# ESBWR Testing Summary and Scale Effects

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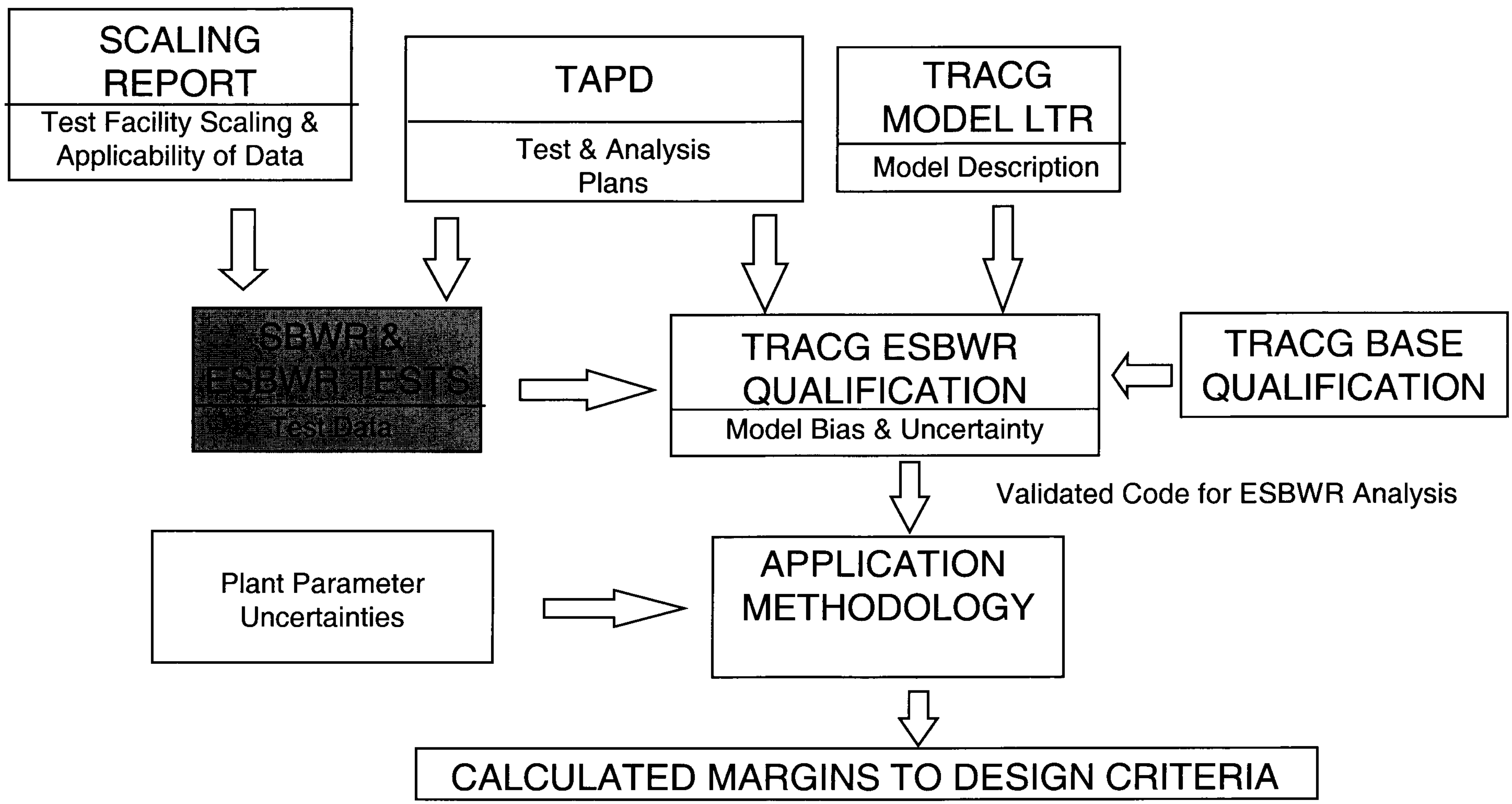
ACRS T/H Subcommittee Meeting
Closed Session
July 8th, 2003
Rockville, Maryland

# *Outline*

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

# ESBWR Technology Program Elements

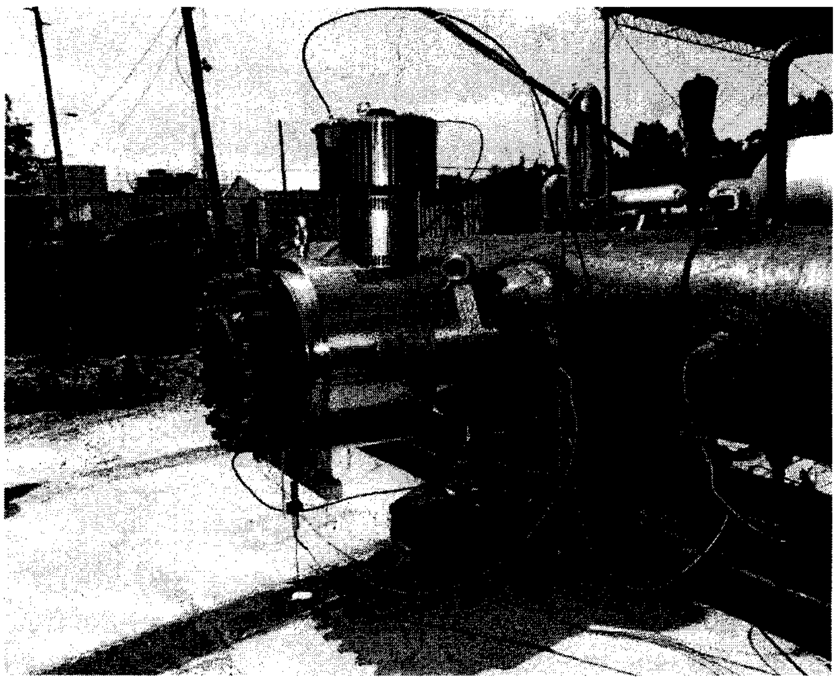


# *Extensive Technology Program for Features New to SBWR*

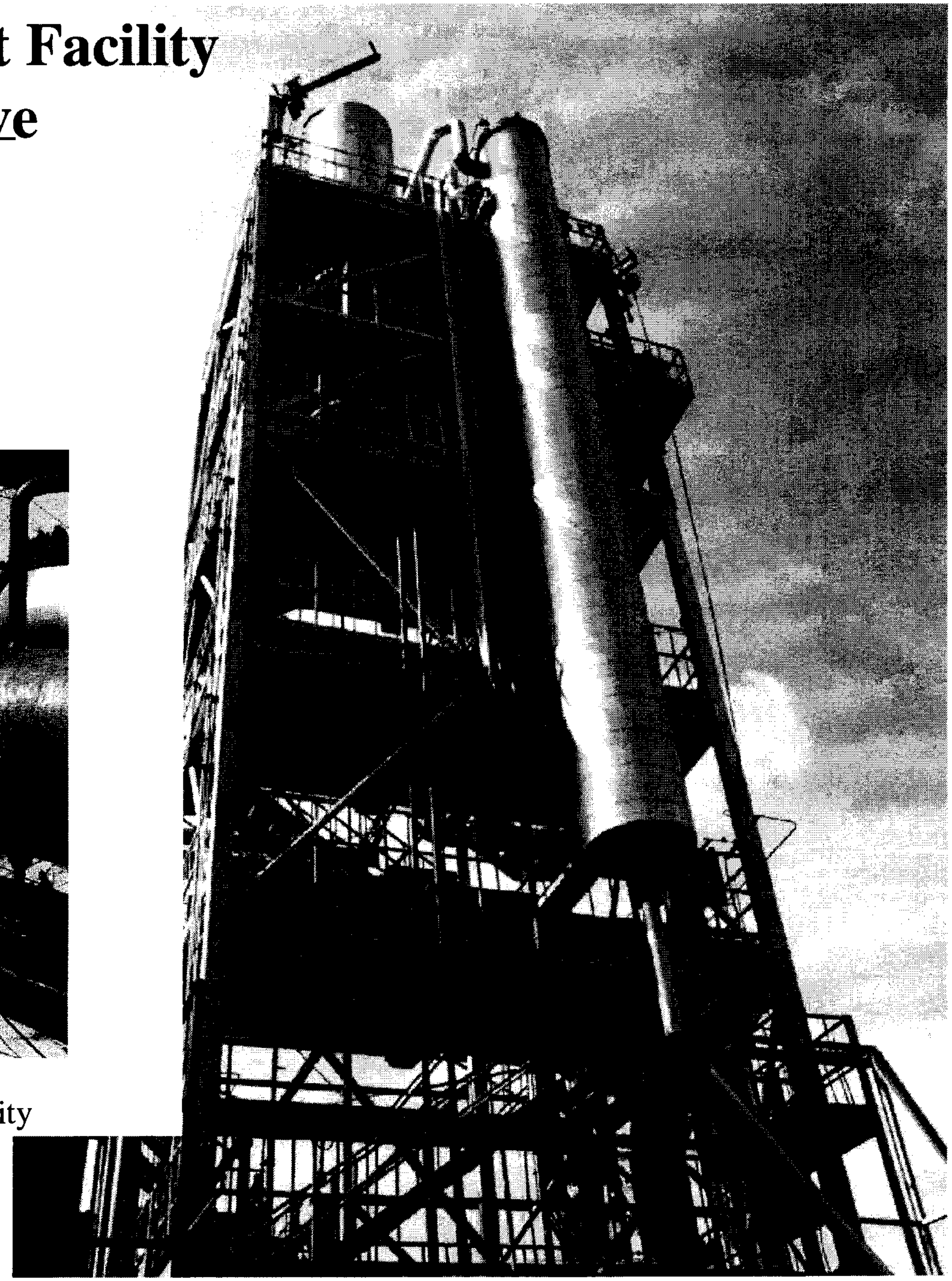
- ***Component tests***
  - Full scale components tests – DPV valves and vacuum breaker
  - Full scale isolation condensers & PCCS heat exchangers,
- ***Integral tests***
  - Integral tests at different scales – 1/400 to 1/25
  - System interaction tests
  - Large hydrogen releases
- ***Testing used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

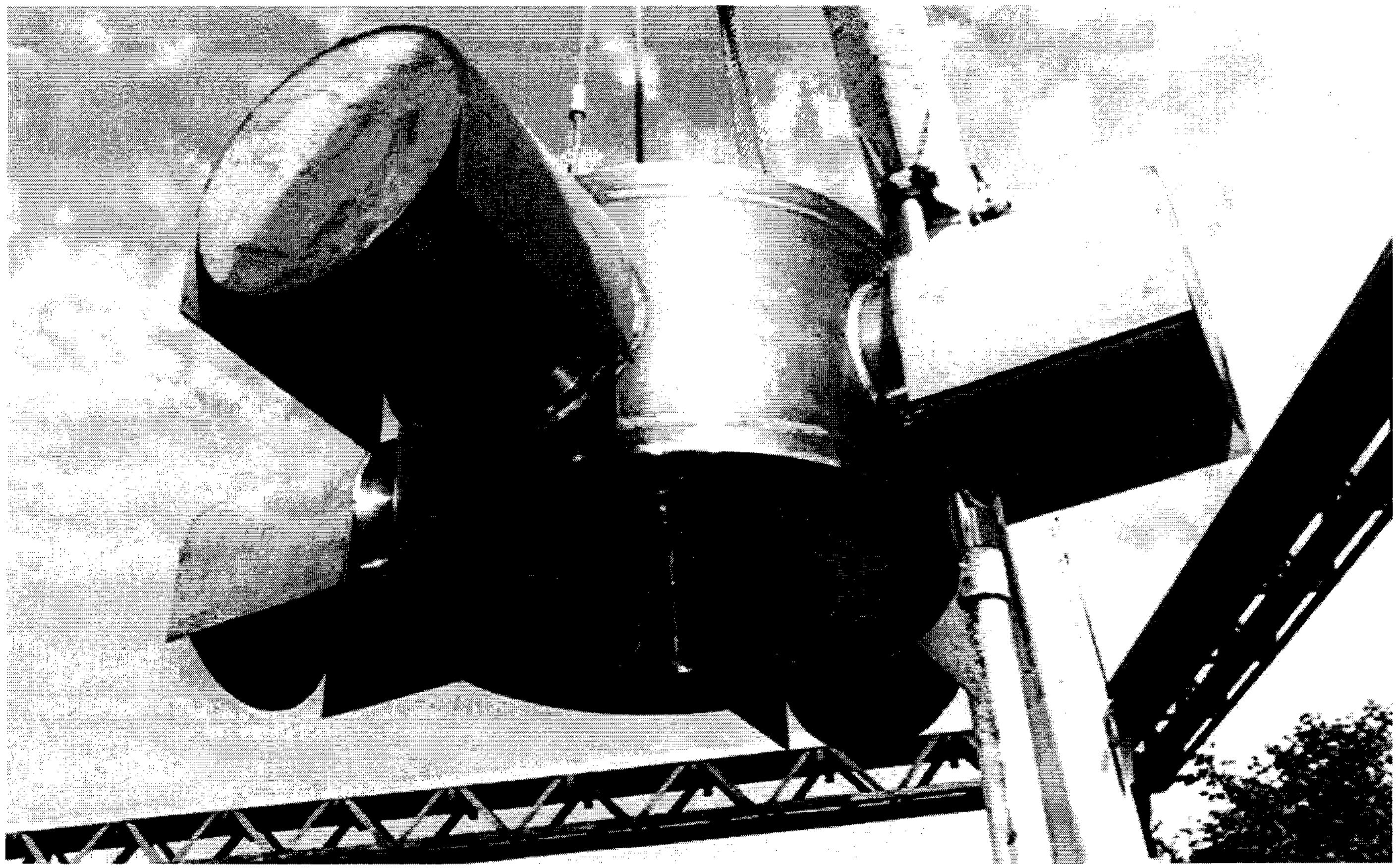
# Safety System (GIST) Test Facility and Depressurization Valve



Reactor Depressurization Valve in the Test Facility



# Prototype Vacuum Breaker



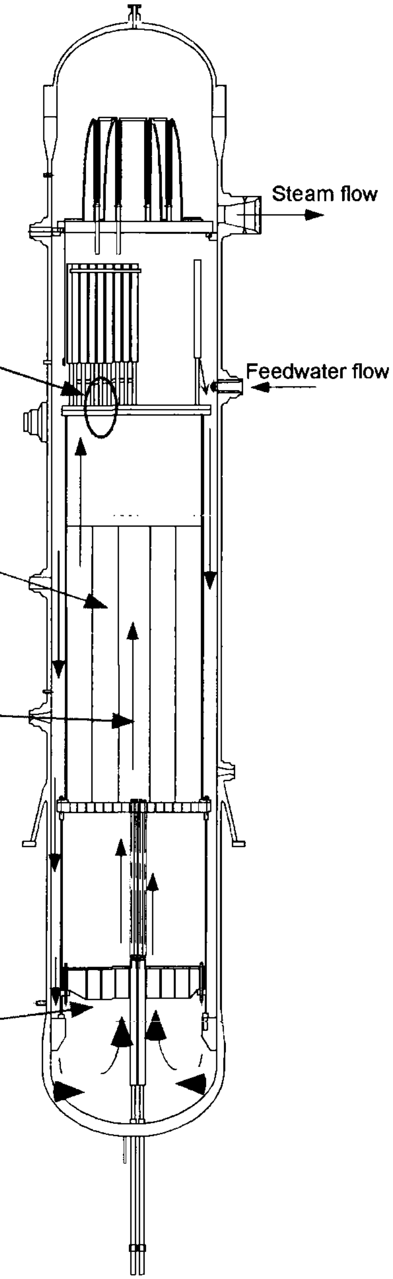
# Core and NC Flow Technology Program Summary

**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

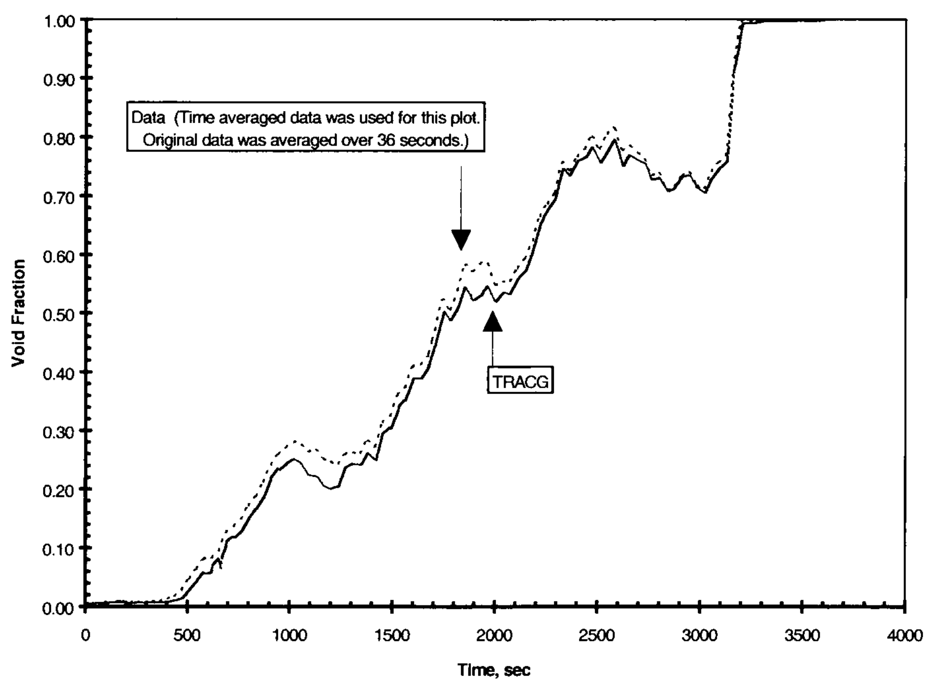
**Startup Flow Oscillation**
CRIEPI Tests
- single chimney
- SBWR conditions
- large margin to oscillation regime
Dodewaard Plant Start-up

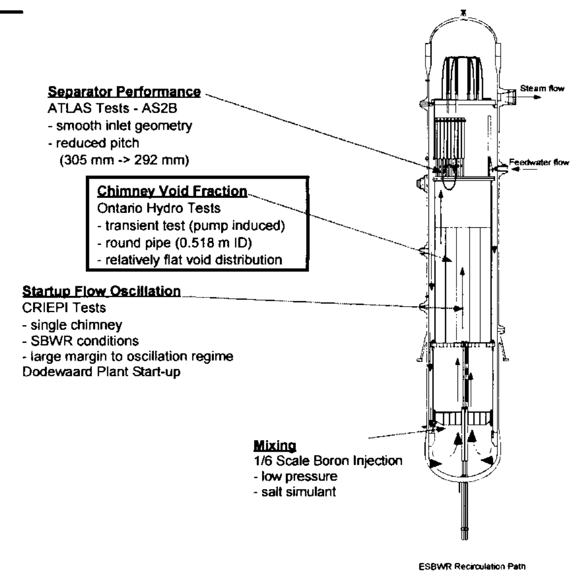
**Mixing**
1/6 Scale Boron Injection
- low pressure
- salt simulant



# Chimney Void Fraction

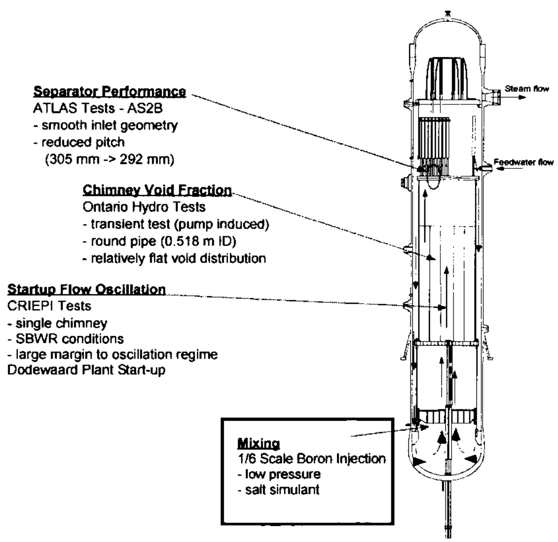
- ***Ontario Hydro Tests***
  - Large pipe void fraction data
  - 0.51 m diameter, 6.4 and 2.8 MPa
- ***Relatively flat void profile across the pipe section***
- ***Pump induced transient tests***



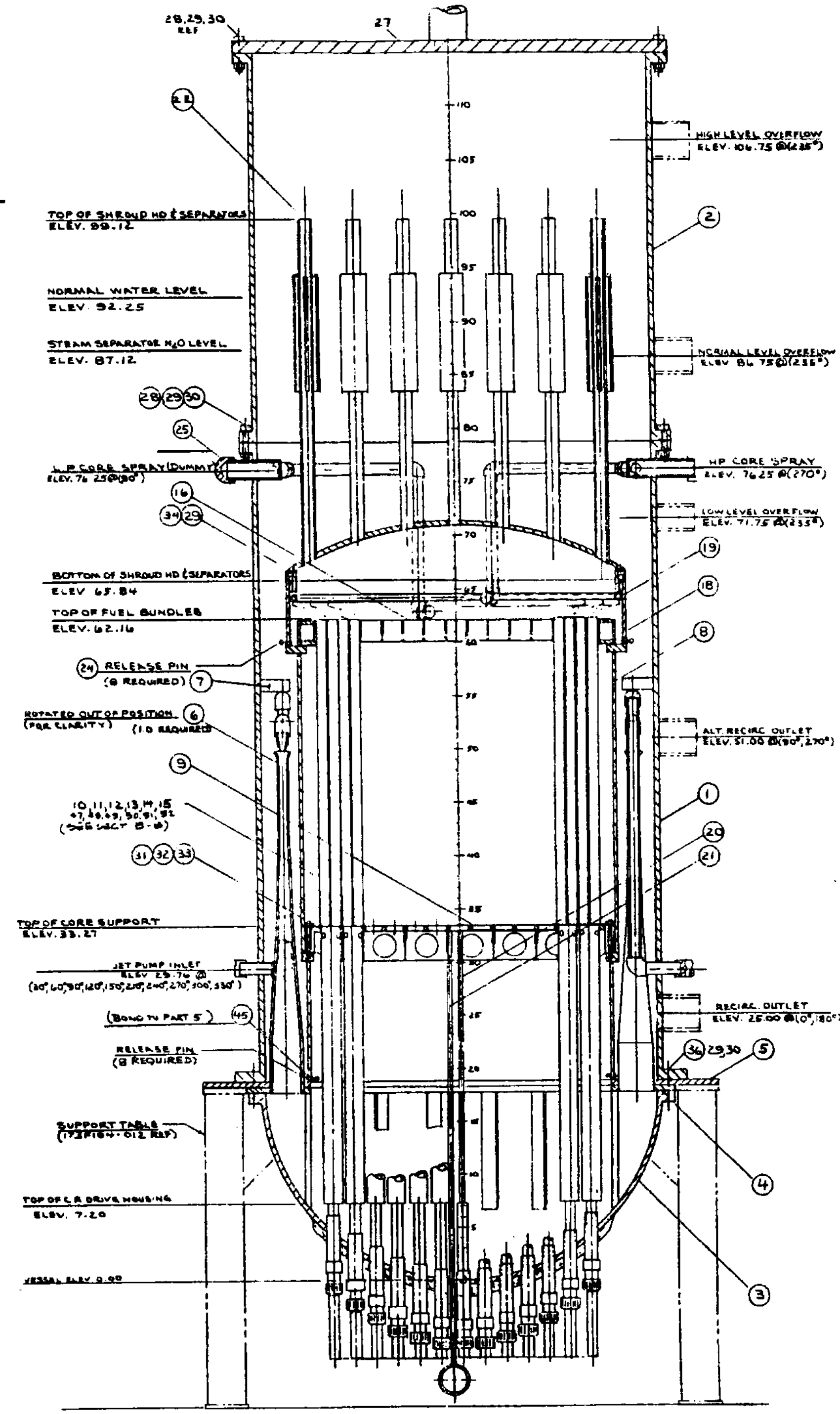



# 1/6th Scale Boron Mixing Test

- *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*



ESBWR Recirculation Path



# 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

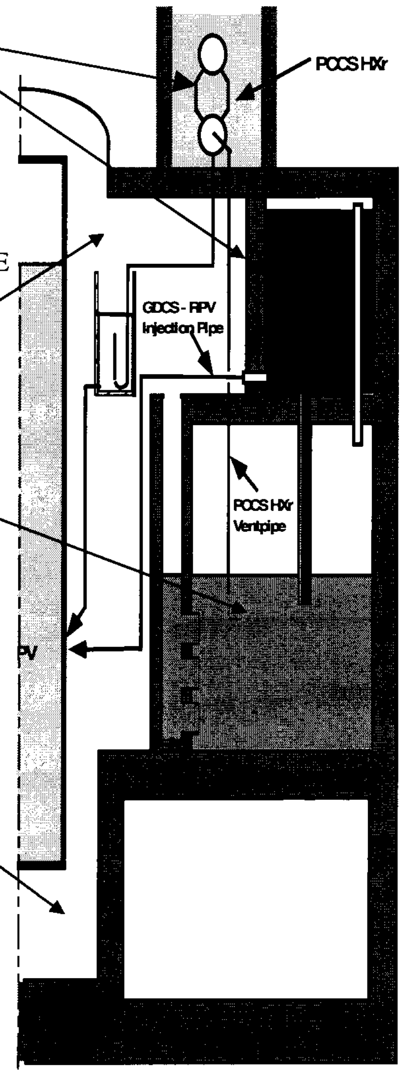
**System Interactions**
PANDA
GIRAFFE

**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*

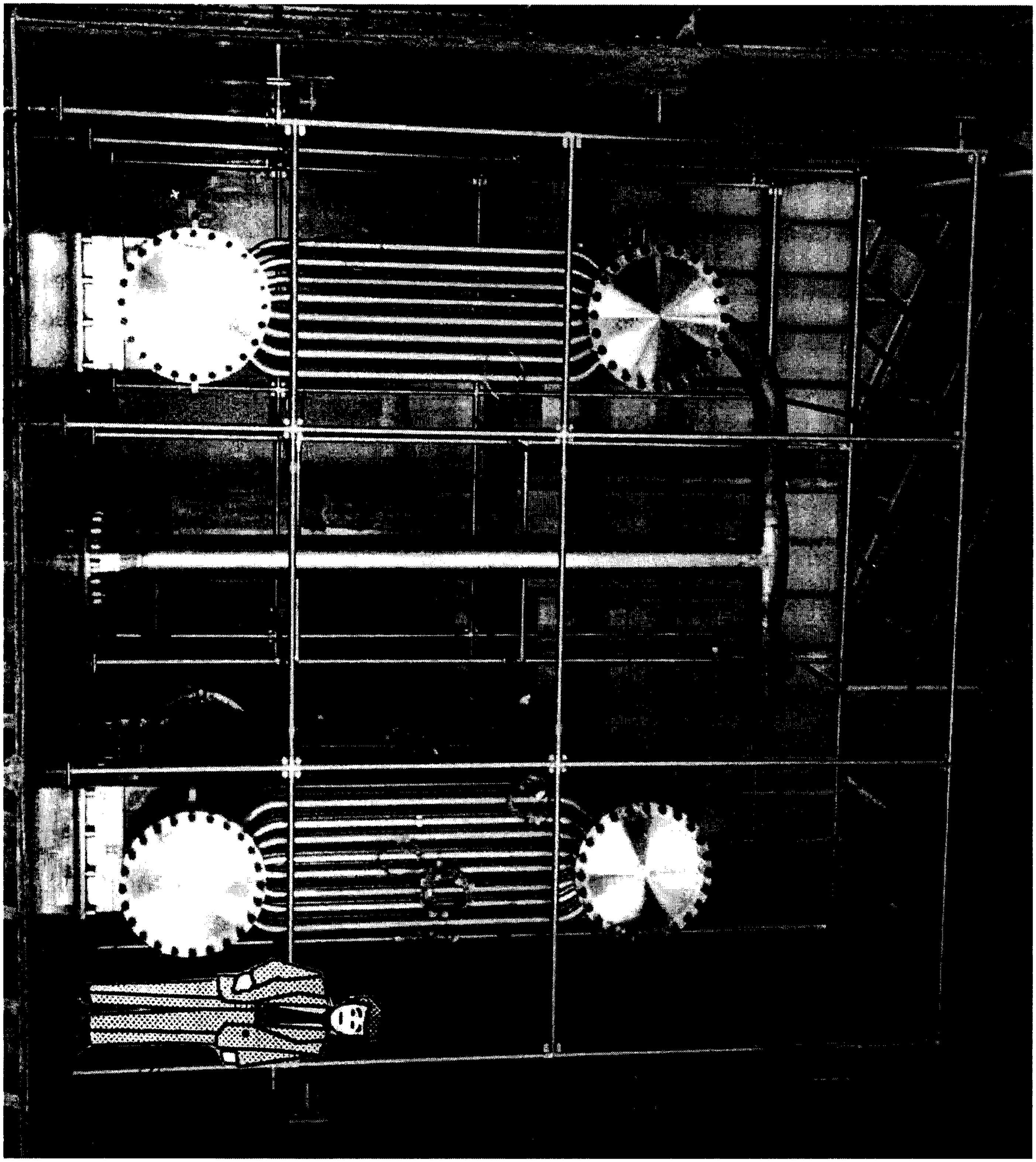
- ***Component***
  - PANTHERS/PCC
  - PANTHERS/IC
  - PANDA-S Series
- ***Integral Systems***
  - PANDA-M Series
  - GIST
  - GIRAFFE/He
  - GIRAFFE/SIT

# *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

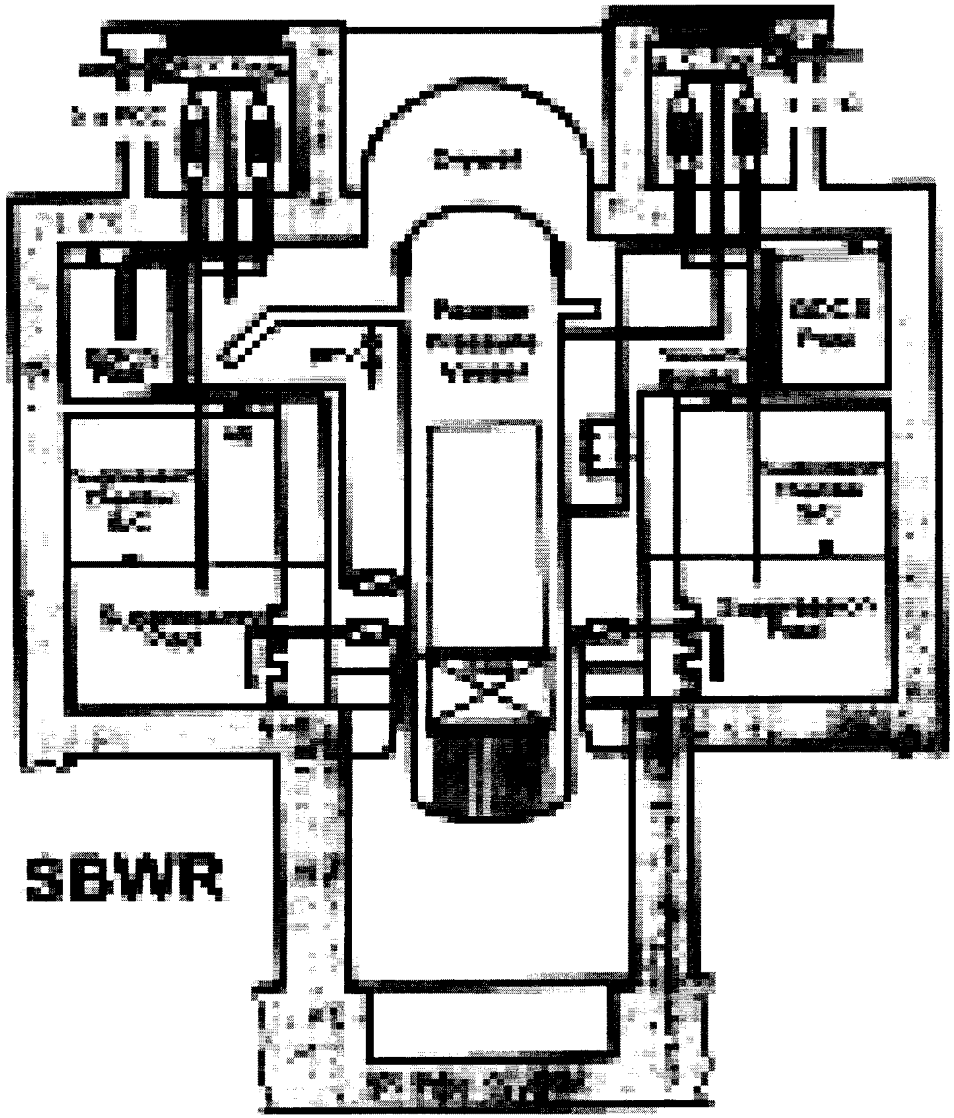
## PANTHERS/IC Key Conclusions

- *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*

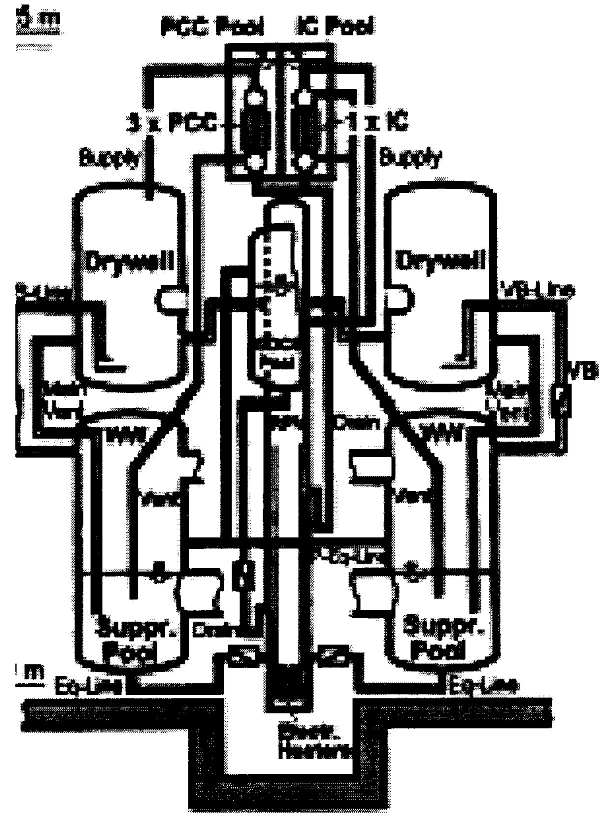
# PANDA S and M Series

- ***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

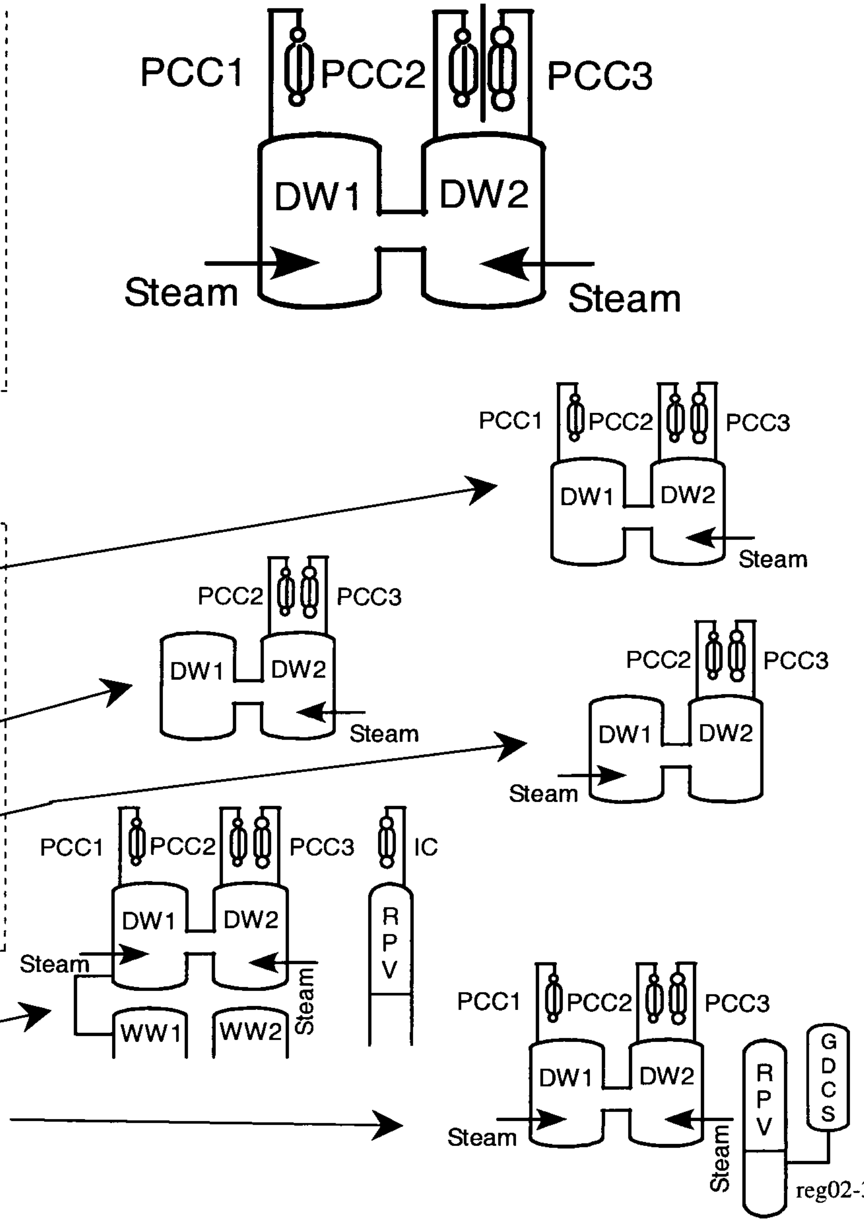



PANDA

# *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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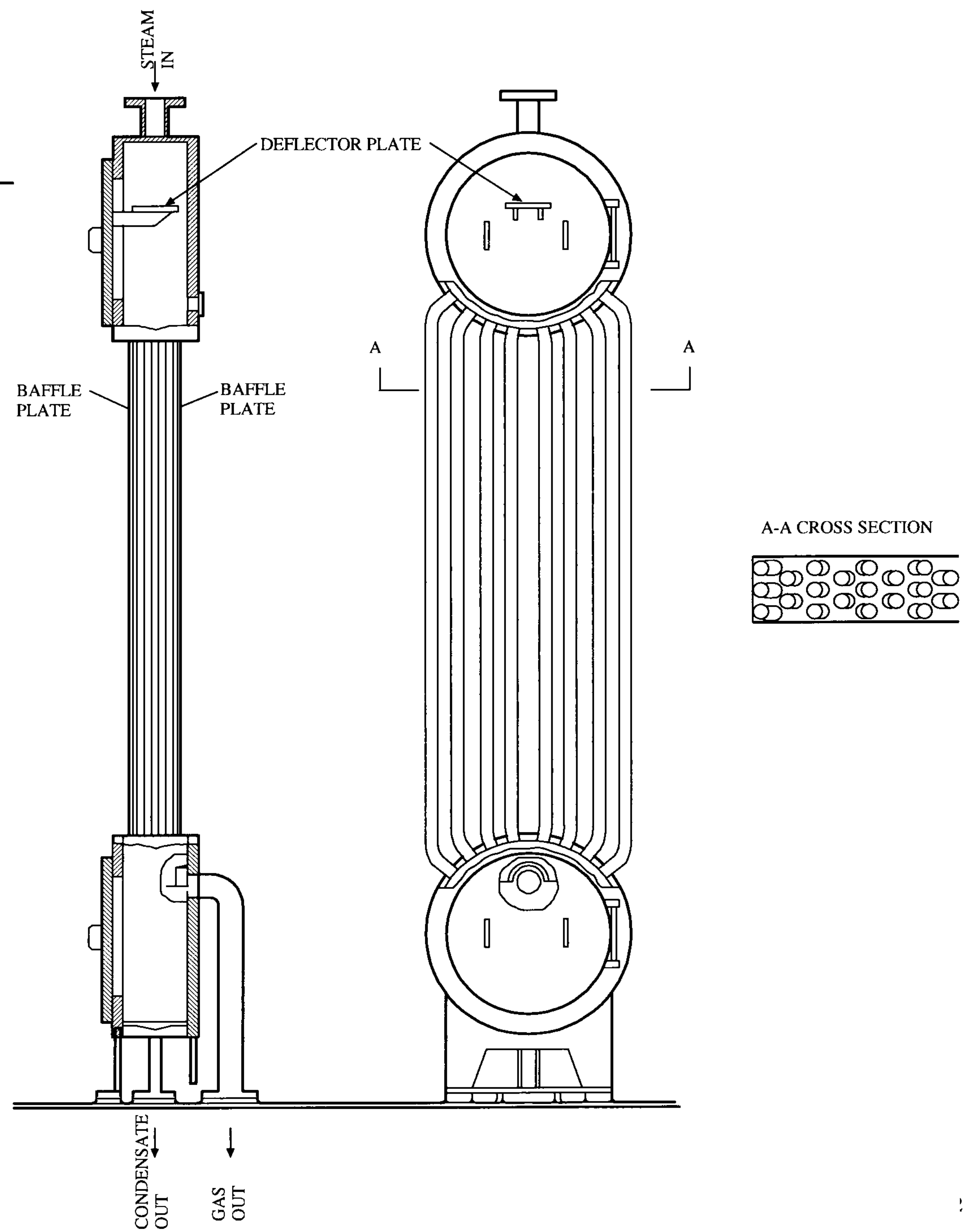
# PANDA IC/PCC Units



# 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

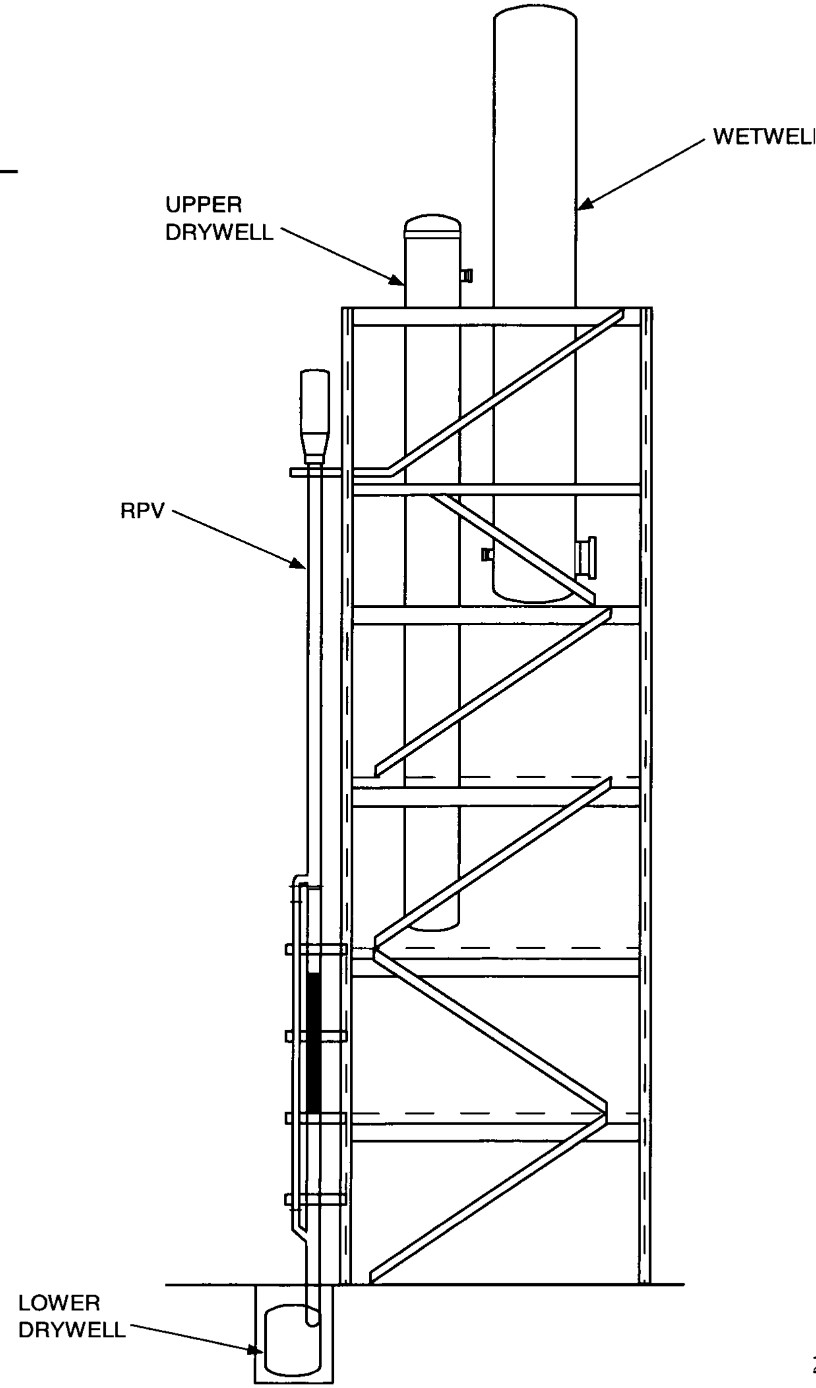
# PANDA Early Start Test (Cont'd)

# PANDA S and M Series Conclusions

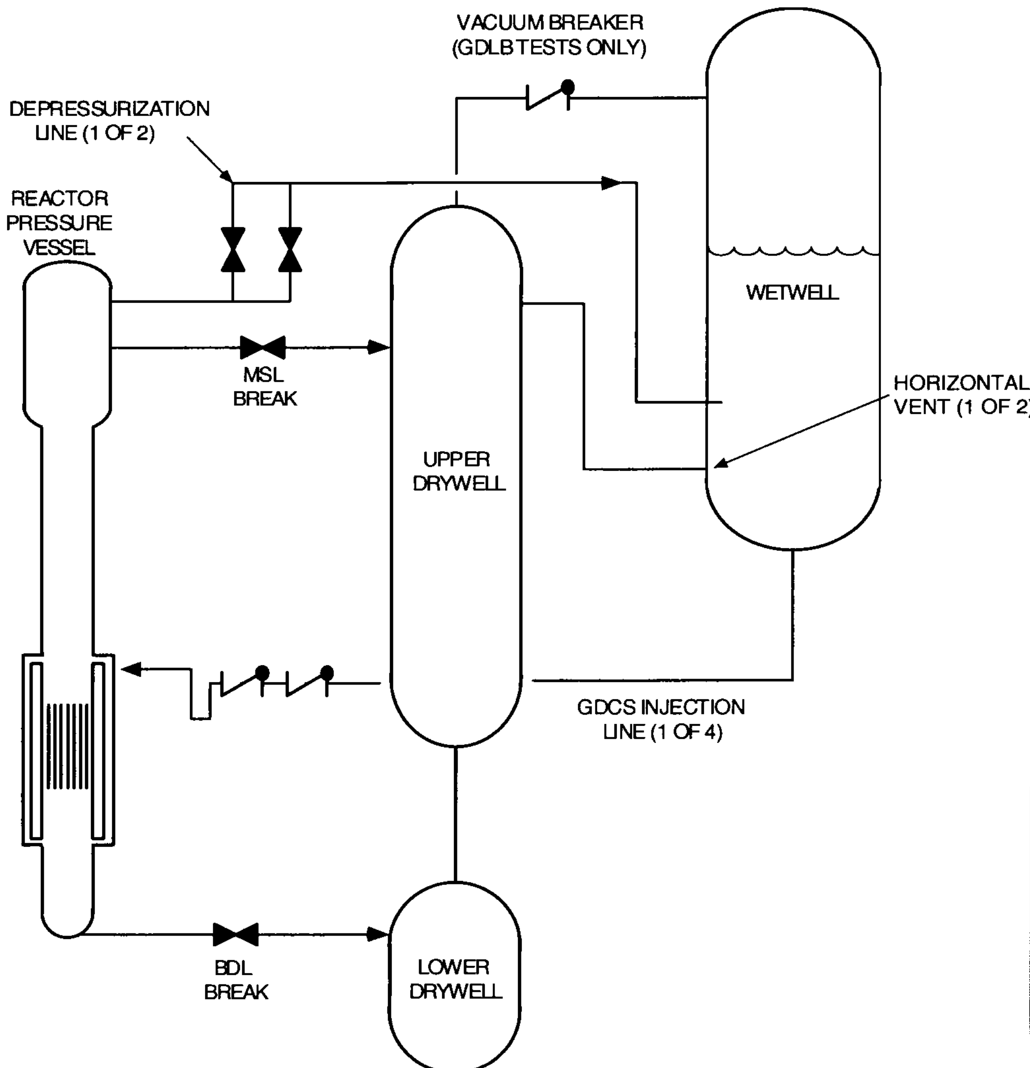
- Overall containment pressure and temperature response is favorable -- SBWR containment design is robust
- PCCS has large margin to remove decay heat after 1 hour into a LOCA
- The PCCS is well behaved and effective in transporting decay heat from the DW to the PCCS pools with no significant deposition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



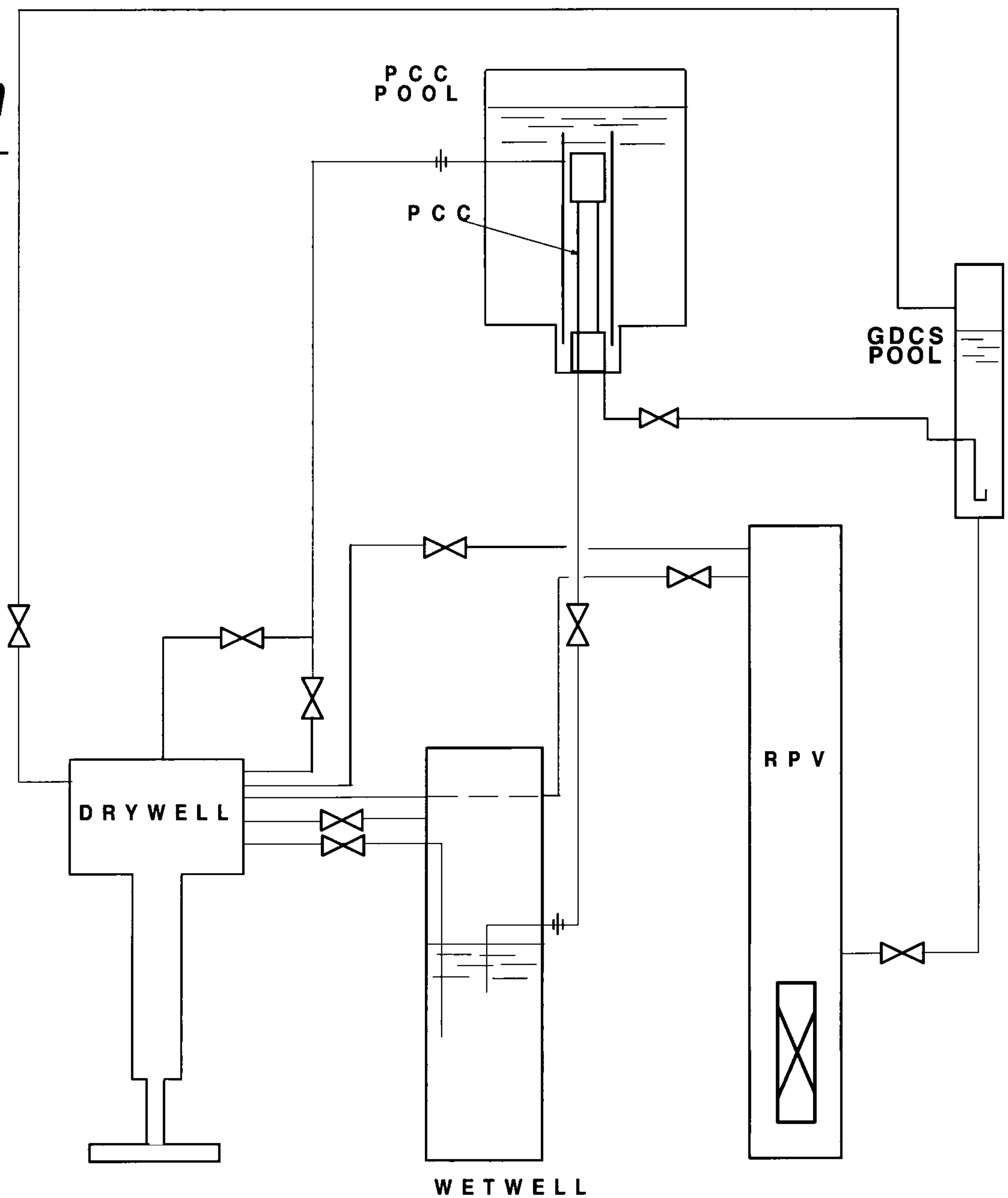
# GIST Facility




# 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

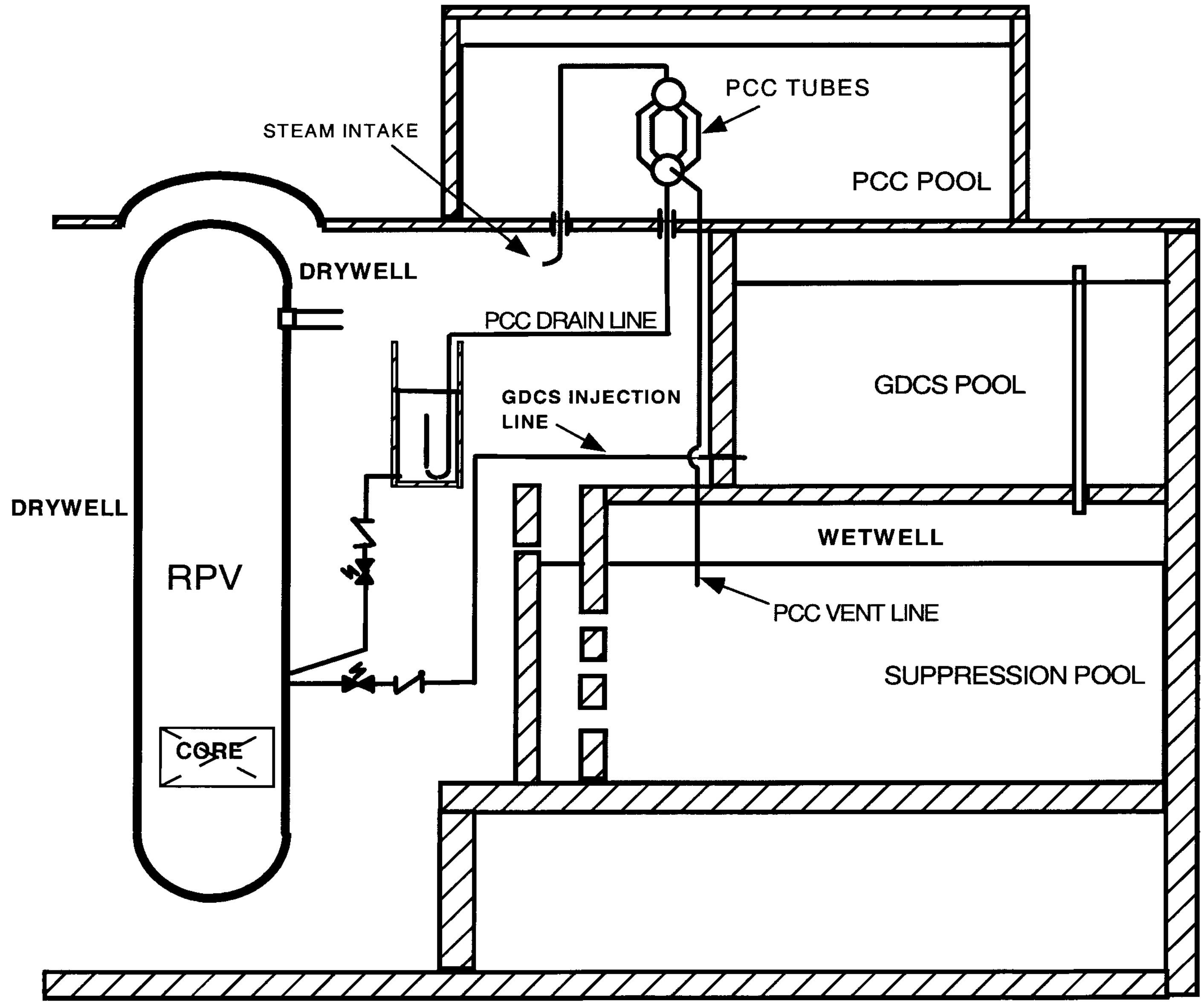
- ***GIRAFFE/Helium***
  - The PCCS operates in the presence of lighter-than-steam noncondensible gases and maintains containment pressure, even with high concentrations of noncondensible gases
  - The PCCS vents lighter-than-steam noncondensible gases, as necessary, to maintain operation
  - Heavier-than-steam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

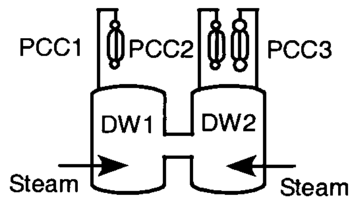


# ESBWR System Modifications

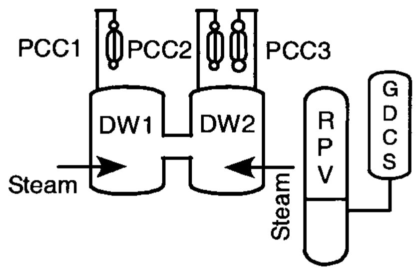
- ***Made GDCS part of WW***
  - Increased WW/DW volume ratio
  - Utilizes GDCS pool draindown space to provide increased wetwell volume
  - PCC Drain Tank added in DW
- ***Power Increased***
  - Number of ICs increased from 3 to 4
  - Number of PCCs increased from 3 to 4
  - PCCS Expanded from 10MW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

# PANDA-P Series Test Matrix

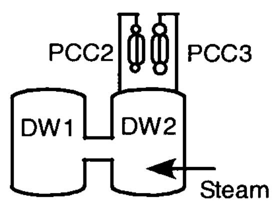
## P1: Base Case
MSL Break + 1 hr
(long-term cooling phase)



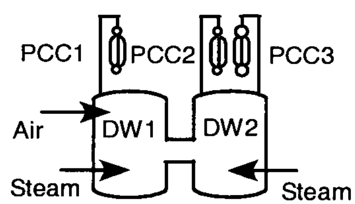

## P2: Early Start
MSL Break + 20 min
(transition from GDCS
injection to long-term
PCCS cooling phase)



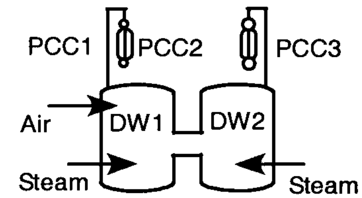

## P3: PCCS Start-up
DW initially filled with air
(deomonstrate PCCS start-up
Under challenging conditions)



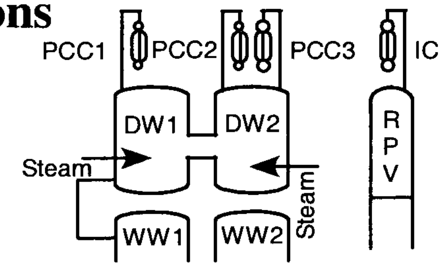

## P4: Trapped Air in DW
Air released during transient
(investigation of how n/c gas
Affects PCCS performance)



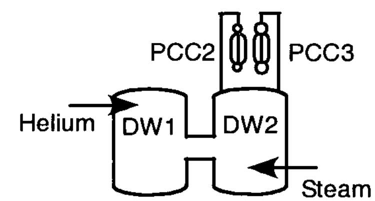

## P5: Symmetric Case
PCC2 Isolated, air supply to
DW later in transient
(MV clearing phase caused by
Reduced PCC capacity)



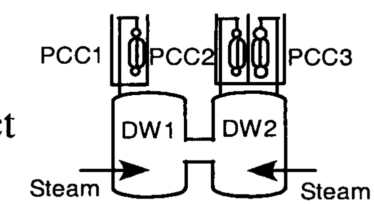

## P6: Systems Interactions
ICs and PCCs in parallel,
DW1 to WW1 leakage
(is PCC performance
adverseley affected?)




## 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**

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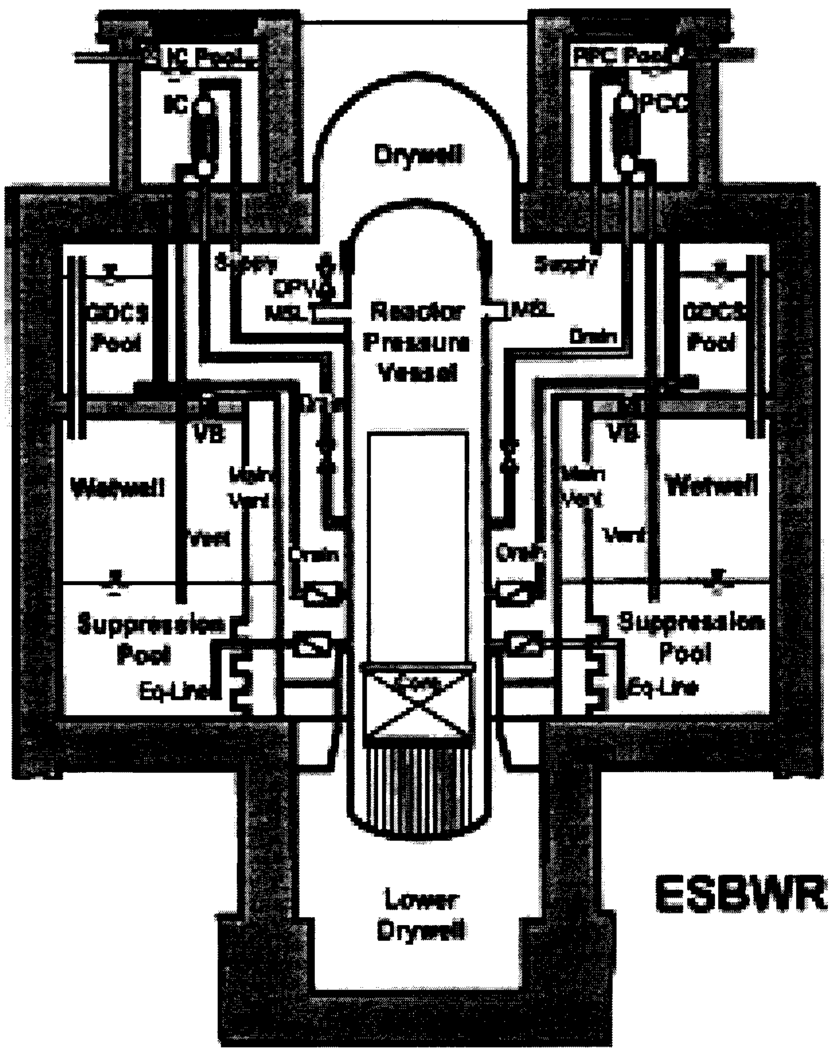
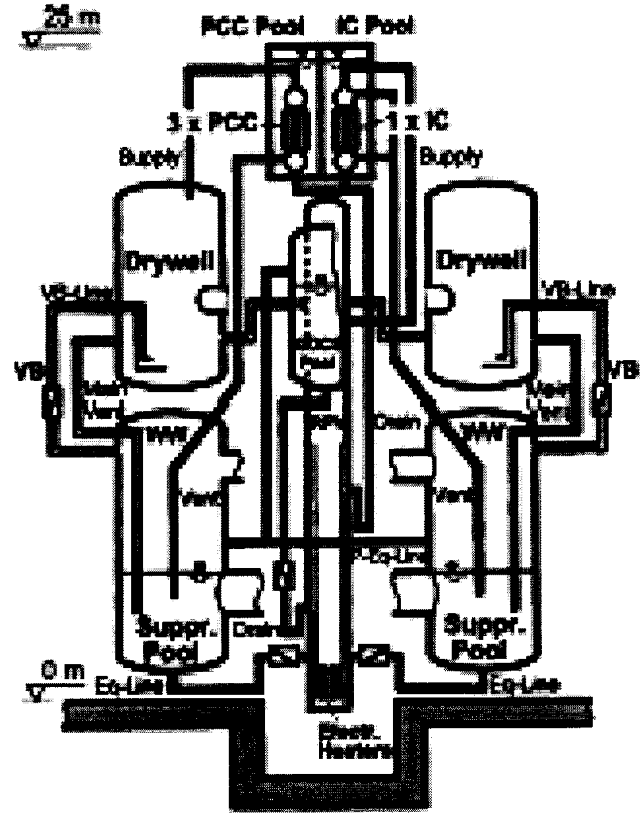
# PANDA -P series Test

- ***~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*

# 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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