GOTHIC Application to GL2008-01 Issues

Numerical Applications, Inc

Objectives

- Advance NRC understanding of GOTHIC
  - General Capabilities
  - Areas of Application
  - Technical Basis
  - Validation Basis
- Describe GOTHIC Application for GL2008-01 Issues
  - Modeling Methods
  - Related Validation

Agenda

- Monday Afternoon
  - GOTHIC Overview (open)
  - Selected GOTHIC Applications (open)
- Tuesday
  - GOTHIC Validation (open)
  - GOTHIC Technical Basis (equations and methods) (closed)
  - Modeling Methods for Gas Transport (closed)

GOTHIC: Overview

Numerical Applications, Inc

GOTHIC

- General Purpose Thermal-Hydraulic Analysis
- Special Features for Nuclear Plant Modeling
- Ongoing Development and Maintenance Support by the EPRI GOTHIC Enhancement Project (since 1993).

Ancestry

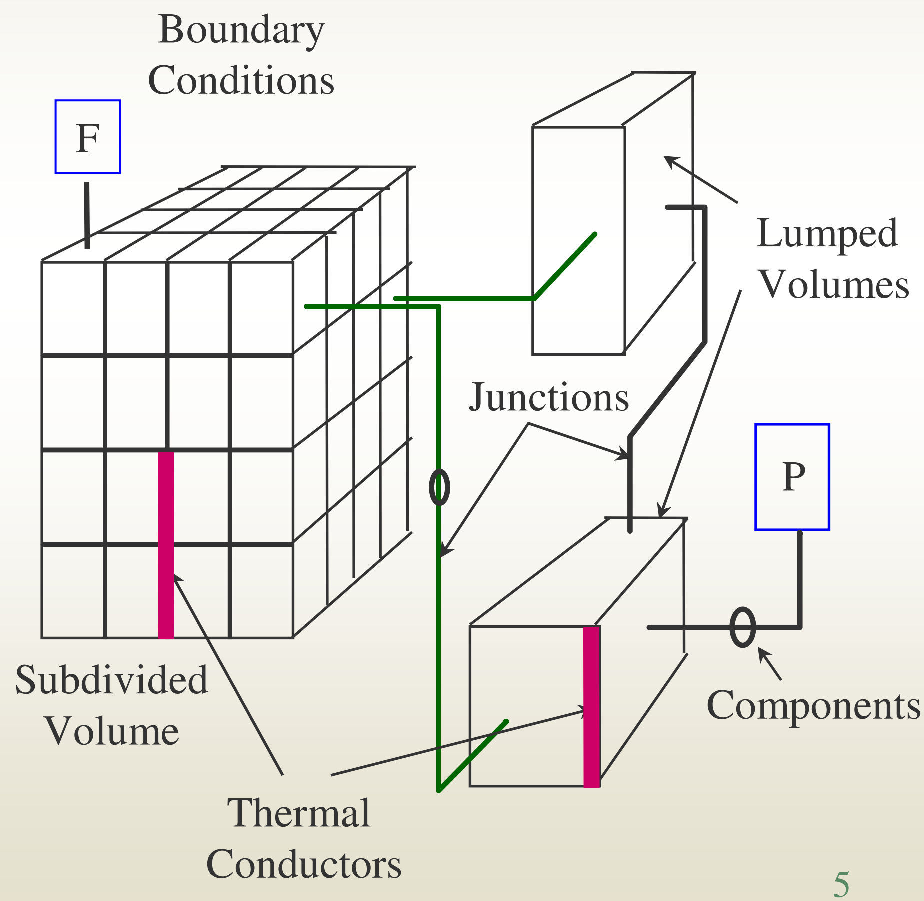
- COBRA (~1965)
  - COBRA-III (~1970)
    - COBRA-IV (~1977)
      - VIPRE (~1979)
      - COBRA-WC (~1980)
      - COBRA-SF (~1984)
      - COBRA-TF (~1979)
        - COBRA-TRAC (~1981)
          - WCOBRA-TRAC (~1985)
        - COBRA-NC (~1983)
          - FATHOMS (~1985)
            - GOTHIC (~1989)

GOTHIC Development

- COBRA-NC
  - Graphical Interface, Junction Model
  - Components (pumps, hx, etc.)
  - Separate Drop Energy Equation
  - Design Review, QA
- GOTHIC 4.0
  - k-e Turbulence Model, Hydrogen Burn, Fan Coolers
  - Improve Interphase Heat and Mass Transfer
  - Control Variables, Radioactive Isotopes, Radiant Heat Transfer
- GOTHIC 6.0
  - Porous Body Model, Rectangular Coordinates, 3D Connectors
  - DLM for Heat and Mass Transfer, Flow Networks, 2nd Order Numerics
- GOTHIC 7.0
  - Dissolved Gases, Solid Particles, Freezing, 2D Conduction
  - Multiple Drop Fields, Parallel Processing
  - Improved Water Properties, Improved Interphase Drag
- GOTHIC 8.0

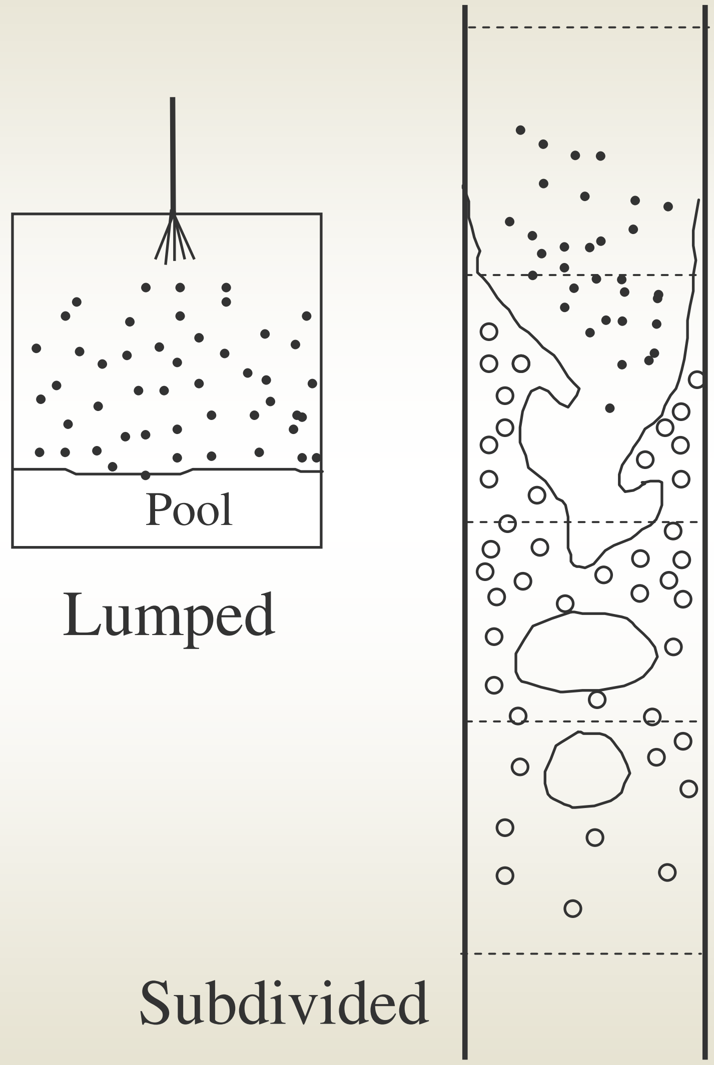
Multi-Zone Modeling

- Combine Lumped and Subdivided Volumes
- Superimposed Conductors
- Finite Volume Solution
  - Semi-explicit



Multiphase/Multicomponent

- Vapor
  - Steam
  - N Gas Components
- Drops
  - N Fields
- Liquid
  - Films
  - Pools
  - Slugs
  - Stratified Flow
- Mist
- Ice



Equation Set

Phase	Description	Mass Balance	Energy Balance	Mom. Balance
Vapor	Steam, gas components in bubbles or free vapor	Steam, each gas component	Yes	Yes
Liquid	Continuous liquid in pools, films, slugs, bubbly flow	Yes	Yes	Yes
Drops	Water drops	Yes	Yes	Yes
Mist	Very small water droplets	Yes	$T=T_{sat}$	$U=U_v$
Ice	Ice formation and melting on conductor surfaces	Yes	Yes	No

Comprehensive Drop Behavior Models

- Drop Breakup
  - Hydrodynamic Forces
  - Flashing
- General Entrainment Model
  - Relative Velocity
  - Film/Pool Thickness
  - Fluid Properties
- Depositions Models
  - Diffusion
  - Turbulent Impaction
  - Bends

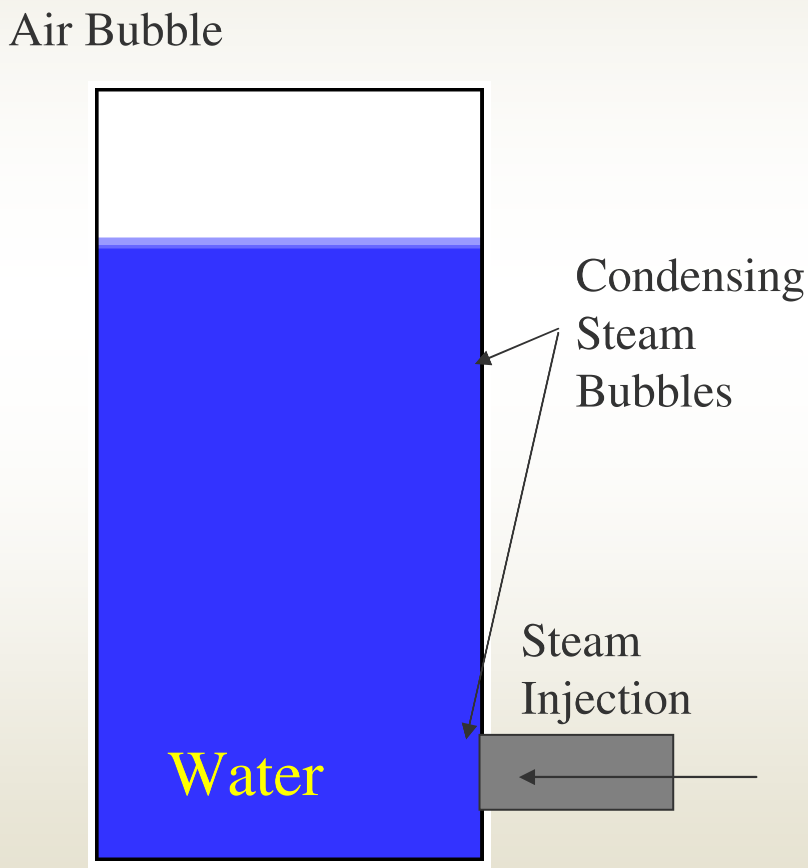
WALE Test Drop Concentration

Multiple Drop Fields

- Interacting drop fields to model wide range of drop sizes in single model
  - Fog– O(<10 μm)
  - Pipe Break – O(100 μm)
  - Spray– O(1000 μm)
- Separate Mass, Energy and Momentum Balances maintained for each drop field.
- Models for agglomeration, breakup, deposition and entrainment.

Interphase Heat, Mass and Momentum Transfer

- Drop/Vapor and Liquid Vapor Interfaces
- Evaporation
- Condensation
  - Diffusion Layer Model for Noncondensing Gas Effects
- Boiling/Flashing
- Drop Entrainment
- Drop Deposition
- Ice Formation and Melting



Liquid Component
Dissolved Gas

- Gas Absorption
- Dissolved Gas Transport
  - Molecular and turbulent diffusion
- Gas Release
  - Incubation phase
    - Bubble nucleation and early growth
    - Undetectable gas release
    - Duration depends on Reynolds number
    - ~1.5 seconds (longer for low velocities)
  - Activity phase
    - Rapid gas release
    - Up to 10% of gas released
    - 5-10 seconds
  - Bubble Growth phase
    - Slow gas release toward equilibrium

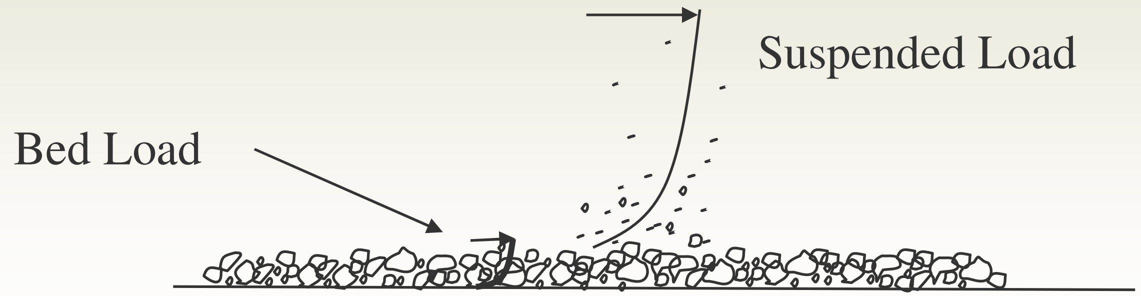
Atmosphere

$$P = P_{Air} + P_{Steam}$$

Pool

$$c_{Air} = S(T)P_{Air}$$

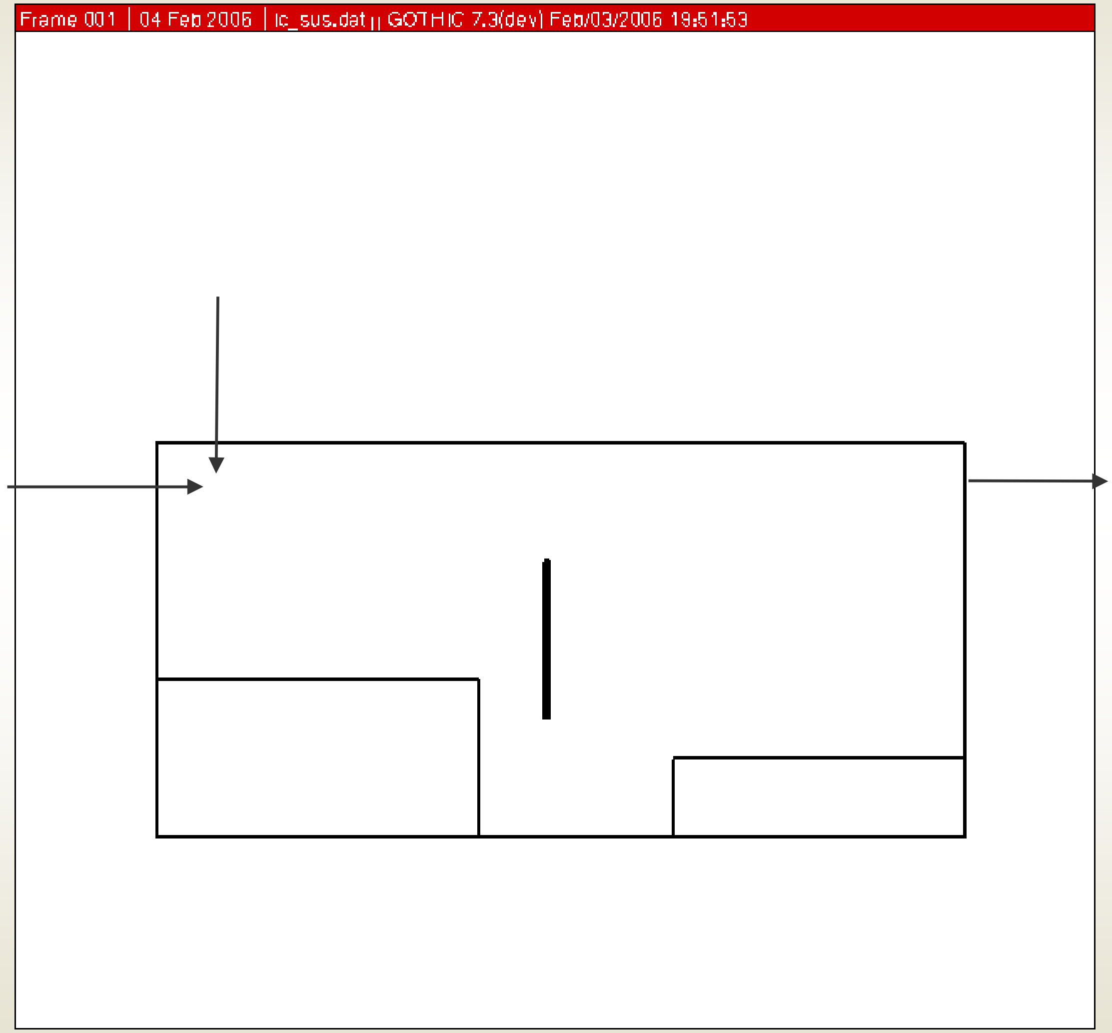
Liquid Component
Particle Transport



- Bed Load
  - Rolling and sliding of particles in the bed
    - Shear controlled
  - Saltation – jumping particles
    - Momentum controlled
- Suspended Load
  - Diffusion (turbulent) controlled resuspension
  - Gravitational settling

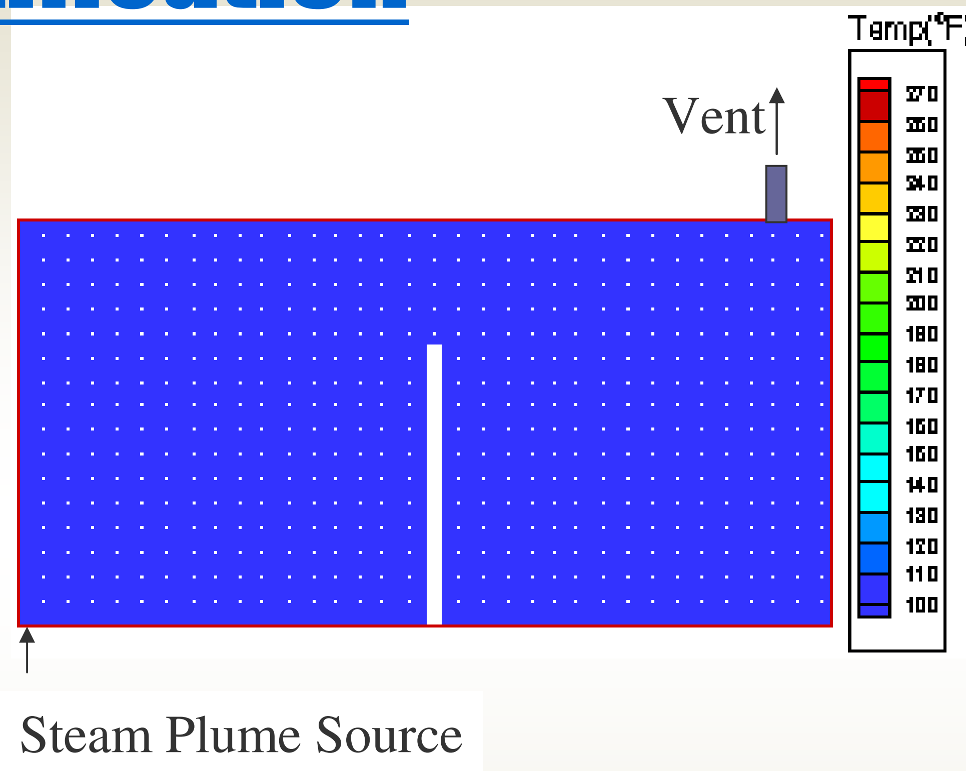
Particle Transport – Sample Problem

- 0-1000s
  - Horizontal injection at 2 ft/s with 2% particles
- 800-1800s
  - Vertical injection at increasing velocity with no particles



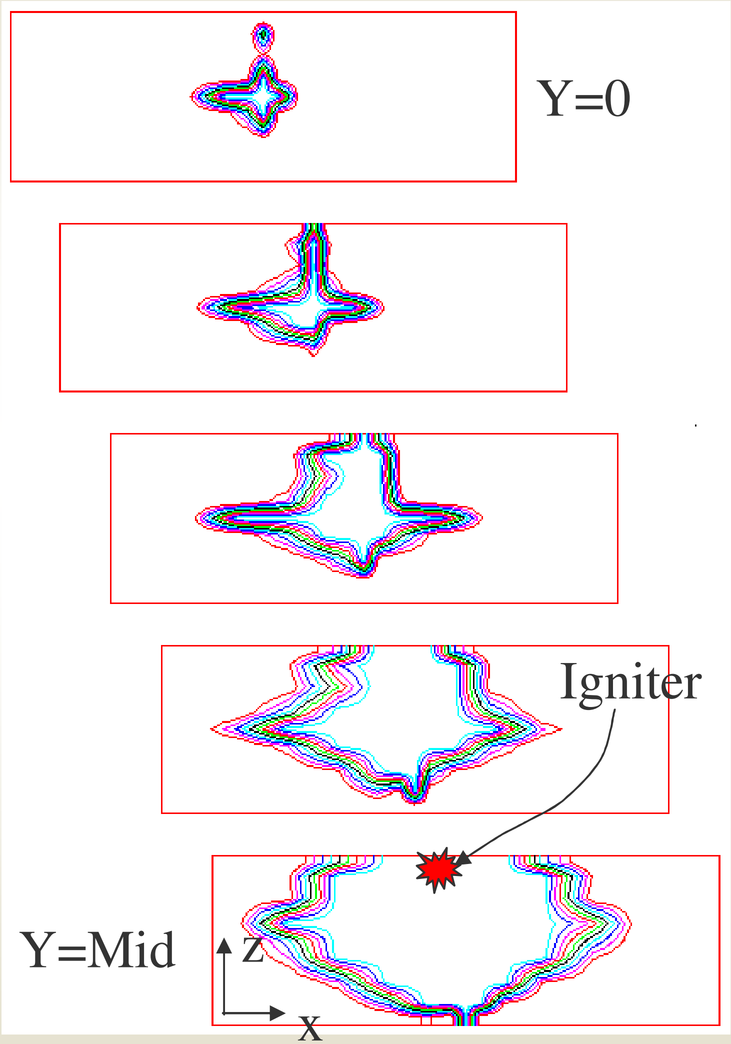
Mixing and Stratification

- Buoyant Flows
- Forced Convection
- Jet Induced Mixing
- Diffusion
  - Molecular
  - Turbulent - k-e Model
  - Mass Diffusion - Vapor
  - Thermal Diffusion - Vapor/Liquid
  - Momentum Diffusion - Vapor/Liquid



Hydrogen Combustion

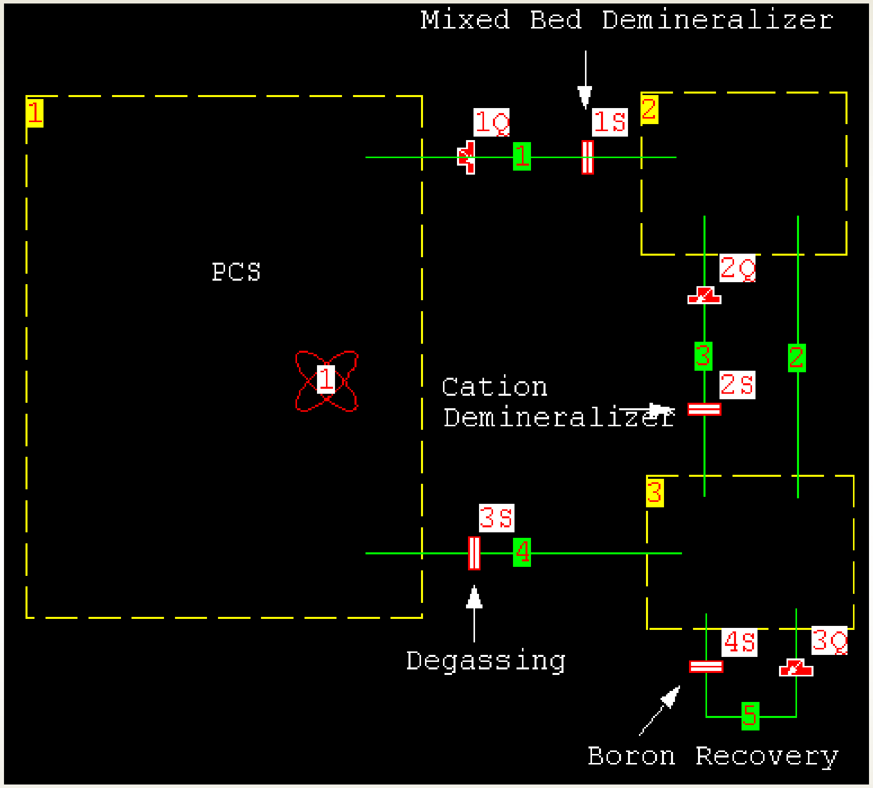
- Recombiners
- Lumped Parameter
  - HECTR Model
  - User Specified Propagation
- Subdivided Volume
  - Calculated Propagation
  - Laminar
  - Turbulent
    - Eddy Diffusivity Model



3D H2 Burn in a Box

Radioactive Nuclides

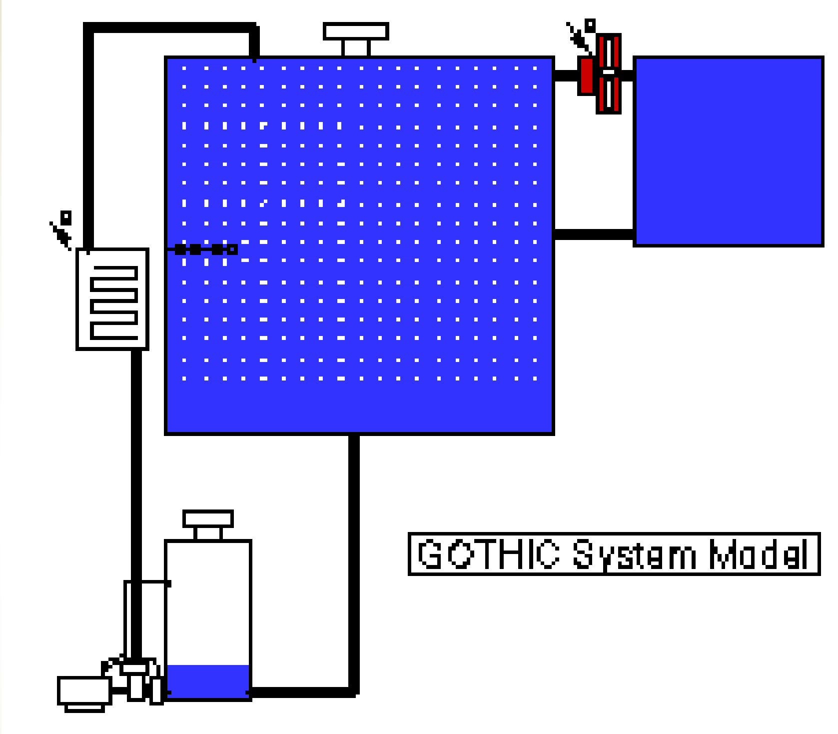
- User specified sources
- Transport in the vapor phase
- Radioactive decay and daughtering
- Filter component



PCS Activity with 1% Fuel Failure

Equipment Models

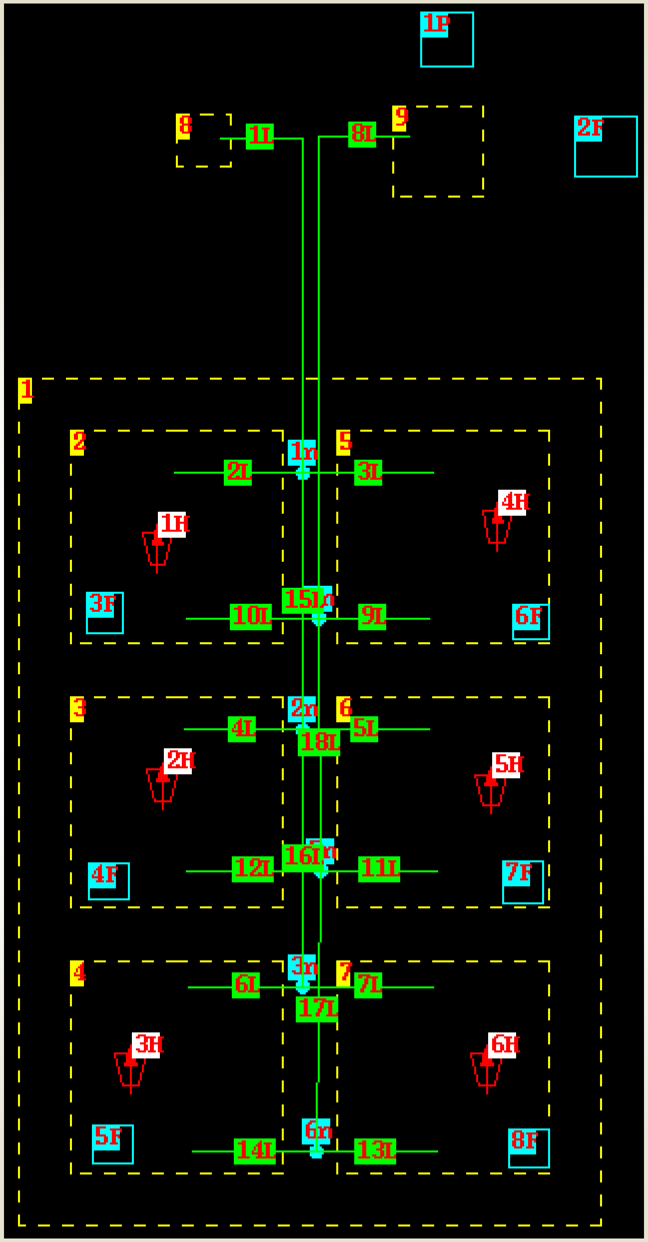
- Pumps/Fans
- Valves
- Vacuum Breakers
- Heat Exchangers
- Fan Coolers
- Igniters
- Recombiners
- Heaters/Coolers
- Spray Nozzles



- Controls
  - Trips
  - Forcing Function
  - Control Systems

Piping and Duct Networks

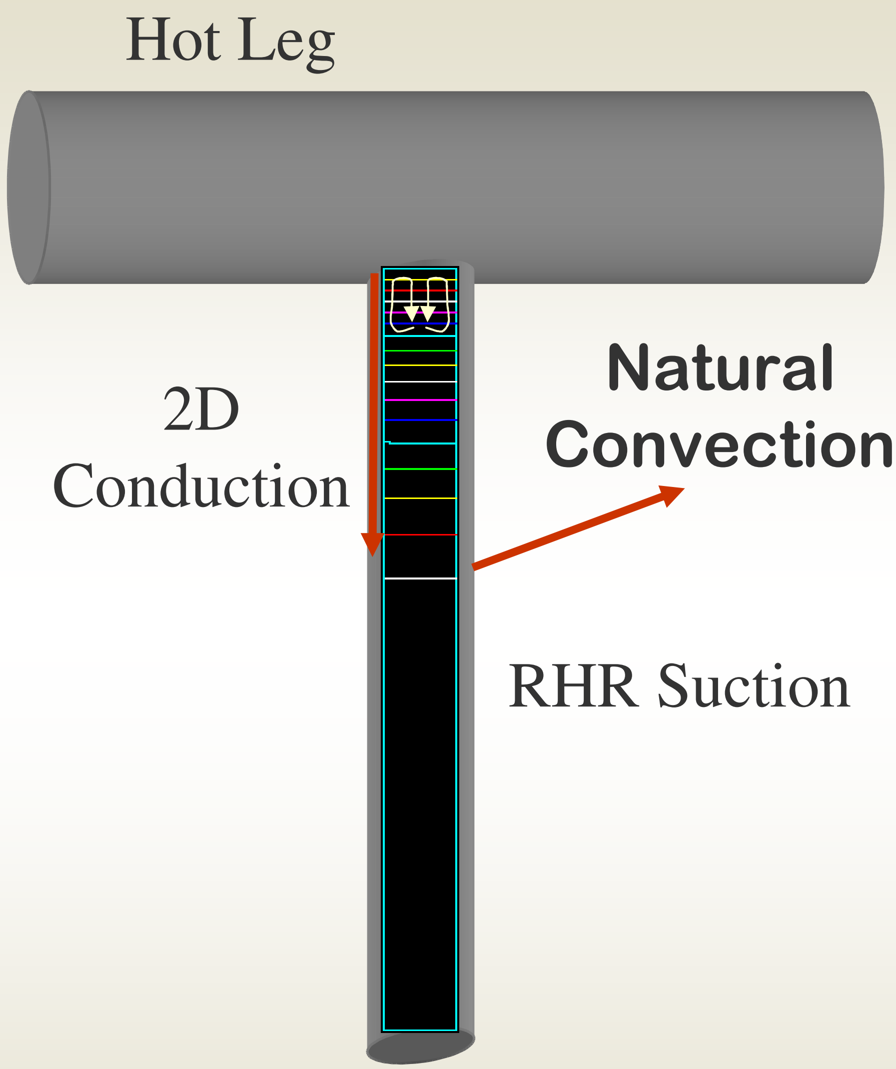
- Networks Consist of Links and Nodes
- Full Implicit Solution
- Two-phase Homogenous Equilibrium Flow
- Heat Addition/Extraction at Nodes
- Connect to
  - Lumped Volumes
  - Subvolumes
  - Boundary Conditions



Tank System Ventilation

Piping System Modeling

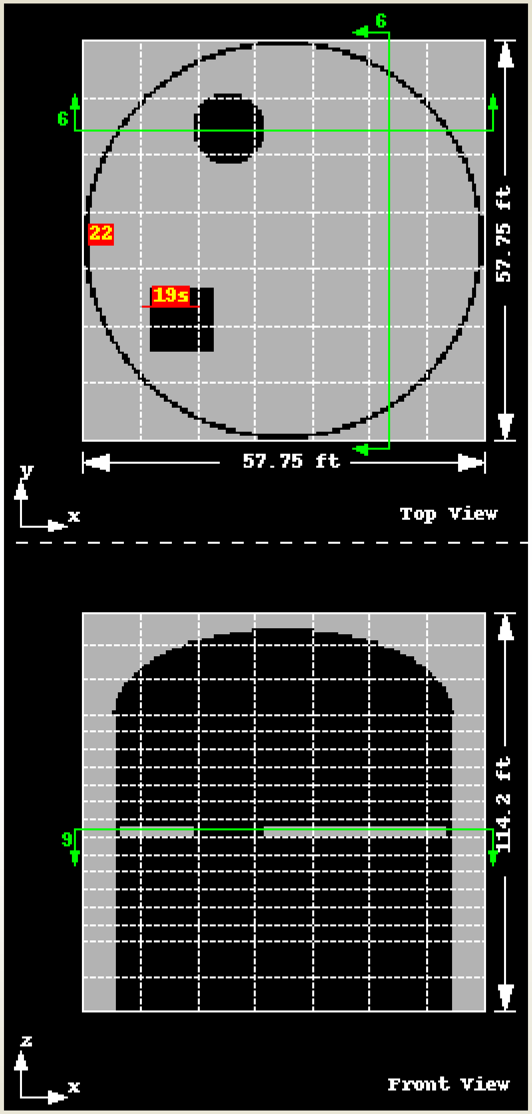
- Loop Performance
  - Pumps
  - Heat Exchangers
- Gas Transport
- Pressure Surge
- Water Hammer
- NPSH
- Thermal Mixing



Thermal Penetration in Stagnate RHR Suction Line

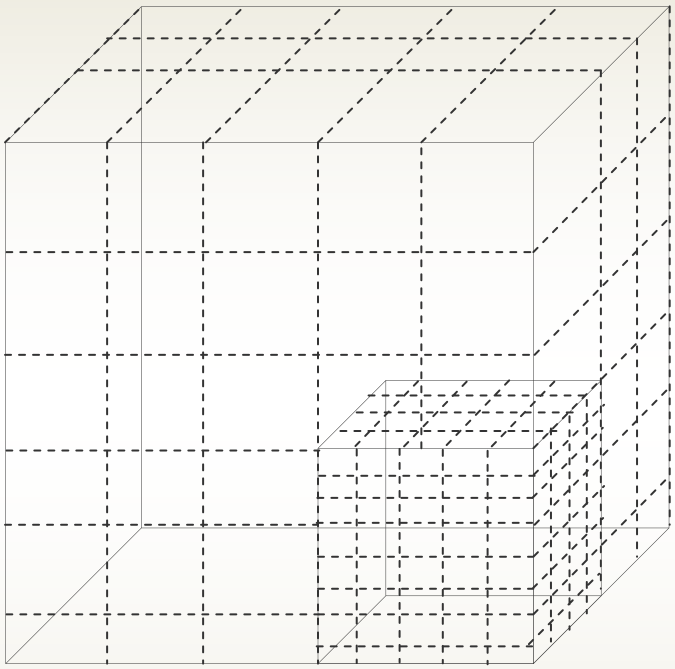
Subdivided Volumes

- Volume and Area Porosity Factors to Model Obstructions and Irregular Boundaries
- Slip/No-Slip Boundaries
- Easy User Interface



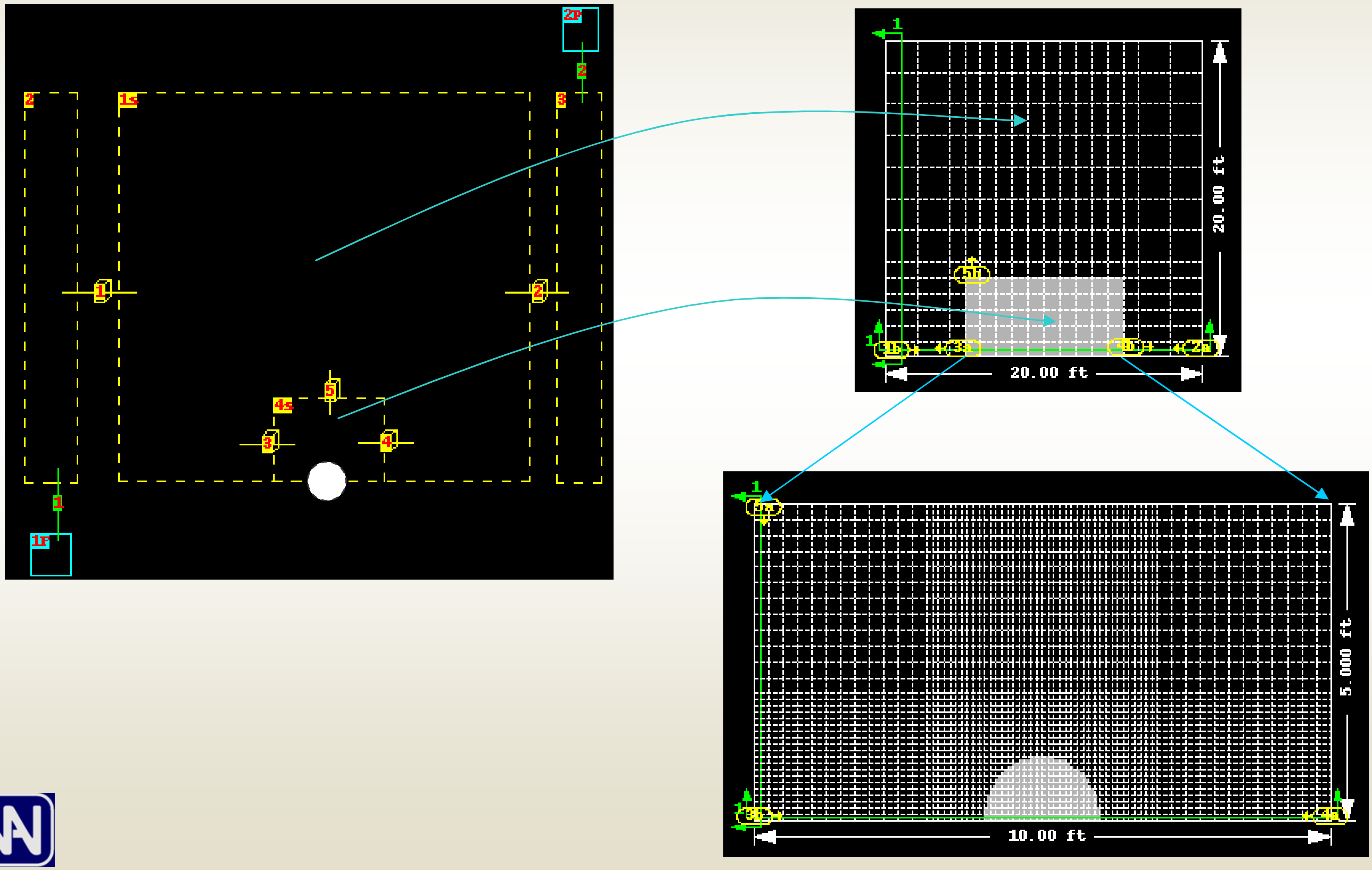
3D Connectors

- Connect Subdivided Volumes to
  - Lumped Volumes
  - Subdivided Volumes
- Embedded Grids
- Full 3D Momentum Solution
- Diffusion Across Connection



3D Connectors at interface between coarse and fine grids.

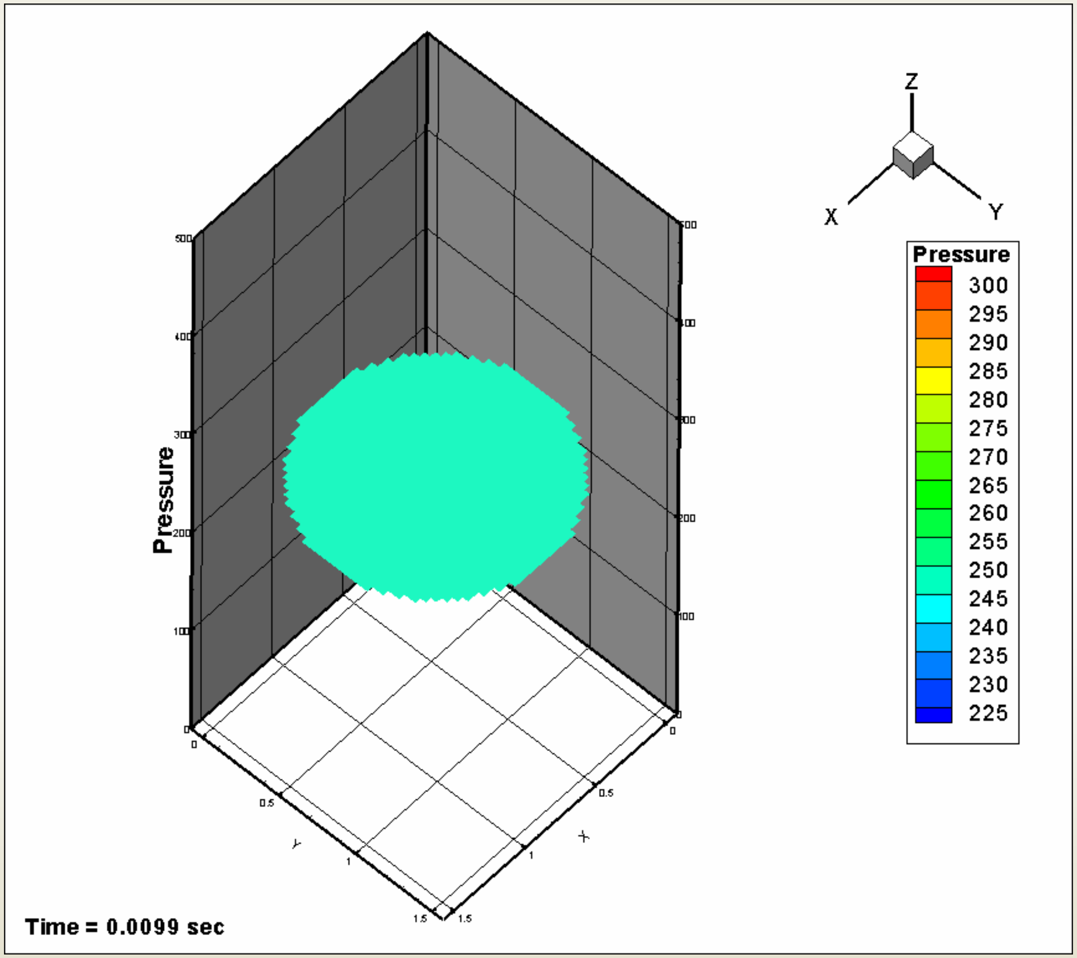
Multiple Detail Levels



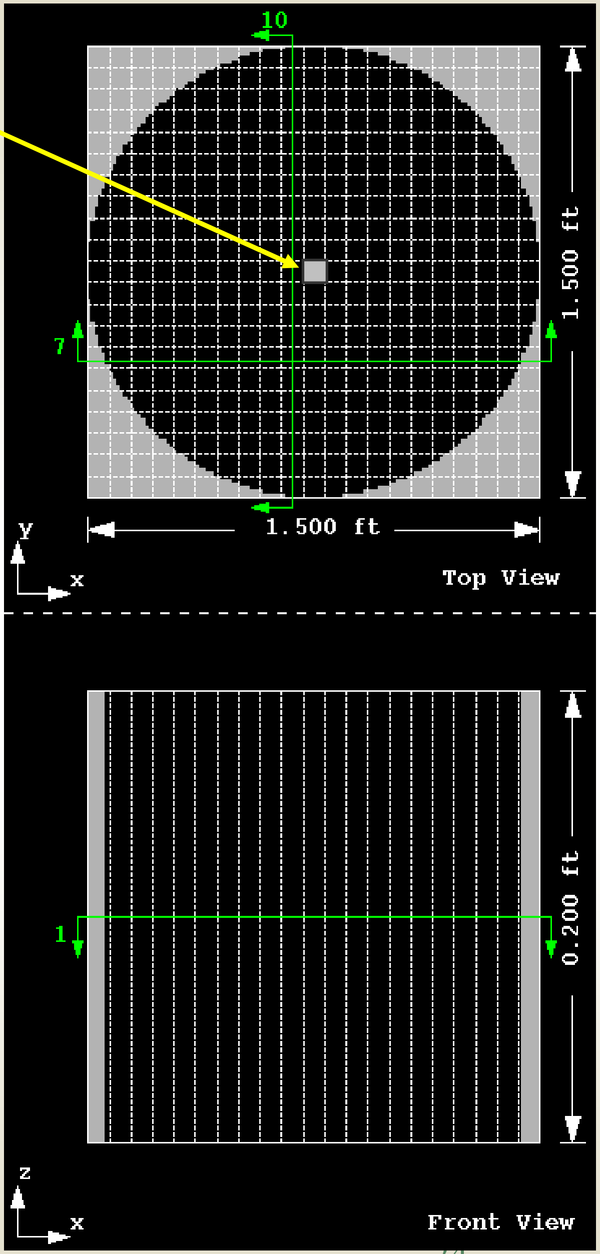
Variable Porosity and Local Control Variables

- User control on cell porosity parameters
  - Allows modeling transient geometry changes
- Local Control Variables use local conditions for evaluation
  - For example, use a single set of control variables to control many recombiners using conditions local to the recombiner.

Variable Porosity Tube Collapse

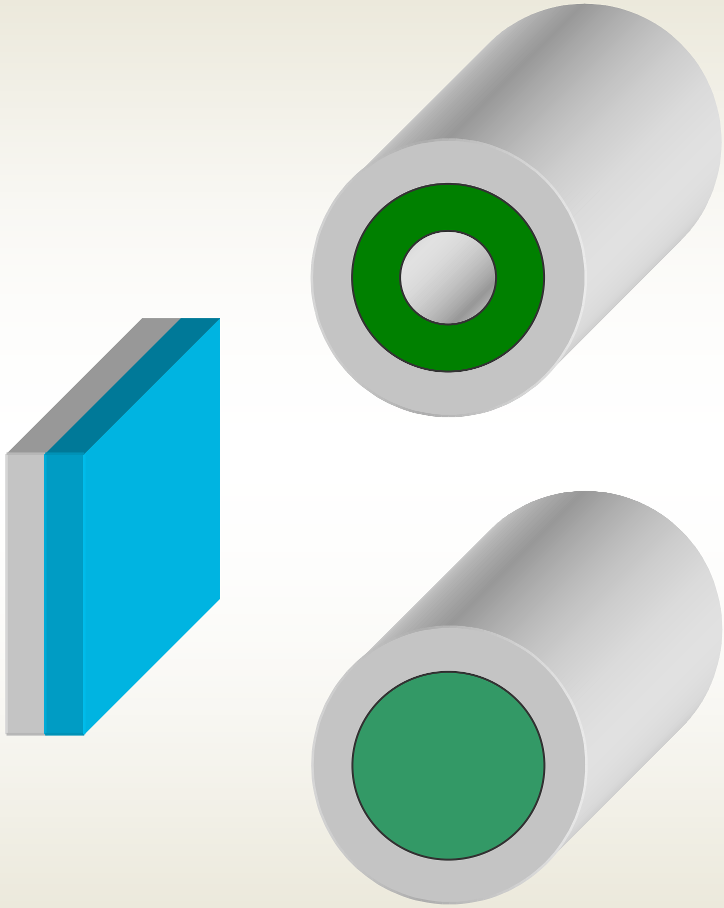


Tube



Wall Heat Transfer and Condensation

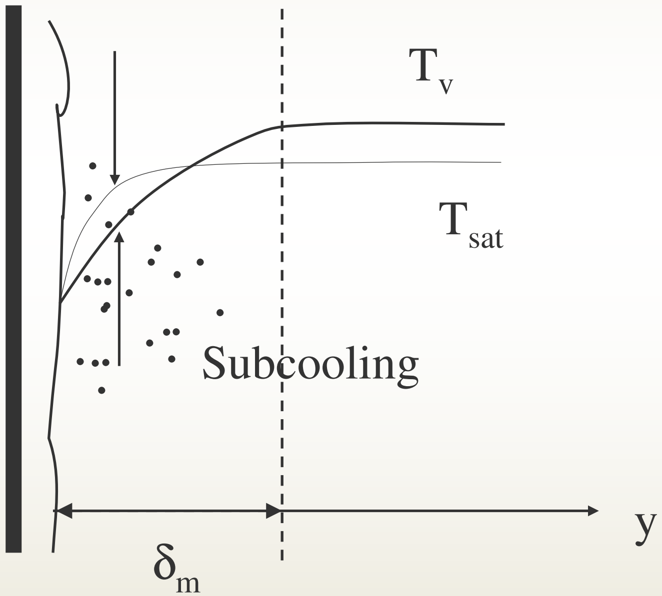
- Free Convection
- Forced Convection
- Radiation
  - Wall - Steam
  - Wall - Wall
- Condensation
  - Uchida
  - Tagami
  - Gido-Koestel
  - Mist/Diffusion Layer Model



- 1D and 2D Conduction

Wall Condensation Model

- Sensible Heat Transfer
  - Free Convection
  - Forced Convection
  - Radiation to Steam
- Mass Transfer
  - Mass Transfer Coefficient from Heat/Mass Transfer Analogy
  - Mist Formation in the Boundary Layer



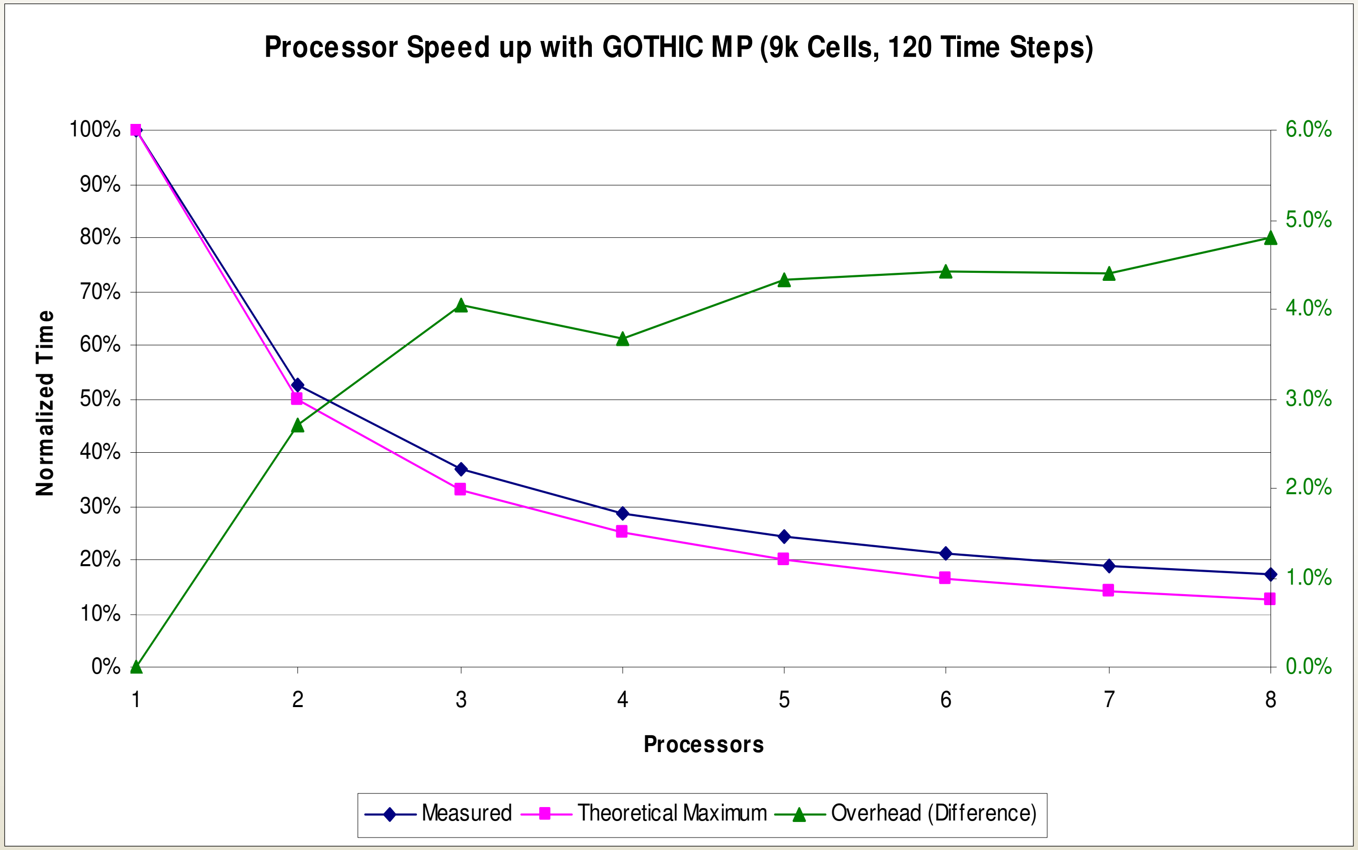
Building Leakage

- Long term leakage through cracks and small holes
  - Laminar
  - Turbulent
  - Combined
- Tuning parameters to match test data

Solution Methods

- Conductor Solution
  - Full implicit finite volume
- Fluids Solution
  - Semi-implicit finite volume
  - 1st and 2nd order upwind differencing options
  - Multigrid, Conjugate Gradient, Block Iterative and Direct Matrix solution options.
- Parallel Processing
  - Shared memory

Parallel Processing
Speedup for Large Problem



Code Coupling

- GOTHIC can be coupled with other codes for more complete system solution
  - InterProcess Communication (IPC) - examples

1	GOTHIC Containment	⟷	GOTHIC SW/CCW Loops
2	GOTHIC Containment	⟷	RELAP Primary System

  - Dynamically Linked Libraries (DLL) – examples
    - Recombiner Performance Model
    - Data Transfer

User Interface

- Graphical model construction
- Structured tables for input parameters
- Consistency and range testing
- Link to Excel
- Model comparison
- Graphical and tabular output

Quality Assurance

- GOTHIC is maintained under NAI's QA Program.
- Conformance to 10CFR50 Appendix B requirements.
- Meets intent of ASME NQA-1
- Audited by NUPIC
- Built in QA features
  - Event Logging
  - File Comparison Utility

Selected
GOTHIC
Applications

Numerical Applications, Inc.

Applications by NAI and Others

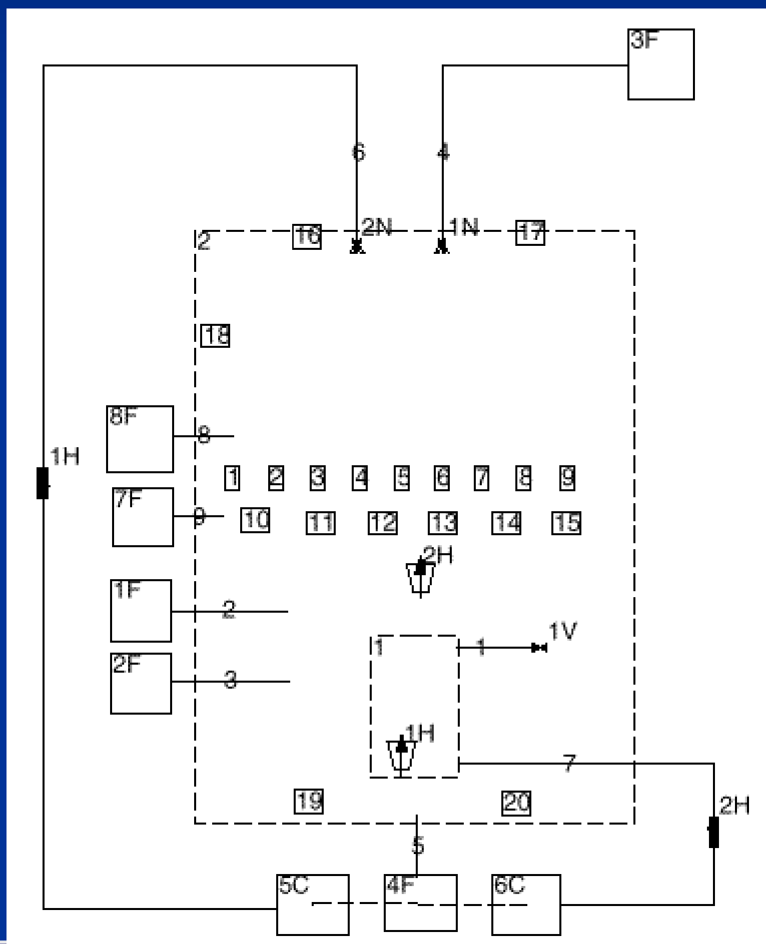
- DBA Licensing Analysis
  - Containment Peak Pressure and Temperature
  - Post LOCA cool down
  - Minimum Pressure for ECCS
  - Subcompartment Analysis
- HELB outside containment
- Loss of ventilation/cooling in secondary buildings
  - Station blackout
- Other applications

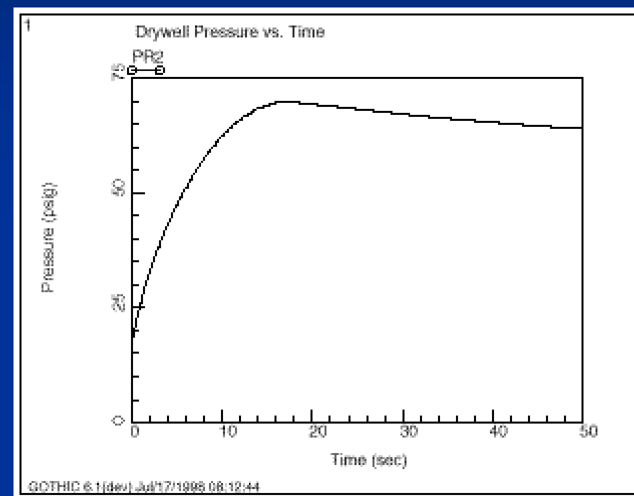
Containment Peak Pressure and Temperature

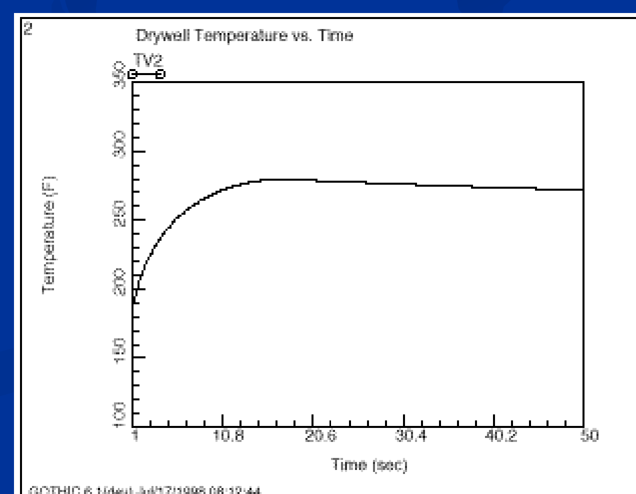
- LOCA and MSLB
  - Mass and Energy from Fuel Vendor
- Replace existing Licensing Analysis and Power Uprate
  - Large Dry Containment – PWR
  - Mark I – BWR
  - Mark 2 – BWR
  - Mark 3 – BWR
  - Ice Condenser - PWR
- New Plant Licensing
  - AP1000 – Westinghouse (WGOTHIC)
  - US-APWR - Mitsubishi
  - ABWR – Toshiba-Westinghouse
  - EPR - Areva

Containment Pressure/Temperature Analysis

- Large Dry Containment - PWR



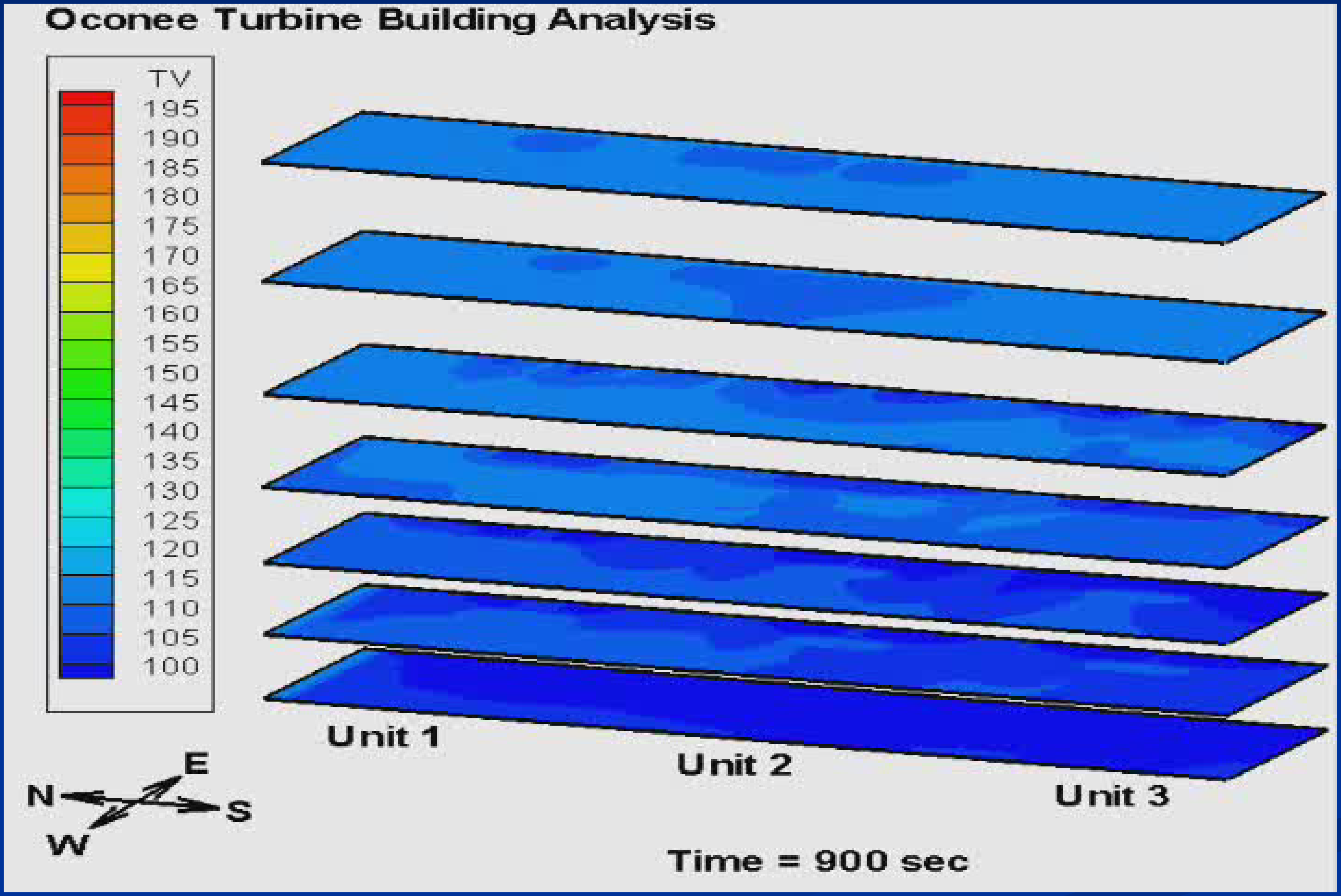




HELB Outside Containment

- Mass and Energy Release
  - Bounding Analysis
- Local compartment pressure and temperature
- Building performance
  - Blowout panels
  - Loss of ventilation and/or cooling
- Flooding Analysis
  - Door failure
  - Drain system

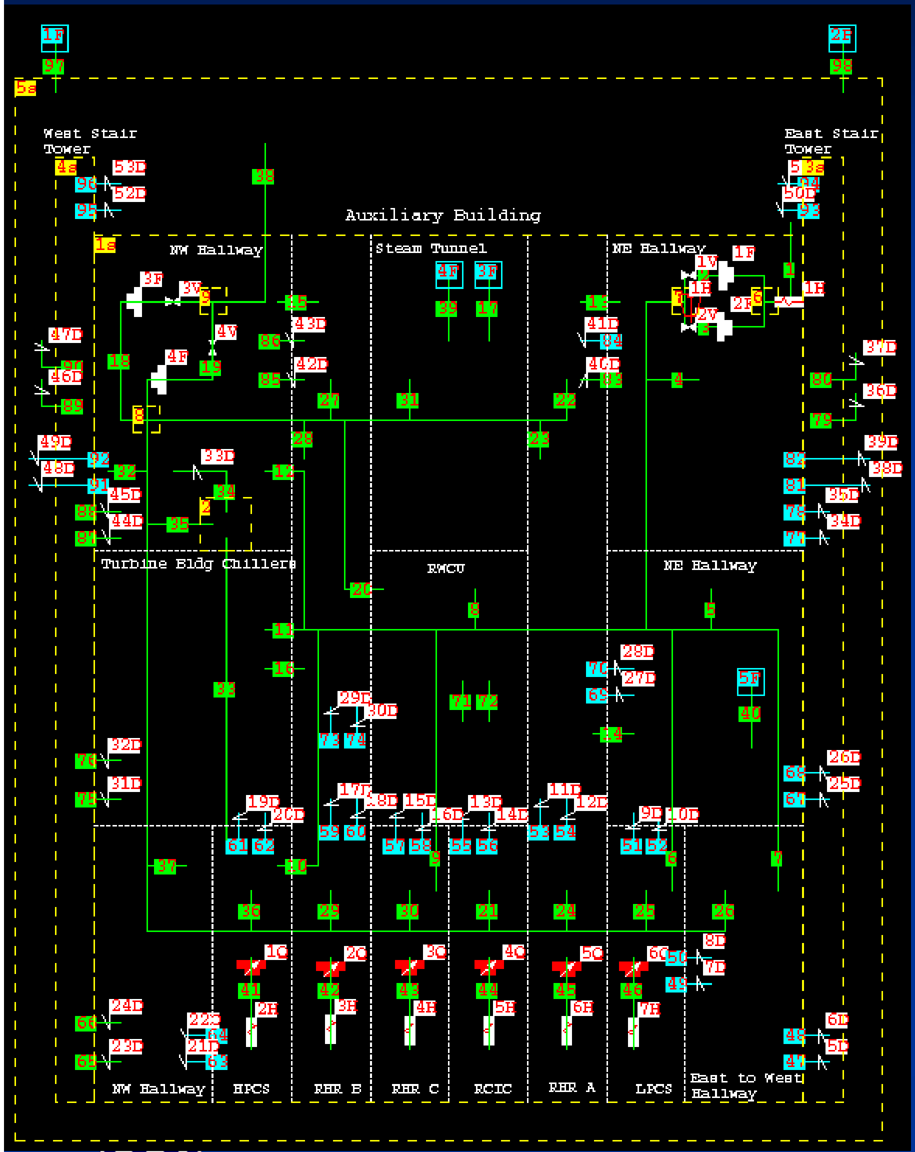
Turbine Building HELB

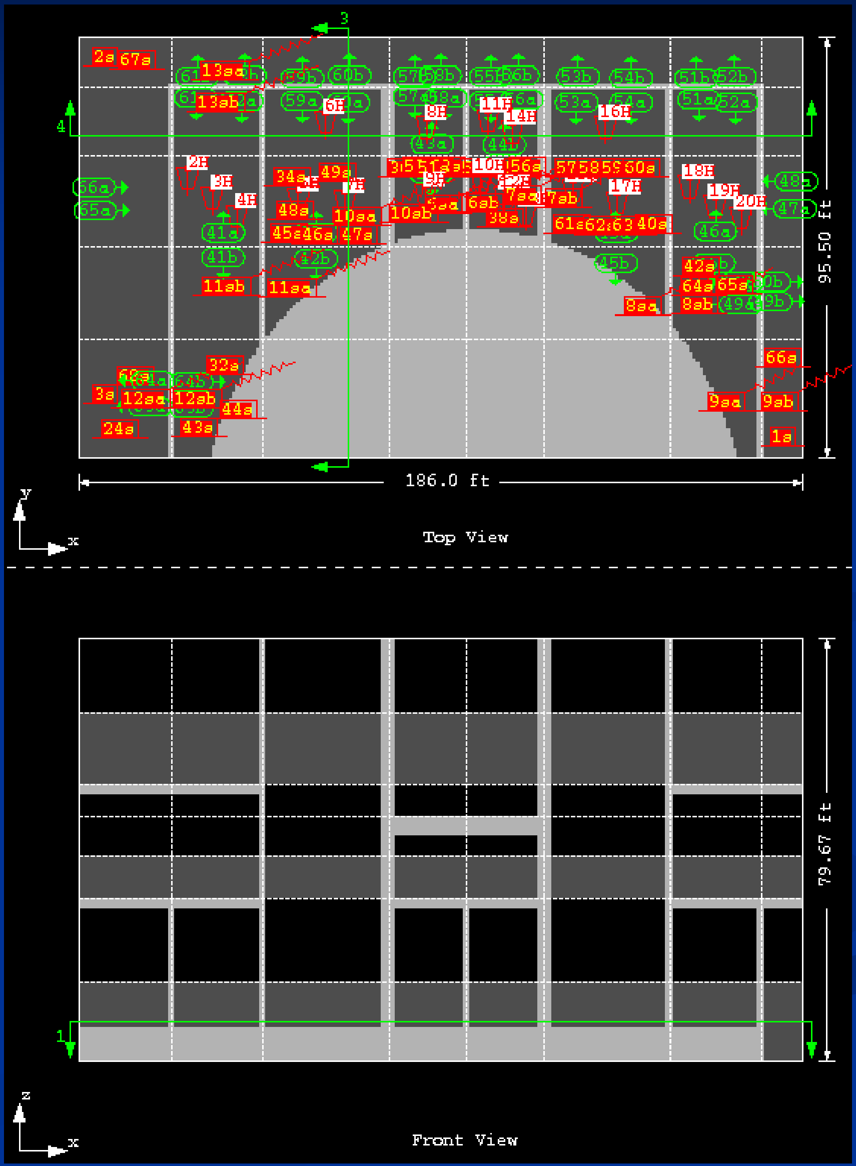


Room Heat Up in Secondary Buildings

- LOCA Heat Loads
  - Loss of Off Site Power
- Loss of cooling and/or ventilation
  - Normal operation
  - Accident heat loads
  - Mitigating actions
    - Door positioning
    - Temporary ventilation equipment
  - Whole building and local circulation effects

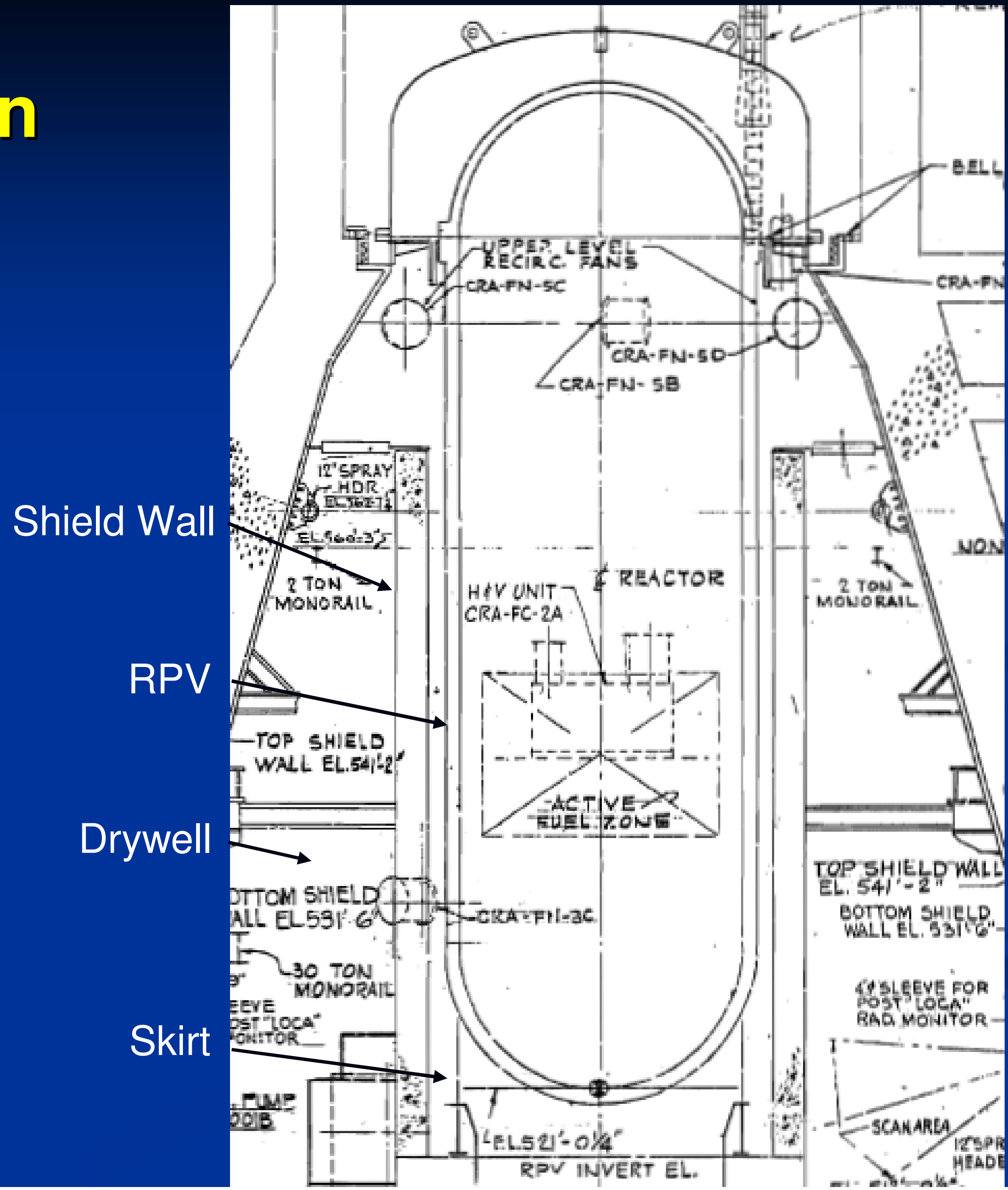
Typical Auxiliary Building Model



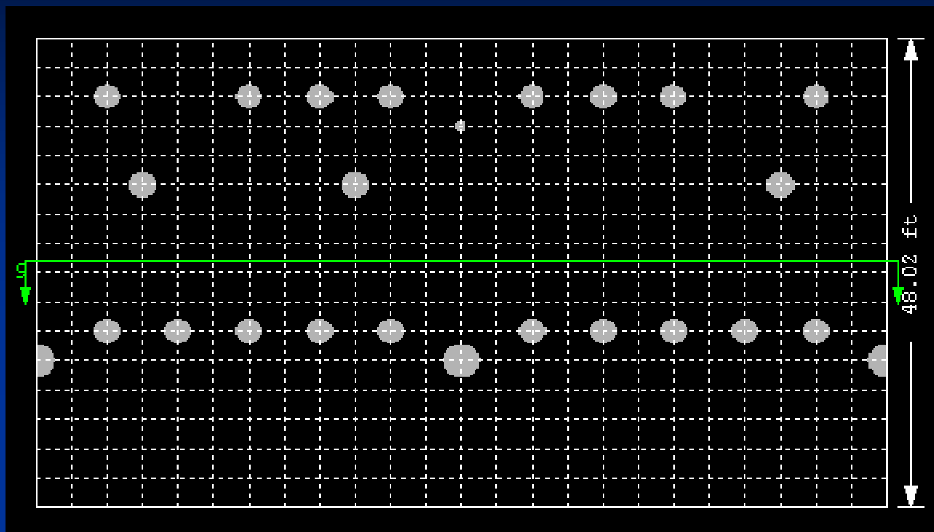


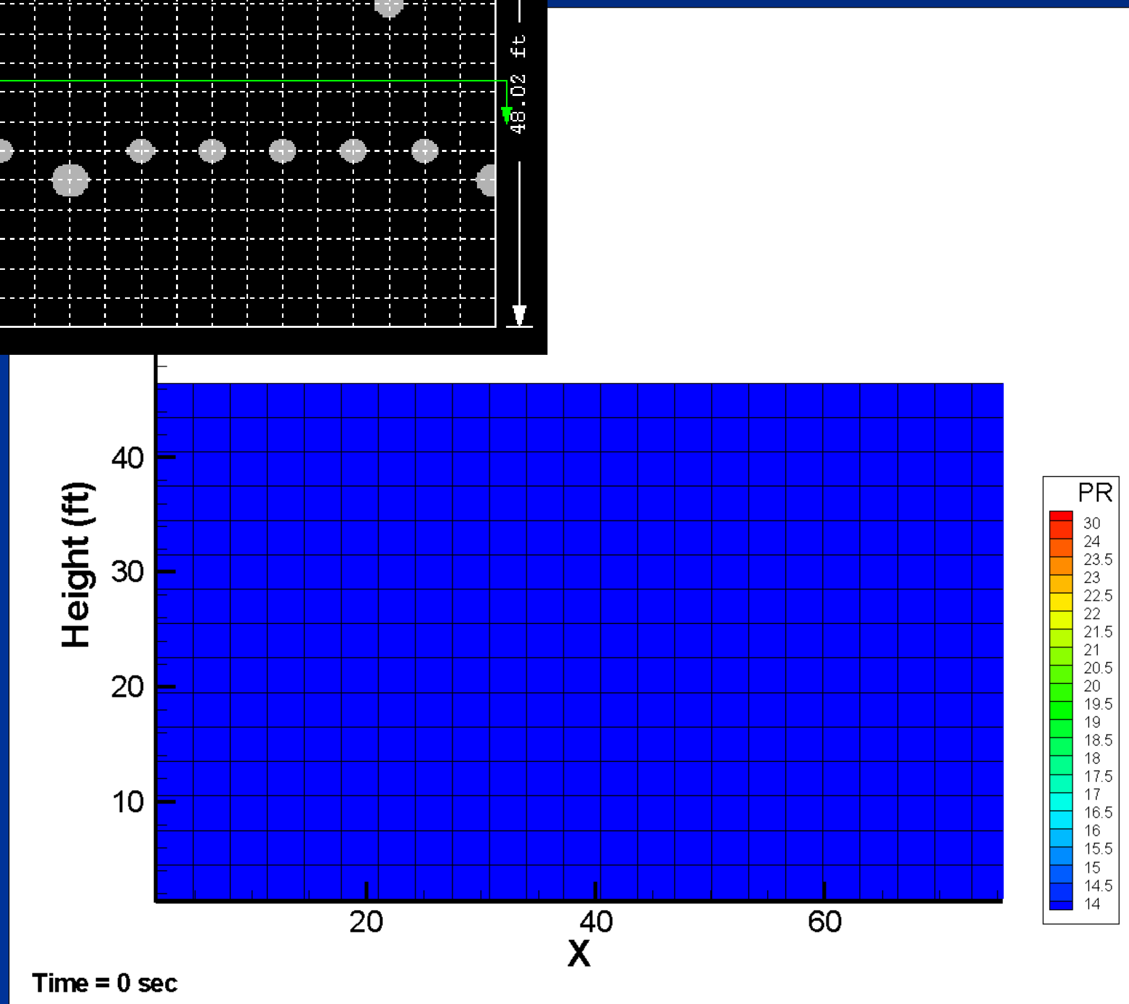
Annulus Pressurization

- Loads on RPV due to break inside annulus



2D Annulus Pressure Response



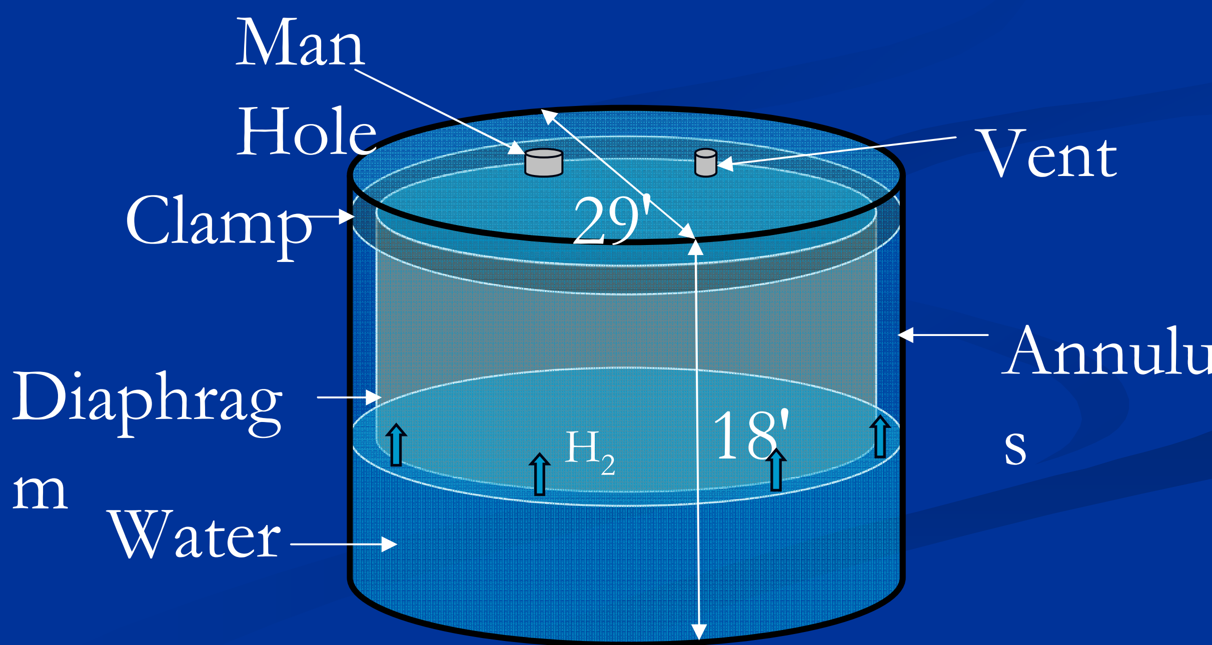


Fast H_2 Burn in a Recycle Holdup Tank

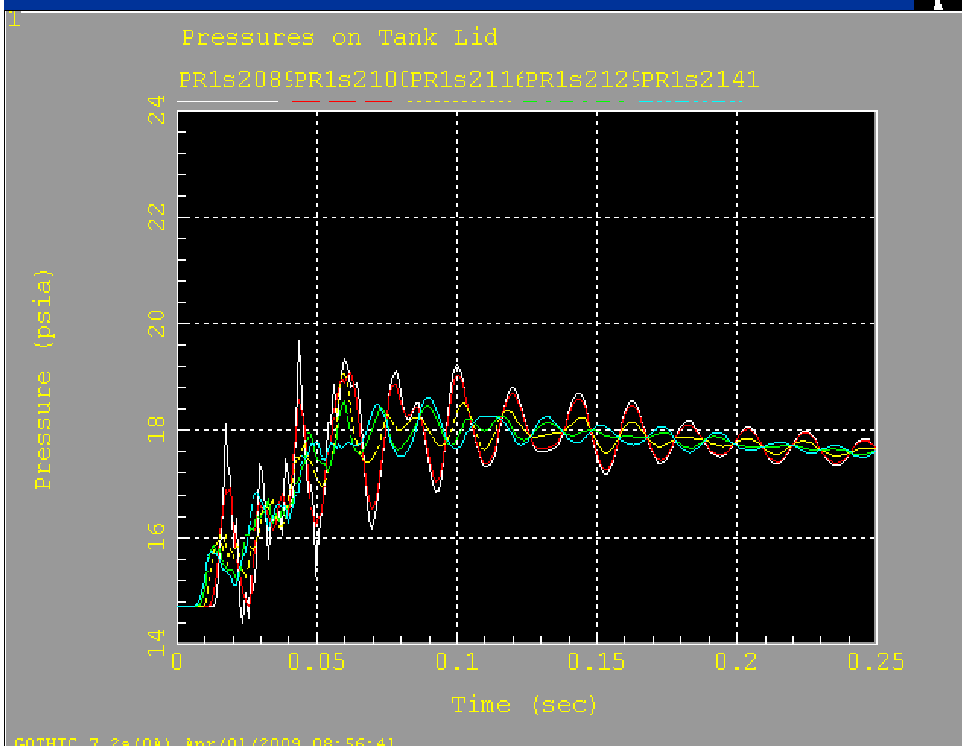
- H_2 accumulates in annular space between tank wall and diaphragm
- H_2 concentrations > 30% observed
- Consequences of H2 burn questioned by NRC – Possible tank explosion
- No known ignition source

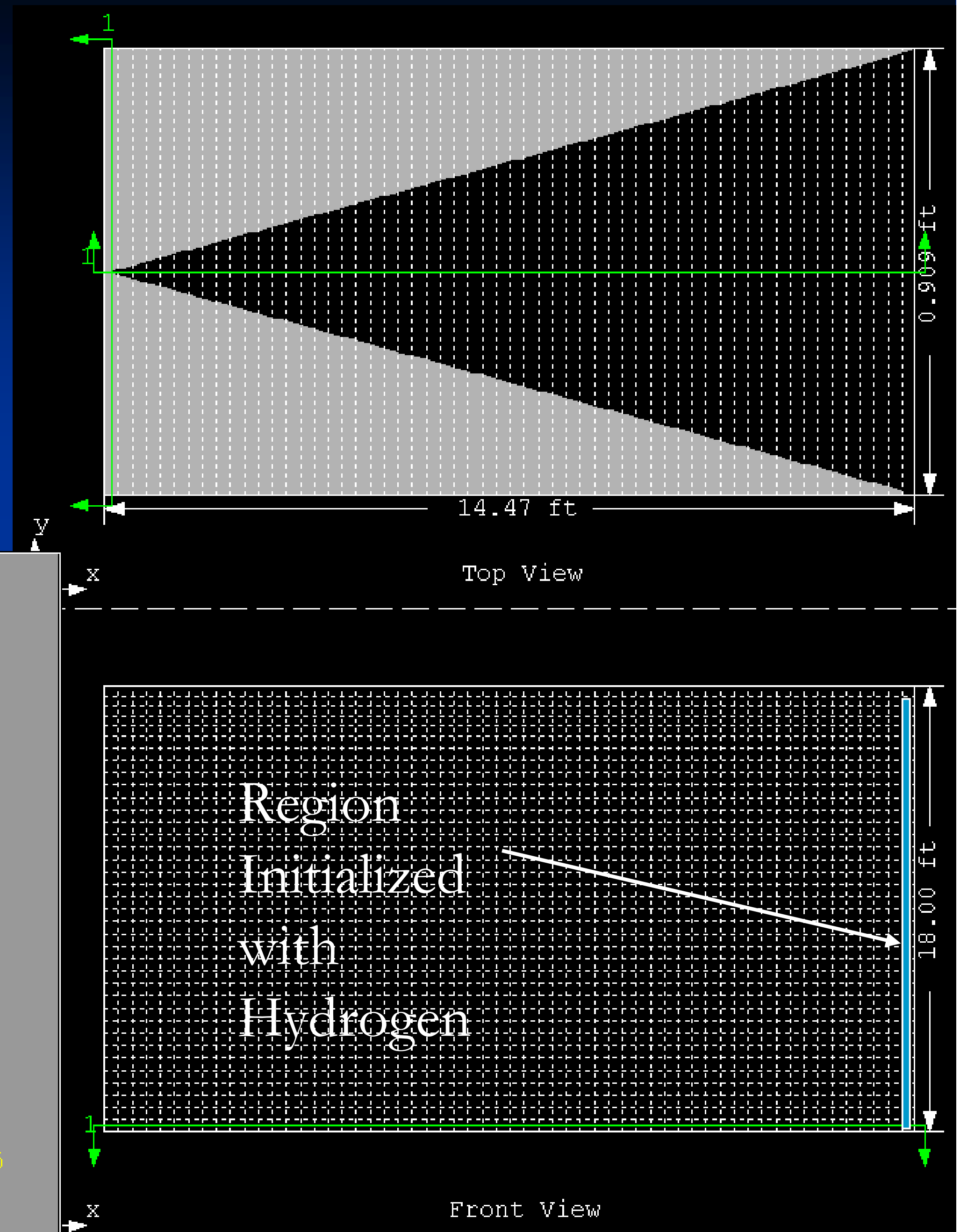
Fast H_2 Burn in a Recycle Holdup Tank

- H2 accumulates in annular space between tank wall and diaphragm
- H2 concentrations > 30% observed
- Consequences of H2 burn questioned
- Infinite flame propagation rate assumed in azimuthal direction (2D model)



Predicted Pressures on Tank Lid





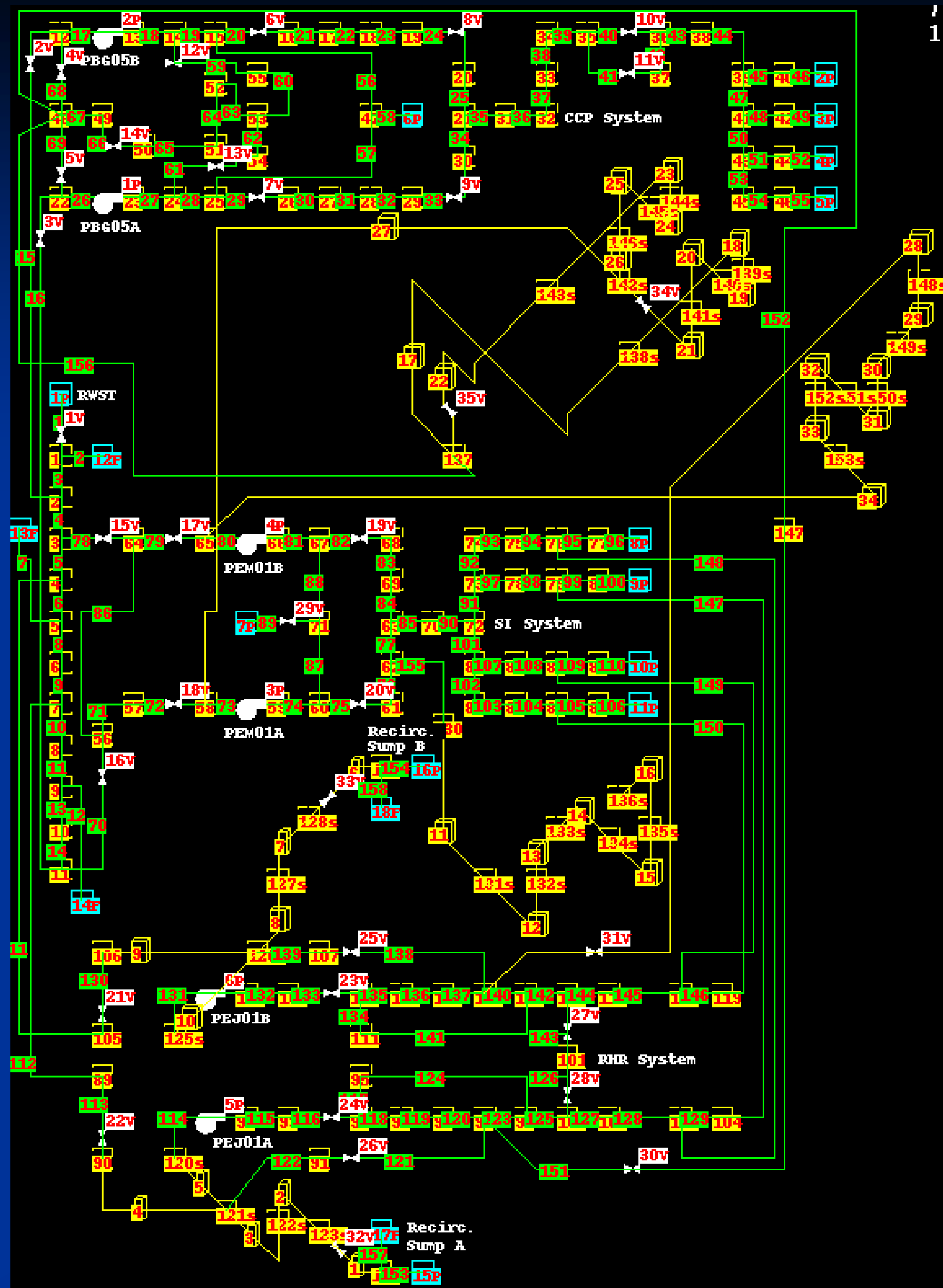
Gas Accumulation in ECCS Piping

- Gas voids have been found in ECCS piping in many plants with potential consequences:
  - Pump damage or failure due to gas ingestion
  - Pressure pulse on pump start up or valve opening
  - Water hammer when gas is expelled through an orifice
- Generic Letter 2008-01: Managing Gas Accumulation In Emergency Core Cooling, Decay Heat Removal, And Containment Spray Systems
  - Licensees must ensure that gas accumulation is maintained less than the amount that challenges operability.
  - Licensees must take appropriate action when conditions adverse to quality are identified.

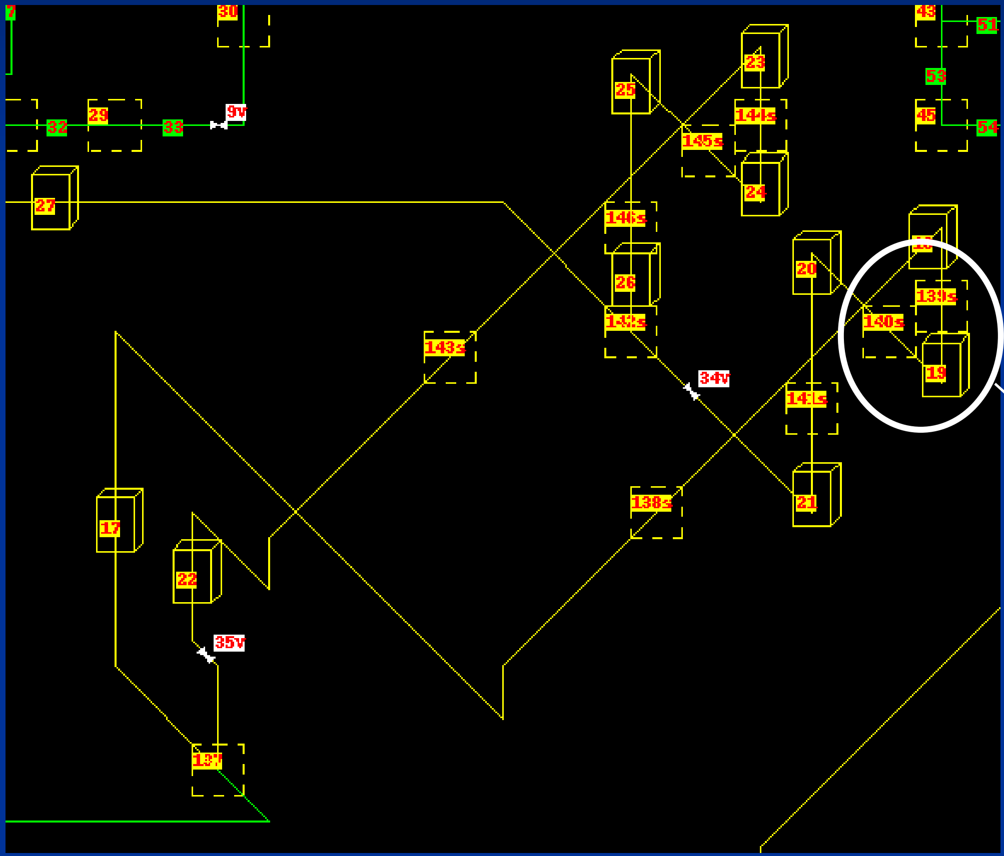
Problem

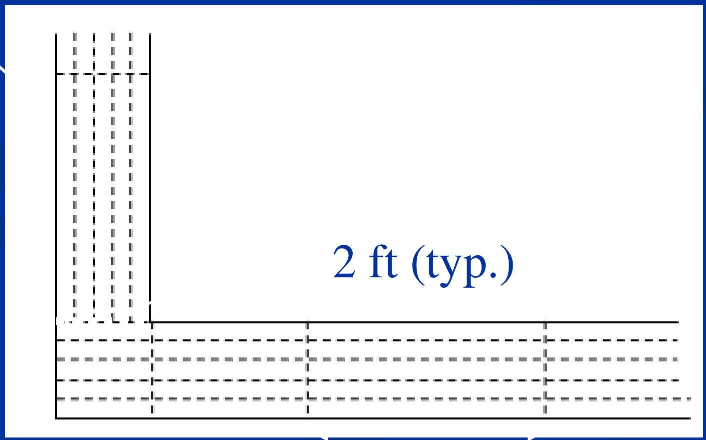
- Gas void discovered in multiple locations in WCGS ECCS piping in January 2008
  - Residual Heat Removal Pump suction and discharge (14" lines)
  - Safety Injection Pump suction and discharge (6" lines)
  - Charging Pump suction and discharge (6" lines)
  - Voids were predominately air with some hydrogen
  - Various void size in various piping sizes.

Typical System Piping Model



Model Detail

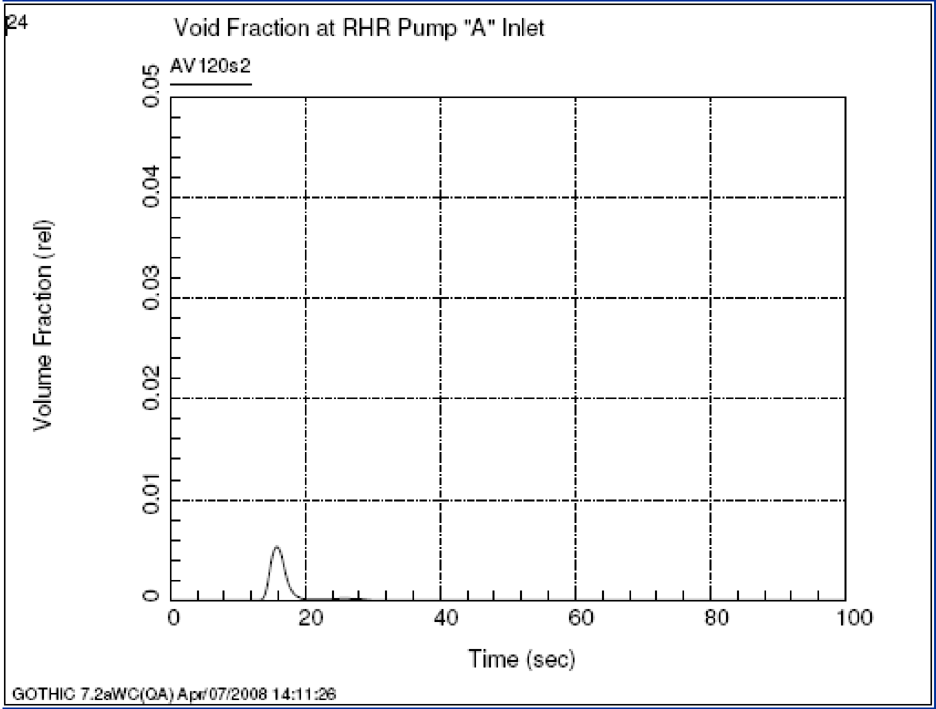




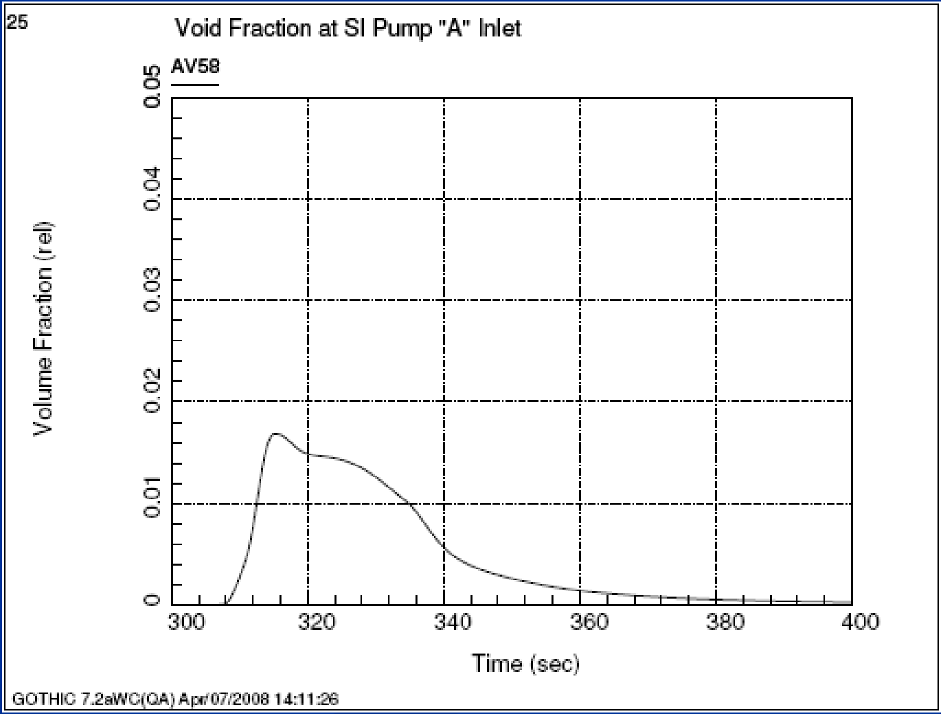
WCGS Simulation Results

- Minimum RCS Pressure
  - Maximum Pump Flow

RHR Pump Intake

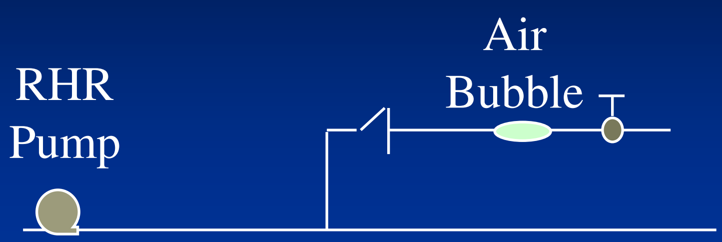


SI Pump Intake

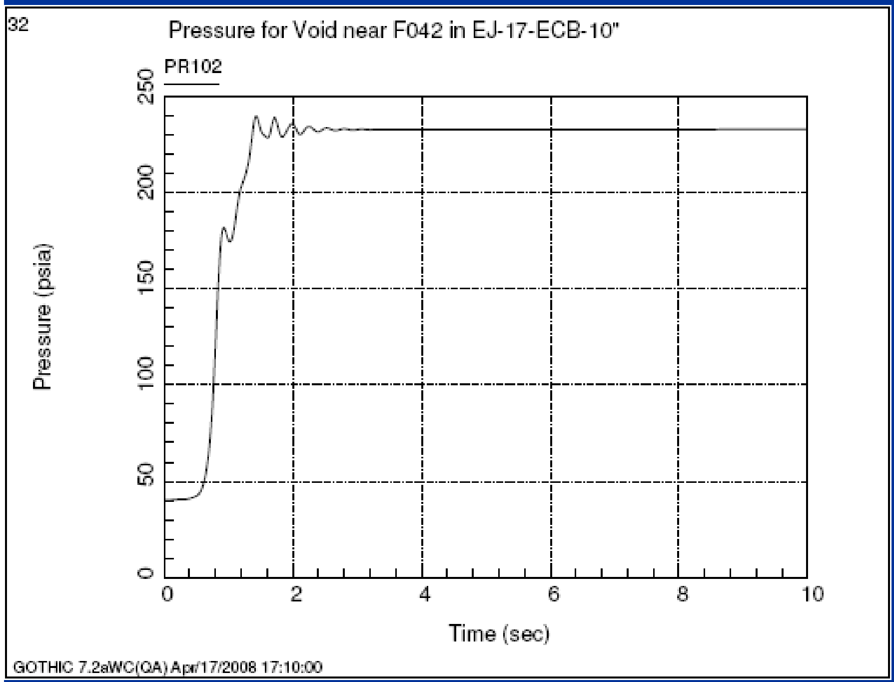


WCGS Simulation Results

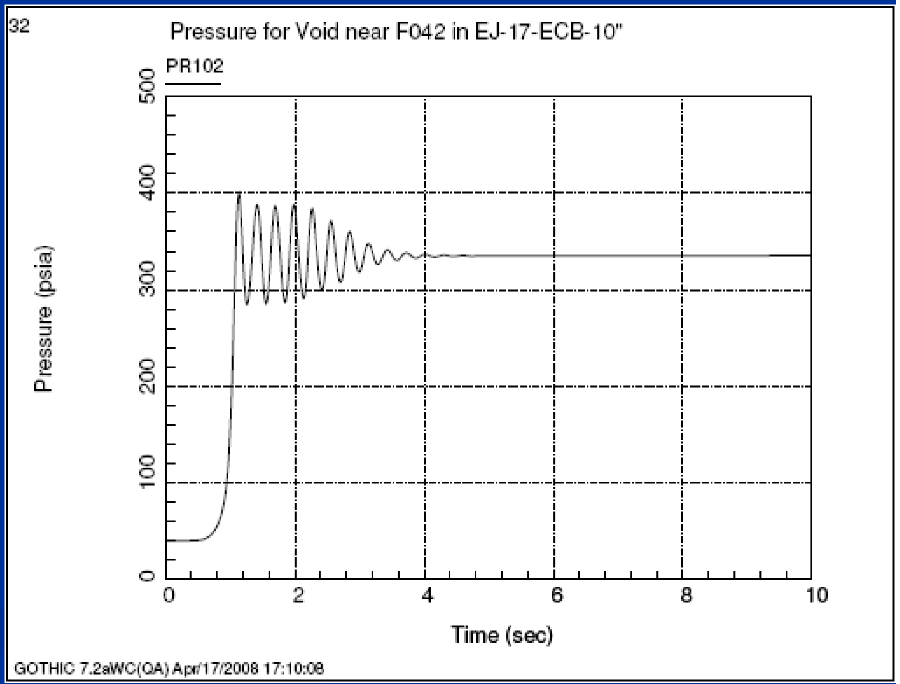
- Pressure Pulses Downstream of Pumps and Valves



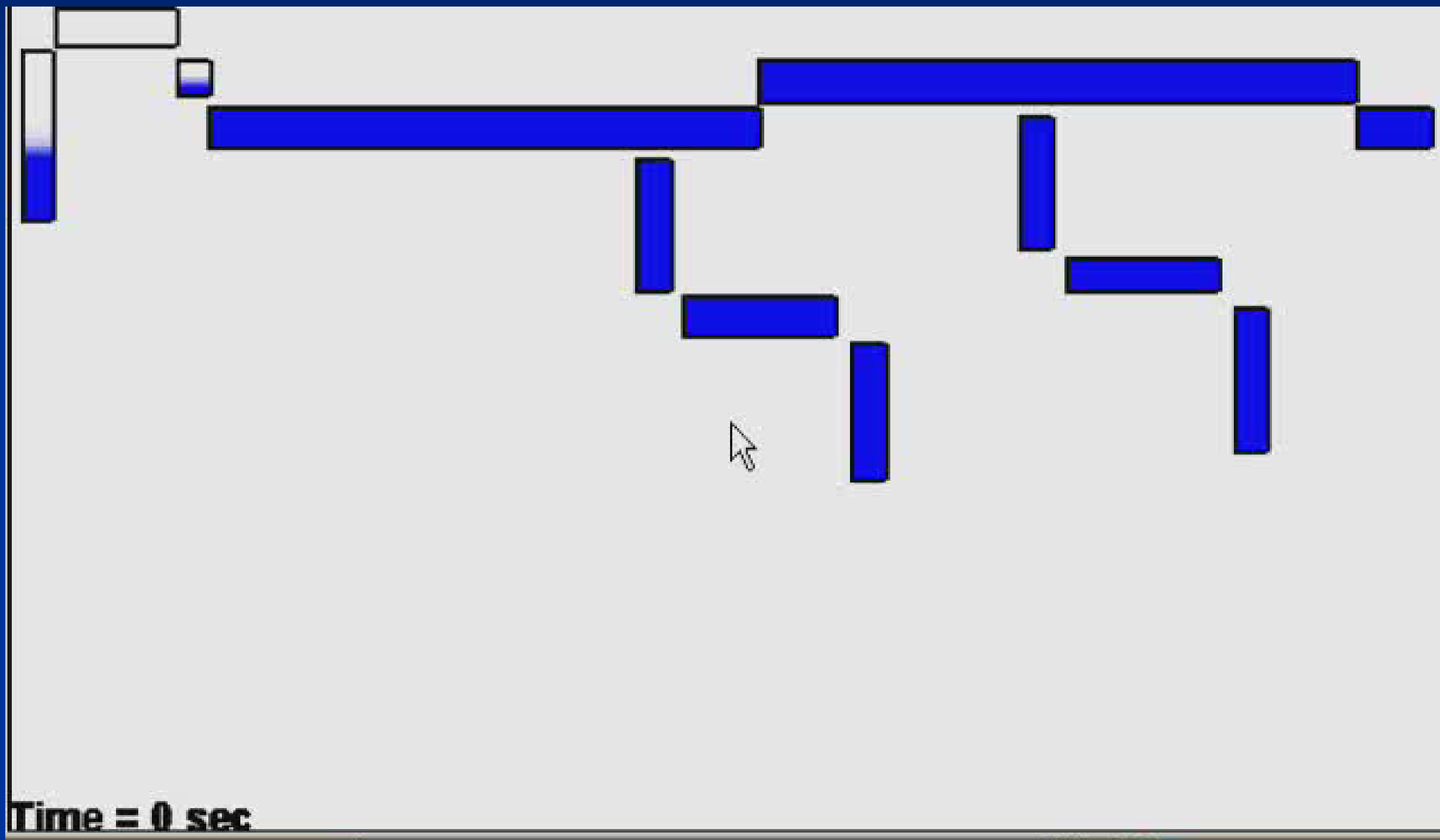
0.25 ft^3 Air Bubble in 10" Line



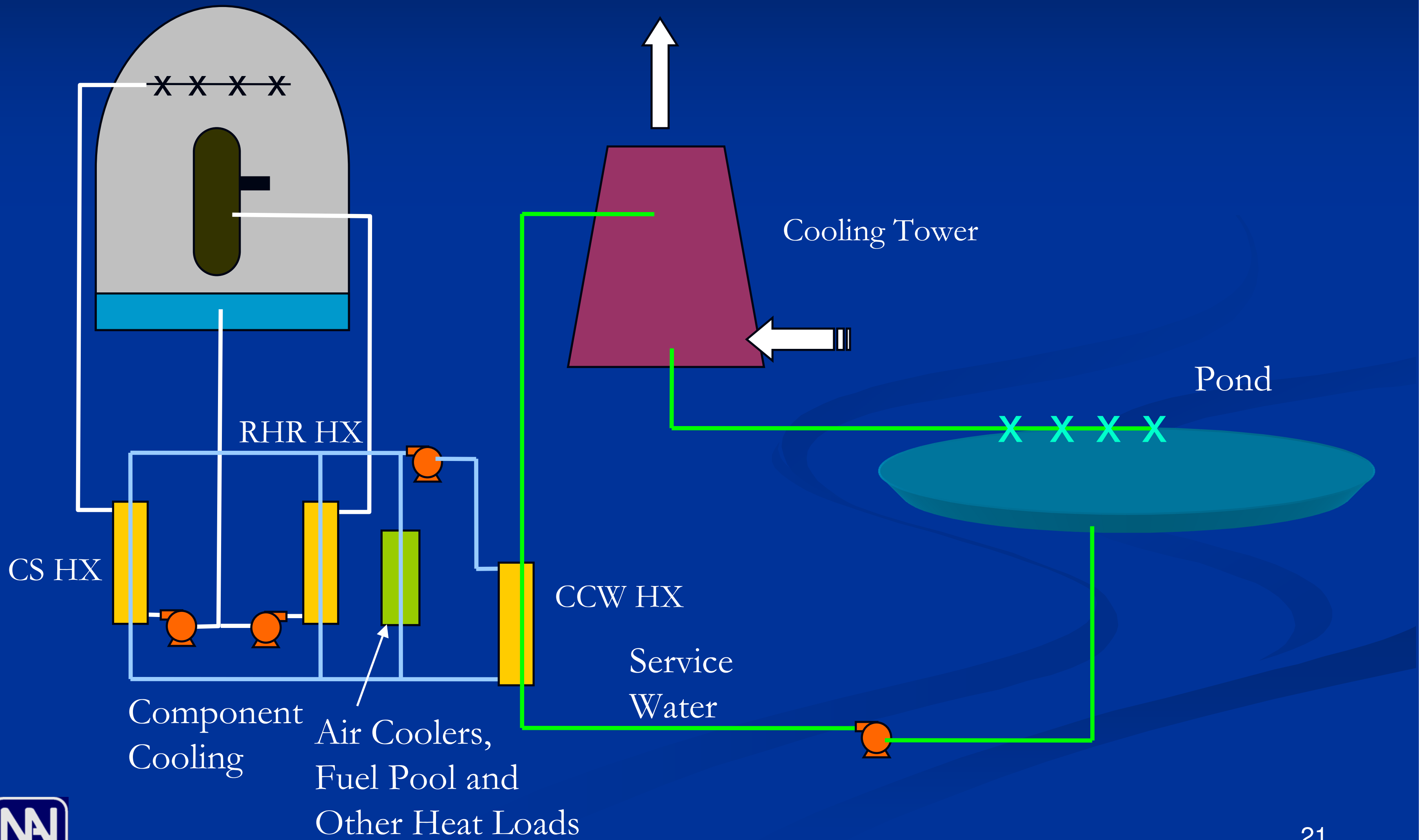
1.0 ft^3 Air Bubble in 10" Line



Harris SI H_2 Bubble Migration



UHS / Long Term Cooling



UHS / Long Term Cooling

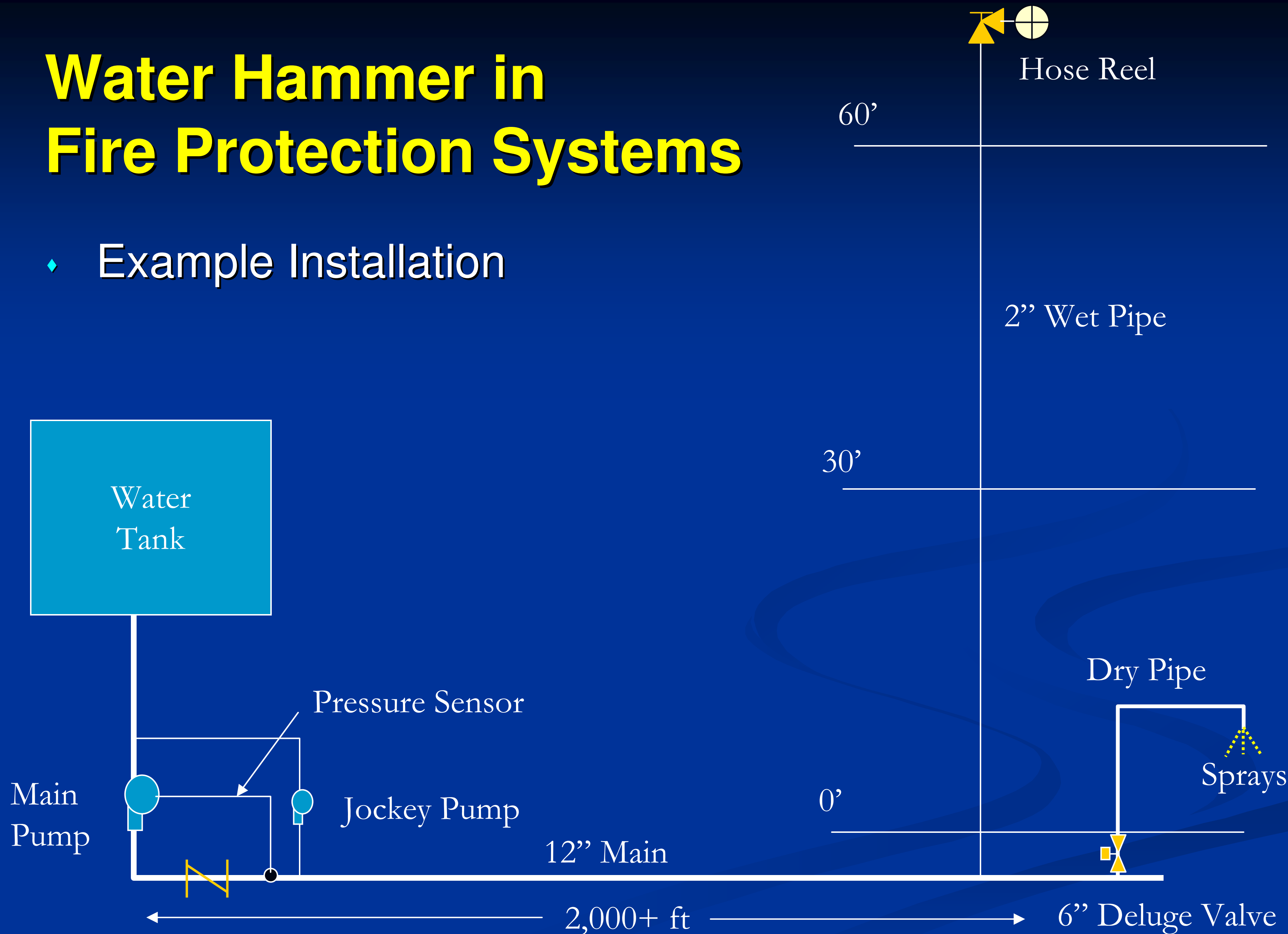
- Heat Exchanger Performance
  - Configurations (Tube and Shell, Counter-flow, Cross Flow, Parallel Flow, Fins)
  - Fouling
  - Convection Correlations
  - Tuning Parameters
- Air Coolers
  - Versatile Geometry Input
  - Condensation

UHS / Long Term Cooling

- Spray Pond
  - Spray cooling
  - Spray evaporation
  - Spray drift loss
  - Spray bypass (out of service spray lines)
  - Pool evaporation
  - Pool solar heating
  - Thermal radiation to sky
  - Variable atmospheric wind speed, temperature and humidity effects

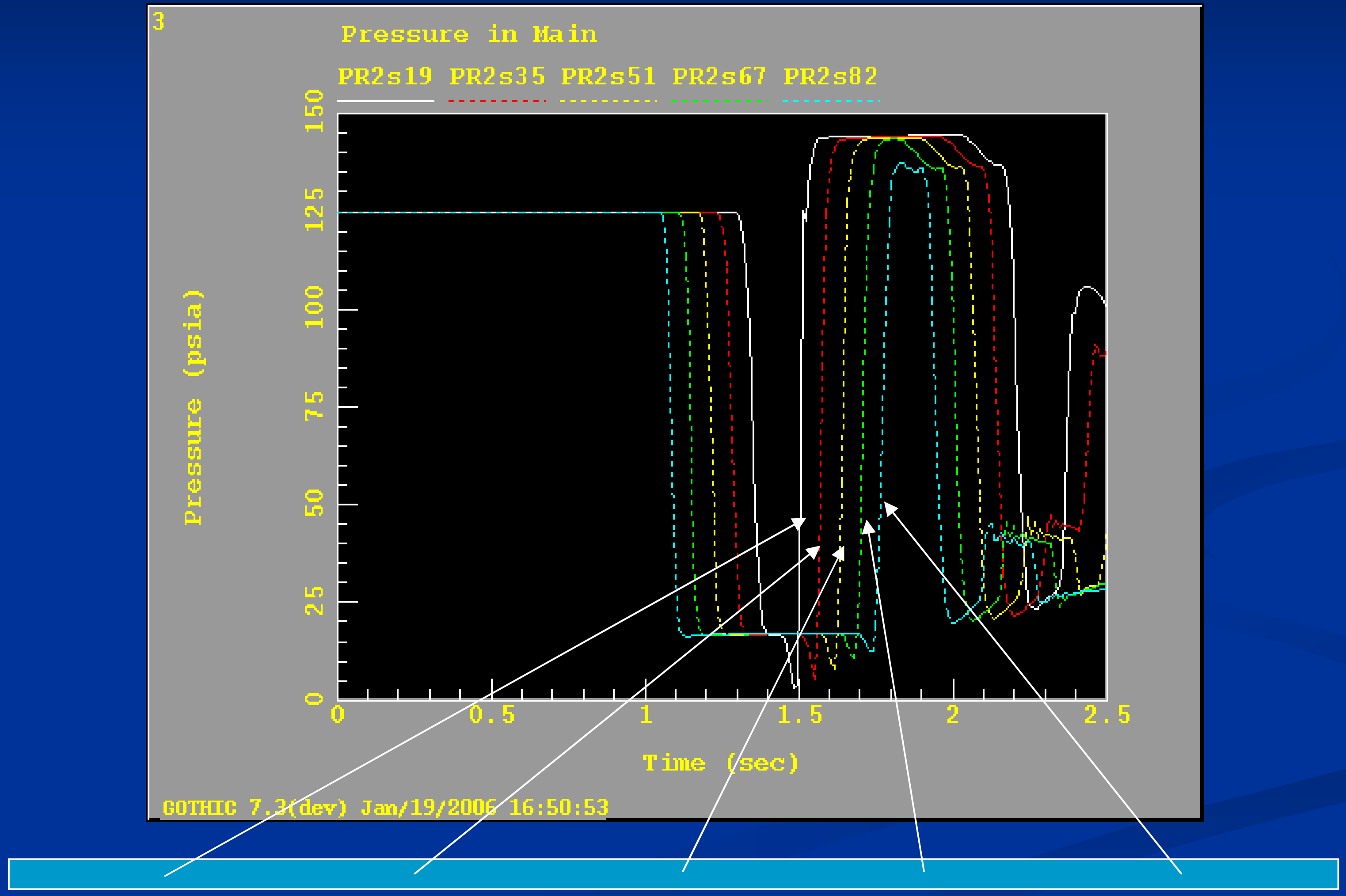
Water Hammer in Fire Protection Systems

- Example Installation



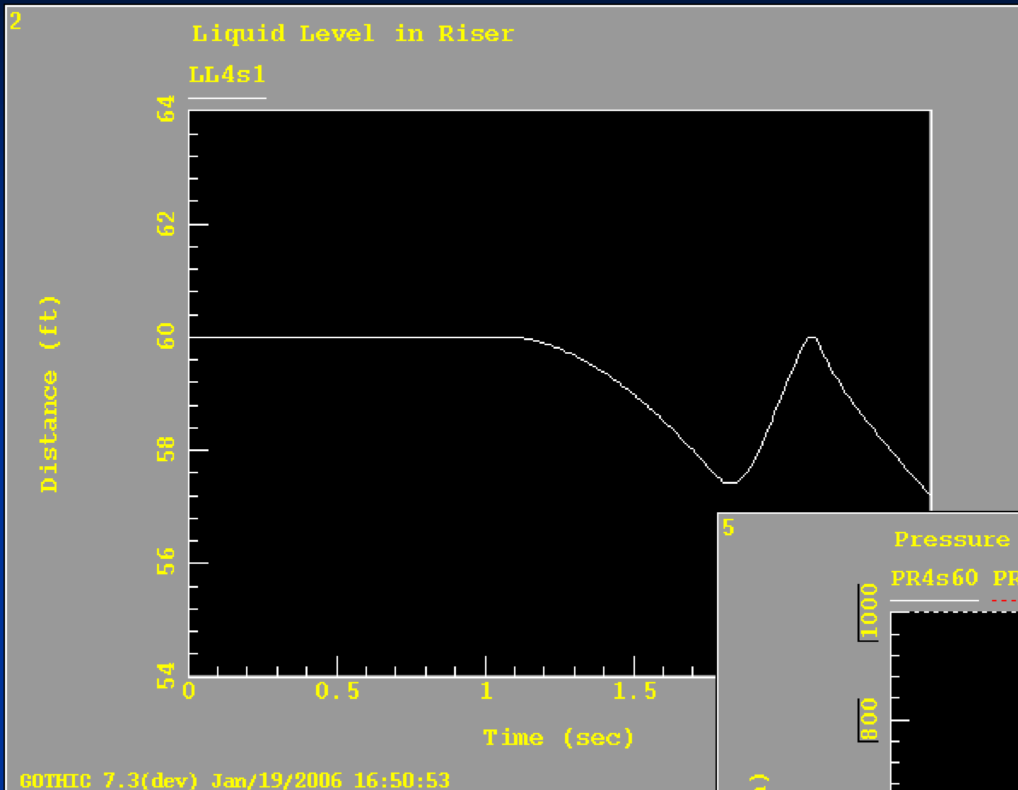
Pressure Transient in Main Piping

- Deluge Valve Opens at Time = 0s

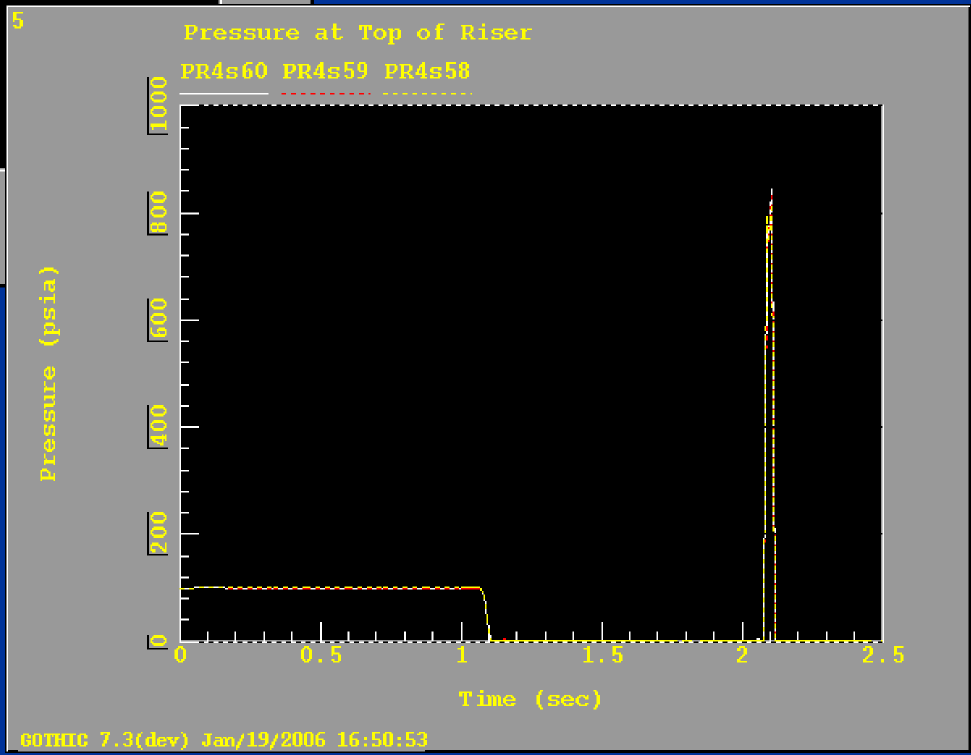


2,000+ ft System Main

Water Hammer in Fire Protection Systems

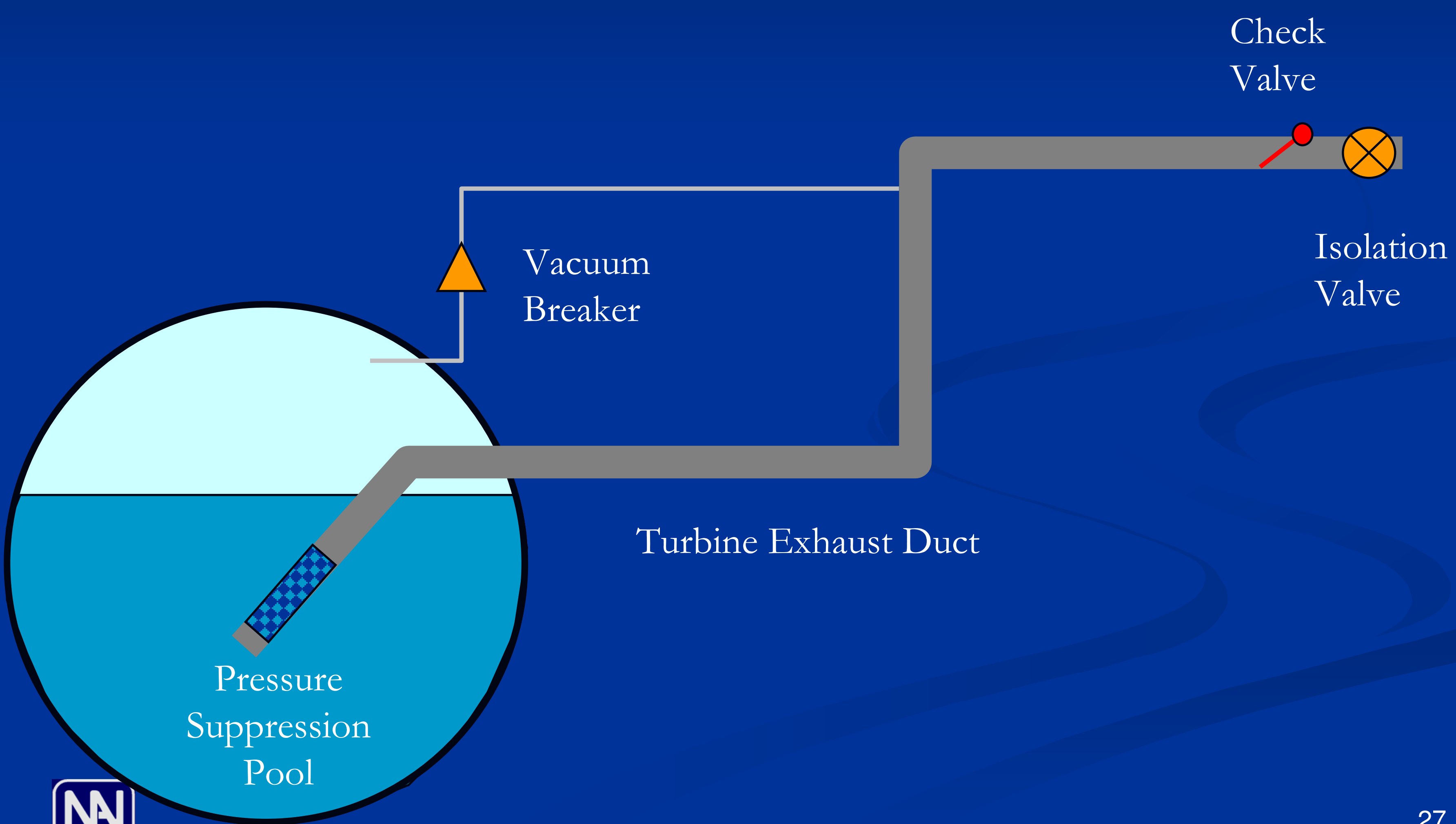


- Liquid Level in Riser

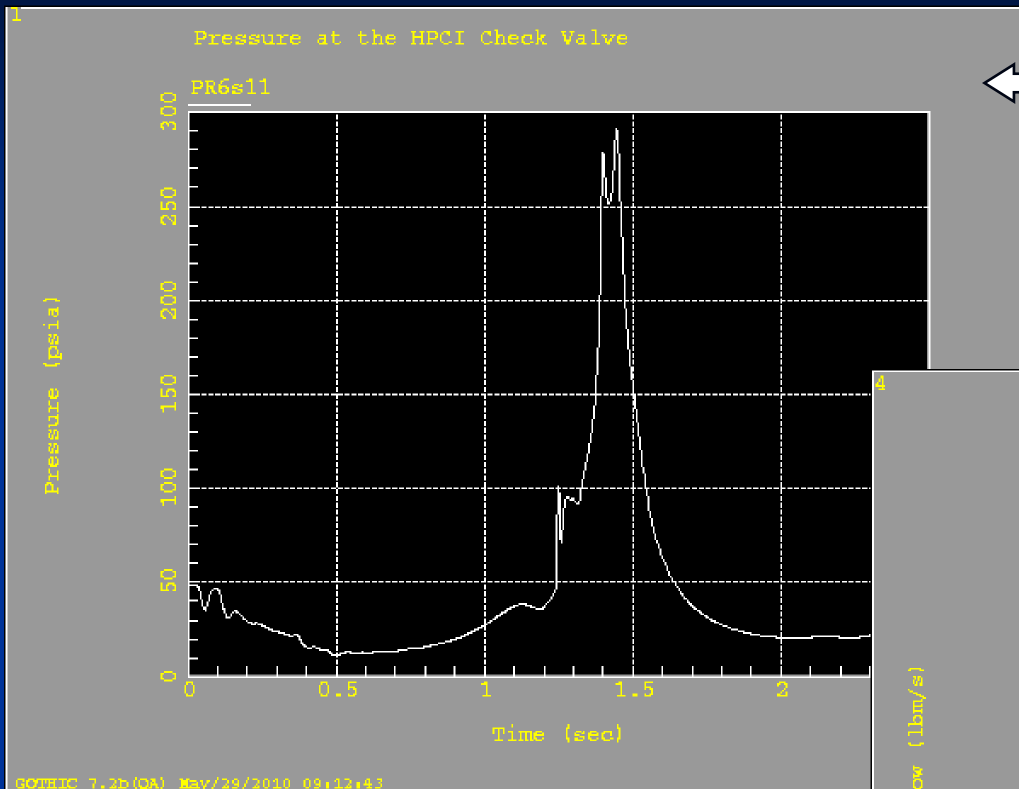


- Pressure at Top of Riser

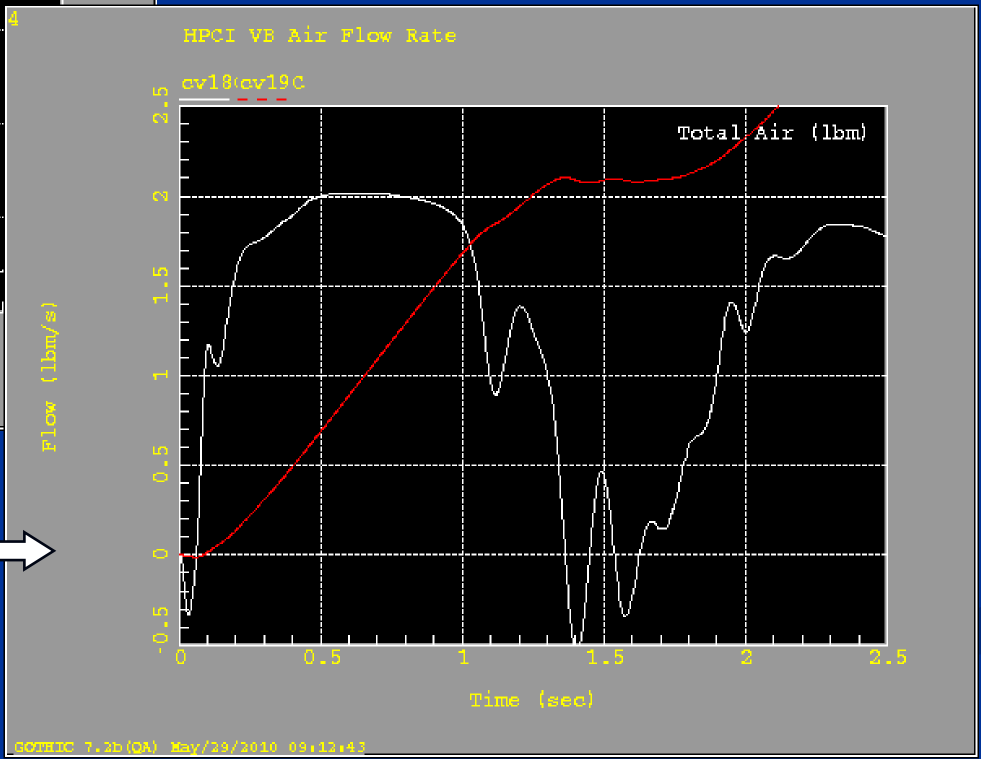
Water Hammer
BWR Turbine Exhaust Isolation



Turbine Exhaust Water Hammer

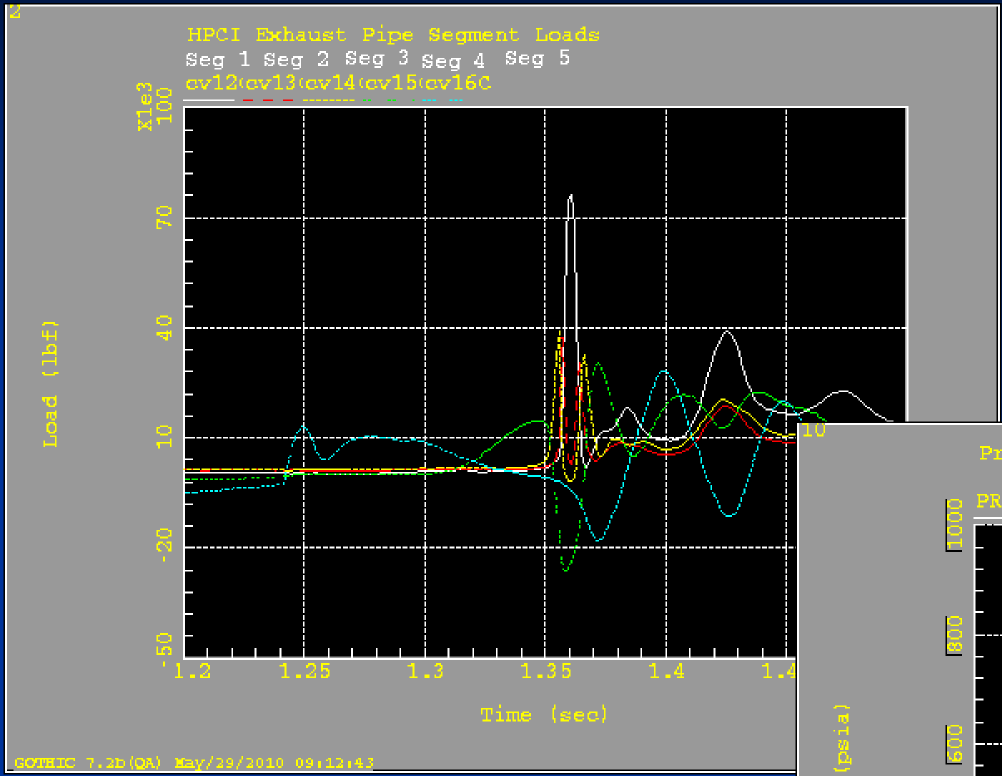


- Pressure at Check Valve

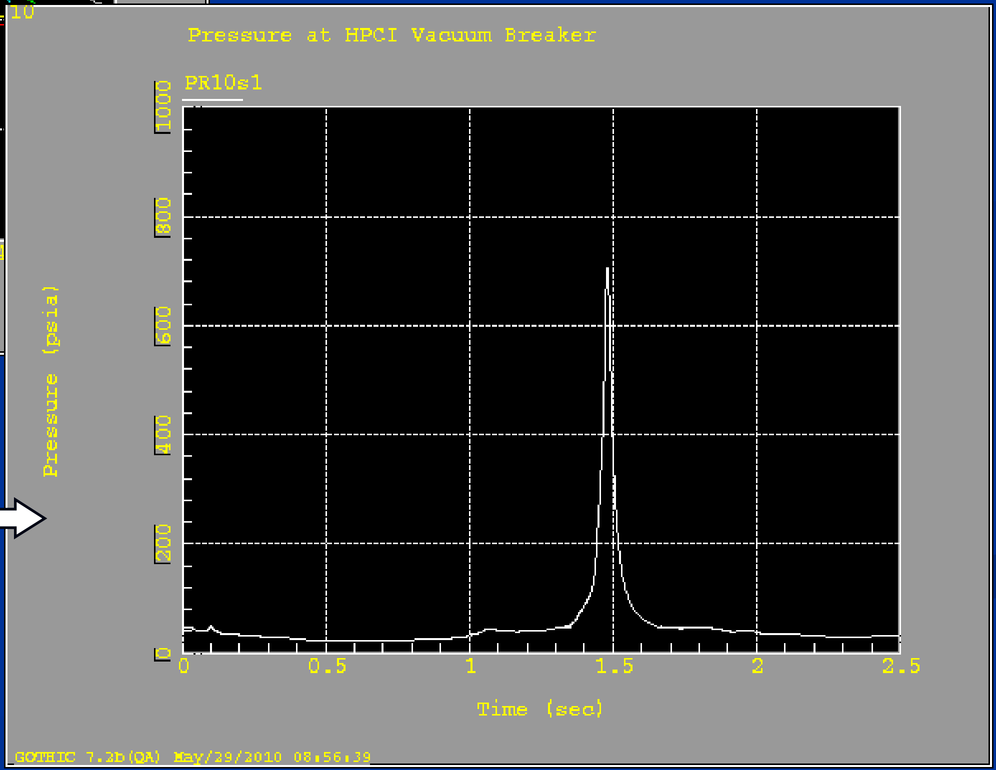


- Air Through Vacuum Breaker

Turbine Exhaust Water Hammer

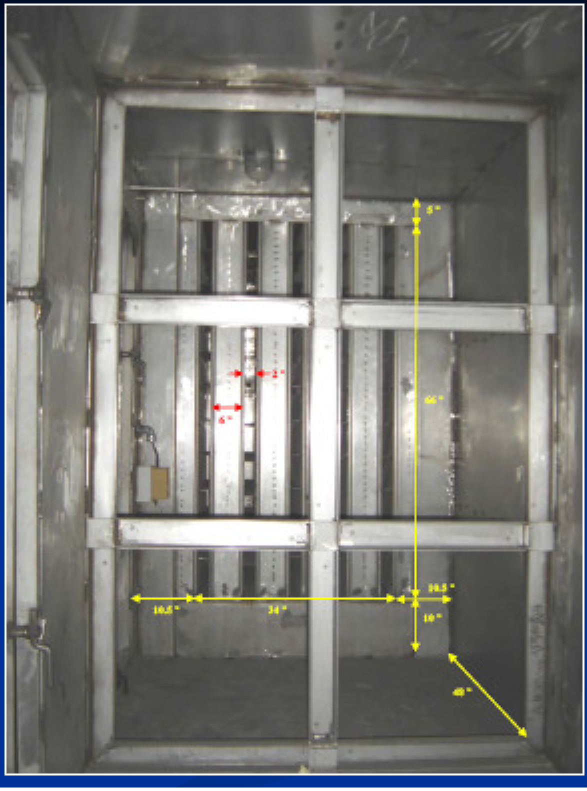


- Exhaust Duct Pipe Segment Loads



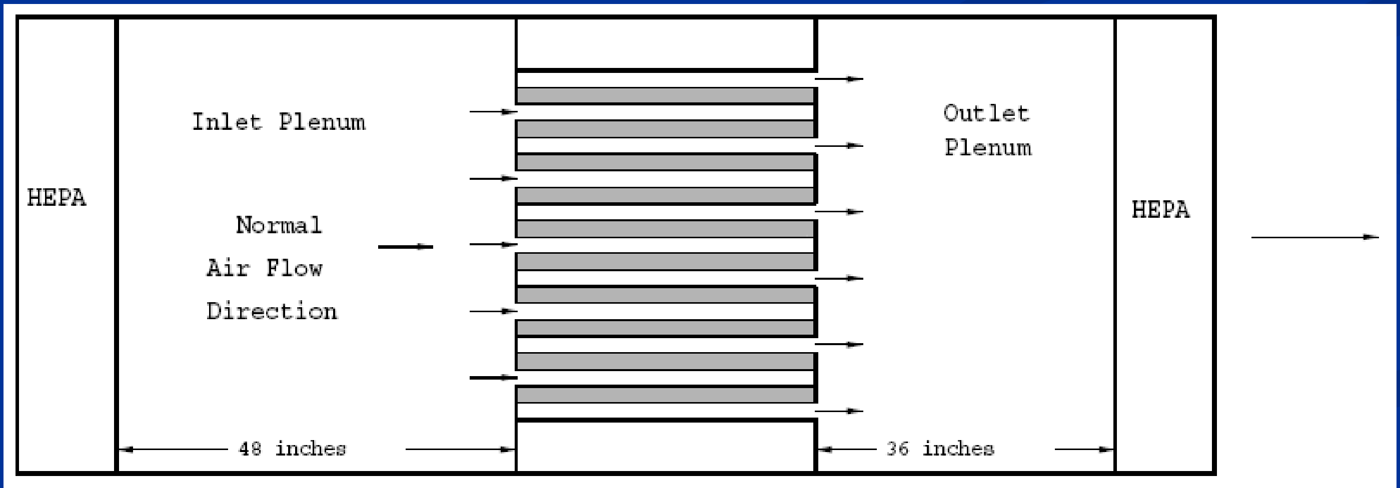
- Pressure at Vacuum Breaker

Charcoal Filter Thermal Analysis

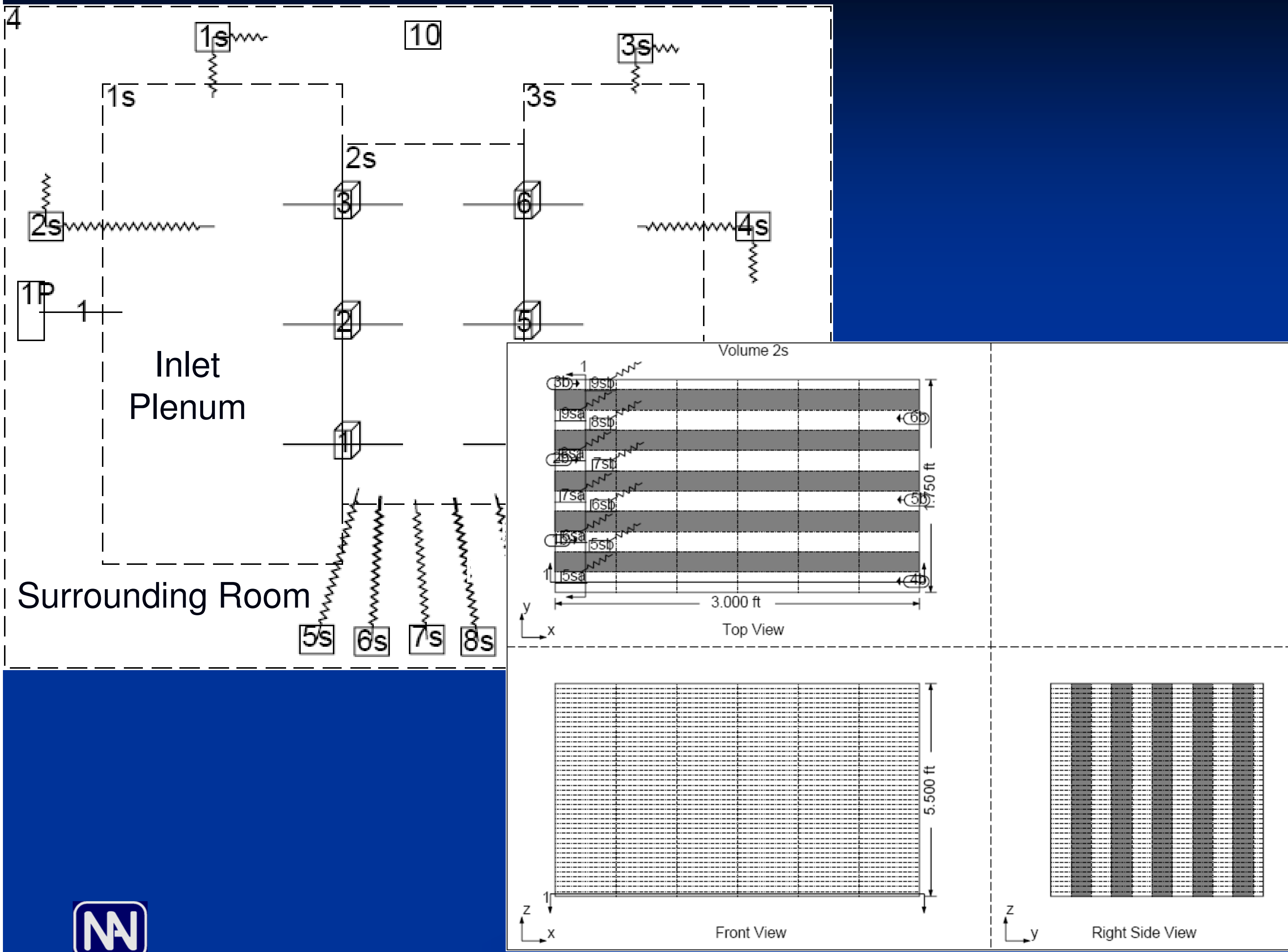


End View

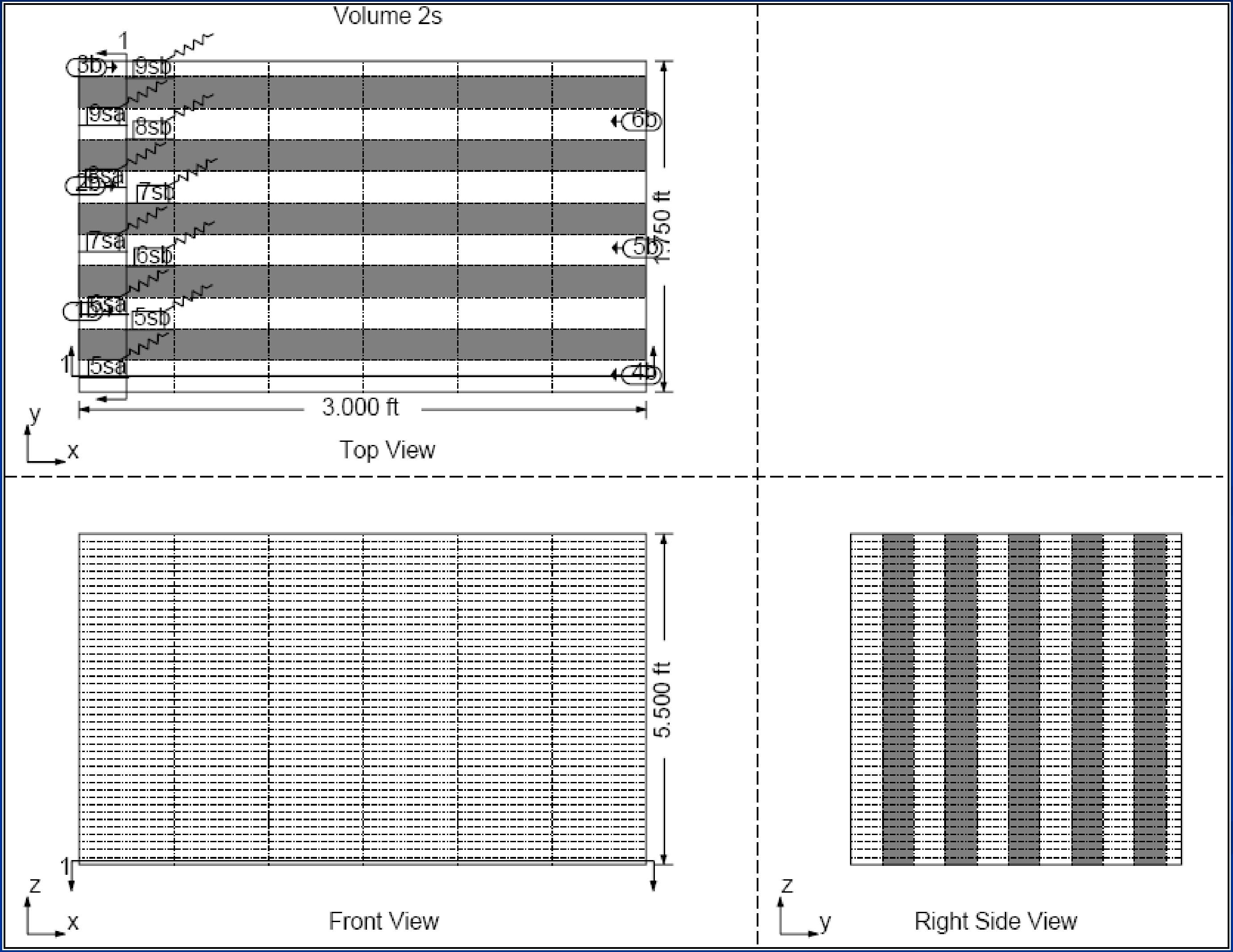
Top View



GOTHIC Filter Model

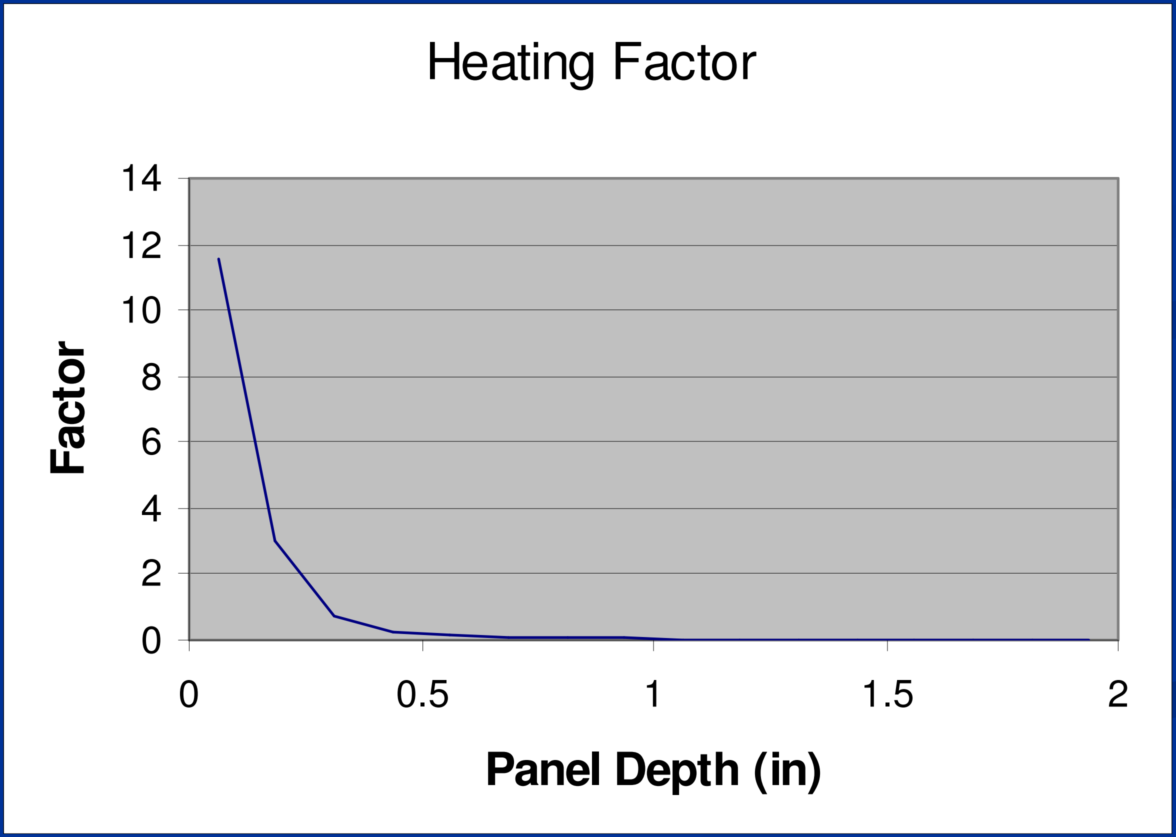


Filter Noding

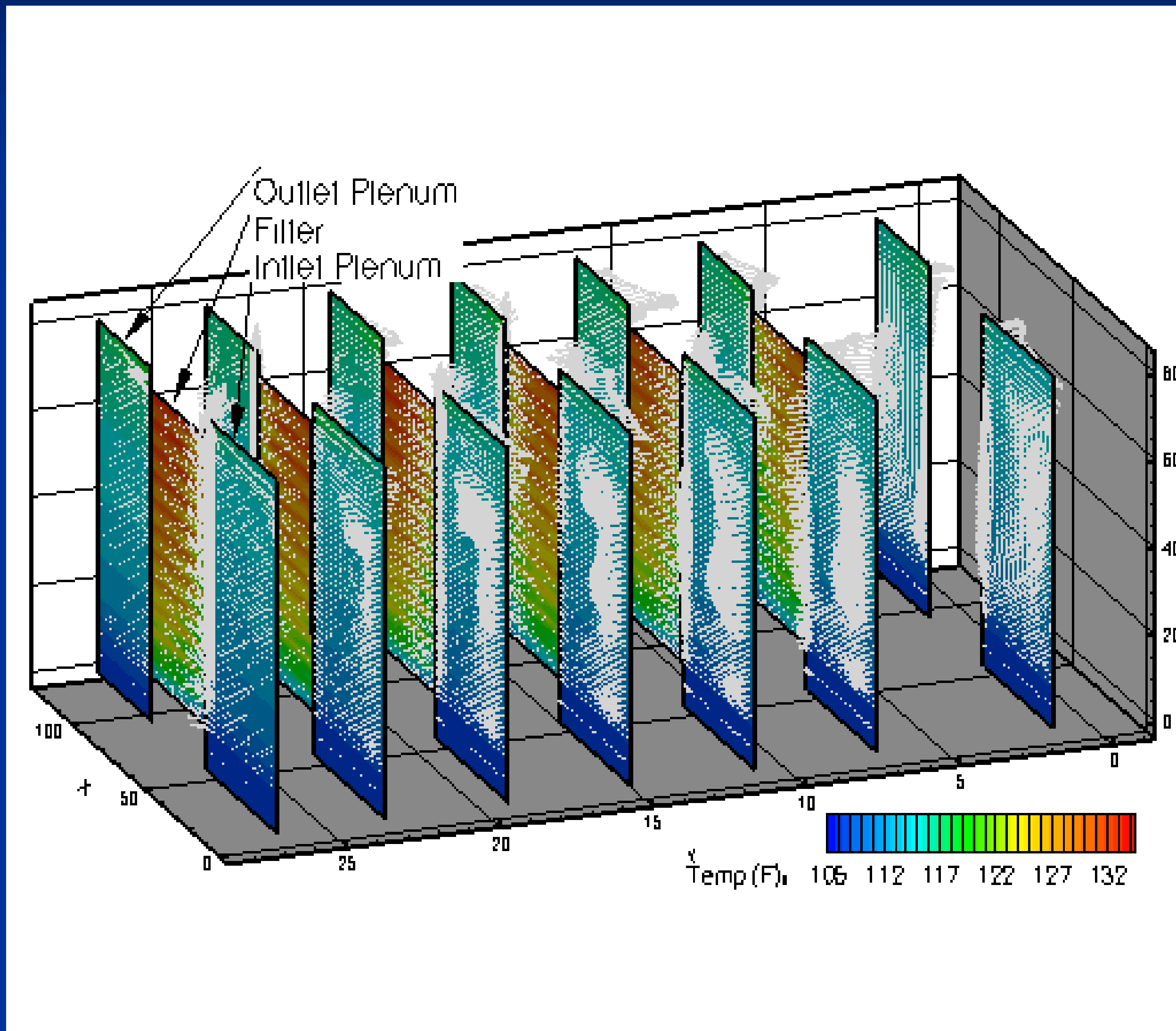


Heat Generation

- Iodine Decay
- Conservative Estimate for Oxidation



Steady State Behavior

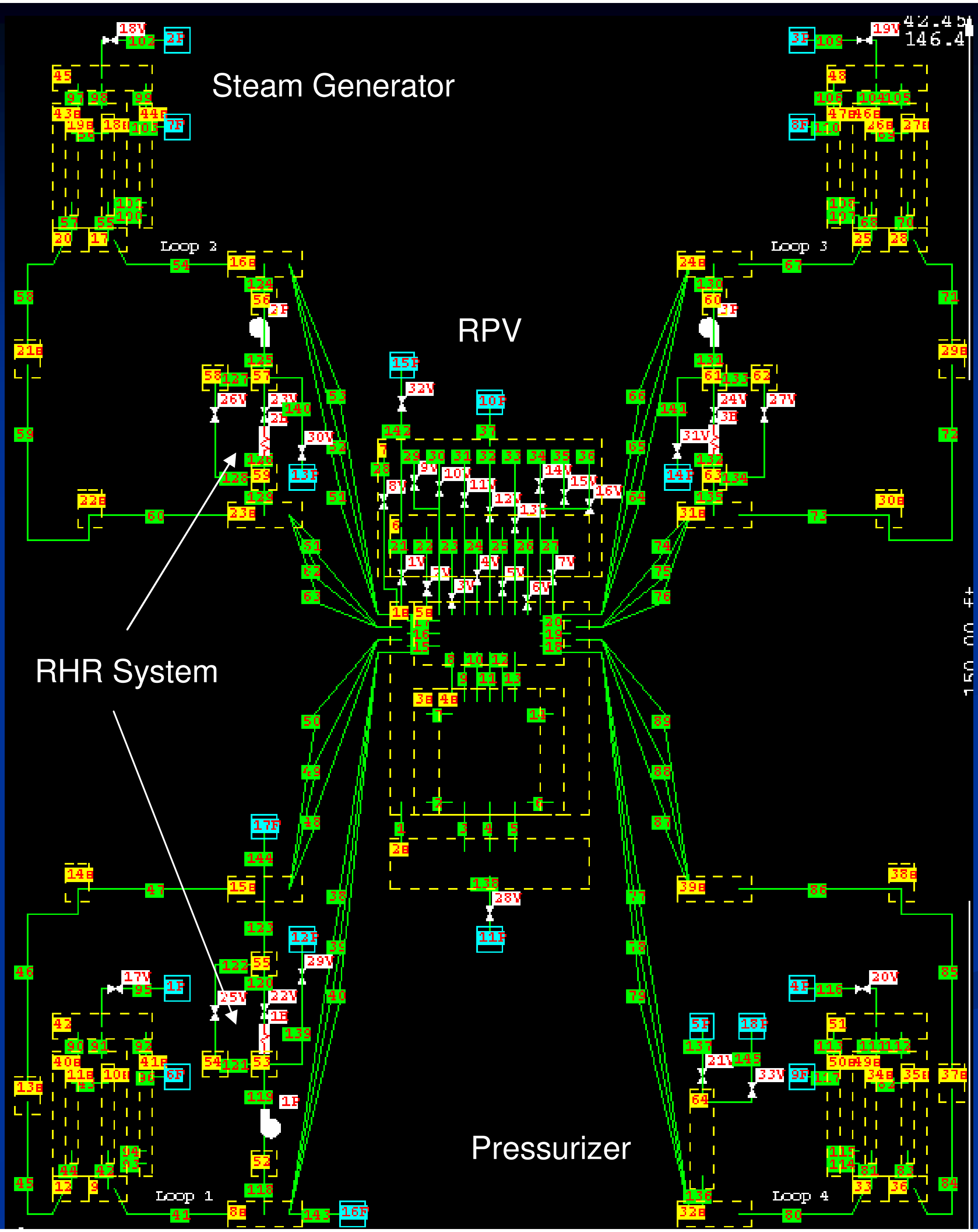


Shutdown Heatup Analysis for 4 Loop PWR

- Events
  - Loss of Residual Heat Removal (RHR) systems
  - Open vessel drain
- Times of Interest
  - Time to RCS > 300F
  - Time to Core Boiling
  - Time to Core Uncovery
  - Time RHR Pressure Relief Valve Lift
  - Time to Pressurizer Relief Valve Lift
  - Time to Steam Generator Dryout (secondary side)
  - Time to Steam Generator Tube Drain
  - Time to Core Outlet Temperature > 1200F

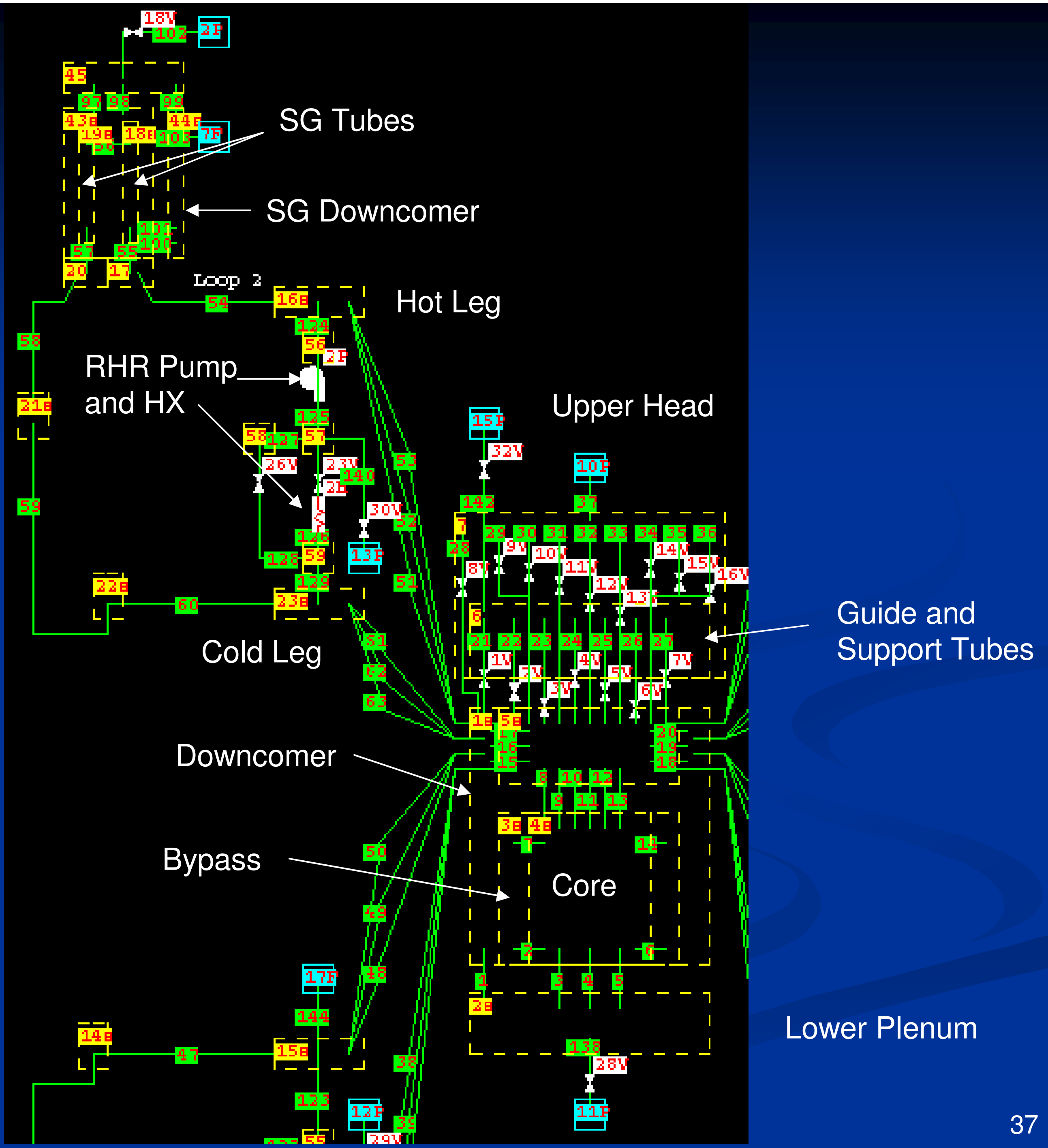
GOTHIC Model

- 4 Loop PWR



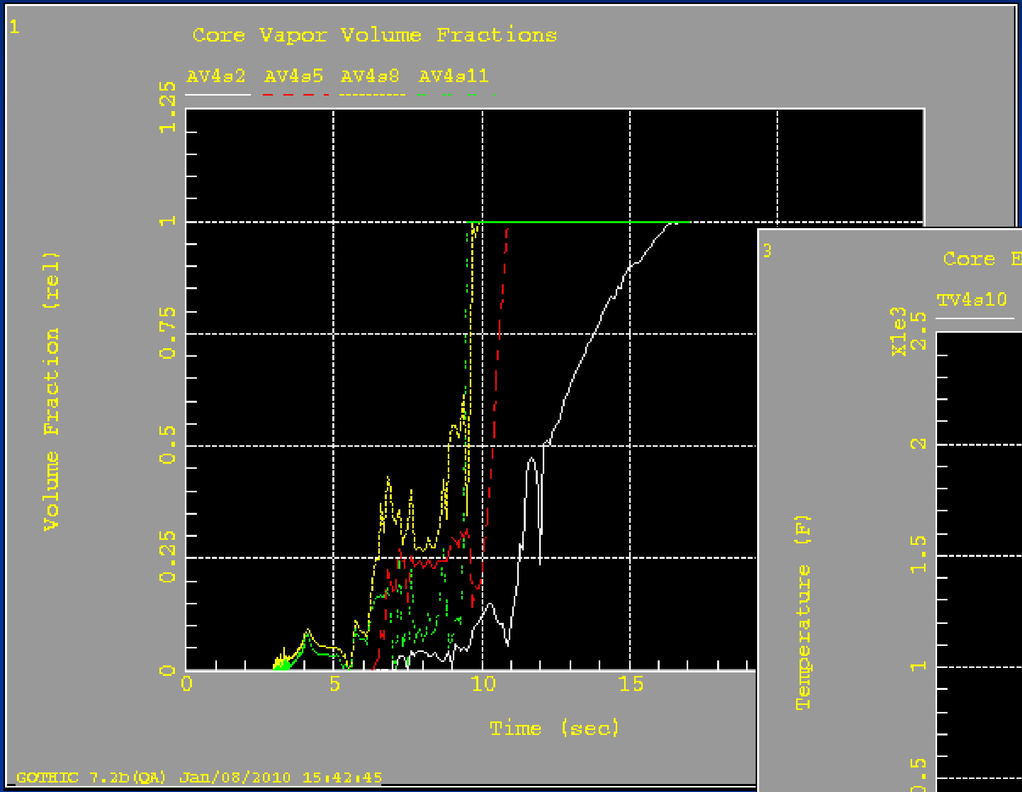
GOTHIC Model

- RPV and and 1 SG

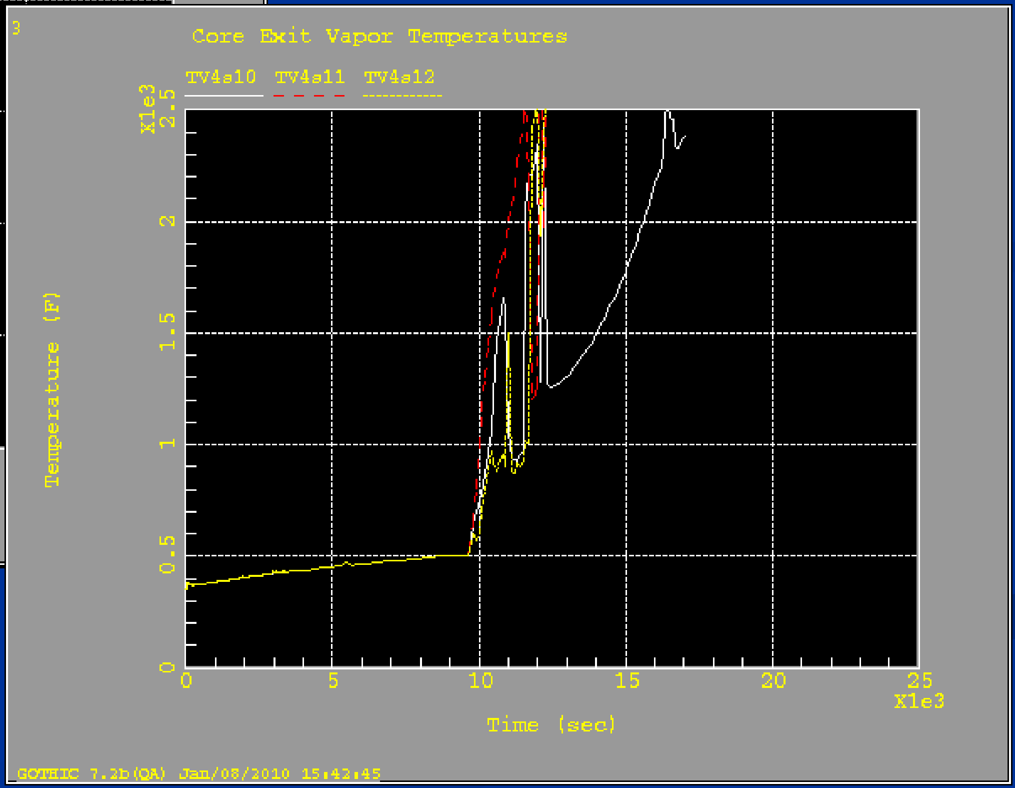


Typical Results – Loss of RHR

Core Vapor Volume Fraction

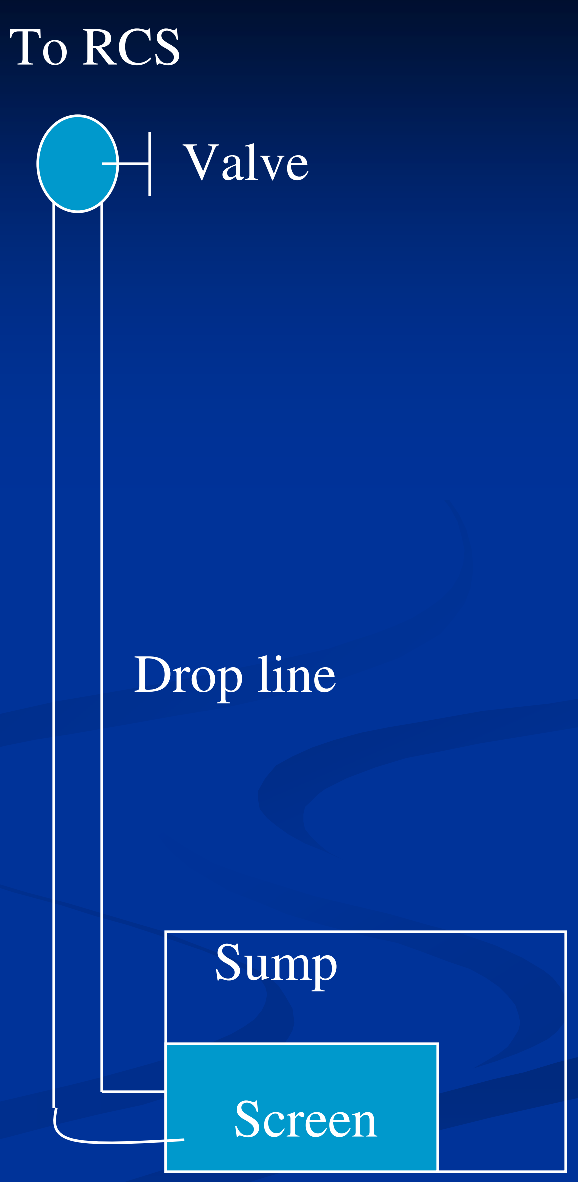


Core Exit Temperature

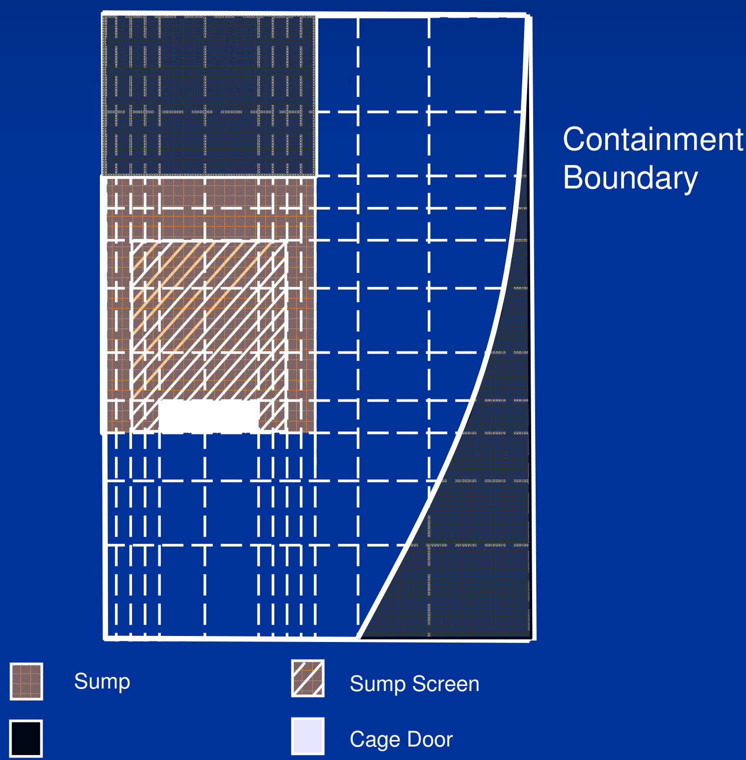


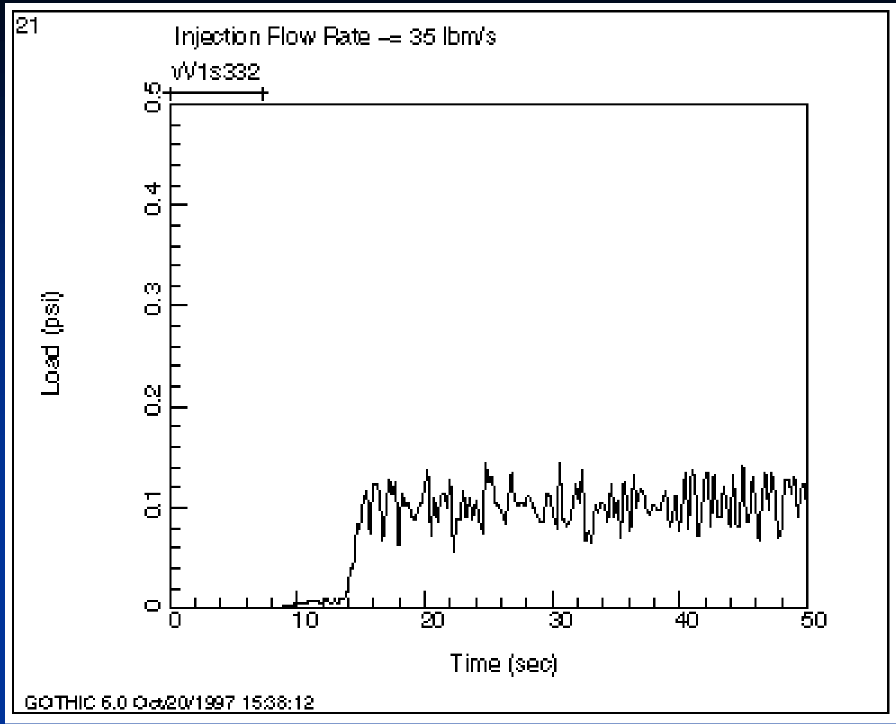
Sump Screen Hydraulic Loads During RCS Venting

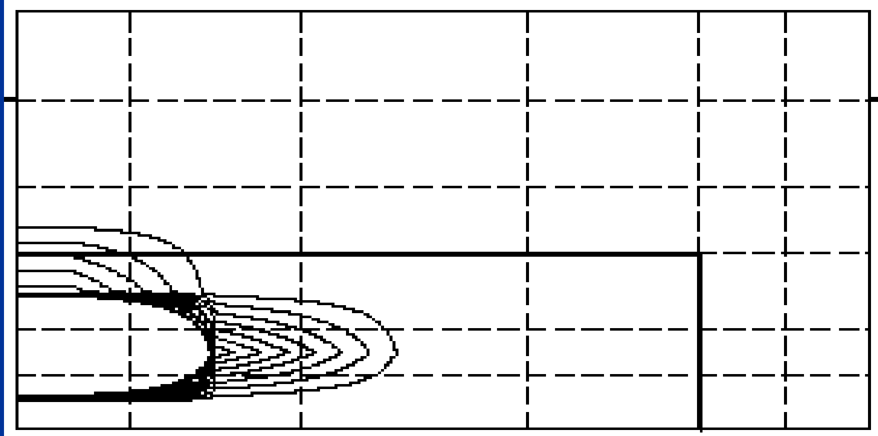
- The drop line is initially full of cold water.
- The RCS contains saturated water at 90 psia.
- Suction from the sump simultaneous with RCS venting.
- Consider
  - Initial water jet loads during drop line water purge.
  - Two phase jet loads after drop line water purge.
  - Possibility of voiding at the suction inlet.



Sump Screen Hydraulic Loads

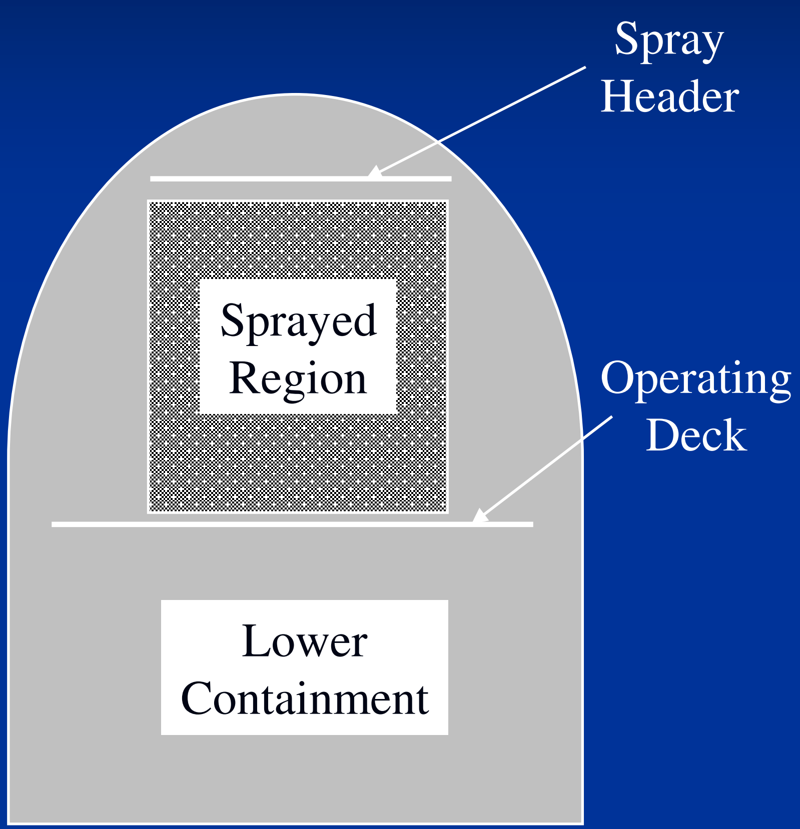




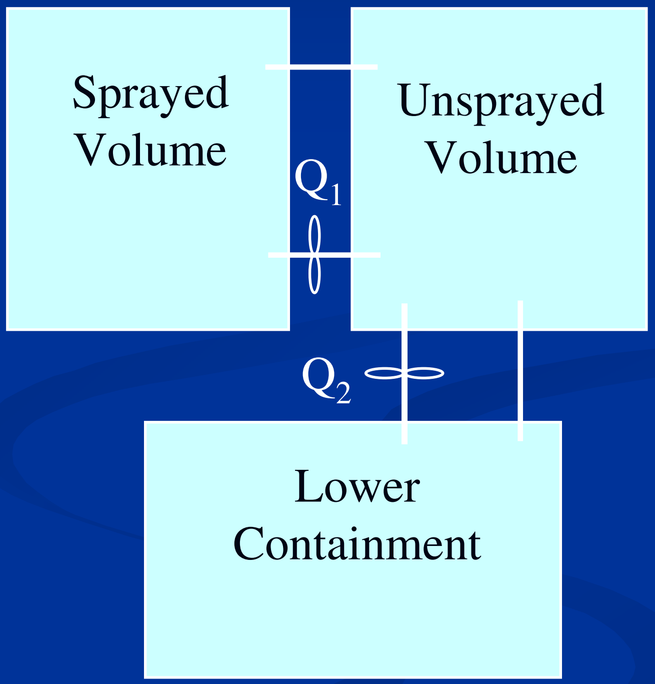


Minimum = 0.01 (rel)
Maximum = 0.1 (rel)
Time = 25.0079 seconds
/ Volume : Channels : Levels /
/ 1 : 46-111 : 1-6 /

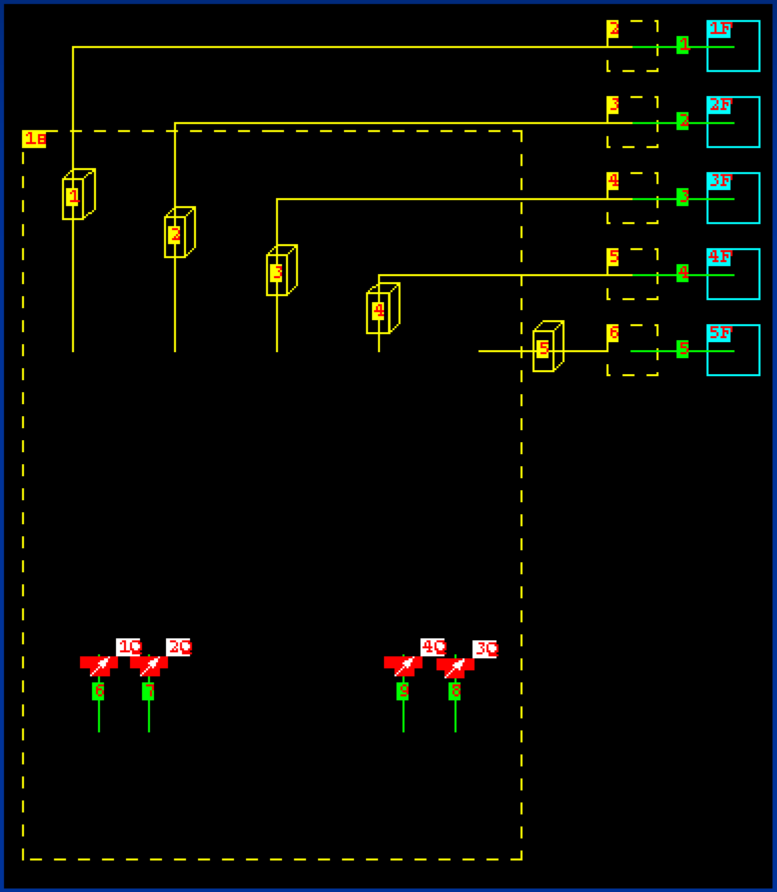
Spray Induced Mixing for Dose Analysis

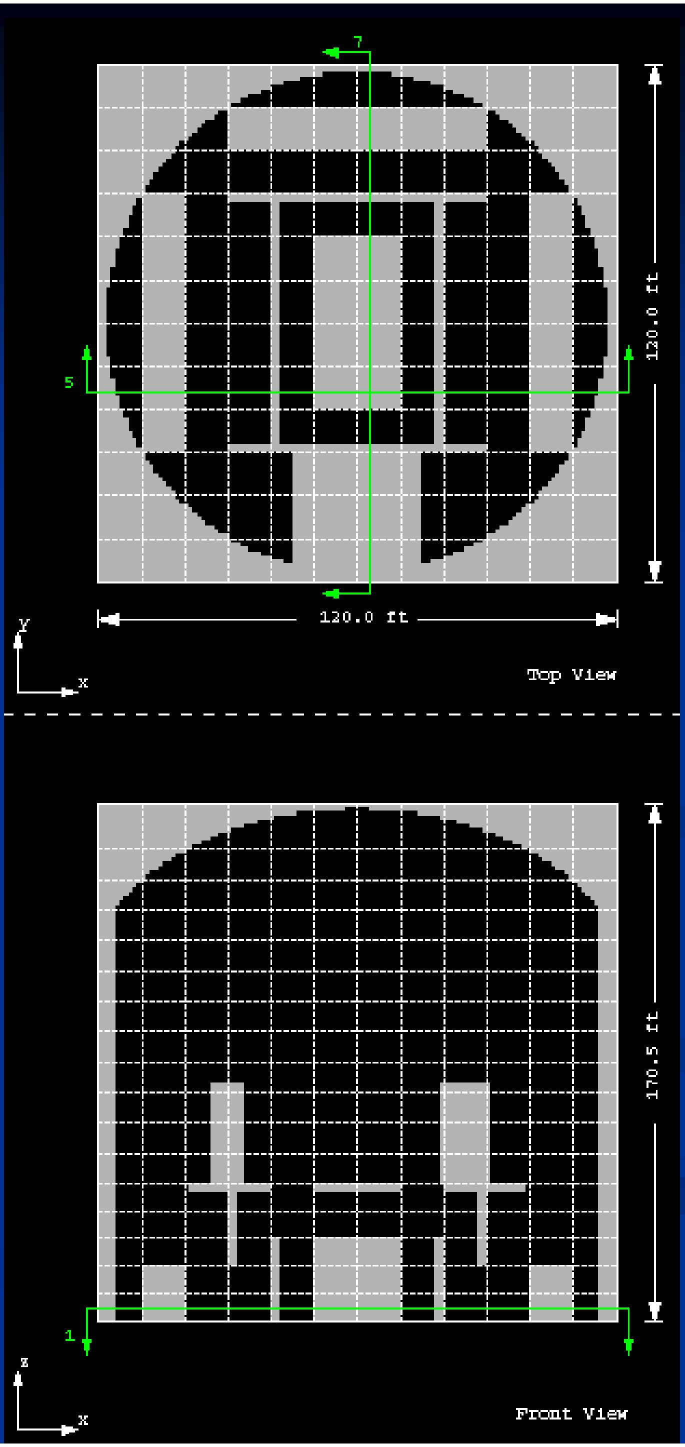


Lumped Model for Dose Analysis



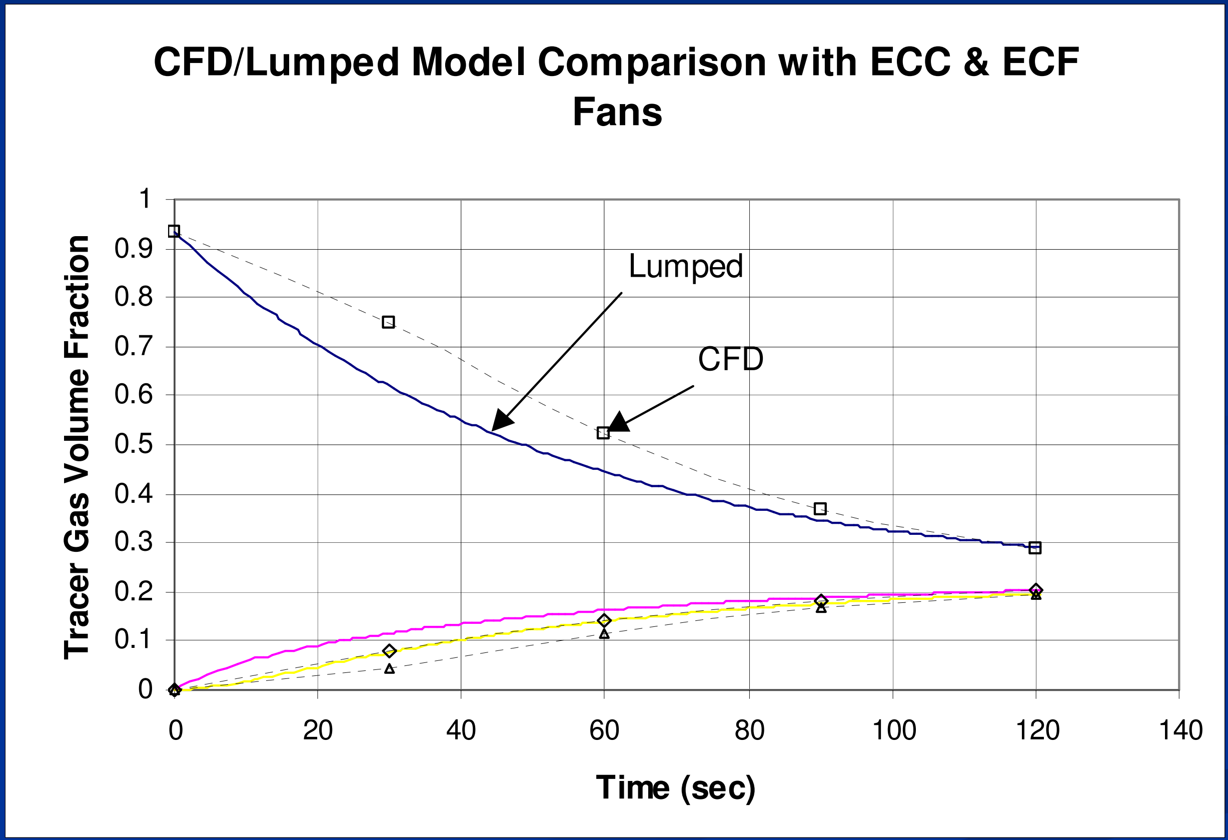
GOTHIC Containment Mixing Model





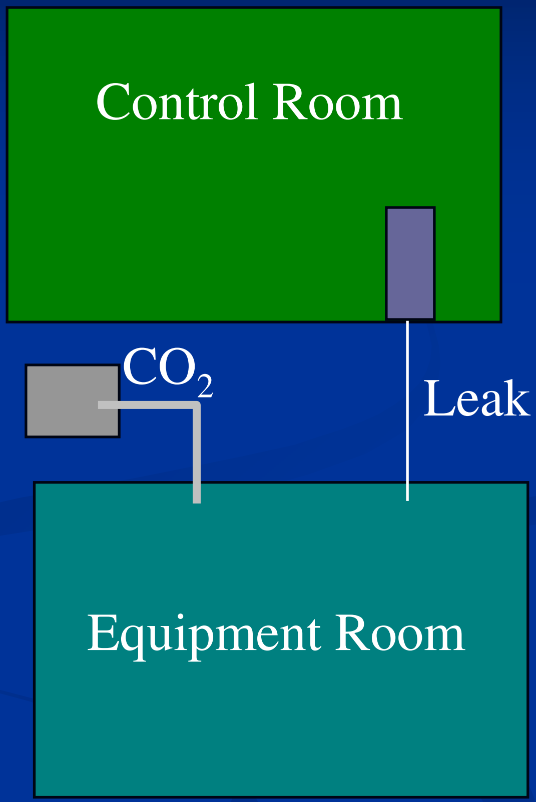
Effective Mixing Rate for Lumped Model

- Initialized lower containment volume with tracer gas.
- Adjusted lumped model mixing fans to approximate CFD model mixing.

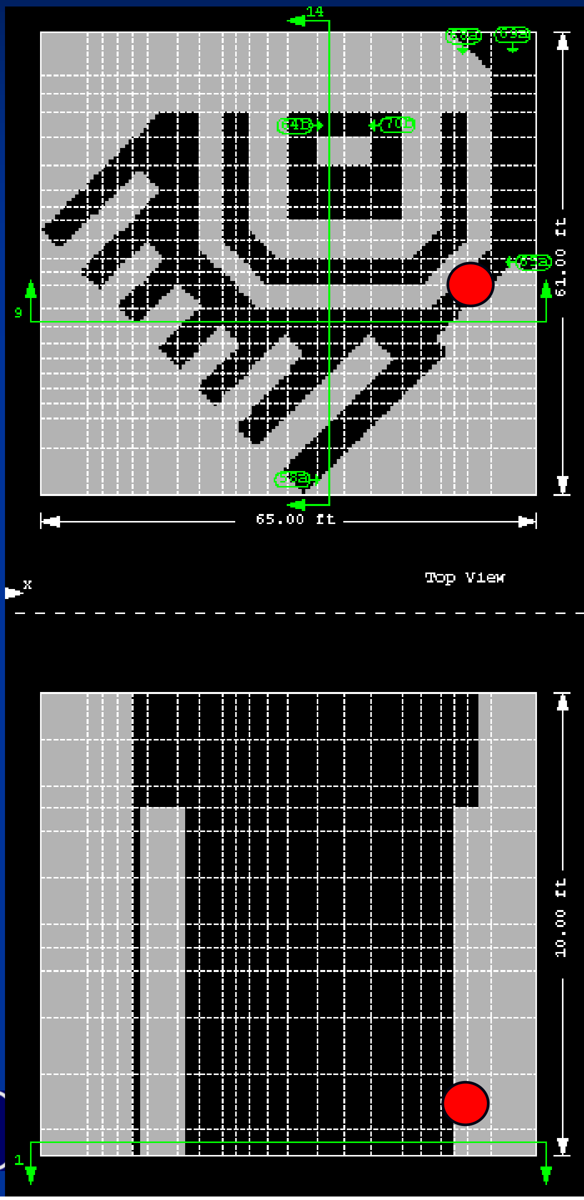


Control Room Habitability CO_2 In Leakage

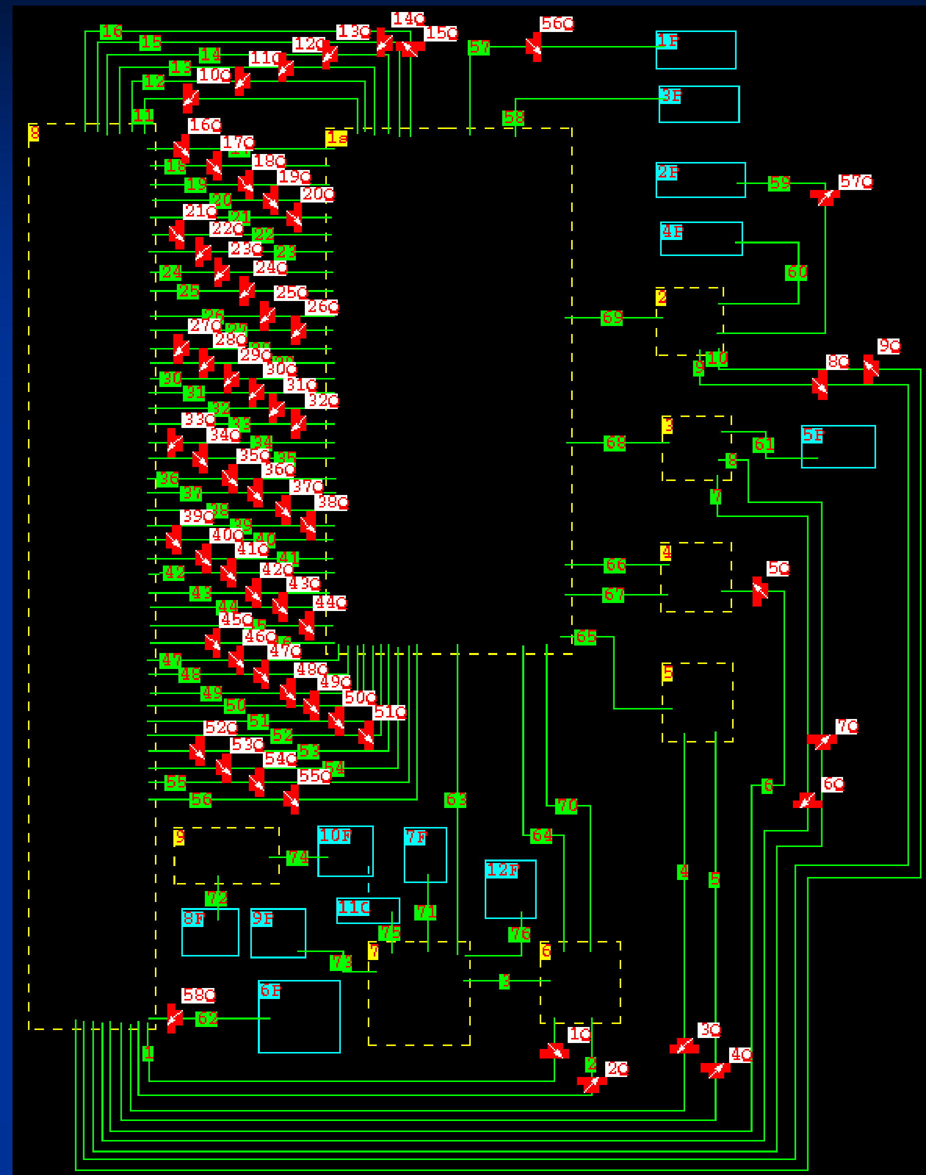
- Objective: Determine local CO_2 and odorant concentrations in the Control Room following a CO_2 release in the Equipment Room below.
- Include Control Room ventilation effects
- Conservative treatment of the CO_2 gas generation from ice. Benchmark to plant data.



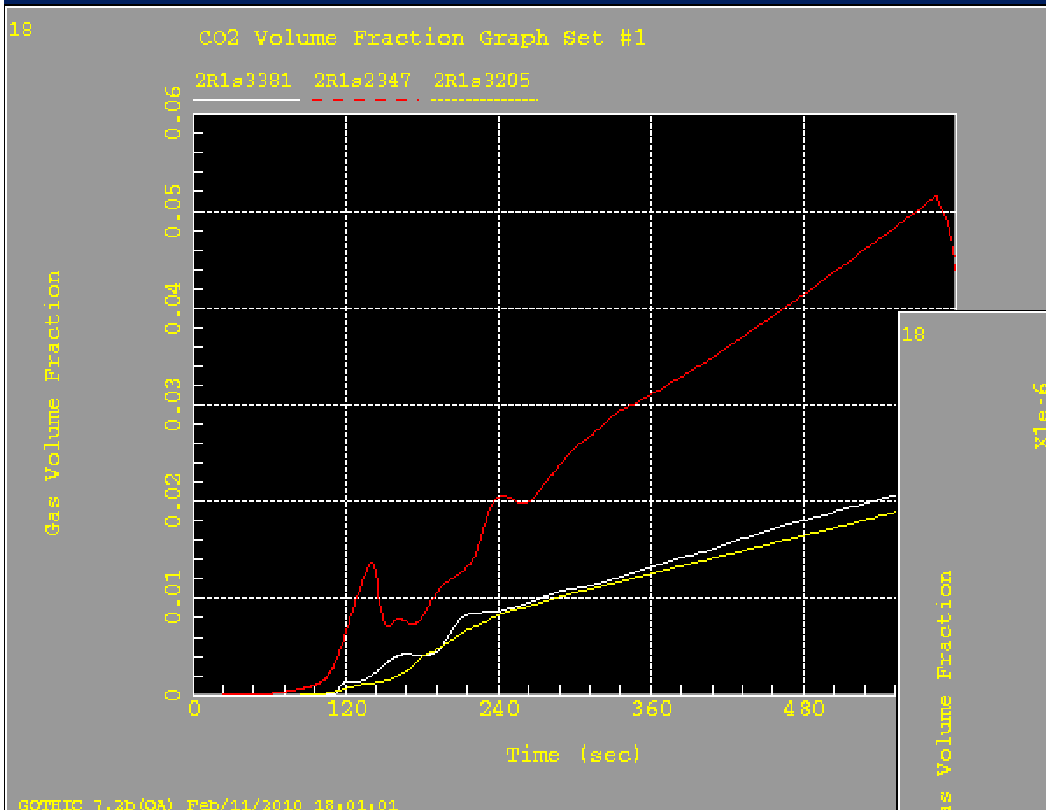
Control Room, Environs and Ventilation



Leak

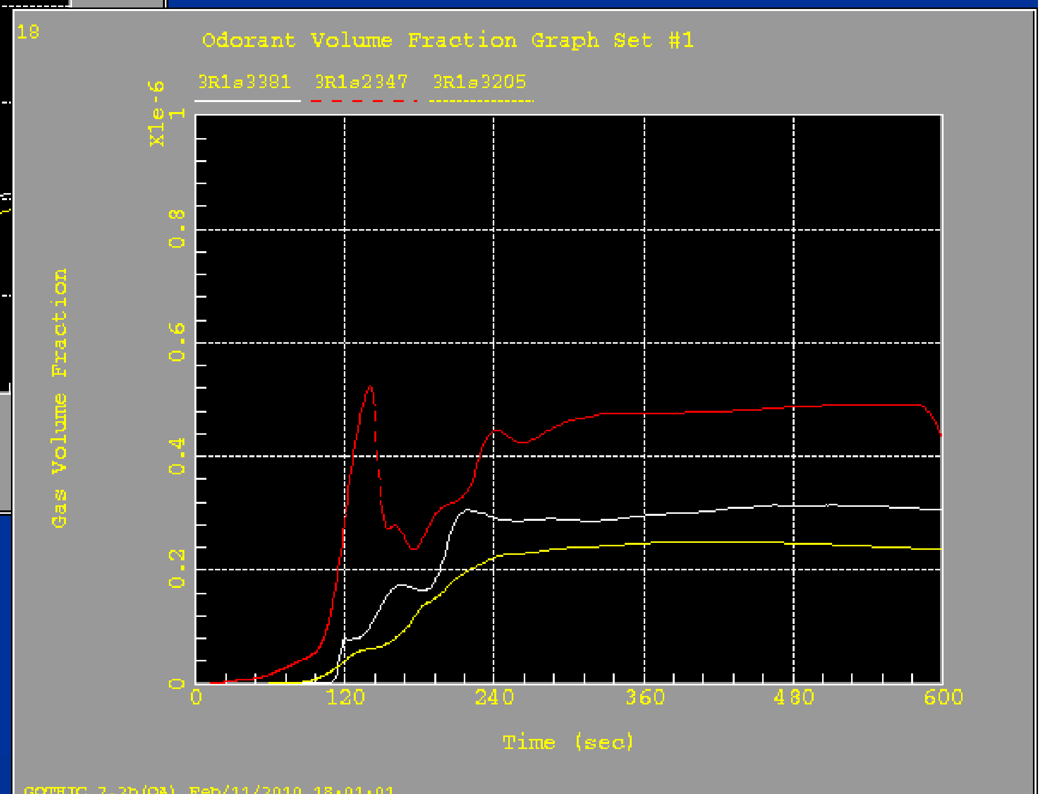


CO2 and Odorant Concentrations



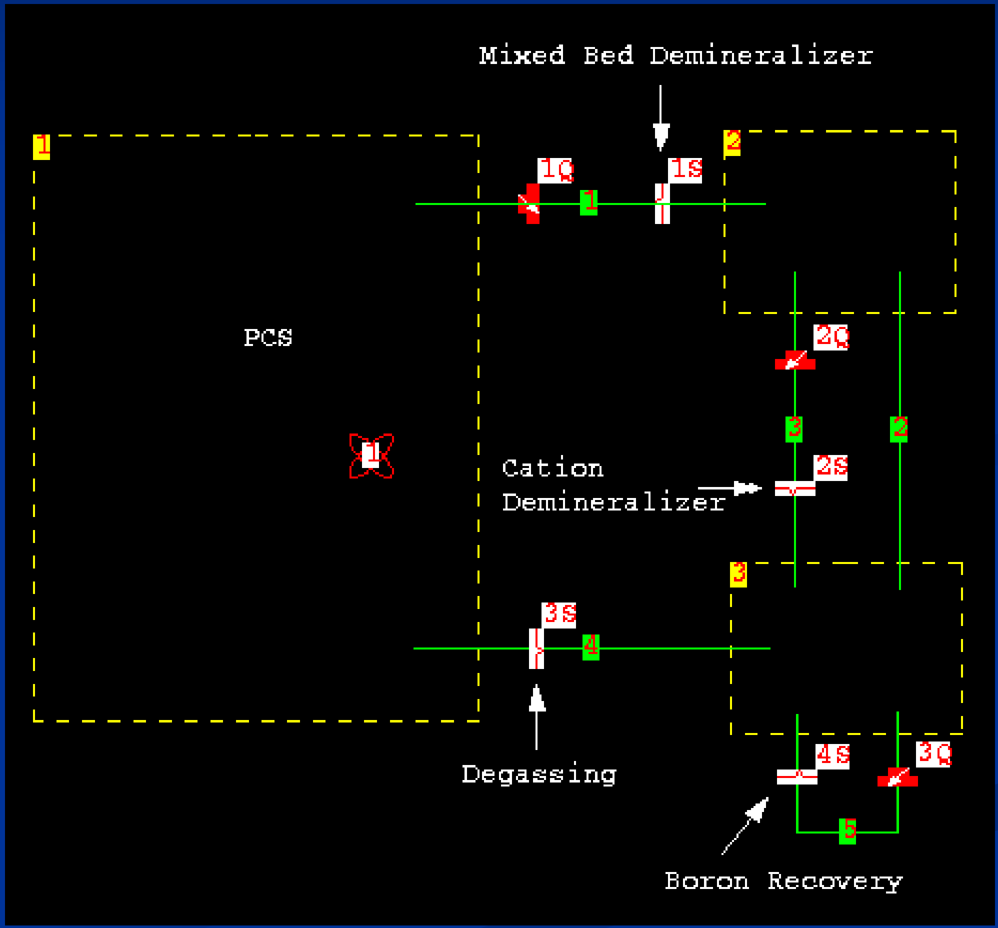
CO_2

Odorant



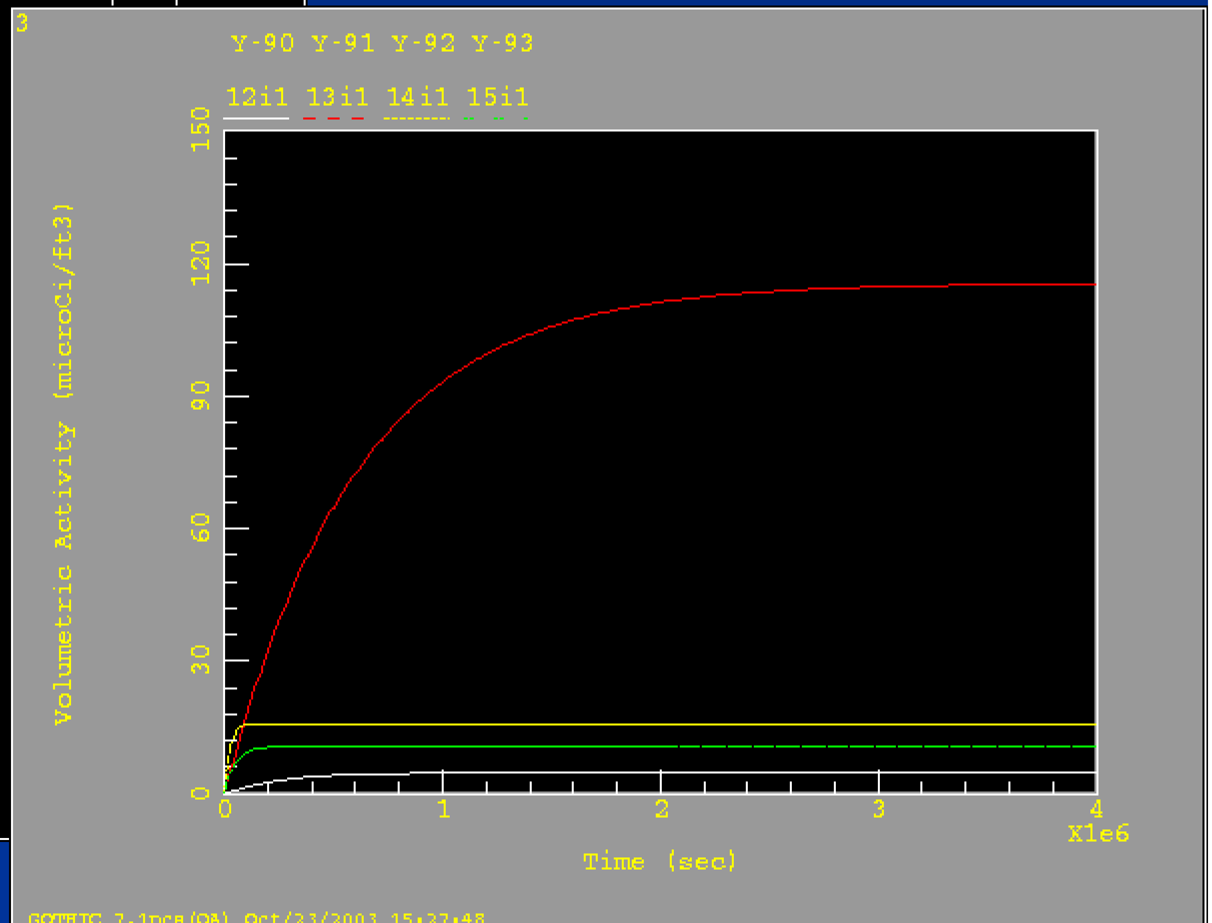
Activity in Primary Coolant System

- Objective: Determine the activity in the PCS assuming 1% fuel failure.
- Include nuclide source from fuel, decay and daughtering.
- Include system filters.
- ORIGEN used to provide End of Cycle nuclide inventory.



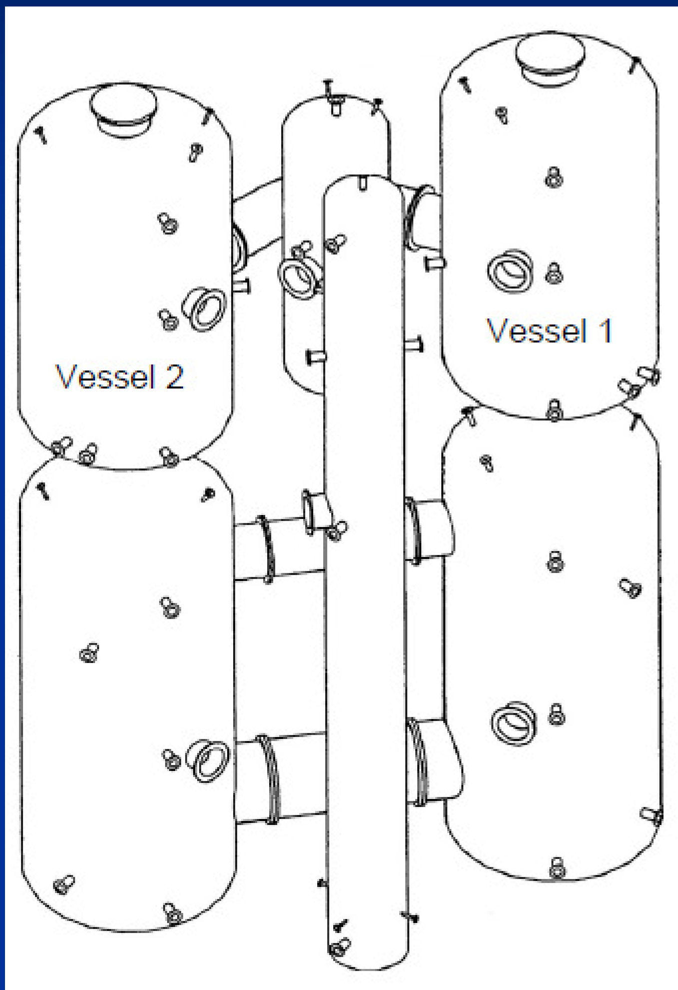
PCS Activity

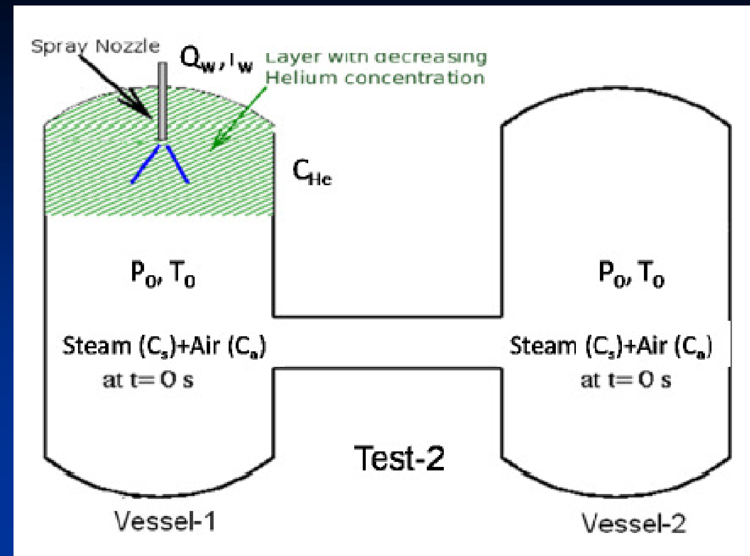
Iso #	Description	Half Life (s)	Dtr #1	Dtr #1 Frac	Dtr #2	Dtr #2 Frac	Dtr #3	Dtr #3 Frac
1	Co-58	6120000.		0.				
2	Co-60	1.66e+08		0.				
3	Kr-85	3.38e+08		0.				
4	Kr-85m	16100.	3	0.211				
5	Kr-87	4580.		1.				
6	Kr-88	10200.	69	1.				
7	Rb-86	1610000.		0.				
8	Sr-89	4360000.		0.				
9	Sr-90	9.19e+08	12	1.				
10	Sr-91	34200.	101	0.578	13			
11	Sr-92	9760.	14	1.				
12	Y-90	230000.		0.				
13	Y-91	5060000.		0.				
14	Y-92	12700.		0.				
15	Y-93	36400.		1.				
16	Zr-95	5530000.	90	0.007	18			
17	Zr-97	60800.		0.947	89			
18	Nb-95	3040000.		0.				
19	Mo-99	238000.	20	0.876				
20	Tc-99m	21700.		1.				
21	Ru-103	3390000.	83	0.997				
22	Ru-105	16000.	24	1.				
23	Ru-106	3.18e+07	82	1.				
24	Rh-105	127000.		0.				
25	Sb-127	333000.	28	0.176	27			
26	Sb-129	15600.	30	0.225	29			
27	Te-127	33700.		0.				
28	Te-127m	9420000.	27	0.976				
29	Te-129	4180.		1.				
30	Te-129m	2900000.	29	0.65				
31	Te-131m	108000.	74	0.222	33			
32	Te-132	282000.	34	1.				
33	I-131	695000.	64	0.0111				
34	I-132	8280.		0.				

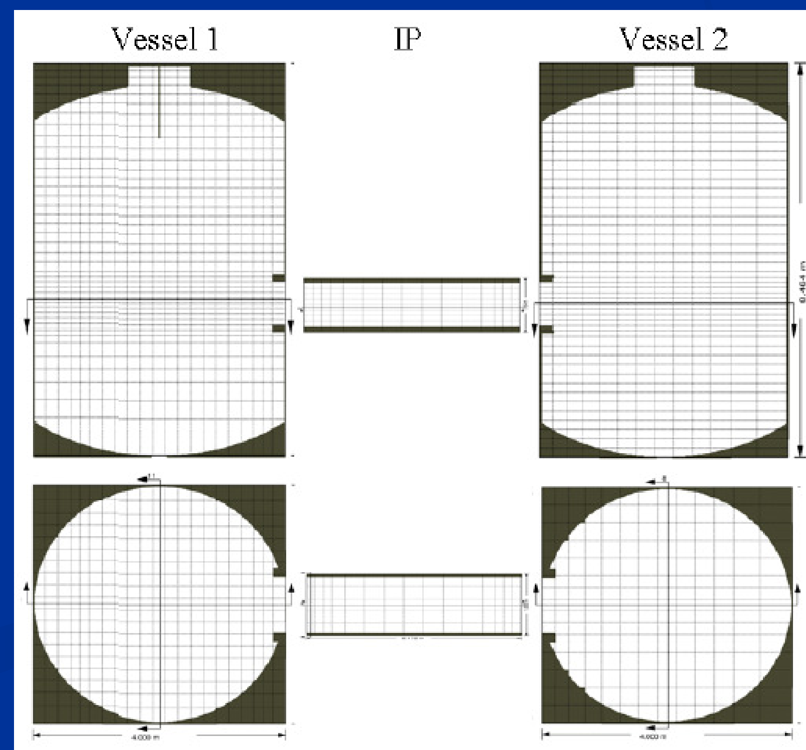


107 Isotopes Tracked

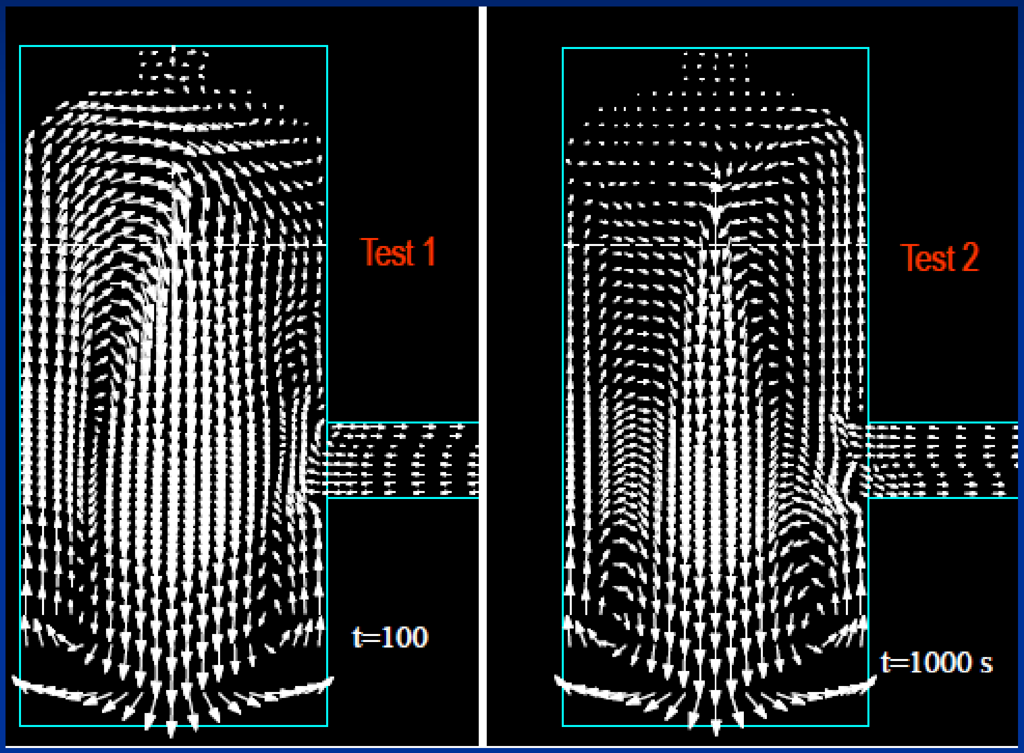
PANDA Tests (PSI)

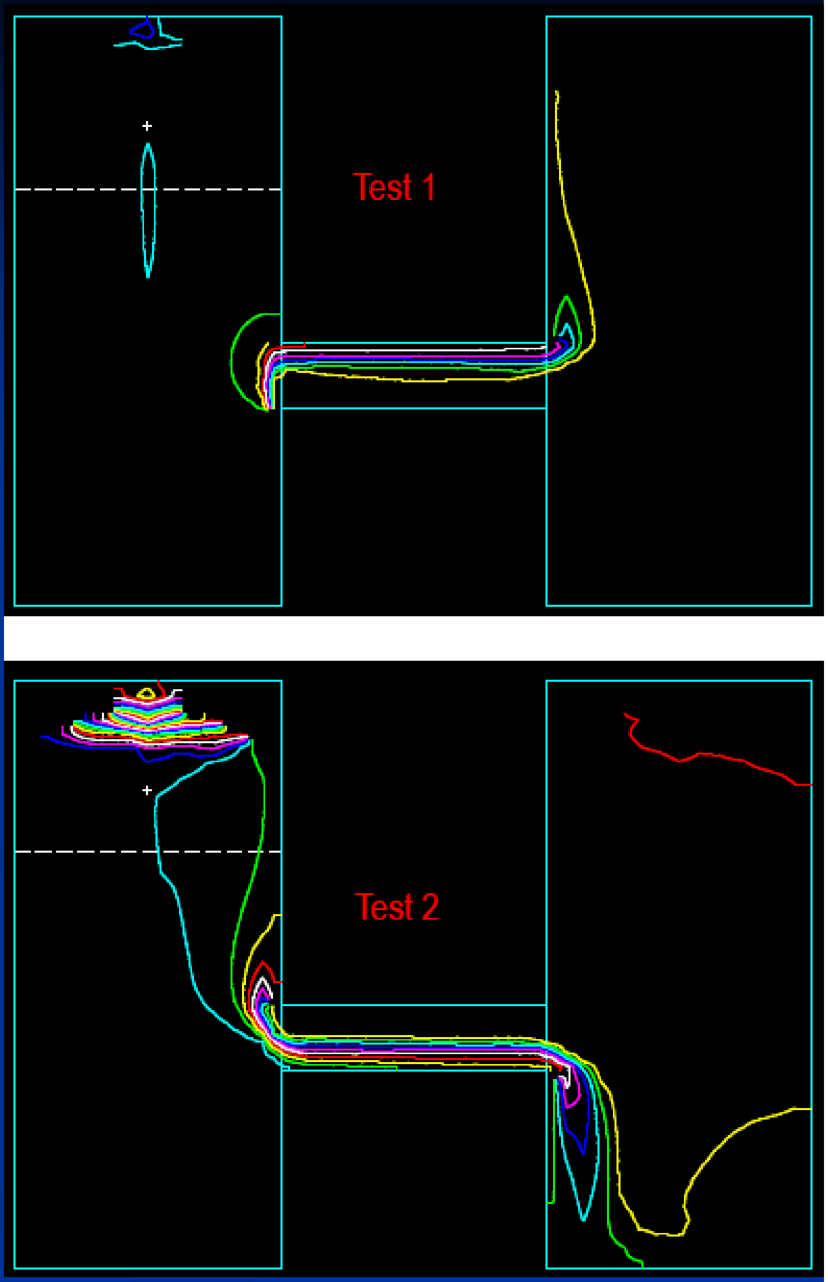






PANDA Tests (PSI)





Helium Distribution

- Wall heat transfer under predicted
    - Spray enhancement effect missing

Other Applications by NAI and Others

- Hydrogen distribution in containment
- Valve EQ for exposure to high water temperature
- Freezing potential in outdoor tank
- Loss of fuel pool cooling
- Gamma heating in fuel pool concrete
- Storage cask refill analysis
- Flooding/Drain analysis
- Drawdown analysis
- Loss of building insulation
- Long term mass and energy release
- Suppression pool swell
- Tornado
- Fan cooler boiling
- …

GOTHIC Use Examples from ADAMS

- NUREG/CP-0119, "Proceedings of the Nineteenth Water Reactor Safety Information Meeting, Volume 2: Severe Accident Research, Severe Accident Policy Implementation, Accident Management, Bethesda, MD, 10/28-30/91 (ML042230460).
  - Comparisons between HDR H2 Distribution Experiments E11.2 and E11.4 and several computer codes with Section 5 focusing on GOTHIC
- Revision 0 to SMNH-94051, "Turbine Building Leak Detection," 1/30/95 (ML033000499).
  - Estimates the temperature rise in the Main Steam Line Area of the Turbine Building at Hatch with a design basis steam leak

GOTHIC Use Examples from ADAMS

- Kewaunee, Flooding Significance Risk Determination Process Risk Assessment Report, 10/31/05 (ML053180483)
  - Dynamic flood level analysis using **GOTHIC**
- Three Mile Island Nuclear Station, Unit 1 – Response to Request for Additional Information Regarding Generic Letter 2004-002, 11/9/09 (ML093220202).
  - GOTHIC used to assess transient NPSH
- Framatome ANP- Non-Proprietary Safety Evaluation Topical Report BAW-10252 (P), Rev. 0, 8/31/05
  - Analysis of Containment Response to Postulated Pipe Ruptures Using GOTHIC

GOTHIC Use Examples from ADAMS

- Acceptance Review Results for Topical Report WCAP-17065-P Rev. 0, Westinghouse ABWR Subcompartment Analysis Methodology Using GOTHIC Related to South Texas Project Units 3 & 4 Combined License , 6/2/10 (ML101530006)
- IR 05000400/2002-006; Shearon Harris Nuclear Power Plant; special inspection to inspect and assess the circumstances associated with gas accumulation in the safety injection system, 5/10/02 (ML021340182).
  - Page 9, Section 06 regarding past operability reviews briefly discusses the NAI analysis to assess gas transport to Charging - Safety Injection pumps
- LER 04-001-01 for Catawba, Unit 1, Gas Accumulation in Centrifugal Charging Pump Suction Piping, 6/15/04 (ML041750112)
  - Independent analytical flow model for gas transport completed with GOTHIC

GOTHIC Use Examples from ADAMS

- TMI Event Notification Report Retraction for Event #42475, 6/5/06
  - States the NAI analysis of suction side gas transport indicated past operability of the LPI and HPI pumps which supported withdrawal of the event notification
- Flame Acceleration and Deflagration-to-Detonation Transition in Nuclear Safety, 8/31/00 (ML031340619)
  - Discusses GOTHIC briefly
- Non-Proprietary SER for Topical Report WCAP-16608-P, Westinghouse Containment Analysis Methodology, 1/27/09 (ML090230441)

NAI

GOTHIC Use Examples from ADAMS

- South Texas Project, Units 1 and 2 - Closeout of Generic Letter 96-06, "Assurance of Equipment Operability and Containment Integrity During Design-Basis Accident Conditions" (TAC Nos. M96868 and M96869)
  - GOTHIC used to evaluate the creation of two-phase flow in the CCW system
- Approved Topical Report DOM-NAF-3 NP-A, “GOTHIC Methodology for Analyzing the Response to Postulated Pipe Ruptures Inside Containment” (ML063190467)
  - GOTHIC used for containment response, post-reflood mass & energy release and primary and secondary modeling

GOTHIC Use Examples from ADAMS

- Containment Air Cooler Heat Transfer During Loss of Coolant Accident with Loss of Offsite Power (ML003687036)
  - Discusses GOTHIC heat transfer and creation of steam regions

GOTHIC
Qualification
Validation and Verification
Selected Examples

GOTHIC Qualification

- Separate Effects Tests
  - Comparison with analytic solutions
  - Comparison with experimental data
  - Component functionality
- Combined Effects Tests
  - Comparison with experimental data
- Most of the tests are document in the GOTHIC “Qualification Report”, NAI 8907-09

GOTHIC Qualification Matrix

- Cross References Tests and Modeled Phenomena
- Included in the Qualification Report

Qualification Matrix (portion)

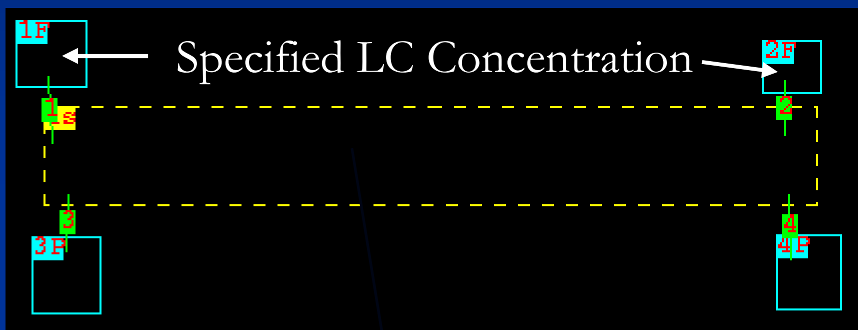
	Test	Drop Entrainment	Drop Deposition	Drop Settling	Drop Breakup	Drop Evaporation	Drop Condensation	Drop Aglomeration	Mist Generation	Mist Depletion	Pressure Wave Propagation	Surface Wave Propagation	Impact Loads	Drag Loads	Pressure Drop / Single Phase	Pressure Drop / Bubbly Flow	Pressure Drop / Film-Drop Flow	Pressure Drop / Stratified Flow	Pressure Drop / Slug Flow	Stratified Flow Transition to Slug	Bouyancy Induced Stratification	Flashing	Boiling Heat Transfer	Natural Convection	Forced Convection	Mixed Convection	Thermal Conduction in Solids	Thermal Diffusion in Vapor	Thermal Diffusion in Liqud	Thermal Radiation	Condensation on Walls	Pool boiling
		4	8	8	2	8	2	3	7	5	1	1	0	0	9	3	5	1	3	1	4	5	1	17	10	7	10	4	1	1	12	1
1	Drop Entrainment	x	x																													
2	Drop Settling Velocity			x																												
3	Jet and Drop Breakup				x																	x										
4	Drop Heat and Mass Transfer					x																										
5	GSP 27 - Heat Transfer Options																							x							x	
6	GSP 14 - CSNI Numerical Benchmark																										x					
7	Horizontal Cylinder in A Rectangular Cavity																							x								

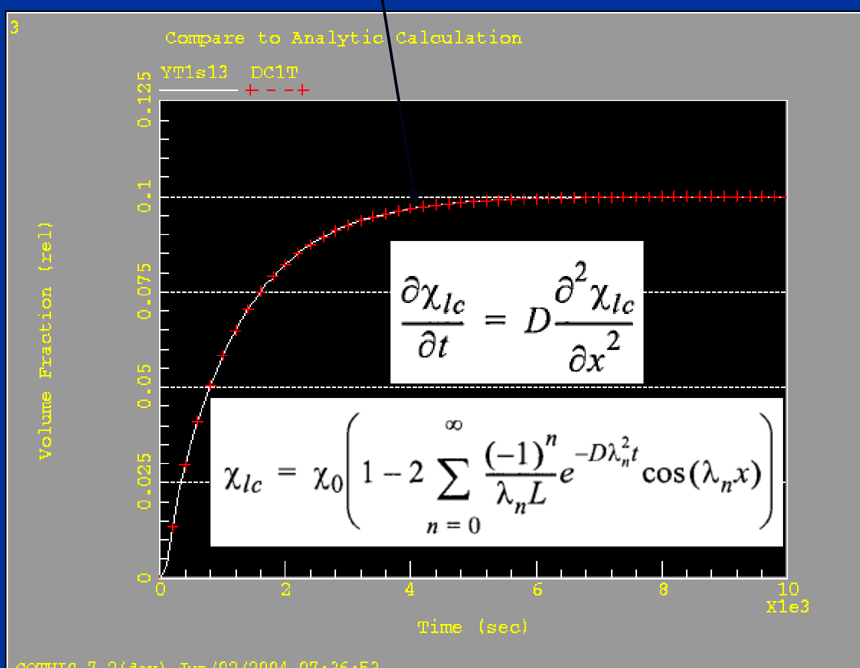
Basic Phenomena and Thermodynamics

- Gas compression and work
- Thermal and mass diffusion
- Buoyancy Driven Flows
- Multiphase phenomena
  - Interphase heat and mass transfer
    - Drop/Vapor
    - Liquid/Vapor
  - Interphase drag
    - Drop/Vapor
    - Liquid/Vapor
- Gas absorption and release

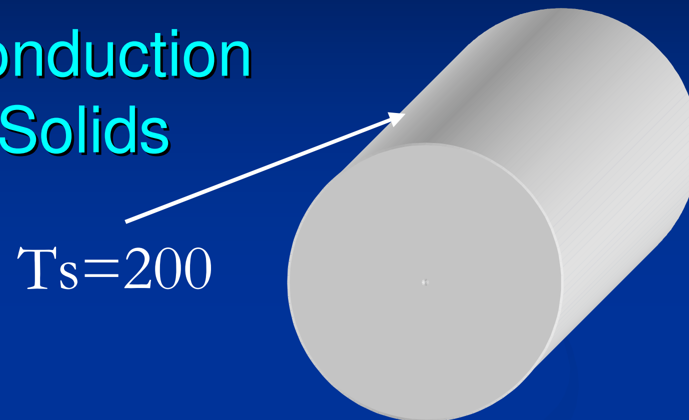
Thermal And Mass Diffusion - Examples

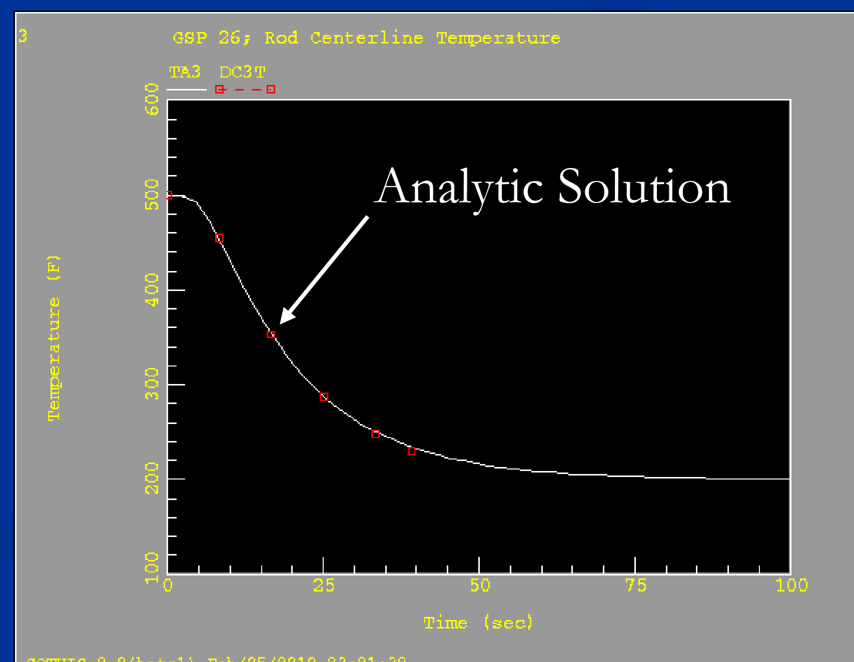
- Liquid Component Diffusion





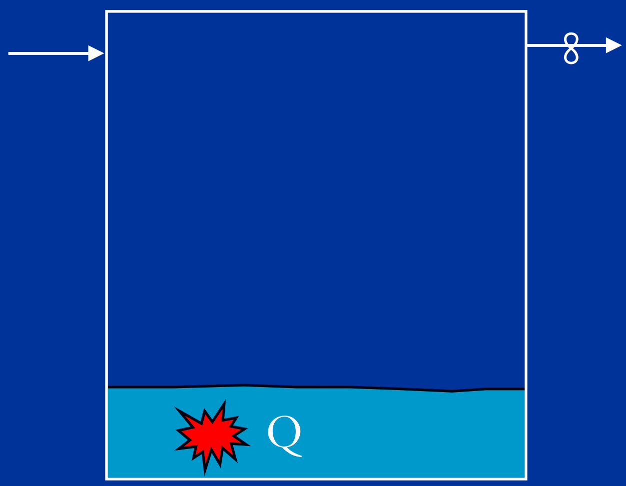
- Conduction in Solids

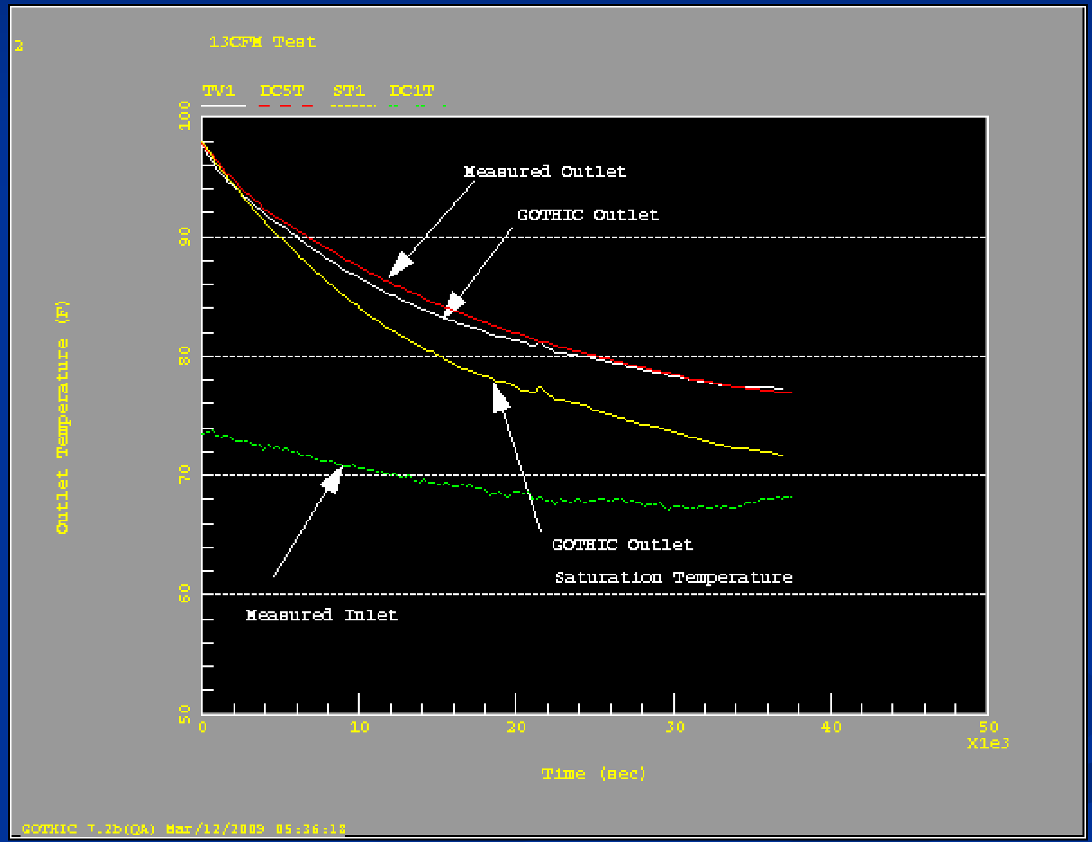




Interphase Heat and Mass Transfer Free Convection for Pool

- PNL Grout Mold Evaporation Tests
  - Varied ventilation rate



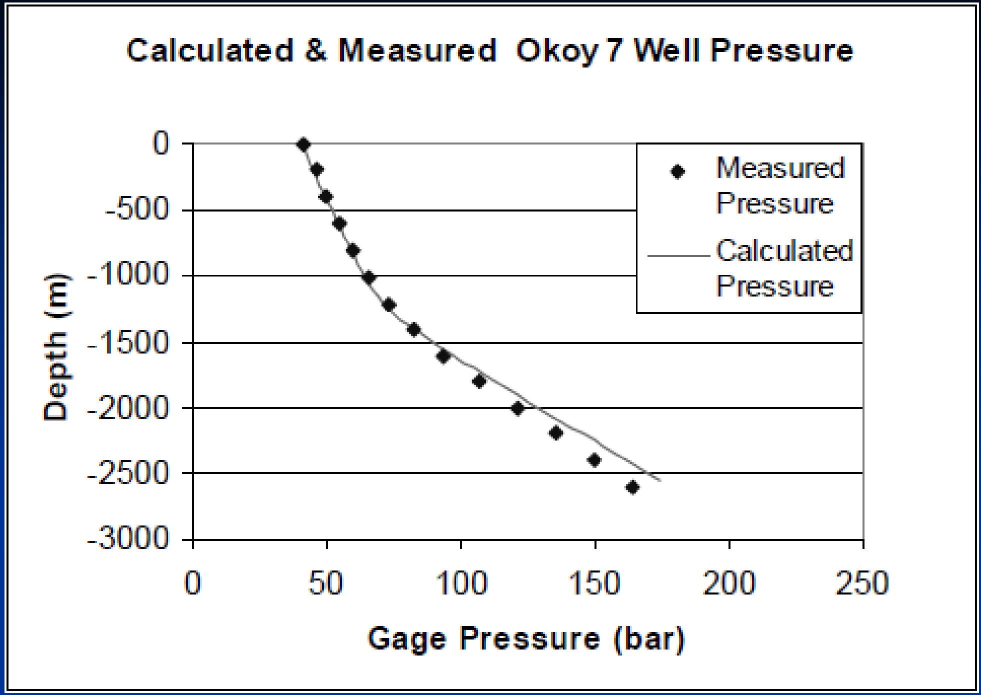


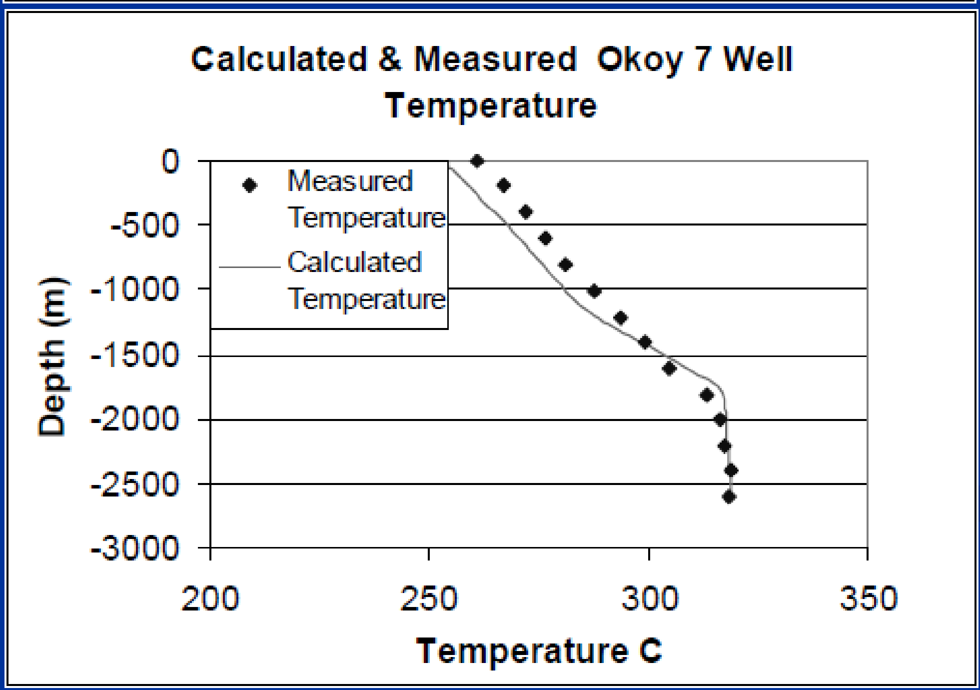
Wall Effects

- Single phase and two phase friction pressure drop
- Heat transfer and condensation
- Drop deposition and Entrainment

Single Friction Pressure Loss

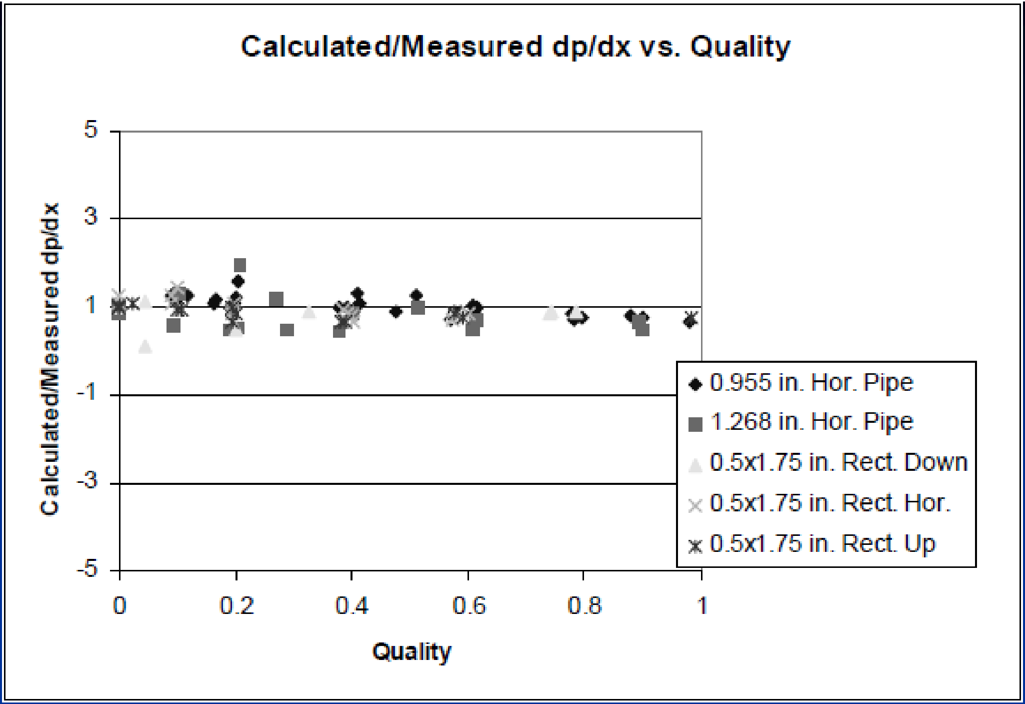
- Okoy Data for Geothermal Well
- Differences may be due to neglected friction heating

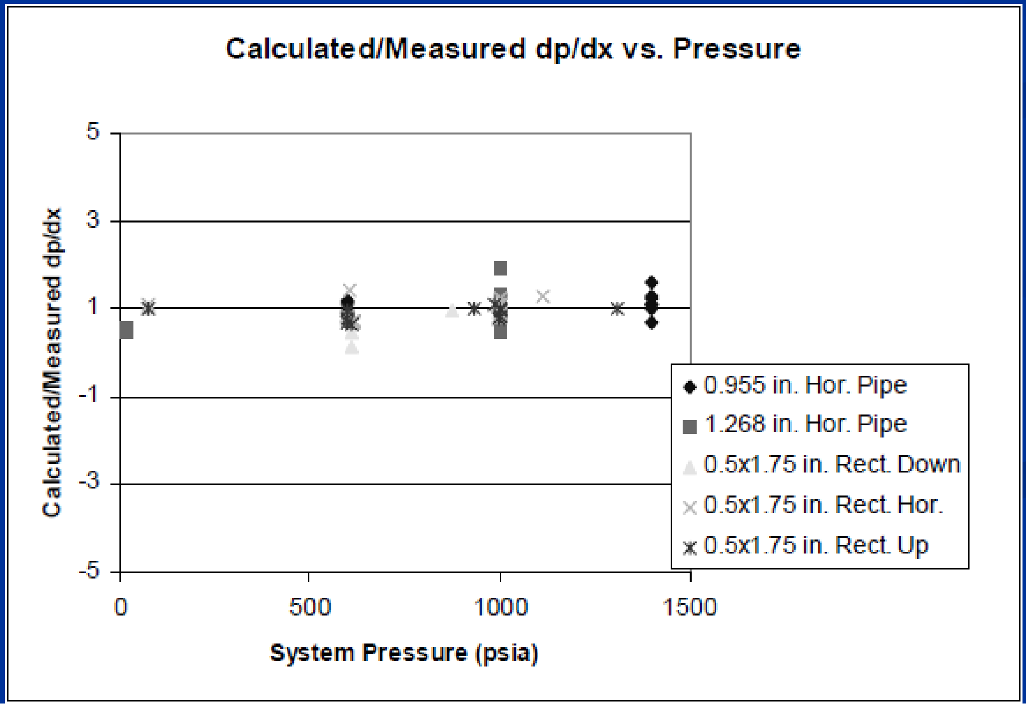




Two-phase Friction Pressure Loss

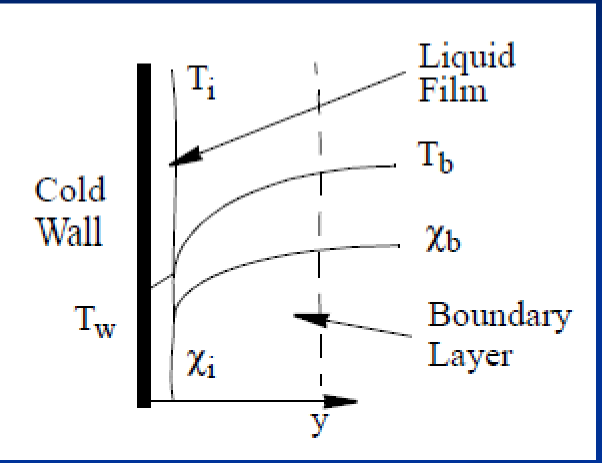
- GE Test data
  - Horizontal
  - Vertical Up
  - Vertical Down





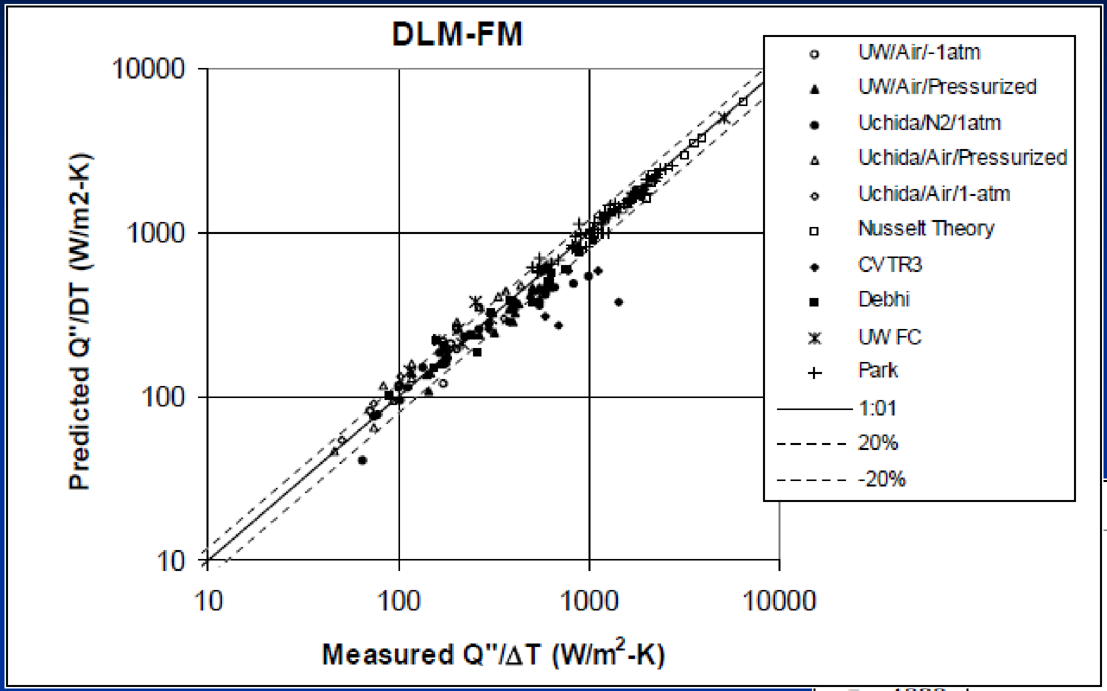
Diffusion Layer Model (DLM)
Wall Heat Transfer with Condensation

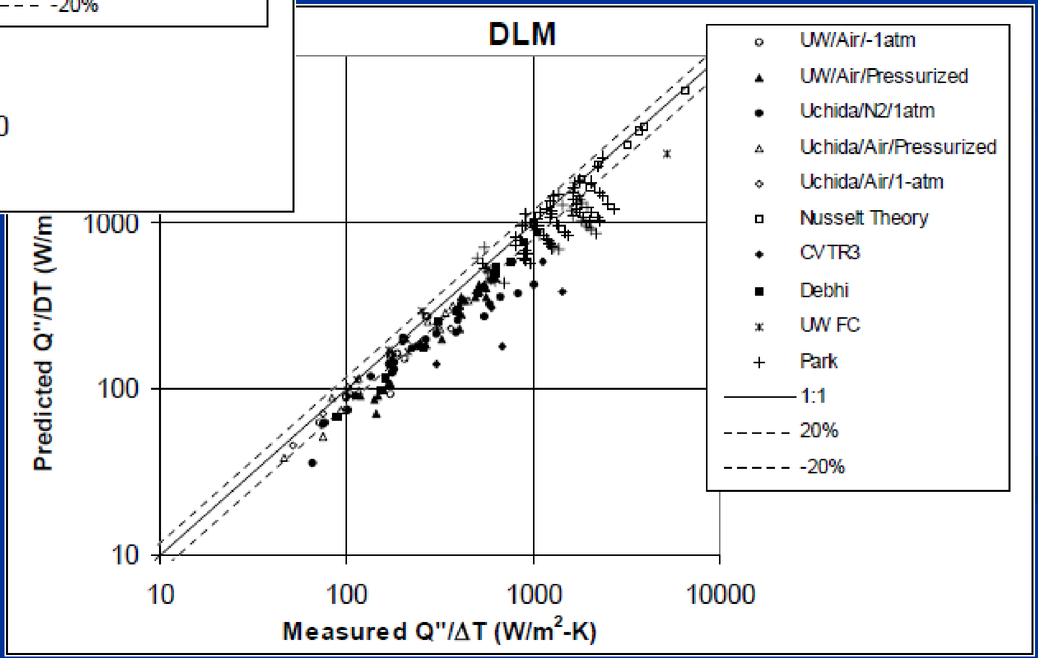
- Test range
  - Pressure, 1 – 4.5 atm
  - Steam Temperature, 47 – 139 C
  - Steam concentration, 0.1 – 1.0
  - Wall Temperature, 28 – 109 C
  - Wall Height, 0.3 – 18.3 m
  - Vapor Velocity, 0 – 7 m/s
- Film roughening effect
- Mist formation effect



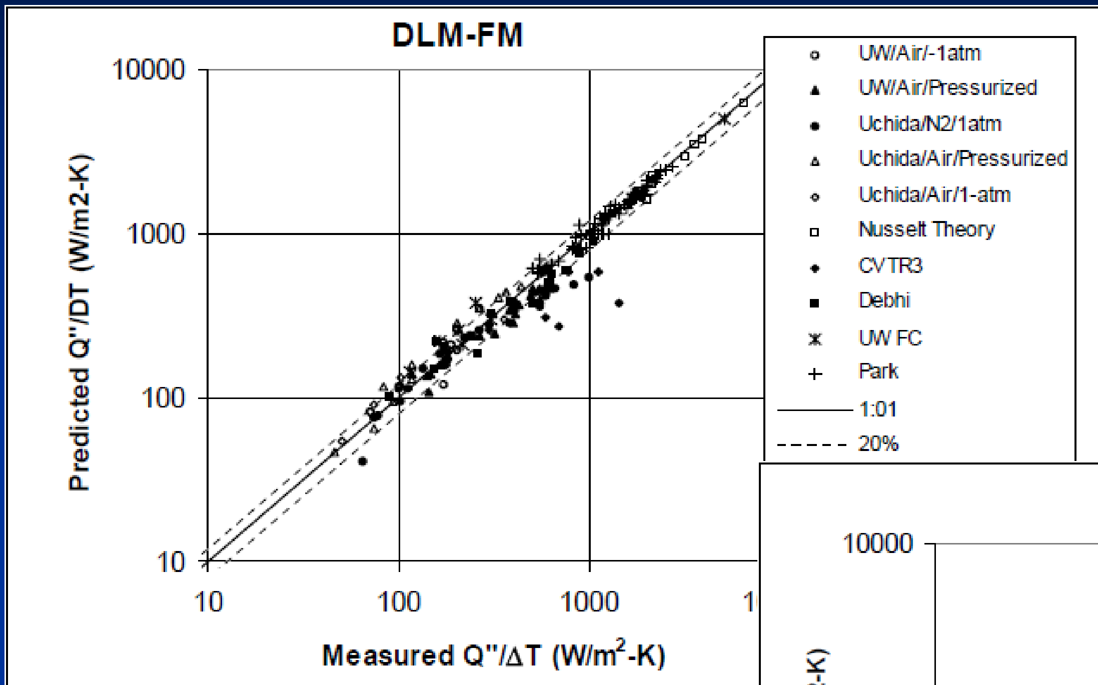
- Data Sets
  - Uchida
  - U of W Vessel
  - U of W Plate Plate
  - MIT
  - Nusselt Theory
  - CVTR
  - Park Film Test

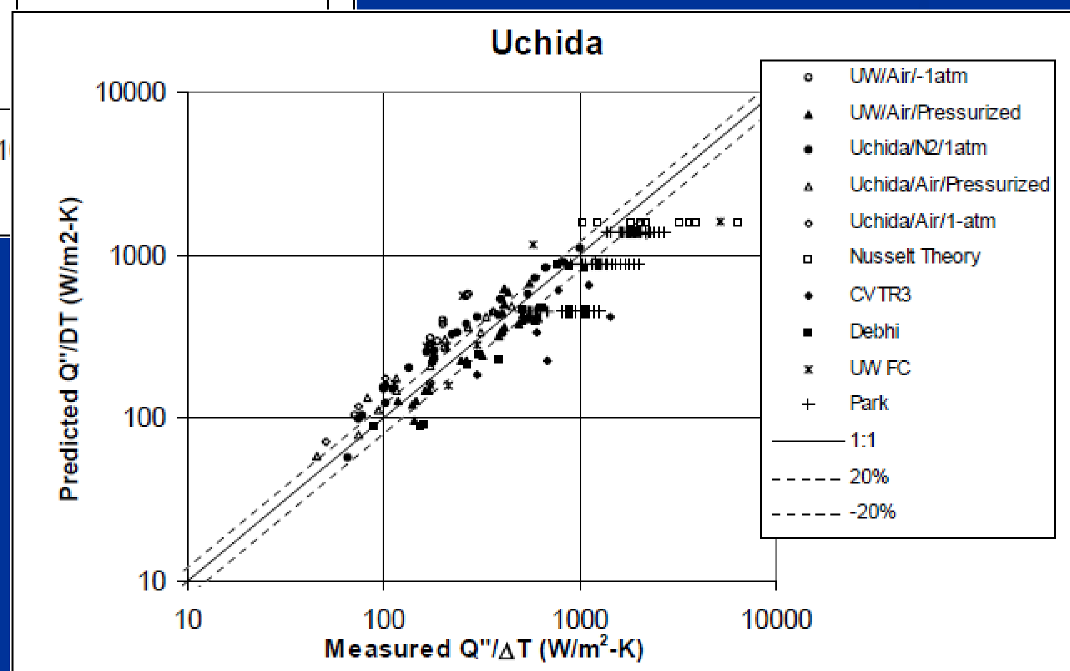
DLM for Heat and Mass Transfer





DLM for Heat and Mass Transfer



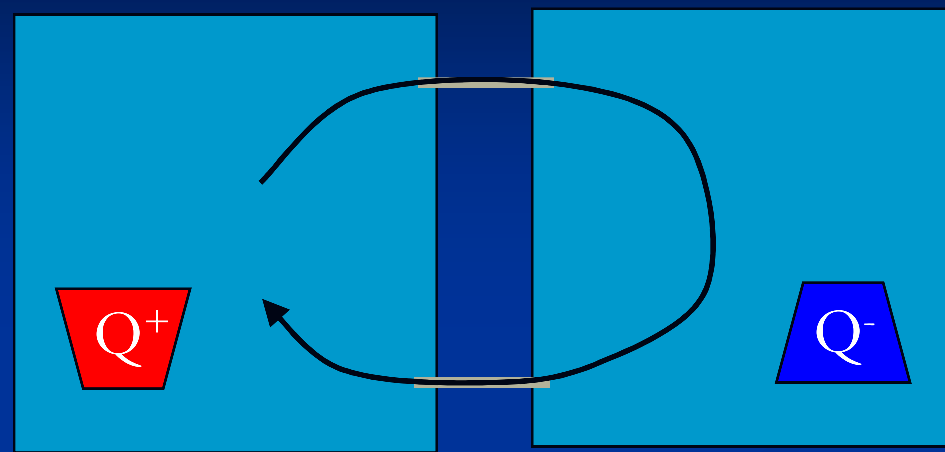


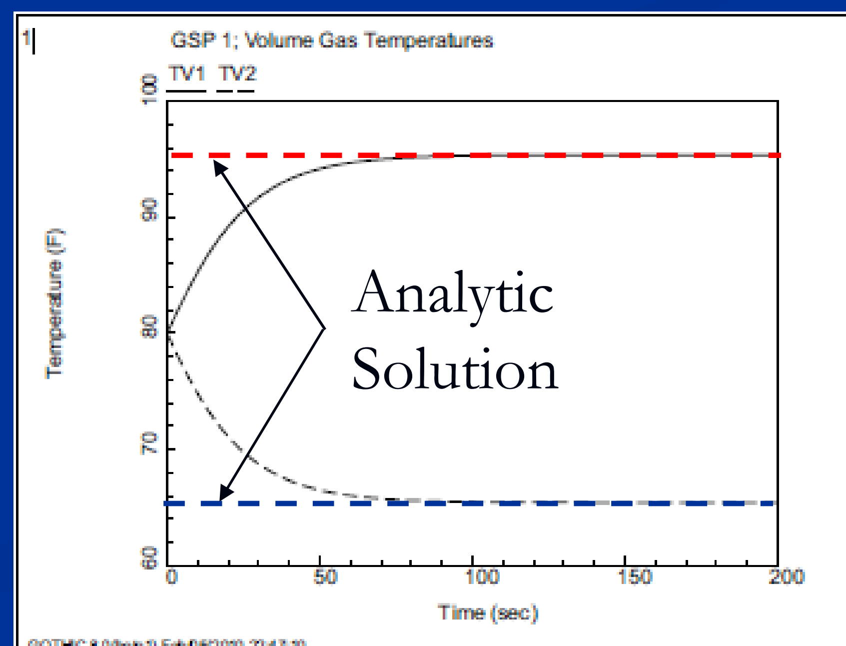
Buoyancy Driven Flow

- Mixing Analysis
- Room/Building Heatup
- Test
  - Analytic
  - Separate effects experiment
  - Large scale – single and multicompartment tests
    - HDR
    - Battelle Frankfurt Model Containment
    - MISTRA
    - TOSQAN
    - THaI
    - Others

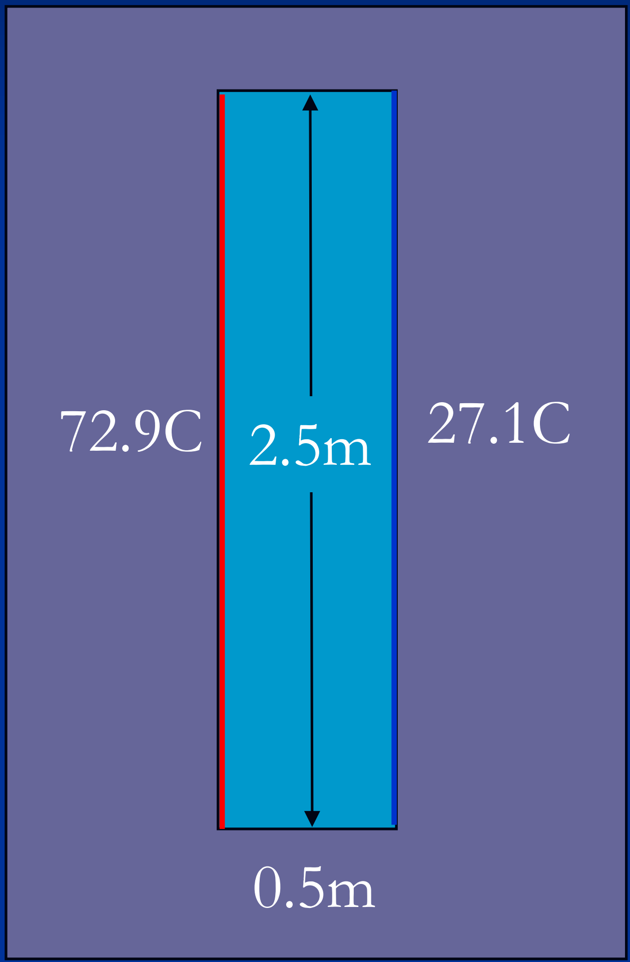
Buoyancy Driven Flow

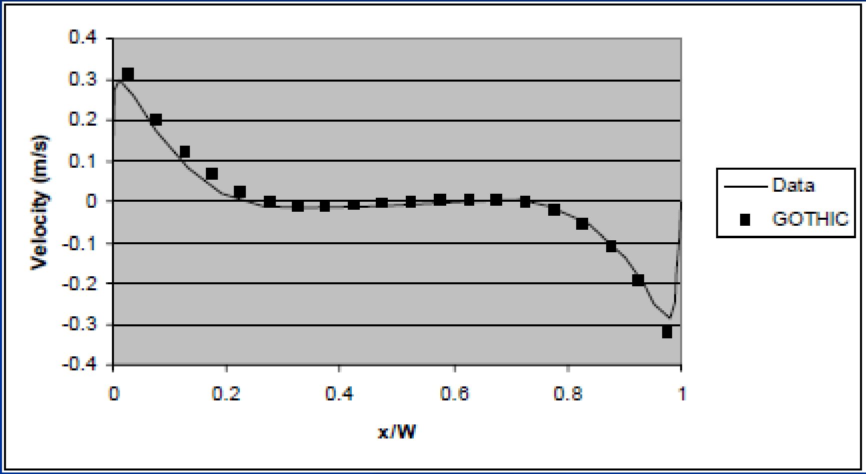
- Analytic Test Checks
  - Gas properties
  - Local in-cell pressure variation
  - Flow path pressure drop for given loss factor
  - Heater/Cooler performance

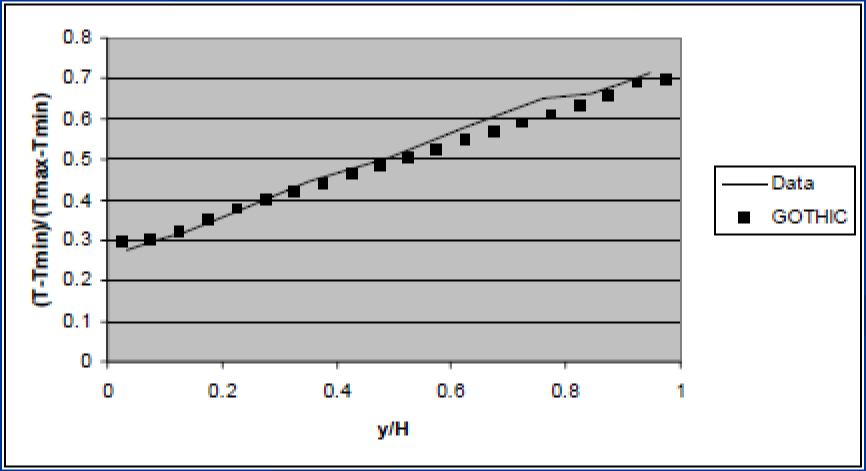




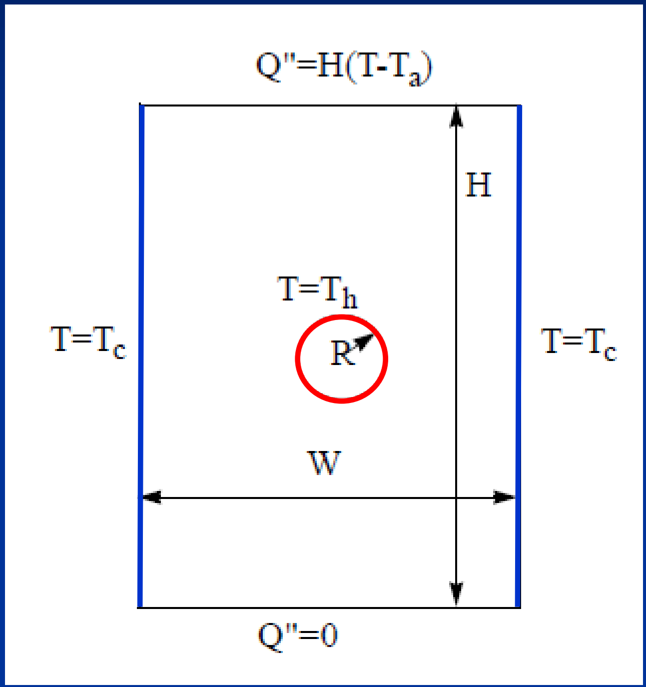
Buoyancy Driven Flow
Thermally Driven Cavity



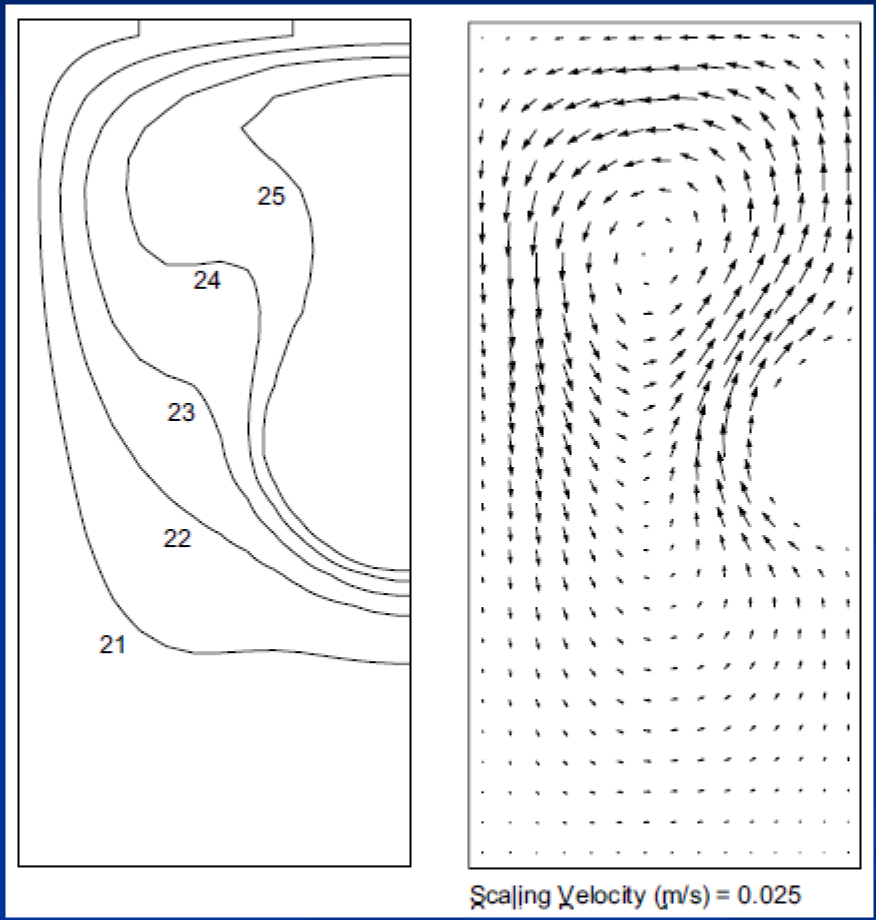




Natural Convection Heat Transfer

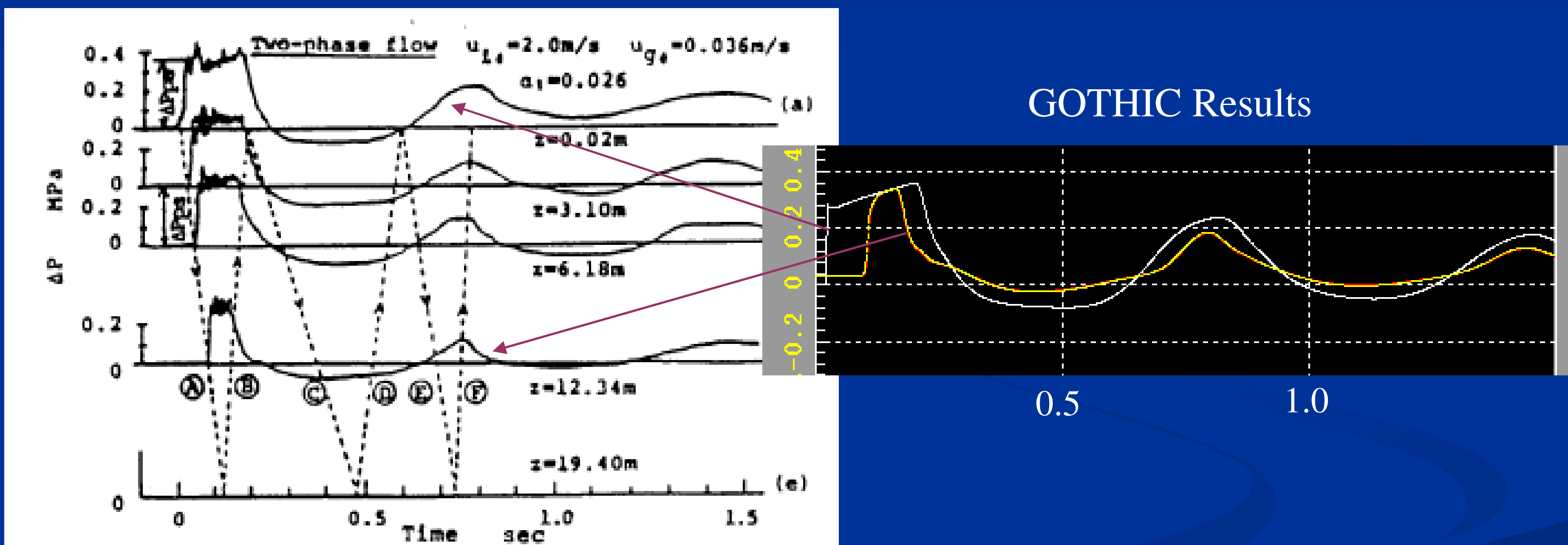


Raleigh No	Nu (Exp.)	Nu (GOTHIC)
1,300	2.35	2.52
2,400	2.79	3.06
3,400	3.06	3.38



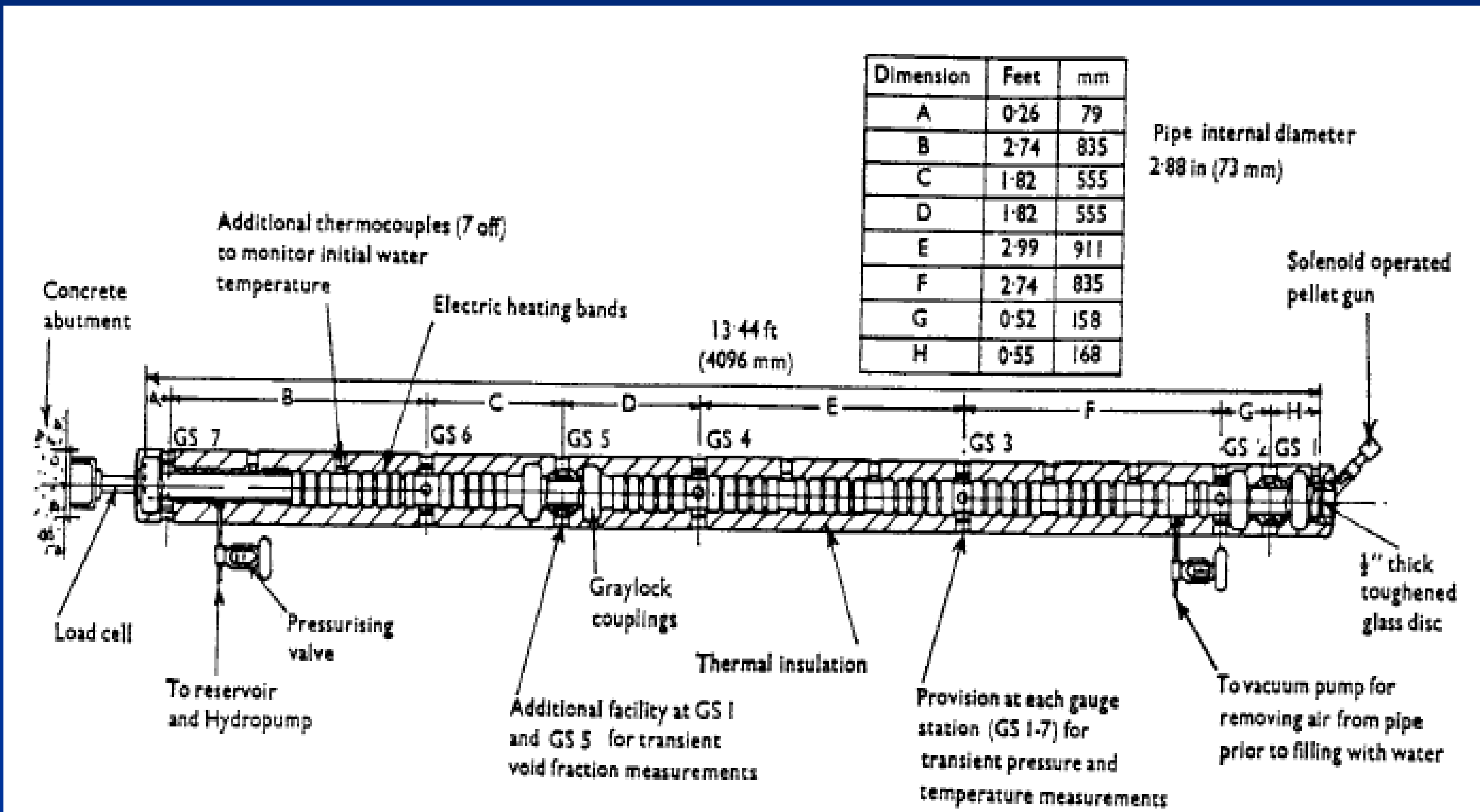
Valve Closure on Bubbly Flow

Experiment by Akagawa and Fujii
Pipe – 19.4m x 20.4mm ID, U_0=2m/s, 2.6% void
20 ms valve closure time



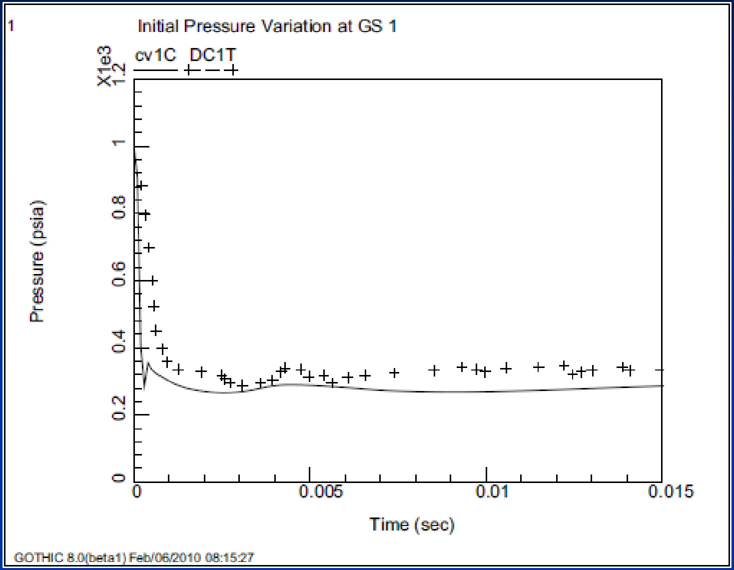
Pressure rise in single phase water would be ~2.8 MPa

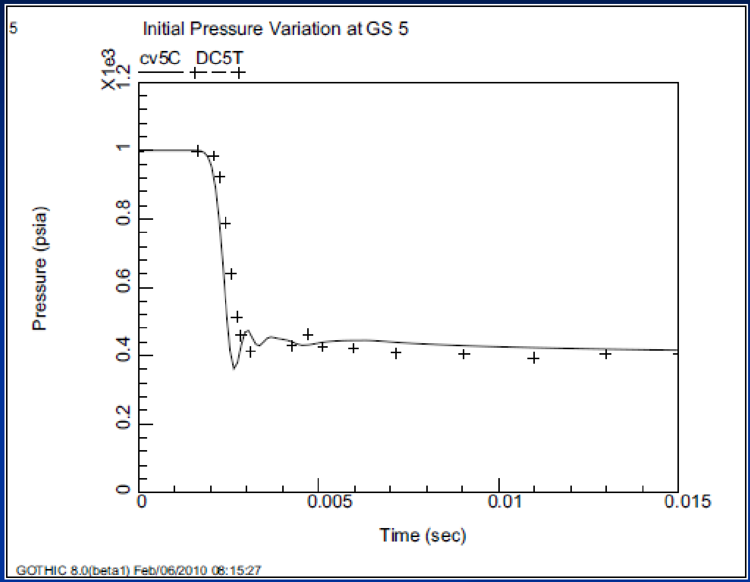
Pipe Blowdown - Edwards

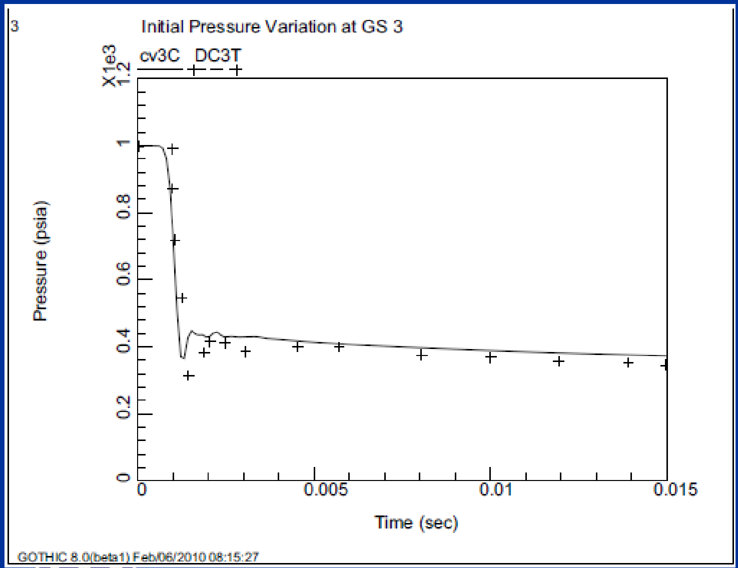


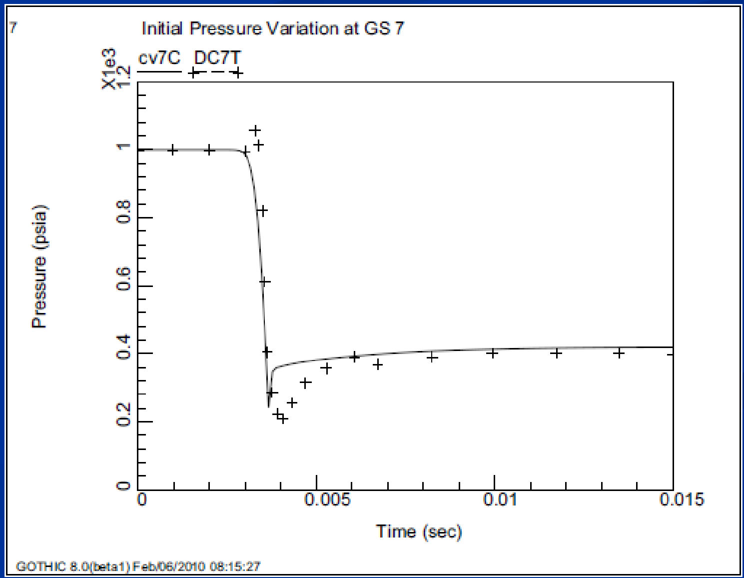
Dimension	Feet	mm
A	0·26	79
B	2·74	835
C	1·82	555
D	1·82	555
E	2·99	911
F	2·74	835
G	0·52	158
H	0·55	168

Pipe Blowdown – Short Term Response

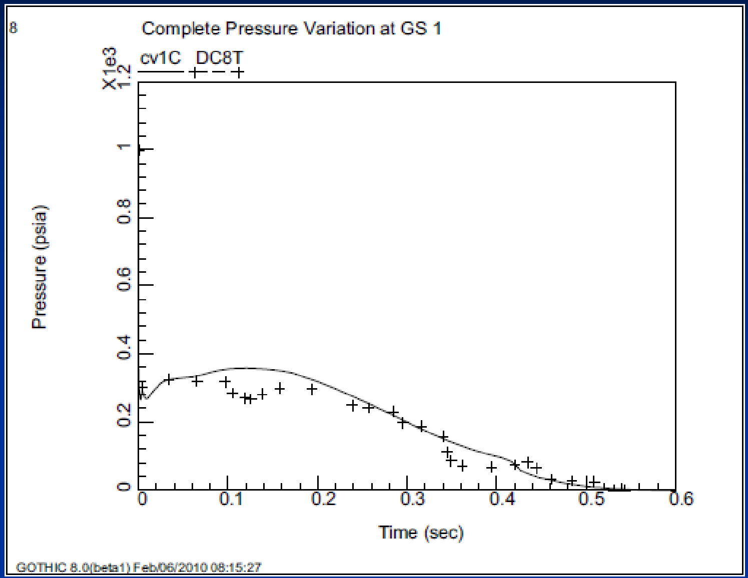


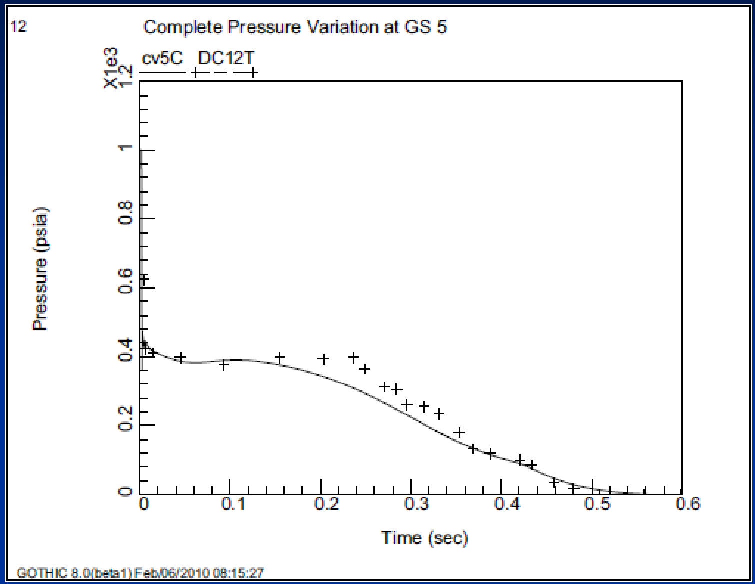


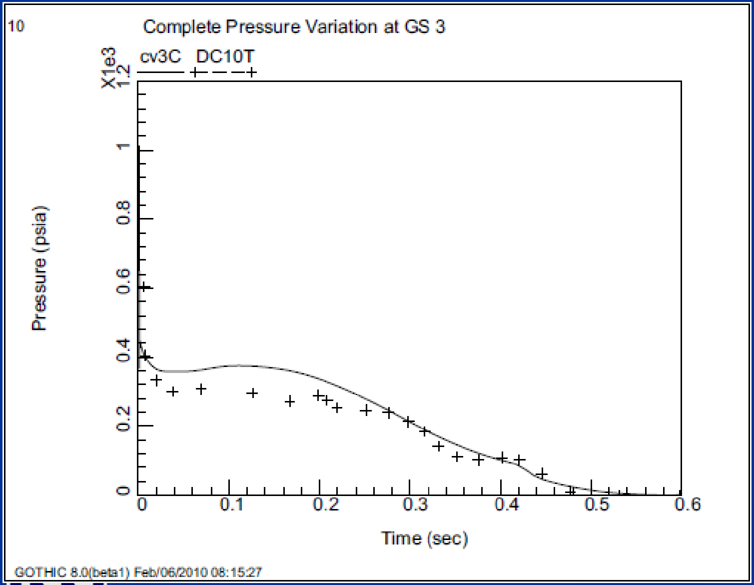


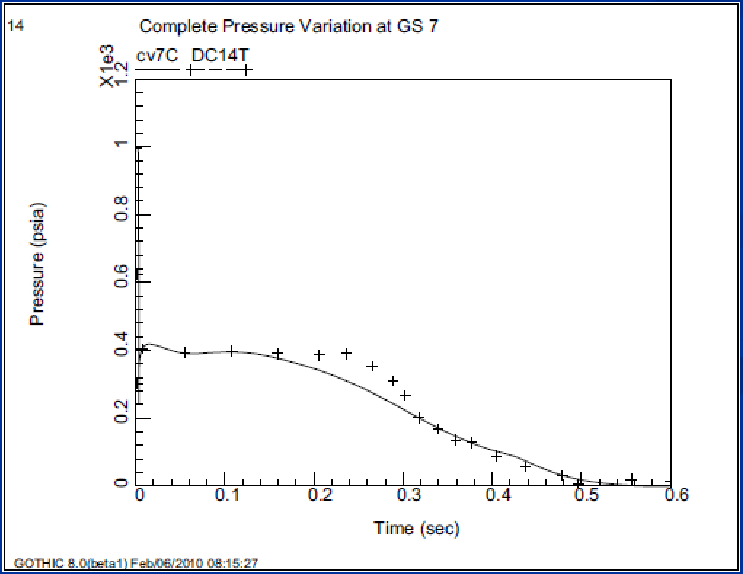


Pipe Blowdown – Long Term Response







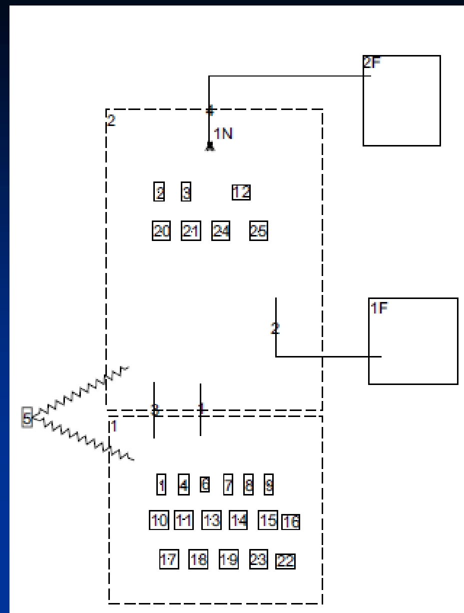


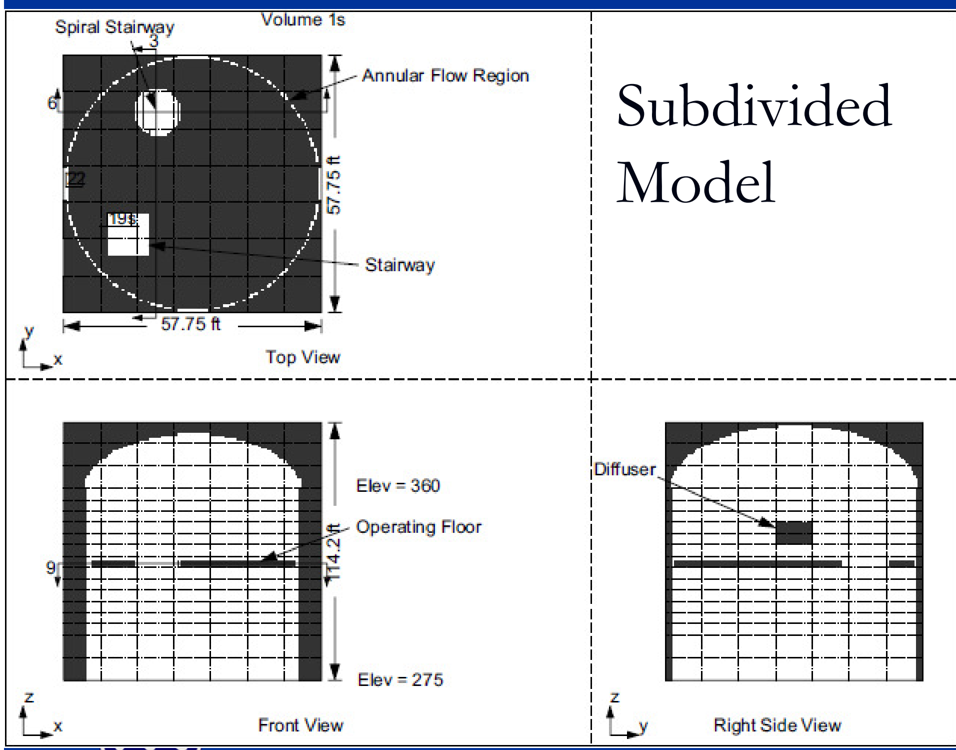
Combined Effects Tests

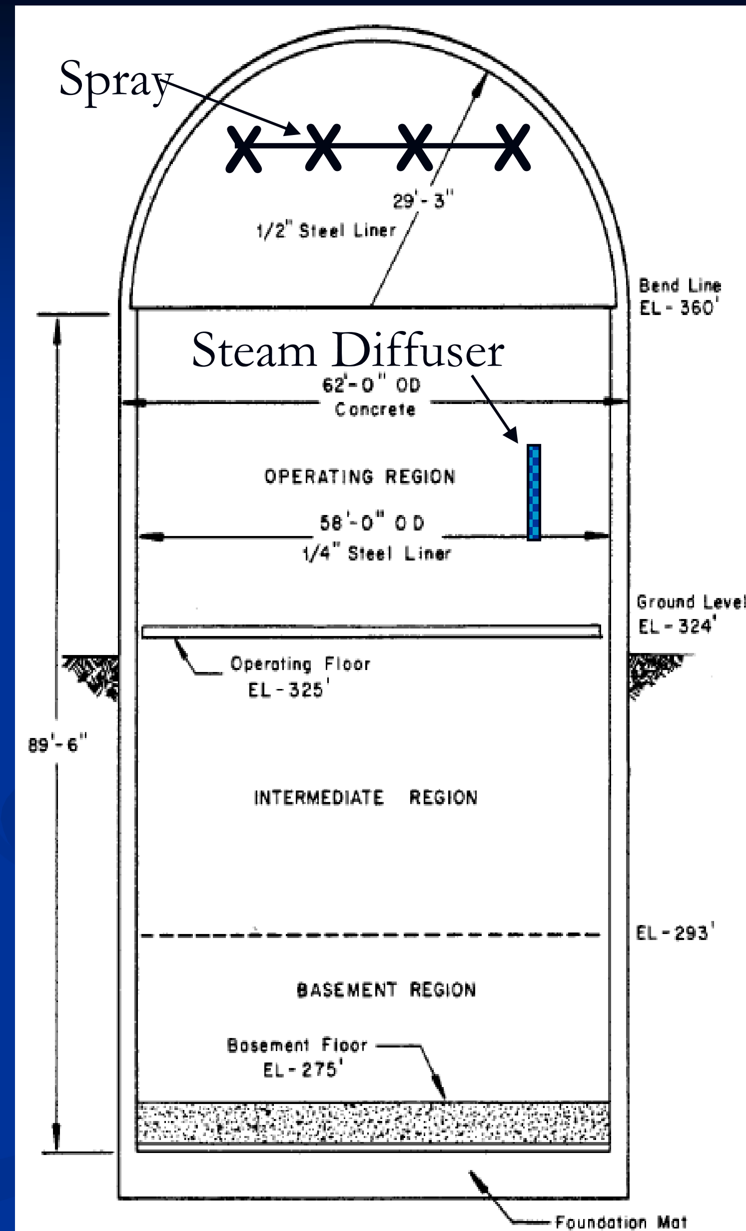
- CVTR
  - Steam Blowdown
  - Sprays
- HDR
  - Steam/Water Blowdown
  - Hydrogen Mixing
- BFMC
  - Steam Blowdown
  - Steam/Water Blowdown
  - Hydrogen Mixing
- NUPEC
  - Steam/Water Blowdown
  - Sprays
  - Hydrogen Mixing
- Marviken
  - Steam/Water Blowdown
  - Pressure Suppression Pool
- TOSQAN/MISTRA/THaI
  - Natural Convection
  - Jets and Plumes
  - Wall Condensation
  - Stratification

CVTR

Lumped Model

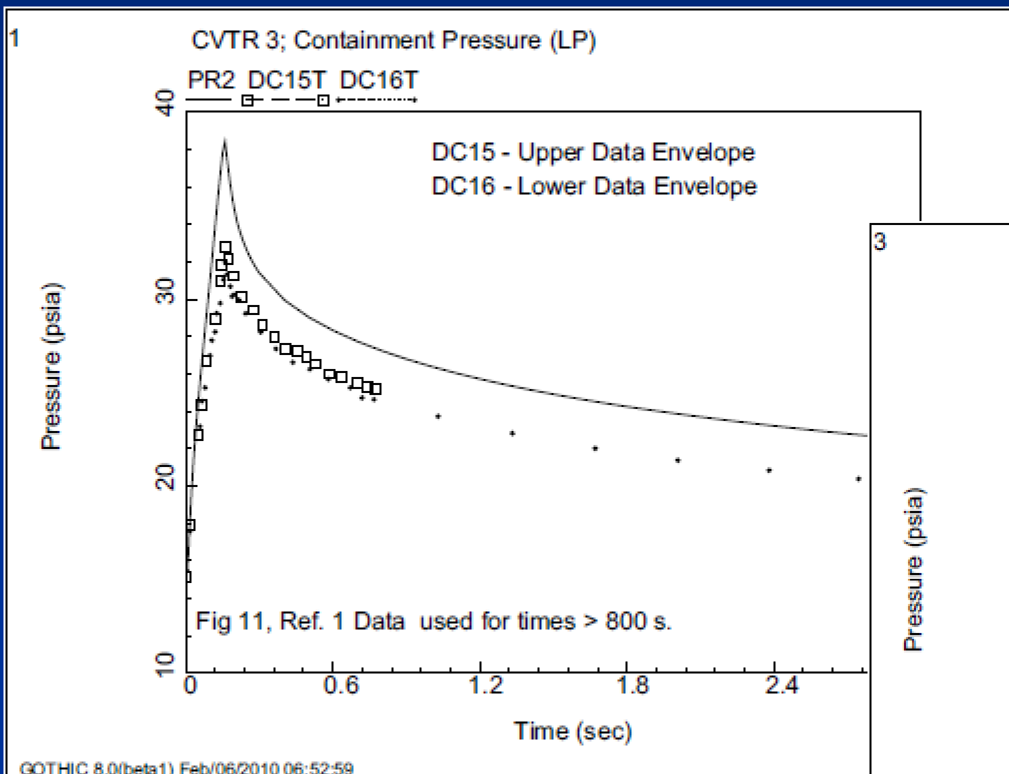




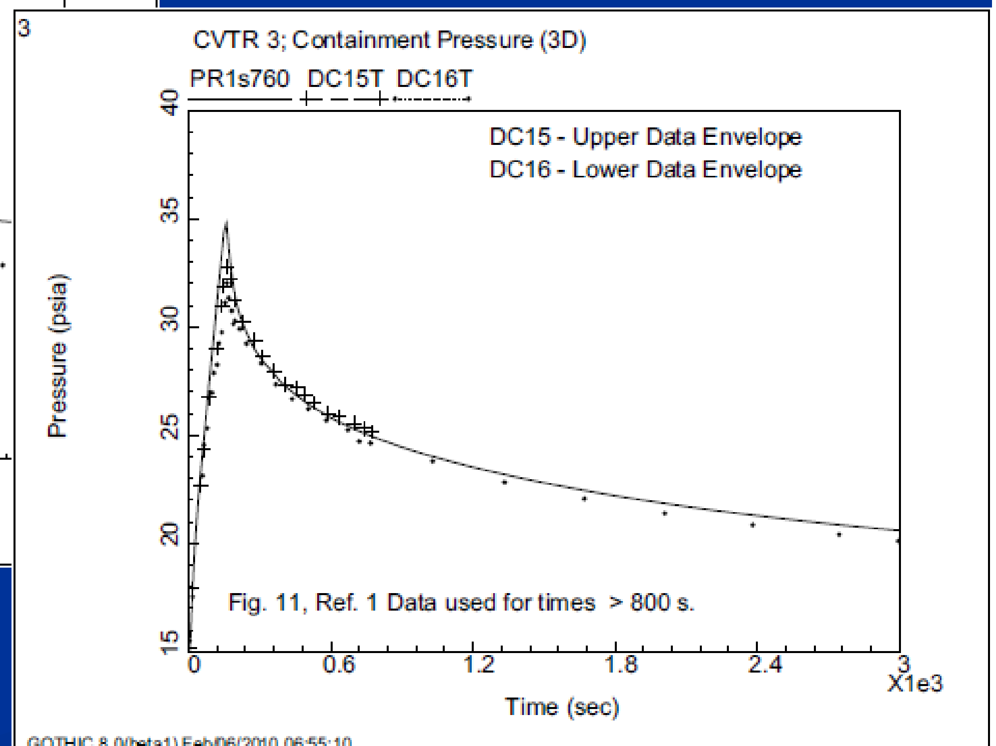


CVTR – Pressure Transient

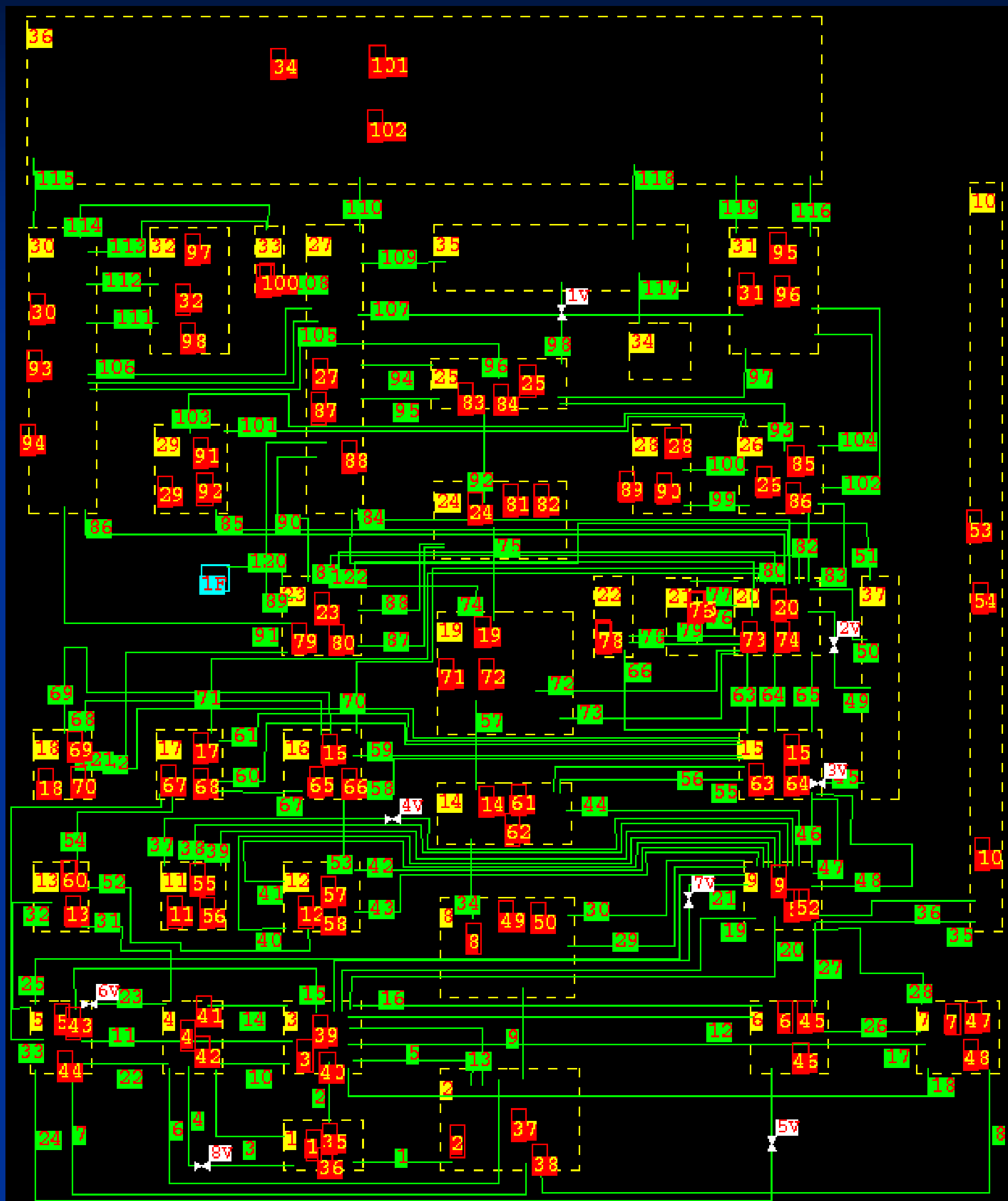
Lumped

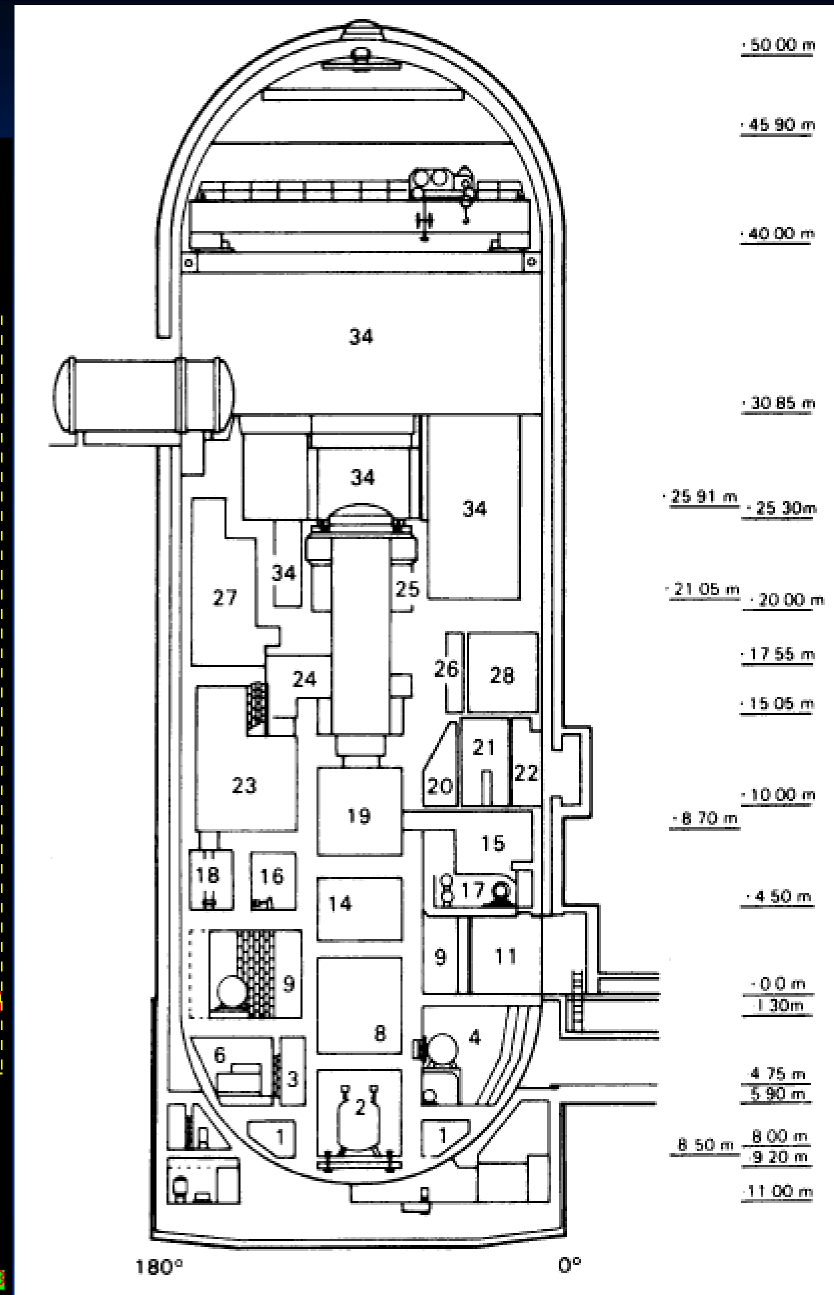


Subdivided



HDR

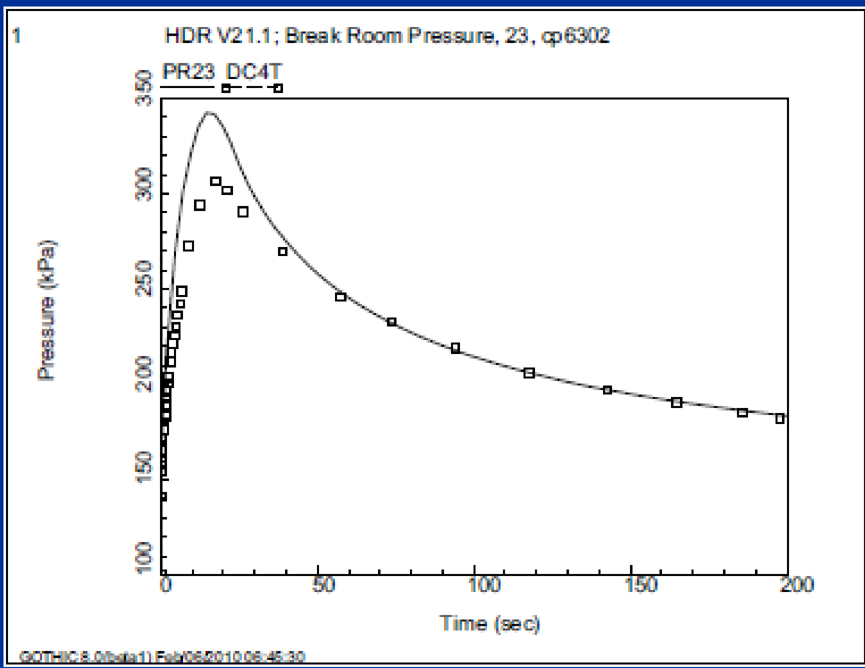




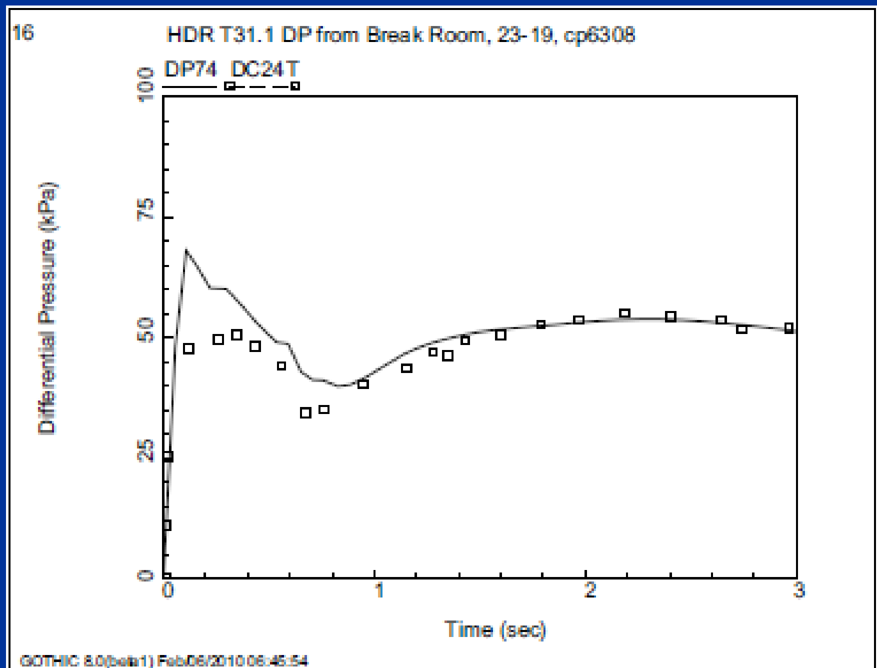
50.00 m
45.90 m
40.00 m
30.85 m
25.91 m
25.30m
21.05 m
20.00 m
17.55 m
15.05 m
10.00 m
8.70 m
4.50 m
0.0 m
1.30m
4.75 m
5.90 m
8.50 m
8.00 m
9.20 m
11.00 m
180°
0°

HDR

- Support for
  - Containment P/T
  - Subcompartment Delta-P
  - EQ



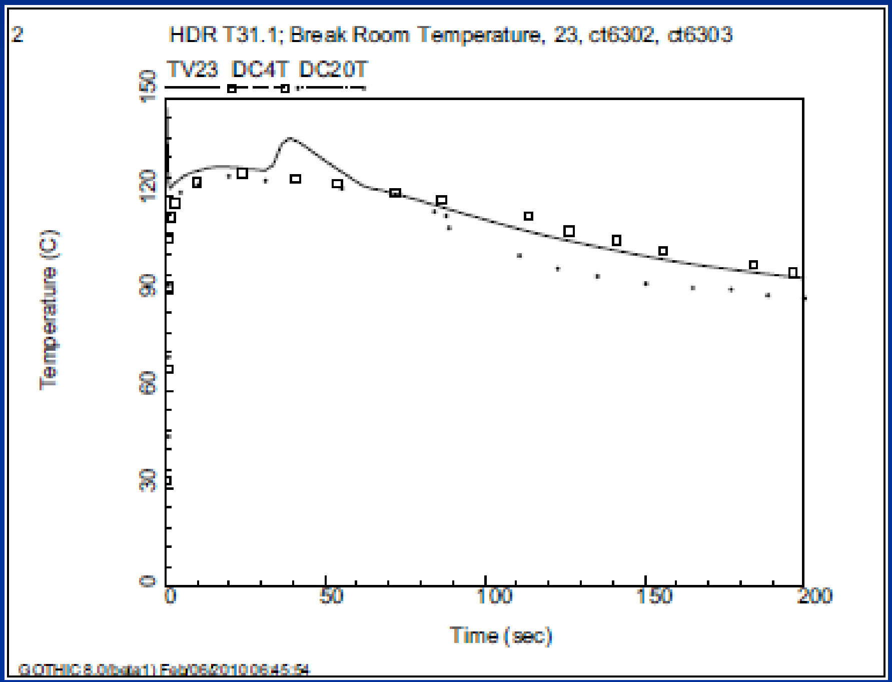
V21.1 Break Room Pressure



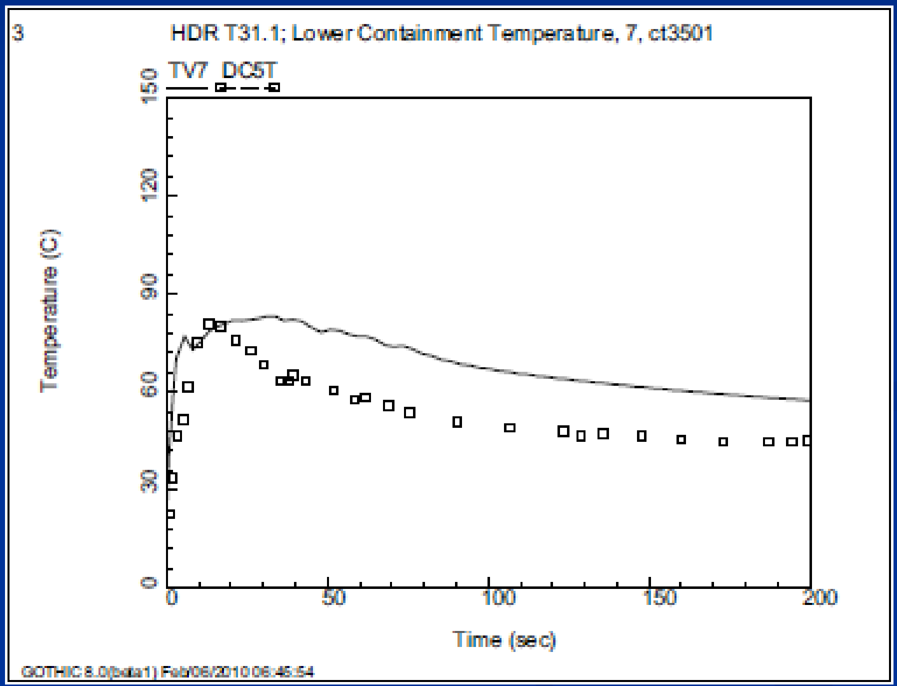
T31.1 Differential Pressure

HDR

- Support for
  - EQ



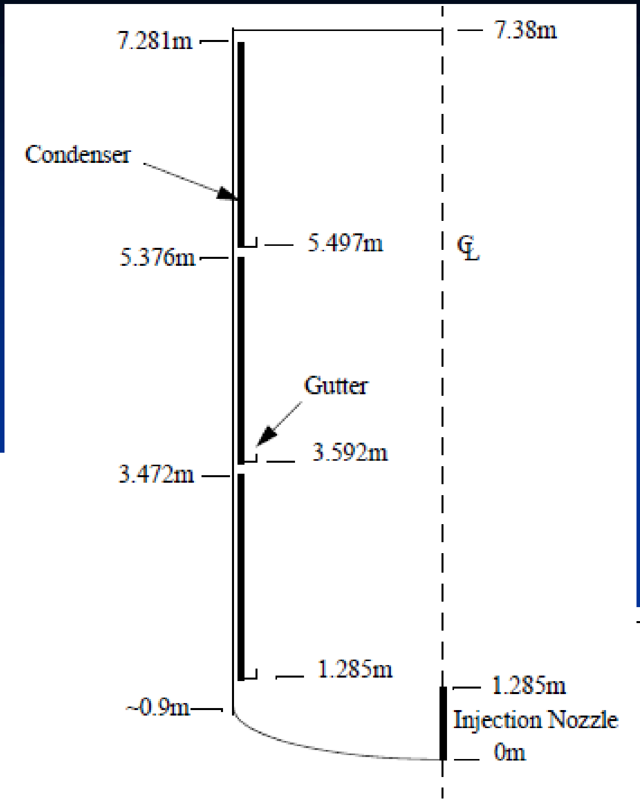
T31.1 Break Room Temperature

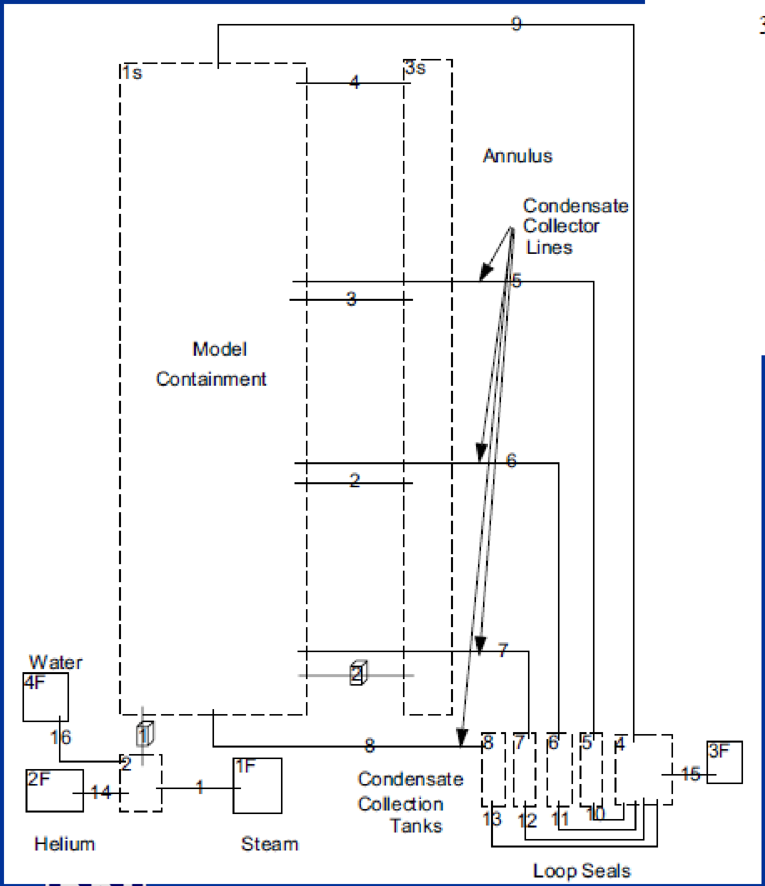


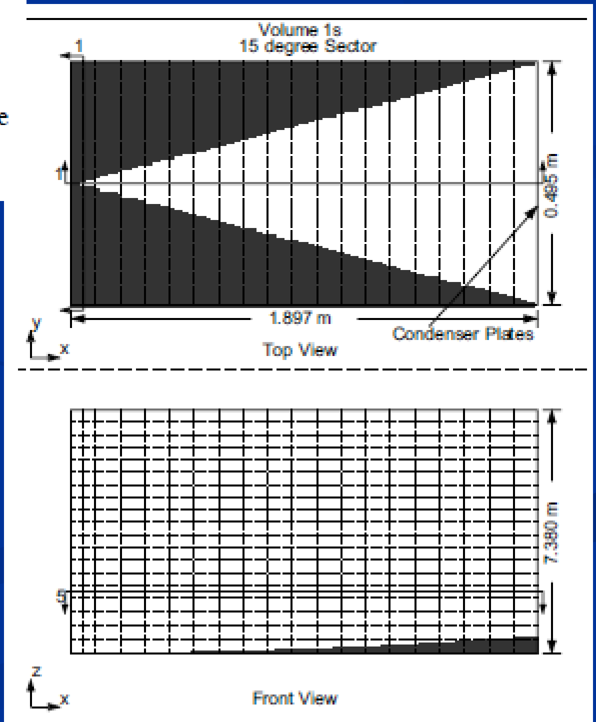
T31.1 Lower Compartment Temperature

MISTRA

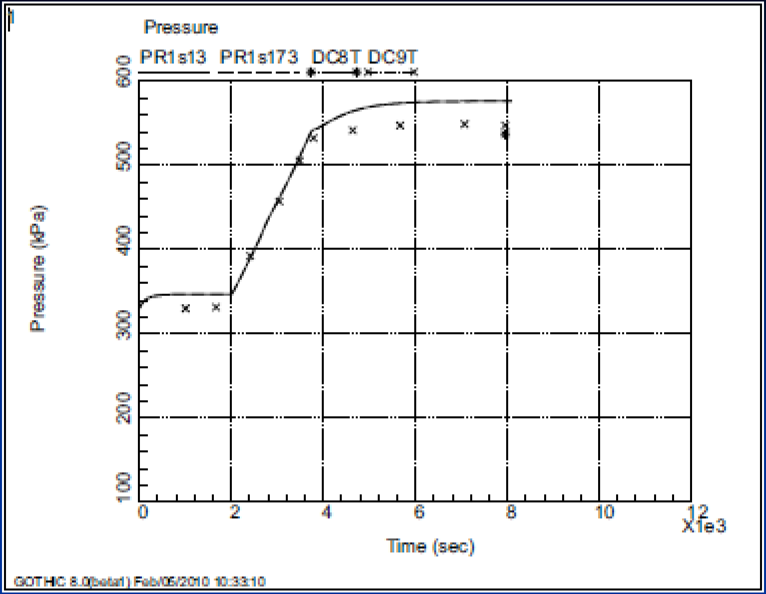
- Axisymmetric
- Steam/Helium Injection







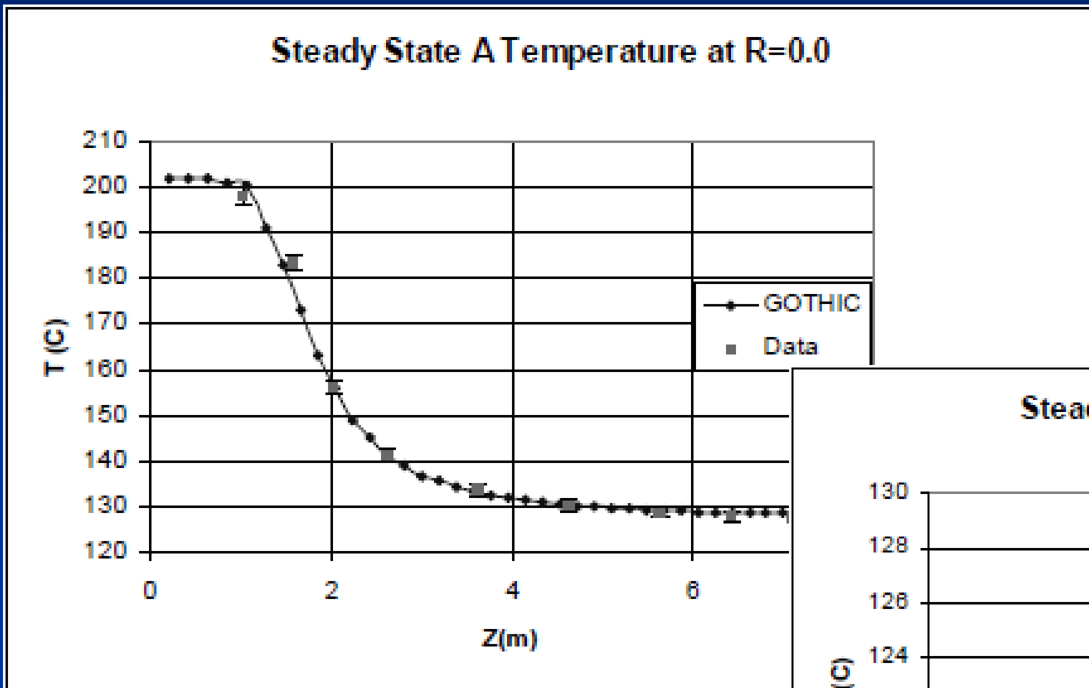
MISTRA



Pressure Transient

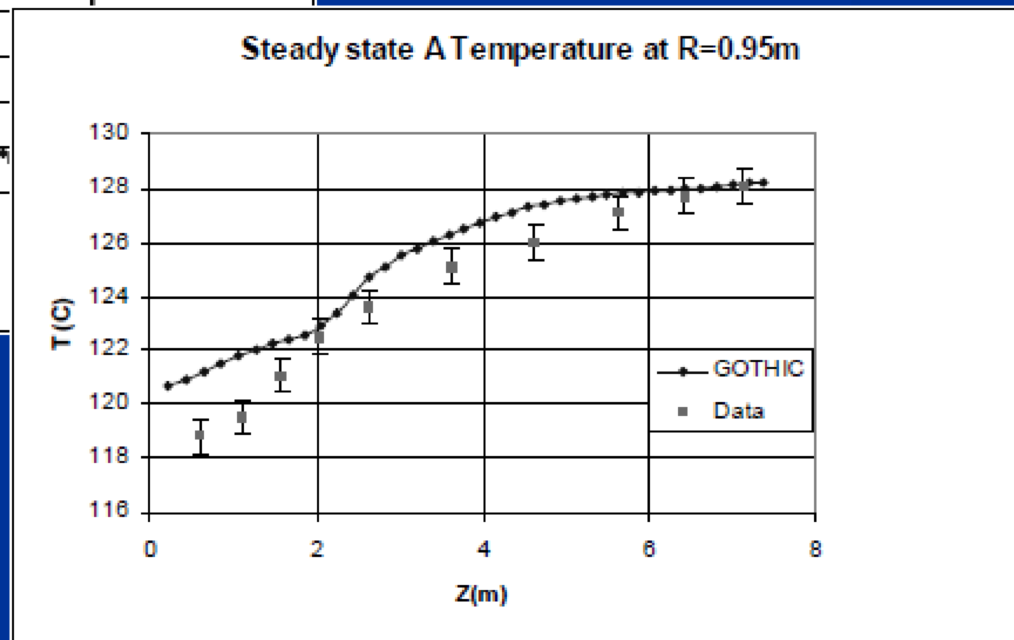
	Condensate Distribution (g/s)			
	Steady State 1		Steady State 2	
Location	GOTHIC	Measured	GOTHIC	Measured
Bottom Condenser	36.6	35.3-39.1	35.3	31.6-32.6
Middle Condenser	36.2	30.1-34.2	34.2	20.5-26.2
Top Condenser	39.4	40.4-43.3	38.5	48.1-53.0
Spurious Condensation	17.8	16.7-18.0	22.0	17.0-19.6

MISTRA Temperatures



Centerline

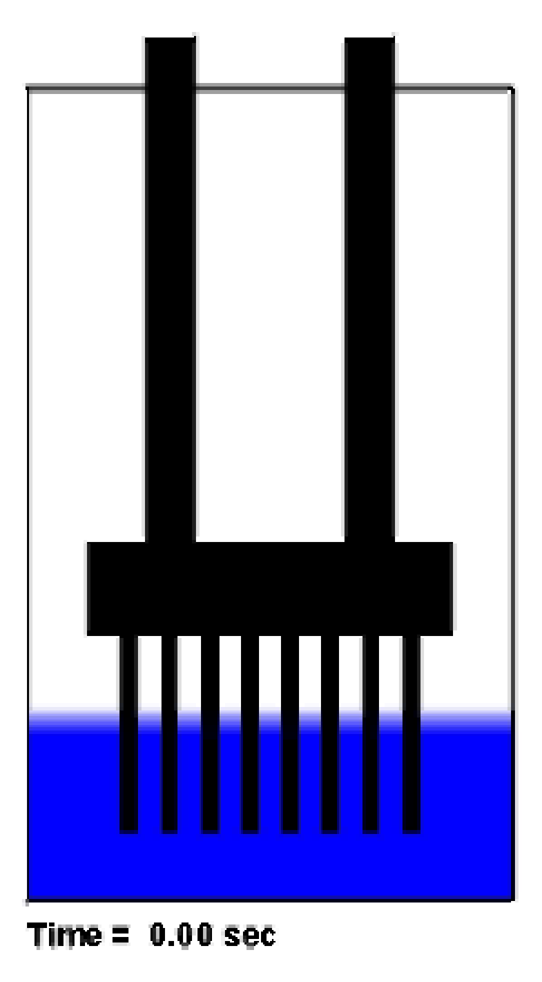
R=0.95m

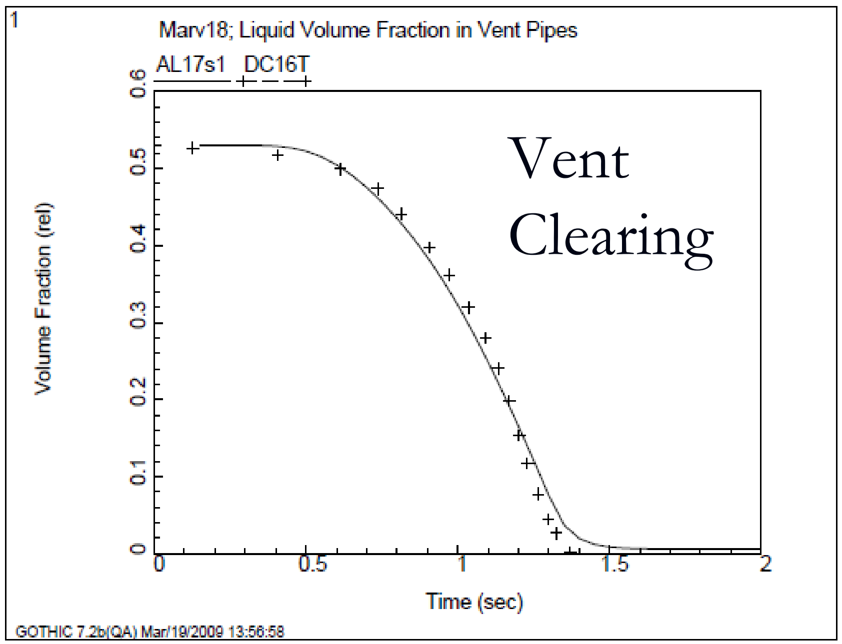


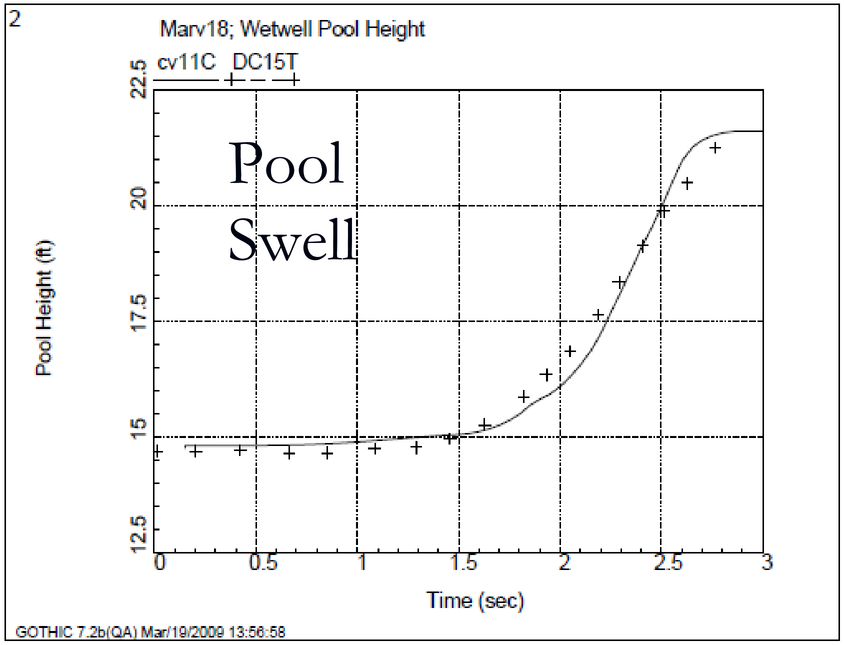
Multiphase Flow Tests

- Suppression Pool Swell
- Subcooled and Saturated Boiling
- PWR Loop Flows
- Piping Components and Systems
  - Horizontal and Vertical Pipe Fill
  - Liquid Holdup in Vertical Flows
  - Millstone 3 System Tests
  - Purdue Gas Transport Tests

Suppression Pool Swell – Marviken Test 18



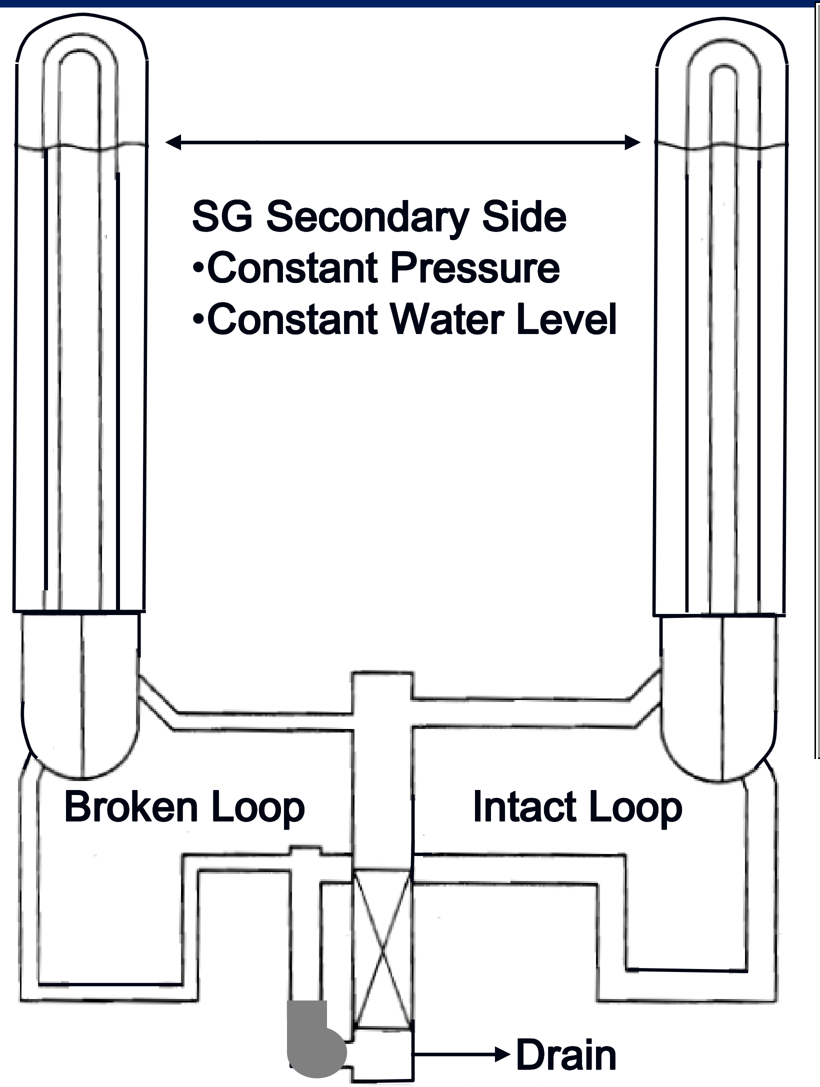


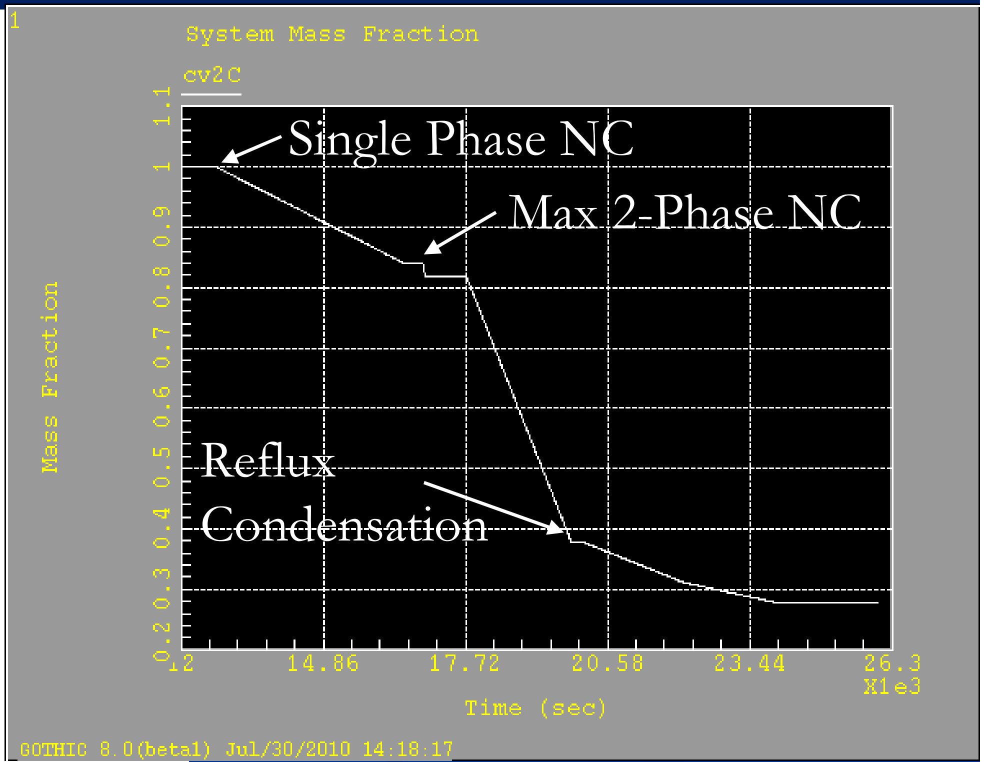


PWR FLECHT SEASET

- 4 Loop PWR
- Forced Circulation
- Single Phase Natural Circulation
- Two Phase Natural Circulation
- Reflux Condensation
- NUREG/CR-3654 "PWR FLECHT SEASET System Effects Natural Circulation and Reflux Condensation"

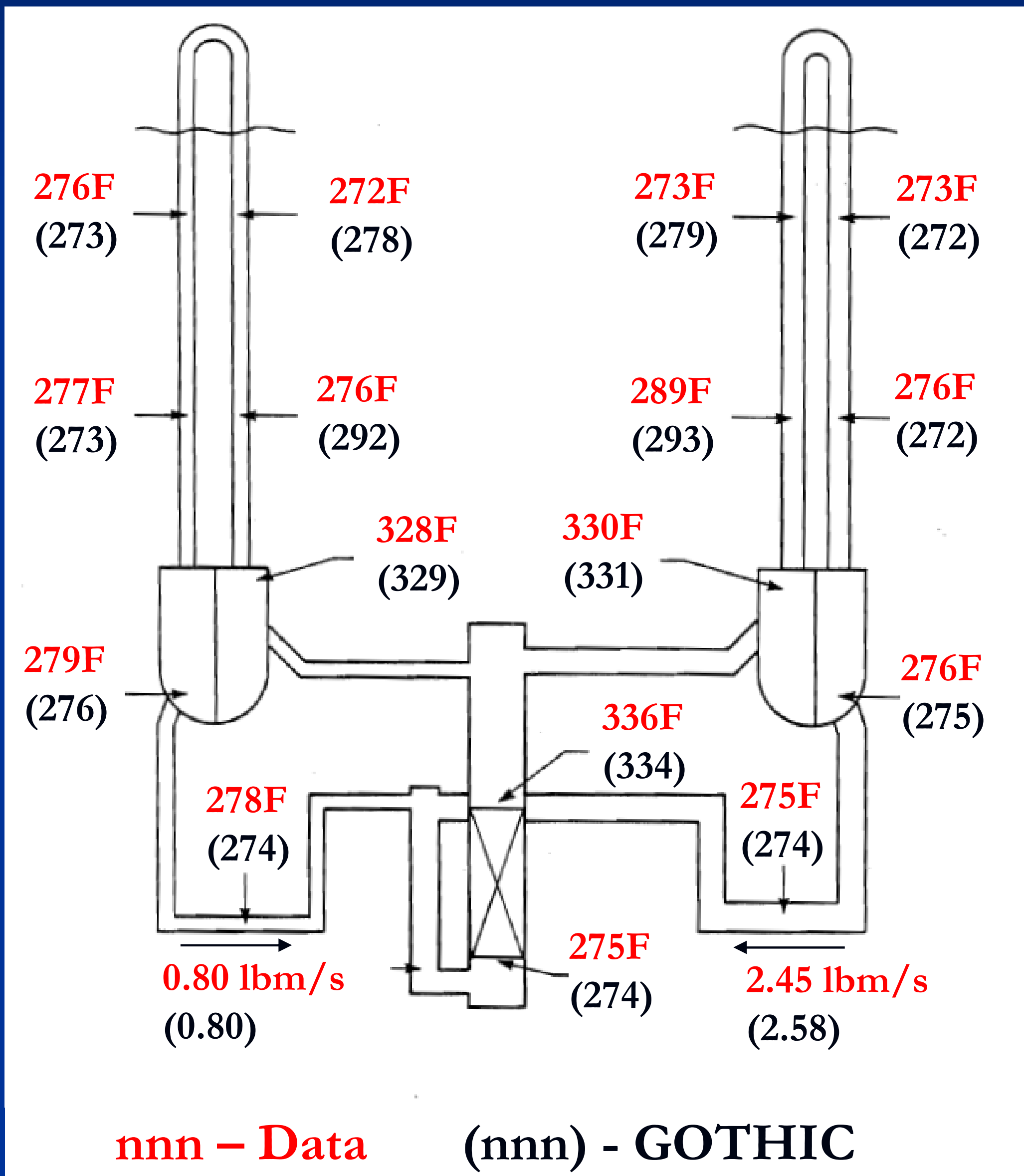
PWR FLECHT SEASET





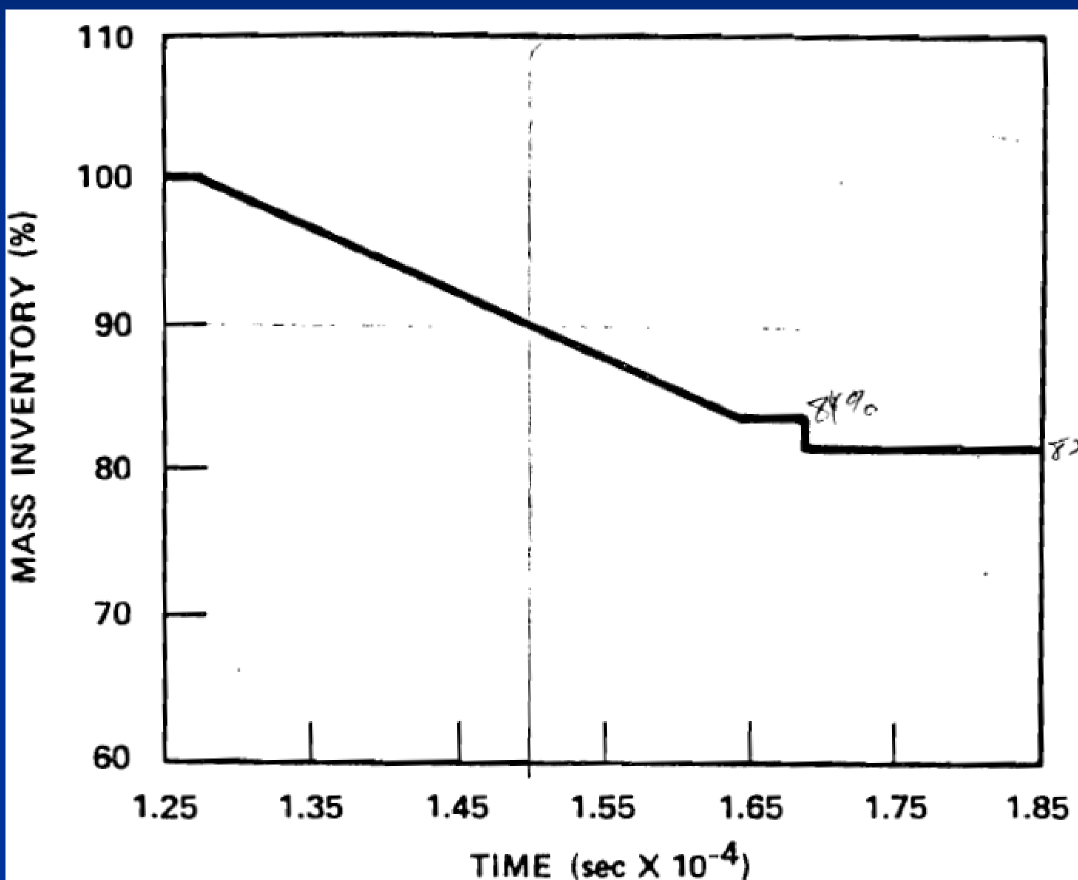
- **Data Comparisons**
  - Loop Flows
  - Steam Generator Performance

Single Phase Natural Circulation – Steady State



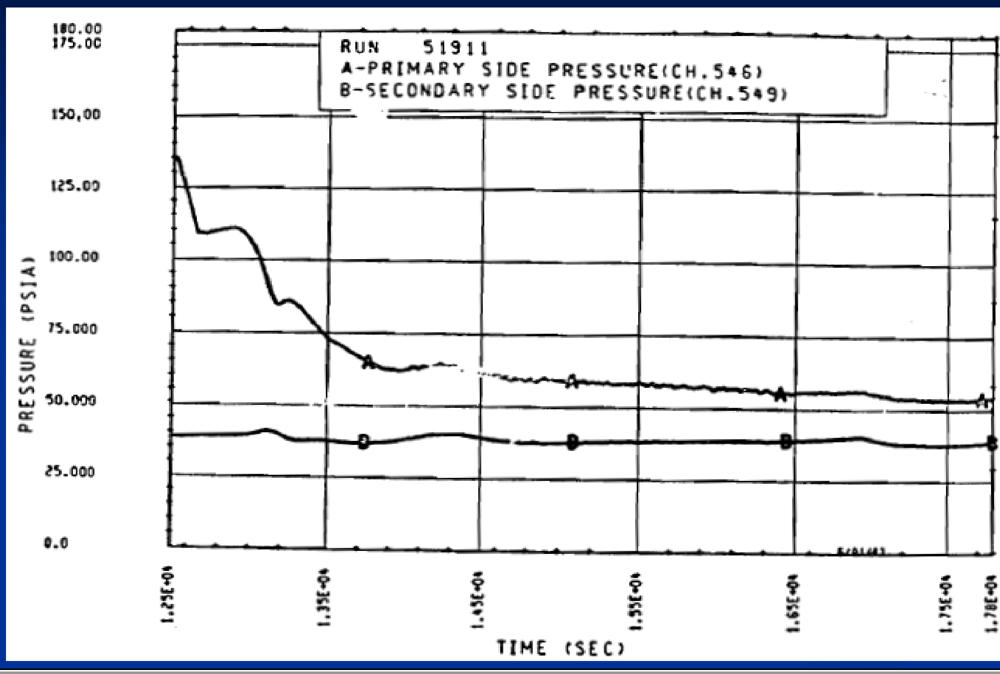
2-Phase Natural Circulation

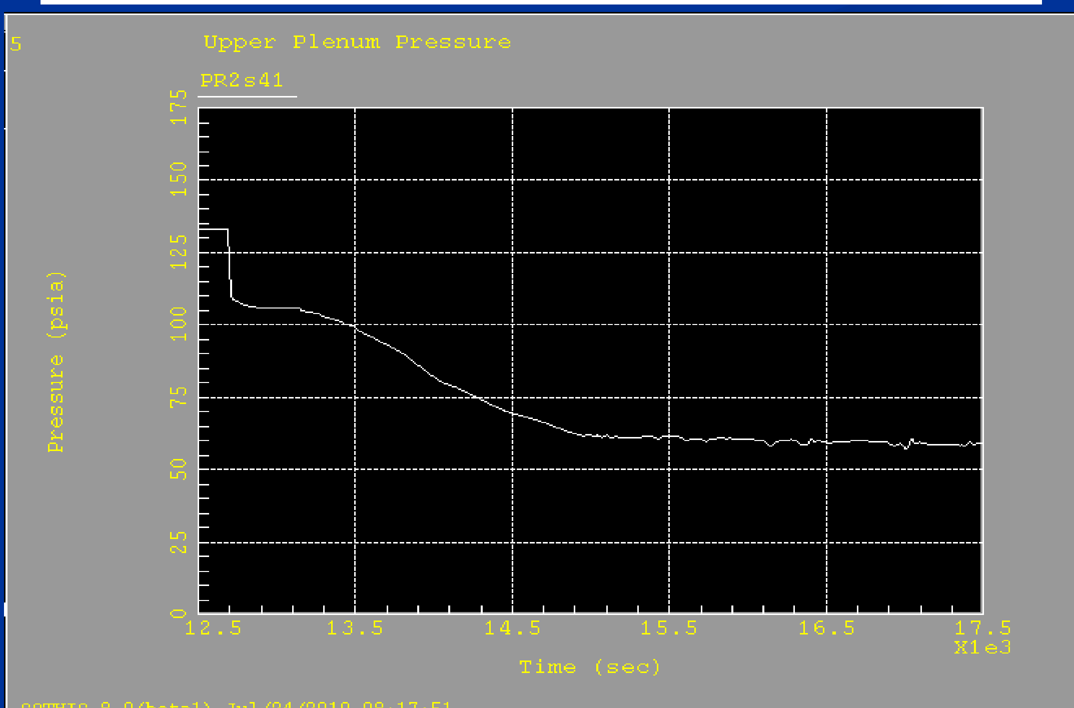
- System Mass Inventory



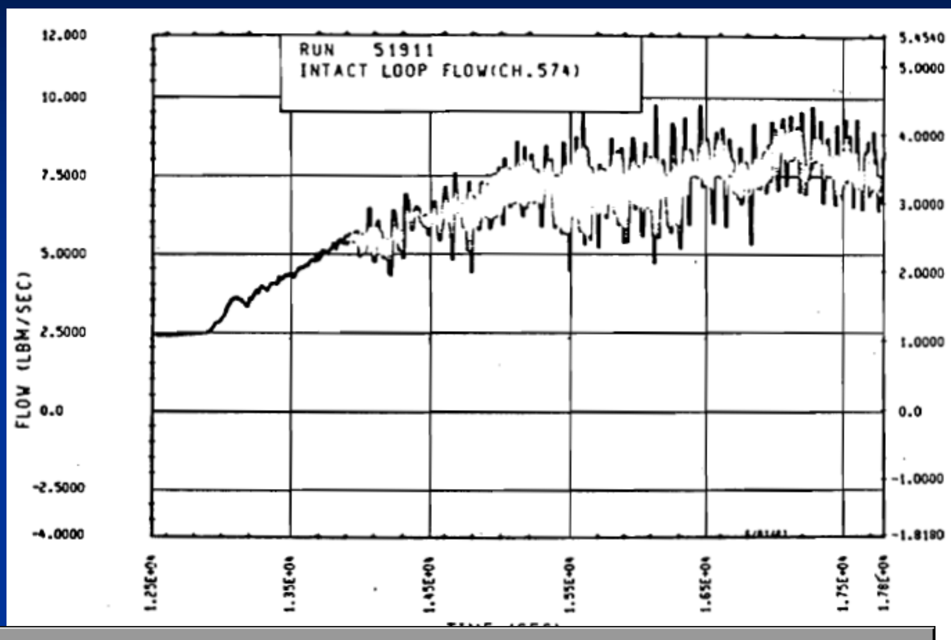
- Actual drawdown procedure is not specified.

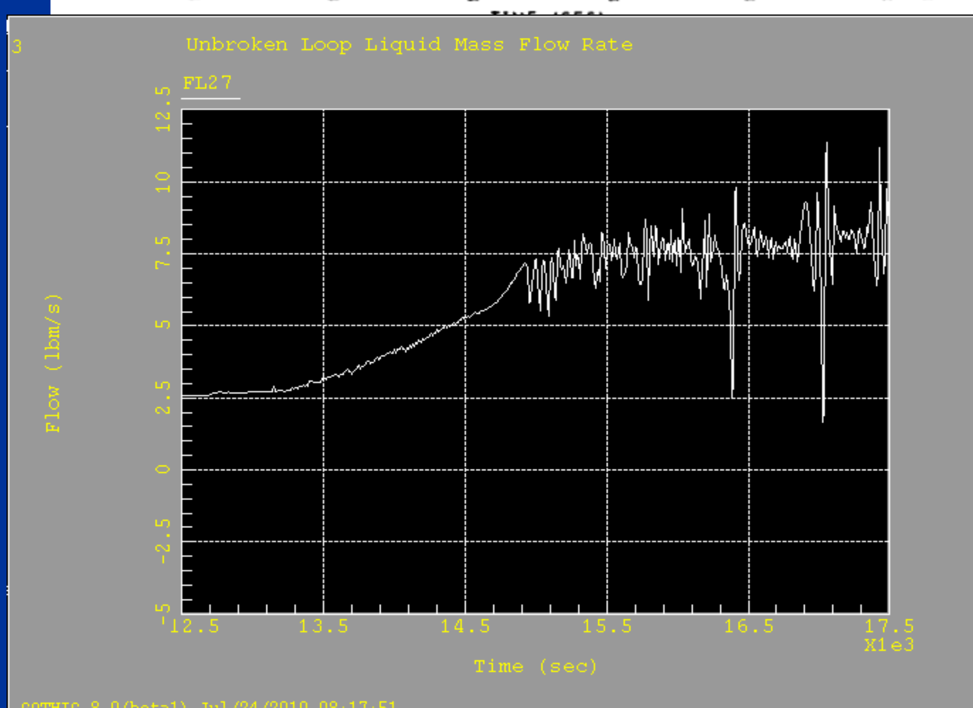
2-Phase Natural Circulation System Pressure





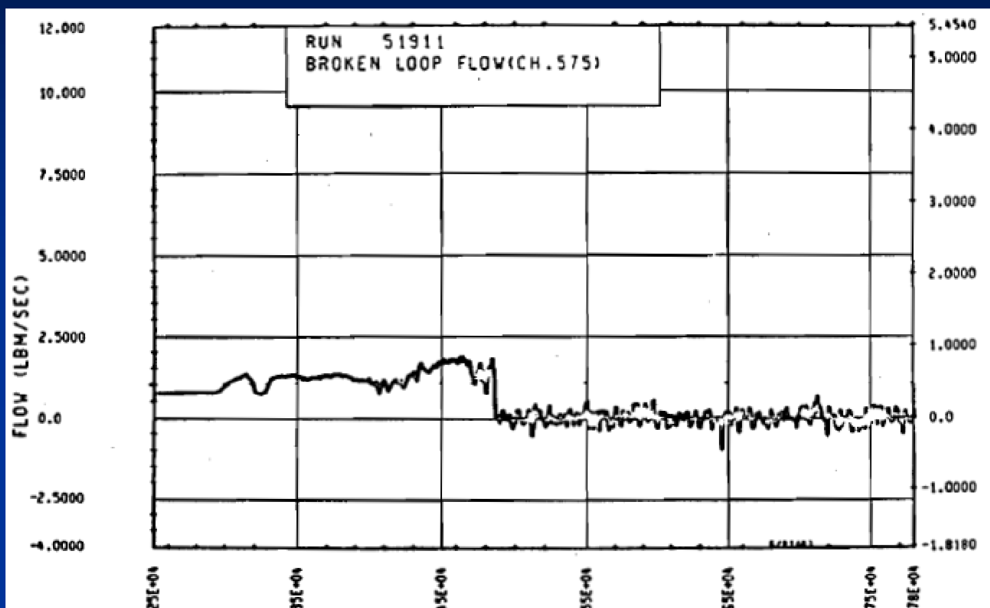
2-Phase Natural Circulation
Intact Loop Flow

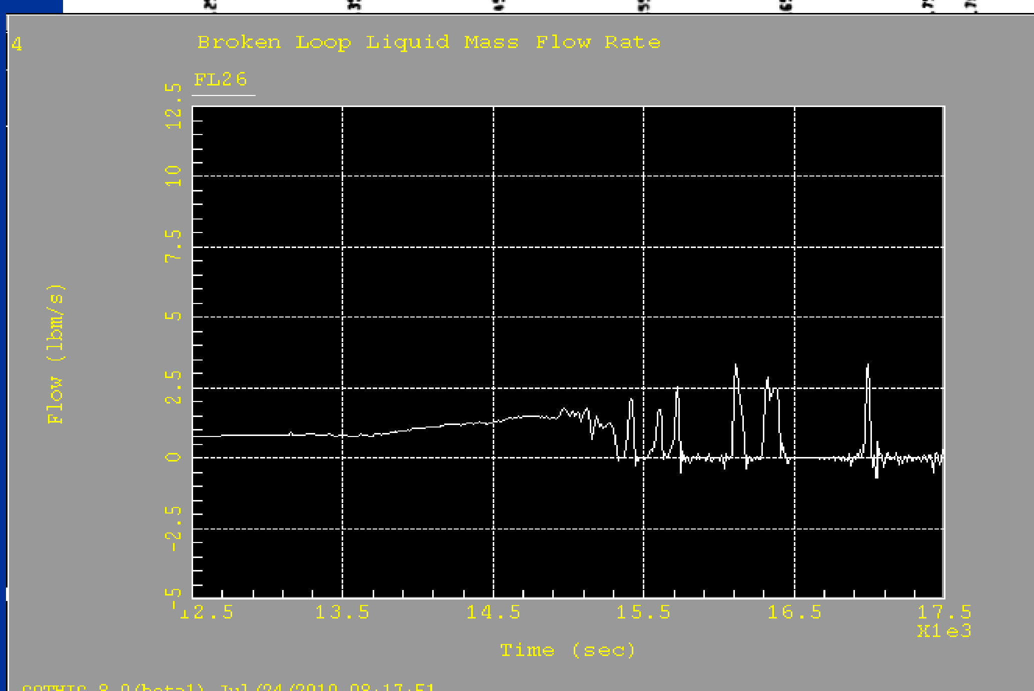




4

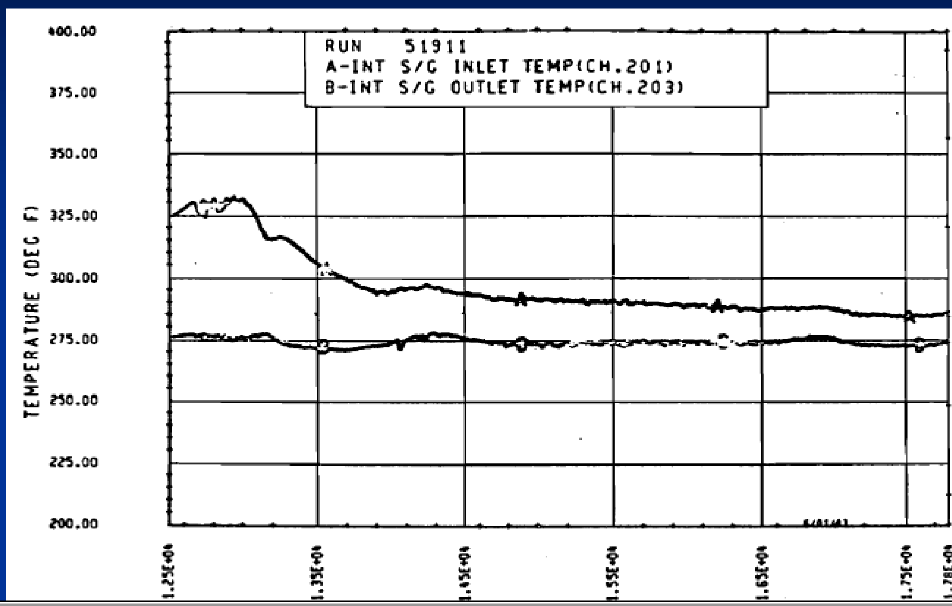
2-Phase Natural Circulation Broken Loop Flow

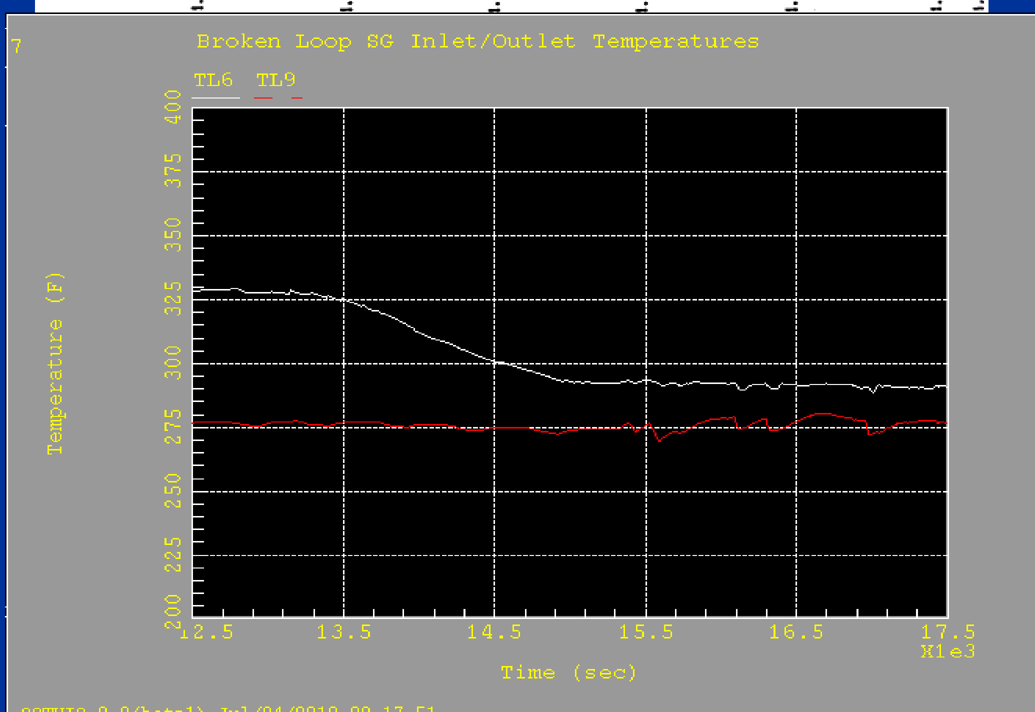




5

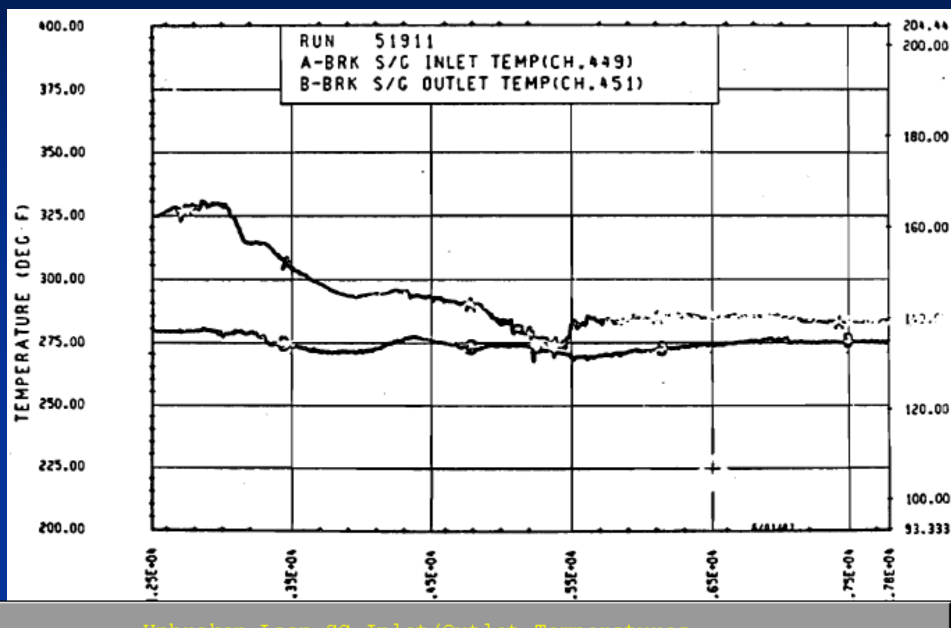
2-Phase Natural Circulation
Intact Loop SG Inlet/Outlet Temp.

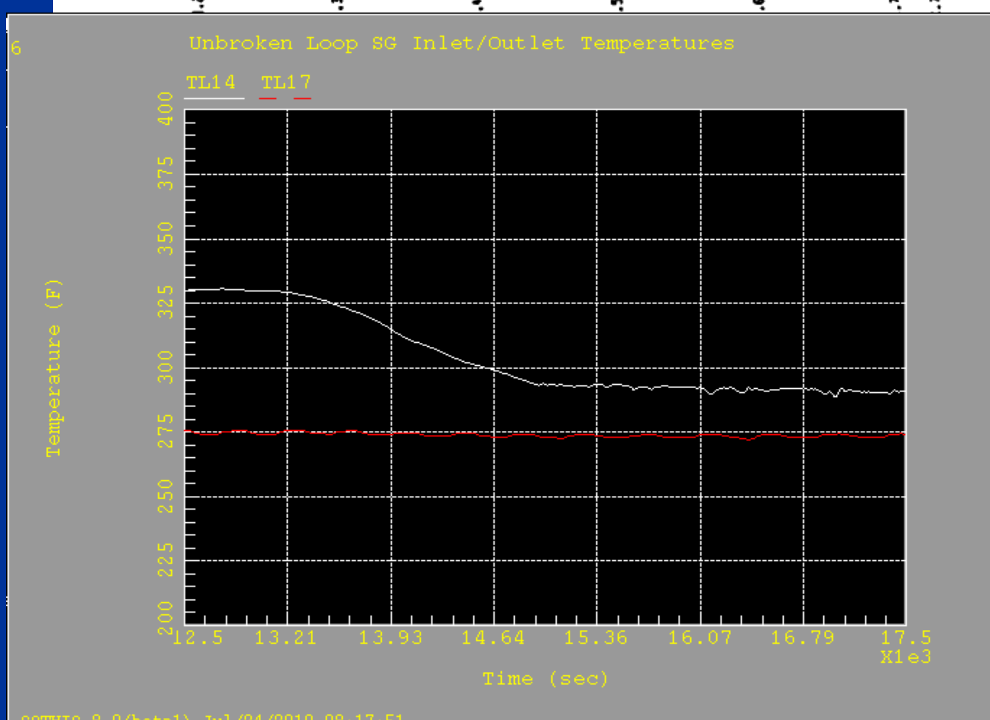




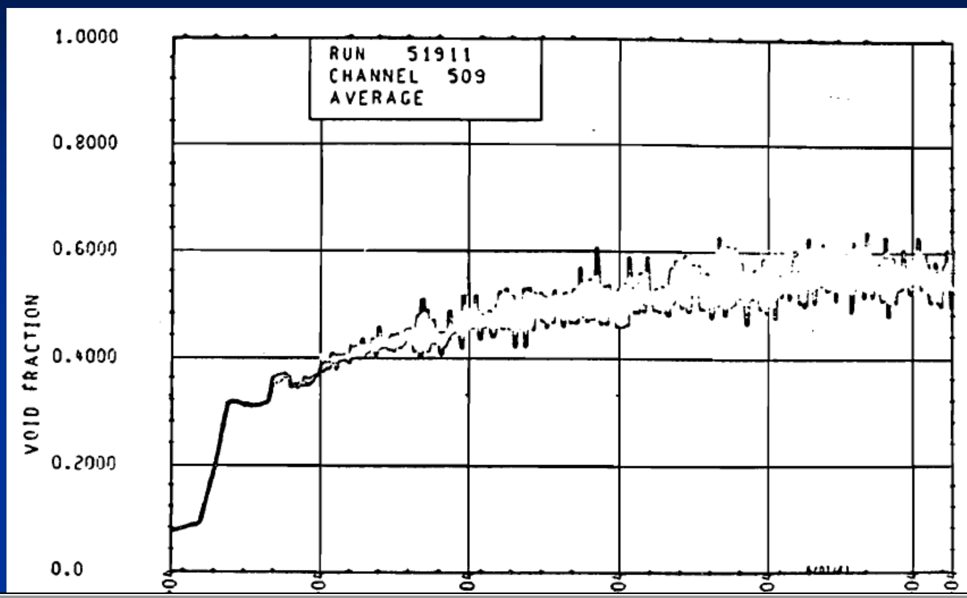
6

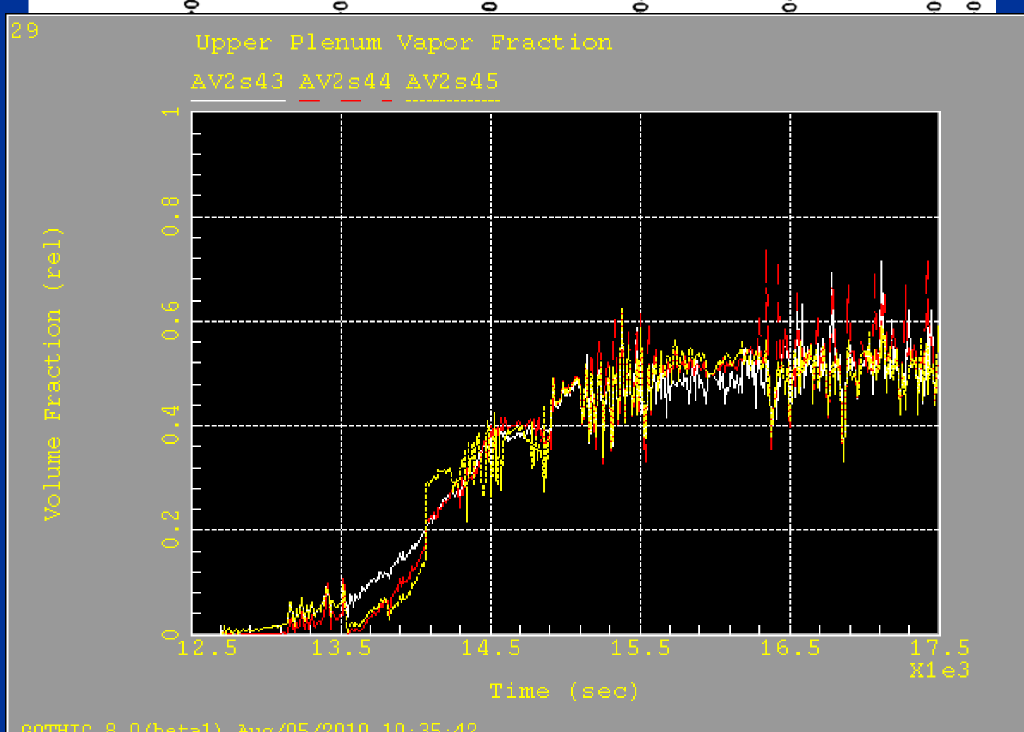
2-Phase Natural Circulation Broken Loop SG Inlet/Outlet Temp.





2-Phase Natural Circulation Upper Plenum Vapor Fraction

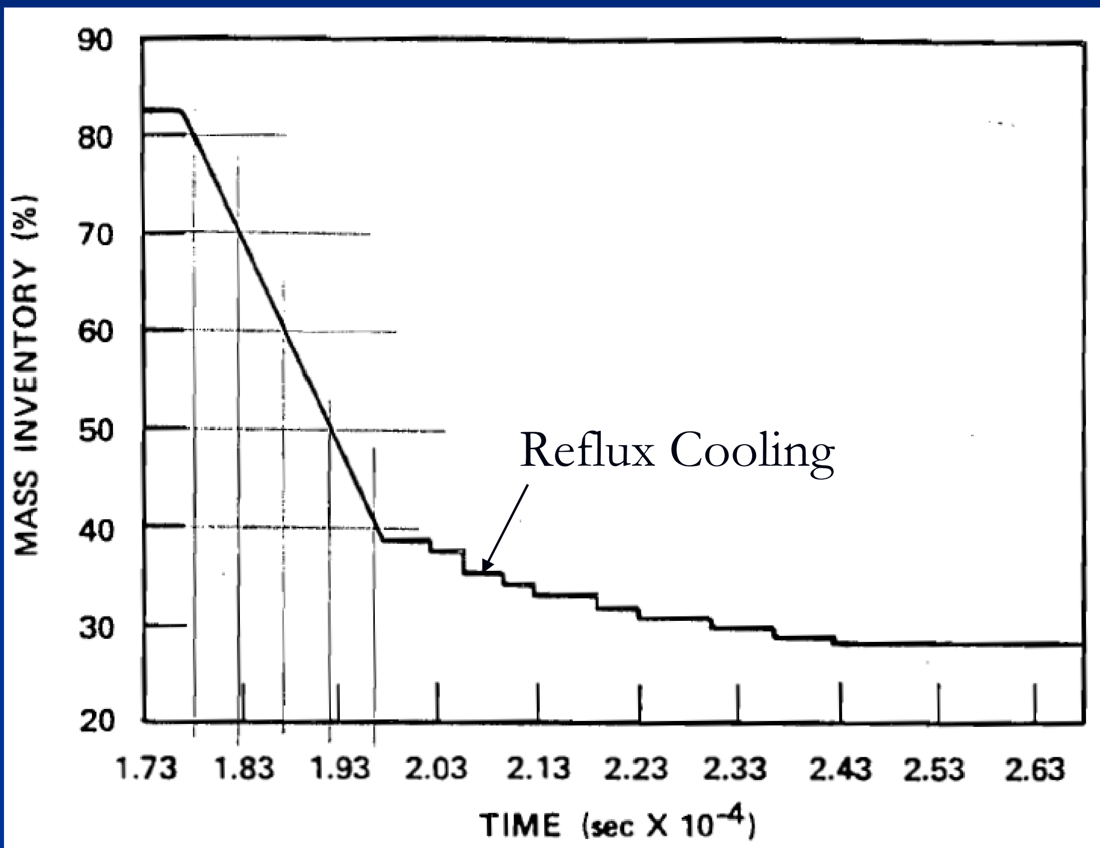




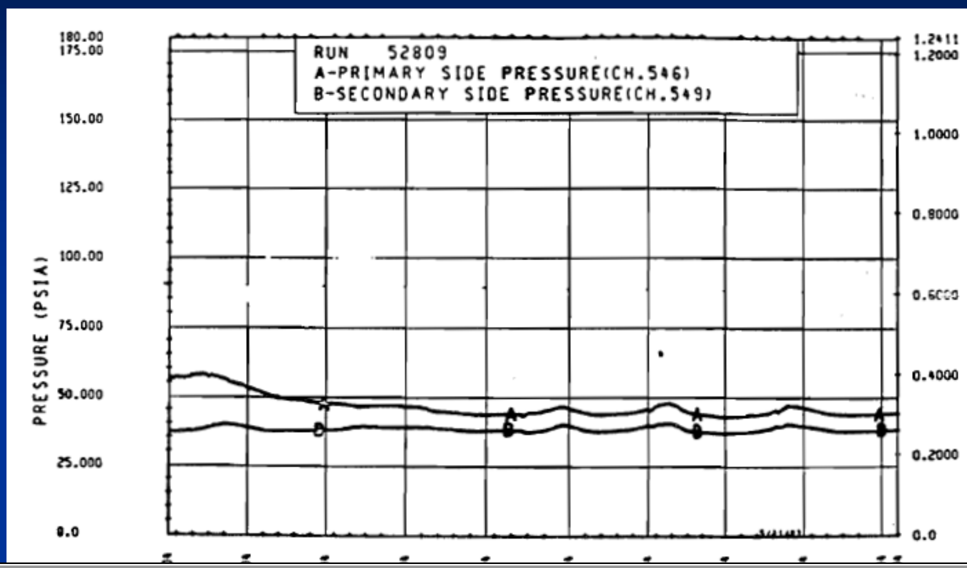
8

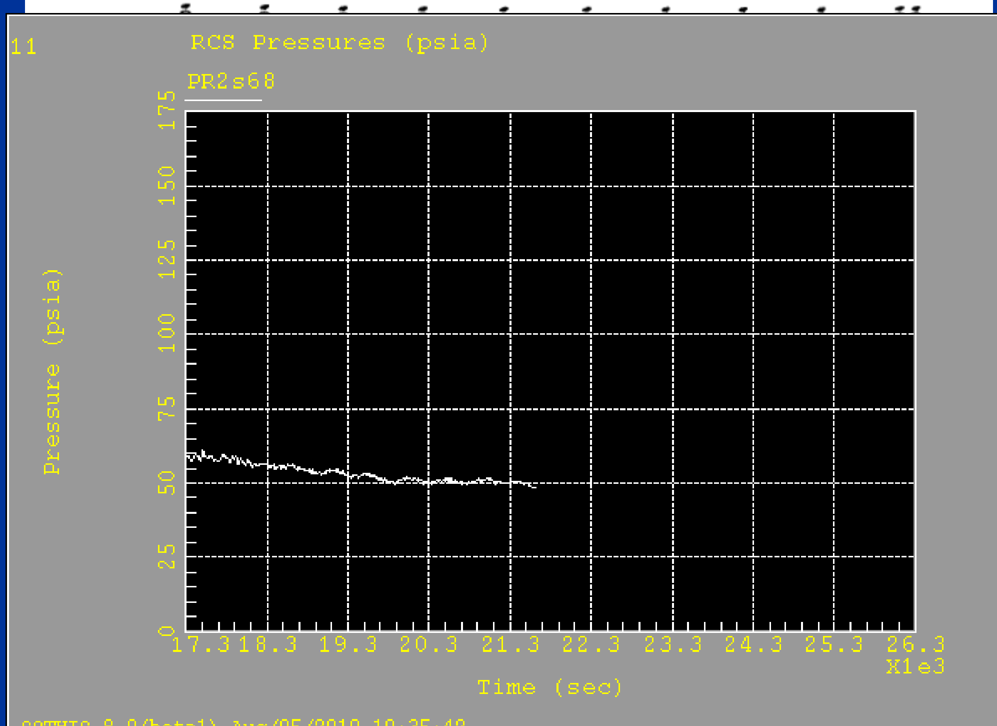
Transition to Reflux Cooling

- System Mass Inventory



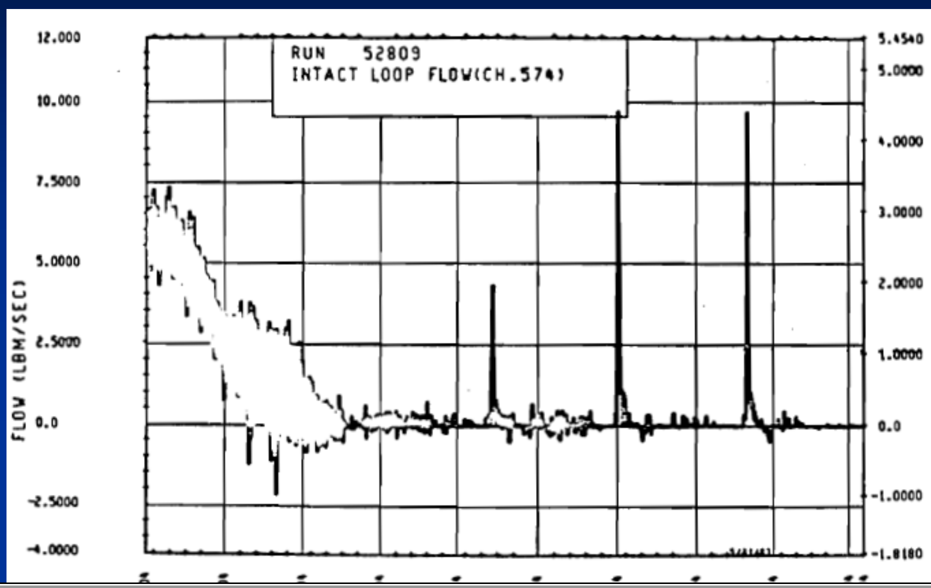
Transition to Reflux Cooling System Pressure

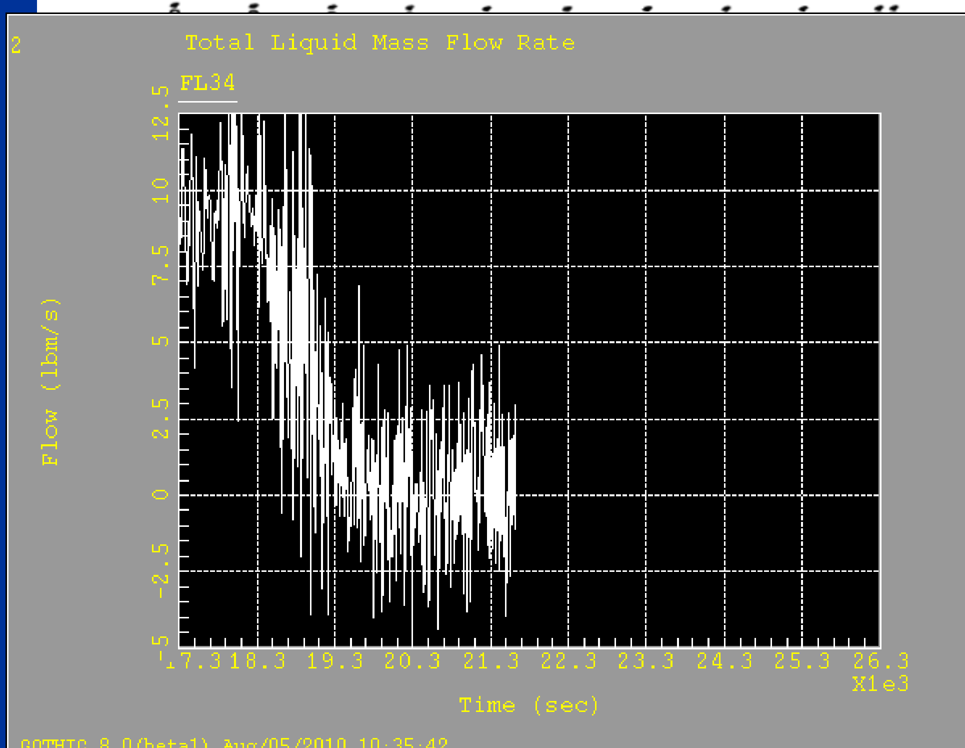




10

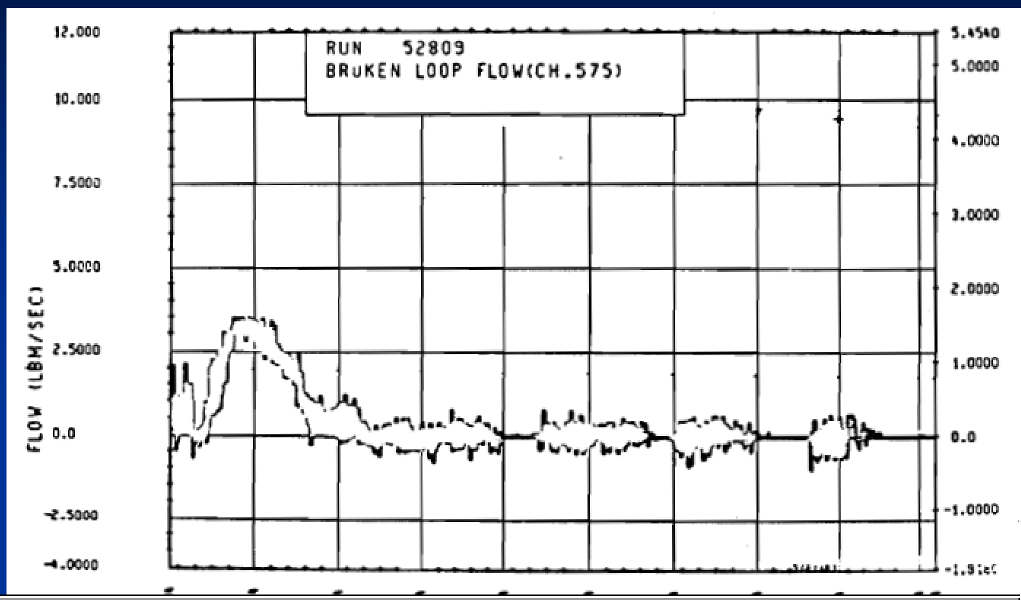
Transition to Reflux Cooling
Intact Loop Flow

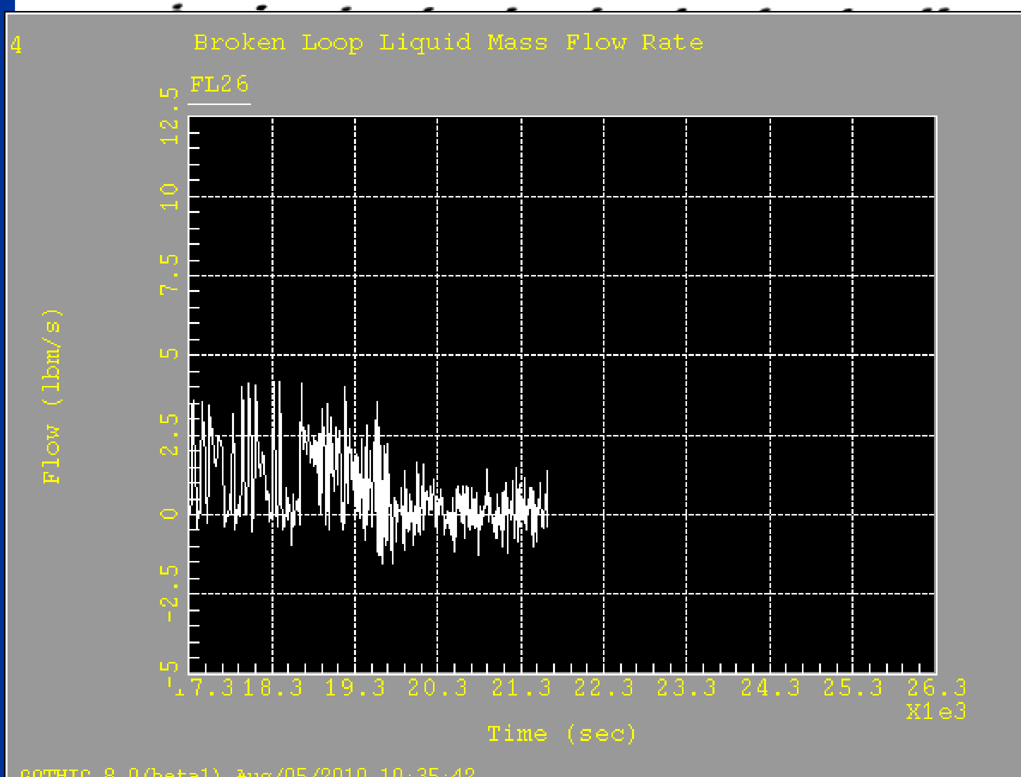




11

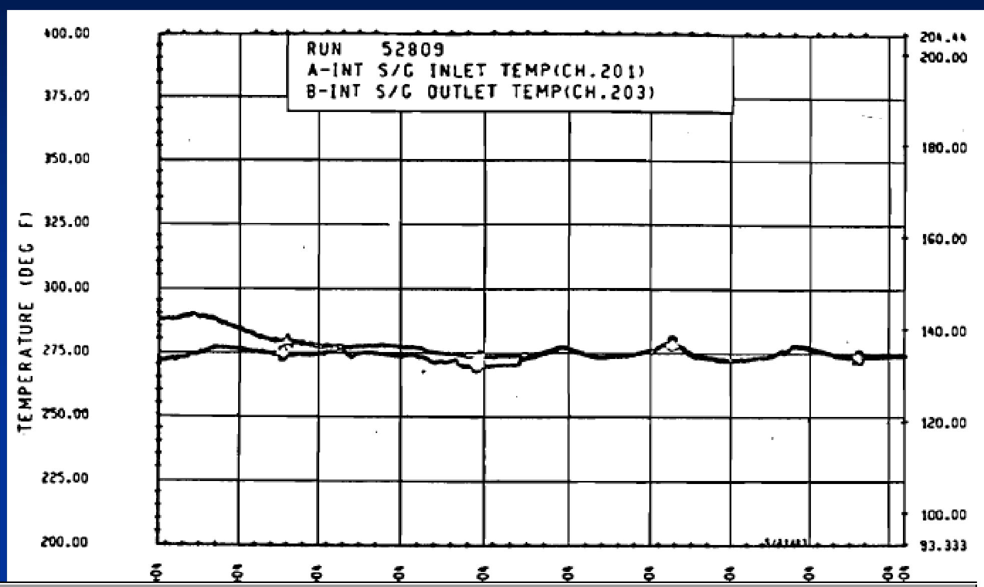
Transition to Reflux Cooling
Broken Loop Flow

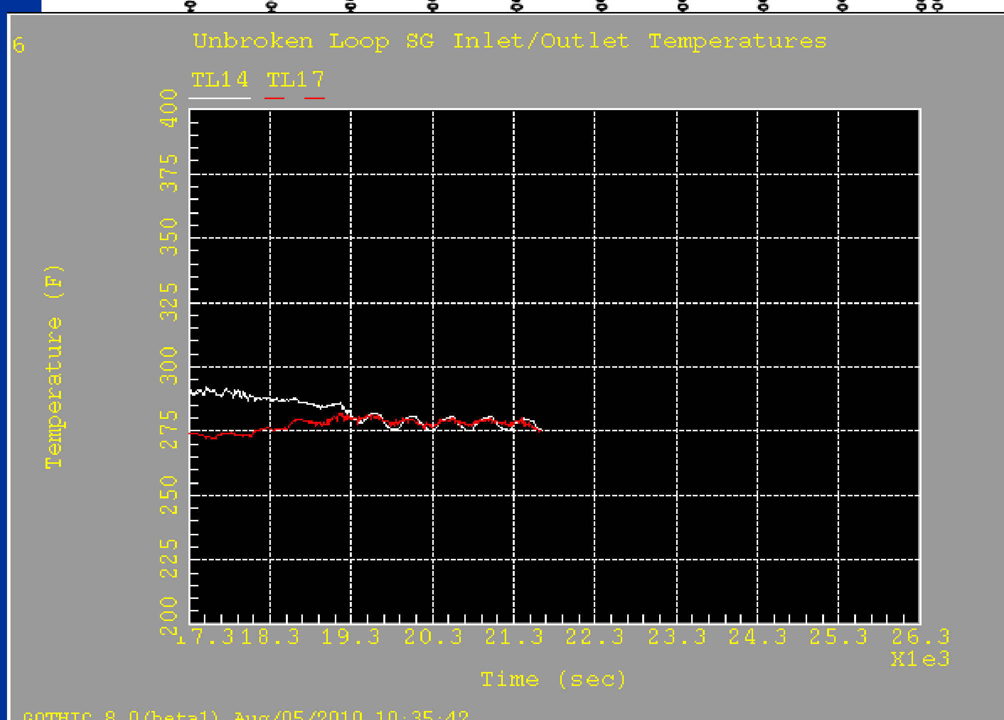




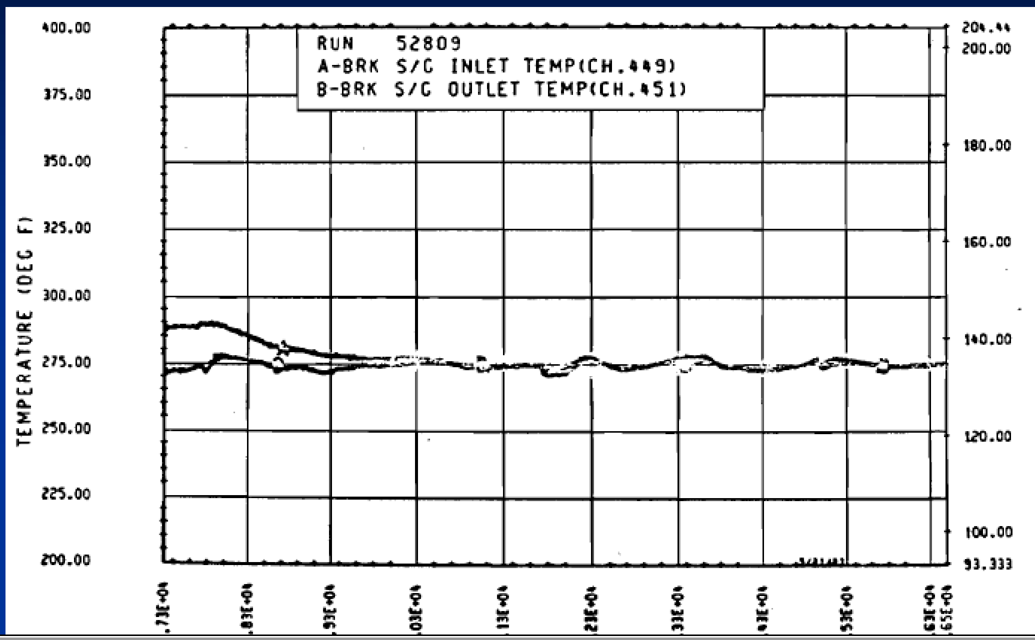
12

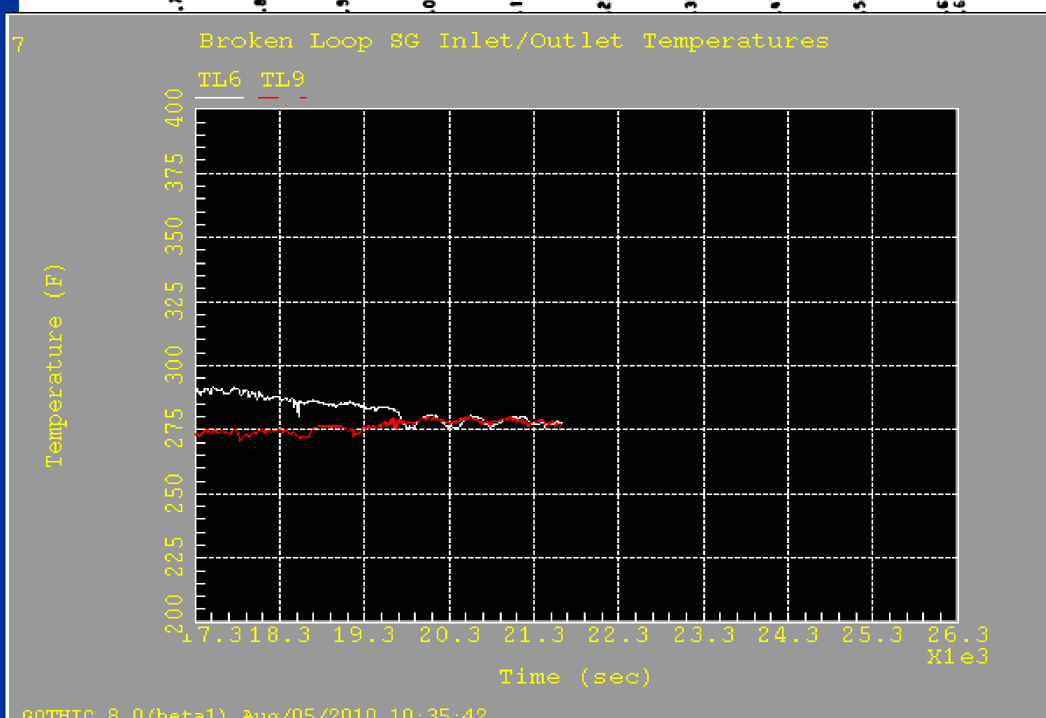
Transition to Reflux Cooling
Intact Loop SG Inlet/Outlet Temp.





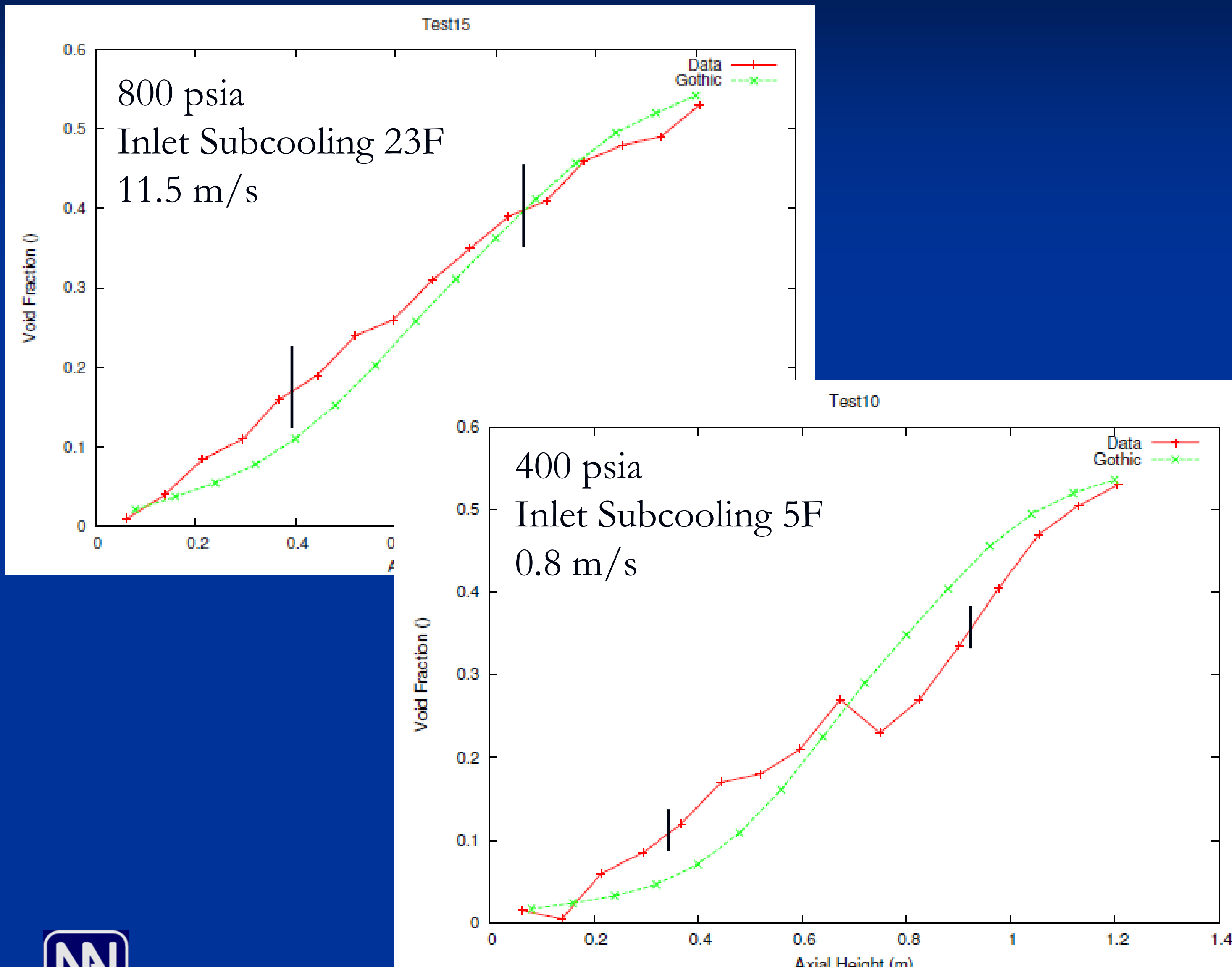
Transition to Reflux Cooling Broken Loop SG Inlet/Outlet Temp.

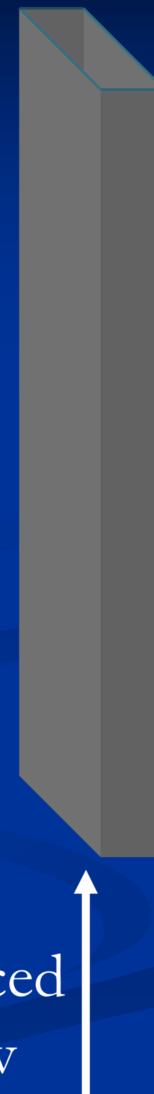




14

Christensen Heated Channel



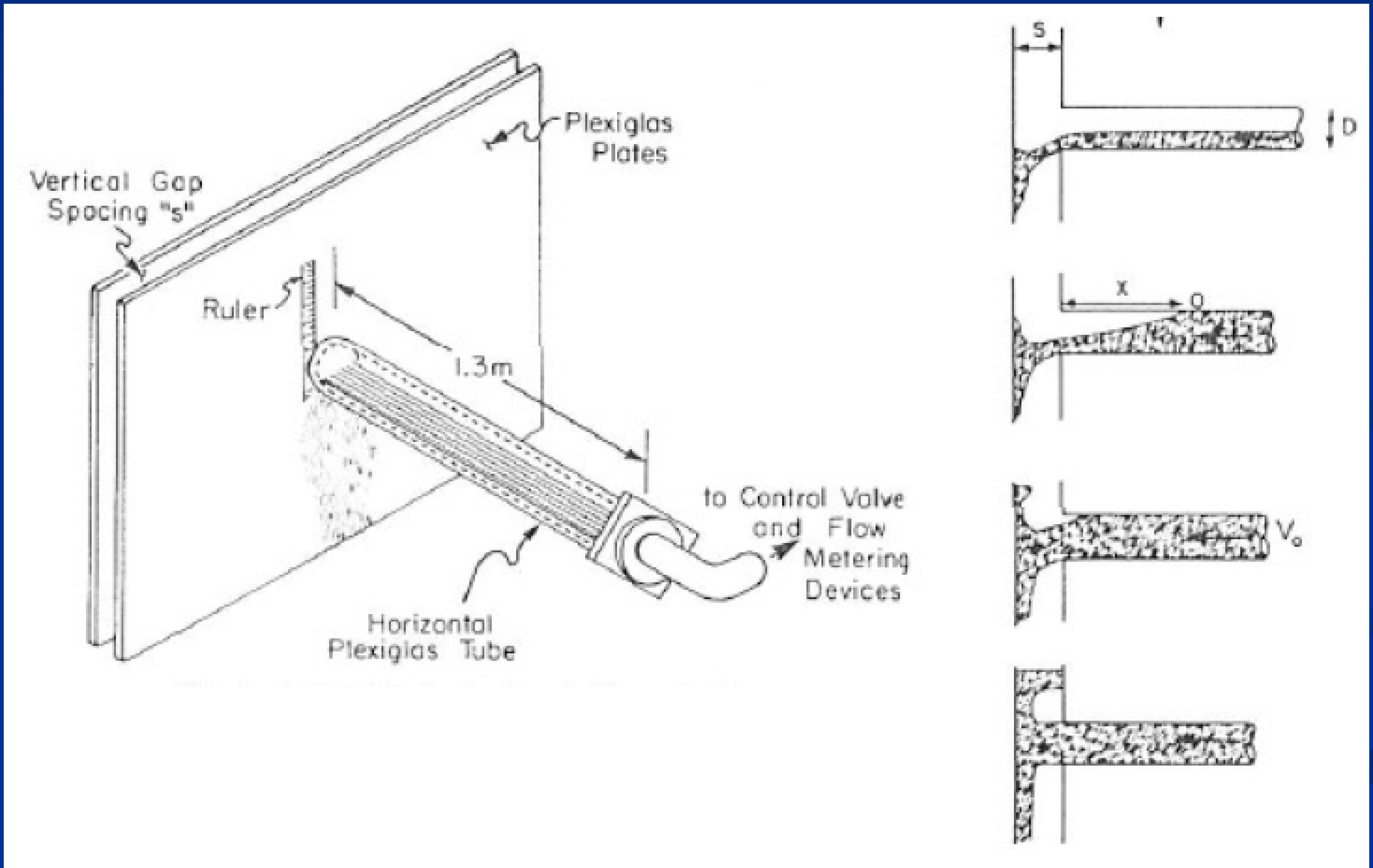


Forced Flow

Gas Transport

Horizontal Pipe Fill

Experiments by Wallis, Crowley and Hagi



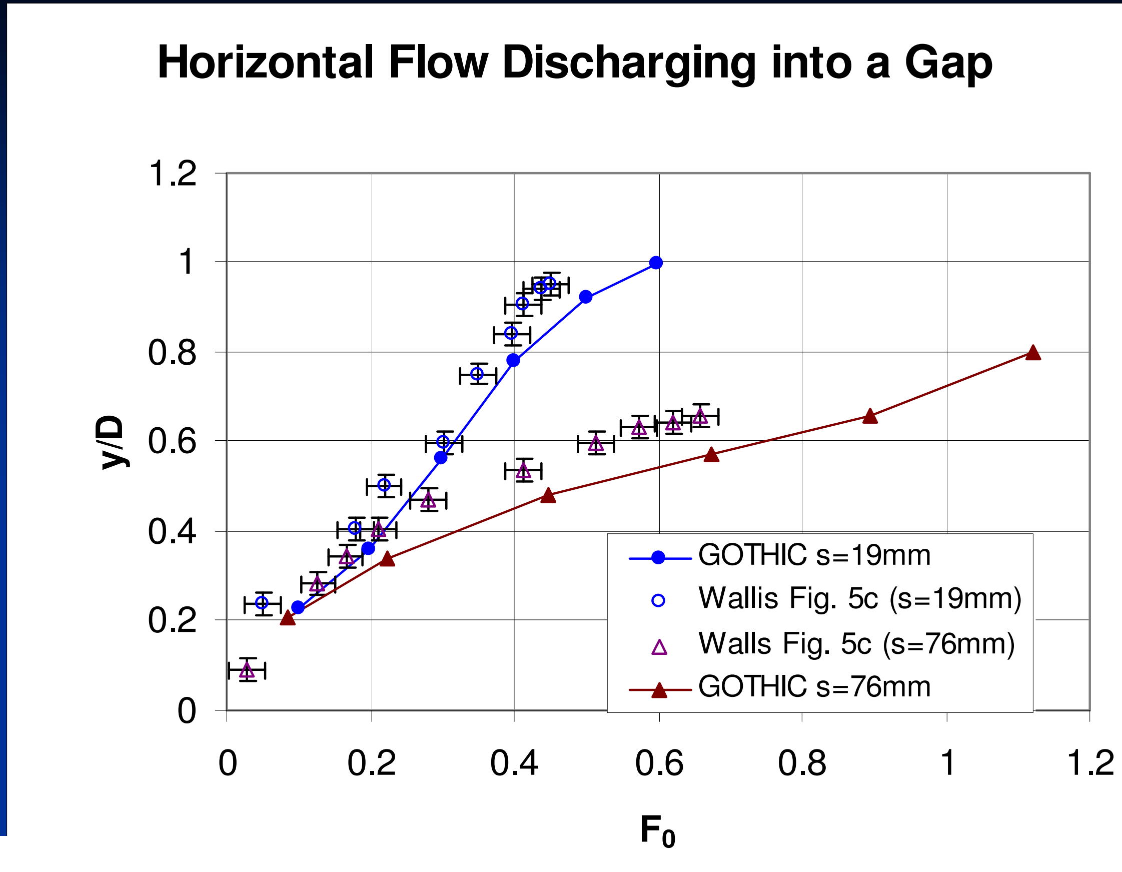
Horizontal Pipe Fill

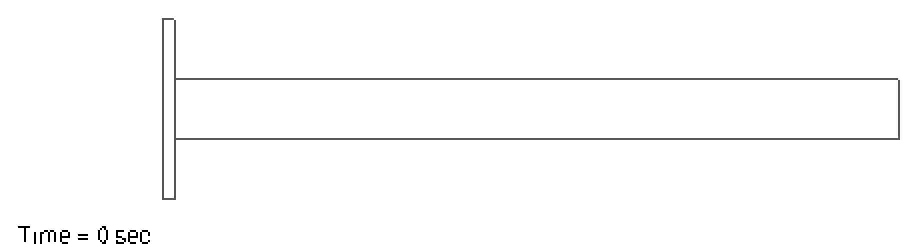
- Experiments by Wallis, Crowley and Hagi
  - Measured water depth at end of the pipe at various Froude numbers, pipe diameters and gap width.
  - Behavior is controlled by Froude number

$$Fr = \frac{U}{\sqrt{gD}}$$

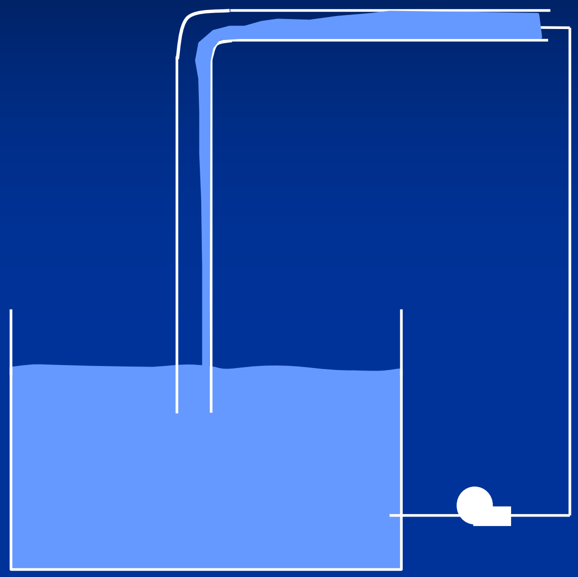
Horizontal Pipe Fill (Wallis)

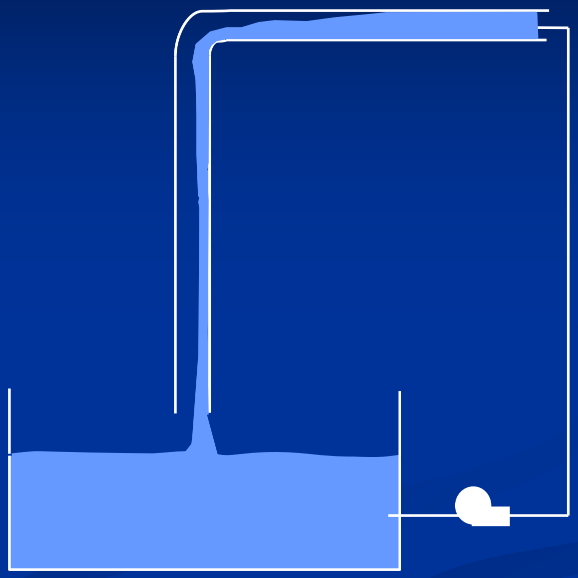
- 4” Pipe with ¾” Gap





Gas Entrainment

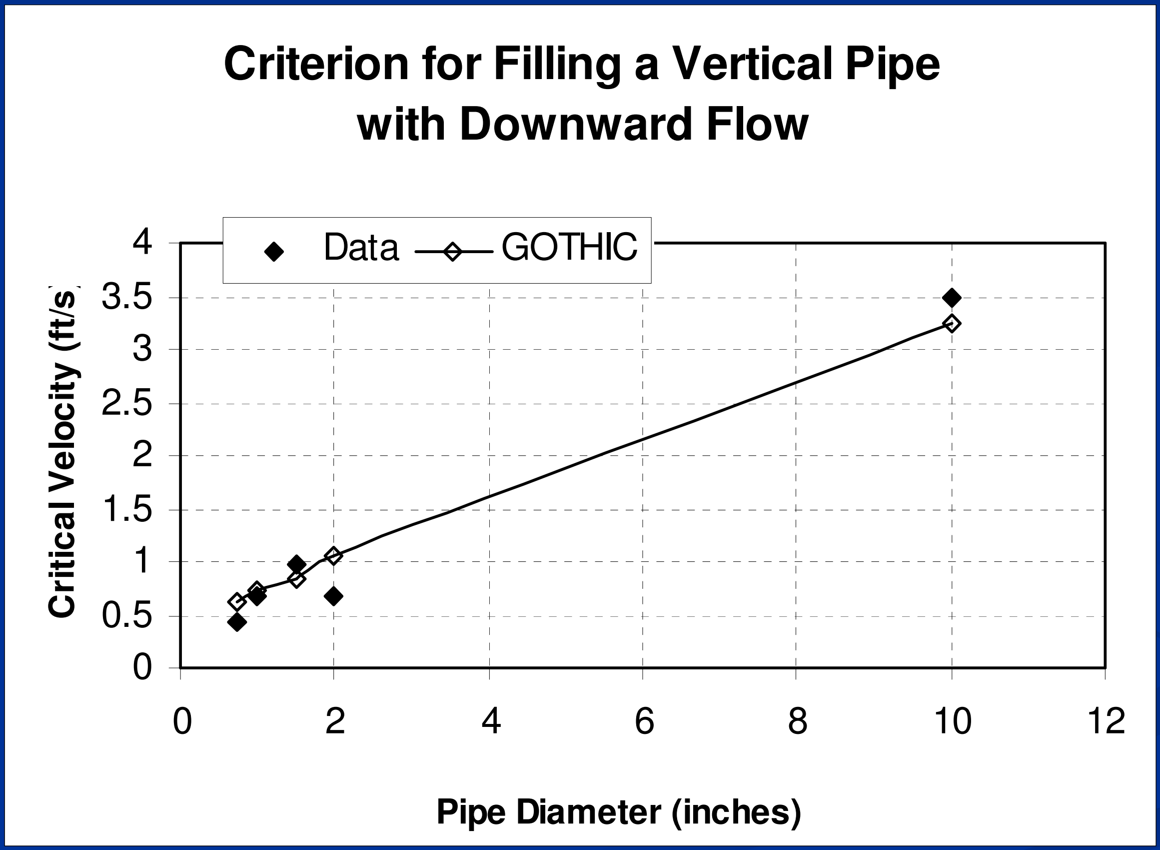




- Experiments by Krishnakumar and Fields
  - Measured flow rate at which vertical pipe fills with water.
- Experiments by Kelly
  - Measured flow rate required to maintain a siphon

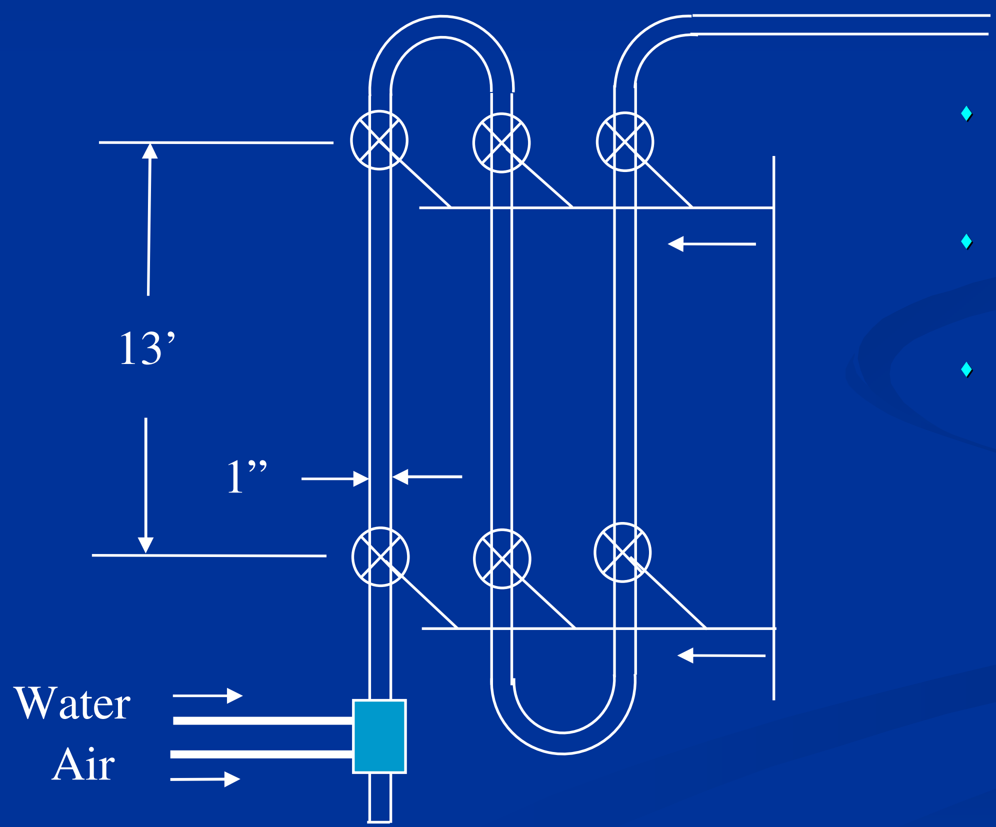
Interface Drag

- Filling a Vertical Pipe (Krishnakumar and Kelly)



Interface Drag - Validation

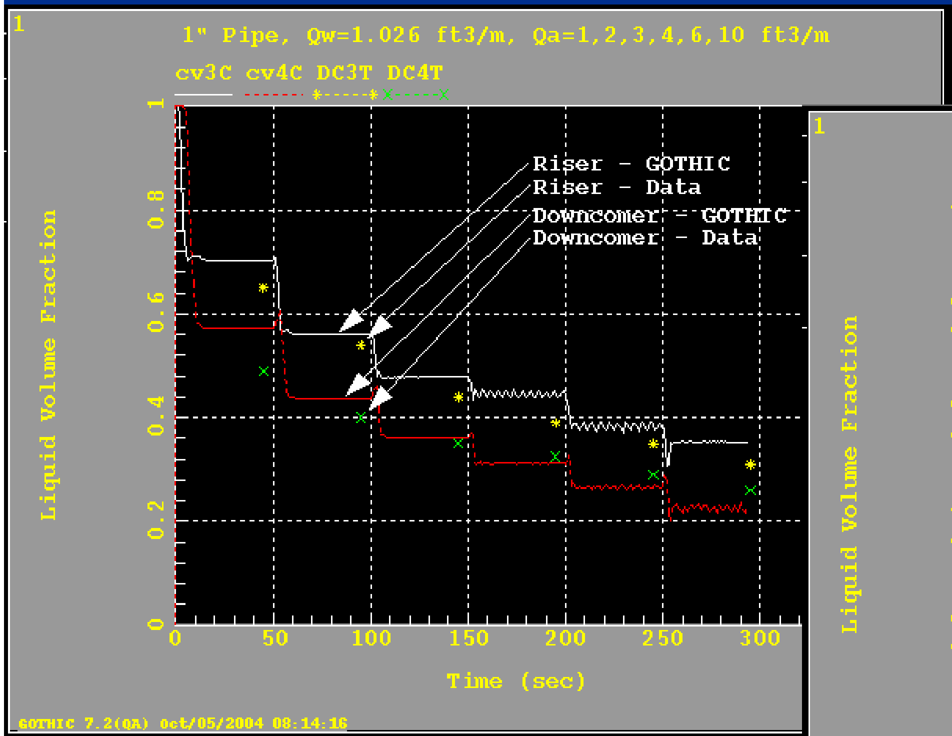
- Liquid Hold up in Vertical 2 Phase Flows (Oshinowo & Charles)



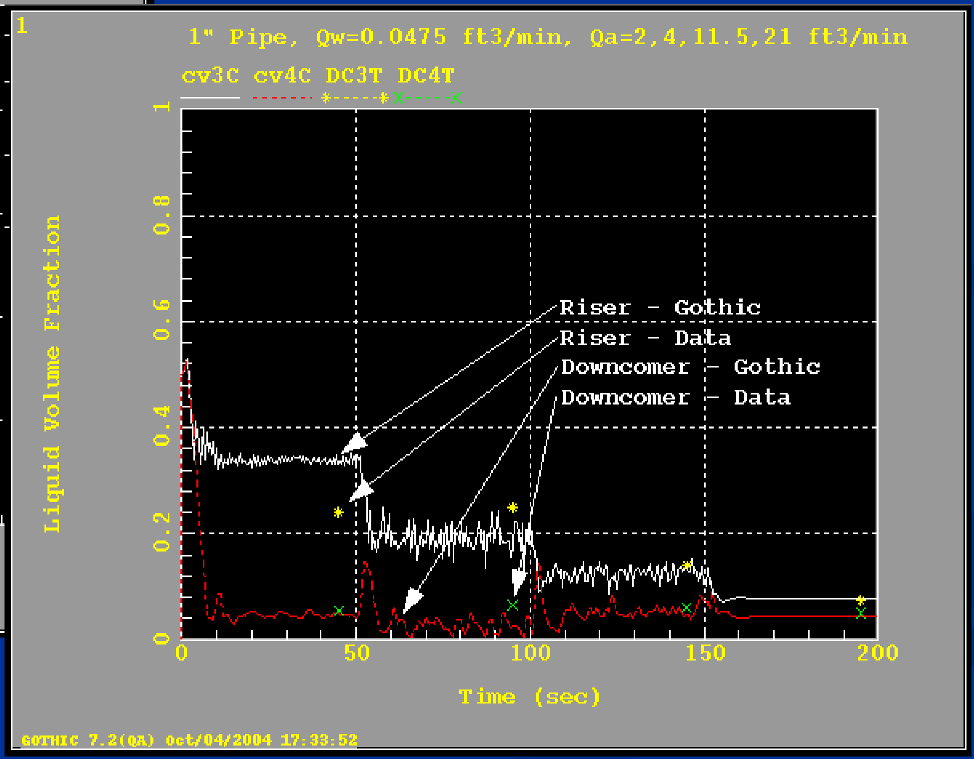
- Simultaneously close all valves
- Measure liquid levels
- Covered
  - Bubble Flow
  - Slug – Churn Flow
  - Film Flow

Interface Drag – Liquid Holdup

- High Liquid Flow (3.1 ft/s)
- Air velocity – 3 to 30 ft/s

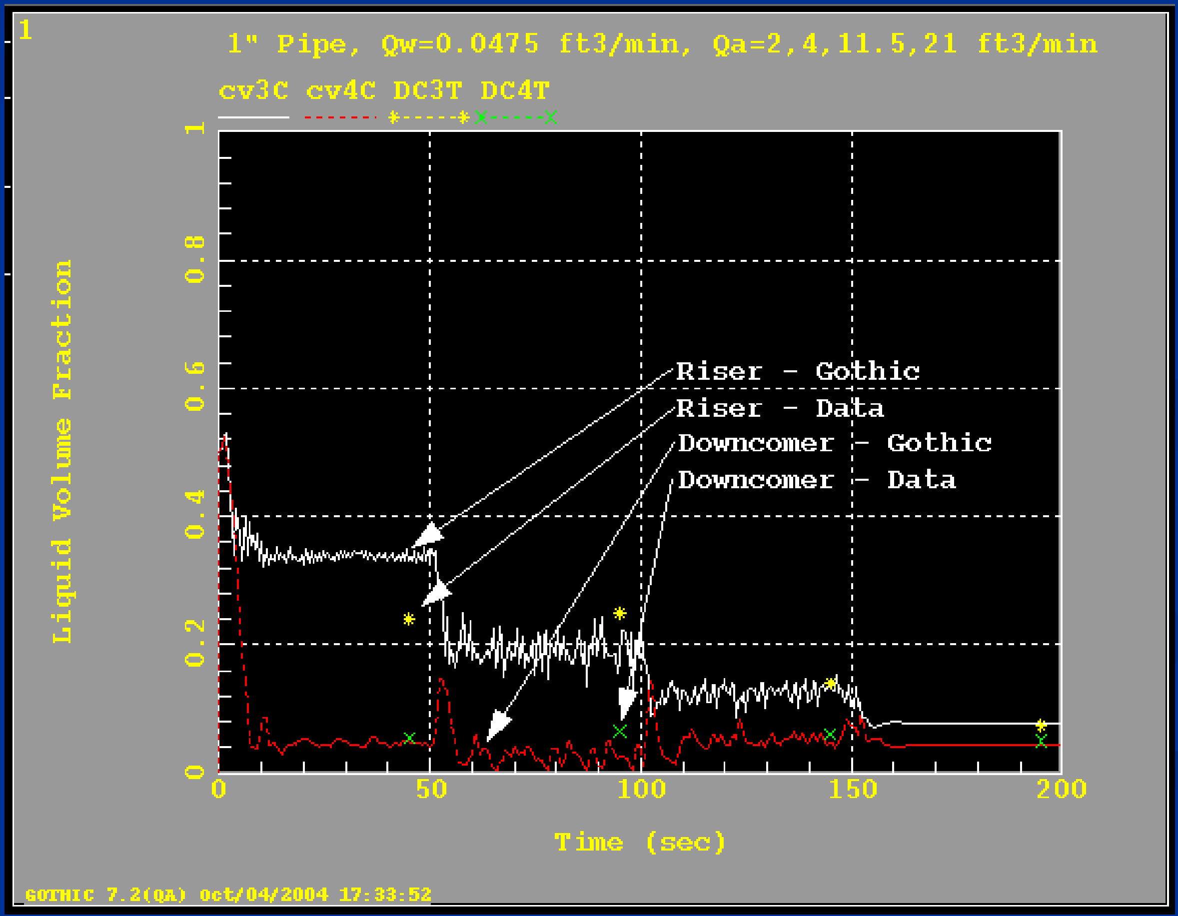


- Low Liquid Flow (0.15 ft/s)
- Air velocity – 6 to 63 ft/s

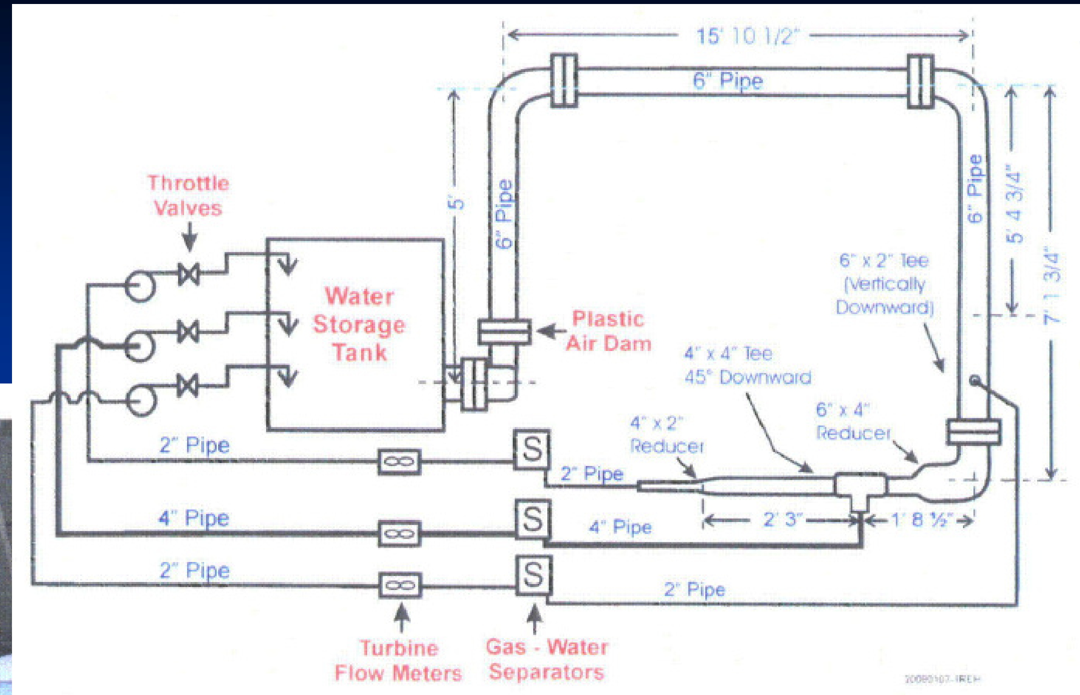


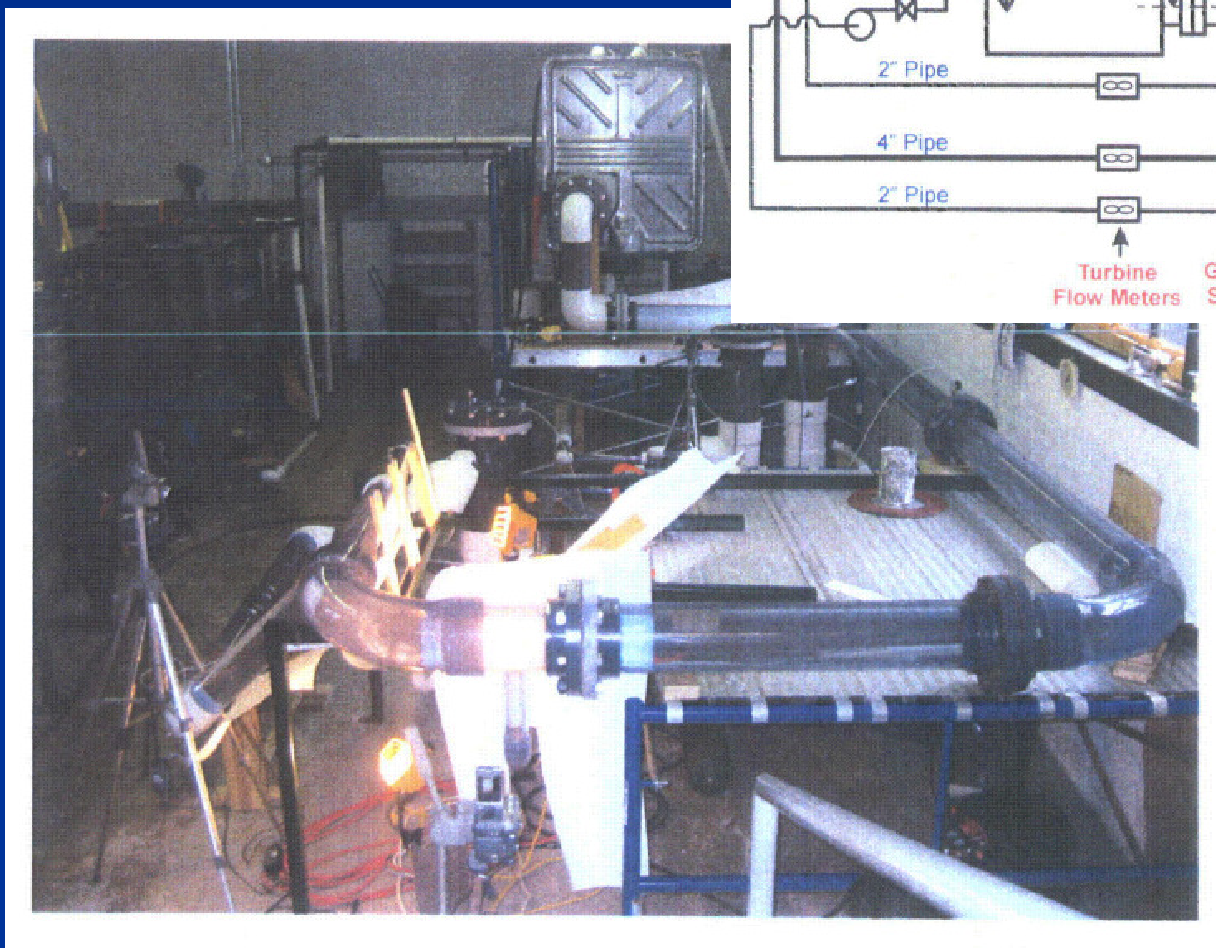
Interface Drag - Validation

- Liquid Holdup – Low Liquid Flow (0.15 ft/s)
  - Air velocity – 6 to 63 ft/s



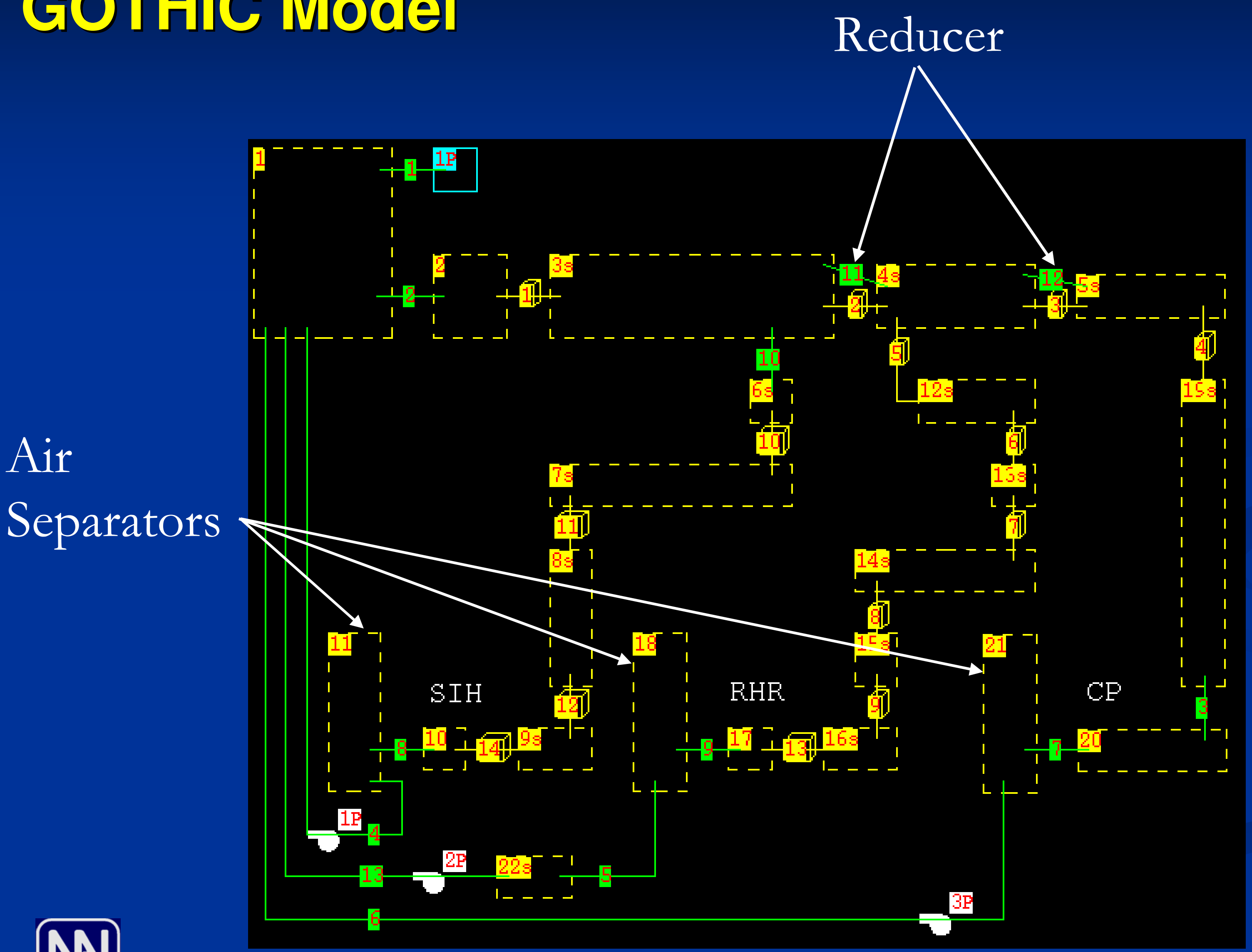
Gas Transport in Pipes



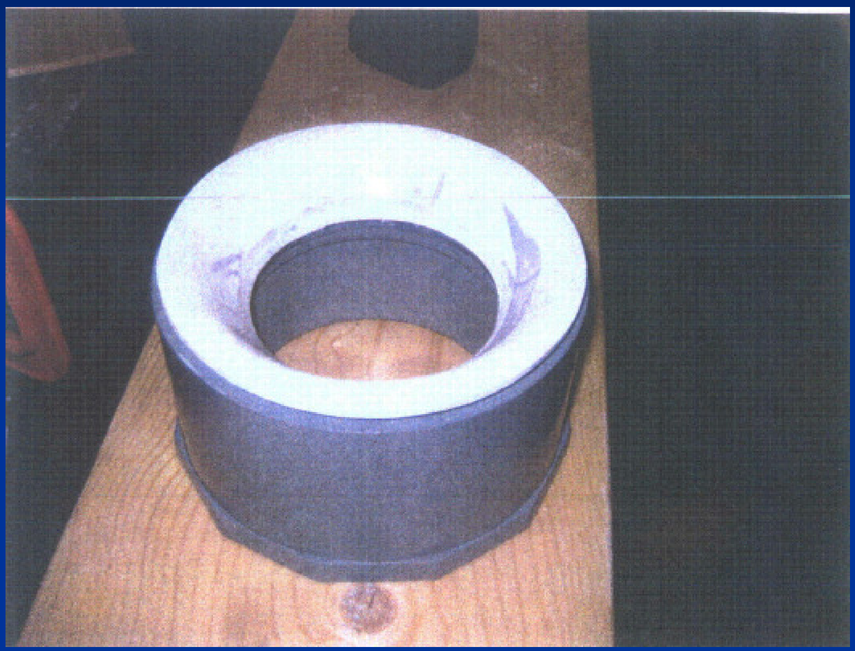


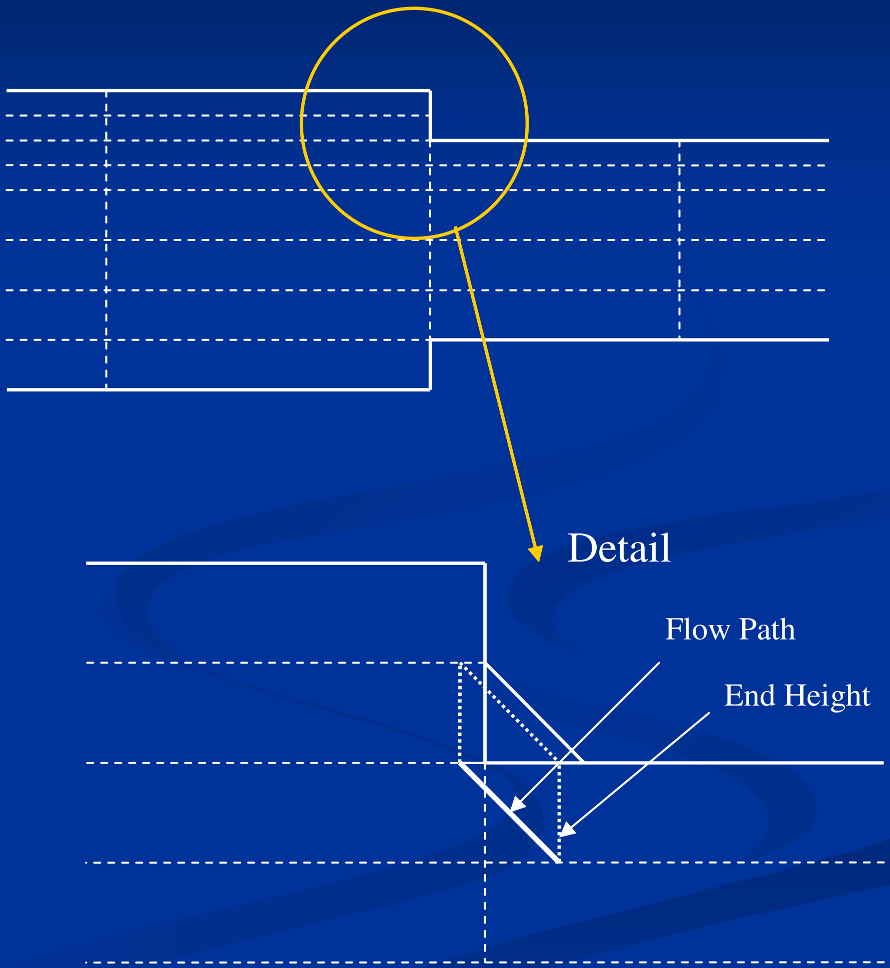
Millstone 3 Tests

Millstone 3 Tests GOTHIC Model



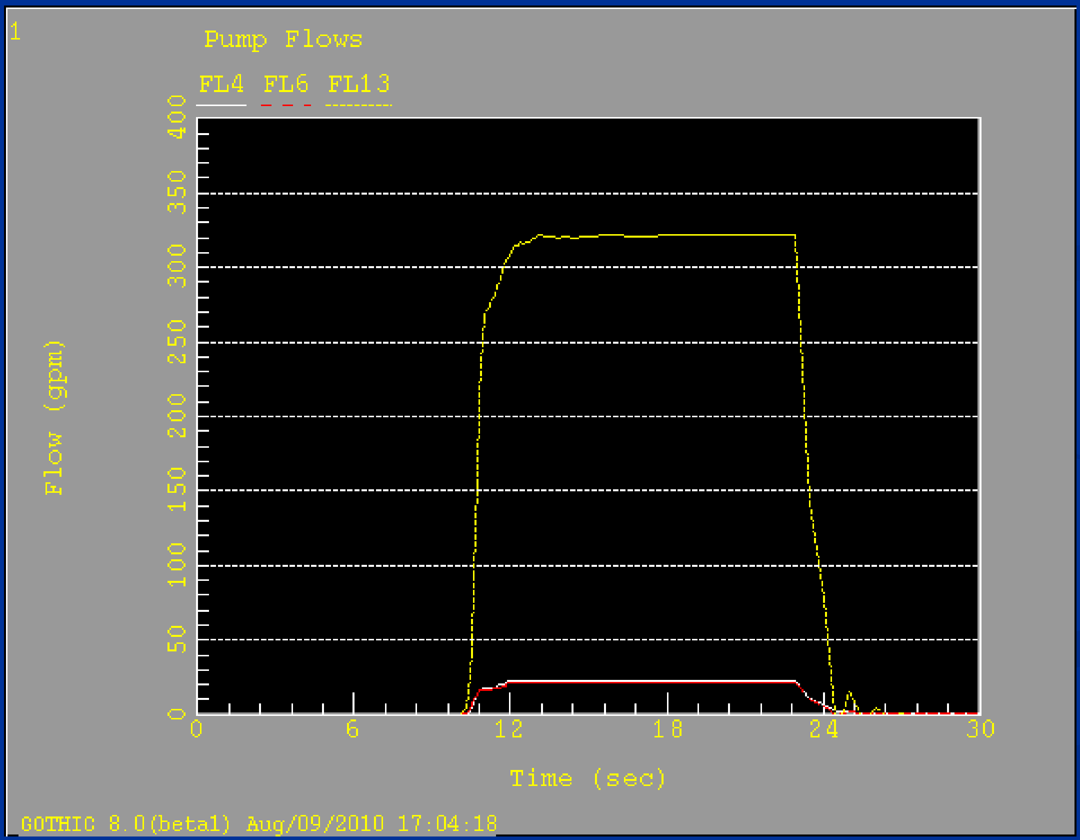
Millstone 3 Tests
Reducer Modeling



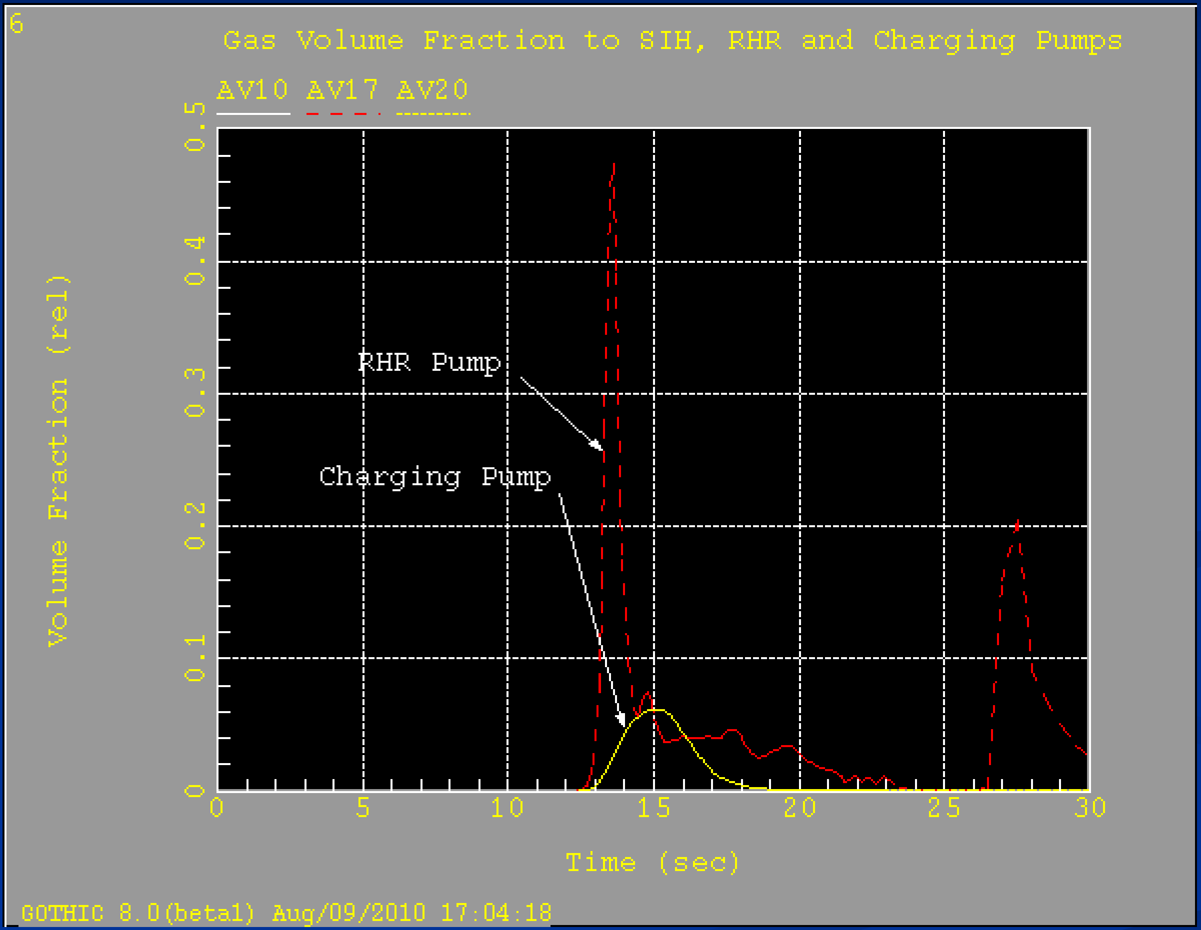


Millstone 3 Tests Case 1

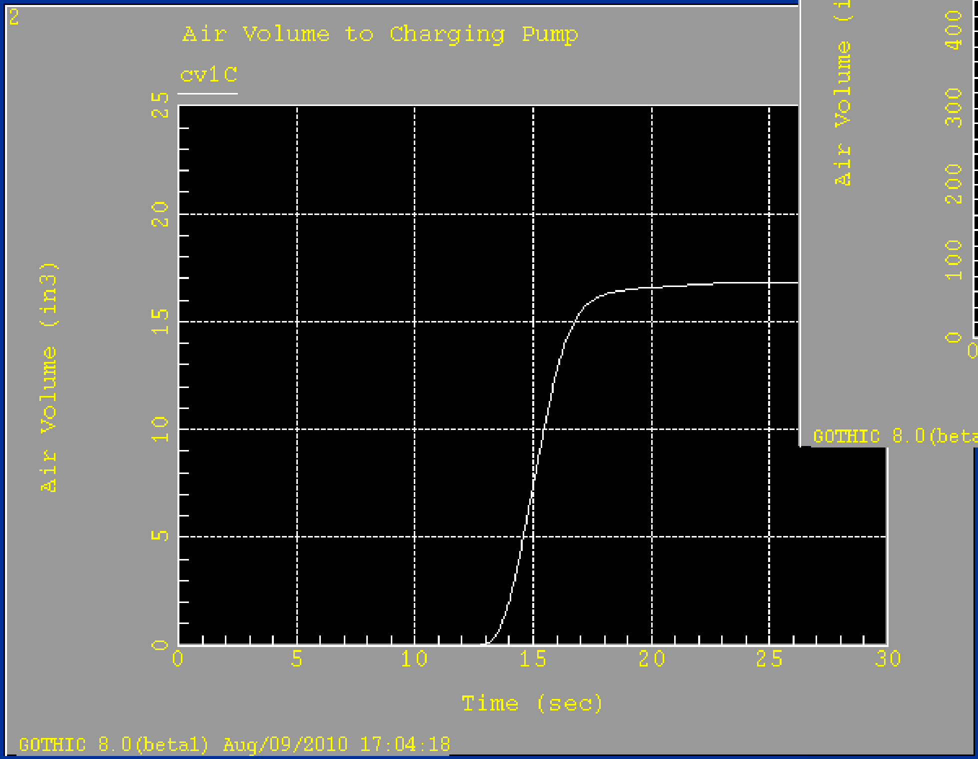
- Initial void – 8%
- Steady Pump Flows
  - RHR – 315 gpm
  - SIH – 23 gpm
  - CHRG – 22 gpm
- Pump start speed transient adjusted to match measured pump performance

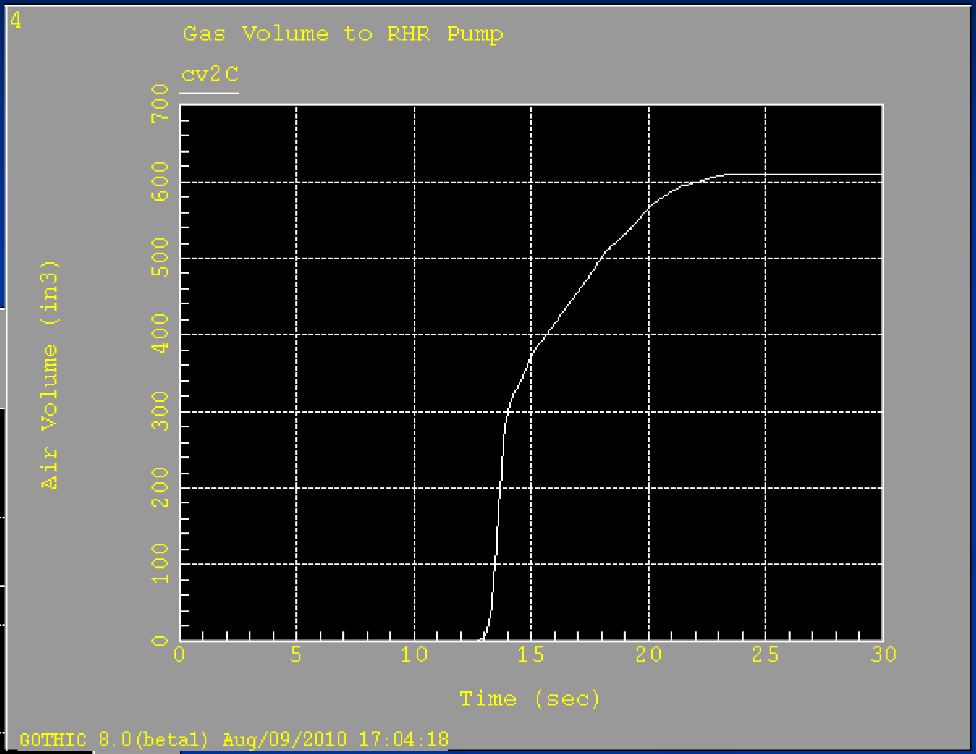


Millstone 3 Tests
Case 1



Millstone 3 Tests Case 1 – Integrated Gas Volume





Millstone 3 Tests

Case	Initial Void (%)	Pump Flows (gpm)			Gas Transport (in^3) measured/calculated		
		RHR	SIH	CHRG	RHR	SIH	CHRG
1	8	315	23	22	na/620	0/0	8.6/16.8
9	8	170	24	21	na/460	0/0	30.1/40.3
10	8	97	24	21	na/420	0/0	98.9/83.1
11	5	0	27	22	0/0	0/0	0/5.3
12	8	0	27	22	0/0	0/0.2	30.1/35.7
21	8	0	25	55	0/0	0/0	393/320-470*

*Pump run time unknown

Purdue Gas Transport Tests

- Used to support plant specific evaluations for plants with access to data.
- Gas Transport through vertical elbows, horizontal and vertical pipe runs.
- 6" and 8" pipe
- Varied Froude number and initial void size.
- Validation Results (proprietary) completed in June 2009.

Purdue Gas Transport Tests

- Tests for 6” and 8” systems were simulated.
- Noted Data Inconsistencies
  - The pressure and flow test data is not consistent with the specified start time for opening the initiating valve .
  - Flow measurements appear inconsistent with the pressure response
    - For simulations, the flow start time was adjusted to be consistent with the time that the pressure begins to fall.

Purdue Gas Transport Tests

- Cases considered
  - D = 6”, 8”
  - Void = 10%, Fr = 0.8
  - Void = 20%, Fr = 1.65
- Predicted void inlet is generally higher than measured.
  - For one 8” case the predicted pump inlet void is substantially lower than measured. The measured value is not supported by other measurements or the test specification.
- Data for 4” and 12” cases will be provided by a PWROG utility to support plant analysis.

Other Tests

- Passive Spray Dousing System for CANDU Vacuum Building
- AECL Whiteshell Large Scale Gas Mixing Facility Tests
- AECL Large Scale Containment Facility Test
  - Gas Mixing and Condensation
- Intermittent Buoyancy Induced Flow (IBIF) cooling for CANDU fuel bundles in a stagnant channel
  - Metastable boiling and venting in a heated horizontal bundle
- UPTF – in progress

Comments on Validation

- Modeling to give best estimate analysis
  - Neither GOTHIC nor input is biased to give conservative results
- Input is generally consistent with modeling guidelines
- Deviations from measurements
  - GOTHIC shortcomings and uncertainty in models and correlations
    - Difficult to quantify – especially for multiphase flow
  - Using single code to model a very wide range of conditions
  - Experimental Uncertainty
    - Measurement uncertainty is usually known
    - Specification uncertainty
      - Repeatability of the experiment from the information available to modelers
        - Important factors may be overlooked
      - Probably larger than measurement uncertainty in many cases

Summary

- Validation covers a wide range of single and two-phase flow situations
- Wide range applicability hinges on capability to simulate fundamental phenomena
  - Interphase heat and mass transfer
  - Interphase drag
  - Momentum dominated flow
  - Gravity dominated flow
- Code results are generally in good agreement with data
- Controlled code versions under NAI QA Program
  - Validation repeated for each code version