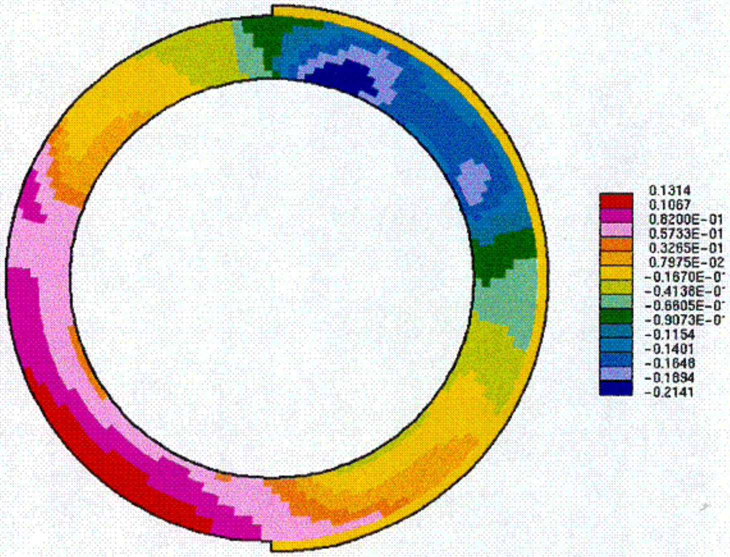
Downcomer Radial Temperature and Velocity Profile





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C09

Conclusions and Recommendations

- The nodalization is too coarse in the full system model to accurately predict the cold leg temperature profile. Higher density meshes on the cold leg alone resulted in better agreement.
- Downcomer temperatures are in good agreement

Conclusions and Reccomendations (cont.)

- Core inlet temperatures are mildly underpredicted due to the omission of the heat transfer through the core barrel
- Cold plume interactions occur and affect the plume velocity

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Conclusions and Reccomendations (cont.)

- The plume's radial location affects the heat transfer coefficient (generally lower than the Dittus-Boelter correlation would suggest)
- More cases should be run to optimize the mesh cell density

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‘Lessons Learned’ in CFD

Daniel M. Wachs - Argonne National Laboratory
Brandon Haugh - Oregon State University
Eric Young - Oregon State University

Presentation to
Advisory Committee on Reactor Safeguards
Thermal Hydraulic Subcommittee Meeting
July 17-18, 2001

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CFD Methodology

- Problem definition
- Mesh construction
- Problem setup
- Run
- Post-processing

Things to consider

- Understand the physics and phenomena prior to modeling
- Mesh building
  - Alternate programs for geometry construction are available
  - Mesh gradients should match physical gradients
  - Cells and time steps can be both too large or too small (Courant condition)

Things to consider (cont.)

- Modeling large systems can be simplified with selection of computing system
  - Parallel computing provided better than linear improvements in performance
  - Homogeneous computing platforms are important

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Things to consider (cont.)

- Comparing model results to experimental data can be difficult
  - O(100) instrumented points vs. O(100,000) numerical points
  - It can be difficult to extract a multi-dimensional image of local behavior from even extremely well instrumented experiments

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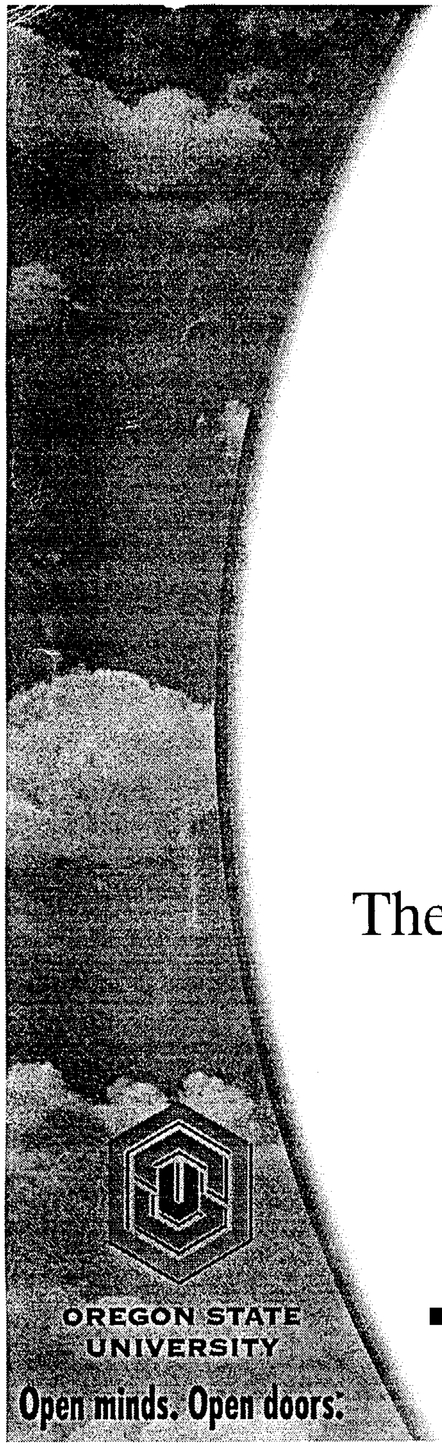

Report Schedule

Jose N. Reyes, Jr.

Presentation To

Advisory Committee On Reactor Safeguards

Thermal Hydraulic Phenomena Subcommittee Meeting

July 17-18, 2001

Schedule

- Scaling Analysis Report, Completed (Awaiting final editorial comments from NRC Publications.)
- Final Report (December 2001) will include:
  - Review of Previous PTS Research
  - Description of the OSU PTS Test Facilities
  - Overview of Palisades Operations
  - Results of OSU PTS Tests
  - RELAP5 Calculations of APEX-CE Overcooling Behavior
  - REMIX and STAR-CD Calculations
  - Data and Drawings