ESBWR Testing Summary and Scale Effects

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ACRS T/H Subcommittee Meeting
Closed Session
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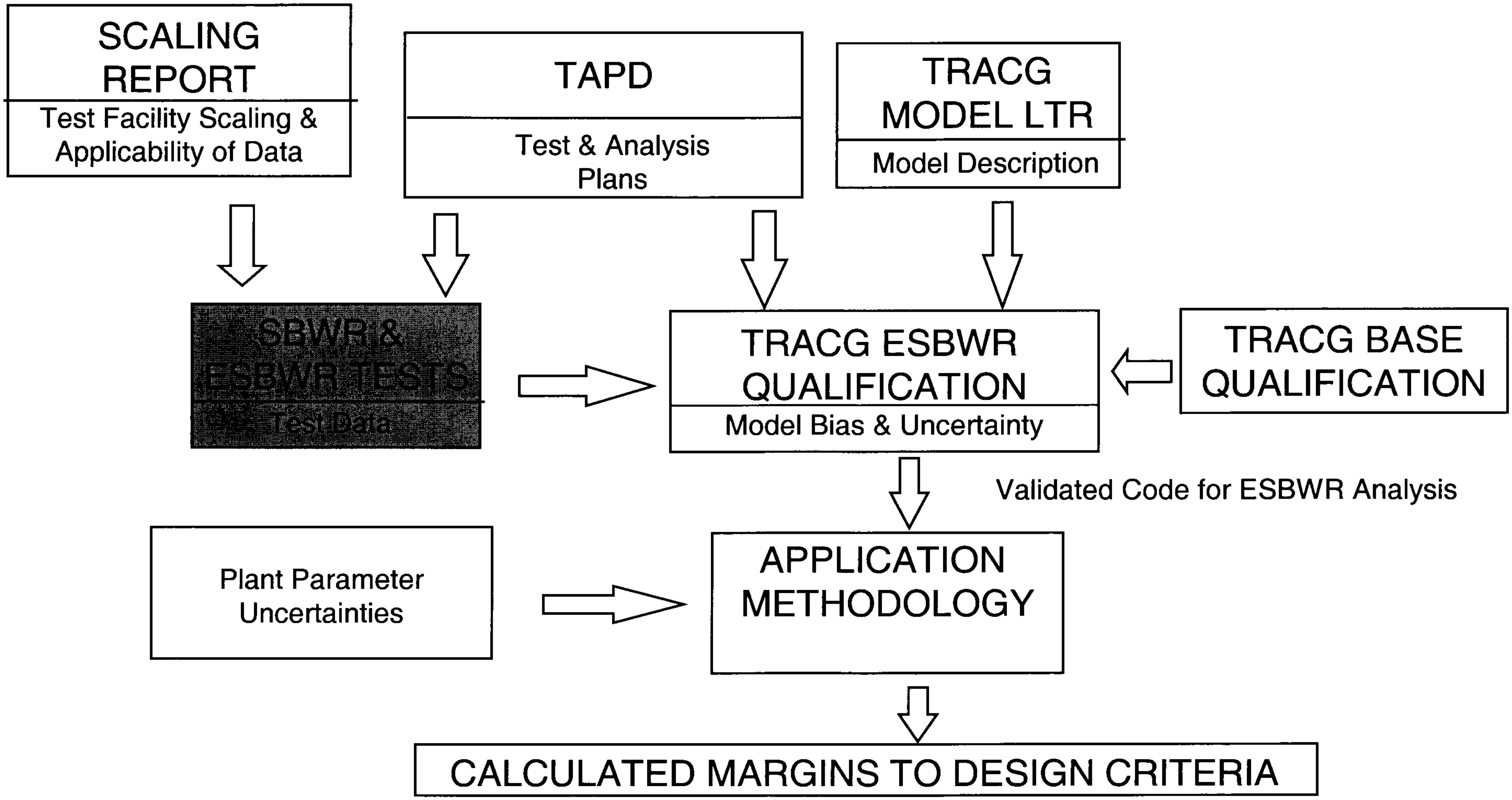
Rockville, Maryland

Outline

- *SBWR Test Summary*
- *ESBWR Design Modifications*
- *Confirmatory ESBWR Transient Tests*
- *Integration of Test Results at Different Scales*
- *Conclusions*

ESBWR Technology Program Elements

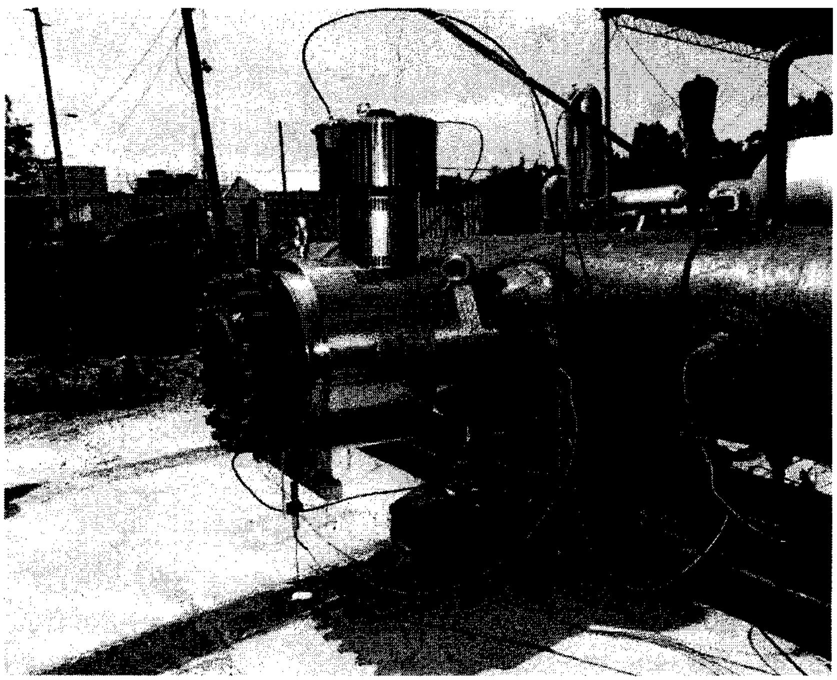


Extensive Technology Program for Features New to SBWR

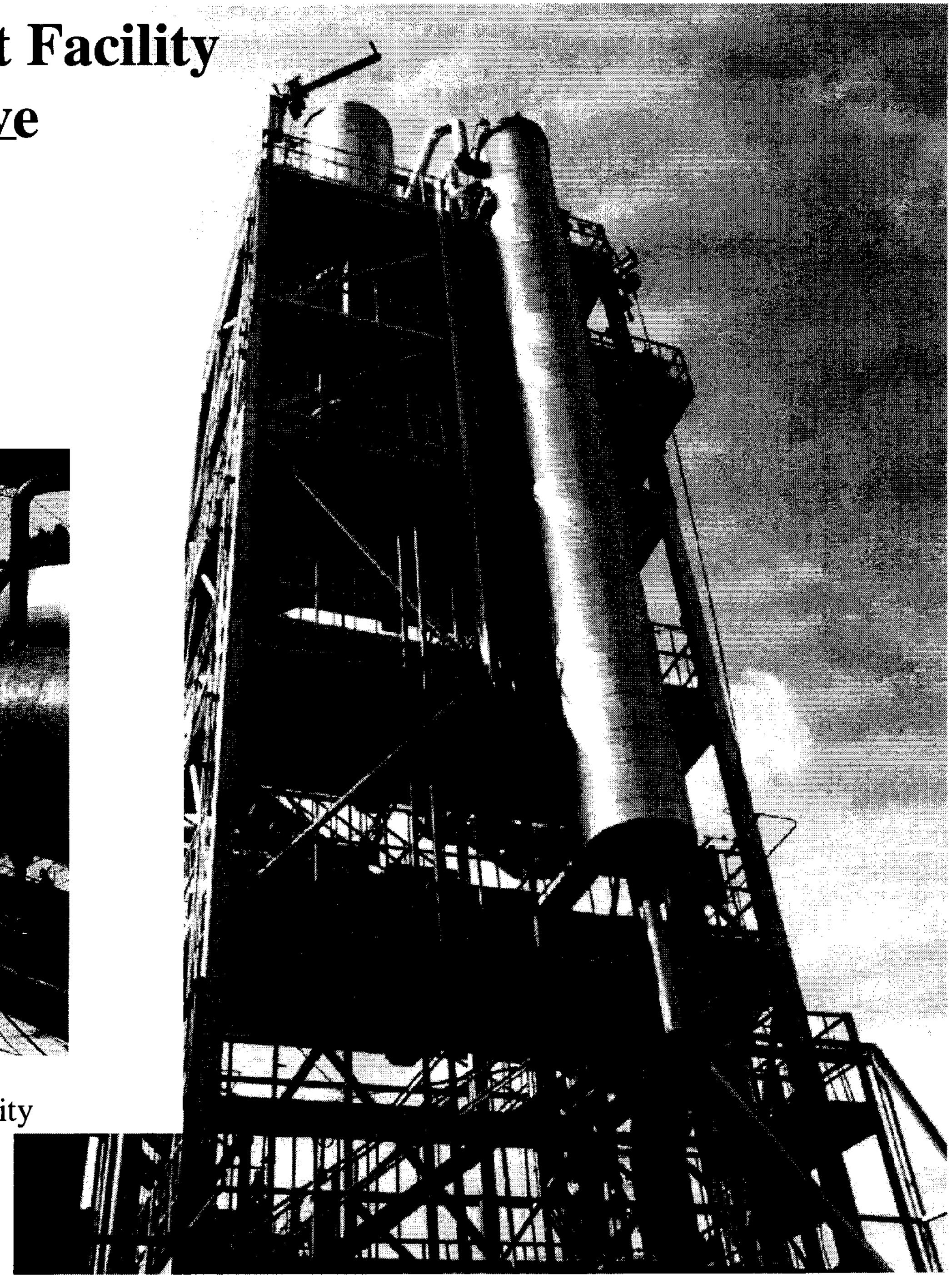
- ***Component tests***
  - Full scale components tests – DPV valves and vacuum breaker
  - Full scale isolation condensers & PCCS heat exchangers,
- ***Integral tests***
  - Integral tests at different scales – 1/400 to 1/25
  - System interaction tests
  - Large hydrogen releases
- ***Testing used 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

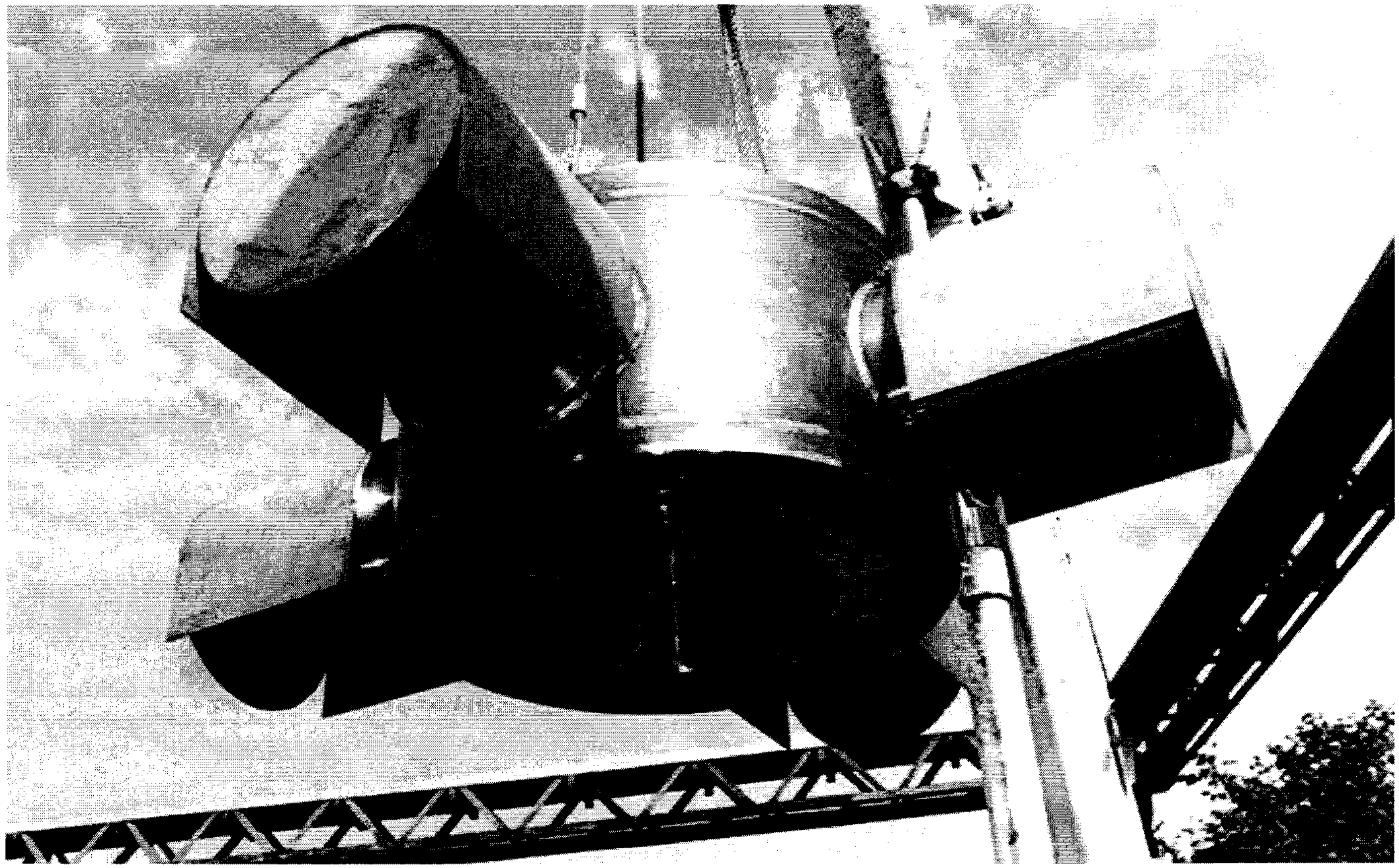
Safety System (GIST) Test Facility and Depressurization Valve



Reactor Depressurization Valve in the Test Facility



Prototype Vacuum Breaker



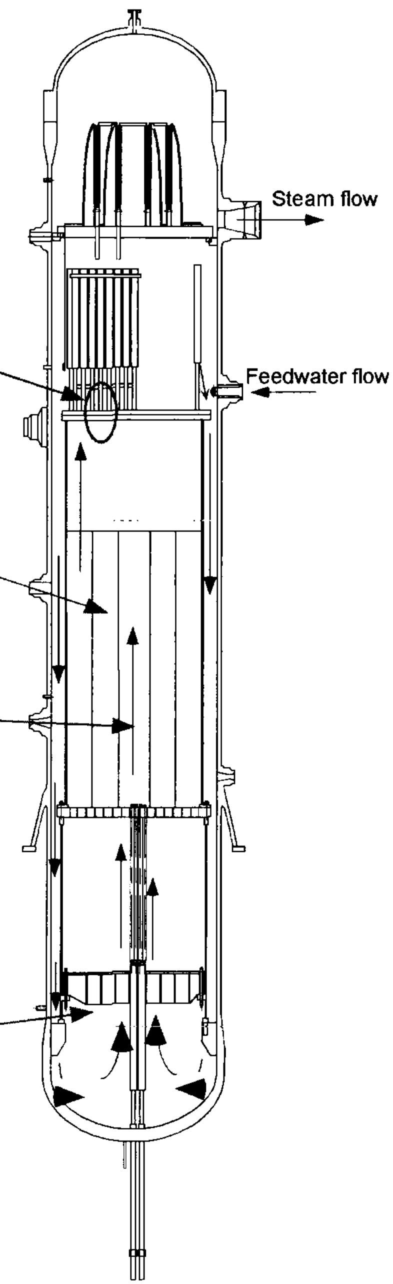
Core and NC Flow Technology Program Summary

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

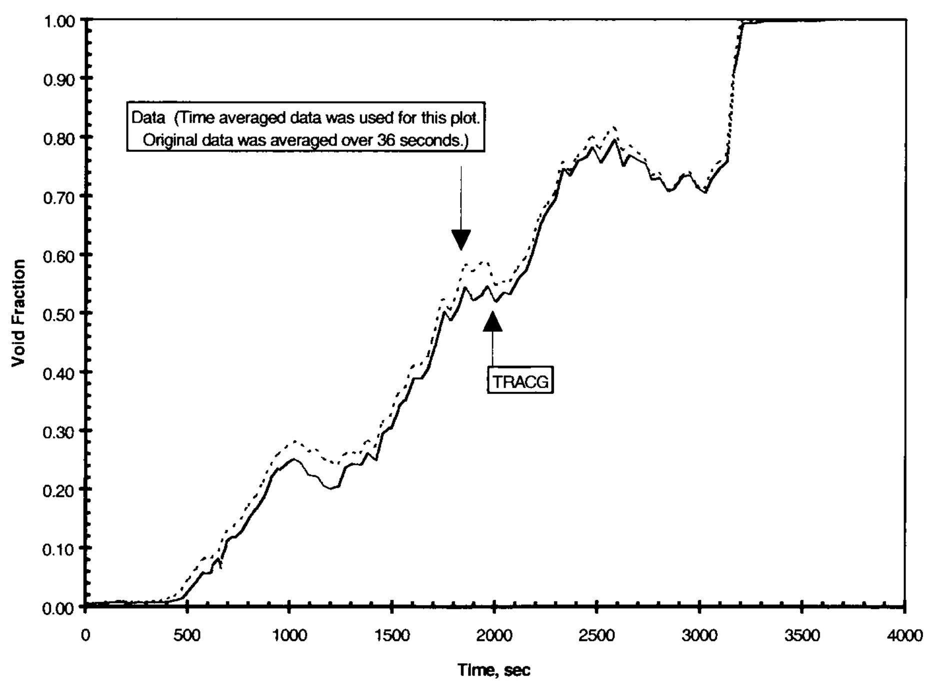
Startup Flow Oscillation
CRIEPI Tests
- single chimney
- SBWR conditions
- large margin to oscillation regime
Dodewaard Plant Start-up

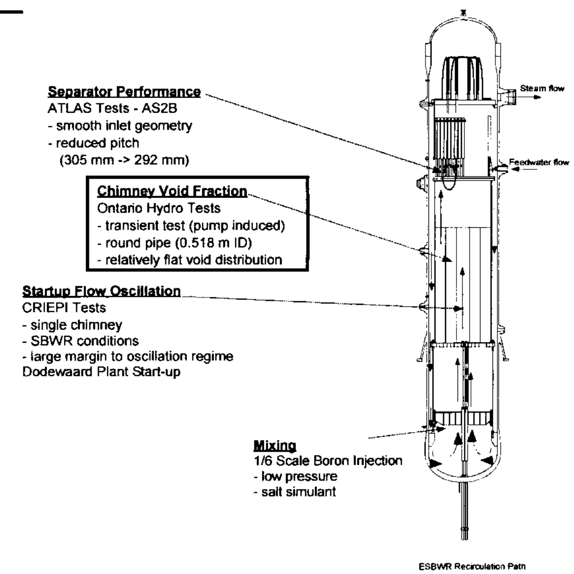
Mixing
1/6 Scale Boron Injection
- low pressure
- salt simulant



Chimney Void Fraction

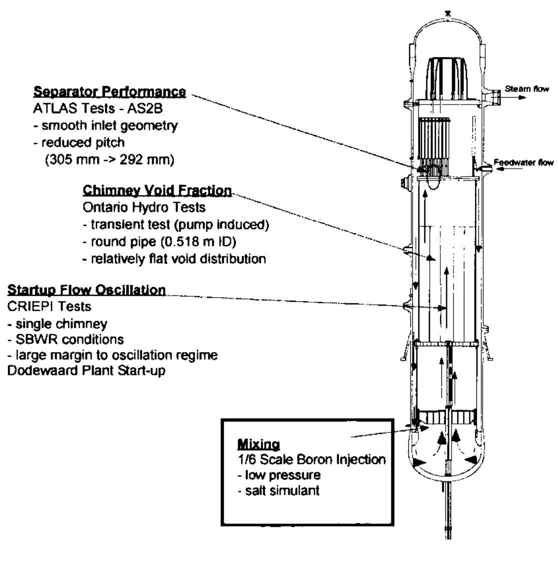
- ***Ontario Hydro Tests***
  - Large pipe void fraction data
  - 0.51 m diameter, 6.4 and 2.8 MPa
- ***Relatively flat void profile across the pipe section***
- ***Pump induced transient tests***

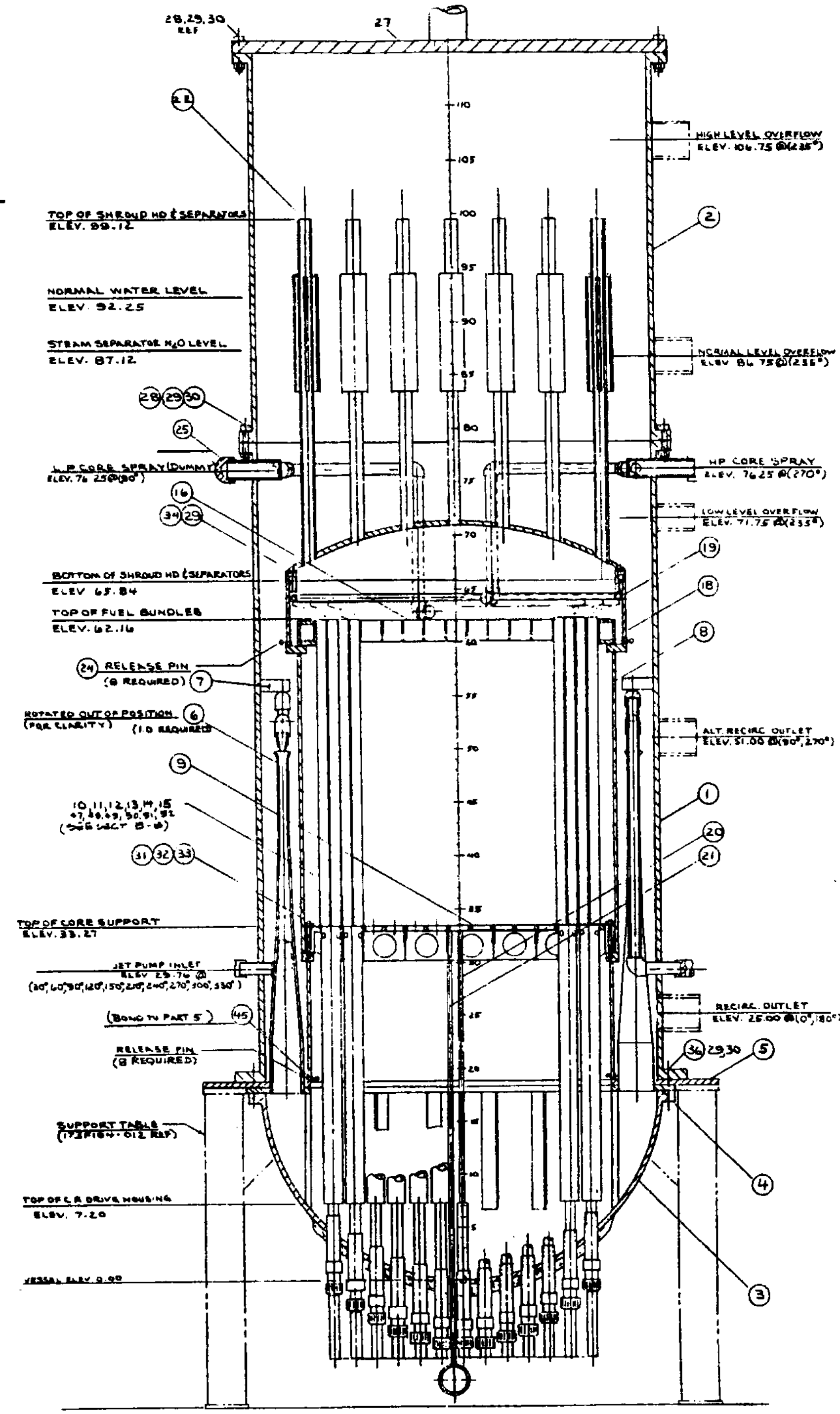




1/6th Scale Boron Mixing Test

- *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*





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

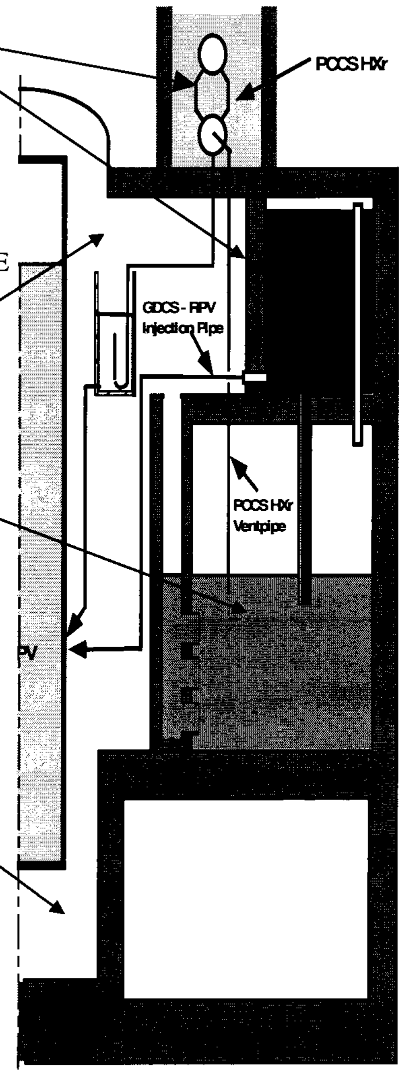
System Interactions
PANDA
GIRAFFE

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



Confirmatory Tests

PCCS Performance
PANDA-P series
- startup
- interactions
- secondary side ht
- N/C Buildup
- Unit interactions

ESBWR Configuration
PANDA -P series
- reduced cont. volume
- GDCS in WW
- PCCS Condensate to RPV

DW Stratification and Hideout
PANDA-P series
- Asymmetric loading
- hydrogen

Tests Covered in Testing Summary Report

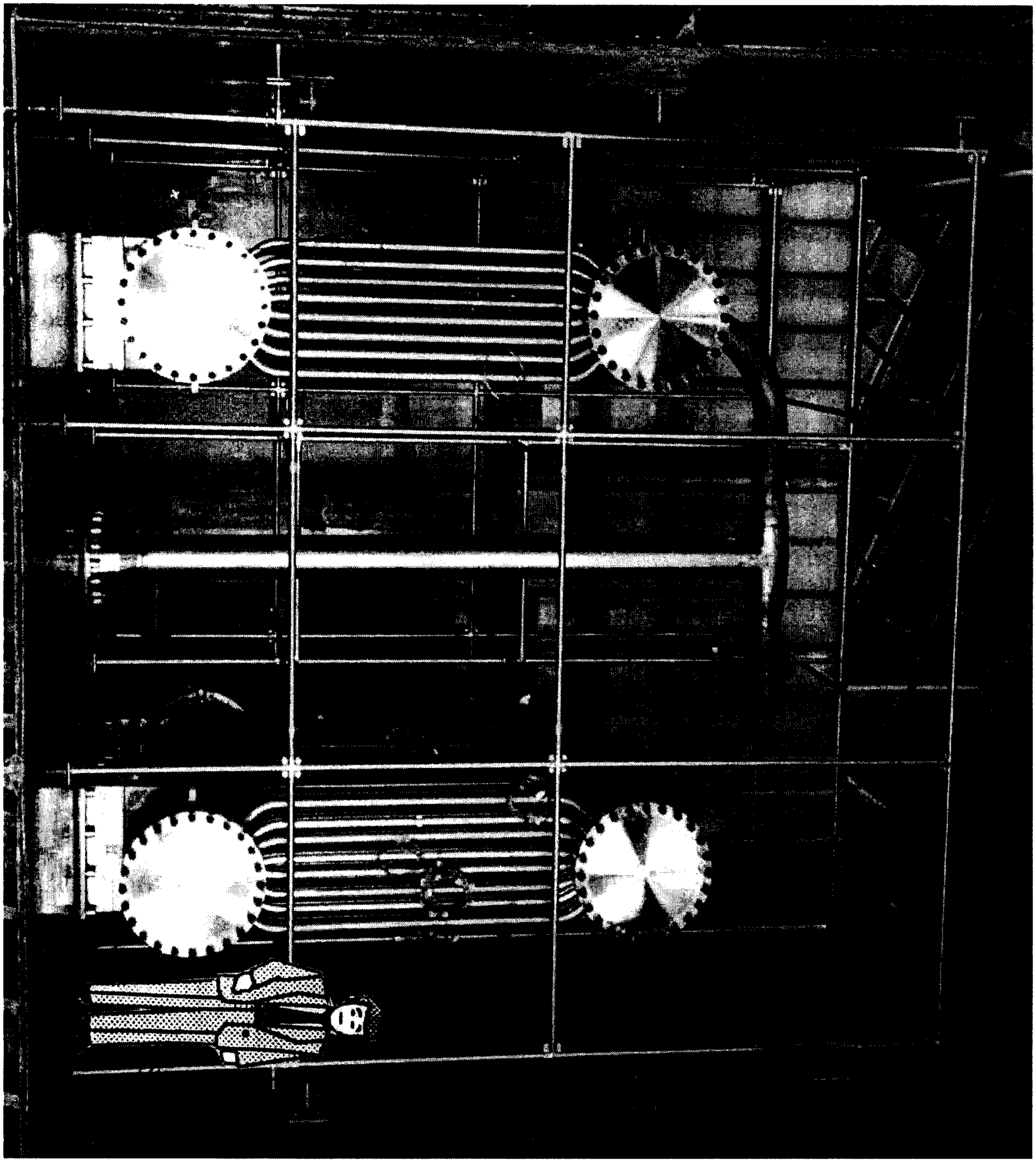
- ***Component***
  - PANTHERS/PCC
  - PANTHERS/IC
  - PANDA-S Series
- ***Integral Systems***
  - PANDA-M Series
  - GIST
  - GIRAFFE/He
  - GIRAFFE/SIT

Integral Test Coverage for ESBWR LOCA

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 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

PANTHER/PCC Power for Saturated Steam Tests

PANTHERS/PCC Power for Air/Steam Tests

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***

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 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

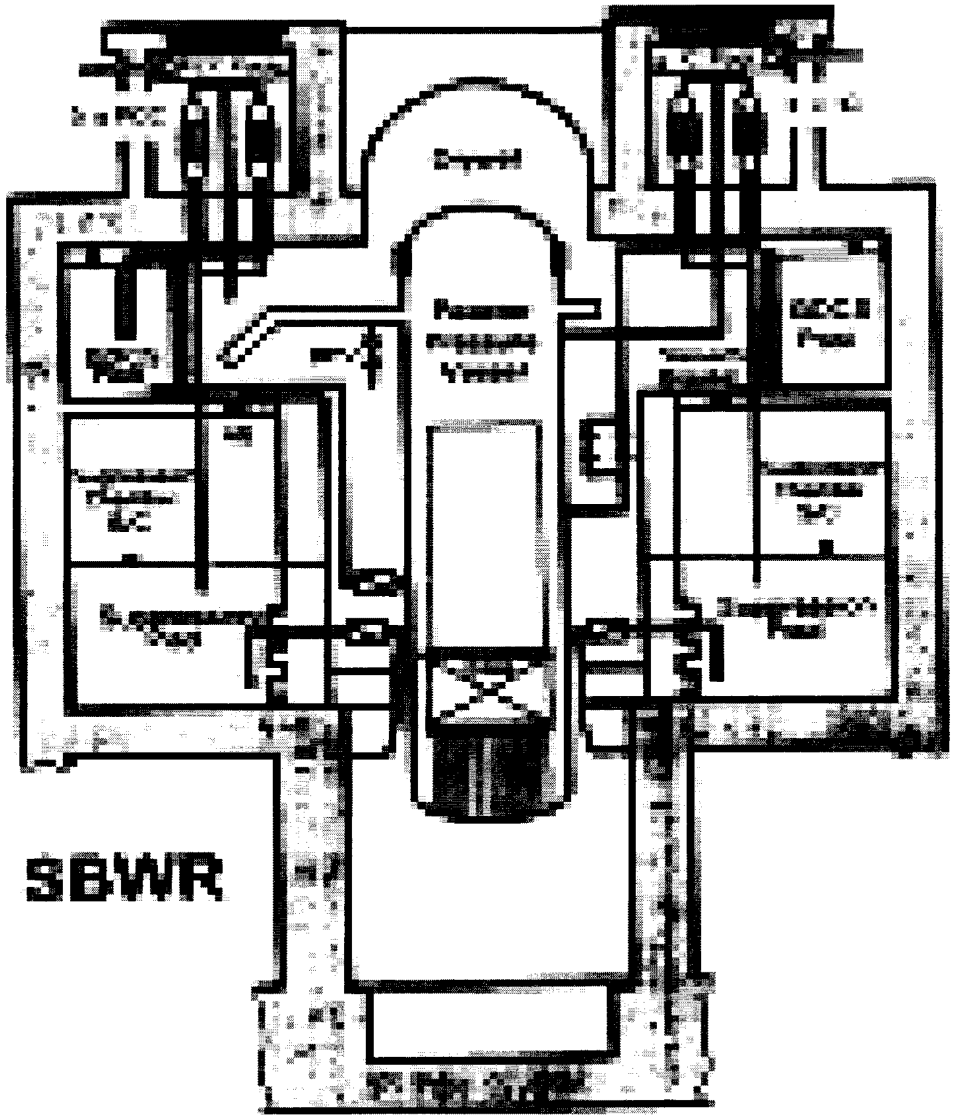
PANTHERS/IC Key Conclusions

- *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*

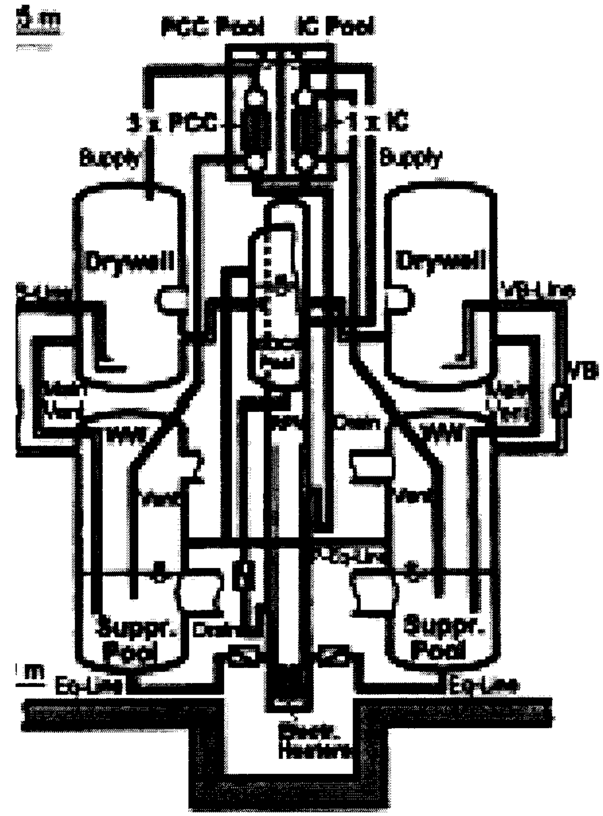
PANDA S and M Series

- ***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. SBWR Facility Schematic



SBWR

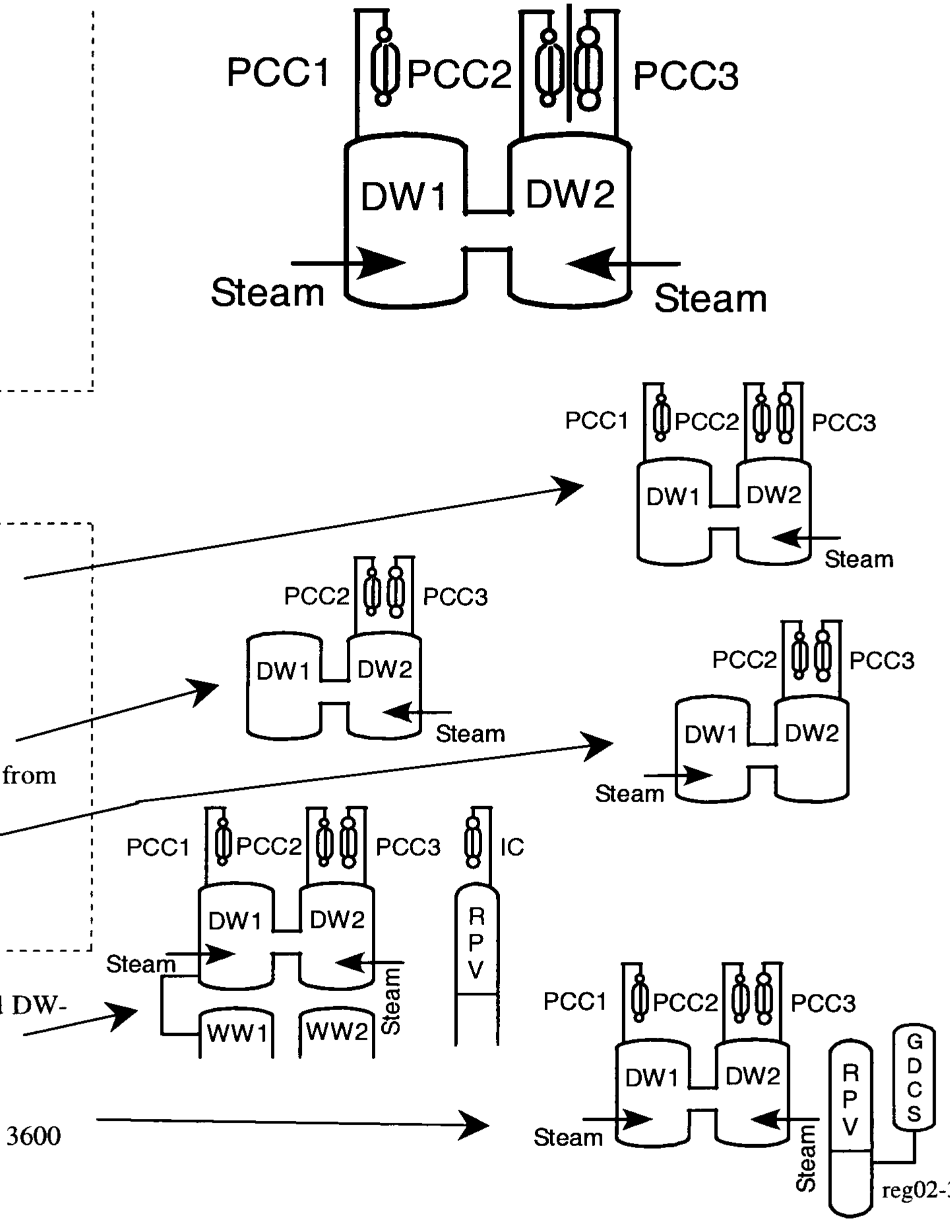


PANDA

Panda Steady State Test Matrix (S-Series)

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)



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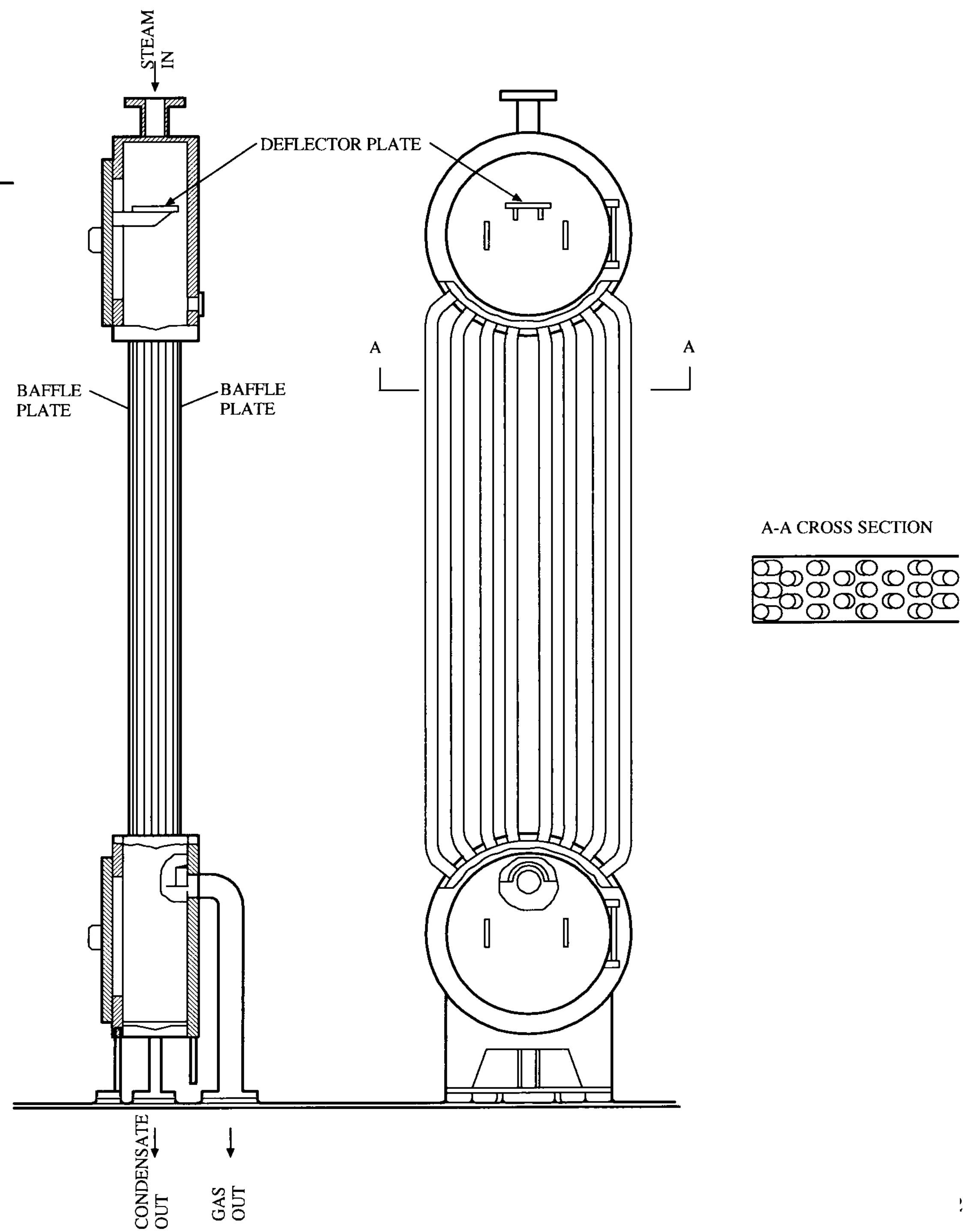
PANDA IC/PCC Units



PANDA Test Facility

Effect of Air Mass Fraction on PANDA S-series Tests

PANDA Tests M3, M3A, M3B Drywell Pressure Response

PANDA Tests - Effect of Asymmetric Steam Injection

PANDA Early Start Test

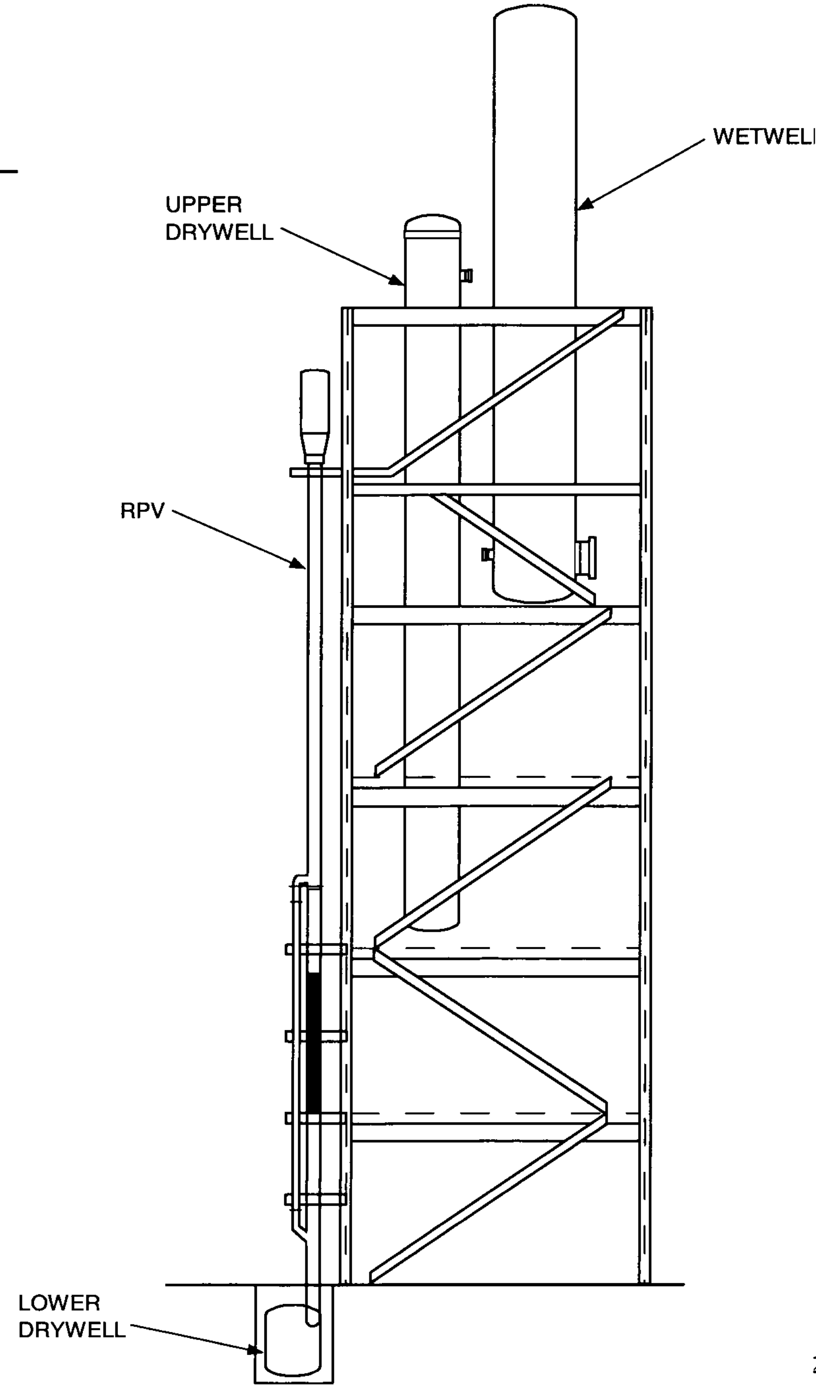
PANDA Early Start Test (Cont'd)

PANDA S and M Series Conclusions

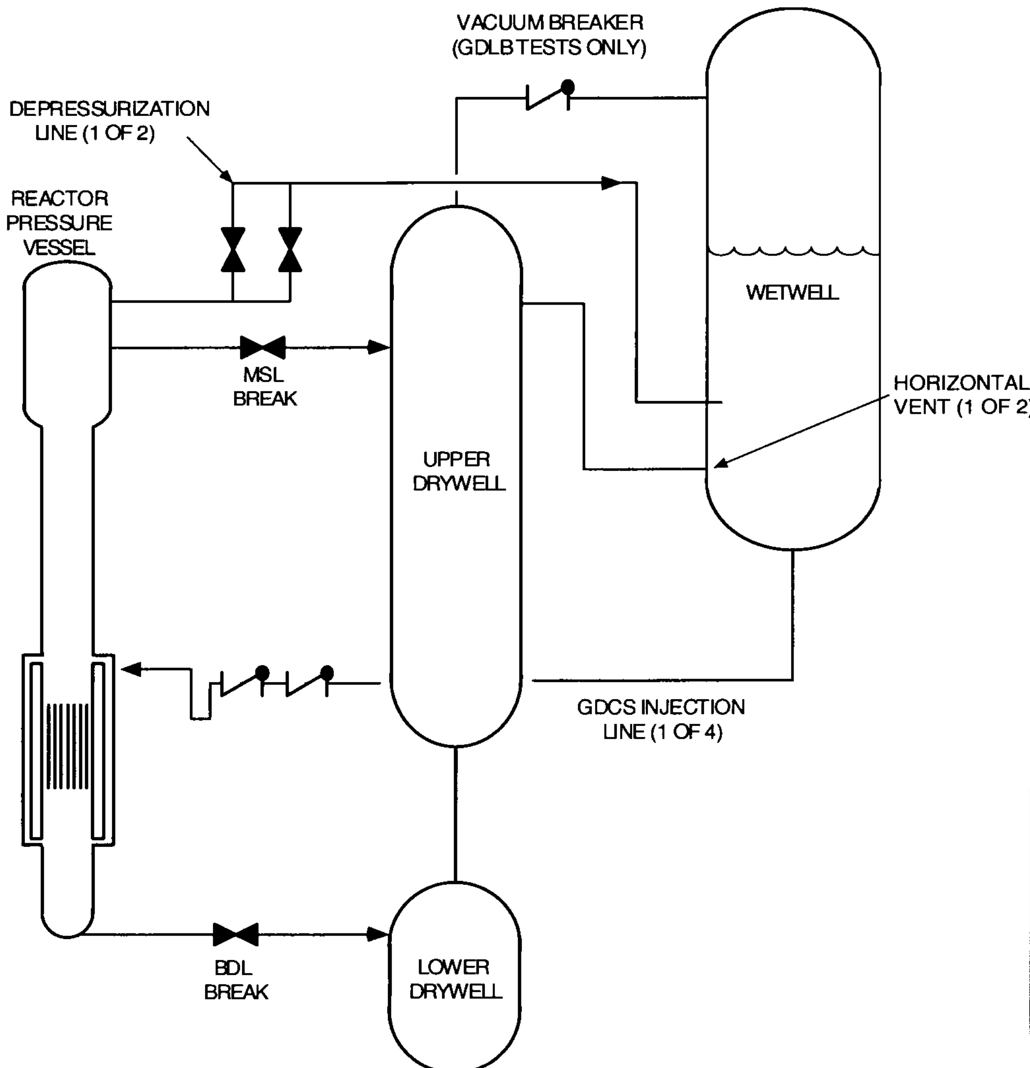
- *Overall containment pressure and temperature response is favorable -- SBWR containment design is robust*
- *PCCS has large margin to remove decay heat after 1 hour into a LOCA*
- *The PCCS is well behaved and effective in transporting decay heat from the DW to the PCCS pools with no significant deposition 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*

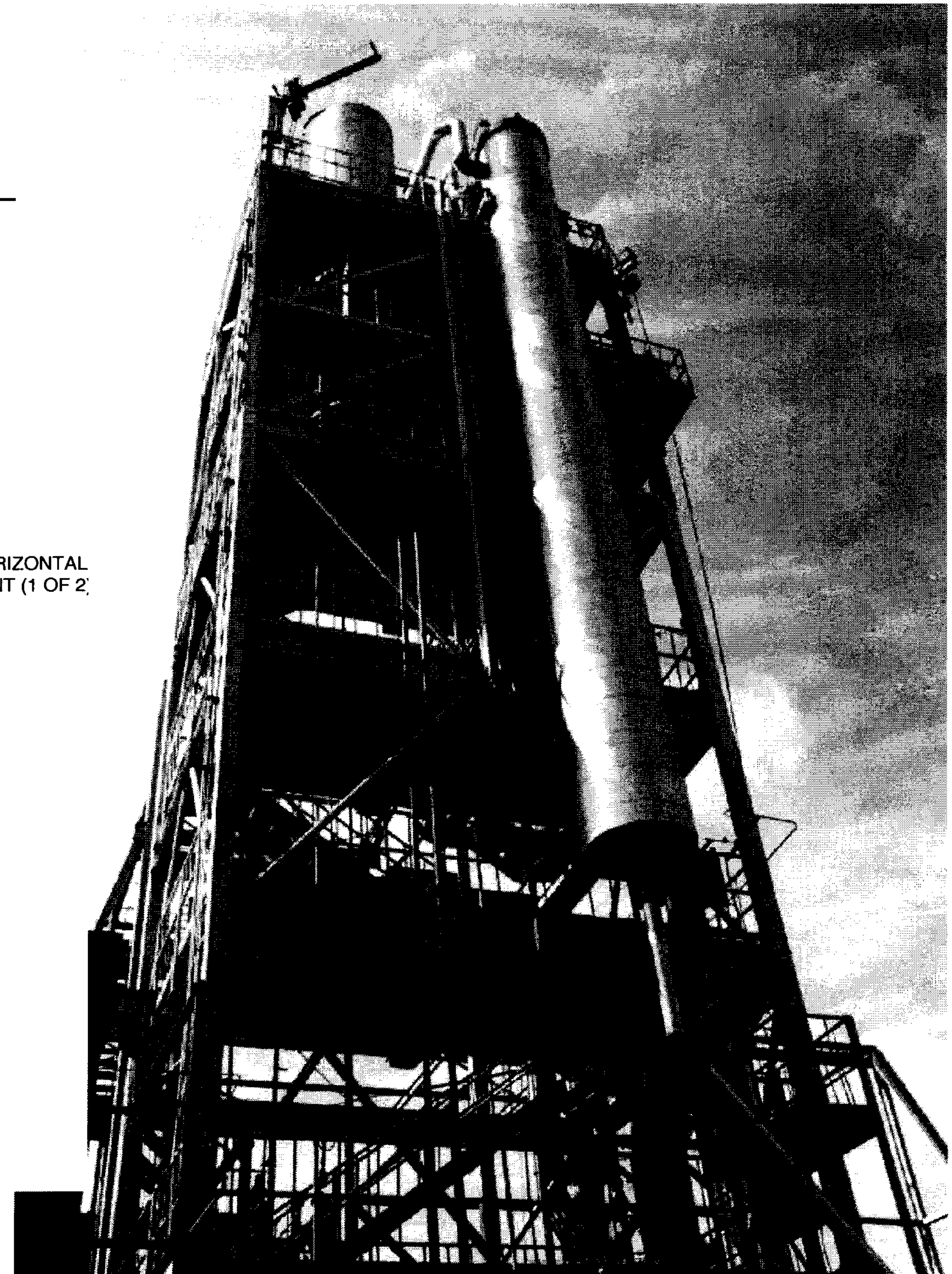
GIST

- ***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

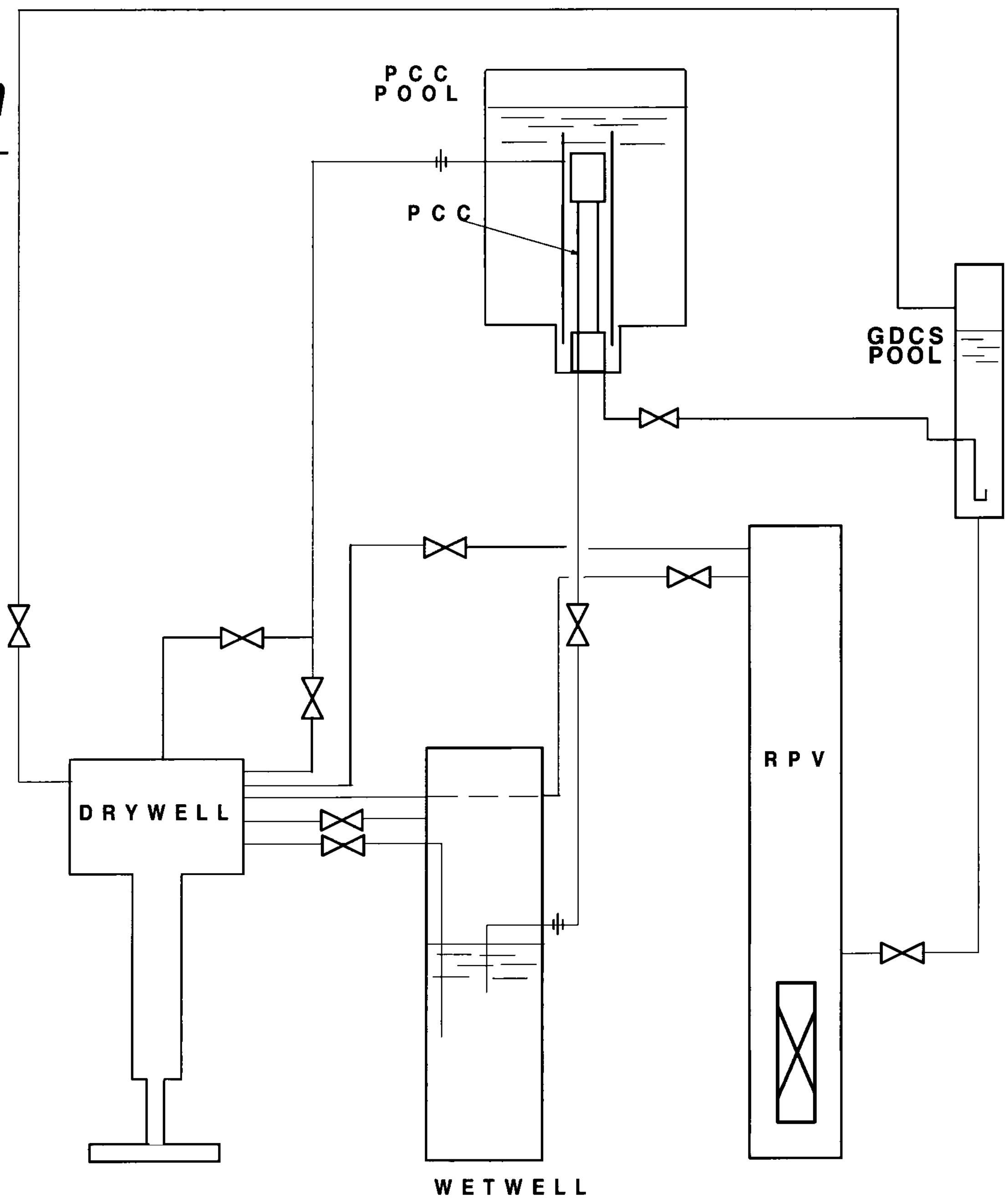




GIRAFFE

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

GIRAFFE Conclusions

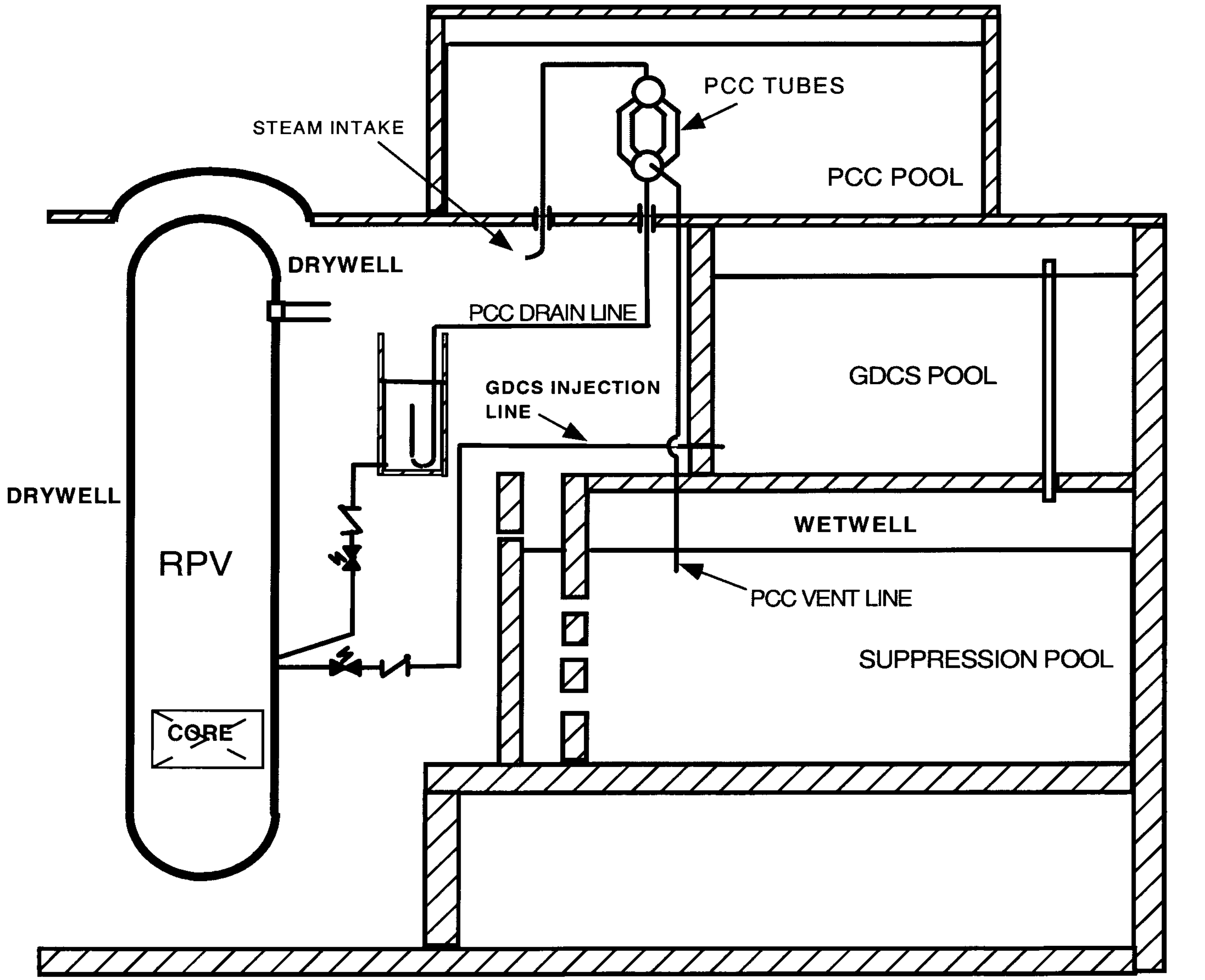
- ***GIRAFFE/Helium***
  - The PCCS operates in the presence of lighter-than-steam noncondensible gases and maintains containment pressure, even with high concentrations of noncondensible gases
  - The PCCS vents lighter-than-steam noncondensible gases, as necessary, to maintain operation
  - Heavier-than-steam 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

SBWR Testing Program Summary

- ***Extensive technology program for features new to SBWR***
  - Component tests
  - Integral tests
- ***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

ESBWR Design Modifications



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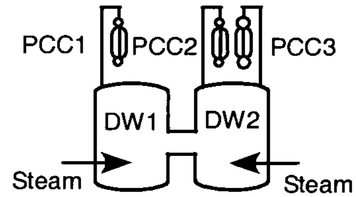
ESBWR System Modifications

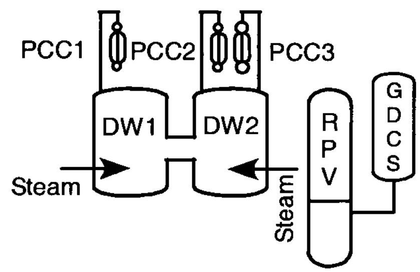
- ***Made GDCS part of WW***
  - Increased WW/DW volume ratio
  - Utilizes GDCS pool draindown space to provide increased wetwell volume
  - PCC Drain Tank added in DW
- ***Power Increased***
  - Number of ICs increased from 3 to 4
  - Number of PCCs increased from 3 to 4
  - PCCS Expanded from 10MW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

PANDA-P Series Test Matrix

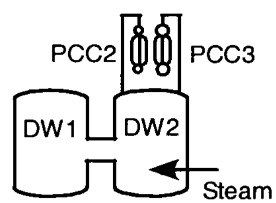
P1: Base Case
MSL Break + 1 hr
(long-term cooling phase)



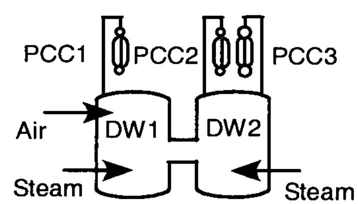
P2: Early Start
MSL Break + 20 min
(transition from GDCS
injection to long-term
PCCS cooling phase)



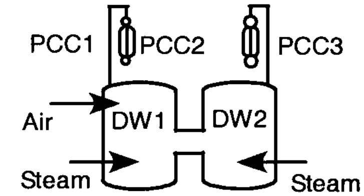
P3: PCCS Start-up
DW initially filled with air
(deomonstrate PCCS start-up
Under challenging conditions)



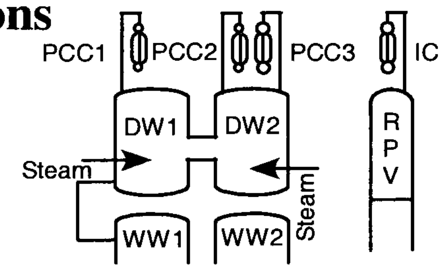
P4: Trapped Air in DW
Air released during transient
(investigation of how n/c gas
Affects PCCS performance)



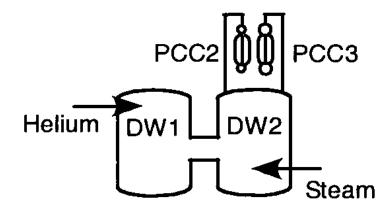
P5: Symmetric Case
PCC2 Isolated, air supply to
DW later in transient
(MV clearing phase caused by
Reduced PCC capacity)



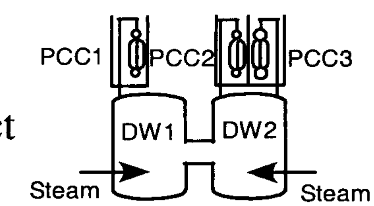
P6: Systems Interactions
ICs and PCCs in parallel,
DW1 to WW1 leakage
(is PCC performance
adverseley affected?)



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)

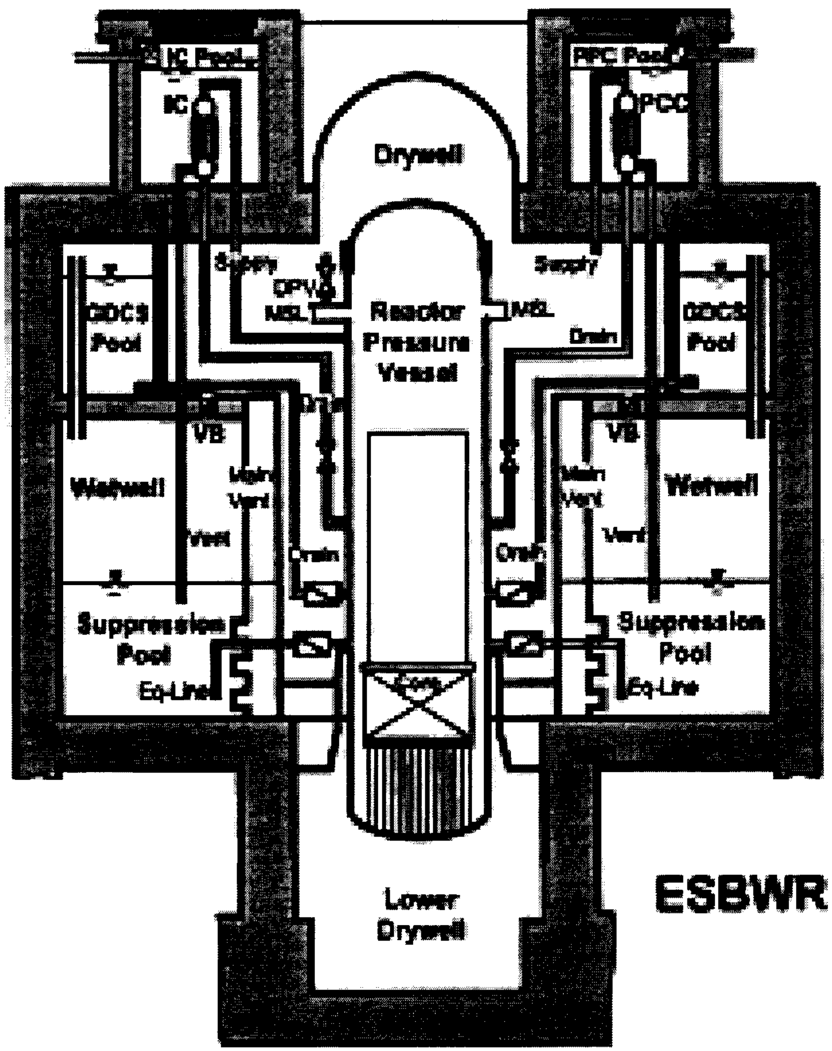


Additional confirmatory testing for ESBWR configuration

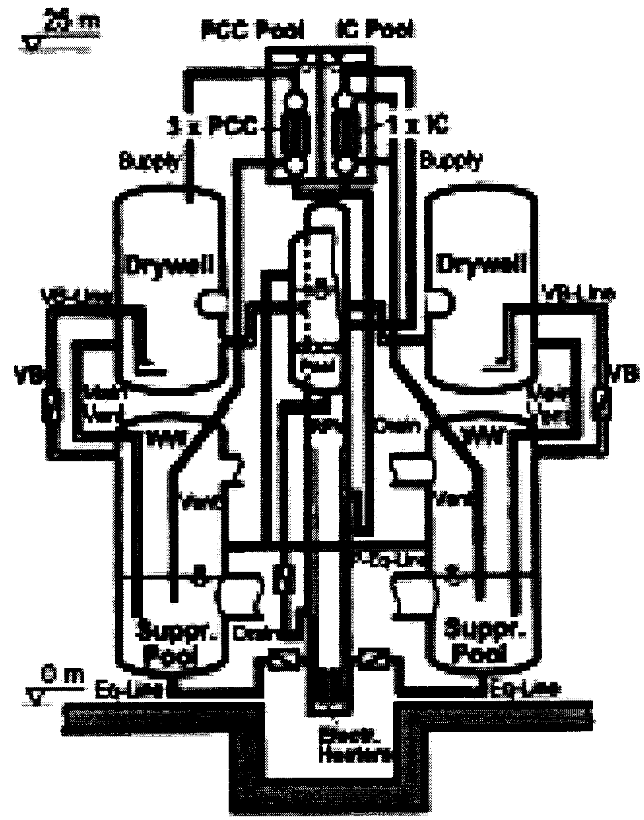
PANDA -P series Test

- ***~1:45 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

ESBWR vs. PANDA Facility Schematic



ESBWR



PANDA

P4 - Effect of Additional Late Air Release on System Performance

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P4 - Effect of Additional Late Air Release on System Performance

Comparison Stratification and Hideout Tests

Integration of Multiple Scale Tests Results

Comparison of M and P Series PANDA Base Tests

PANDA Early Start Test

Conclusions From PANDA-P Series Tests

- ***Containment pressure reduced relative to M series tests due to larger WW gas space***
- ***No change in systems interaction from moving GDCS pool to wetwell***
- ***Containment system operated robustly over all conditions tested***
- ***All objectives met***
  - 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

No surprises – System behavior has not changed as a result of configuration changes

Effect of N/C Gas Transport on Wetwell Pressure

PCC/IC Performance - Data at Different Pressure and Scale

PCC Performance - Effect of Non-condensables at Different Scales

Conclusions from Integrated Test Results

- ***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 quantity in wetwell for different scales and different gases***

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

All testing identified as needed by TAPD has been completed

Testing Program Summary

- ***Extensive technology program for features new to SBWR***
  - Component tests
  - Integral tests
- ***Additional Tests to confirm ESBWR performance***
- ***Testing used to qualify computer codes***
- ***Extensive international cooperation***
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