ESBWR Scaling Report – NEDC 33082P

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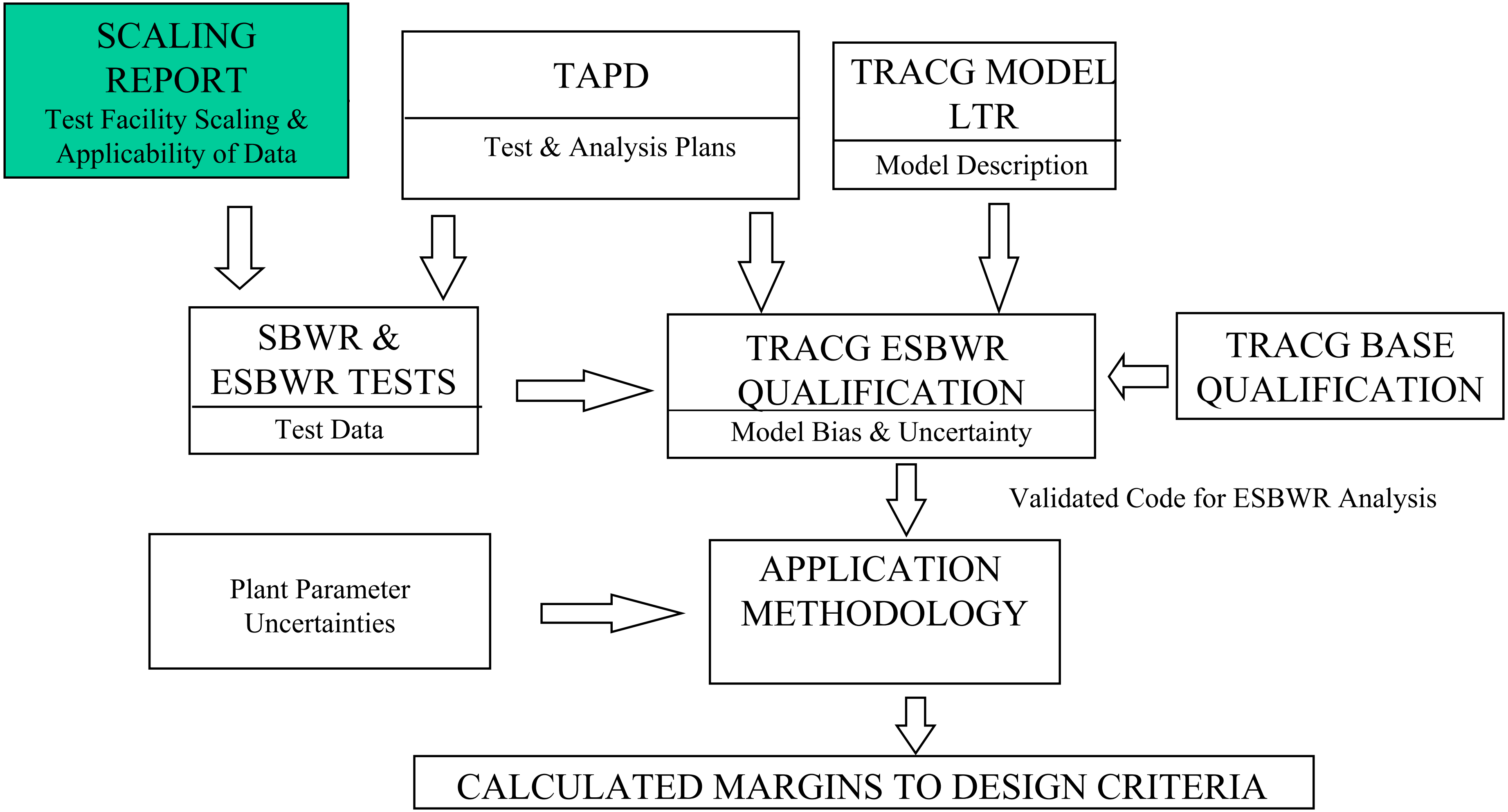
ESBWR Technology Program Elements



SCALING REPORT
Test Facility Scaling & Applicability of Data

TAPD
Test & Analysis Plans

TRACG MODEL LTR
Model Description

SBWR & ESBWR TESTS
Test Data

TRACG ESBWR QUALIFICATION
Model Bias & Uncertainty

TRACG BASE QUALIFICATION

Validated Code for ESBWR Analysis

Plant Parameter Uncertainties

APPLICATION METHODOLOGY

CALCULATED MARGINS TO DESIGN CRITERIA

Outline

- ***Objectives and Scope***
- ***Methodology***
  - Hierarchical Two-tiered Scaling (H2TS)
    - Top-down
    - Bottom-up
  - Two-parallel applications
    - 1) obtain general scaling criteria
      (for ideal case of perfectly scaled facilities)

    - 2) detect the scaling distortions and evaluate their importance
      (for the actual test facilities)
      - What phenomena are important
      - How well are they scaled
- ***ESBWR Results***
  - What phenomena are important
- ***Comparison of ESBWR and Test Facility - Scaling Results***
  - How well are important phenomena scaled in tests
- ***Observed Effects of Scale***
- ***Conclusions***

Scaling Objectives

- *Obtain criteria for test facility design*
- *Show how well various experiments represent behavior of ESBWR systems*
- *Determine if experimental data is sufficiently representative for validation of TRACG code phenomenological models*

Scope

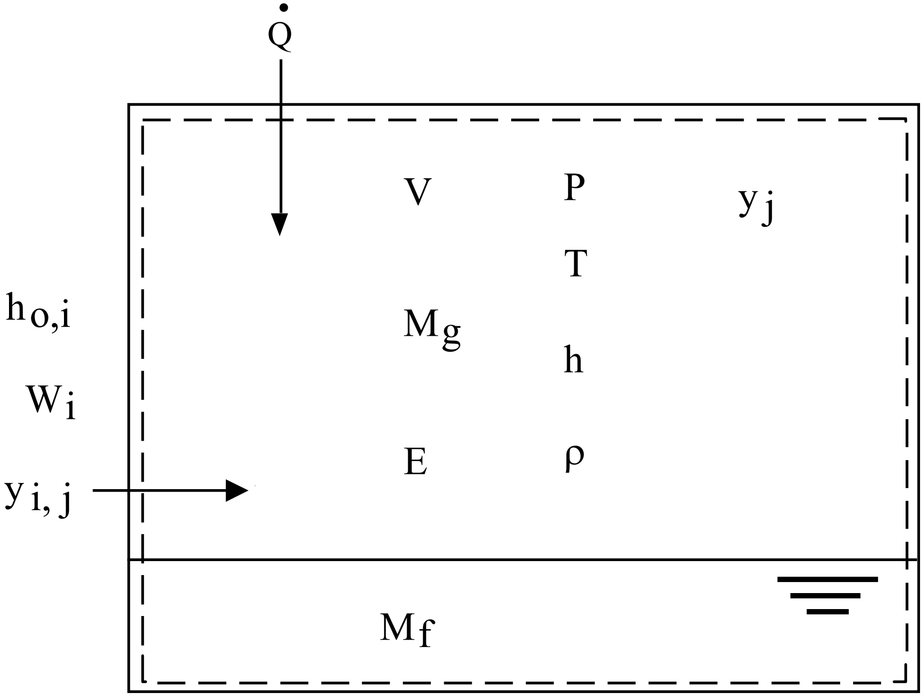
- ***LOCA ACCIDENTS***
  - MAIN STEAM LINE
  - GRAVITY DRIVEN COOLING SYSTEM LINE
  - BOTTOM DRAIN
- ***SBWR SAFETY SYSTEMS***
  - GRAVITY DRIVEN COOLING SYSTEM (GDCS)
  - ISOLATION CONDENSER SYSTEM (ICS)
  - PASSIVE CONTAINMENT COOLING SYSTEM (PCCS)
- ***IMPORTANT PHENOMENA***
  - SYSTEM PRESSURE RATES
    - REACTOR PRESSURE VESSEL
    - DRYWELL
    - WETWELL
  - MASS
    - REACTOR VESSEL
- ***TEST FACILITIES***
  - GIST
  - GIRAFFE
  - PANDA
  - PANTHERS

H2TS Methodology

- ***Top-down scaling analysis is performed at the system level (e.g., RPV, DW, WW)***
- ***Top-down scaling identifies important processes for bottom-up scaling analysis***
- ***Bottom-up scaling is performed at the local level for important phenomena***

- ***Two main applications of top-down scaling***
  - thermodynamic evolution in volumes → mass, energy and pressure
  - Transfer of mass between volumes → momentum

Thermodynamic Evolution of Containment Volumes with Mass and Energy Additions

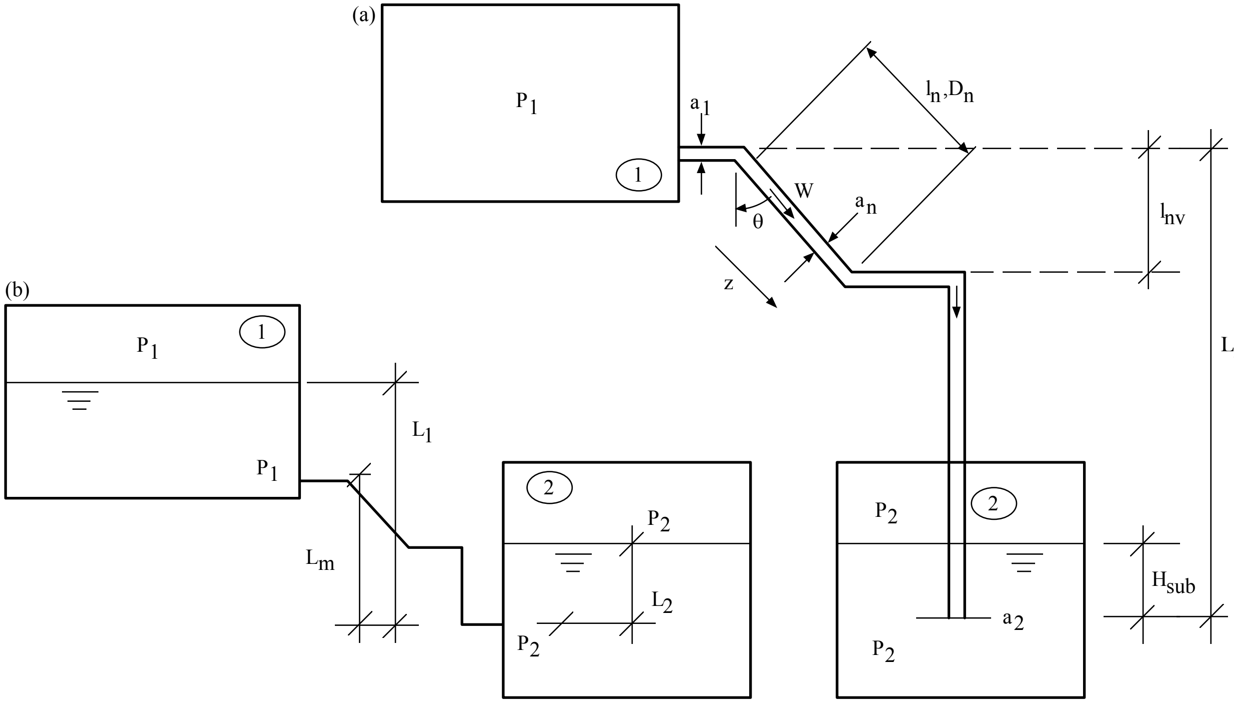


$$e = \frac{E}{M} = e\left(P, v, y_j\right)$$

A containment volume receiving mass flow rates W_i with corresponding total enthalpies $h_{o,i}$, and heat at rate $\dot{Q}$

Transfers of Mass Between Volumes Driven by Pressure Differences

Piping Configurations of Interest



(b) Pipe Connecting Two Pools;
$L_m = L_1 - L_2$, $H_m = 0$

(a) Pipe Connecting Two Volumes and Submerged in
Volume 2: $H_m = H_{sub}$, $\rho_m g L_m = 0$

Momentum Equation for path 1-2:

$$\sum_n \frac{\ell_n}{a_n}\frac{dW}{dt} = \Delta P_{12} + \rho g \sum_n \ell_{nv} - \rho_L g H - \sum_n \frac{F_n}{a_n^2}\frac{W^2}{2\rho}$$

$$F_n = \frac{f_n \ell_n}{D_n} + k_n$$

$$L_m = \sum_n \ell_{nv} \qquad \Delta P_{1,2} = P_1 - P_2$$

Summary of System Equations

- **For Volumes**
  - **total mass** $$\frac{dM}{dt} - \sum_i W_i = 0$$
  - **conservation of constituent j** $$\frac{dM_j}{dt} - \sum_i W_{ij} = 0$$
  - **energy** $$V\rho\frac{de}{dt} = -P\frac{dV}{dt} + \dot{Q} + \sum_i (h_i - h)W_i + \frac{P}{\rho}\sum_i W_i$$
  - **rate of P change** $$\frac{dP}{dt} = \frac{1}{Vf_2}\left\{\sum_i \left[W_i(h_i - h)\right] + \sum_i W_i \frac{P^*}{\rho} + \dot{Q} - P^*\frac{dV}{dt} - V\sum_j \left[f_{1j}\frac{dy_j}{dt}\right]\right\}$$
  - **vapor volume fraction** $$\rho_g\frac{d\alpha}{dt} = \frac{1}{V}\sum_i W_{g,i} + \frac{\sum_i (h_{\ell,i} - h_f)W_{\ell,i}}{Vh_{fg}} + \frac{\dot{Q}}{V} + \frac{\psi}{h_{fg}}\frac{dP}{dt}$$
- **For Flow Paths**
  - **momentum** $$\left(\frac{L}{a}\right)\frac{dW}{dt} = \Delta P - \frac{1}{\rho}\left(\frac{F}{a^2}\right)\frac{W^2}{2} - \rho g H$$

Two Parallel Scaling Procedures

- ***(1) General scaling rules for facility design***
  - For ideal case of perfectly scaled facilities
  - A minimal set of unique (global) reference scales is used:

$$\{z_r\} = t_r, v_r, W_r, \dot{Q}_r, \rho_r, \Delta P_r, \Delta h_r$$

  - non-dimensional variables are formed as: $z^+ = \frac{z}{z_r}$
- ***(2) Detect the scaling distortions and evaluate their importance***
  - For the actual plant design and test facilities
  - the minimal set $\{z_r\}$ is supplemented by additional specific reference scales

Derivation of General Scaling Criteria – Test Facility Design Rules

- ***Definition of the minimal set of reference scales*** $\{z_r\}$
  - — ***For time,*** t_r
  - — ***For volume:*** V_r
  - — ***For mass flow rates:*** W_r
  - — ***For heat addition:*** $\dot{Q}_r$
  - — ***For densities:*** ρ_r
  - — ***For pressure, a reference pressure difference:*** ΔP_r
  - — ***For constituent j fraction:*** $y_{j,r}$
  - — ***For properties involving vapor mass fraction:*** ψ_r
  - — ***For enthalpies and internal energies, a reference specific enthalpy difference:*** $\Delta h_r \rightarrow h_{fg,r}$

- ***Normalize equation variables as*** $z^+ \equiv \dfrac{z}{z_r}$

Derivation of General Scaling Criteria - 2

Non dimensionalized equations

- **Mass Conservation**

$$\frac{d}{dt^+}\left(V^+\rho^+\right) - \Pi_t \sum_i W_i^+ = 0$$

$$\frac{d}{dt^+}\left(V^+\rho_j^+\right) - \Pi_{t,j} \sum_i W_i^+ y_{i,j}^+ = 0$$

- **Energy**

$$V^+\rho^+ \frac{de^+}{dt^+} = -\frac{1}{\Pi_{hp}}\rho^+ \frac{dV^+}{dt^+} + \Pi_t \Pi_{pch} \dot{Q}^+ + \Pi_t \sum_i W_i^+ h_i^+ + \frac{\Pi_t}{\Pi_{hp}} \frac{P^+}{\rho^+} \sum_i W_i^+$$

- **Pressure Rate**

$$\frac{dP^+}{dt^+} = \frac{1}{V^+ f_2^+}\left\{\Pi_t \sum_i W_i^+ h_i^+ + \frac{\Pi_t}{\Pi_{hp}} \frac{P^{*+}}{\rho^+} \sum_i W_i^* + \Pi_t \Pi_{pch} \dot{Q}^+ - \frac{1}{\Pi_{hp}} P^{*+} \frac{dV^+}{dt^+} - V^+ \sum_j f_{1,j}^+ \frac{dy_j^+}{dt^+}\right\}$$

- **Vapor Fraction**

$$\rho_g^+ \frac{d\alpha}{dt^+} = \Pi_t \sum_i W_{g,i}^+ + \Pi_t \frac{\sum_i h_{sub,i}^+ W_{\ell,i}^+}{h_{fg}^+} + \Pi_t \Pi_{pch} \frac{\dot{Q}^+}{h_{fg}^+} + \frac{\Pi_\psi}{\Pi_{hp}} \psi^+ \frac{dP^+}{dt^+}$$

- **Momentum**

$$\Pi_{in} \frac{dW^+}{dt^+} = \Pi_{pd} \Delta P^+ - \Pi_{loss} \frac{W^{+2}}{\rho^+} + \Pi_{hyd}\, \rho^+ L^+ - \Pi_{sub}\, \rho^+ H^+$$

Resulting Scaling Criteria

- ***8 Pi Groups:*** $\Pi_t, \Pi_{in}, \Pi_{pd}, \Pi_{loss}, \Pi_{sub}, \Pi_{hp}, \Pi_{pch}$ and Π_ψ
- ***Define a system scale R:*** $R \equiv \frac{\dot{Q}_{prot}}{\dot{Q}_{mod}} = \dot{Q}_R$
- ***Choose H_R = 1 (full height to preserve pressure differences) then:***
- ***The following scaling rules result***

  Volumes
  - $(h_{fg})_R = \rho_R = 1$
  - $H_R = (y_j)_R = \alpha_R = \Delta P_R = 1$
  - $Q_R = (A_{lg})_R = W_R = R$

  Piping
  - $L_R = F_R = 1$
  - $a_R = R$

Global Momentum Scaling

- ***Two primary objectives***
  - Identify any additional nondimensional numbers that may result
  - Identify any interactions between different flow paths that may occur
- ***Results of SBWR global momentum scaling work***
  - No new nondimensional groups resulted
  - No significant interaction terms identified
  - Most interaction terms scaled relatively well
  - Confirmed result from sepearate line analyses:
    - flow controlled by balance of resistance and pressure difference (ΔP, hydrostatic head)
    - Inertia not important
- ***Global momentum scaling for SBWR yielded no new results***
- ***ESBWR configuration basically the same as the SBWR***

Global momentum scaling not repeated for ESBWR

Summary of General Scaling Criteria and System Design Rules

- ***Minimum set of criteria for system design***
- ***All facilities nominally scaled according to "General Scaling Criteria"***
  - Full-vertical-scale
  - Flow area/Heat transfer area/Mass/Power/Flow scaled to system scale
  - Prototypical fluids
  - Prototypical initial conditions
- ***Various unique modifications within these criteria to meet facility constraints or improve some aspect of facility such as:***
  - Removal of unimportant volumes in PANDA (bottom of vessel and SP)
  - Pancaking of LDW in GIRAFFE
  - Use of 2 DW and WW in PANDA to study larger horizontal length scale and hideout

Scaling for Important Phenomena and Facility Distortions

- ***Different focus from general scaling criteria***
  - What are important phenomena
  - How well are important phenomena scaled for use in code qualification
- ***More detailed reference values are used***
- ***Special care is taken to assure nondimensional variables are close to 1 so that PI group comparisons are meaningful***
- ***Selection of Reference Values***
  - Pressures, temperatures and mass fractions taken from test initial conditions
  - Flows calculated using choked or unchoked flow formulations
  - Reference flow, pressure and time changes selected to maintain variables and their derivatives of order one
  - No code calculations used for tests other than for test initial conditions
    - Tests cover range of initial conditions

Summary of System Equations…again

- ***Start with same set of equations***
  - ***For Volumes***
    - ***total mass*** $$\frac{dM}{dt} - \sum_i W_i = 0$$
    - ***conservation of constituent j*** $$\frac{dM_j}{dt} - \sum_i W_{ij} = 0$$
    - ***energy*** $$V\rho \frac{de}{dt} = -P\frac{dV}{dt} + \dot{Q} + \sum_i (h_i - h) W_i + \frac{P}{\rho}\sum_i W_i$$
    - ***rate of P change*** $$\frac{dP}{dt} = \frac{1}{Vf_2}\left\{\sum_i \left[W_i (h_i - h)\right] + \sum_i W_i \frac{P*}{\rho} + \dot{Q} - P*\frac{dV}{dt} - V\sum_j \left[f_{1j}\frac{dy_j}{dt}\right]\right\}$$
    - ***vapor volume fraction*** $$\rho_g \frac{d\alpha}{dt} = \frac{1}{V}\sum_i W_{g,i} + \frac{\sum_i (h_{\ell,i} - h_f) W_{\ell,i}}{Vh_{fg}} + \frac{\dot{Q}}{V} + \frac{\psi}{h_{fg}}\frac{dP}{dt}$$
  - ***For Flow Paths***
    - ***momentum*** $$\left(\frac{L}{a}\right)\frac{dW}{dt} = \Delta P - \frac{1}{\rho}\left(\frac{F}{a^2}\right)\frac{W^2}{2} - \rho g H$$

Non Dimensionalized Equations for Facility Comparison

New nondimensionalized equations

- ***Mass Conservation*** $\frac{d}{dt^+}\left(V^+\rho^+\right) - \Pi_t \sum_i W_i^+ = 0$ $\frac{d}{dt^+}\left(V^+\rho_j^+\right) - \Pi_{t,j} \sum_i W_i^+ y_{i,j}^+ = 0$

- ***Energy*** $M^+ \frac{de^+}{dt^+} = -\Pi_{e,\dot{V}} P^+ \frac{dV^+}{dt^+} + \sum_i \Pi_{e,\dot{Q}} \Pi'_{\dot{Q}} \dot{Q}_i^+ + \sum_i \Pi_{e,wh,i} W_i^+ h_i^+ + P^+ \big/ \rho^+ \sum_i \Pi_{e,mech,i} W_i^+$

- ***Pressure Rate*** $f_2^+ V^+ \frac{dP^+}{dt^+} = \sum_i \Pi_{P,\dot{Q},i} Q_i^+ - \Pi_{P,\dot{V}} P^{*+} \frac{dV^+}{dt^+} + \sum_i \Pi_{P,Wh,i} W_i^+ h_i^+$

$$+ \frac{P^{*+}}{\rho^+} \sum_i \Pi_{P,mech,i} W_i^+ - V^+ \sum_j \Pi_{P,y,j} \left(f_{1,j}^+ \frac{dy_j^+}{dt^+} \right)$$

- ***Liquid Mass**** $h_{fg}^+ \frac{dM_\ell^+}{dt^+} = -\sum_i \Pi_{M,\dot{Q},i} \dot{Q}_i^+ + h_{fg}^+ \sum_i \Pi_{M,W,i} W_{\ell,i}^+ + \sum_i \Pi_{M,sub,i} h_{sub,i}^+ W_{\ell,i}^+$

$$-\left[\Pi_{M,\dot{P}1} V_{RPV}^+ f_3^+ + \Pi_{M,\dot{P}2} f_4^+ M_\ell^+\right] \frac{dP^+}{dt^+}$$

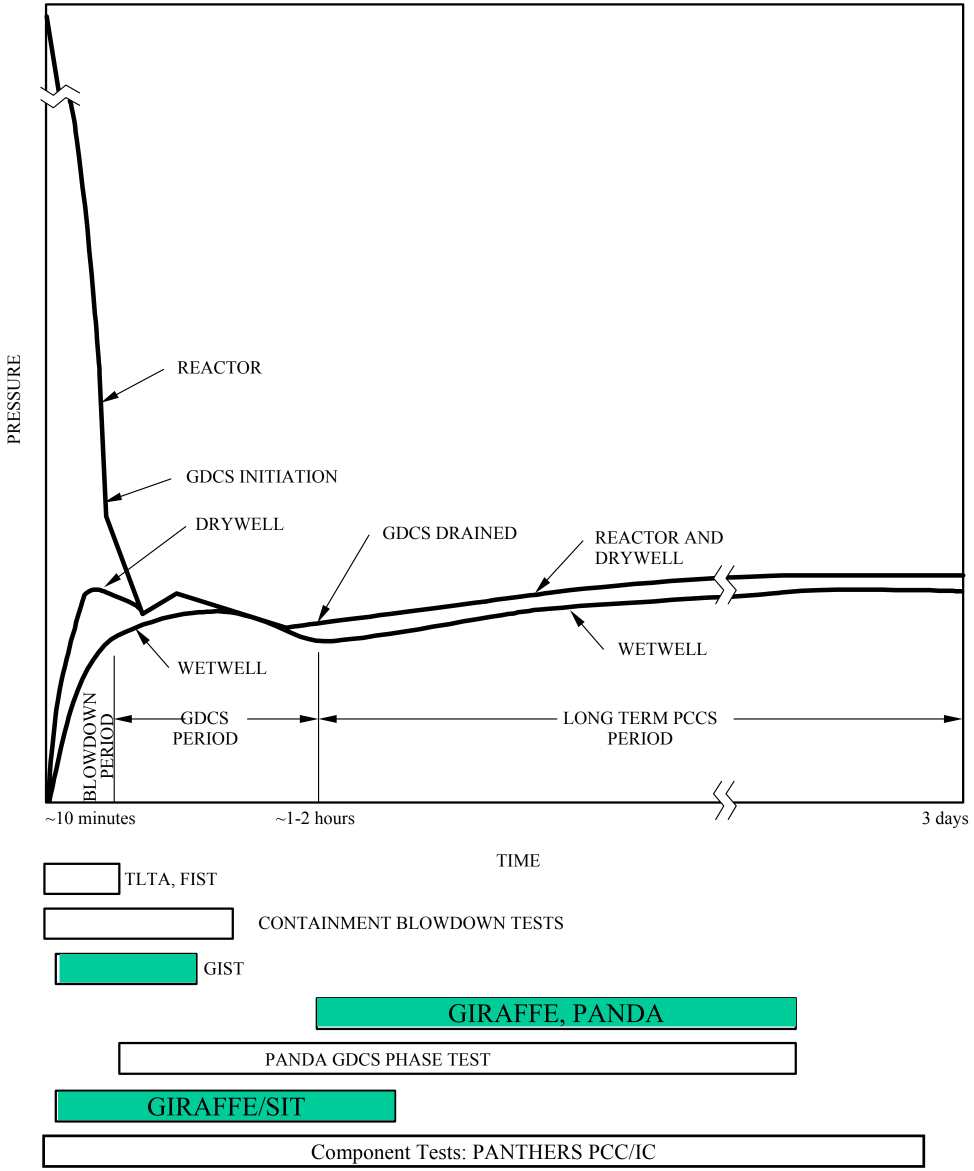
- ***Momentum*** $\Pi_{in} \frac{dW^+}{dt^+} = \Pi_{pd} \Delta P^+ - \Pi_{loss} \frac{W^{+2}}{\rho^+} + \Pi_{hyd}\, \rho^+ L^+ - \Pi_{sub}\, \rho^+ H^+$

Switched to liquid mass from void fraction - result is the same

Application - Important Parameters in ESBWR

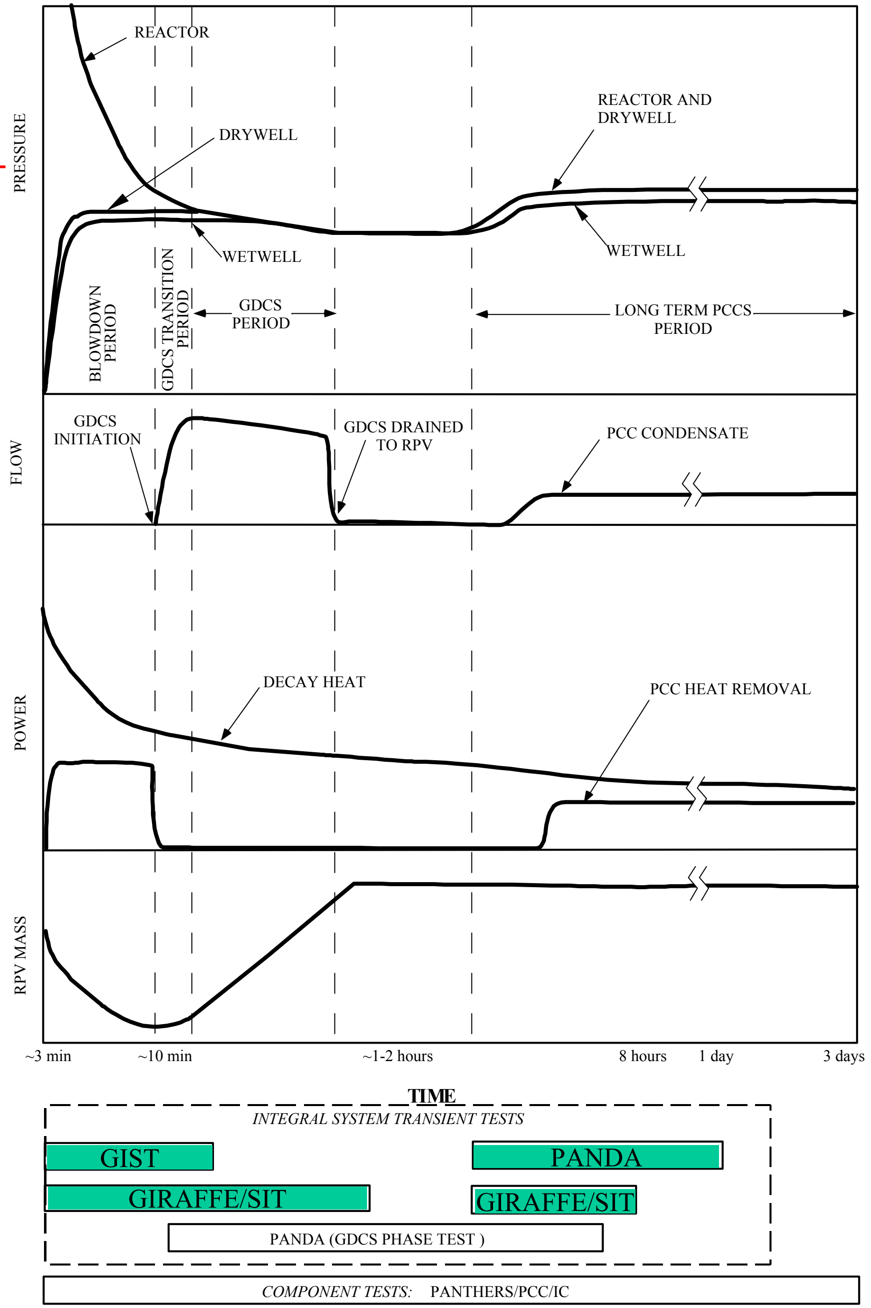
- ***RPV***
  - – Primary parameter: Water level
    - Keep the core covered
  - – Secondary parameter: Pressure
    - Controls initiation of GDCS
- ***Containment***
  - – Primary parameter: Pressure
    - Maintain pressure below design limit

Integral Test Coverage for ESBWR LOCA



Time periods for scaling evaluation

- ***Break transient into periods where:***
  - Dominant phenomenon remains the same
  - Magnitudes of phenomenon are *relatively* constant
  - Or, there is a special interest



Parameters and Regions Selected for Scaling

Evaluation Points

ESBWR Results

→ *What phenomena are important to plant behavior*

Momentum Scaling

- ***Momentum Equation***

$$\Pi_{in}\frac{dW^{+}}{dt^{+}}=\Pi_{pd}\Delta P^{+}-\Pi_{loss}\frac{W^{+2}}{\rho^{+}}+\Pi_{hyd}\,\rho^{+}L^{+}-\Pi_{sub}\,\rho^{+}H^{+}$$

- ***Terms for:***
  - Inertia, pressure drop,flow losses, hydrostatic head and submergence
- ***SBWR Results:***

- ***Nothing has changed in the ESBWR with the exception of the GDCS being in the WW***

GDCS Initiation Timing

- ***Momentum Equation for GDCS Line***

Hydrostatic driving head

Hydrostatic head above nozzle in RPV

$$\Pi_{in}\frac{dW^{+}}{dt^{+}}=\Pi_{pd}\Delta P^{+}-\Pi_{loss}\frac{W^{+2}}{\rho^{+}}+\Pi_{hyd}\,\rho^{+}L^{+}-\Pi_{sub}\,\rho^{+}H^{+}$$

Difference in cover gas pressures

SBWR: $\Delta P_{PD} = P_{RPV} - P_{DW}$ in

ESBWR: $\Delta P_{PD} = P_{RPV} - P_{WW} = P_{RPV} - P_{DW}$ - PCC vent submergence head

RPV Late Blowdown: Time Rate of Pressure Change (Pdot)

RPV Pressure – Late Blowdown

RPV Late Blowdown: Time Rate of Liquid Mass Change (Mdot)

RPV Liquid Mass – Late Blowdown

RPV Pressure – GDCS Transition

- ***Pressure change during transition phase small compared to late blowdown and VERY small compared to entire blowdown***
- ***Depressurization driven by ADS flow***
- ***Stored energy release and GDCS subcooling make measurable contribution***
- ***IC and break flow contribution negligible***
  - No IC interactions expected
- ***No volume change***

Transition phase of limited interest. Timing of phase initiation of most interest.

RPV Liquid Mass – GDCS Transition

- ***Mass loss affected by all parameters except IC***
- ***GDCS and Flashing contributions are very transient during phase***
  - GDCS contribution given at ¼ of rated GDCS flow
  - GDCS ranges from 0 to 4 times height shown
  - Flashing ranges from bar shown to 0

RPV Liquid Mass – GDCS Transition

- ***Mass change during transition phase small compared to blowdown***
- ***Mass loss affected by all parameters except IC***
- ***GDCS and Flashing contributions are very transient during phase***
  - GDCS contribution given at 1/4 rated GDCS flow
  - GDCS ranges from 0 to 4 times height shown
  - Flashing ranges from bar shown to 0

Mass controlled by timing of transition phase start

RPV Liquid Mass – Reflood

- ***GDCS flow dominates all other phenomena after transition period***
- ***GDCS subcooling (blue) will offset boiling due to decay heat collapsing voids***

Reflood is a straightforward single phase calculation

Drywell Long Term/PCCS: Time Rate of Pressure Change (Pdot)

DW Pressure – Long Term

- ***The DW volume is purged many times over (indicated by large bars)***
  - Pressure will quickly adjust to boundary condition controlling outlet flow (i.e. WW pressure)
- ***Energy inputs are unimportant to behavior***
- ***PCC heat removal has no direct effect on DW***
  - PCC flow would be the same with no heat removal

Details of DW are unimportant except as they affect timing of release of noncondensible gas to WW

Wetwell Long Term/PCCS: Time Rate of Pressure Change (Pdot)

WW Pressure – Long Term

- ***WW is a balance of very small terms in the long term***
- ***Pressure increase is dominated by short term noncondensible gas addition***
- ***Heat capacity of wall is sufficient to absorb VB leakage for many days***
  - Wall heat absorption adjusts to heat sources from VB leakage or pool evaporation

Important parameter for WW is addition of noncondensibles - as long as heat inputs are weaker than wall energy storage capability

Summary for ESBWR

- ***RPV***
  - Blowdown dominated by ADS flow and flashing
  - Short transition period where several phenomena are of similar magnitude but mass change is unimportant
  - GDCS flow dominates RPV mass behavior during reflood

RPV Mass controlled by blowdown period. Minimum mass determined by timing of GDCS initiation.

- ***Containment***
  - Pressure change dominated by movement of noncondensible from DW to WW
  - DW pressure just follows WW pressure
    - Hide out of noncondensibles can change timing of pressure change
  - PCC only important in controlling amount of energy into SP
  - Long-term changes in containment pressure small compared to initial pressurization due to noncondensibles

Containment pressure change dominated by movement of noncondensibles from DW to WW

Comparison of ESBWR and Test Facilities

→ *How well are facilities scaled*

What Constitutes "Well Scaled" Facility

- ***Goal of tests is to:***
  - Represent phenomena important to system behavior at scaled magnitudes similar to the prototype so that models can be qualified for predicting important phenomena over a range of conditions similar to those expected in prototype
    - Important phenomena should be represented in test at similar magnitude to prototype
    - Unimportant phenomena need not be modeled
    - Phenomena not important in prototype should not be important in test
- ***No specific criteria exists to define well scaled***
  - An acceptable criteria is to maintain important phenomena within factor of ~3 of prototype
    - Same order of magnitude in test and prototype
    - Differentiates from factor of 15 used to identify unimportant phenomena

RPV Pressure – Late Blowdown

- ***Parameters are well matched***

RPV Liquid Mass – Late Blowdown

- ***Parameters are well matched***

RPV Pressure – GDCS Transition

- ***Parameters well matched***
- ***Parameters not very important to overall system behavior***

RPV Liquid Mass – GDCS Transition

- ***Although transition period is not important to minimum mass, parameters are still matched well***

RPV Liquid Mass – Reflood

- ***Parameters are well matched***

DW Pressure – Long Term

- ***Important Parameters are well matched***

WW Pressure – Long Term

- ***Pressure change in long term is small compared to early pressure increase due to noncondensible movement***
- ***Parameters are matched reasonably well***

PCC Scaling

Bottom-up Scaling

Bottom up scaling not extended beyond what was done in SBWR report

Summary for Test Facility Comparison

- ***Only a small number of phenomena important to system behavior***
- ***Dominant phenomena are well scaled in test facilities***
- ***Less important phenomena scaled well also, although not necessary to do so***
- ***No new phenomena in tests***

Observed effects of scale from tests

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

Scaling Summary

- ***Only a small number of phenomena important to system behavior***
- ***Important phenomena well scaled in tests***
- ***No surprises – no unexpected phenomena present in tests****
- ***No additional bottom-up scaling needed as part of ESBWR work***
- ***Comparison of test results at different scales confirm these results***

****some non prototypic heat leakage for portions of tests resulted in non representative phenomena for short periods***