ESBWR Technology Program: Test Programs

Robert Gamble

NRC Staff - GE Meeting
June 20 and 21, 2002
Rockville, Maryland

Outline

- ***SBWR Technology Program***
- ***ESBWR Containment Modifications from SBWR***
- ***ESBWR Technology Program***
- ***Conclusions***

Extensive Technology Program for Features New to SBWR

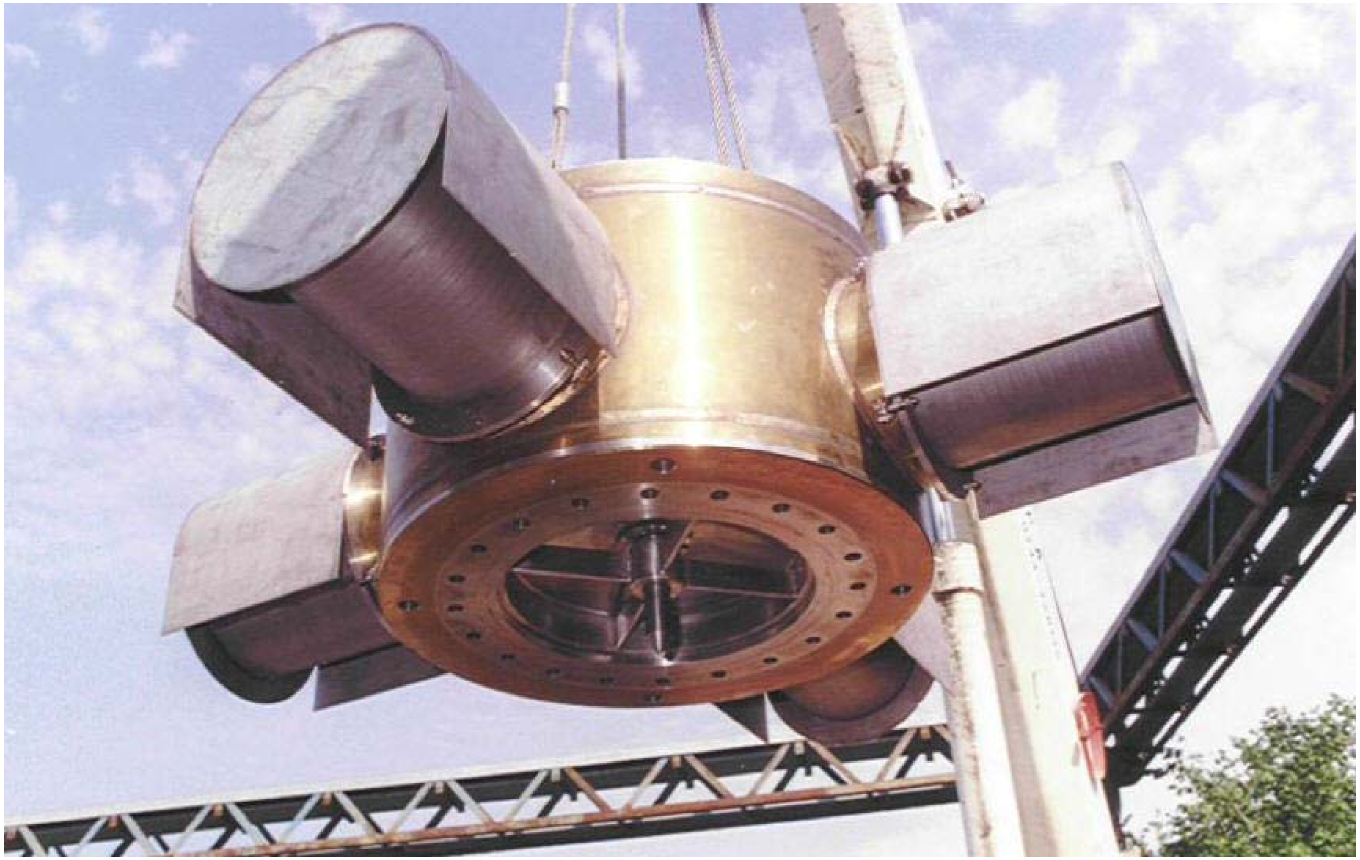
- ***Component tests***
  - Full scale components tests – DPV valves and vacuum breaker
  - Full scale isolation condensers & PCCS heat exchangers,
- ***Integral tests***
  - Integral tests at different scales – 1/400 to 1/25
  - System interaction tests
  - Large hydrogen releases
- ***Testing used to qualify computer codes***
- ***Extensive international cooperation***
- ***Extensive review and participation by NRC staff***
  - Test matrix
  - Running of actual tests

A Complete, Multi-year International Technology Program Supports the Design

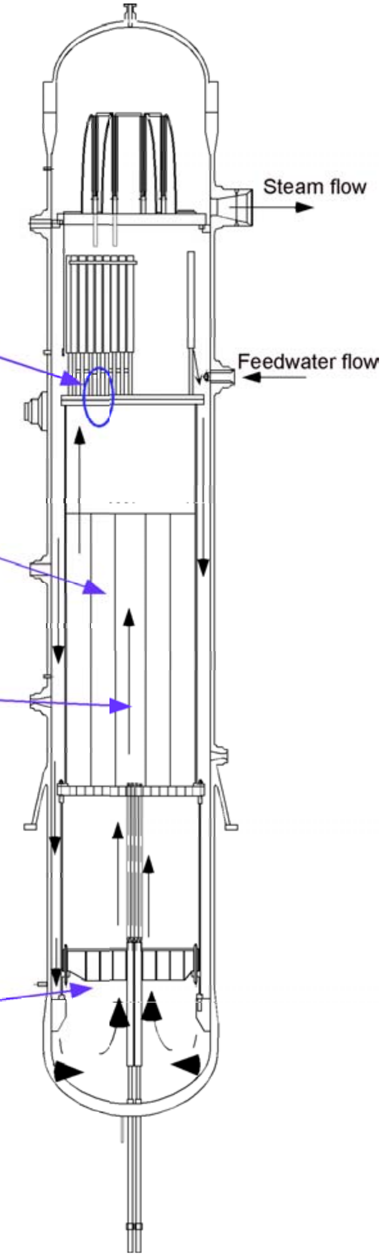
Safety System (GIST) Test Facility and Depressurization Valve

Reactor Depressurization Valve in the Test Facility

Prototype Vacuum Breaker



Summary - Core and NC Flow Technology Program



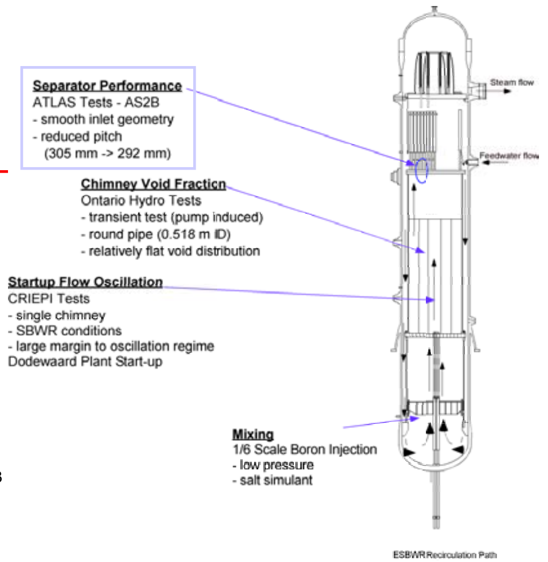
Separator Performance
ATLAS Tests - AS2B
- smooth inlet geometry
- reduced pitch
  (305 mm -> 292 mm)

Chimney Void Fraction
Ontario Hydro Tests
- transient test (pump induced)
- round pipe (0.518 m ID)
- relatively flat void distribution

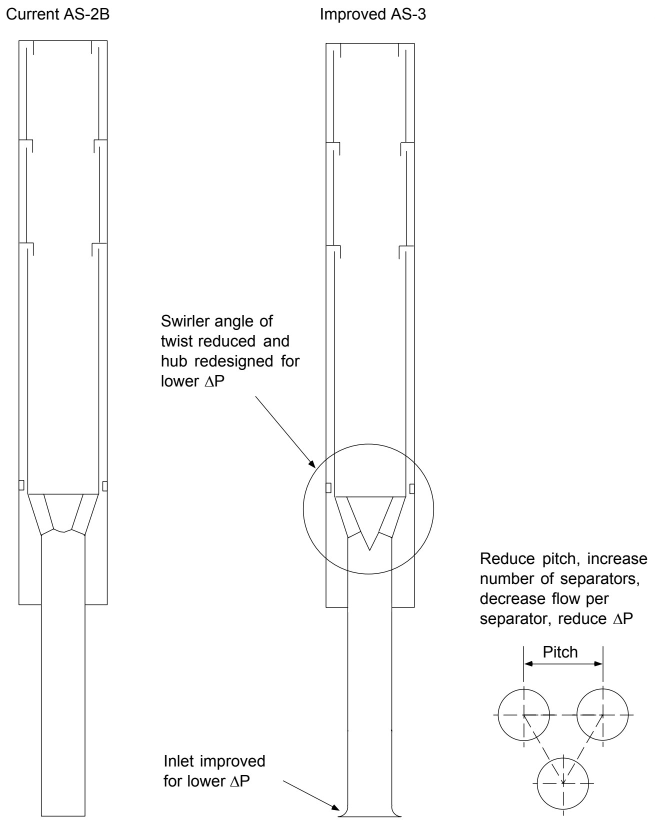
Startup Flow Oscillation
CRIEPI Tests
- single chimney
- SBWR conditions
- large margin to oscillation regime
Dodewaard Plant Start-up

Mixing
1/6 Scale Boron Injection
- low pressure
- salt simulant

ATLAS steam separator test

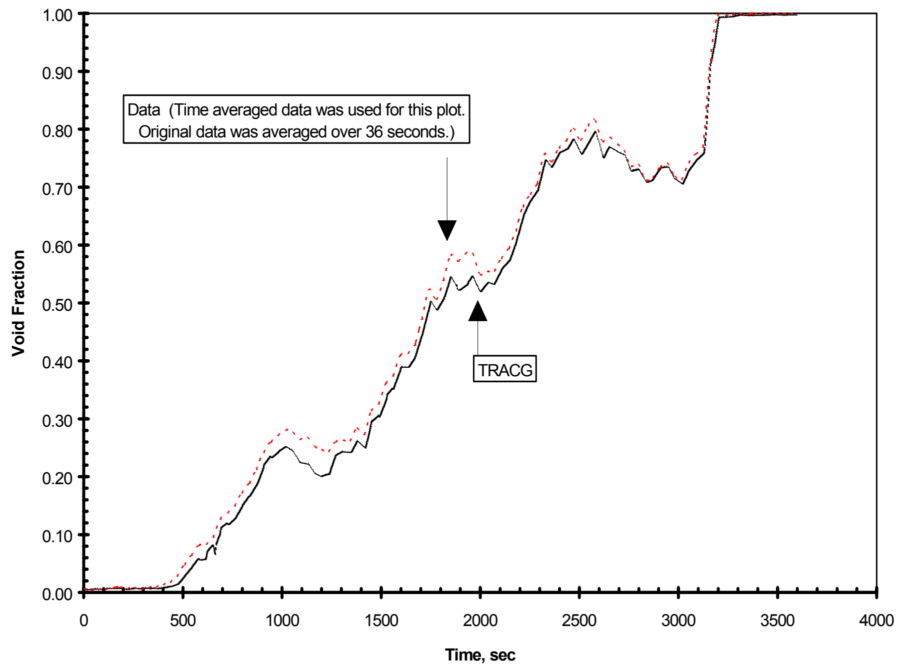


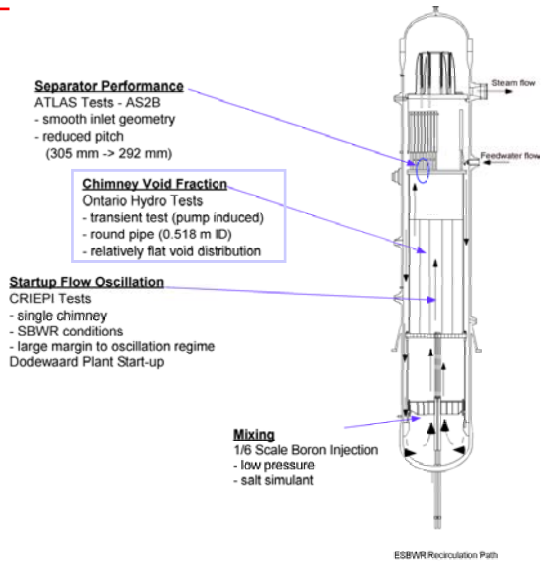
- ***Steam/water full pressure test***
  - 3 separators connected to 1 dryer
  - Data for various flow rates, inlet qualities and water levels
- ***Current BWR separator is the AS-2B***



Chimney Void Fraction

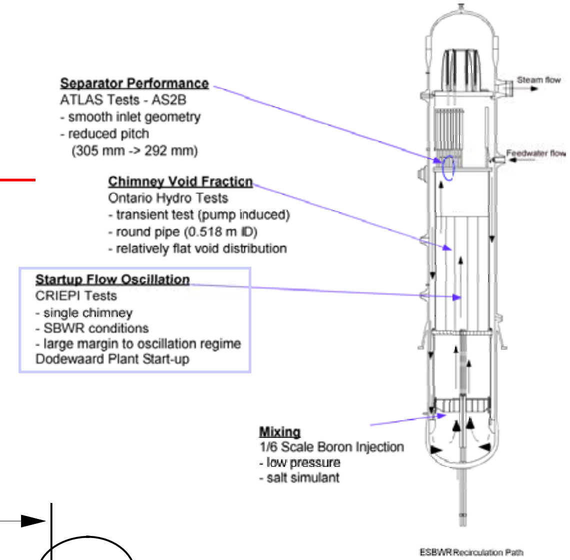
- ***Ontario Hydro Tests***
  - Large pipe void fraction data
  - 0.51 m diameter, 6.4 and 2.8 MPa
- ***Relatively flat void profile across the pipe section***
- ***Pump induced transient tests***

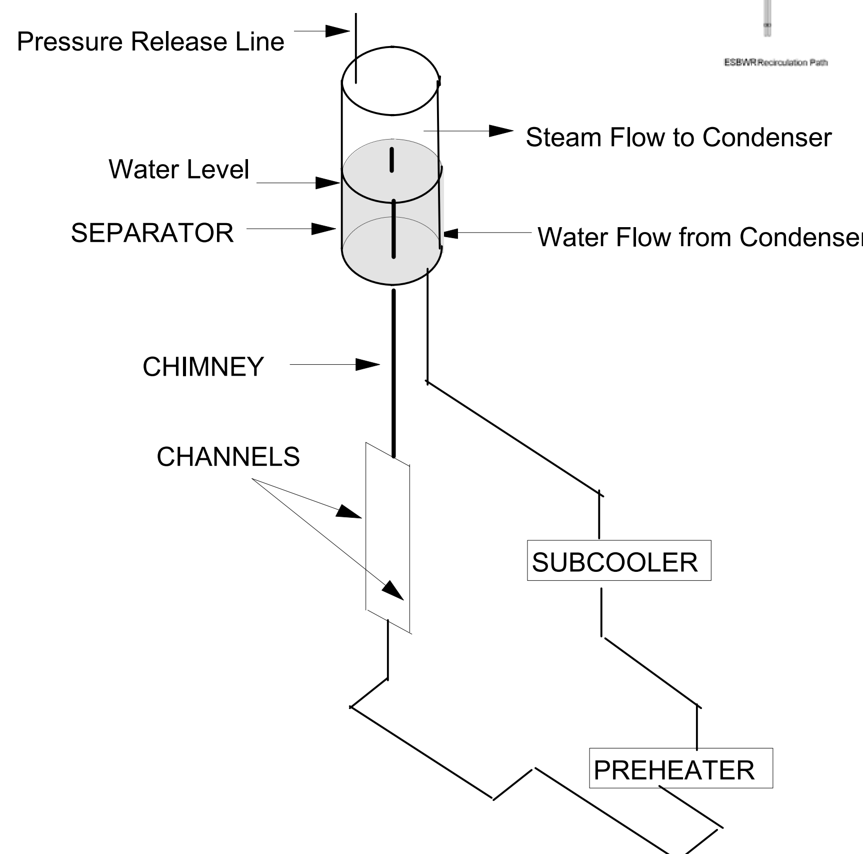




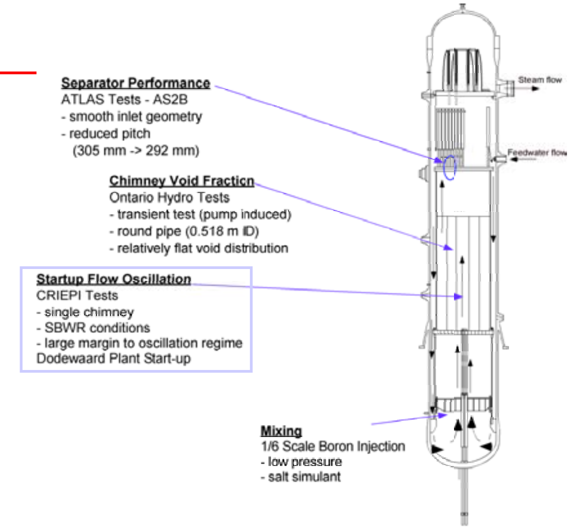
CRIEPI Startup Flow Oscillation

- ***SBWR Specific Test***
  - 2 channels, 1.8m long electrically heated
  - 5.5m chimney
  - Free surface separator
- ***Data for 0.1 MPa (1 bar) and various power and inlet subcooling***
- ***Map of instability region obtained***





February 1992 Startup of Dodewaard Natural Circulation BWR

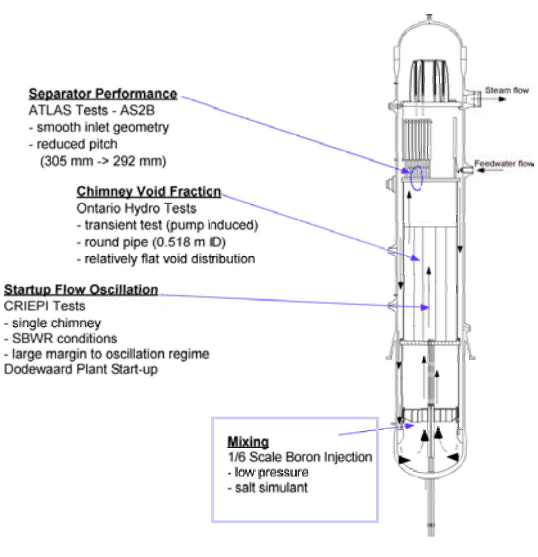


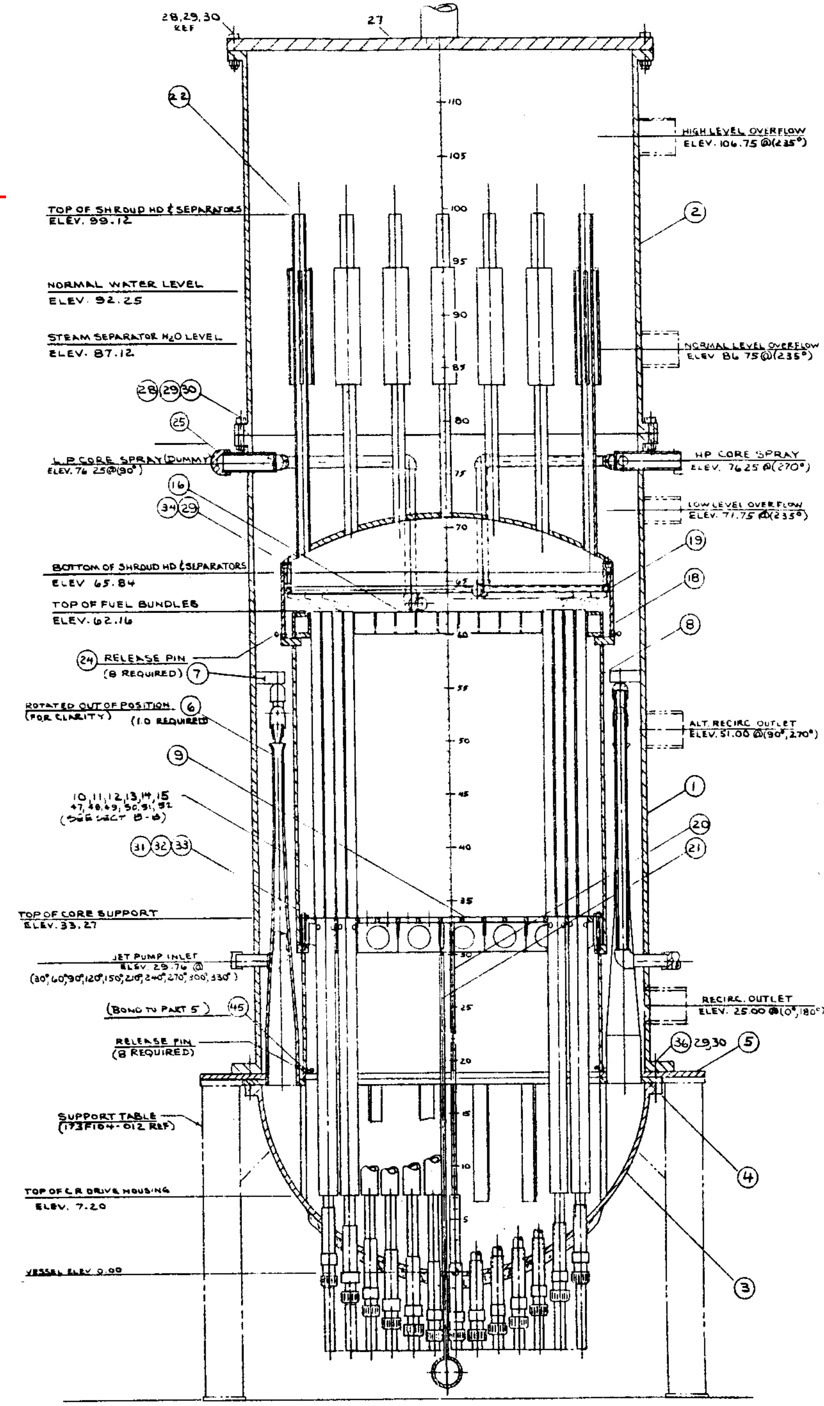
- ***Special startup procedure for detailed measurements at large number of steps***
- ***Parameters set by operators:***
  - System pressure
  - Water level
  - Control rod pattern
- ***Measured quantities:***
  - Flows and temperatures of :
    - Feedwater (FW)
    - Steam flow
    - Reactor water cleanup (RZS)
    - Control rod drive (RSA)
  - Downcomer temperature noise
  - Downcomer subcooling
  - Downcomer pressure differences
  - Bypass temperatures
  - Bypass temperature noise
  - Ex-vessel neutron flux

- *Parameters calculated from measured quantities:*
  - Thermal power: calculated form (a) heat balance and (b) ex-vessel neutron flux
  - Downcomer velocity: from cross-correlation of downcomer temperature noise
  - Bypass velocity: calculated from cross-correlation of bypass temperature noise
  - Decay ratio: calculated from ex-vessel neutron flux

1/6th Scale Boron Mixing Test

- ***Study mixing process whereby liquid borate is transported and maintained in core***
- ***Model replicates BWR vessel at 1/6 linear scale***
- ***Low pressure test with core void fraction simulated by air injection***
- ***Sodium pentaborate injection simulated by hot salt solution with correct density difference with surrounding water***
- ***Local boron concentrations are deduced from detailed temperature measurements***





Summary -- Containment and Safety Systems Technology Overview

SBWR

Condensation with N/C
MIT - external condensation
UCB - single tube tests
GIRAFFE - component tests
PANTHERS - component tests
PANDA - steady state tests

PCCS Performance
Steady-state: PANDA, GIRAFFE, PANTHERS
Start-up: PANDA, GIRAFFE
Secondary Side ht: PANDA, PANTHERS, GIRAFFE
N/C Buildup: PANDA, PANTHERS, GIRAFFE
Interactions: PANDA
Unit interactions PANDA

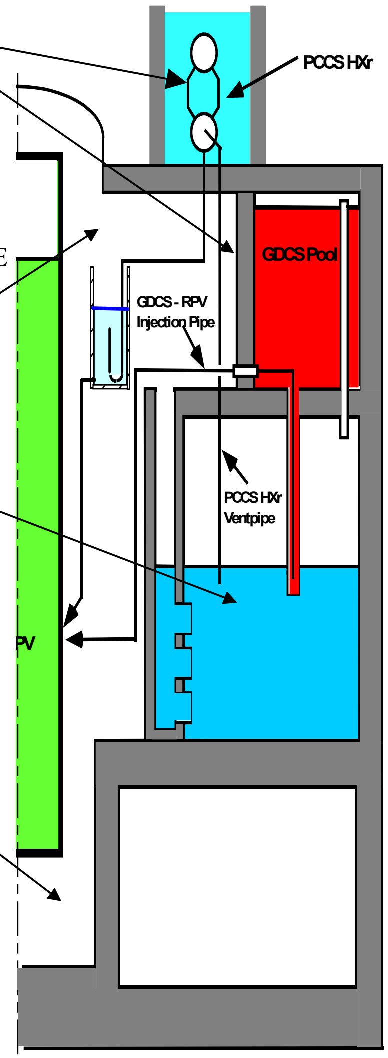
System Interactions
PANDA
GIRAFFE

SP Stratification
PANDA
SP Stratification

DW Stratification and Hideout
PANDA
GIRAFFE

Steam Quenching
Main Vent:
-Horiz. Vent Test/MK III tests (PSTF)
-Mark II 4T
PCC Vent:
- PANDA

Heat/Mass Leakage DW to WW
VB Testing



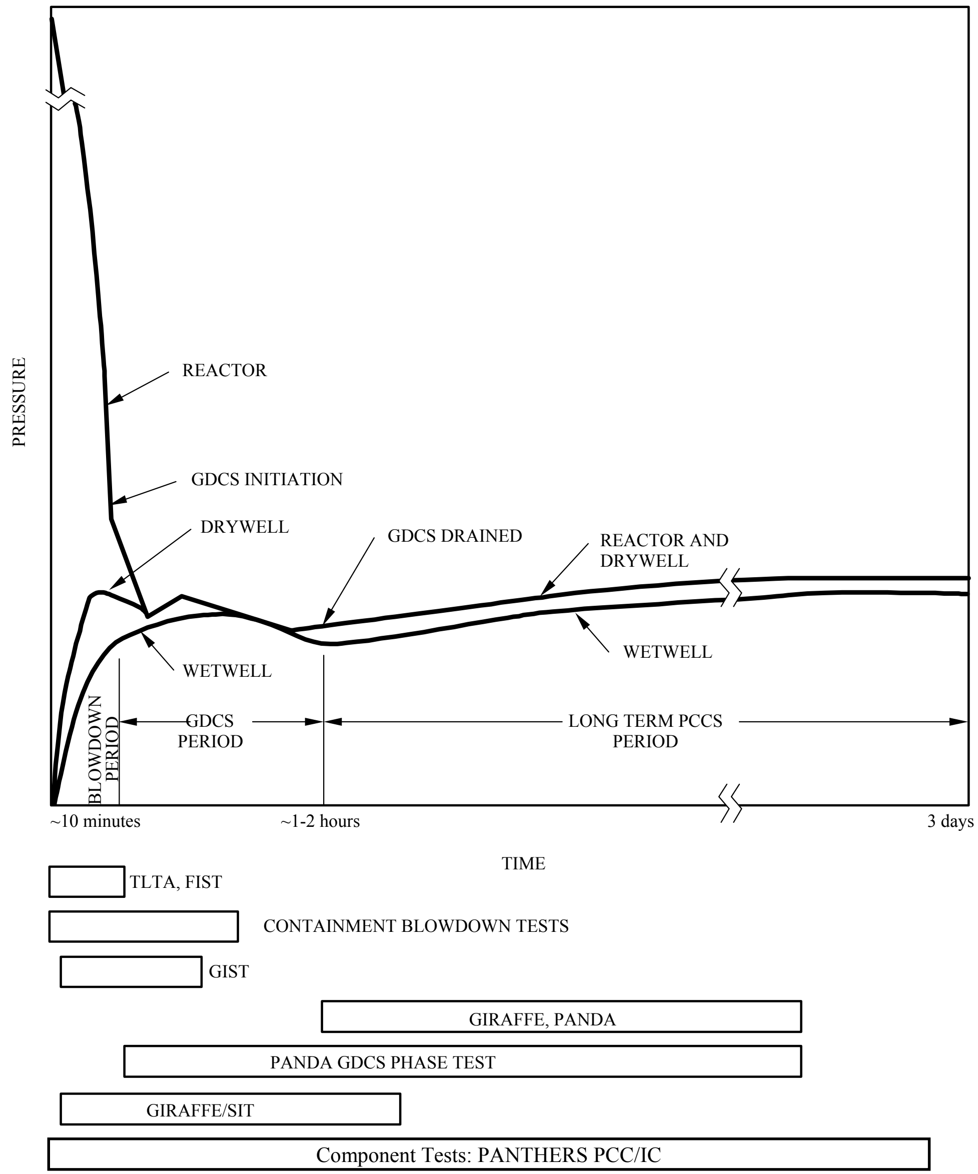
ESBWR Specific

PCCS Performance
PANDA (TEPSS)
- startup
- interactions
- secondary side ht
- N/C Buildup
- Unit interactions

ESBWR Configuration
PANDA (TEPSS)
- reduced cont. volume
- GDCS in WW
- PCCS Condensate to RPV
VTT
- Modeling of larger PCC

DW Stratification and Hideout
PANDA(TEPSS)
- Asymmetric loading
- hydrogen

Integral Test Coverage for ESBWR LOCA

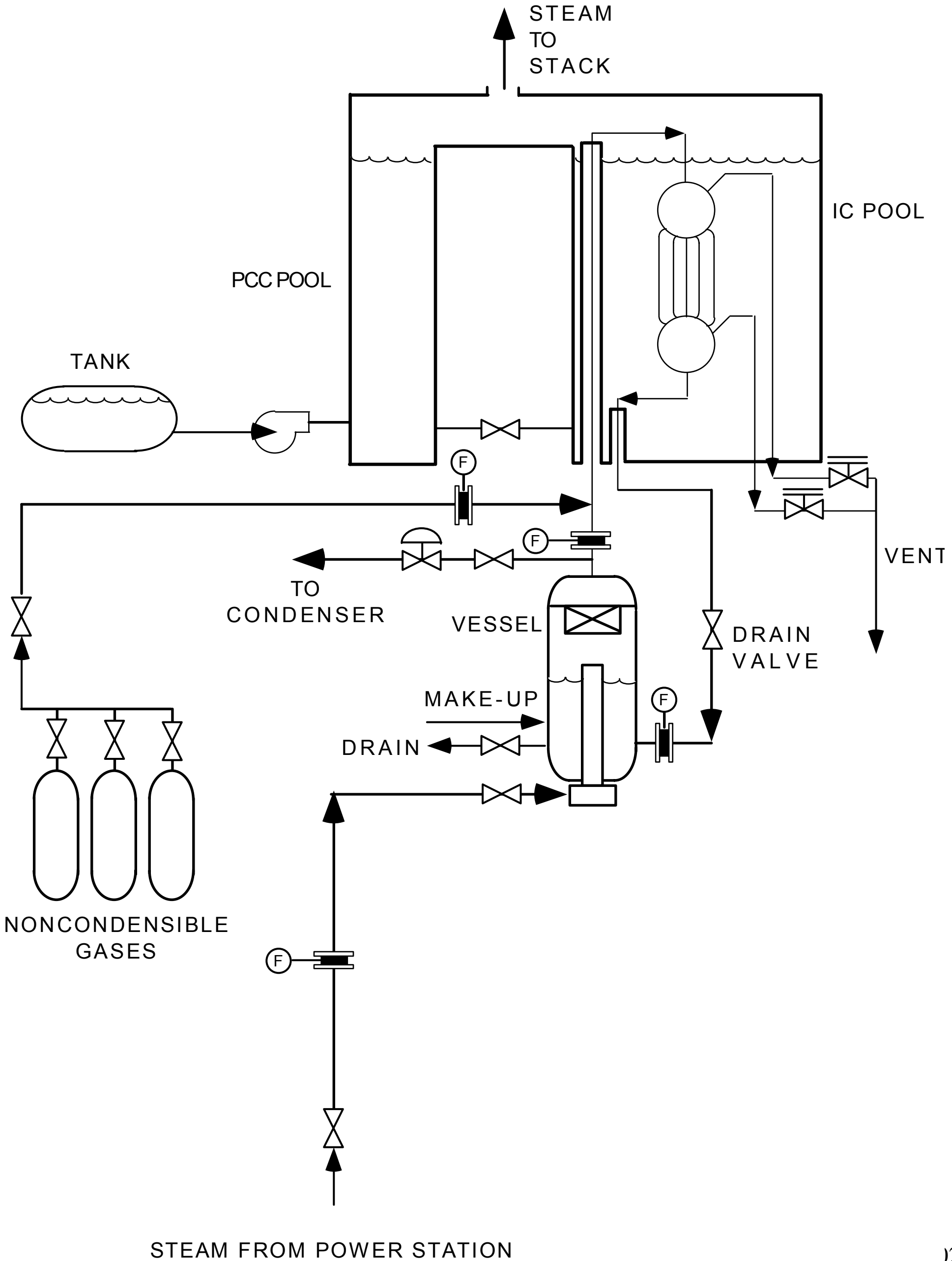


PANTHERS/IC

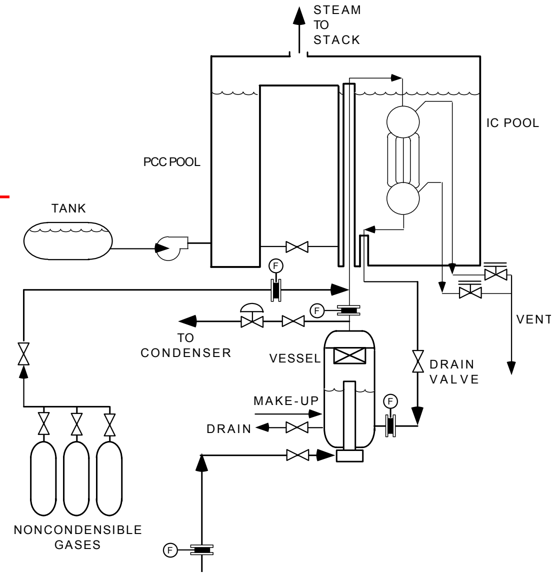
- ***Objectives***
  – Demonstrate that prototype heat exchanger is capable of meeting design requirements
  – Provide database for TRACG (code) qualification to predict heat exchanger performance spanning the range of conditions expected in the SBWR (i.e. steam flow, air flow, pressure, temperature)
  – Demonstrate the startup of the IC unit under anticipated transient conditions
  – Demonstrate the capability of the IC design to vent non-condensable gases and to resume condensation following venting

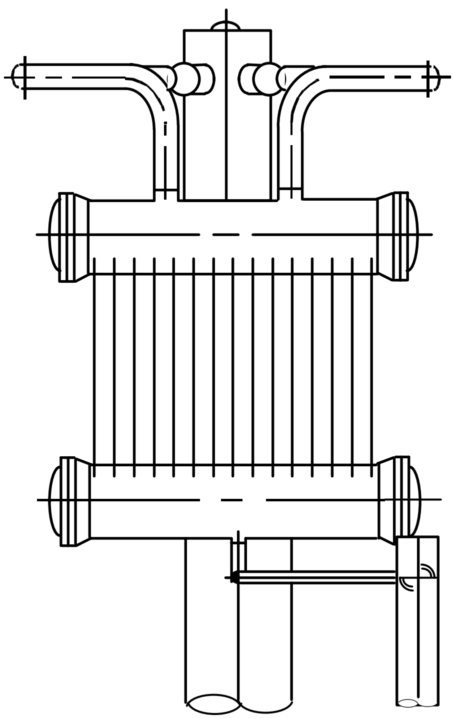
- ***One module of a full-scale, two-module vertical tube heat exchanger***

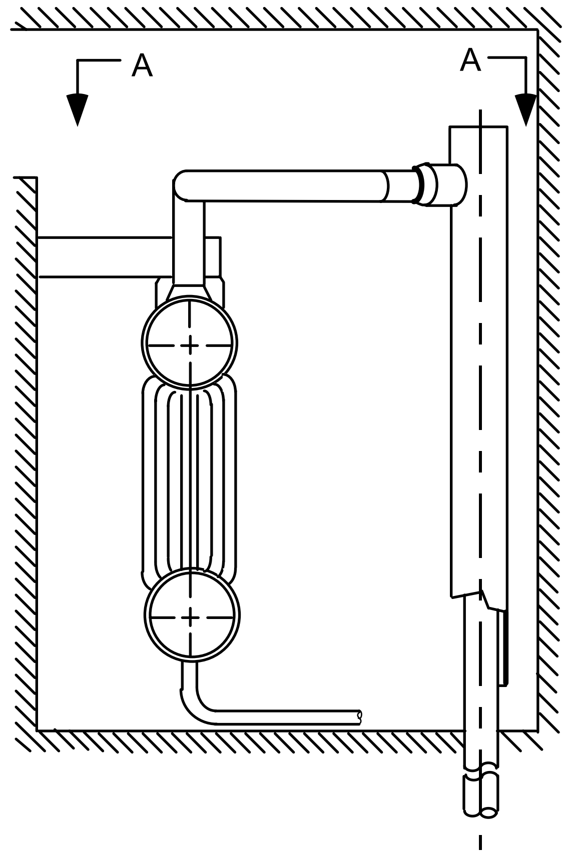
PANTHERS/IC Test Facility Schematic (backup)

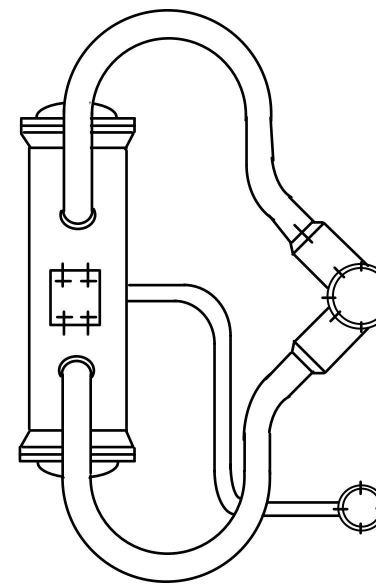


PANTHERS/IC Test Article (backup)







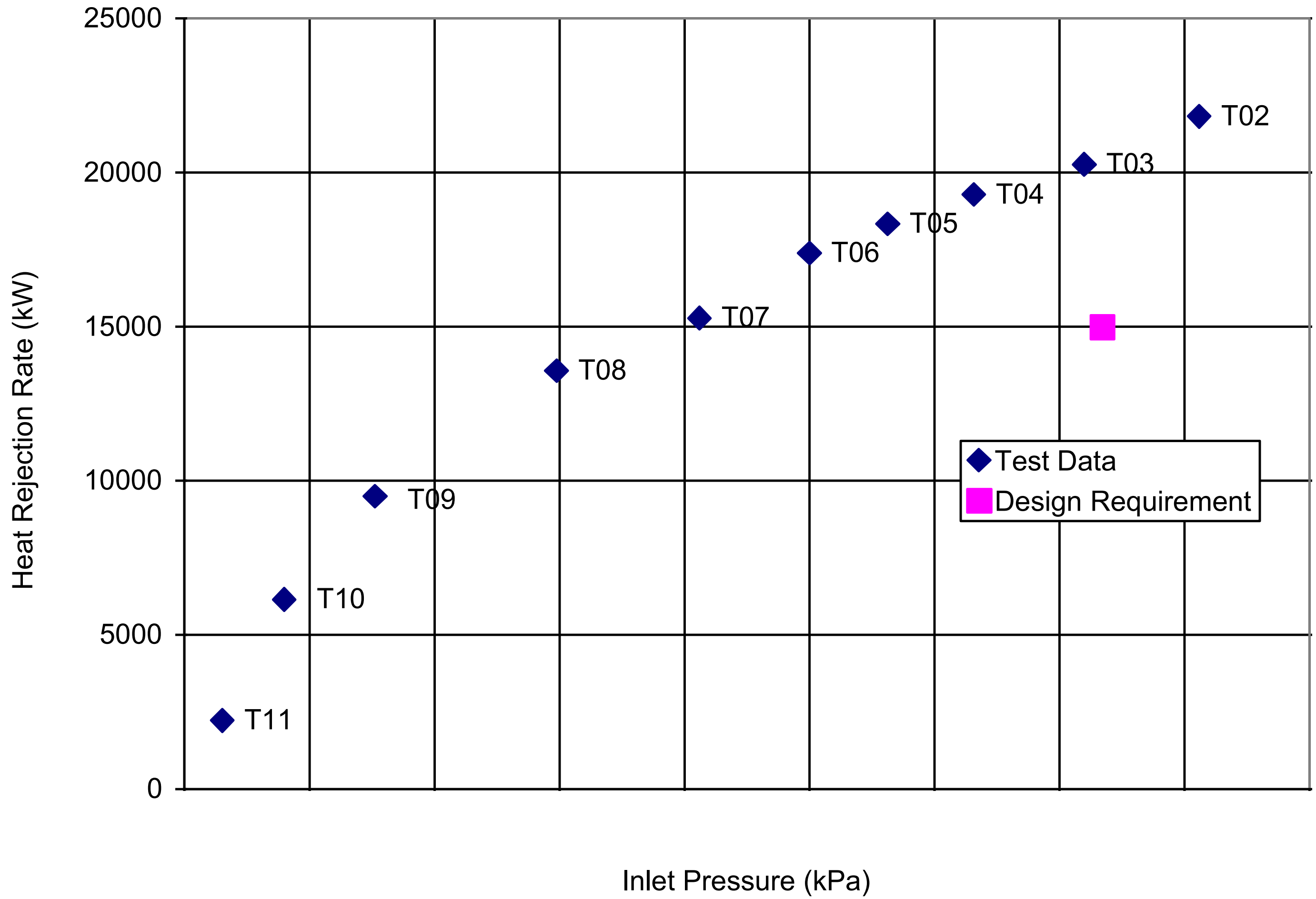


VIEW A-A

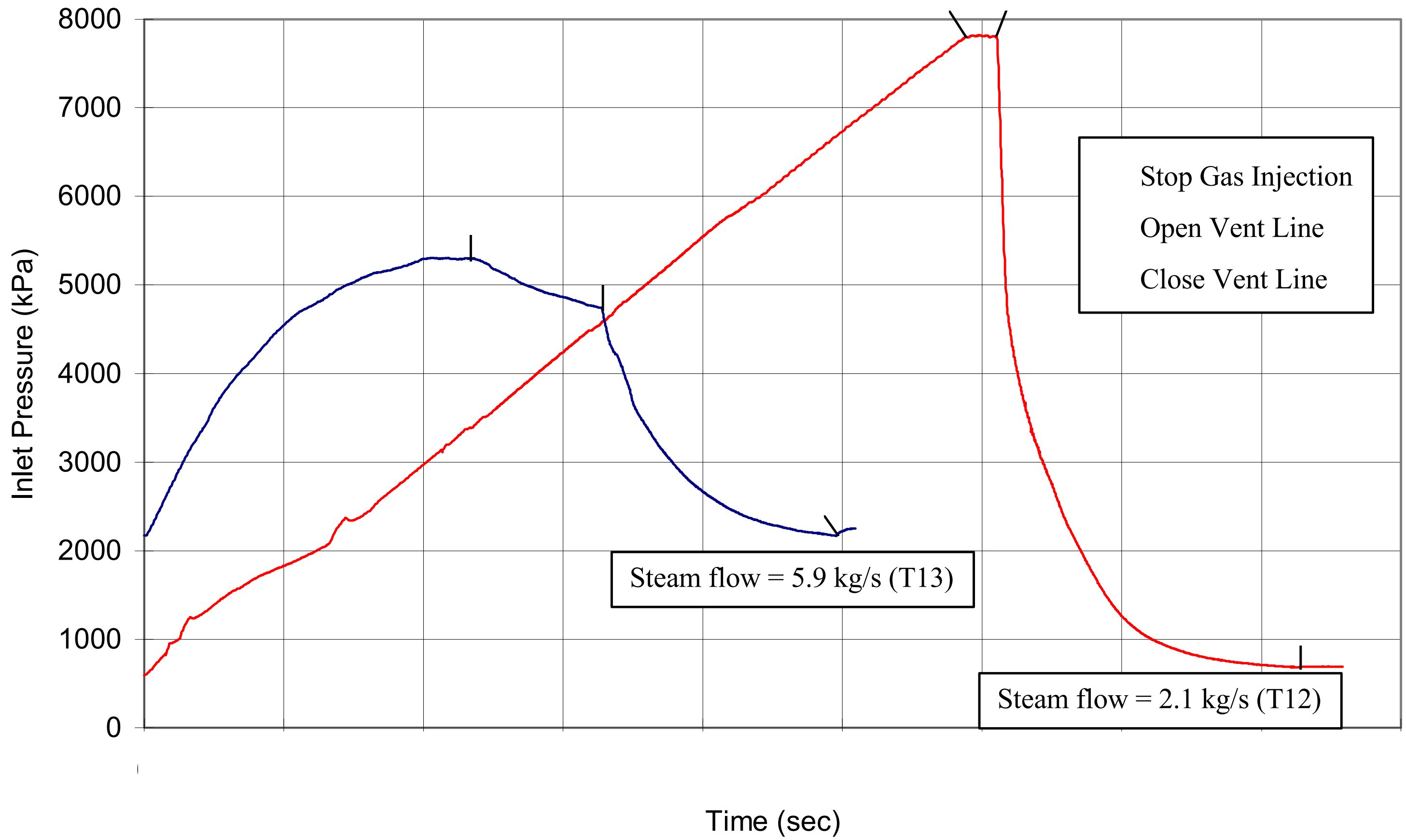
PANTHERS/IC -- Test Matrix

- ***10 Steady-state steam only tests***
  - Obtain baseline heat exchanger capability
- ***1 Start-up Test***
  - Establish air-steam performance map
  - Variables are pressure, air flow, steam flow and superheat
- ***4 Transient Tests:***
  - Determine and quantify differences in the effects of lighter-than-steam and heavier-than-steam non-condensable gas buildup in the PCC heat exchanger tubes
  - 4 test with air; 2 with He; 2 with air + He
  - Determine pool water level effect

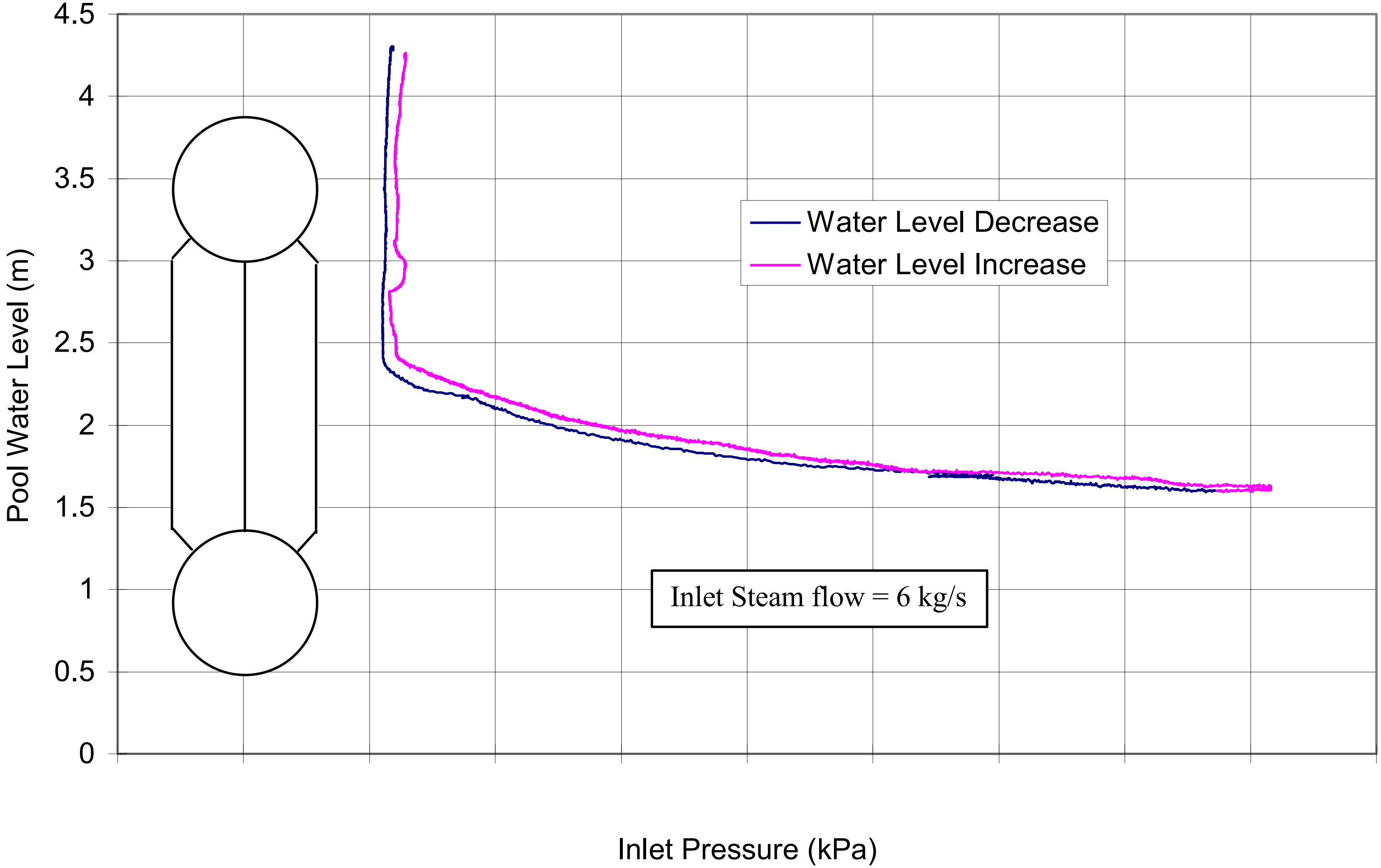
PANTHERS IC Tests - Heat Rejection Performance



PANTHERS IC Tests - Effectiveness of Venting



Pressure Response to IC Pool Water Level



PANTHERS/IC Key Conclusions

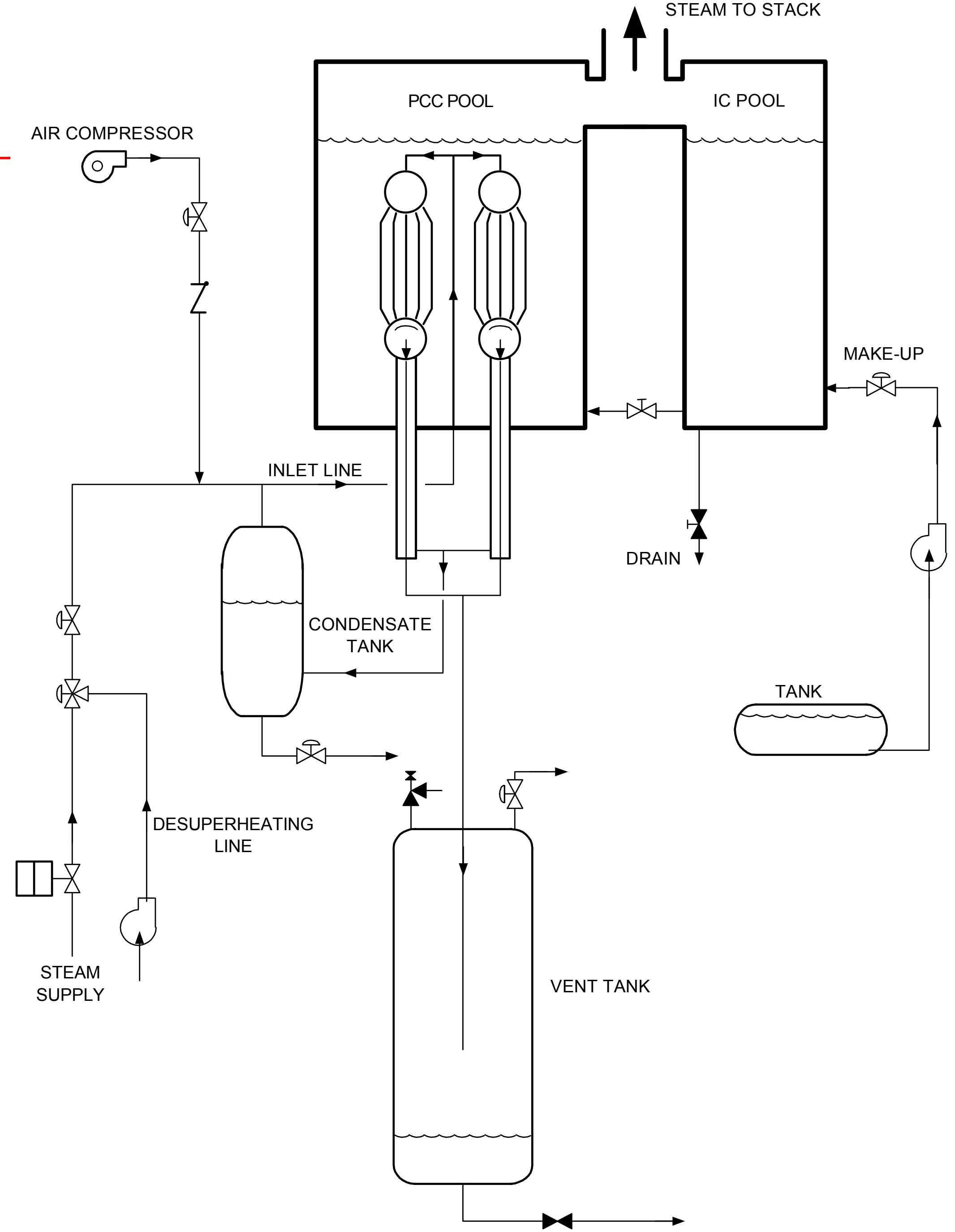
- ***The IC meets the design performance capacity with margin***
- ***The IC performance is well behaved and understood***
- ***The IC is able to vent non-condensable gases and resume condensation following venting***
- ***The IC is able to quickly startup from standby and condense steam at rated conditions***

PANTHERS/PCC

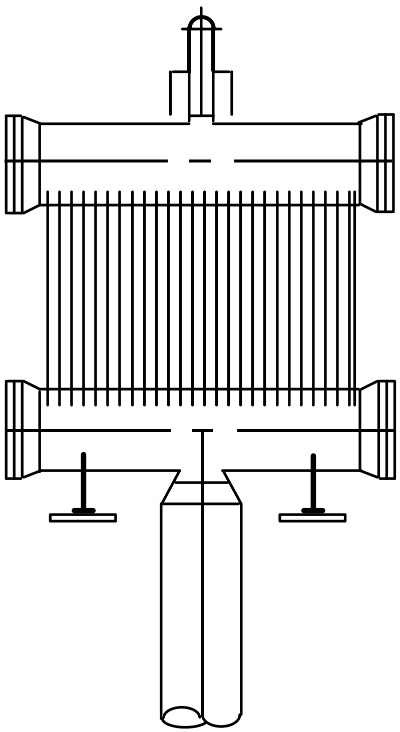
- ***Objectives***
  - Demonstrate that prototype heat exchanger is capable of meeting design requirements
  - Provide database for TRACG (code) qualification to predict heat exchanger performance spanning the range of conditions expected in the SBWR (i.e. steam flow, air flow, pressure, temperature)
  - Investigate the difference between lighter-than-steam and heavier-than-steam noncondensibles
  - Structural component qualification

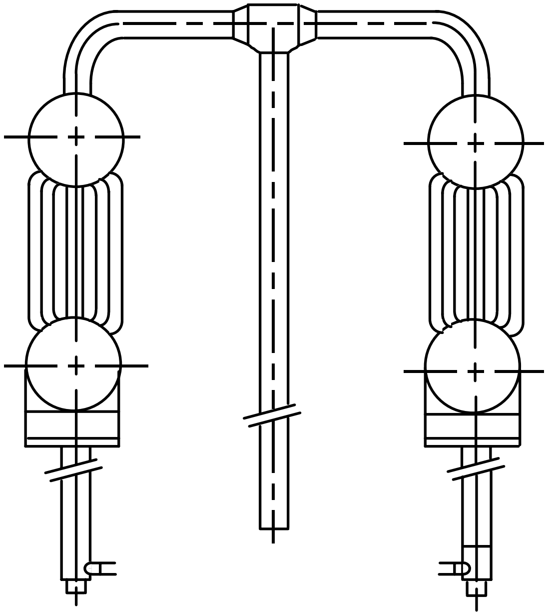
- ***Full Scale, two-module, Passive Containment Condenser Test***

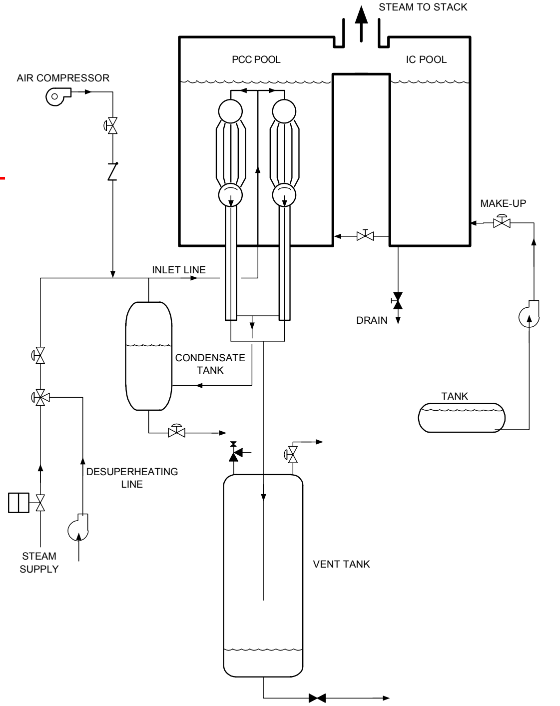
PANTHERS/PCC Test Facility Schematic (backup)

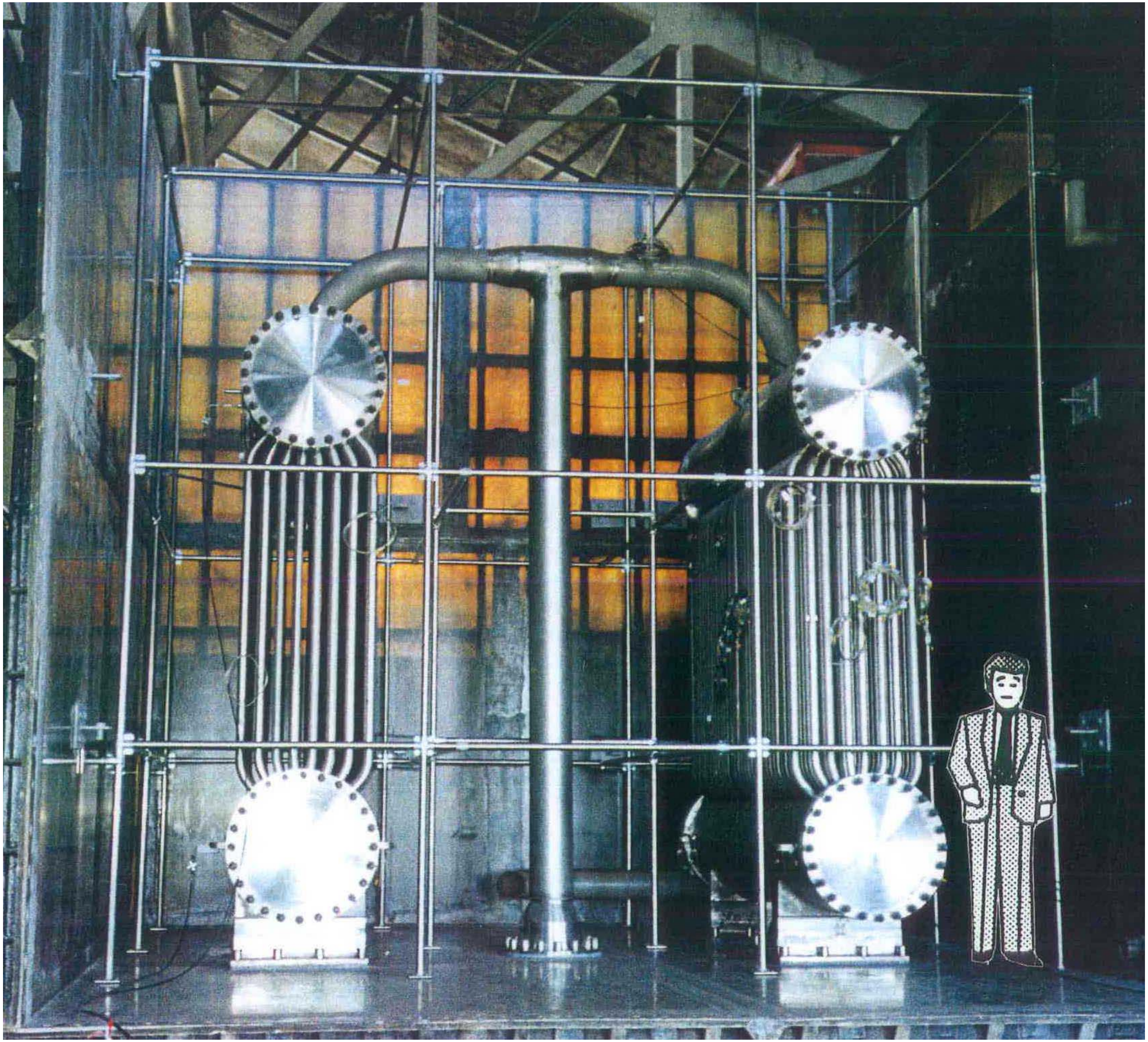


PANTHERS/PCC Test Article





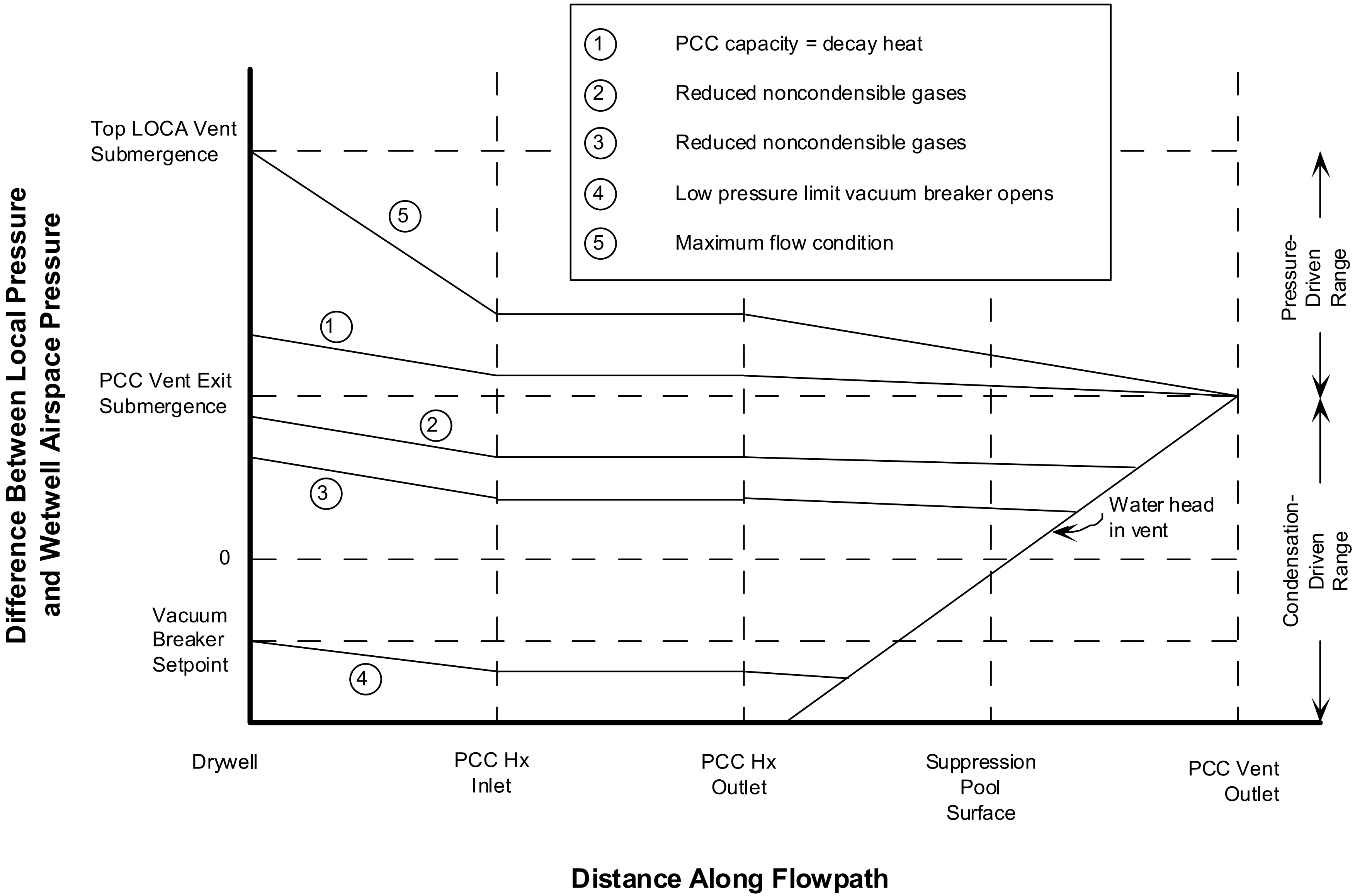




PANTHERS/PCC -- Test Matrix

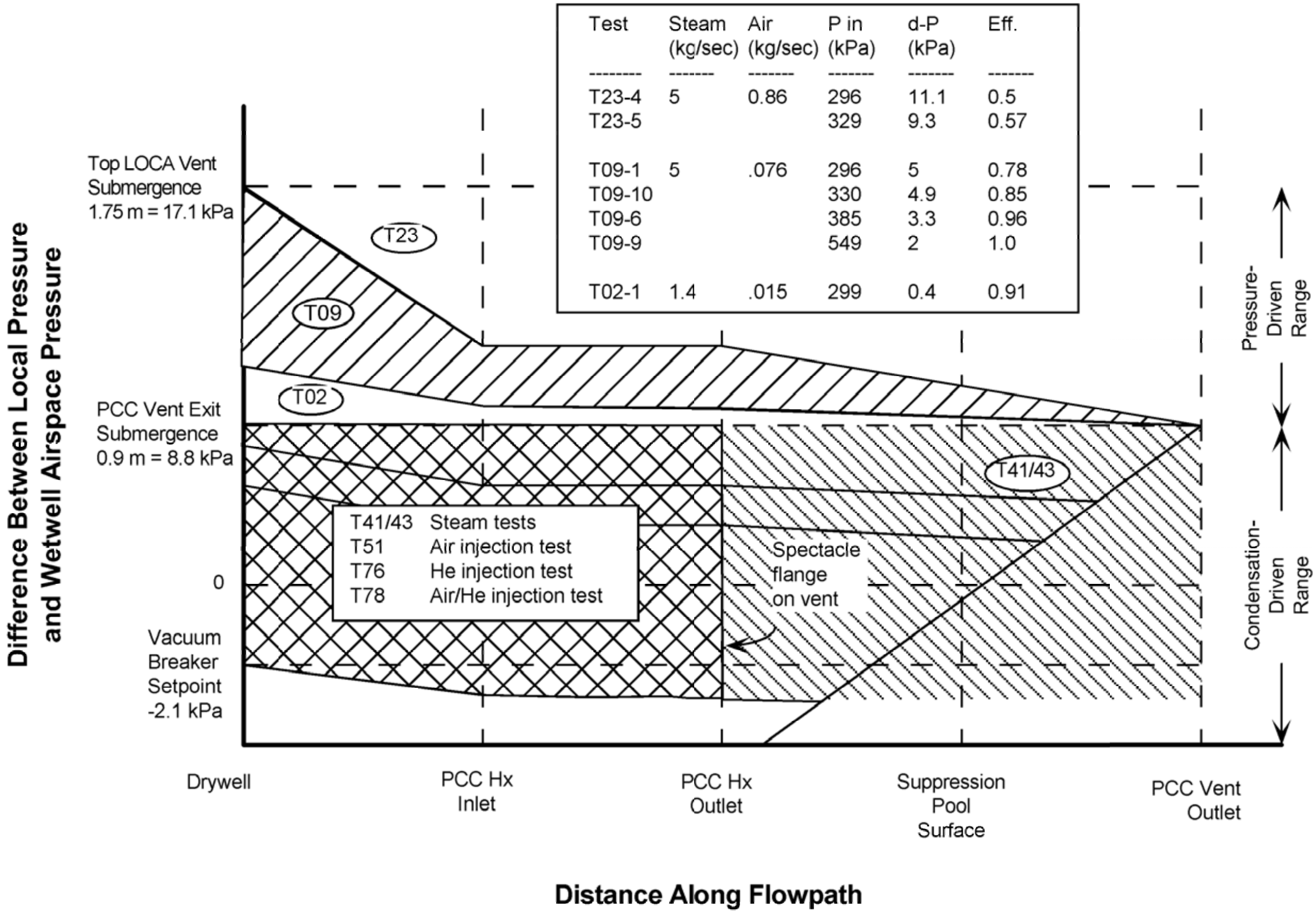
- ***13 Steady-state steam only tests***
  - obtain baseline heat exchanger capability (7 tests)
  - measure effect of superheat (6 tests)
- ***42 Air-steam tests:***
  - Establish air-steam performance map
  - Variables are pressure, air flow, steam flow and superheat
- ***8 non-condensable gas buildup tests:***
  - Determine and quantify differences in the effects of lighter-than-steam and heavier-than-steam non-condensable gas buildup in the PCC heat exchanger tubes
  - 4 test with air; 2 with He; 2 with air + He

PCC Operational Modes



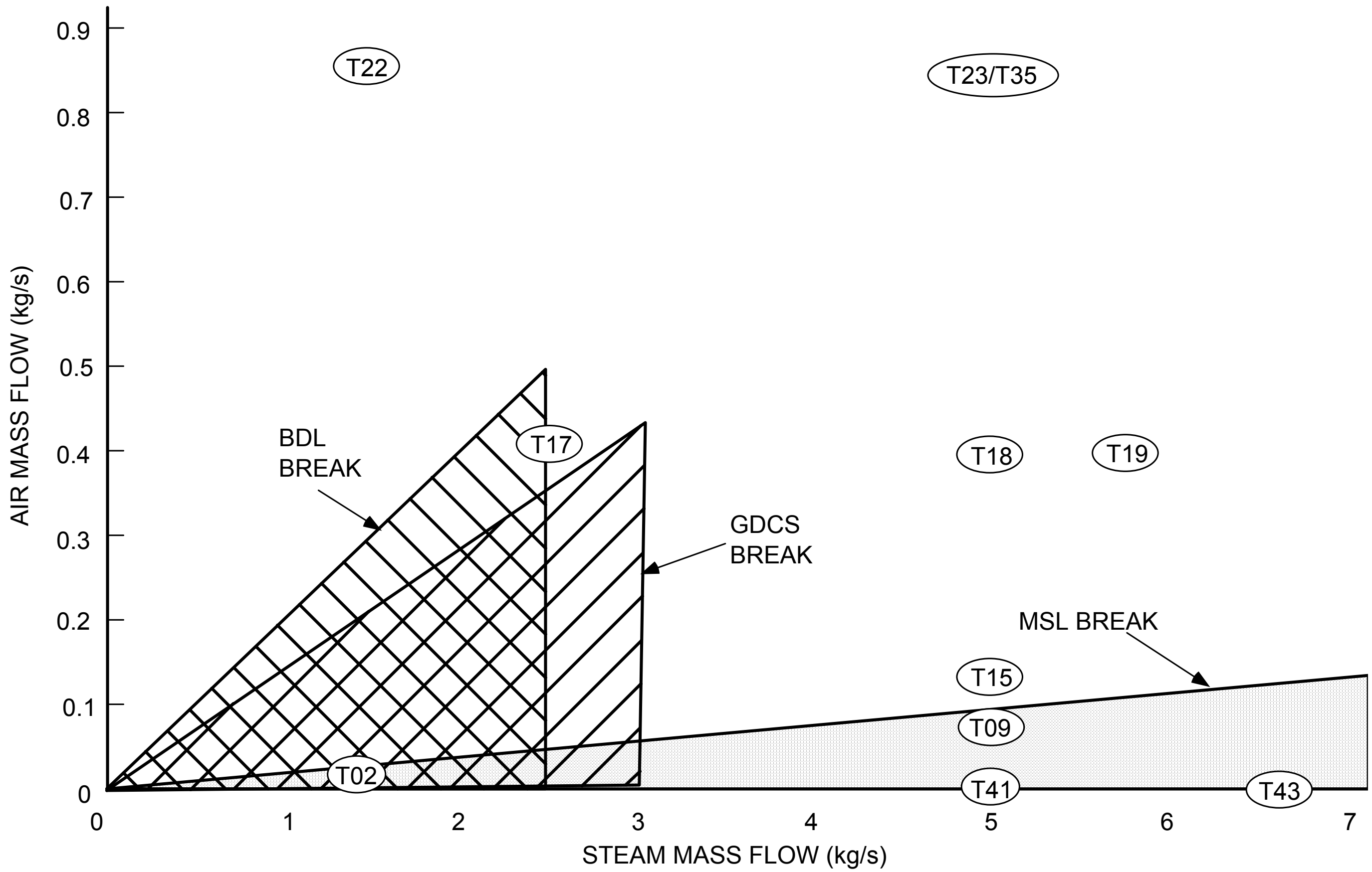
reg02-27

PCC Operational Modes and Test Coverage

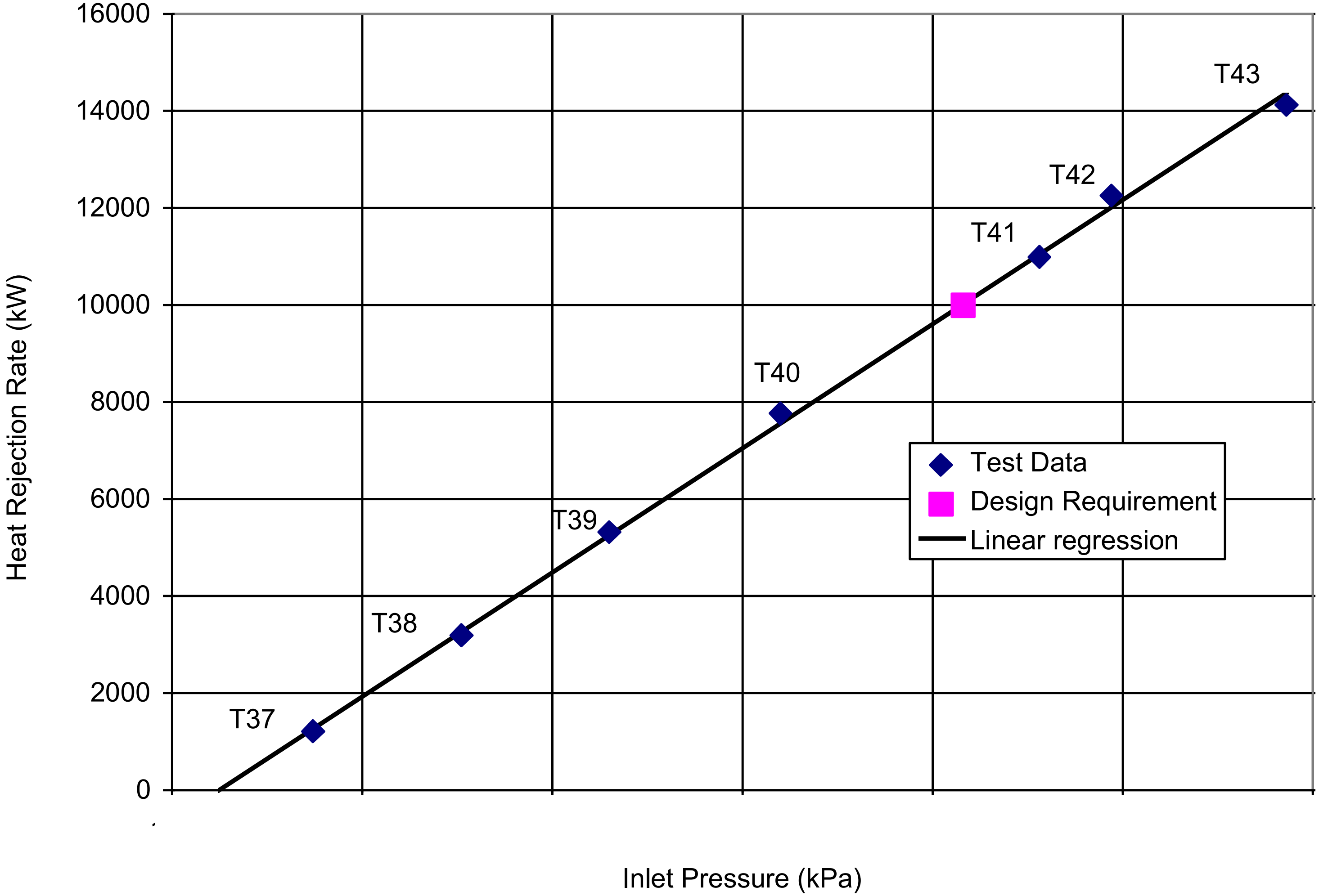


Test	Steam (kg/sec)	Air (kg/sec)	P in (kPa)	d-P (kPa)	Eff.
T23-4	5	0.86	296	11.1	0.5
T23-5			329	9.3	0.57
T09-1	5	.076	296	5	0.78
T09-10			330	4.9	0.85
T09-6			385	3.3	0.96
T09-9			549	2	1.0
T02-1	1.4	.015	299	0.4	0.91

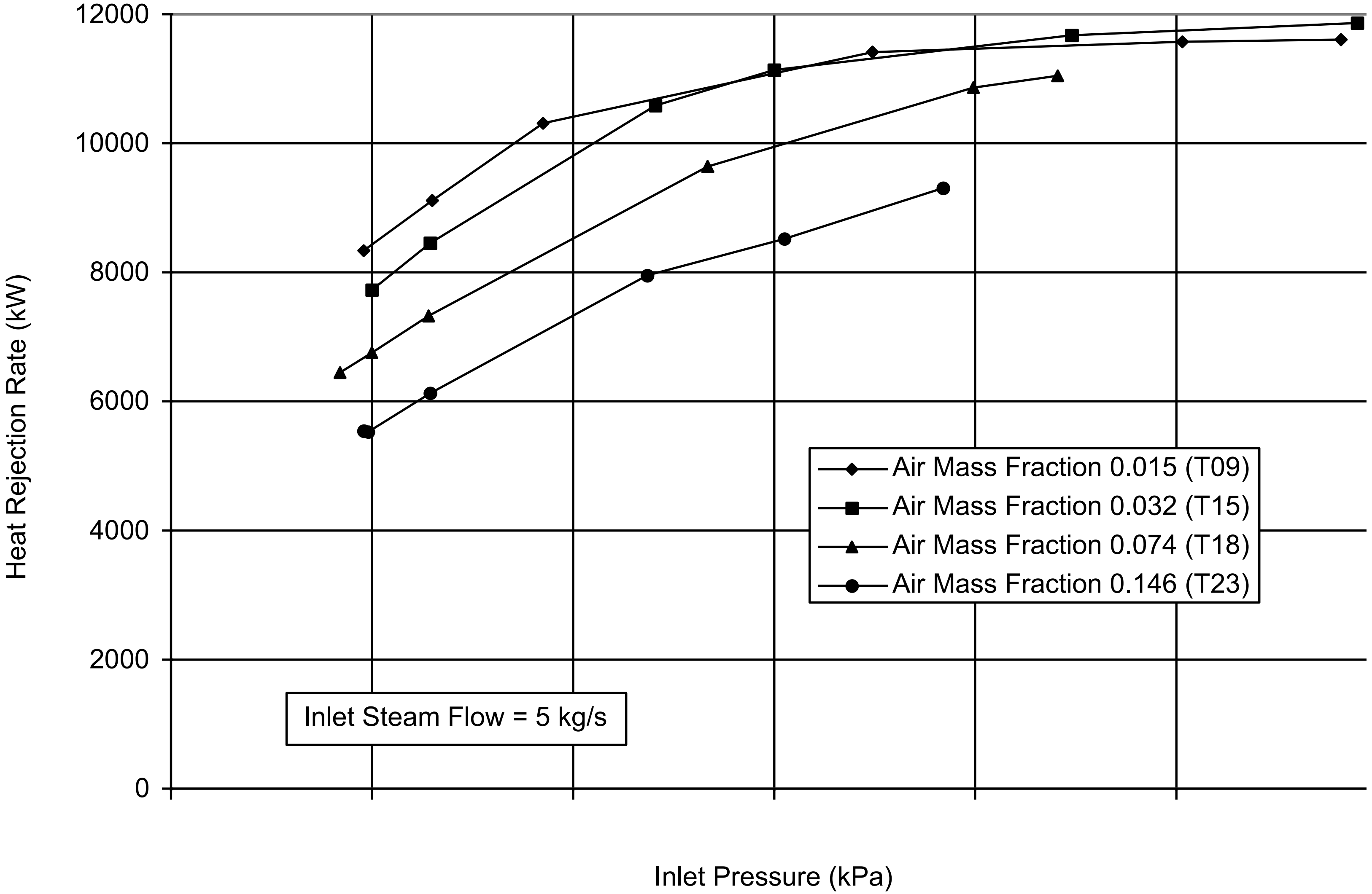
TRACG PANTHERS/PCC Qualification Points (backup)



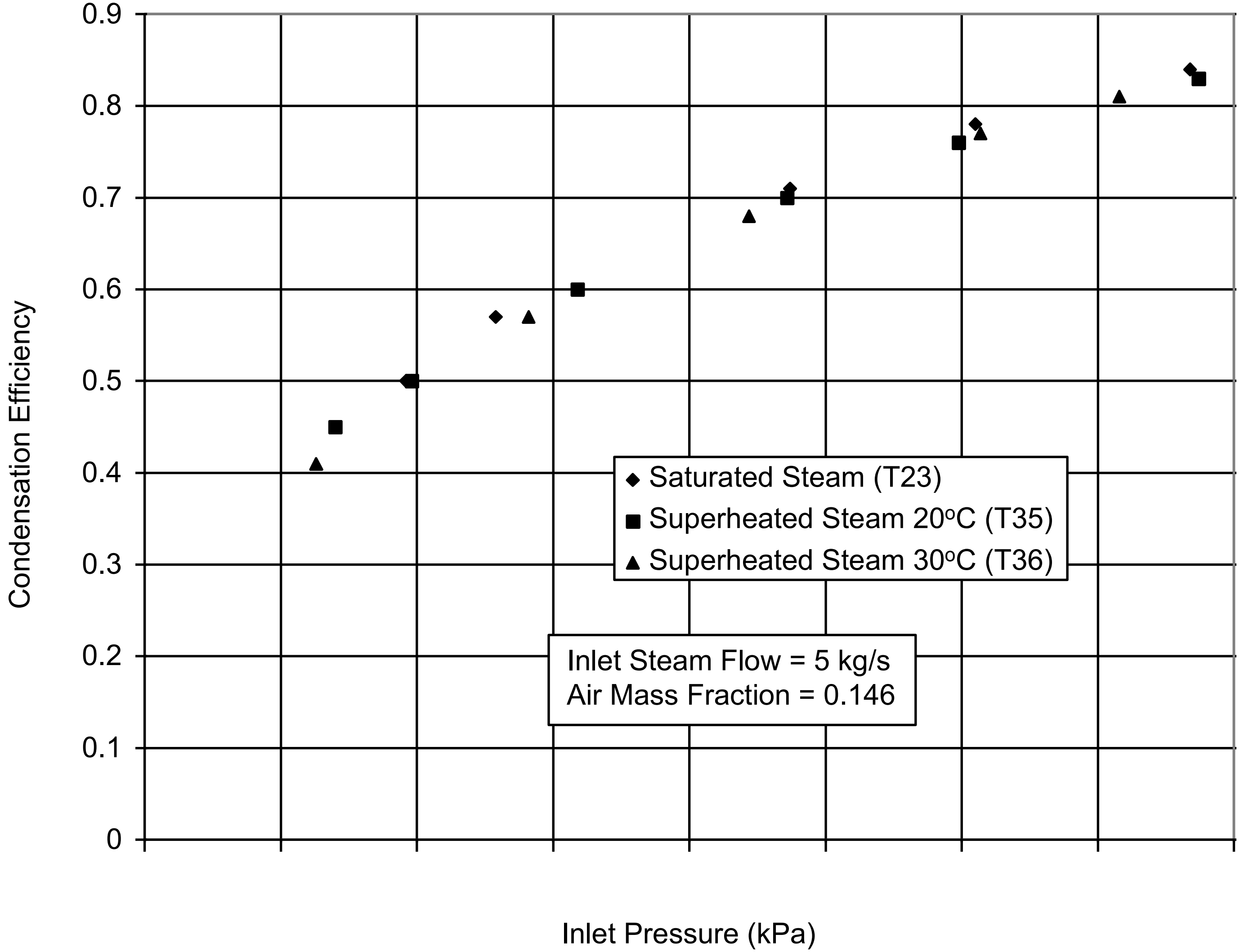
PANTHER/PCC Power for Saturated Steam Tests



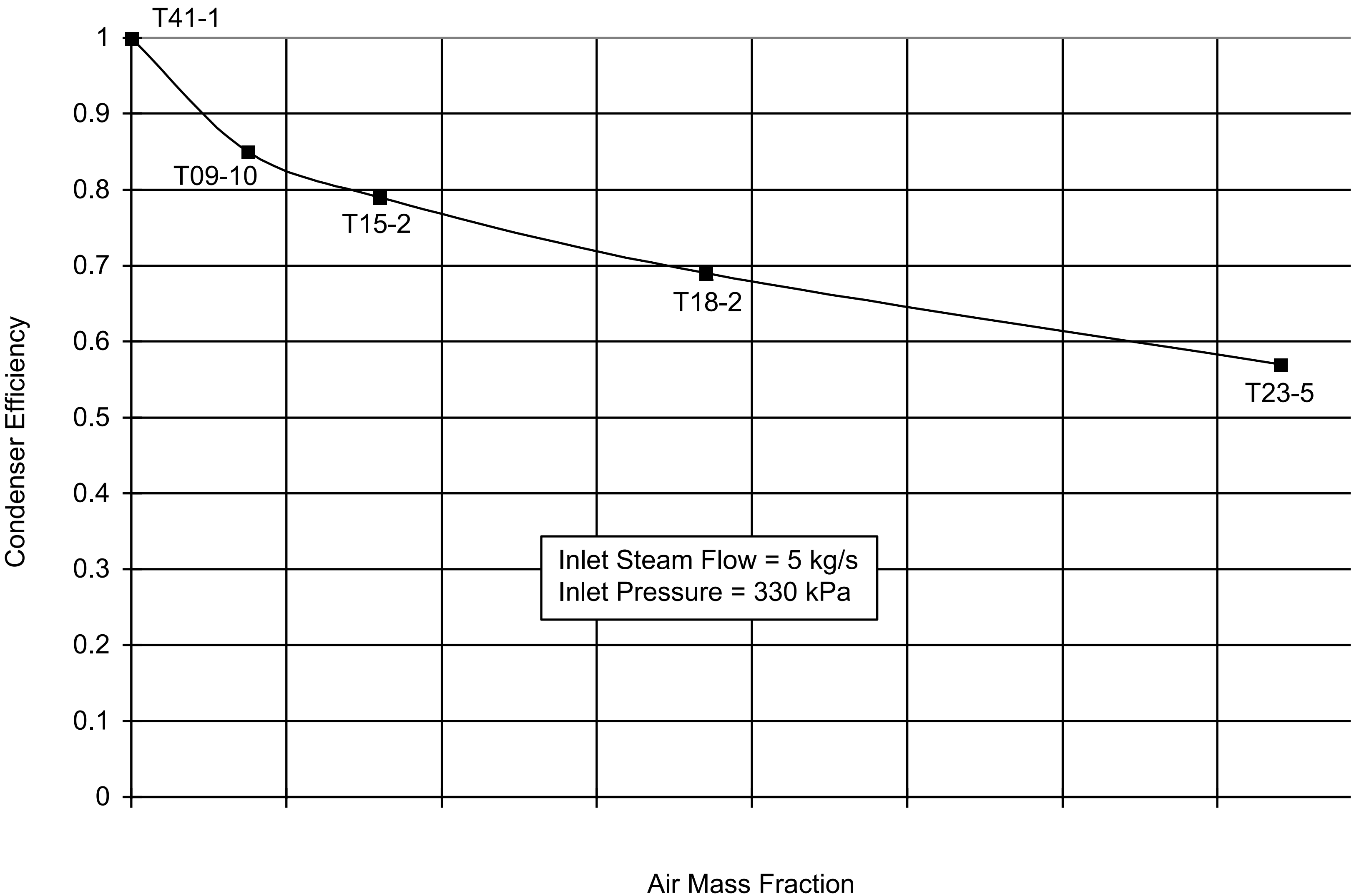
PANTHERS/PCC Power for Air/Steam Tests



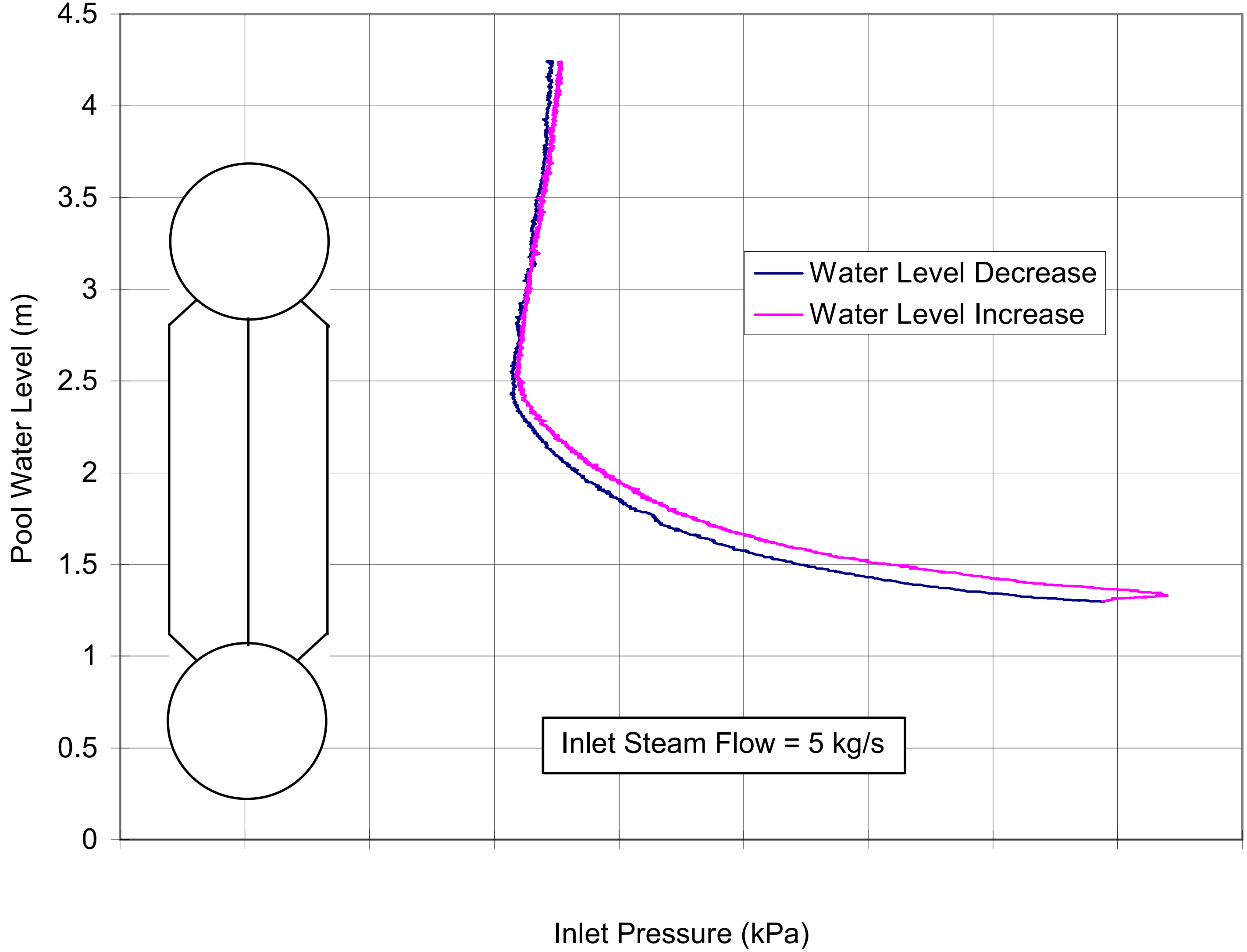
Effect of Superheat on Condensation Efficiency for PANTHERS/PCC Air/Steam Tests (backup)



Effect of Air Mass Fraction on Condensation Efficiency for PANTHERS/PCC Air/Steam Tests



PANTHERS/PCC Test T54 Inlet Pressure Response to Pool Water Level



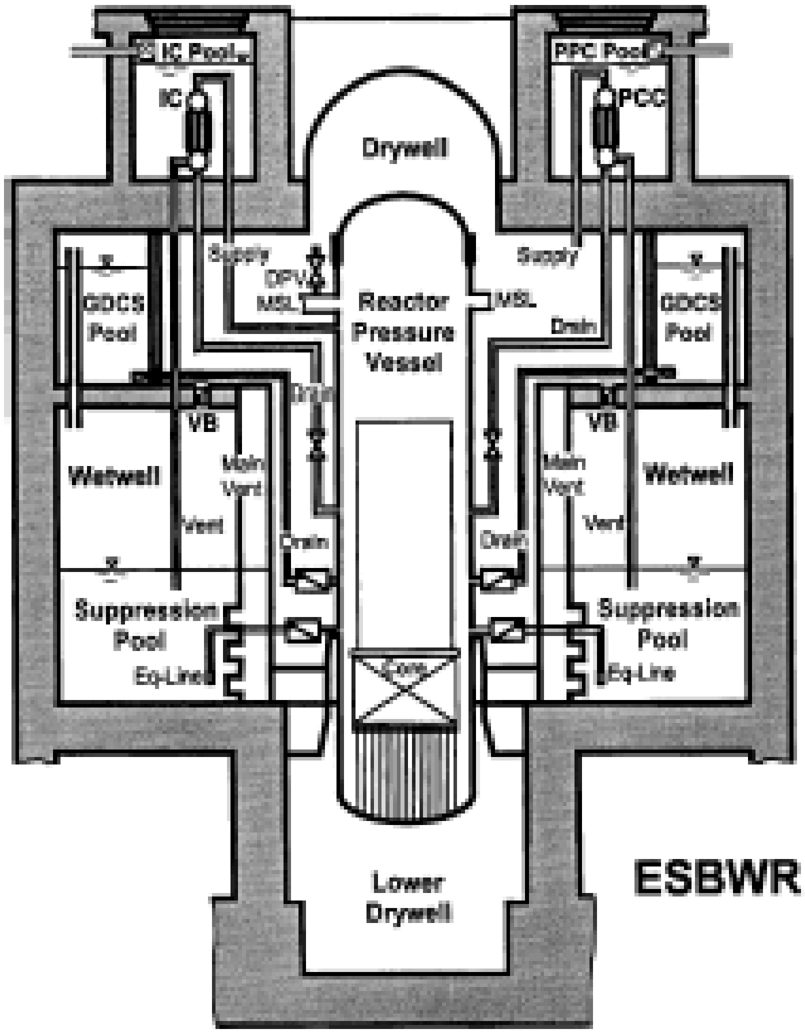
PANTHERS/PCC Key Conclusions

- ***The PCC meets the design performance capacity***
- ***The PCC performance is well behaved and understood***
- ***The PCC can condense steam in the presence of both heavier-than-steam and lighter-than-steam noncondensible gases***
- ***The PCC can operate in both pressure-driven and condensation-driven modes***
- ***Heavier-than-steam gas tends to collect in the bottom of the PCC, while lighter-than-steam-gas tends to distribute throughout the PCC***
- ***No significant tube-to-tube or module-to-module differences occur with heavier-than-steam noncondensible gases***
- ***With lighter-than-steam gases, tube-to-tube noncondensible gas holdup fluctuations occur but do not affect overall condenser response***

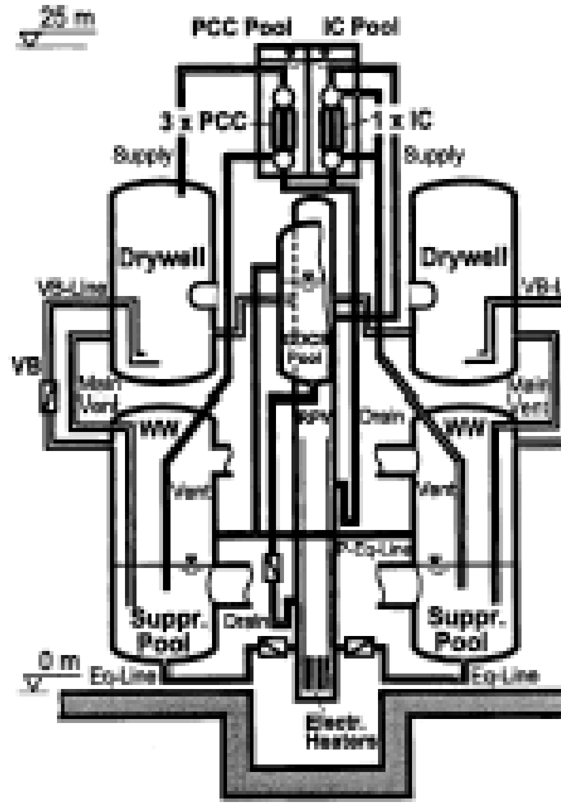
PANDA S and M Series

- ***1:25 scale, full height, integral systems test facility***
- ***Objectives***
  - Demonstrate steady-state, startup and long-term operation of the PCCS system
  - Demonstrate effects of scale on PCC performance
  - Data for TRACG (code) qualification to predict SBWR containment system performance including potential system interactions
- ***10 steady state PCC component tests over a wide range of steam and air flow rates***
- ***12 transient tests representative of post-loca conditions with different configurations***

PANDA vs. ESBWR Facility Schematic



ESBWR



PANDA

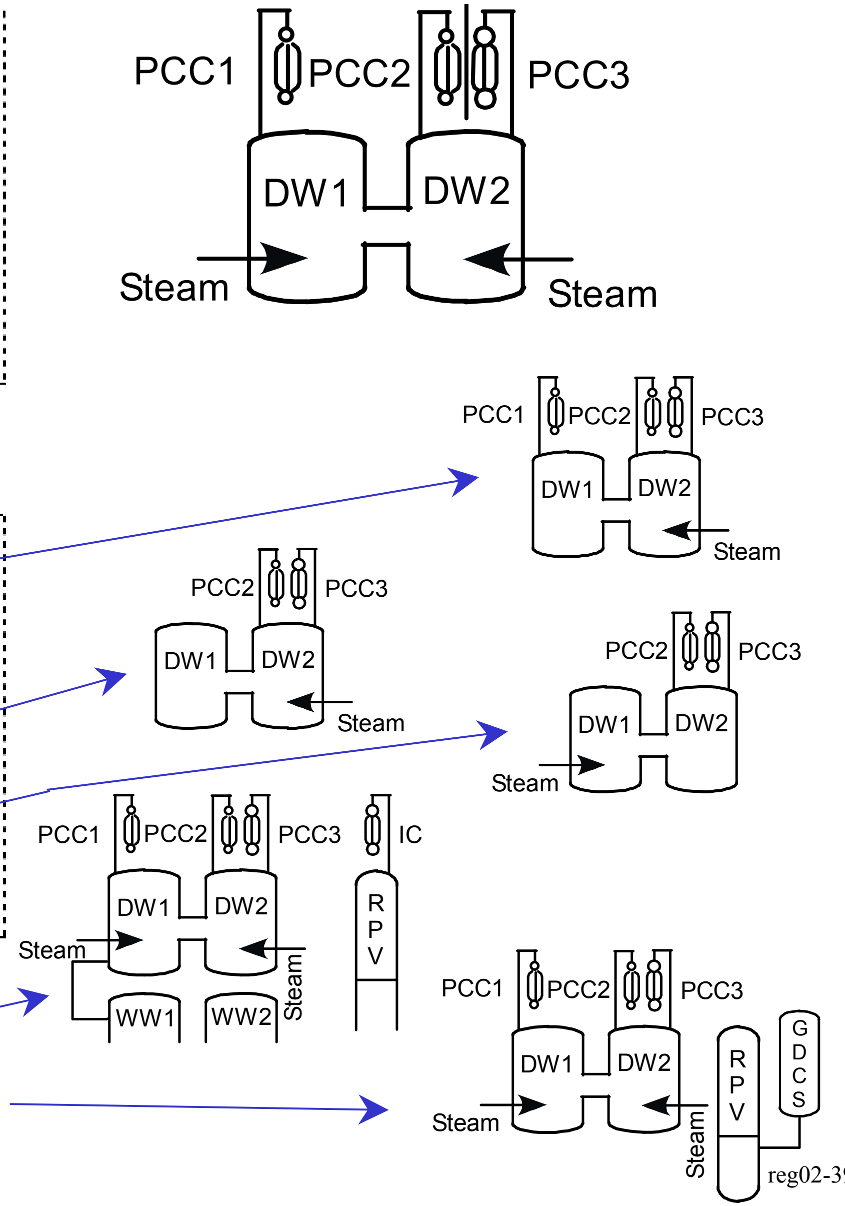
Panda Steady State Test Matrix (S-Series)

PANDA Test No.	Steam Flow (kg/s)	Air Flow (kg/s)	Inlet Pressure (bar)	Remarks
S1	0.195	0	Self adjusting	Pure steam test
S2	0.195	0.003	3	Air/steam test
S3	0.195	0.006	3	Air/steam test
S4	0.195	0.016	3	Air/steam test
S5	0.195	0.028	3	Air/steam test
S6	0.260	0	Self adjusting	Pure steam test
S10	0.195	0.006	3	Repetition of S3
S11	0.195	0.028	3	Repetition of S5
S12	0.260	0	Self adjusting	Repetition of S6
S13	0.260	0	Self adjusting	Repetition of S12 with Low Pool Level (Top of Tubes)

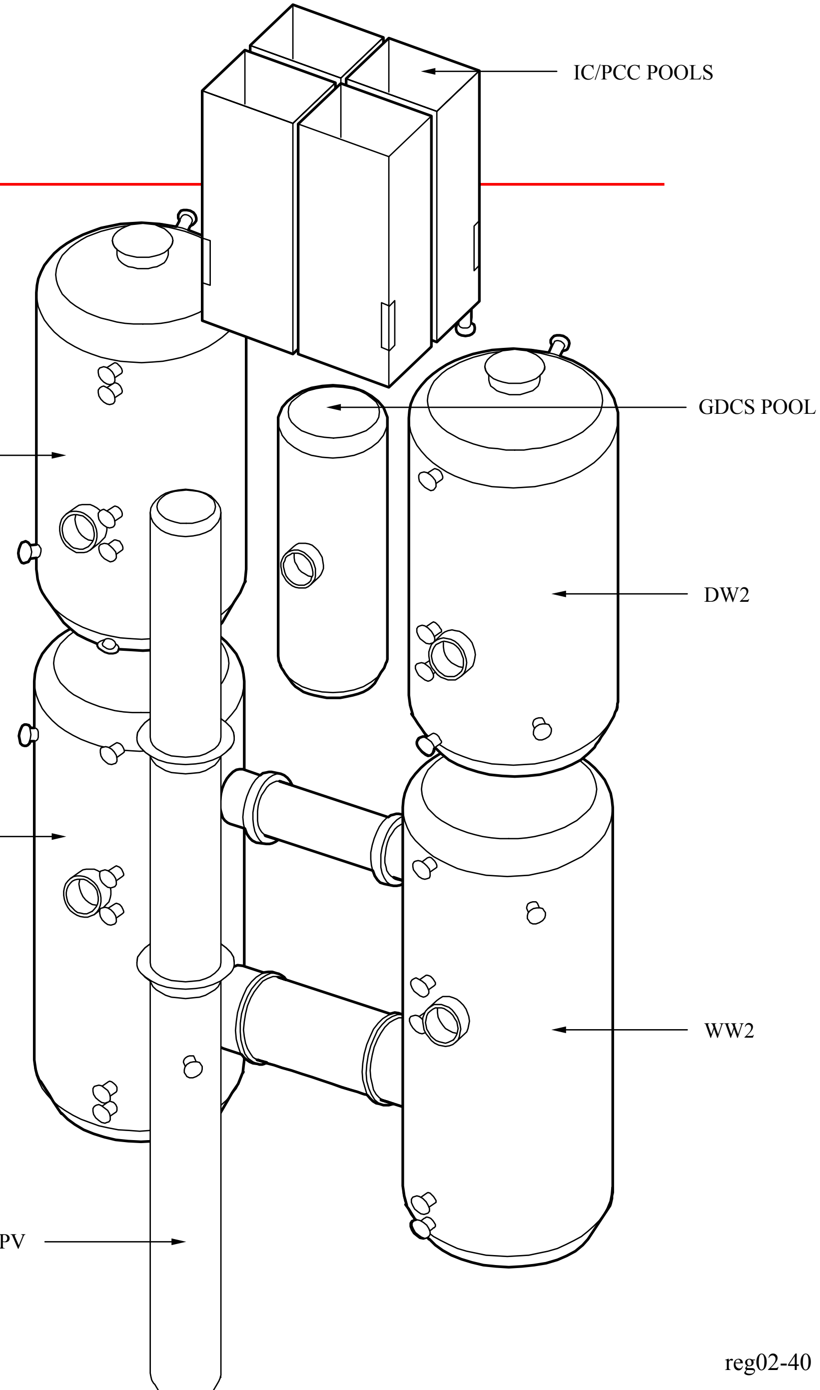
Various steam and air flow rates and pool level

PANDA Transient Test Matrix

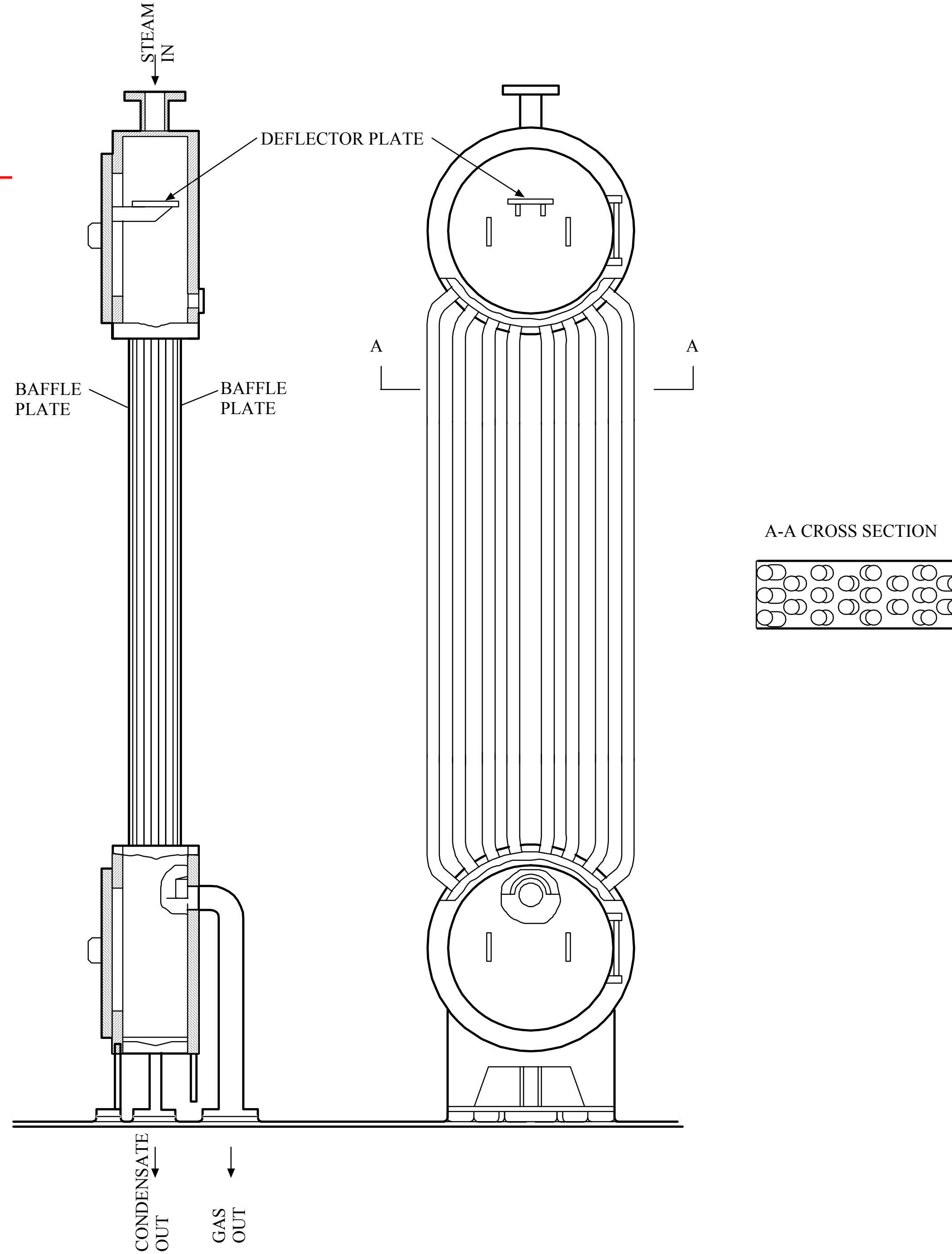
M3 Series:		
	M3	Base Case (Main steam line break LOCA + 1 hour)
	M3A	Repeatability (PCC/IC pools isolated)
	M3B	Repeatability (PCC/IC pools interconnected)
M7		PCC Startup (Bounding noncondensible gas concentrations)
M2		Asymmetric Case 1 (relative to M3 Series) (Total steam flow to DW2)
M10 Series:		Asymmetric (Two PCC units only)
	M10A	Asymmetric Case 2 (DW1 essentially isolated, slow gas migration from DW1 to DW2)
	M10B	Asymmetric Case 3 (Good mixing in both DWs)
M6/8		System Interaction with IC operation (M6) and DW-to-WW bypass leakage (M8)
M9		Early Start / GDCS injection into RPV (LOCA + 1040 seconds rather than LOCA + 3600 seconds)



PANDA Facility Isometric



PANDA IC/PCC Units



PANDA Test Facility

PANDA Test Facility

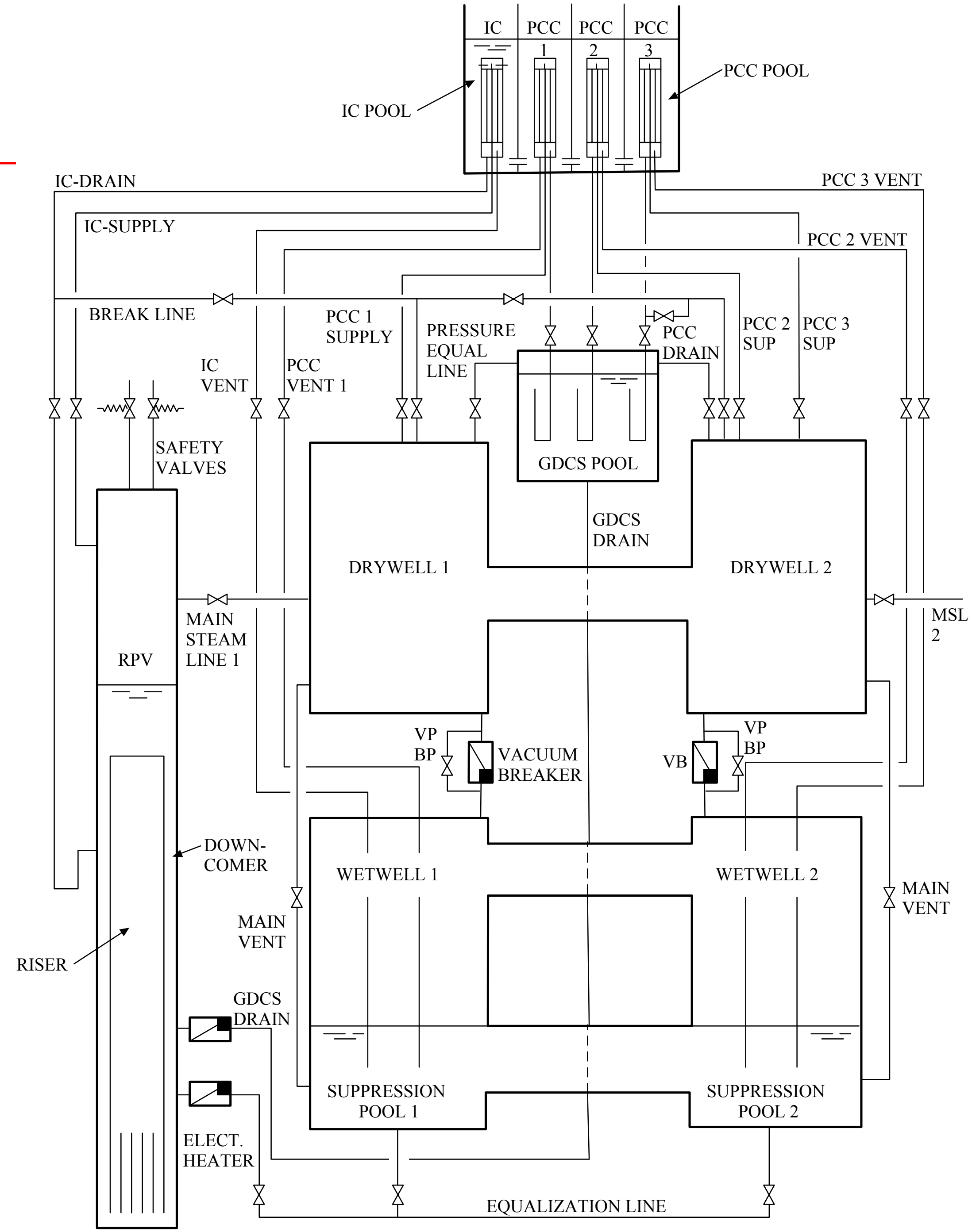
PANDA Vessel Assembly
Pressure vessels' maximum design operating conditions: $10bar_g$, 200°C.
(Worm's-eye view with building shell visible in the background.)
[PSI–LTH B12/20, Tues 23 Mar 1993]

PANDA TEST Facility

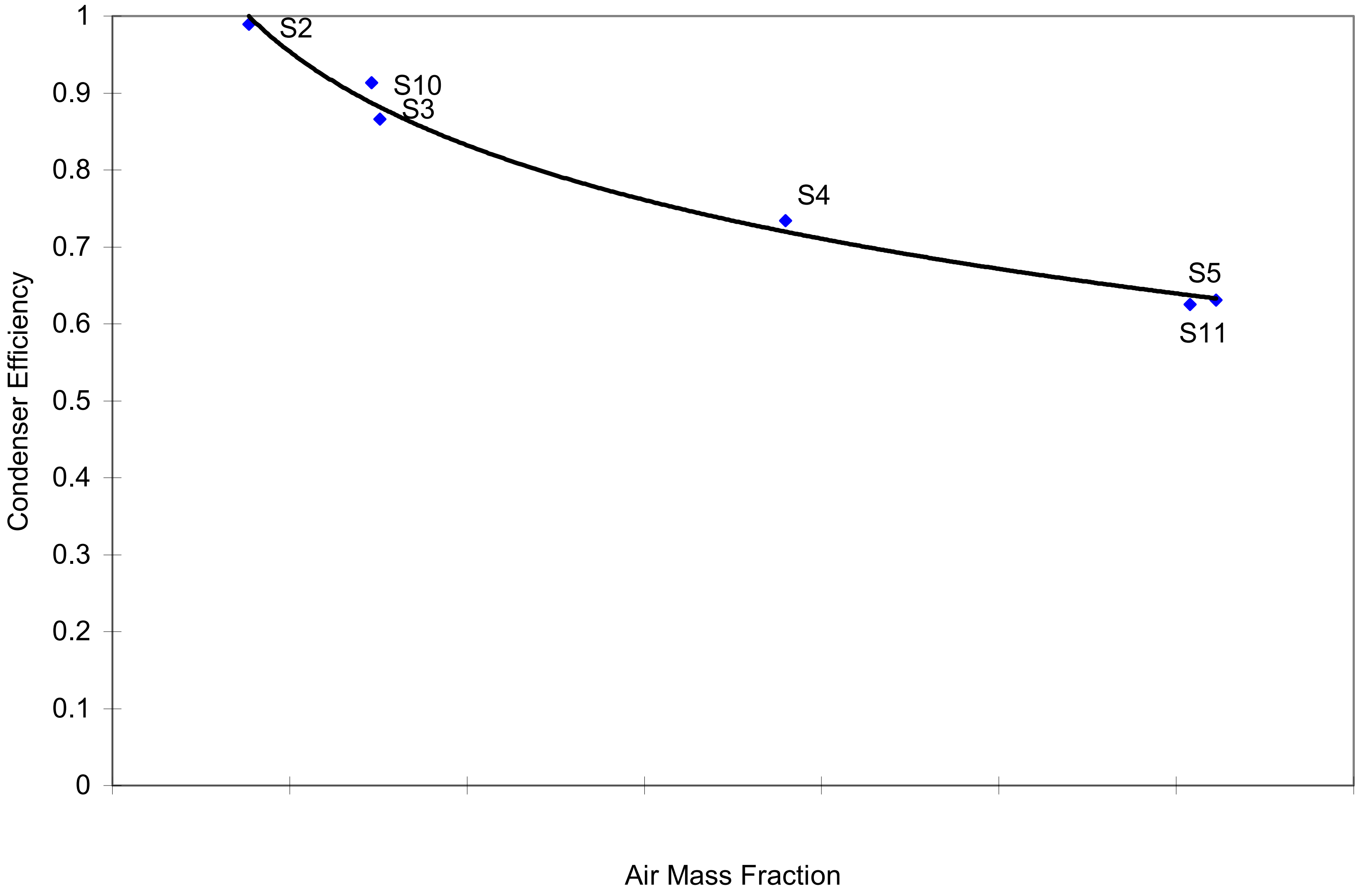
PANDA Test Facility

PANDA Test Facility (March 1993)

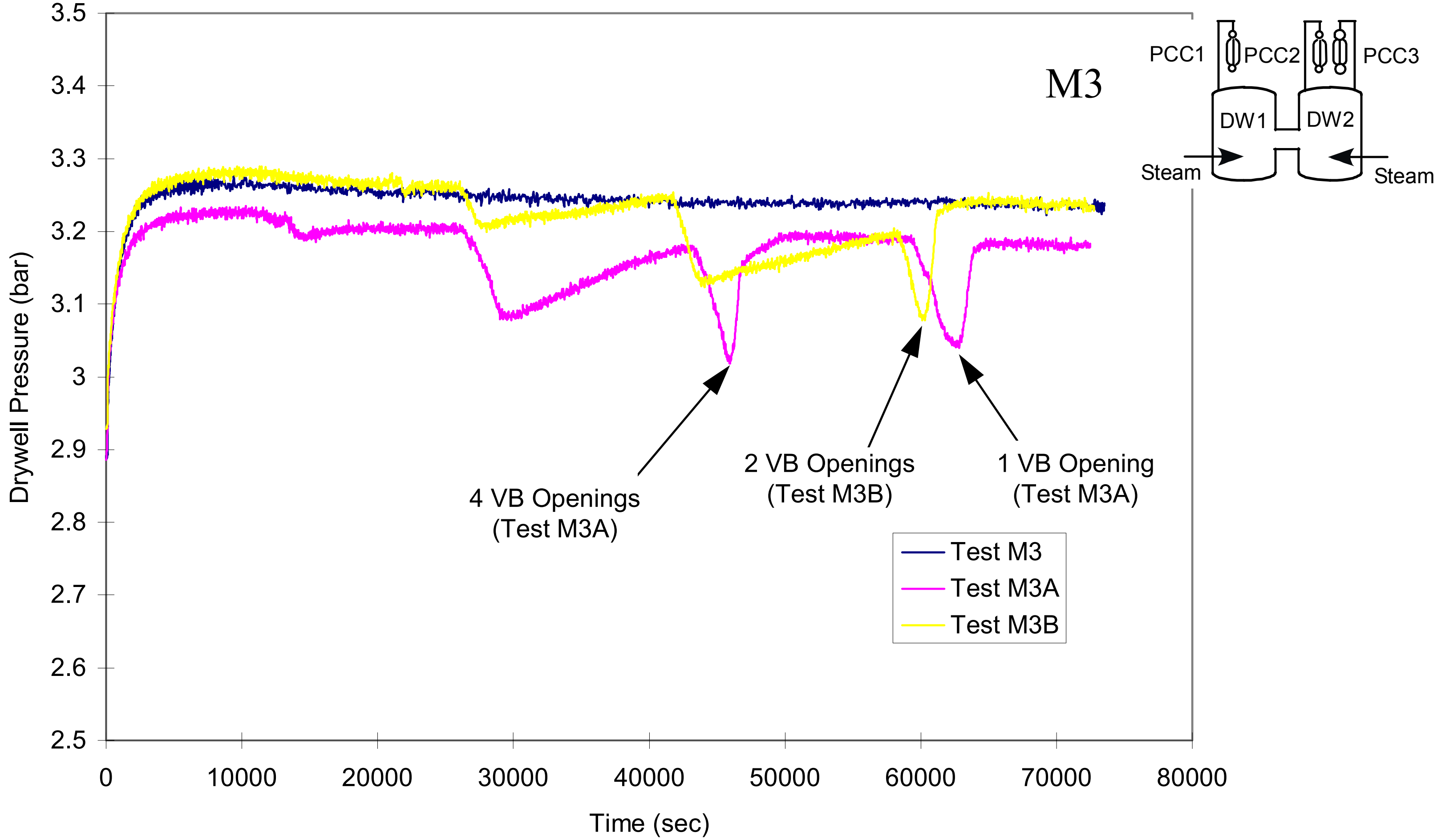
PANDA Schematic (backup)



Effect of Air Mass Fraction on PANDA S-series Tests

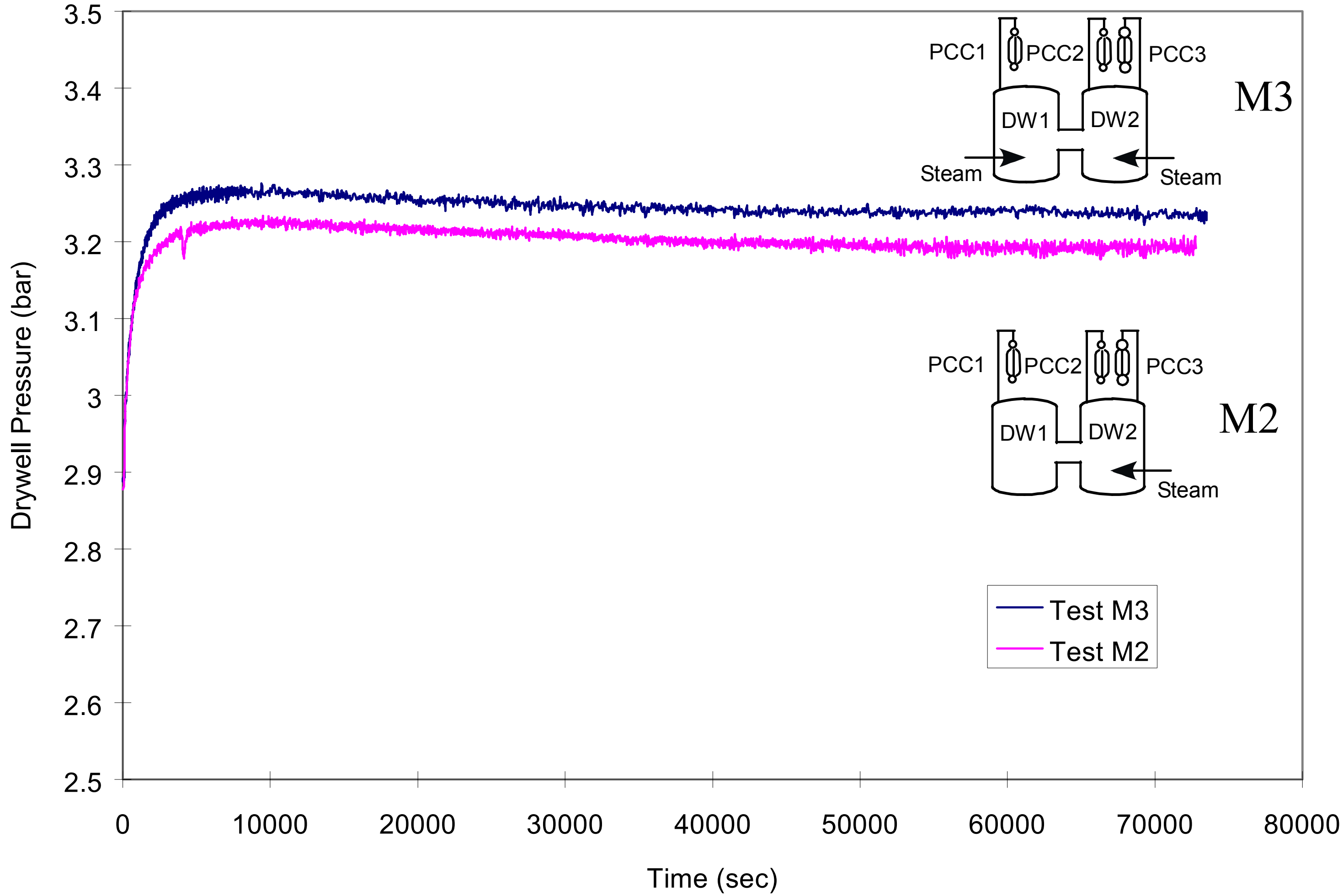


PANDA Tests M3, M3A, M3B Drywell Pressure Response



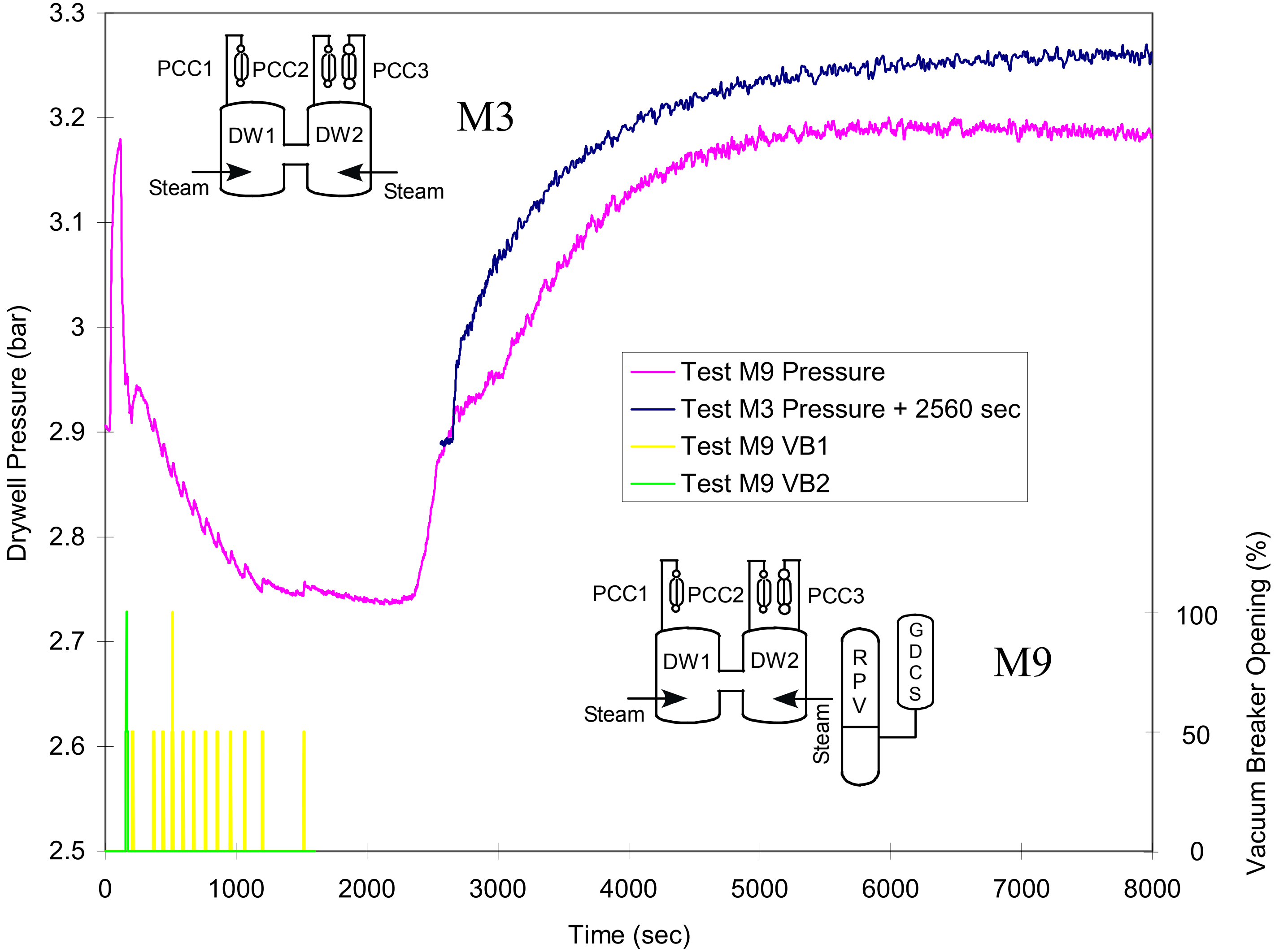
Transient details including repeated VB openings do not affect final pressure

PANDA Tests - Effect of Asymmetric Steam Injection

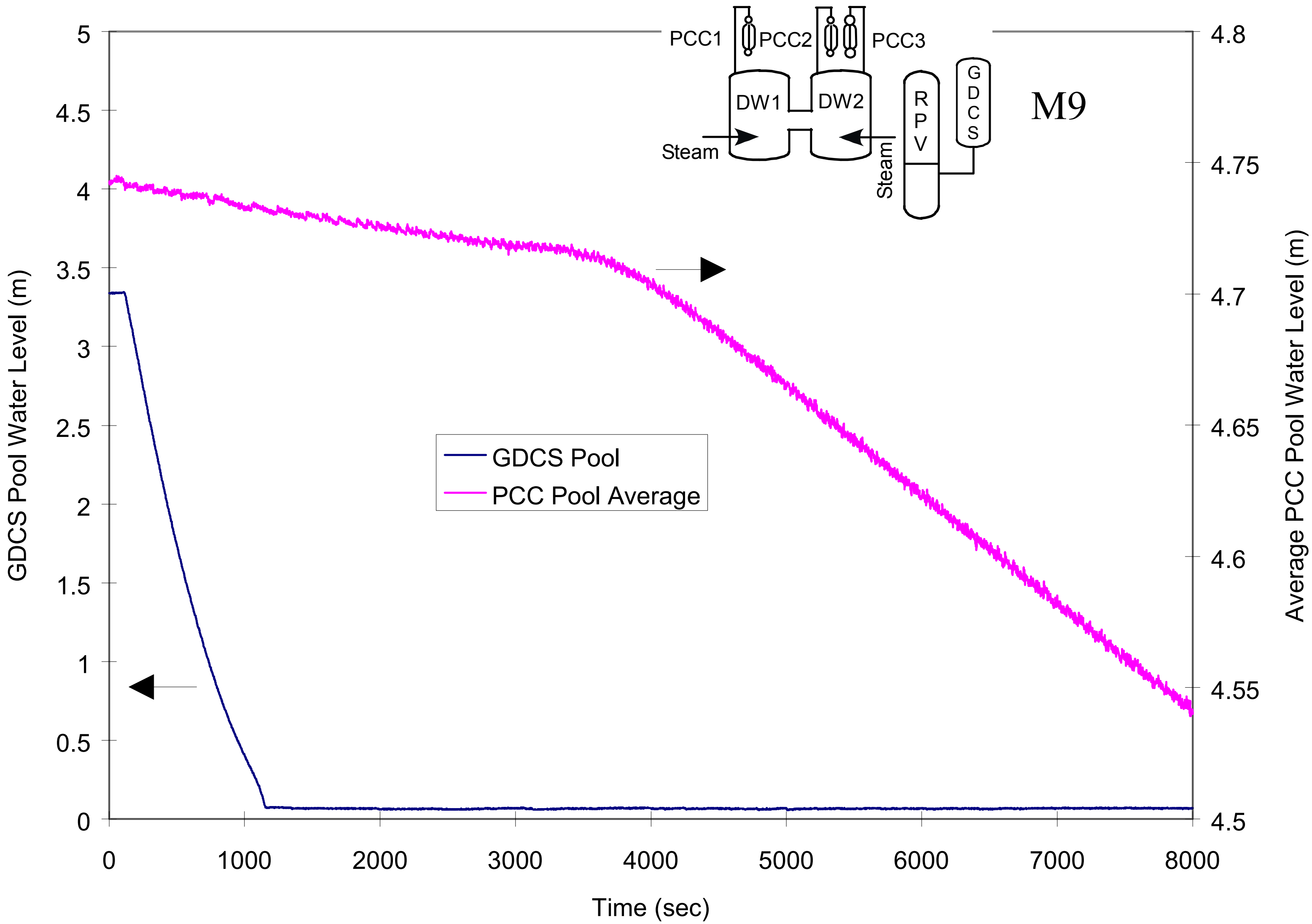


Non-condensable distribution has small effect

PANDA Early Start Test



PANDA Early Start Test (Cont'd)

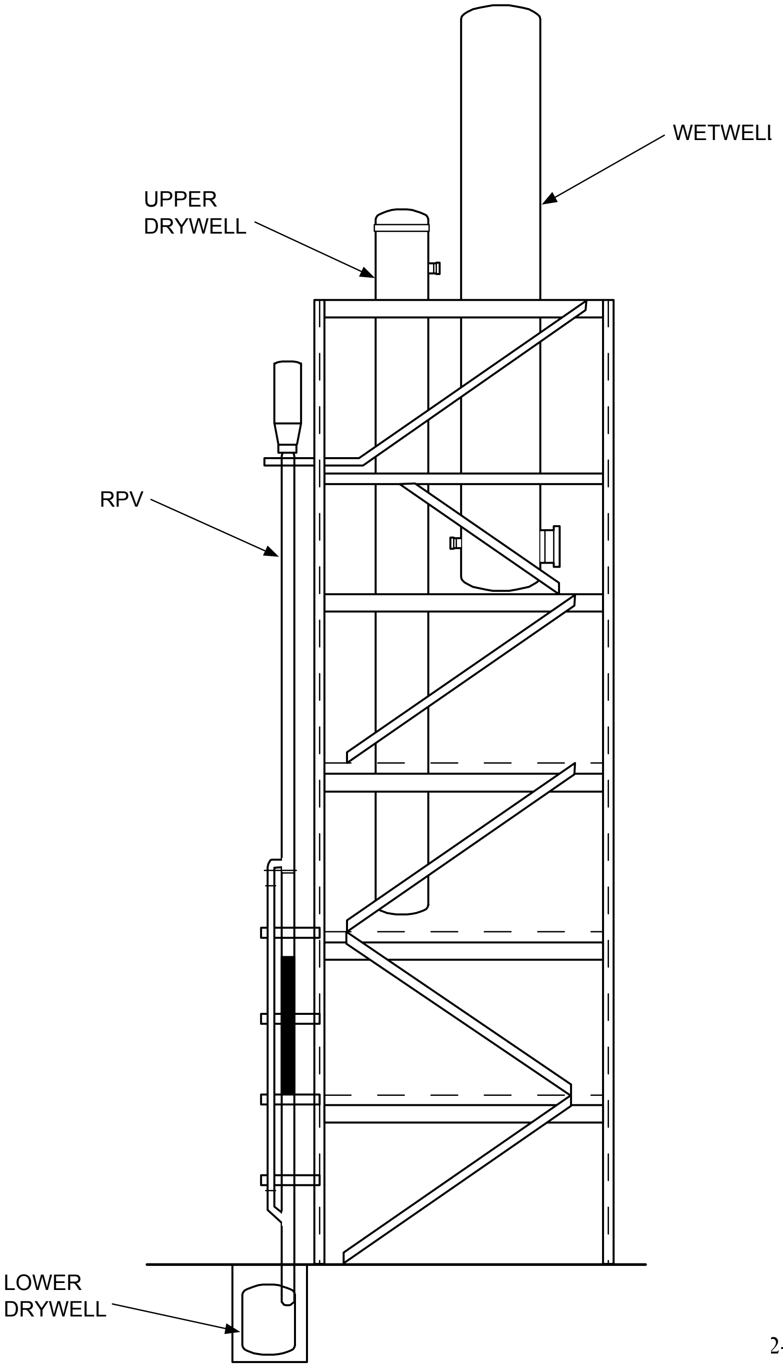


PANDA S and M Series Conclusions

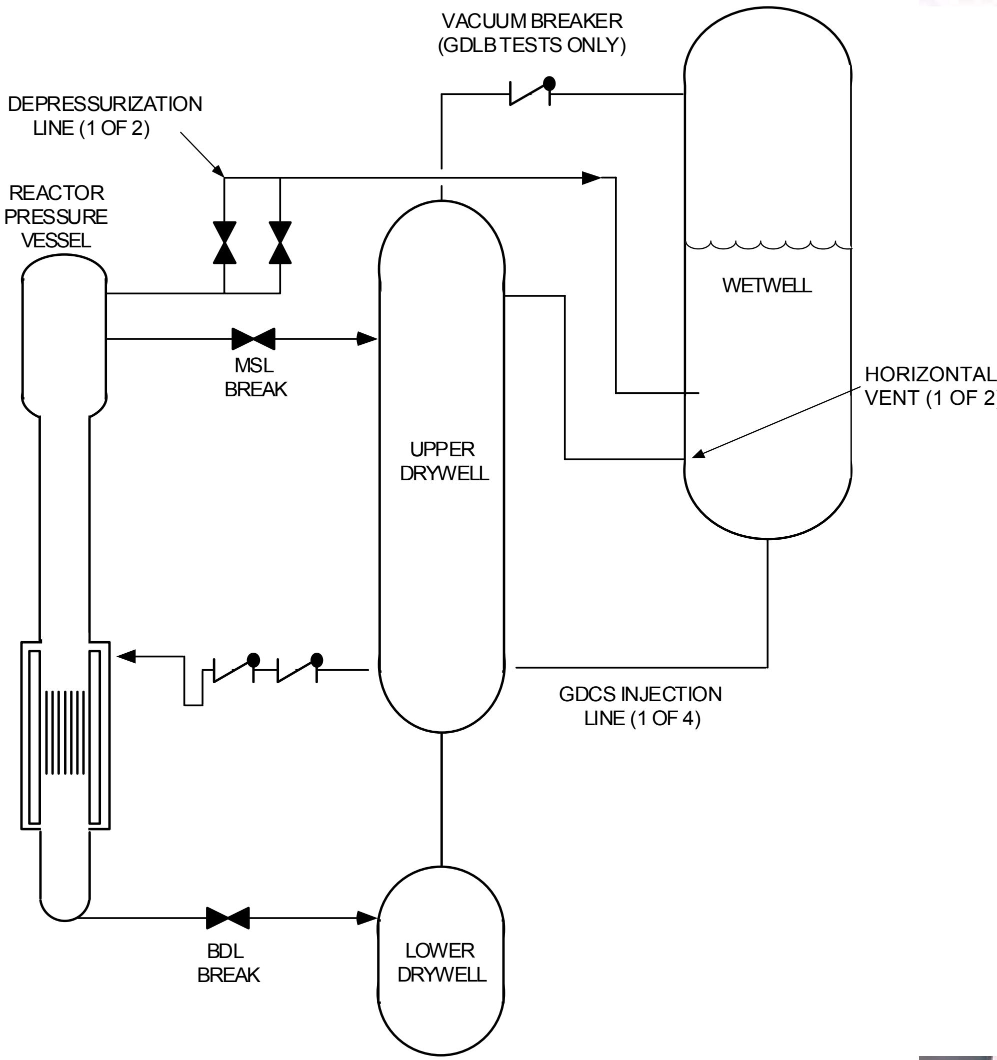
- ***Overall containment pressure and temperature response is favorable -- SBWR containment design is robust***
- ***PCCS has large margin to remove decay heat after 1 hour into a LOCA***
- ***The PCCS is well behaved and effective in transporting decay heat from the DW to the PCCS pools with no significant deposition of heat in the WW***
- ***The PCCS units share the heat load among themselves as needed***
- ***The PCCS is capable of starting up and removing heat under the most bounding conditions (i.e., pure noncondensible gas in condensers and DW)***
- ***Asymmetries and disturbances of system operation and distribution of noncondensible gases affect the operation of individual PCC units, but do not affect the overall system behavior***
- ***The IC operation has a positive effect on DW-to-WW leakage***

GIST

- ***Objectives***
  - Demonstrate technical feasibility of GDCS concept
  - Database for qualification of TRACG (codes) to predict GDCS initiation times, flow rates and RPV water levels
- ***26 tests representing a range of conditions encompassing 3 LOCA's and a no break condition***
- ***Conclusion***
  - Confirmed the technical feasibility of the GDCS concept under various LOCA scenarios



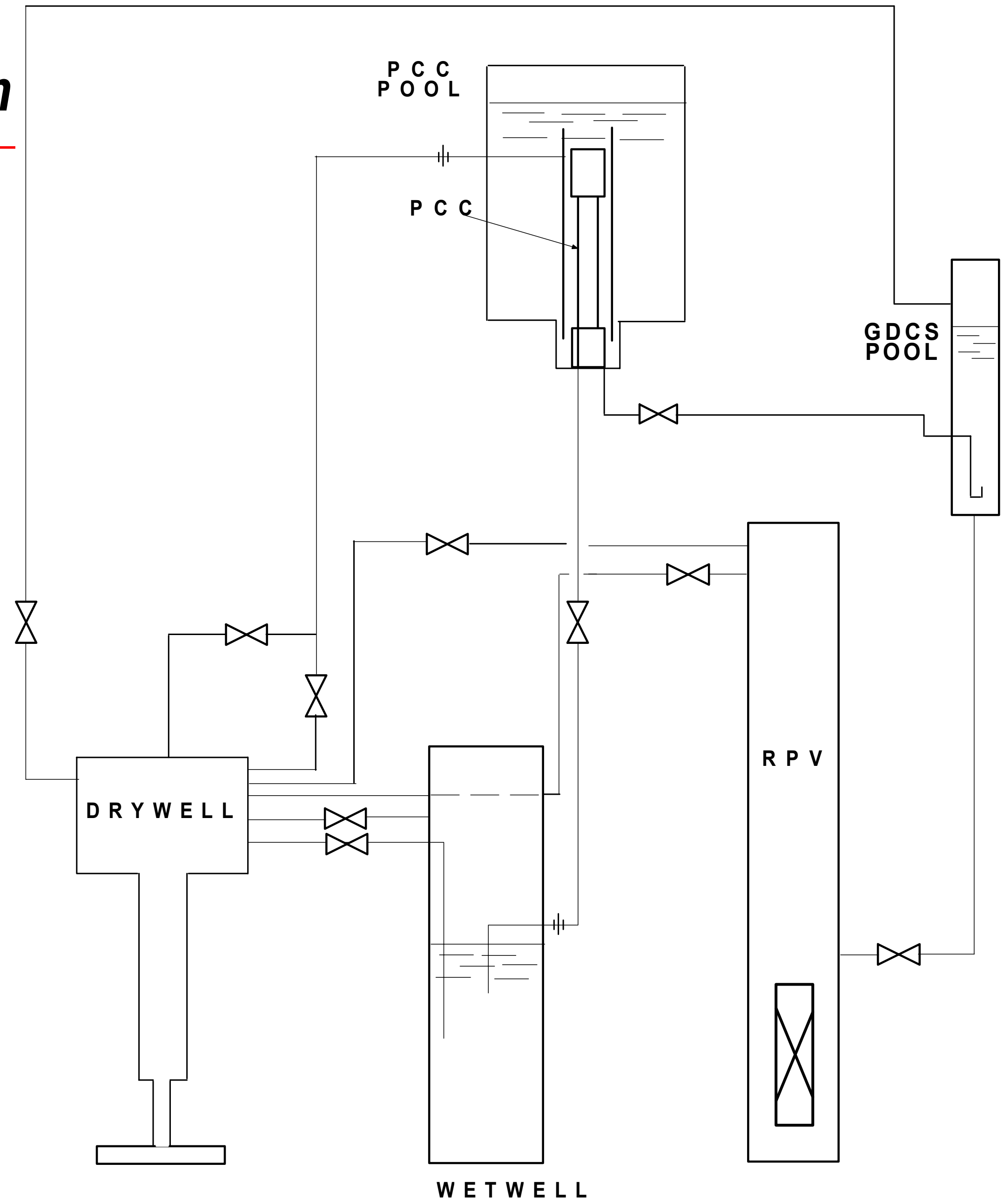
GIST Facility



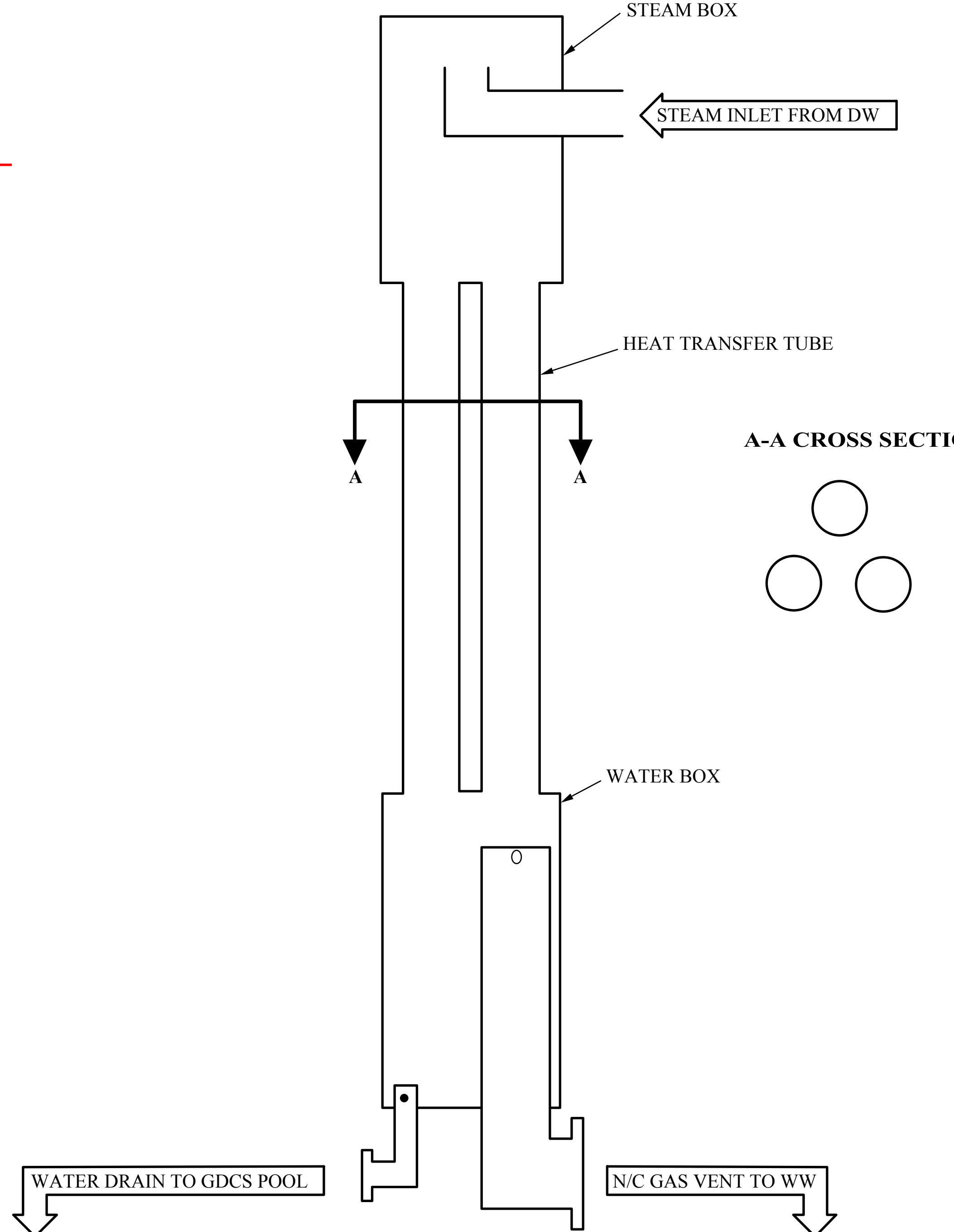
GIRAFFE

- ***3 Test series:***
  - GIRAFFE/Helium
    - Demonstrate system operation with lighter-than-steam noncondensibles including purging noncondensibles from the PCC
    - Data for TRACG (code) qualification to predict SBWR containment system performance including potential system interactions with l-t-s gas
  - GIRAFFE/SIT
    - Data for TRACG (code) qualification to predict SBWR ECCS performance during late blowdown/early GDCS phase of a LOCA - specific focus on system interactions
  - GIRAFFE/Step 1 and 3
    - Steady state performance of PCCS
    - System performance

GIRAFFE Facility Diagram



GIRAFFE PCC Unit



GIRAFFE/HE Test Matrix (backup)

GIRAFFE Test No.	Helium Injection Rate (kg/sec)	Drywell Initial Partial Pressures (kPa) and Mole Fractions (%)					
		Nitrogen		Steam		Helium	
		(kPa)	(%)	(kPa)	(%)	(kPa)	(%)
H1	0	13	4.4	281	95.6	0	-
H2	0	0	-	281	95.6	13	4.4
H3	0	13	4.4	214	72.8	67	22.8
H4	0.00027	13	4.4	281	95.6	0	-

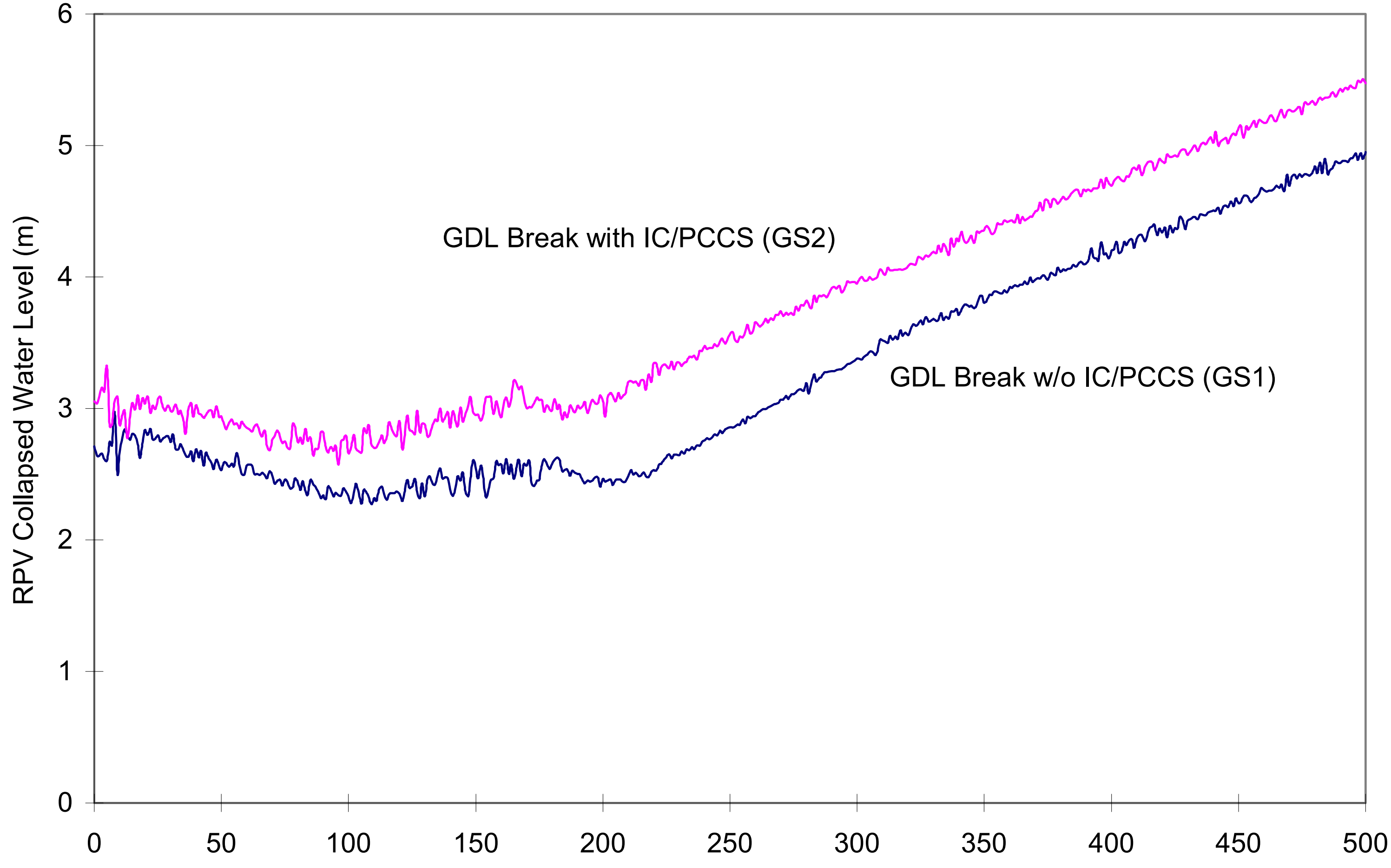
GIRAFFE/SIT Test Matrix (backup)

Objective	Option			Test ID
	Break	Failure	IC/PCC Operation	
Worst Break/Single Failure Combination	GDL	DPV	No	GS1
Benefit of IC/PCC	GDL and GDL	DPV DPV	No Yes	GS1 GS2
Slow Water Level Recovery	GDL	GDCS	Yes	GS4
Fast Water Level Recovery	BDL	DPV	Yes	GS3
Case showing GDCS void quenching and break flow depressurizing drywell	GDL GDL	DPV DPV	Yes No	GS2 GS1

Test	Break	Single Failure	IC/PCCS on?
GS1	GDL	DPV	No
GS2	GDL	DPV	Yes
GS3	BDL	DPV	Yes
GS4	GDL	GDCS	Yes

GDL = Gravity Drain Line
BDL = Bottom Drain Line
DPV = Depressurization Valve
GDCS = GDCS Injection Valve

GIRAFFE/SIT Tests - Effect of IC and PCCS on Downcomer Level

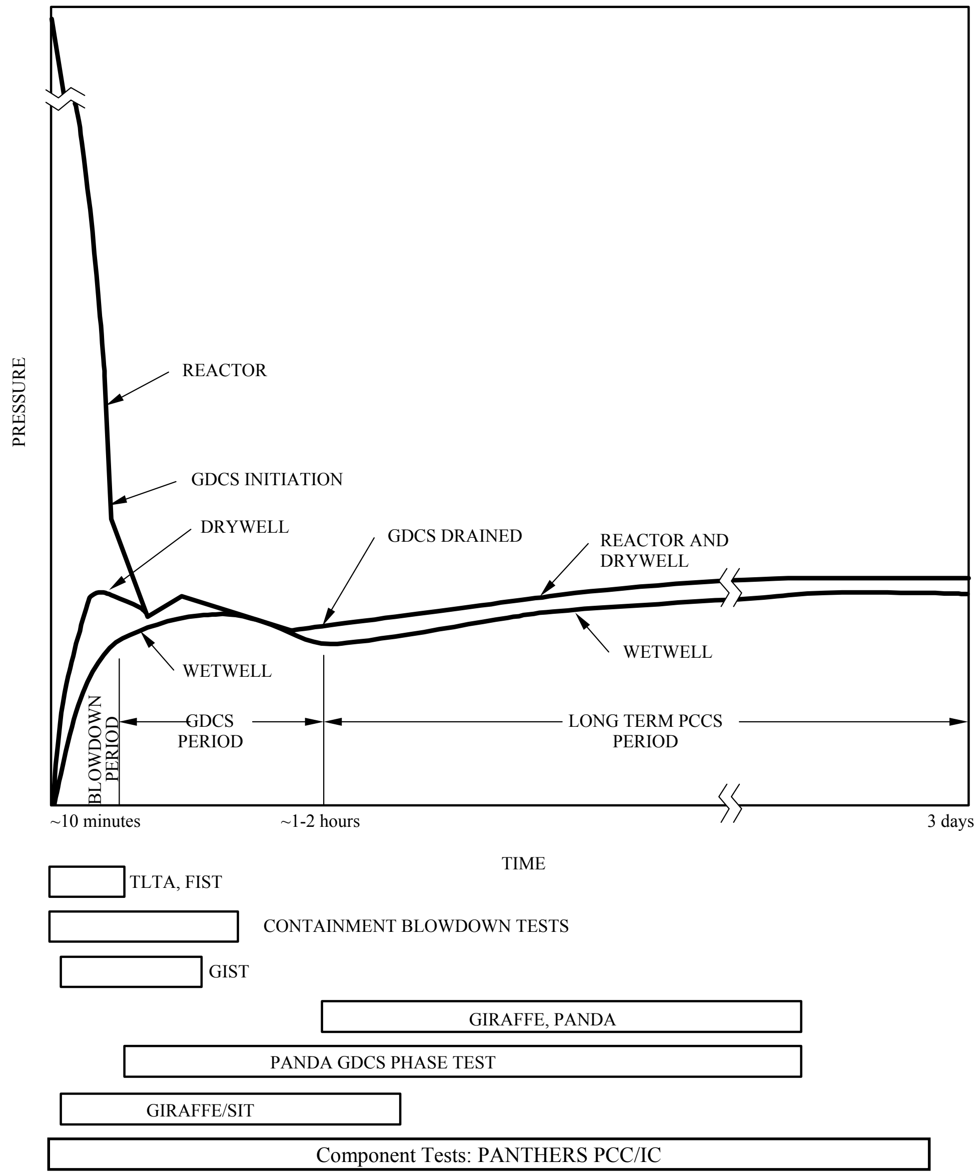


Addition of Condensers is Beneficial to Response – No Adverse Interaction

GIRAFFE Conclusions

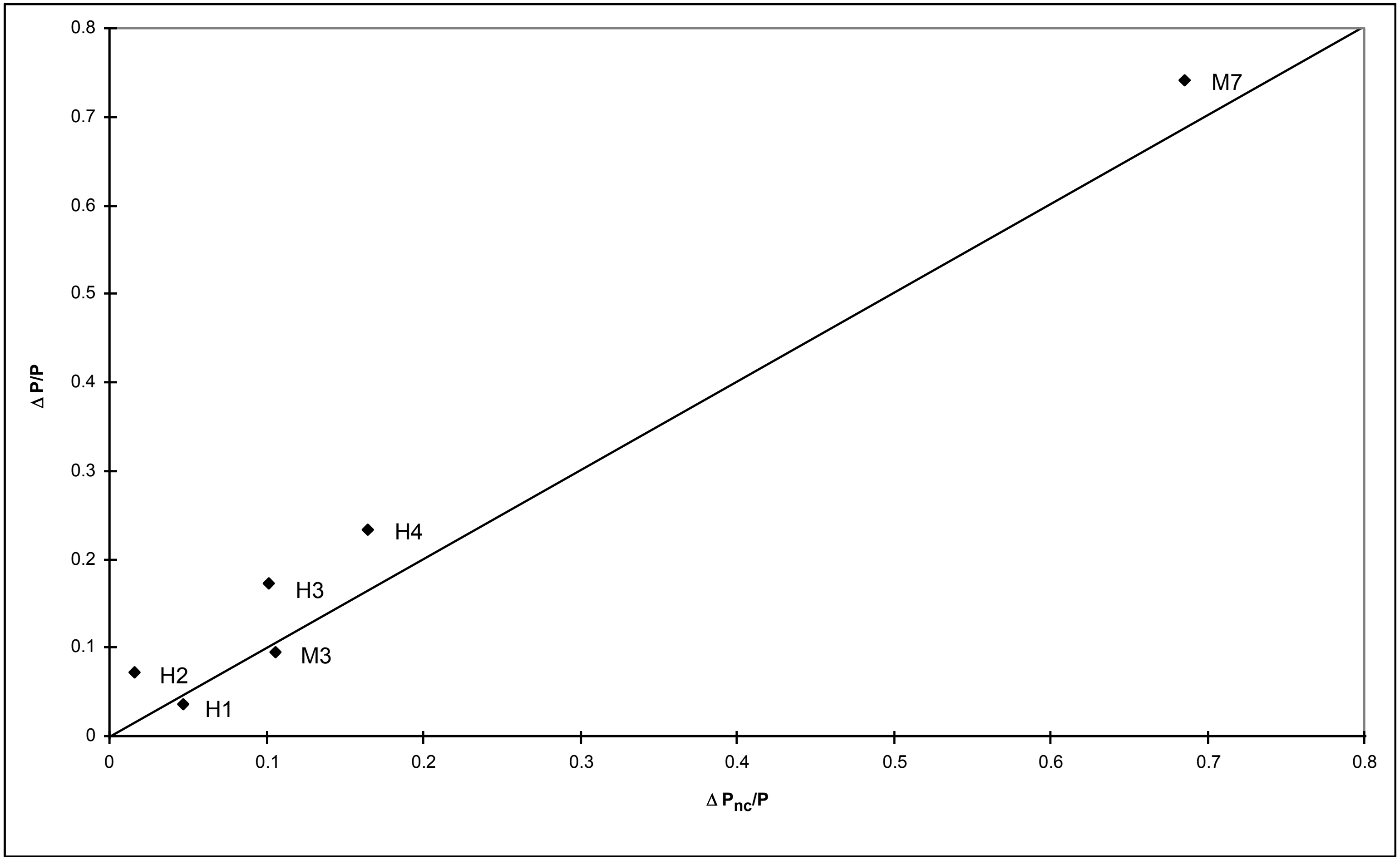
- ***GIRAFFE/Helium***
  - The PCCS operates in the presence of lighter-than-steam noncondensible gases and maintains containment pressure, even with high concentrations of noncondensible gases
  - The PCCS vents lighter-than-steam noncondensible gases, as necessary, to maintain operation
  - Heavier-than-steam gas tends to collect in the bottom of the PCC, while lighter-than-steam-gas tends to distribute throughout the PCC
- ***GIRAFFE/SIT***
  - IC operation has a positive effect on RPV inventory
  - PCC operation has a favorable effect on containment pressure
  - No adverse system interactions occur among the SBWR safety systems during the blowdown and reflood of the RPV
  - These tests confirm the validity of the GIST tests which did not incorporate the IC or PCCS

Integral Test Coverage for ESBWR LOCA



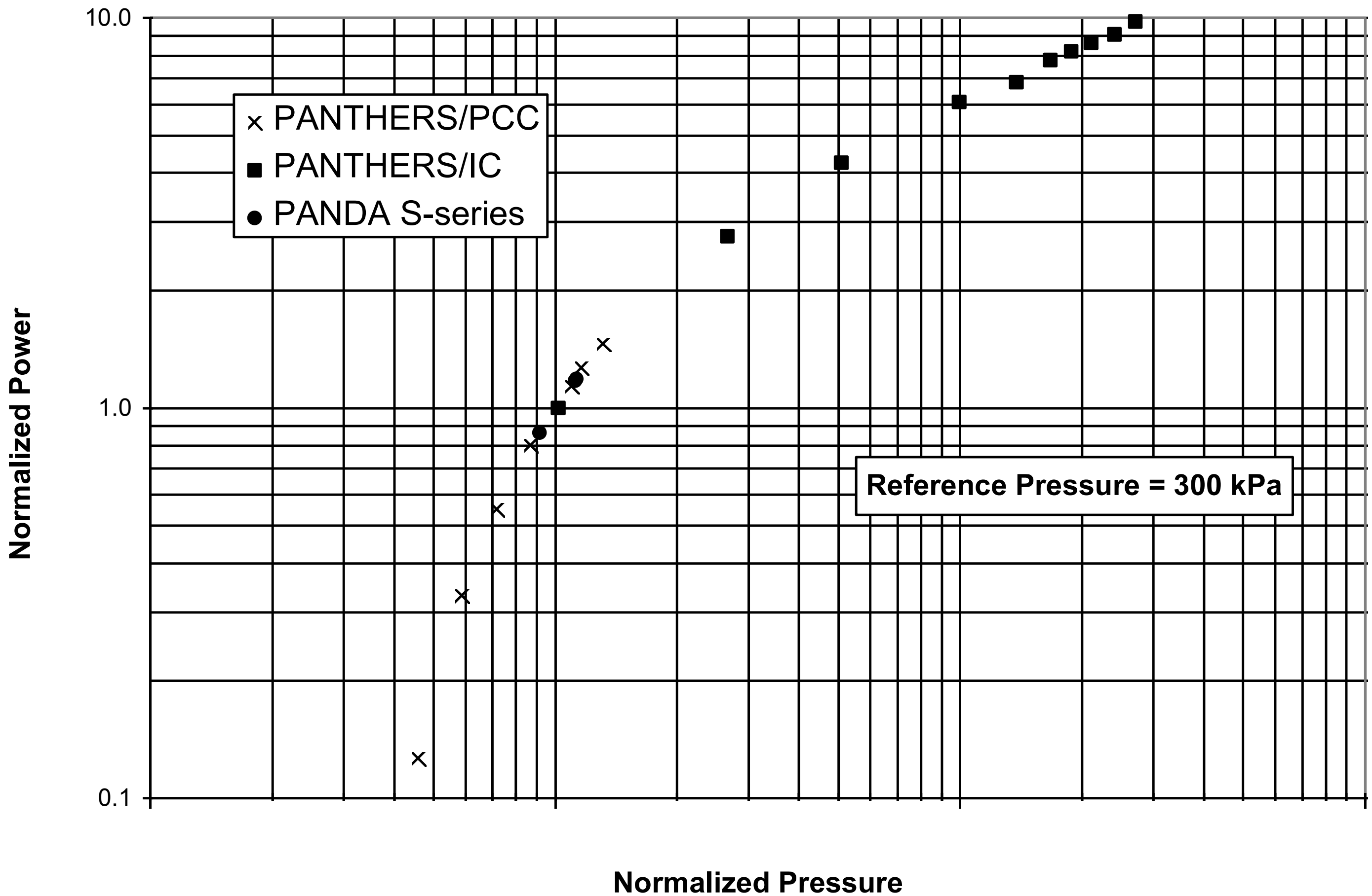
Cross-comparison of Tests Results

Effect of N/C Gas Transport on Wetwell Pressure



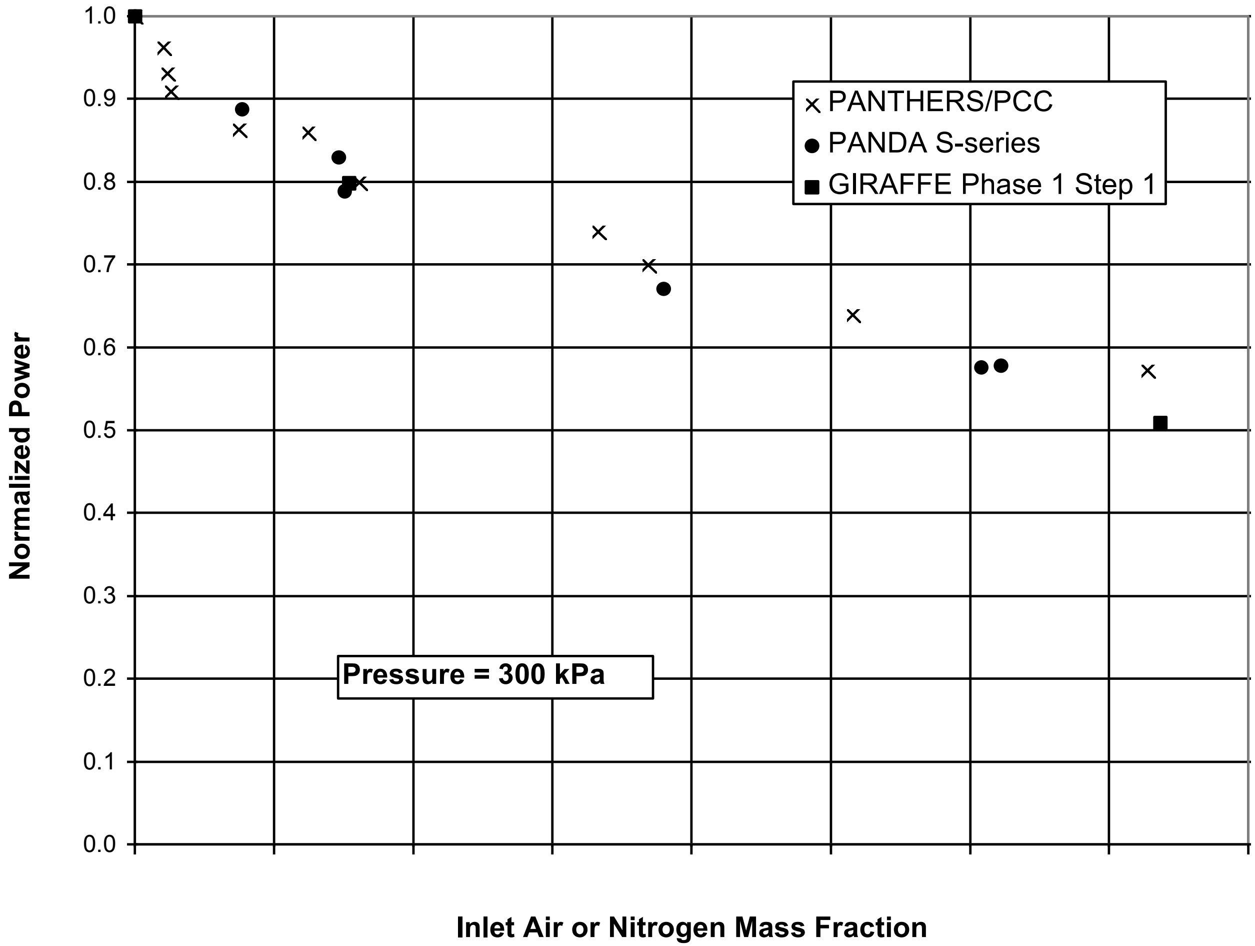
Containment Pressure Varies with Non-condensable Gas Quantity in Wetwell

PCC/IC Performance - Data at Different Pressure and Scale



No Scale Effects in IC/PCC for Pure Steam

PCC Performance - Effect of Non-condensables at Different Scales



No Scale Effects on PCC Performance with Non-condensable Gas

Conclusions from Comparing Test Programs

- ***PCC/IC's are Readily Scalable***
  - PANDA IC/PCC is a section of PANTHERS IC/PCC
  - PANTHERS PCC is a slice of ESBWR PCC
  - GIRAFFE PCC has significantly different header configuration
- ***Containment pressure varies with non-condensable gas quanitity in wetwell for different scales and different gases***

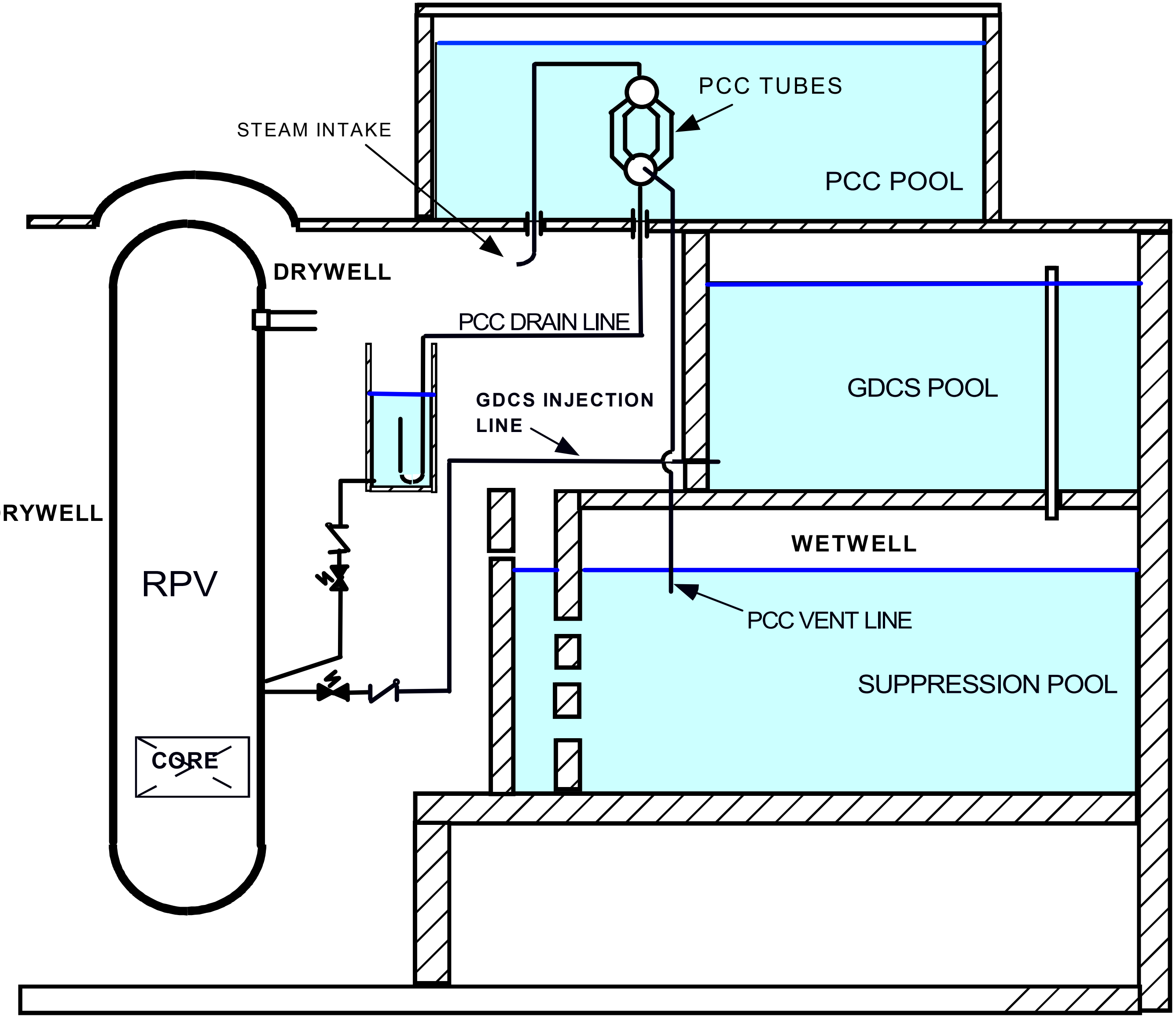
Outline

- SBWR Technology Program
- ESBWR Containment Modifications from SBWR
- ESBWR Technology Program
- Conclusions

ESBWR System Modifications

- ***Made GDCS part of WW***
  - Increased WW/DW volume ratio
  - Utilizes GDCS pool draindown space to provide increased wetwell volume
  - PCC Drain Tank added in DW
- ***Power Increased***
  - Number of ICs increased from 3 to 4
  - Number of PCCs increased from 3 to 4
  - PCCS Expanded from 10MW to 13.5MW per unit

ESBWR Design Modifications



Outline

- ***Past Technology Program - SBWR***
- ***ESBWR Containment Modifications from SBWR***
- ***ESBWR Technology Program***
- ***Conclusions***

Additional testing for ESBWR configuration

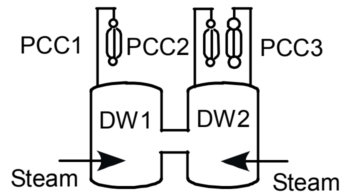
- ***Decay Heat Removal***
  - 8 Integrated system tests run in PANDA - TEPSS
  - Pre- and post-test predictions
    - TRACG, TRAC-BF1, RELAP5 and MELCOR

- ***Natural circulation tests at CRIEPI***

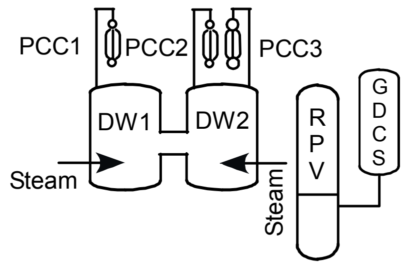
Multi-year program extended the SBWR database to ESBWR

PANDA-P Series (TEPSS) Test Matrix

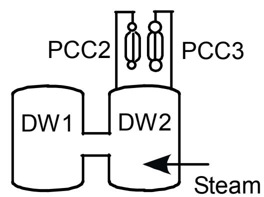
P1: Base Case
MSL Break + 1 hr
(long-term cooling phase)



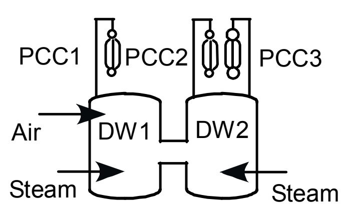
P2: Early Start
MSL Break + 20 min
(transition from GDCS injection to long-term PCCS cooling phase)



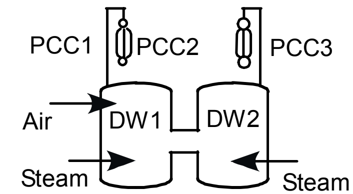
P3: PCCS Start-up
DW initially filled with air
(deomonstrate PCCS start-up
Under challenging conditions)



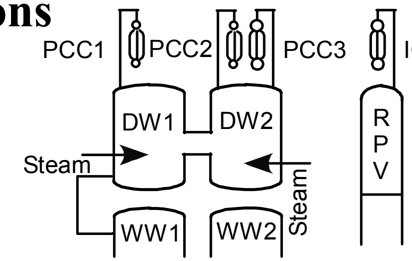
P4: Trapped Air in DW
Air released during transient
(investigation of how n/c gas
Affects PCCS performance)



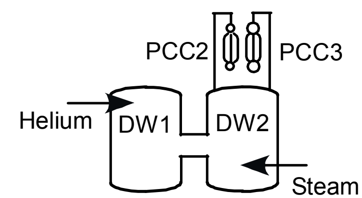
P5: Symmetric Case
PCC2 Isolated, air supply to DW later in transient
(MV clearing phase caused by
Reduced PCC capacity)



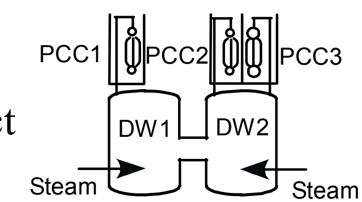
P6: Systems Interactions
ICs and PCCs in parallel,
DW1 to WW1 leakage
(is PCC performance
adverseley affected?)



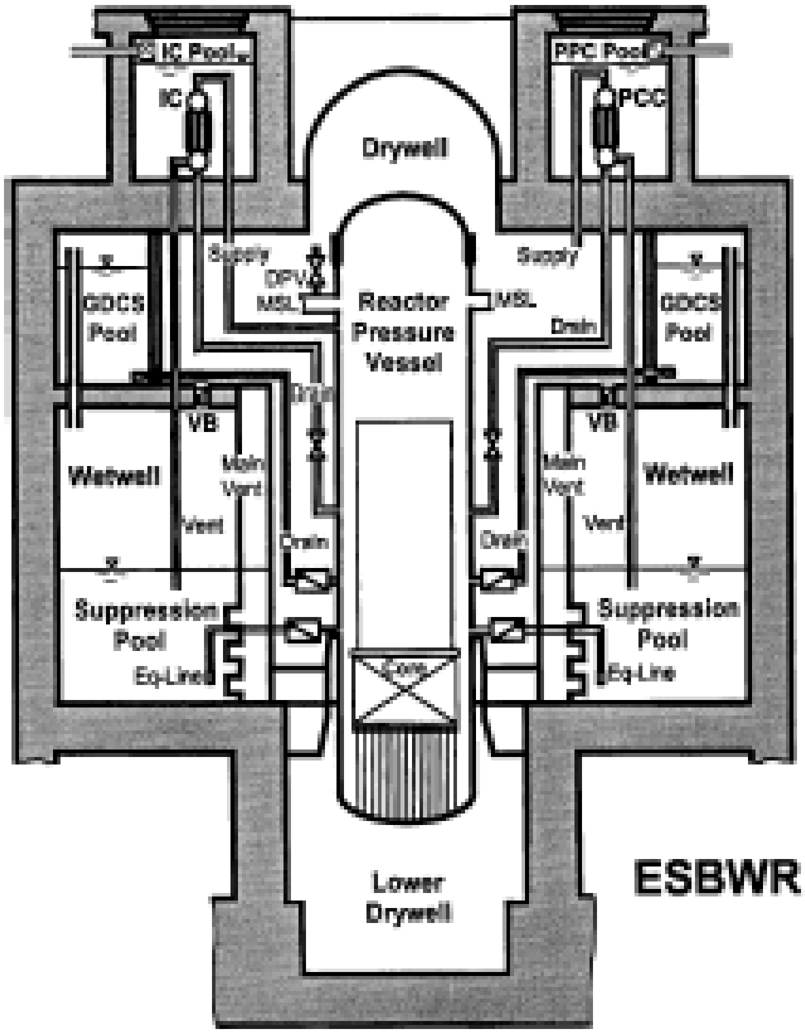
P7: Severe Accident
All break flow to DW2,
PCC1 isolated,
He supply to DW later in transient
(simulation of hydrogen release
And reduced PCC capacity)

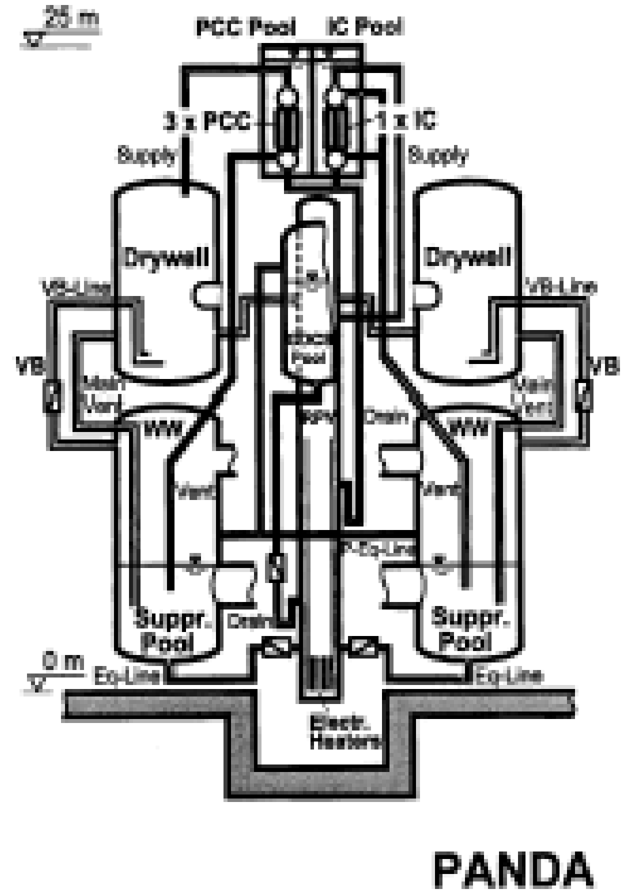


P8: PCC Pool Boil Down
Extension of Base Case, P1
(how do PCC pool levels affect
containment performance)



ESBWR vs. PANDA Facility Schematic

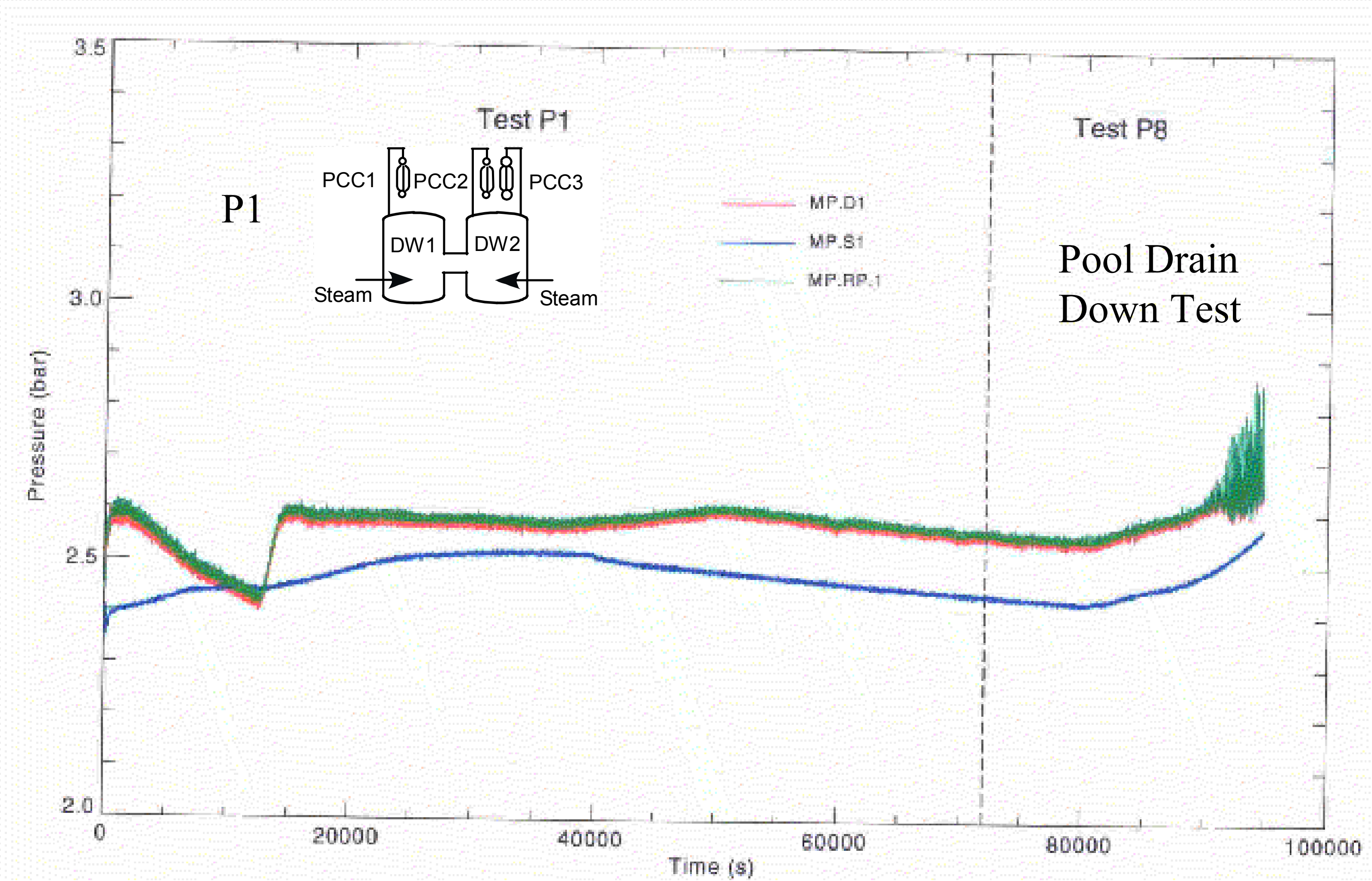




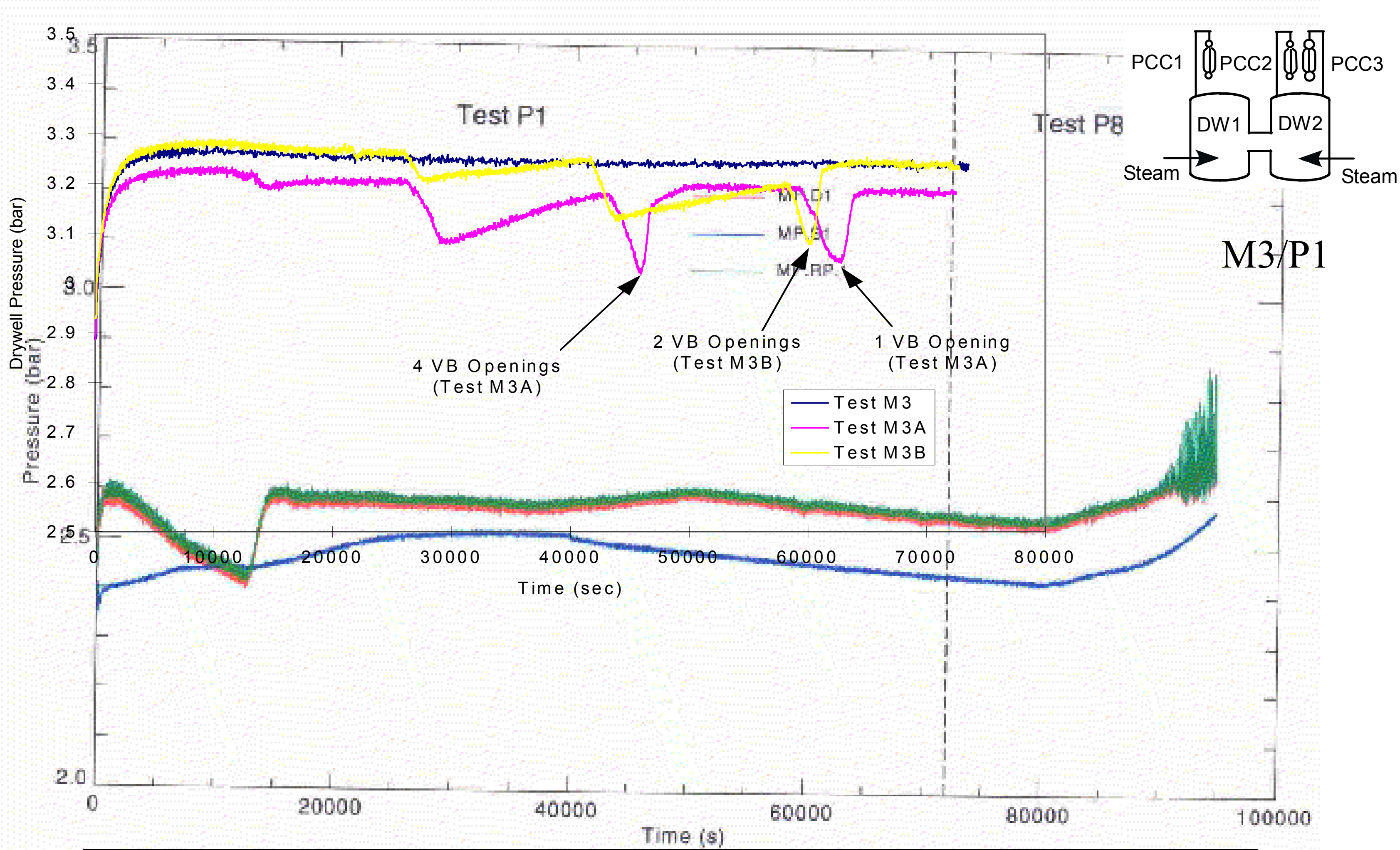
PANDA TEPSS Test

- ***~1:40 scale integral test facility***
- ***Objectives***
  - Testing of new containment features with respect to: PCCS long-term performance, PCCS start-up and systems interaction and distribution of steam and gases within the containment
  - Database to confirm the capability of TRACG to predict ESBWR containment system performance, including potential systems interaction effects
  - Effect of lighter-than-steam gas on system behavior
- ***Conclusions***
  - All objectives met
  - Containment system operated robustly over all conditions tested
  - No change in systems interaction from moving GDCS pool to wetwell

TEPSS Test P1 and P8 Drywell Pressure Response

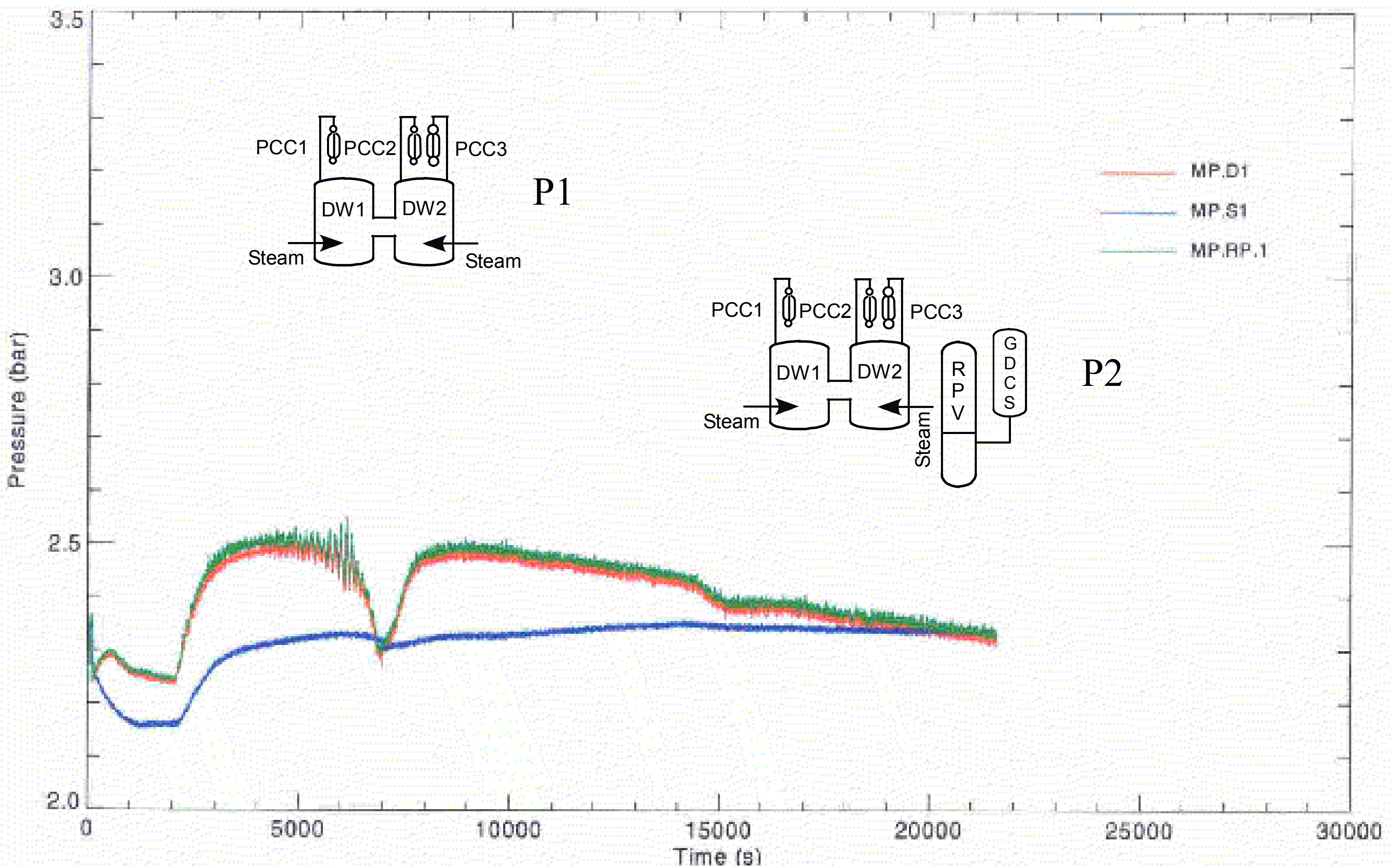


Comparison of SBWR and ESBWR PANDA Base Tests

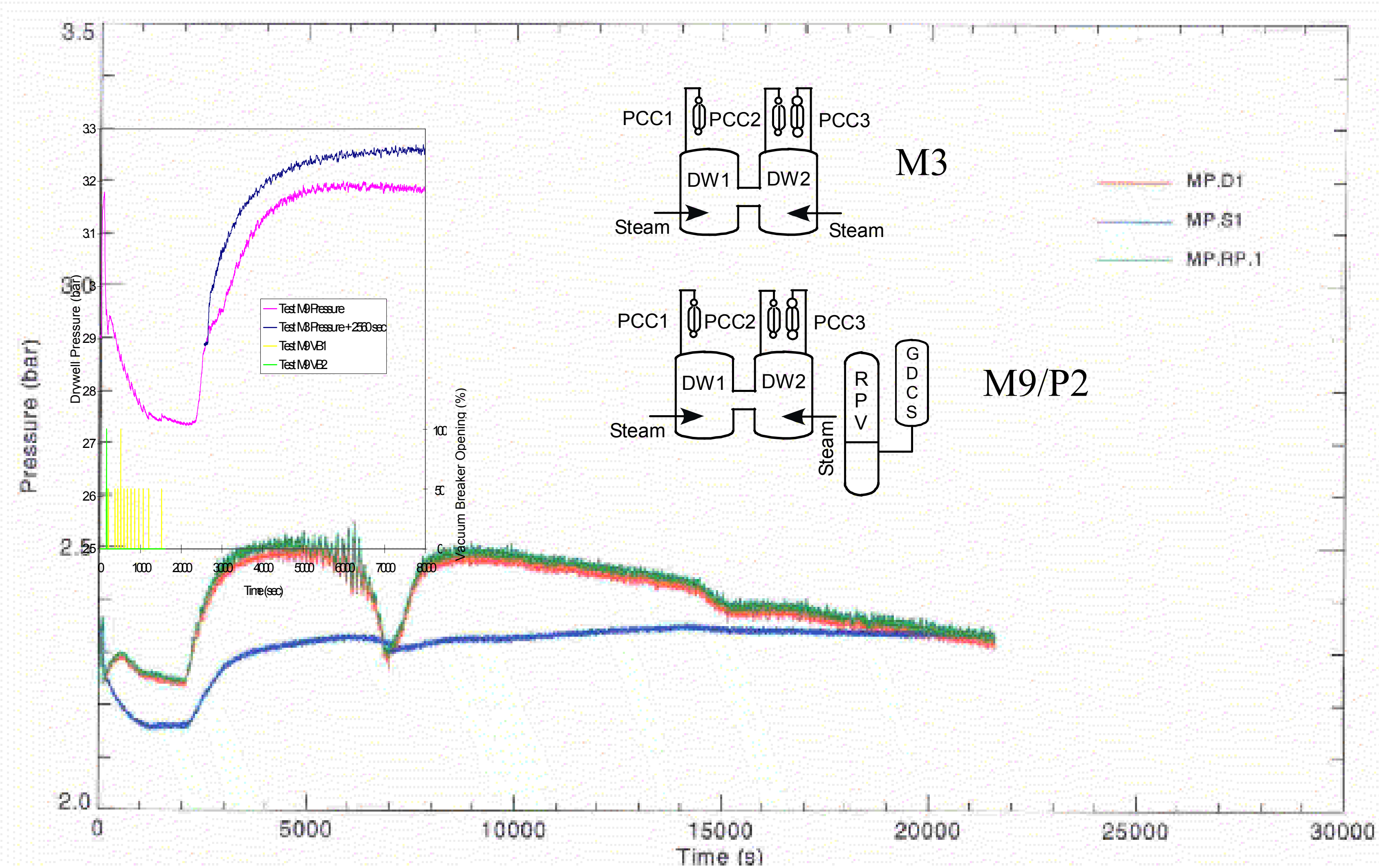


Pressure is reduced for ESBWR test due to addition of GDCS in WW – behavior is similar to SBWR test

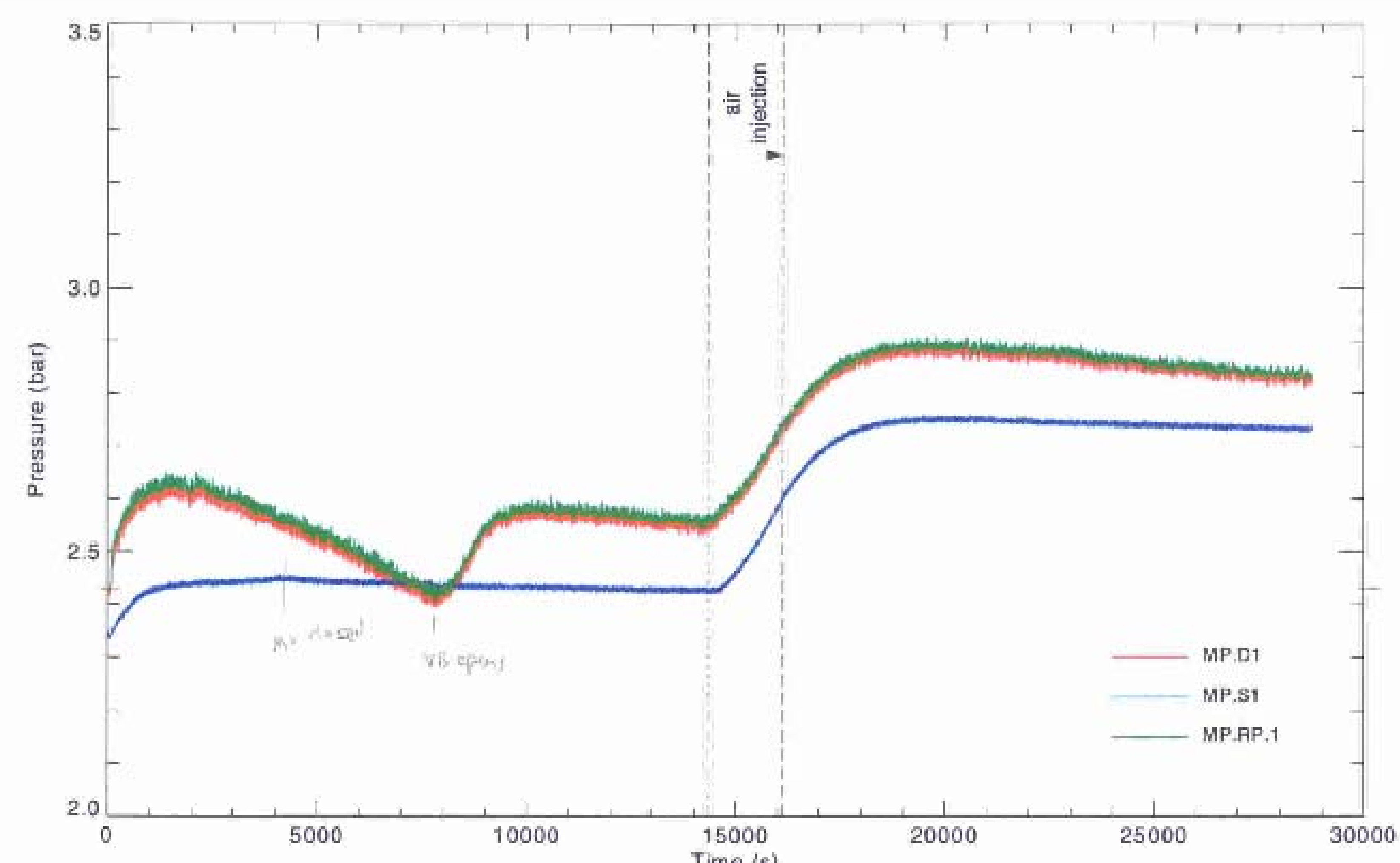
PANDA Early Start Test



PANDA Early Start Test



Effect of Additional Late Air Release on System Performance



PCC performance is quickly recovered -- containment pressure increases due to additional air mass

Containment Testing Conclusions

- ***Extensive database obtained for TRACG Qualification***
- ***Robust behavior of ESBWR containment demonstrated***
  - ESBWR containment modifications improve pressure performance
  - Significant margins for Design Basis Accidents
  - Asymmetry effects not important
  - System interactions do not adversely effect performance
- ***PCCS capabilities confirmed***
  - Start-up and long-term operation with noncondensibles confirmed
  - Heat removal capability adequate over the range of conditions expected in ESBWR
  - Good performance with both light and heavy noncondensibles
  - Scalable technology

Testing Program Summary

- ***Extensive technology program for features new to SBWR***
  - Component tests
  - Integral tests
- ***Additional Tests to extend database to ESBWR***
- ***Testing used to qualify computer codes***
- ***Extensive international cooperation***
- ***Extensive review and participation by NRC staff***
  - Test matrix
  - Running of actual tests

A Complete, Multi-year International Technology Program Supports the Design