STP 3&4 DESIGN BASIS ACCIDENT CONTAINMENT LOADS: CONFIRMATORY ASSESSMENT OF POOL SWELL ANALYSES

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Outline

- Background
- Objectives
- Summary of Key Results
- Identification and Ranking of Dominant Phenomena (PIRT)
- ERI Mechanistic Model
- GOTHIC and ERI Model Features
- Benchmarking of ERI Model Against the PSTF Data
- Application to STP 3&4 ABWR Containment
- Comparison with GOTHIC Results
- Summary & Conclusions

Background

- Applicable Hydrodynamic Loads:
  - Loads during loss of coolant accident (LOCA)
    - Pool swell
    - Condensation oscillations (CO)
    - Chugging (CH)
  - Loads during safety/relief valve (SRV) Actuation
- Applicable Figures-of-Merit for Pool Swell Load:
  - Swollen level (rise height)
  - Pool surface velocity
  - Gas bubble pressure
  - Wetwell gas space pressure

Background Cont.)

- Existing Models/Analyses:
  - ABWR DCD Pool Swell Analysis
    - GE analytical model (NEDE-21544P) (developed for Mark II)
    - Benchmarked against PSTF data (Mark III data)
  - Westinghouse Pool Swell Analysis
    - GOTHIC code based approach (NAI-1397-001-Rev 1)
    - Benchmarked against PSTF test 5806-1

Objectives

- Perform a confirmatory evaluation of the GOTHIC pool swell analysis results using approach consisting of:
  - Identification and ranking of relevant phenomena (i.e., PIRT)
  - Development of mechanistic model for prediction of relevant figures-of-merit
  - Benchmarking against PSTF experimental data
  - Application to STP3&4 pool swell under DBA conditions
  - Sensitivity studies to assess the impact of key modeling assumptions and governing parameters on pool swell parameters
  - Comparisons with GOTHIC Results

Summary of Key Results

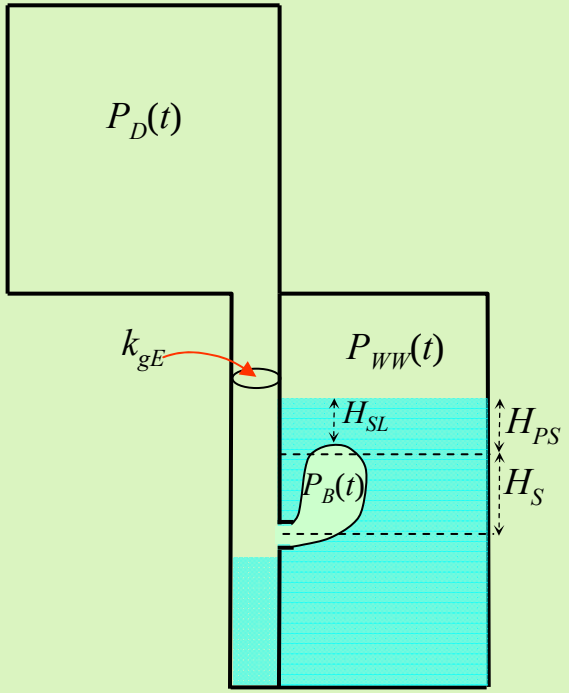
- Good agreement between the PSTF data & the predictions of ERI model for:
  - Vent clearance time
  - Pool swell parameters:
    - Pool surface elevation
    - Pool surface velocity
    - Pressure inside vent
  - Liquid slug thickness and bubble breakthrough time
- Sensitivity calculations showed that frictional losses in the vent system significantly affect pool swell results

Summary of Key Results – Cont.

- Best estimate values predicted by ERI model for the pool swell parameters are lower compared to the predictions of GOTHIC model for the design case
- GOTHIC model input assumptions are conservative
- For the similar conservative model input assumptions (& values of model parameters), ERI model predicted higher pool swell height and pool surface velocity compared to the predictions of GOTHIC model

Identification & Ranking of Dominant Phenomena (PIRT)

- Important Mechanisms
  - Drywell pressurization
  - Vent clearance
  - Flow through vents (pressure drop and critical flow)
  - Bubble formation and growth rate
  - Bubble rise and breakthrough

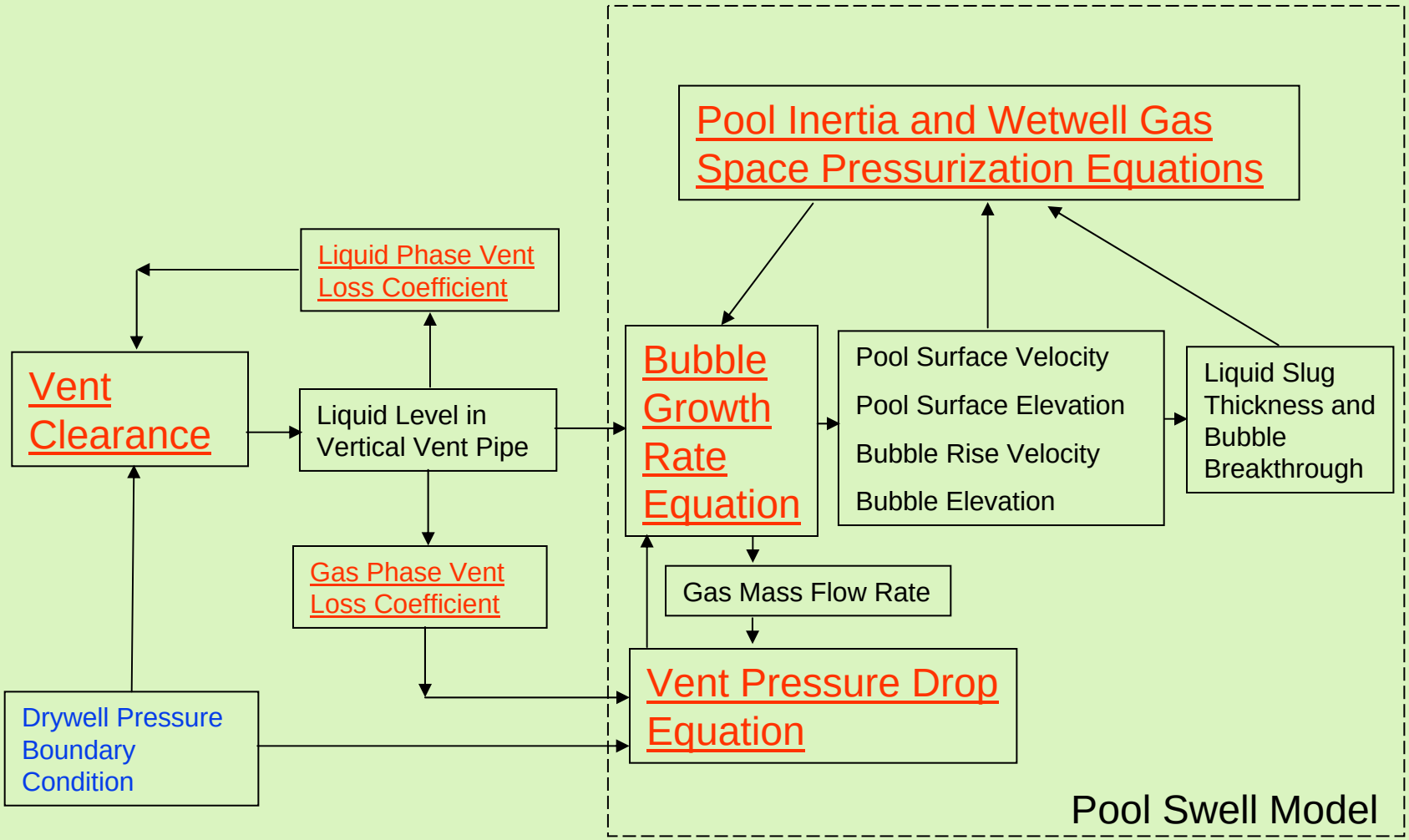


Identification & Ranking of Dominant Phenomena (PIRT) – Cont.

- The identified phenomena, rationale for importance and knowledge rankings are being documented.

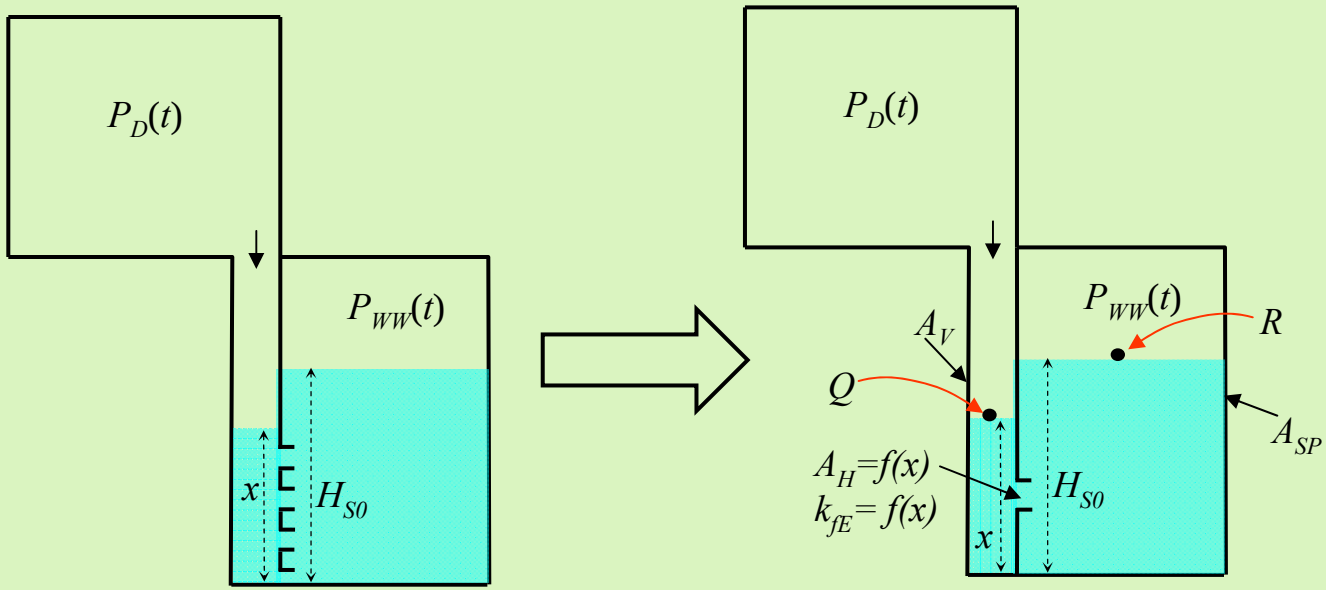
- Highly ranked phenomena include:
  - Drywell pressurization – Use W-supplied conditions (not modeled)
  - Vent clearance & flow through vents
    - Fluid inertia
    - Effect of back pressure
    - Flow losses (bends, turns, geometric losses)
    - Flow conditions (subcritical and critical)
  - Bubble formation and growth rate
  - Bubble rise and breakthrough

Overview of the ERI Model



Modeling of Vent Clearance

- Vent Clearance



$$\left(\rho_f x + \rho_f L \frac{A_V}{A_H}\right)\frac{dV_V}{dt} - \rho_f V_V^2 = \left(P_D - P_W\right) - \rho_f k_{fE}\frac{V_V^2}{2} + \rho_f g_z\left(x - H_{S0}\right)$$

- Level in vertical vent $\frac{dx}{dt} = V_V$

Modeling of Vent Clearance – Cont.

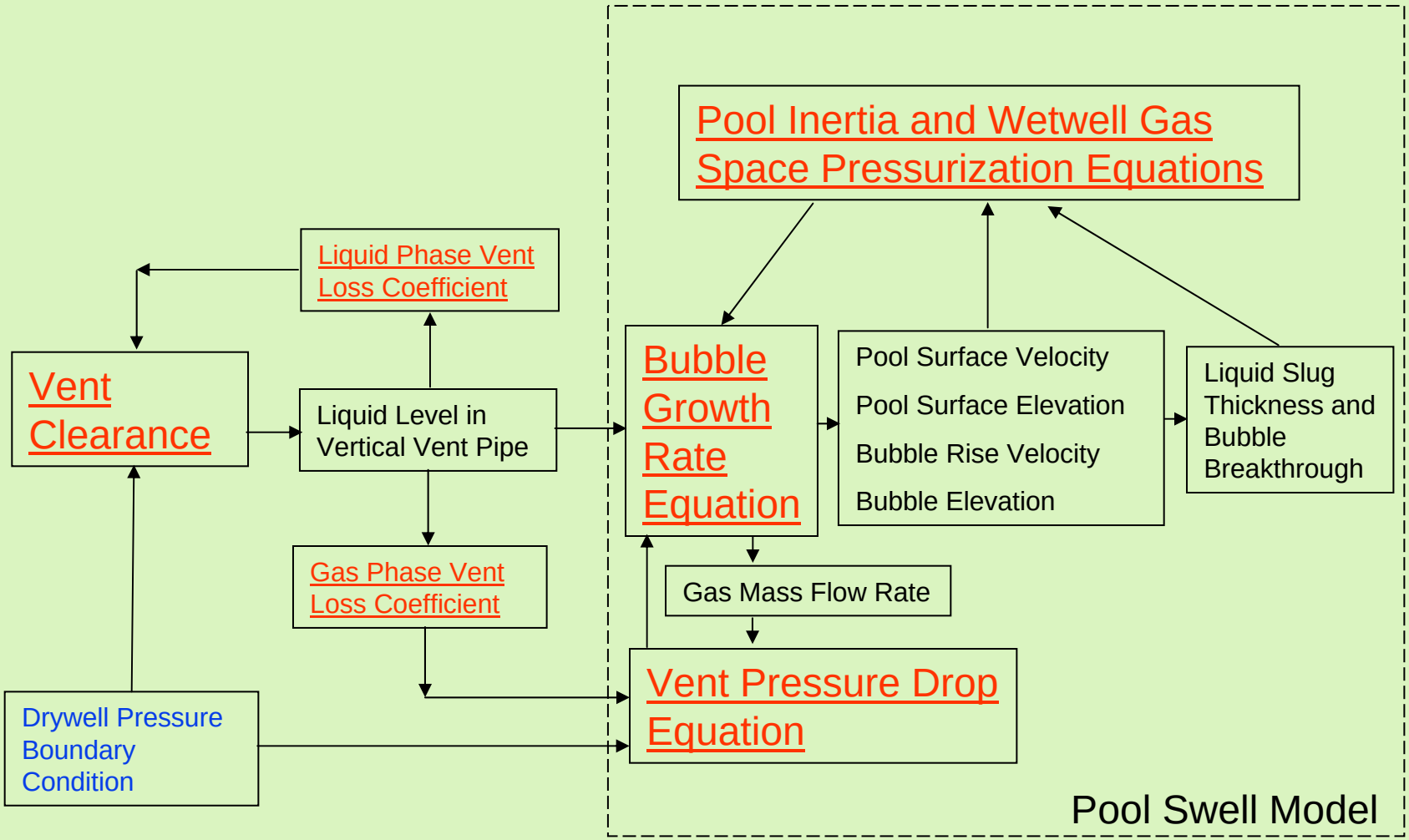
- Effective vent loss coefficient for liquid phase,

$$k_{fE} = f(x)$$

- Horizontal vent flow area,

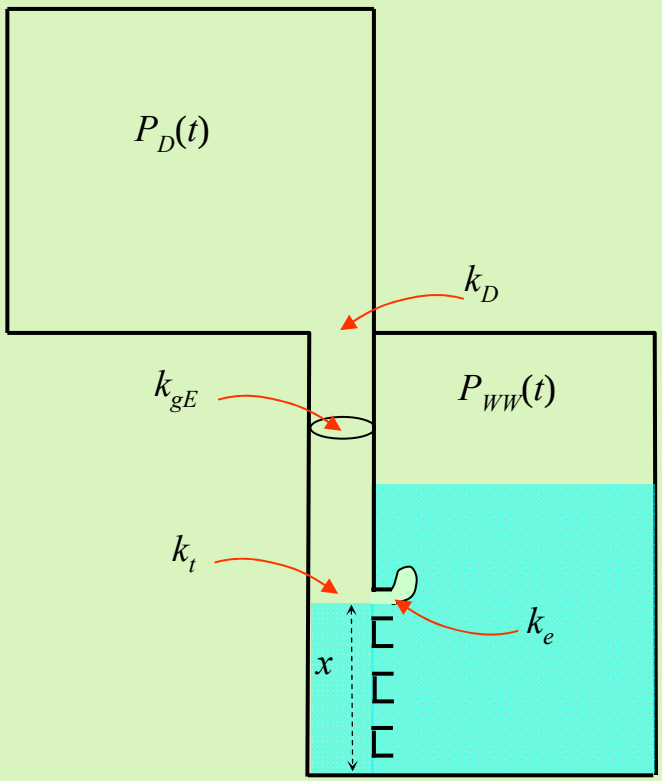
$$A_H = f(x)$$

Overview of the ERI Model



Estimations of Vent Losses

- Effective Vent Loss Coefficients
  - Effective vent loss coefficient for gas phase

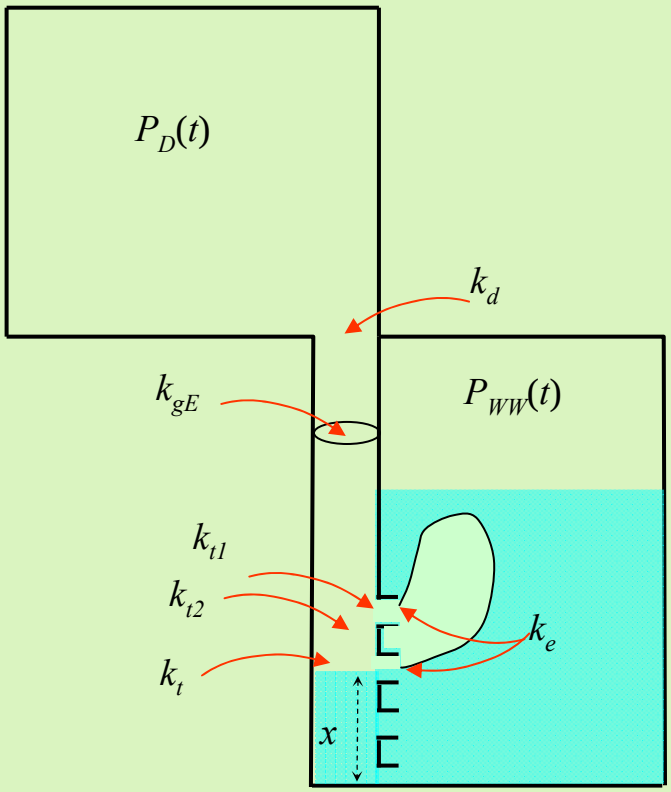


$$\frac{k_{gE}}{A_V^2} = \frac{k_D}{A_V^2} + \frac{k_t + \frac{\left(1-\beta_1^2\right)}{2\beta_1^4}}{A_V^2} + \frac{k_e}{A_{H1}^2}$$

k_{gE}	Effective gas phase vent loss coefficient
k_D	Vertical vent entrance loss
k_t	90° elbow turning loss
k_e	Horizontal vent exit loss
β_1	Ratio of diameters (d_{H1}/d_V)

Estimations of Vent Losses – Cont.

– Effective vent loss coefficient for gas phase



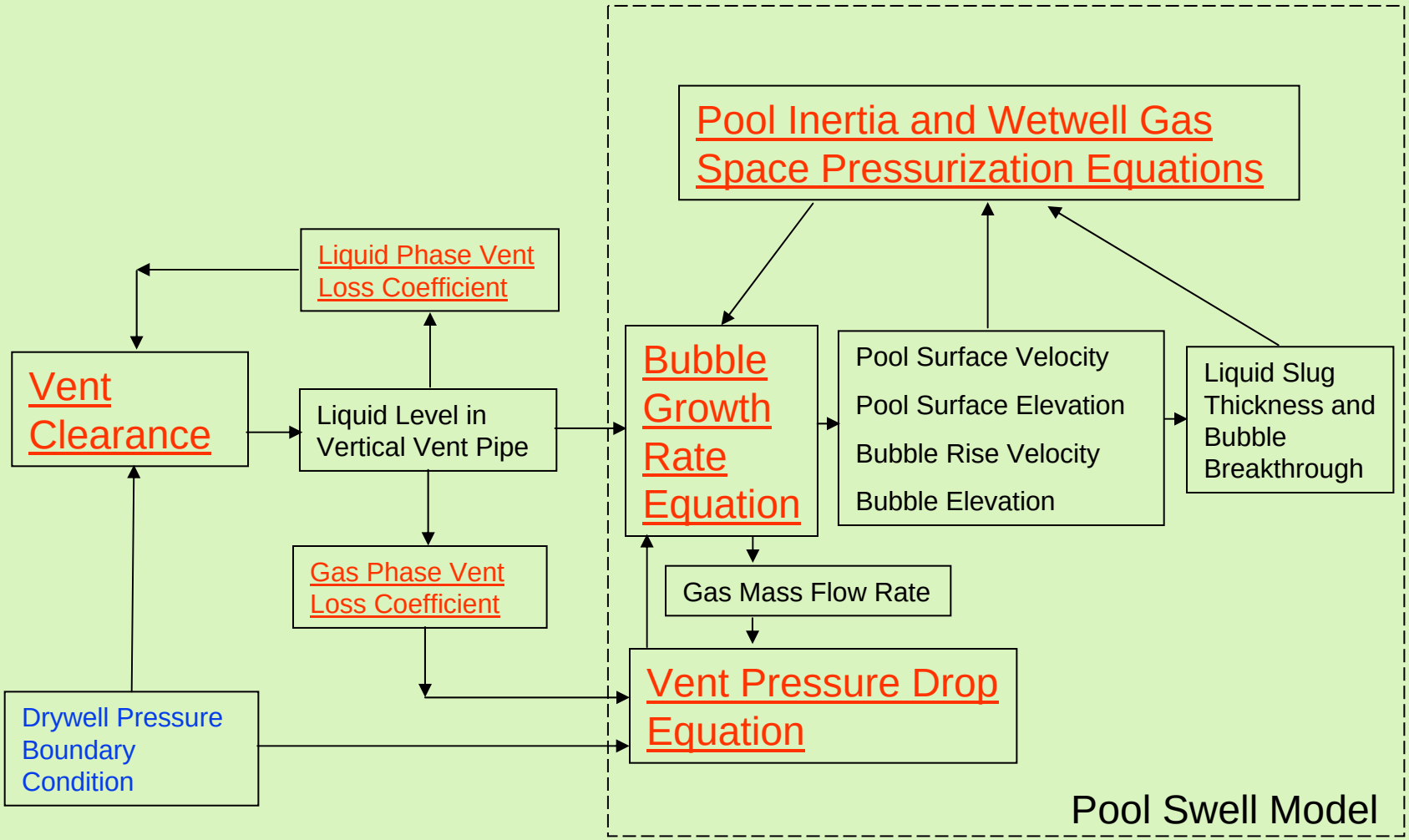
$$\frac{k_A}{A_V^2} = \frac{k_{t1} + \frac{\left(1-\beta_1^2\right)}{2\beta_1^4}}{A_V^2} + \frac{k_e}{A_{H1}^2}$$

$$\frac{k_B}{A_V^2} = \frac{k_{t2}}{A_V^2} + \frac{k_t + \frac{\left(1-\beta_2^2\right)}{2\beta_2^4}}{A_V^2} + \frac{k_e}{A_{H2}^2}$$

$$\frac{A_V}{\sqrt{k_C}} = \frac{A_V}{\sqrt{k_A}} + \frac{A_V}{\sqrt{k_B}}$$

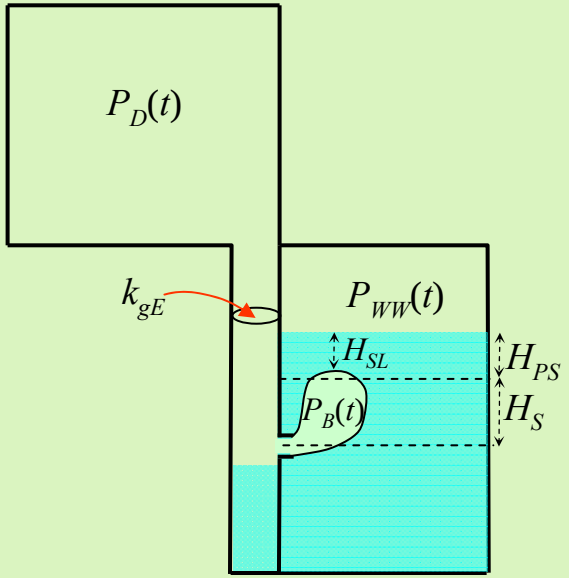
$$k_{gE} = k_C + k_d$$

Overview of the ERI Model



Vent Pressure Drop Equation

- All horizontal vents located at the elevation of top vent
- Area averaged momentum equation integrated from the entrance of vertical vent to the exit of horizontal vent
- Horizontal vent area (A_H) and vent effective loss coefficient (k_{gE}) varied as vents are cleared



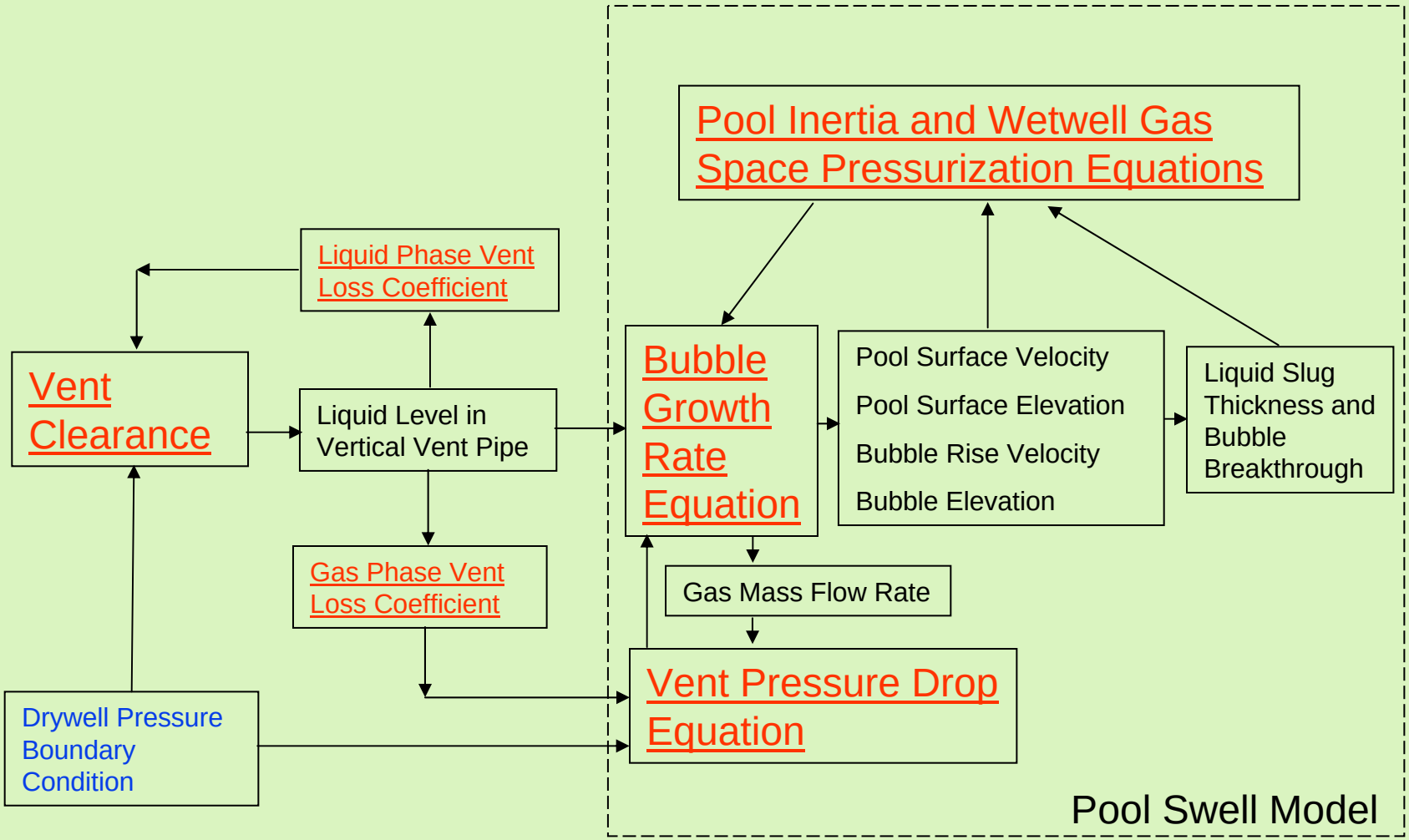
Vent Pressure Drop Equation – Cont.

- Inertia and frictional losses considered
- Spatial acceleration and gravitational losses neglected (i.e., negligible)

$$\bar{\rho}_g L_V \frac{d\bar{u}_{gv}}{dt} + \left(\frac{fL_V}{D_v} + k_{gE} \right) \frac{\bar{u}_{gv}^2}{2} \bar{\rho}_g = \left[P_D(t) - P_B(t) \right]$$

$\bar{u}_{gv}$	Average gas phase velocity in vertical vent
$\bar{\rho}_g$	Average gas phase density
L_V	Total length of vertical and horizontal vents
P_B	Pressure inside bubble
D_v	Diameter of vertical vent pipe

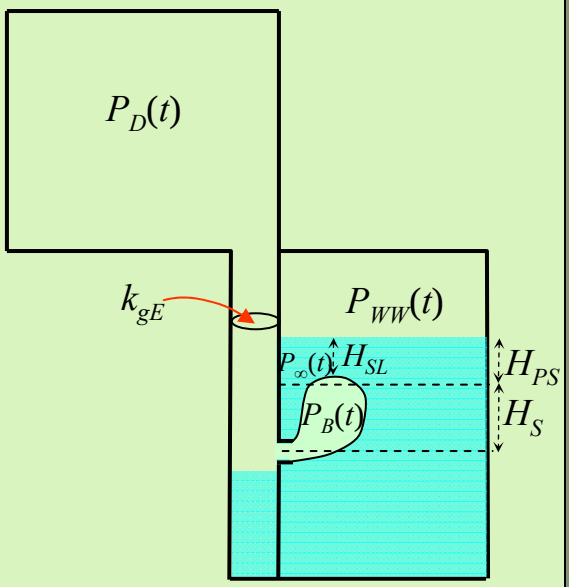
Overview of the ERI Model



Bubble Dynamics

- Rayleigh Equation for a Spherical Bubble

$$R\frac{d^2R}{dt^2}+\frac{3}{2}\left(\frac{dR}{dt}\right)^2=\frac{\left(P_B(t)-P_\infty(t)\right)}{\rho_f}$$



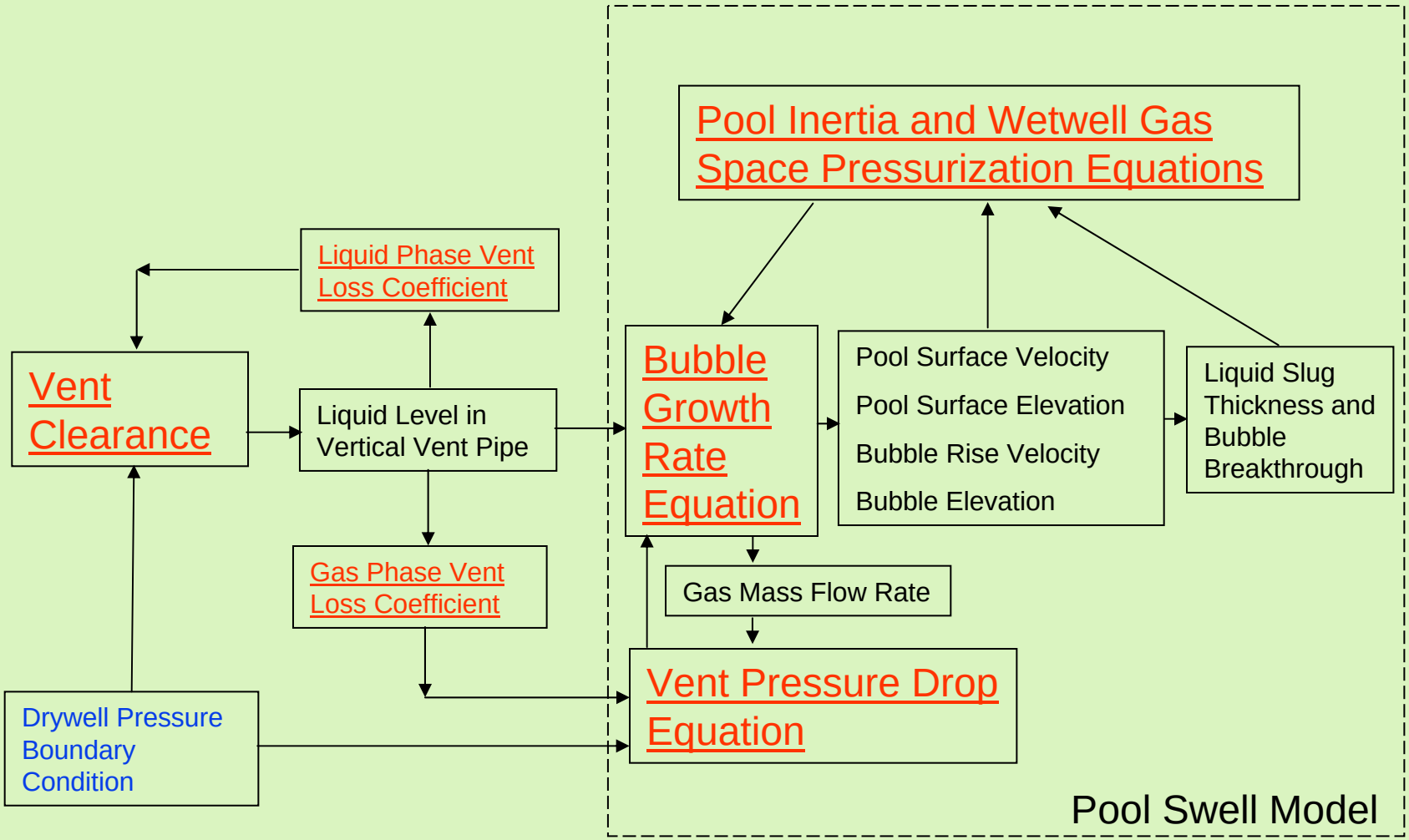
- Bubble volumetric growth rate

$$\frac{dV_b}{dt}=\dot{V}_b=4\pi R^2\frac{dR}{dt}$$

- Gas mass flow and velocity

$$\dot{m}_{gv}=\dot{V}\rho_{gB} \qquad \bar{u}_{gv}=\frac{\dot{m}_{gv}}{A_V\bar{\rho}_g}$$

Overview of the ERI Model



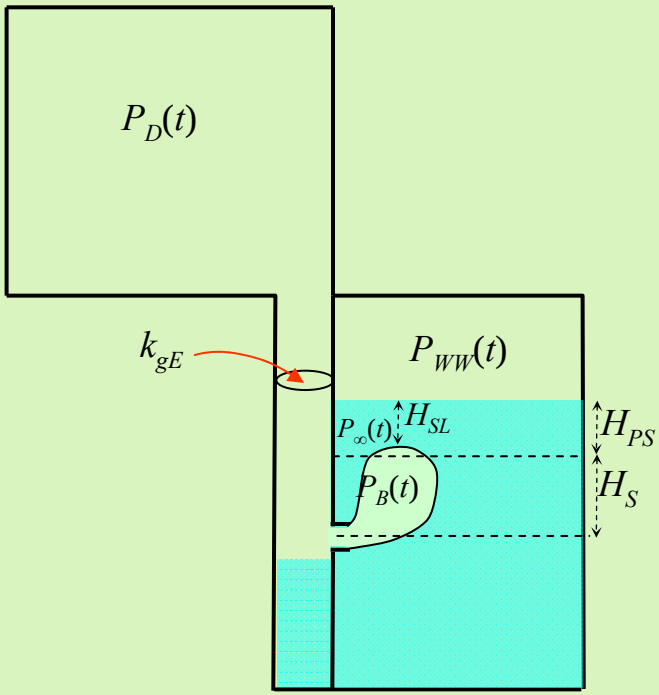
Pool Swell Parameters

- Pool surface velocity

$$V_p = \frac{dH_P}{dt} = \frac{N}{A_{SP}} \dot{V}_b$$

- Pool swell height

$$H_{PS} = \int_0^t \frac{dH_P}{dt} dt$$



H_p	Pool surface elevation
N	Number of vents
H_{PS}	Pool swell height

Pool Swell Parameters – Cont.

- Bubble Rise Velocity and Elevation
  - Bubble assumed to rise as spherical cap in a stagnant pool at its terminal velocity
  - Balancing buoyancy and drag forces on bubble results in

$$v_\infty = \frac{dz}{dt} = \sqrt{\frac{8}{3C_D} Rg}$$

  - For cap bubble of equivalent spherical radius R

$$C_D = 8/3$$ Wallis (1969)

Pool Swell Parameters – Cont.

- Bubble elevation

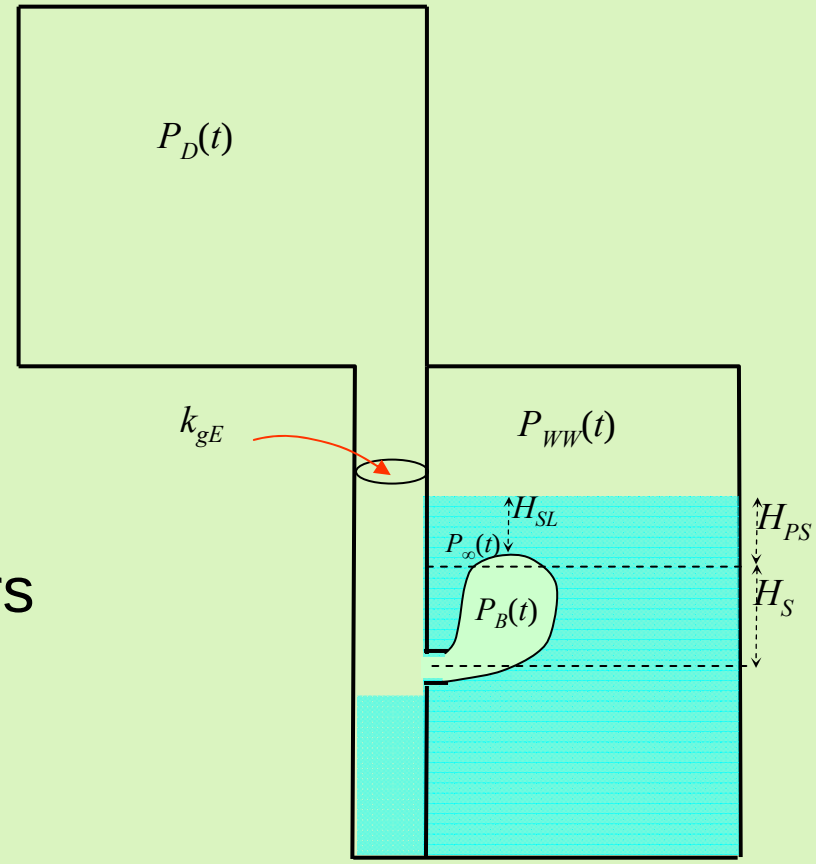
$$z = \int_0^t v_\infty dt = \int_0^t \sqrt{Rg}\, dt$$

- Liquid slug thickness

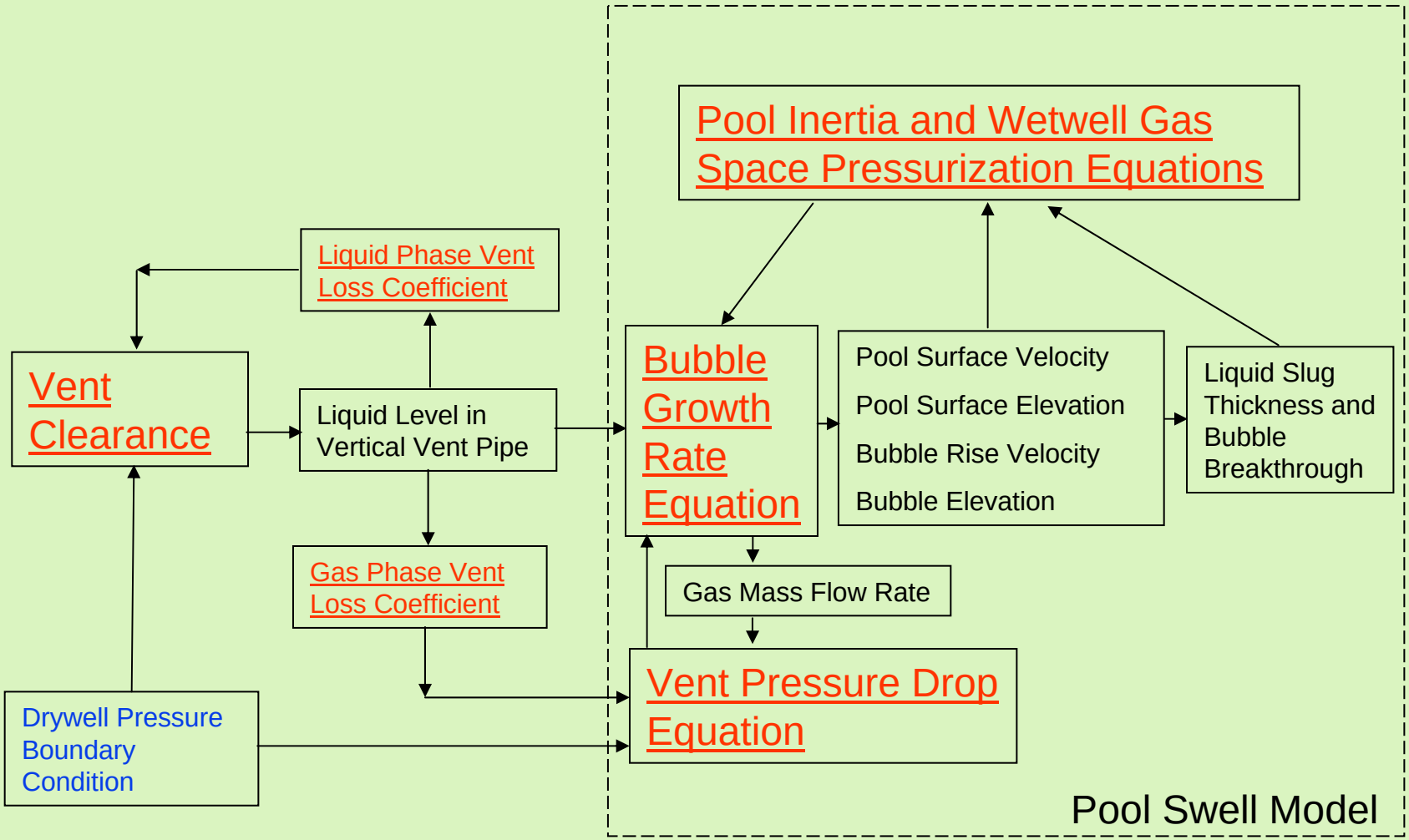
$$H_{SL} = \left(H_{PS} + H_S\right) - \left(z + R\right)$$

- Bubble breakthrough occurs when

$$H_{SL} = 0.0$$



Overview of the ERI Model



Other Aspects of the Model

- Pool Inertia Considered
- Gas Space Pressurization Using Ideal Gas
- Critical Flow Condition at Vent Considered
  - Bubble Growth Rate Limited to Critical Mass Flow Rate through the Vents

ERI and GOTHIC Model Features

Model Features	ERI Model	GOTHIC Model	Remarks
Drywell			
Drywell Pressure	Applied as boundary condition	a,c	Experimental Benchmark: Measured drywell pressure; ABWR Design: GOTHIC calculated pressure
Drywell Gas Composition	100% N_2		Conservative assumption for pool swell analysis
Drywell Gas Temperature	Isothermal compression (at initial drywell temperature)		In GOTHIC analysis, effect of drywell gas temperature was found to be negligible

ERI and GOTHIC Model Features-Cont.

Model Features	ERI Model	GOTHIC Model	Remarks
Vents			
Horizontal Vent Location	**Vent clearance:** All vents located at actual elevations **Pool swell**: All vents located at elevation of top vent centerline	a,c	-
Initial Water in Vertical & Horizontal Vent	**Vent clearance:** Included **Pool swell**: Ignored		ERI model ignores initial pool surface rise due to transfer of water inside vents into suppression pool
Horizontal Vent Area	Increases gradually as water level in vertical vent drops		Sensitivity calculation (ERI) to study effect of vent area

ERI and GOTHIC Model Features-Cont.

Model Features	ERI Model	GOTHIC Model	Remarks
Vents			
Vent Form Loss Factor	Variable effective form loss coefficient (include horizontal vent exit losses): Top vent open: 15 Top two vents open: 6 All three vents open: 4.3	a,c	Sensitivity calculations (ERI) to study effect of form loss coefficients
Vent Wall Frictional Loss	Included		-
Vent Inertia Length	Included		-
Critical Flow in Vents	Included		-
Vent Clearance	Sequential clearance of top, middle and bottom vents		Sensitivity calculation (ERI) to study effect of delayed vent clearance

ERI and GOTHIC Model Features-Cont.

Model Features	ERI Model	GOTHIC Model	Remarks
Wetwell			
Gas Temperature in Bubble	Isothermal Compression (at initial drywell temperature)	a,c	-
Pool Swell Frictional Loss	Included		Pressure drop due to pool swell friction is negligible
Wetwell Gas Space Temperature	Adiabatic compression (γ = 1.4)		Sensitivity calculation (ERI) to study effect of value of polytropic constant
Heat & mass transfer between gas bubble and pool (condensation & evaporation)	Ignored		-

ERI and GOTHIC Model Features-Cont.

Model Features	ERI Model	GOTHIC Model	Remarks
Two-Phase Flow in Wetwell			
Two-Phase Flow Regimes	Single cap or slug bubble	a,c	In GOTHIC, various flow regimes can exist in wetwell depending on local void fraction. Flow regime map based on data from small diameter tubes at equilibrium
Bubble Rise Velocity	Based on terminal velocity of a single cap or slug bubble		In GOTHIC, effective gas-phase transport affected by interfacial drag in each computational cell depending on local flow regime in that cell

Benchmarking Against PSTF Data

- Selected Tests
  - 1/3rd scale PSTF test series 5800

a,c

Benchmarking Against PSTF Data – Cont.

- Test Section Geometry (PSTF 1/3rd Scale)

a,c

Benchmarking Against PSTF Data – Cont.

- Bubble Rise Model for the PSTF Experiment
  - Bubble size can reach the size of test section leading to transition from cap to slug bubble
  - Terminal velocity of slug bubble in a rectangular section is given by

$$v_\infty = k\sqrt{\frac{D_l\left(\rho_f - \rho_g\right)g}{\rho_f}} = k\sqrt{D_l g}$$

[Wallis (1969)]

D_l	Length of longer side of rectangle
D_s	Length of shorter side of rectangle
$k = 0.23 + 0.13\frac{D_s}{D_l}$	

Benchmarking Against PSTF Data – Cont.

- Because test section top is open to atmosphere, liquid around the slug bubble may not remain stagnant
- Effective bubble rise velocity

$$v_T = v_\infty + j = v_\infty + V_P$$

- Transition from cap to slug is given by following criteria

$$R_{cap} \geq \frac{D_l}{2}$$

$$R_{cap} = 2.26 \times R$$ [Wallis (1969)]

(assuming spherical cap bubble with included angle of about 100° and flat tail)

v_T	Effective bubble rise velocity
j	Mixture velocity (approximately same as pool surface velocity)
R_{cap}	Cap bubble radius

Benchmarking Against PSTF Data – Cont.

- Results of Comparison with PSTF Test 5806-1
  - Vent Clearance Time

a,c

Benchmarking Against PSTF Data – Cont.

- Pool surface elevation (rise level)

a,c

Benchmarking Against PSTF Data – Cont.

– Pool surface velocity

a,c

Benchmarking Against PSTF Data – Cont.

– Liquid slug thickness

a,c

Benchmarking Against PSTF Data – Cont.

- Pressure inside top horizontal vent

a,c

Benchmarking Against PSTF Data – Cont.

- Summary of Comparisons with the Experimental Data
  - Pool surface elevation

a,c

Benchmarking Against PSTF Data – Cont.

- Pool surface velocity

a,c

Benchmarking Against PSTF Data – Cont.

- Liquid slug thickness

a,c

Benchmarking Against PSTF Data – Cont.

– Vent clearance time

a,c

Benchmarking Against PSTF Data – Cont.

- Bubble breakthrough

a,c

Benchmarking Against PSTF Data – Cont.

- Sensitivity Study
  - Sensitivity to vent loss coefficient

a,c

Pool Surface Elevation

a,c

Pool Surface Velocity

Benchmarking Against PSTF Data – Cont.

- Sensitivity to vent loss coefficient
  - Liquid slug thickness

a,c

Benchmarking Against PSTF Data – Cont.

– Sensitivity to pool surface area

a,c

Pool Surface elevation

a,c

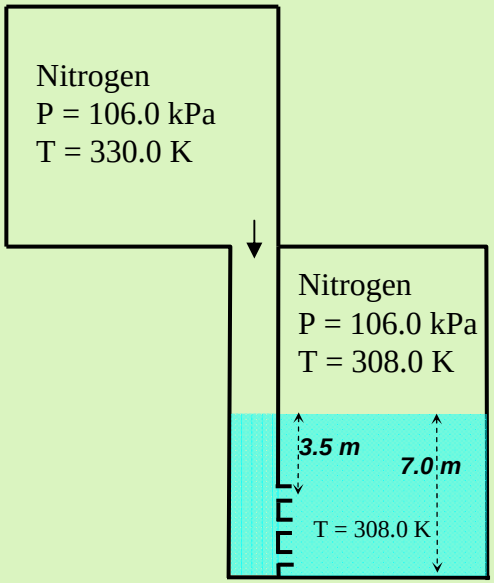
Pool Surface velocity

Benchmarking Against PSTF Data – Cont.

- Vent clearance time, pool swell height, and bubble breakthrough elevation predicted within 10%
- Pool surface velocity & liquid slug thickness predicted within 30%
- Pool swell height & surface velocity data for steam blowdown over-predicted due to effect of condensation (not considered in ERI model) – Model assumption of 100% N_2 in drywell conservative
- Results show the approach to estimation of vent losses appropriate
- Sensitivity studies showed:
  - Maximum swell height & surface velocity inversely proportional to the vent loss coefficient
  - Effect of reduced pool surface area is negligible (significant increase in pool inertia losses with reduced pool area in absence of wetwell gas space pressurization)
  - GOTHIC model predicted the PSTF data using conservative input parameters (e.g. vent loss factor zero) and failed to predict liquid slug thickness and bubble breakthrough)

Application to STP 3&4 – Cont.

- STP 3&4 ABWR Containment
  - Geometry
  - Initial Conditions



Geometrical Parameter/Initial Condition	Assumption
Initial drywell pressure, kPa	106.0
Initial drywell temperature, K	330.0
Drywell atmosphere composition	100% N_2
Suppression pool water temperature, K	308.0
Wetwell atmosphere composition	100% N_2
Initial wetwell gas space temperature, K	308.0
Initial wetwell gas space pressure, kPa	106.5
Top vent centerline submergence, m	3.5
Initial wetwell gas free volume, m^3	5958.0
Total suppression pool surface area, m^2	507.0
Vent area of one vertical vent, m^2	1.13
Diameter of horizontal vent, m	0.7
Total number vertical vents	10
Total number of horizontal vents	30

Application to STP 3&4 – Cont.

- Drywell Pressure (Input)
  - GOTHIC analysis (bounding curve, MSLB and FWLB simulations)

a,c

Application to STP 3&4 – Cont.

Vent Clearance Time Sensitivity

Vent Clearance Equation	Top Vent Clearance Time, s
Hydrostatic pressure drop $0.0 = (P_D - P_W) + \rho_f g_z (x - H_{S0})$	0.36
Hydrostatic + Inertial pressure drop $\left(\rho_f x + \rho_f L \frac{A_v}{A_H}\right)\frac{dV_V}{dt} = (P_D - P_W) + \rho_f g_z (x - H_{S0})$	1.13
Hydrostatic + Inertial + frictional pressure drop $\left(\rho_f x + \rho_f L \frac{A_v}{A_H}\right)\frac{dV_V}{dt} = (P_D - P_W) - \rho_f k_{fE} \frac{V_V^2}{2} + \rho_f g_z (x - H_{S0})$	1.18
Hydrostatic + Inertial + Spatial acceleration pressure drop $\left(\rho_f x + \rho_f L \frac{A_v}{A_H}\right)\frac{dV_V}{dt} - \rho_f V_V^2 = (P_D - P_W) + \rho_f g_z (x - H_{S0})$	1.09
Hydrostatic + Inertial + Spatial acceleration + Frictional pressure drop $\left(\rho_f x + \rho_f L \frac{A_v}{A_H}\right)\frac{dV_V}{dt} - \rho_f V_V^2 = (P_D - P_W) - \rho_f k_{fE} \frac{V_V^2}{2} + \rho_f g_z (x - H_{S0})$	1.12
GOTHIC Results	[ ] a,c

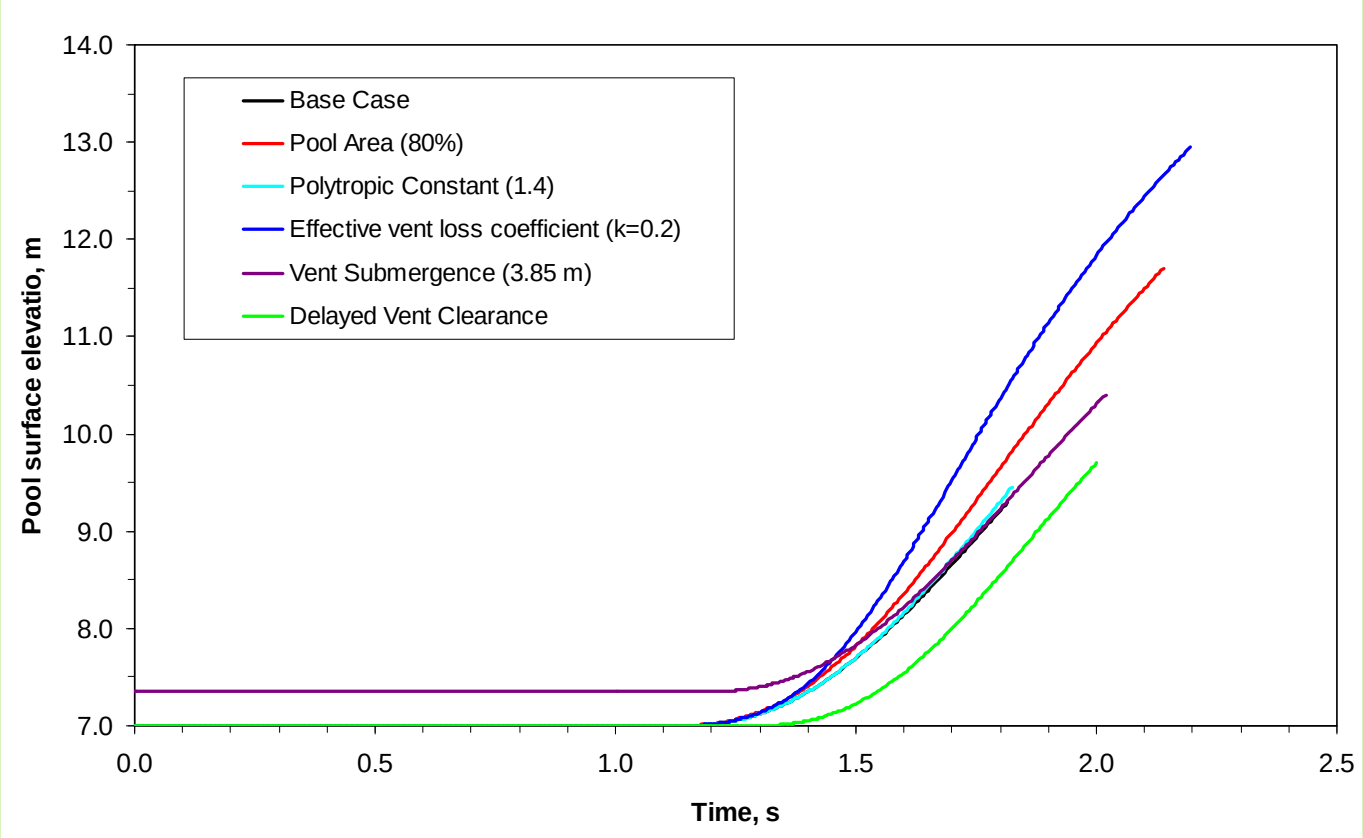
Application to STP 3&4 – Cont.

➢ Calculations for ABWR Containment

Parameters		Base Case	Sensitivity Cases				
			1	2	3	4	5
Sensitivity Parameters							
Suppression pool surface area, %		100.0	***80.0***	100.0	100.0	100.0	100.0
Polytropic Constant		1.4	1.4	***1.0***	1.4	1.4	1.4
Top vent submergence height, m		3.5	3.5	3.5	***3.85***	3.5	3.5
Effective vent loss coefficient	Top vent open	14.9	14.9	14.9	14.9	***0.2***	14.9
	Top & middle vents open	5.9	5.9	5.9	5.9	***0.2***	5.9
	All vents open	4.3	4.3	4.3	4.3	***0.2***	4.3
Vent clearance time, s	Top	1.12	1.12	1.12	1.18¥	1.12	***1.23***
	Middle	1.25	1.25	1.25	1.3¥	1.25	***1.38***
	Bottom	1.45	1.45	1.45	1.5¥	1.45	***1.59***
Results							
Breakthrough time, s		1.80	2.14	1.83	2.00	2.20	2.00
Maximum pool swell, m		2.2	4.7	2.5	2.9	6.0	2.7
Maximum pool surface velocity, m/s		5.6	6.7	6.0	5.5	8.7	5.9
Maximum bubble pressure, kPa		139	177	131	158	271	146
Maximum wetwell gas space pressure, kPa		142	183	135	159	286	154

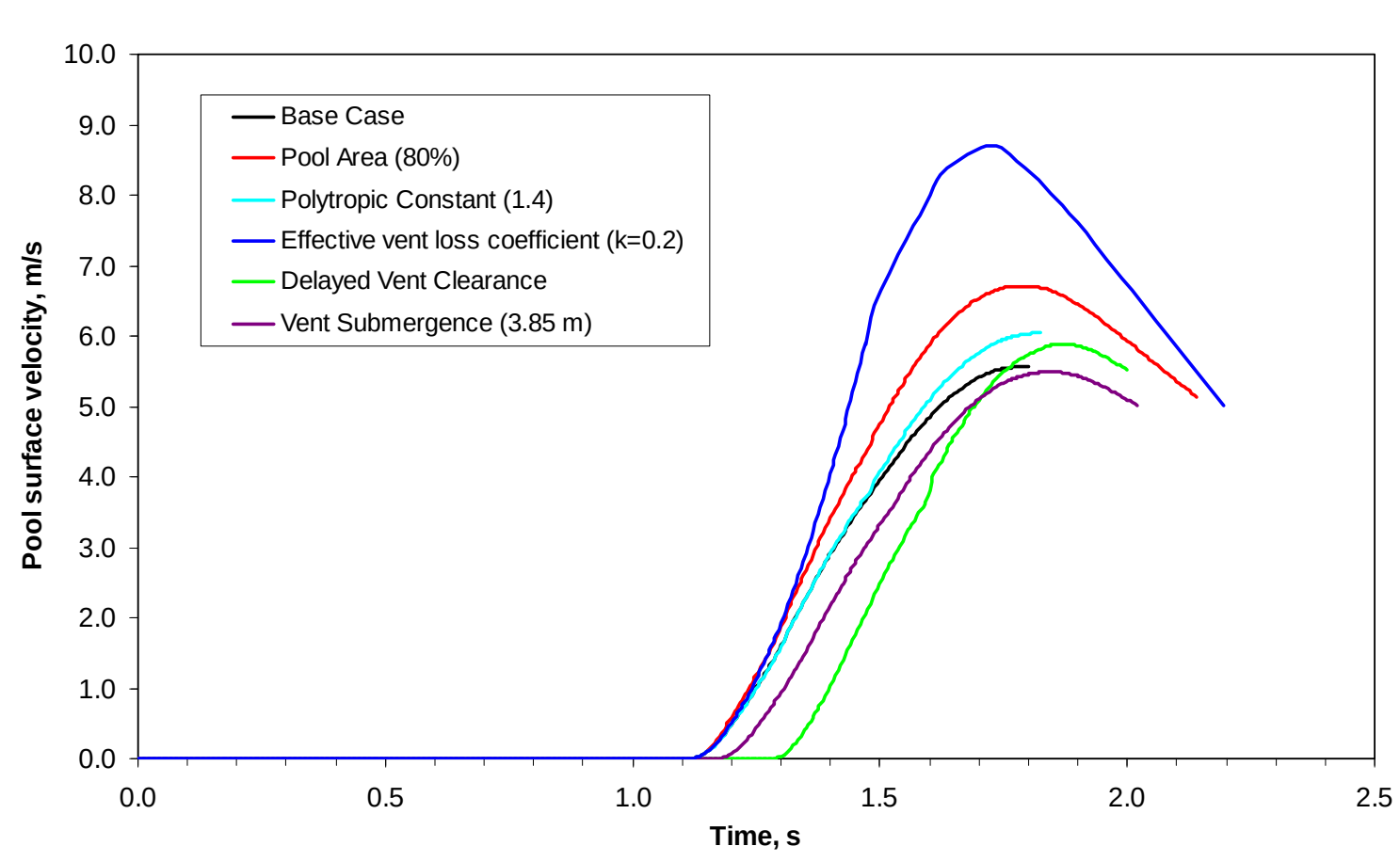
Application to STP 3&4 – Cont.

- Summary of ABWR Calculation Results
  - Pool surface elevation



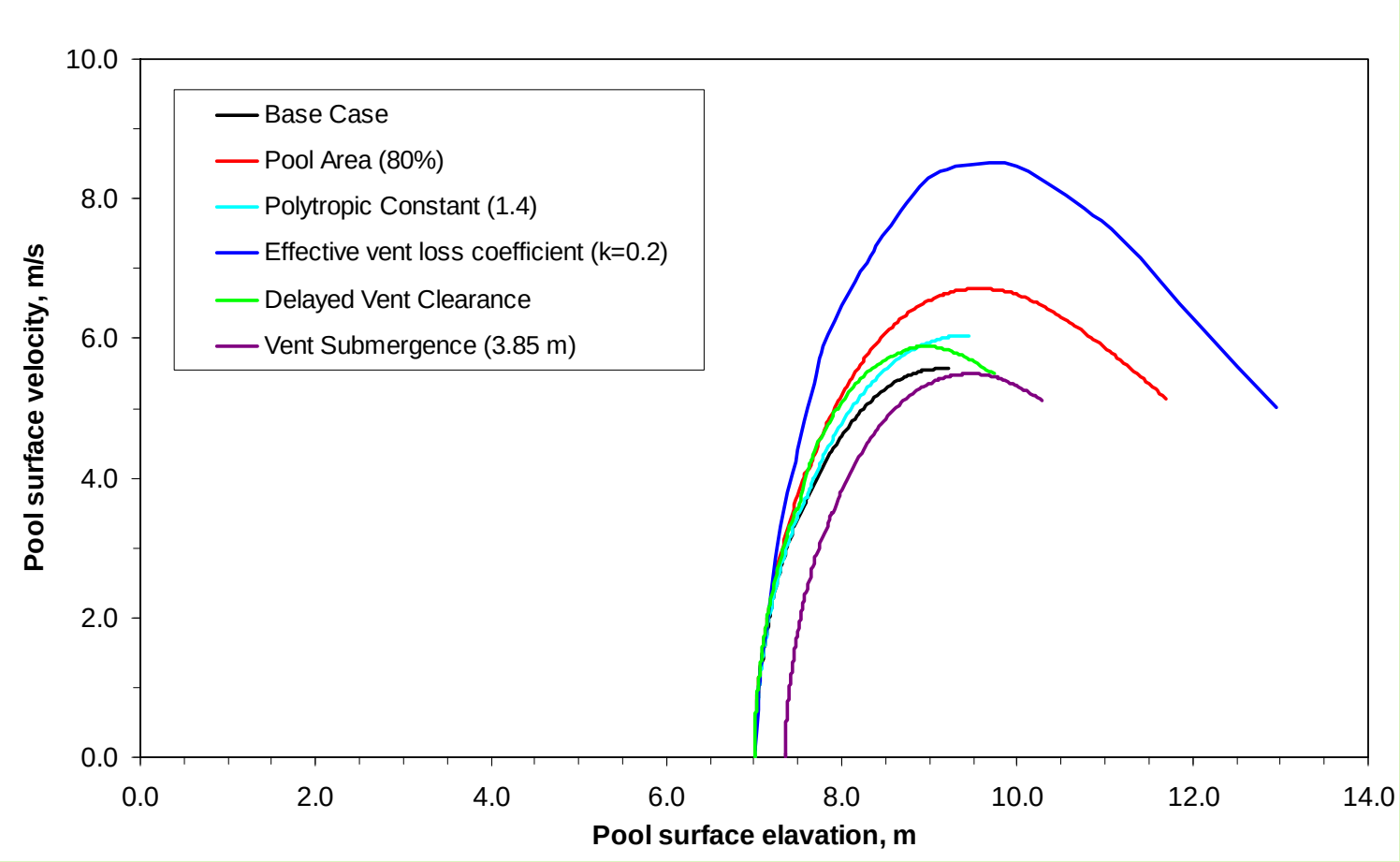
Application to STP 3&4 – Cont.

– Pool surface velocity



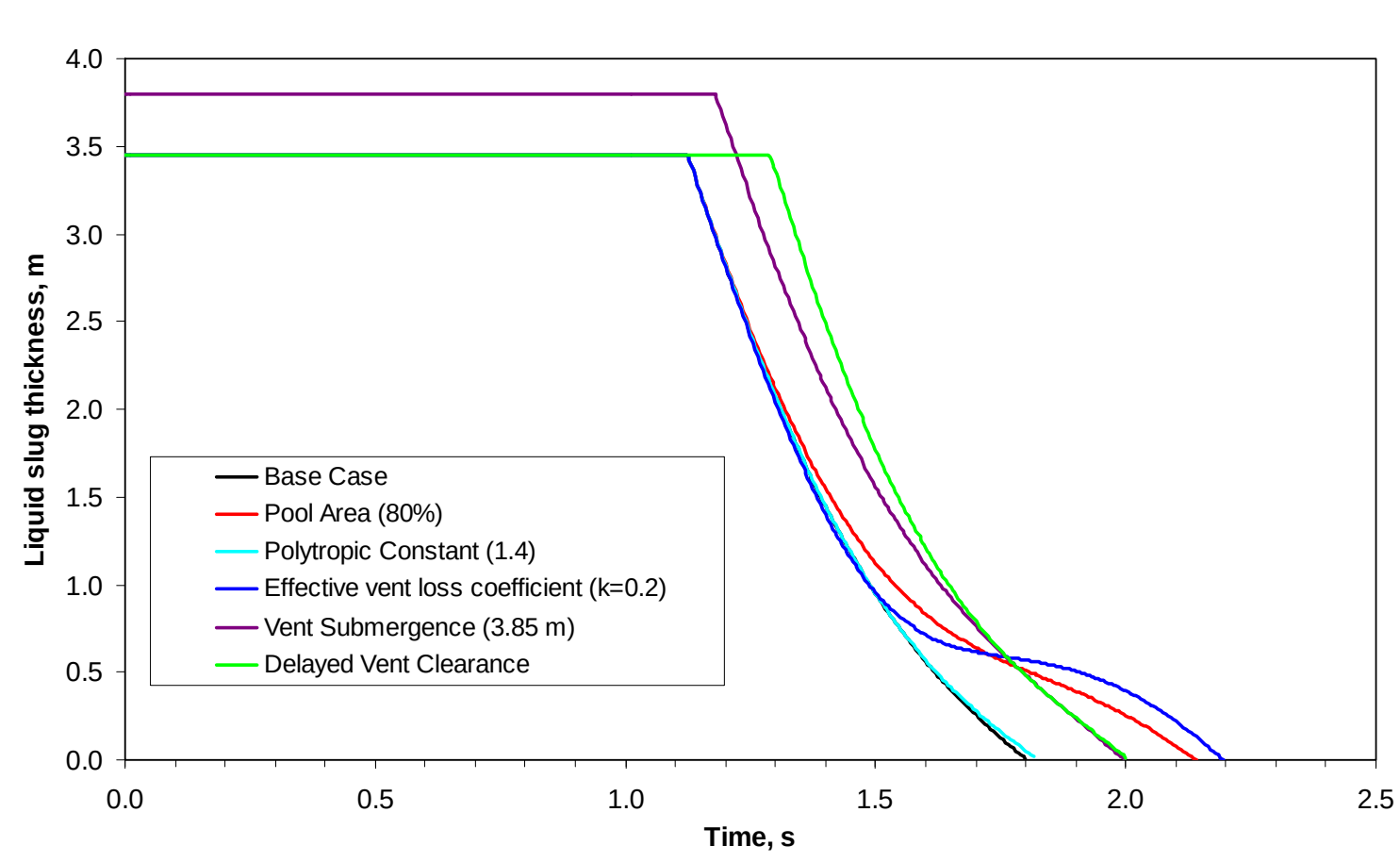
Application to STP 3&4 – Cont.

– Pool surface elevation and velocity



Application to STP 3&4 – Cont.

– Liquid slug thickness



Comparison with GOTHIC Results

- Comparison with GOTHIC Analysis
  - Sensitivity parameters values similar to GOTHIC analysis
  - Sensitivity to vent loss coefficient

Parameters	GOTHIC	Case 1	Case 2
Pool surface area, %	a,c	80.0	100.0
Polytropic constant		1.0	1.0
Top vent centerline submergence, m		3.5	3.5
Vent clearance time, s		1.12	1.12
Effective vent loss coefficient		2.0, 3.0, 4.0	0.2, 1.0, 2.0, 3.0, 4.0

Comparison with GOTHIC Results– Cont.

- Maximum pool swell

a,c

Comparison with GOTHIC Results – Cont.

- Maximum pool surface velocity

a,c

Summary and Conclusions

- Good agreement between the PSTF data & the predictions of the ERI model for:
  - Vent clearance time
  - Pool swell parameters:
    - Pool surface elevation
    - Pool surface velocity
  - Liquid slug thickness and bubble breakthrough time
- Sensitivity calculations showed that frictional losses in the vent system can significantly affect the pool swell parameters

Summary and Conclusions – Cont.

- Best estimate values predicted by ERI model for the pool swell parameters are lower compared to the predictions of GOTHIC model for the design case
- GOTHIC model input assumptions are conservative
- For the similar conservative model input assumptions (and model parameters), ERI model predicted higher pool swell height and pool surface velocity as compared to the GOTHIC predictions
- GOTHIC predicted trends in pool swell parameters for the lower end of the loss coefficient values could not be reproduced using the ERI mechanistic model

Recommendations

- Desirable to perform:
  - Additional GOTHIC benchmark calculations for other PSTF tests
  - GOTHIC sensitivity calculations for PSTF cases using more realistic vent loss coefficients
  - GOTHIC sensitivity calculations with delayed vent clearance
    - ERI sensitivity study showed that delayed vent clearance is more conservative. However, GOTHIC model parameters are adjusted so that vent clearance occurs earlier.
- The submittal should be expanded to discuss the GOTHIC modeling of pool swell physics:
  - Basis for WW node size being limited to [ ]^{a,c} in GOTHIC model (a sensitivity study to determine effect of node size is recommended).
  - Discuss the impact of node size selection on the consistency of global and local flow regimes (as suggested in manual).
  - Discuss the rationale for the maximum bubble size in GOTHIC (i.e., [ ]^{a,c}) calculations.