UNENE Graduate Course
Reactor Thermal-Hydraulics Design and Analysis

McMaster University

Whitby

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T-H Computer Codes

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Outline

- Code development and validation process
- CATHENA – Network code (**AECL,HQ,NBP**)
- TUF – Network code (**OPG,BP**)
- ASSERT – Sub-channel code (**AECL**)
- MODTURC-CLAS – Moderator code (**OPG,AECL,BP,NBP,HQ**)
- NUCIRC – Network code (**AECL,OPG,BP,HQ,NBP**)

Introduction

Definition:

"A code is a mathematical representation of the physical world which allows simulation of system design and performance"

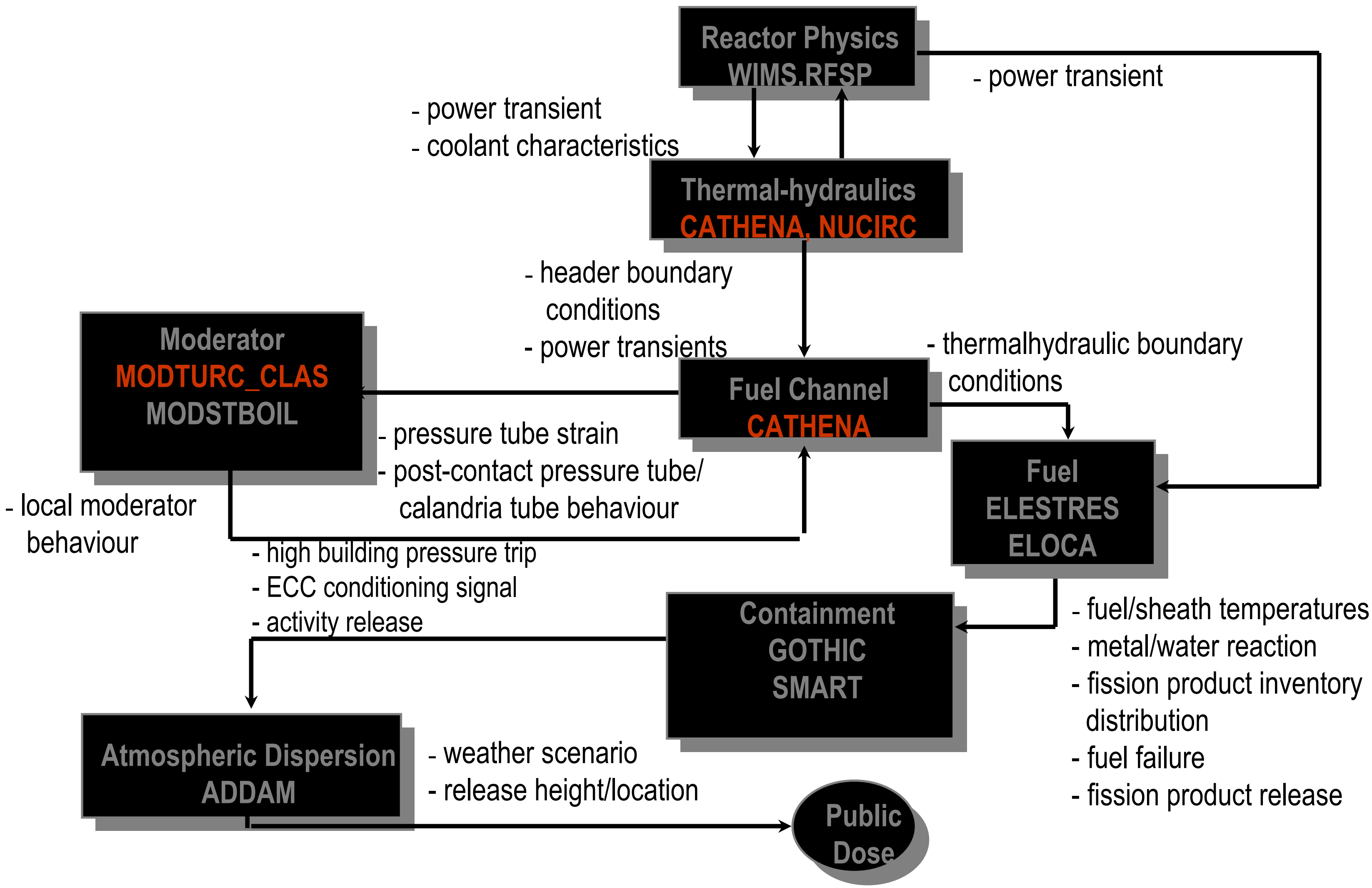
Code Development Methodology:

- **Perform small scale tests to develop understanding of a physical phenomena**
- **Write mathematical model to capture understanding**
- **Integrate series of physical phenomena models into a code to describe behaviour of system or component**
- **Perform integral tests on system or component under controlled conditions to test code (validation)**
- **Define uncertainty of code predictions**
- **Apply code to simulating performance of system or component within range of validated conditions**

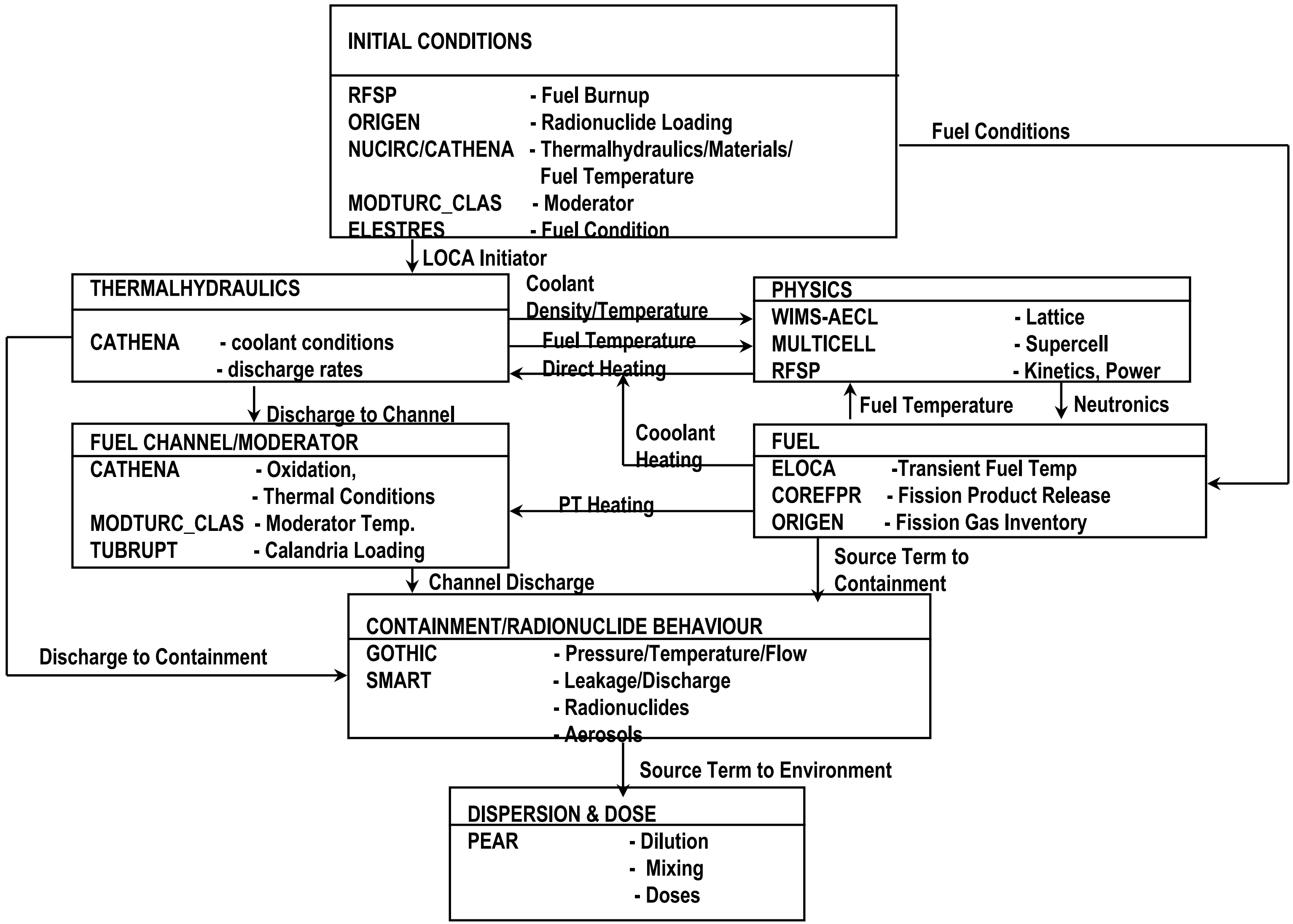
Safety Analysis Codes

WIMS, RFSP DRAGON	REACTOR PHYSICS
CATHENA, ASSERT,MODTURC NUCIRC	THERMALHYDRAULICS
ELESTRES, ELOCA, TUBRUPT, MAAP	FUEL & FUEL CHANNEL
SOURCE, SOPHAEROS, SMART, ADDAM	FISSION-PRODUCT BEHAVIOUR
GOTHIC	CONTAINMENT

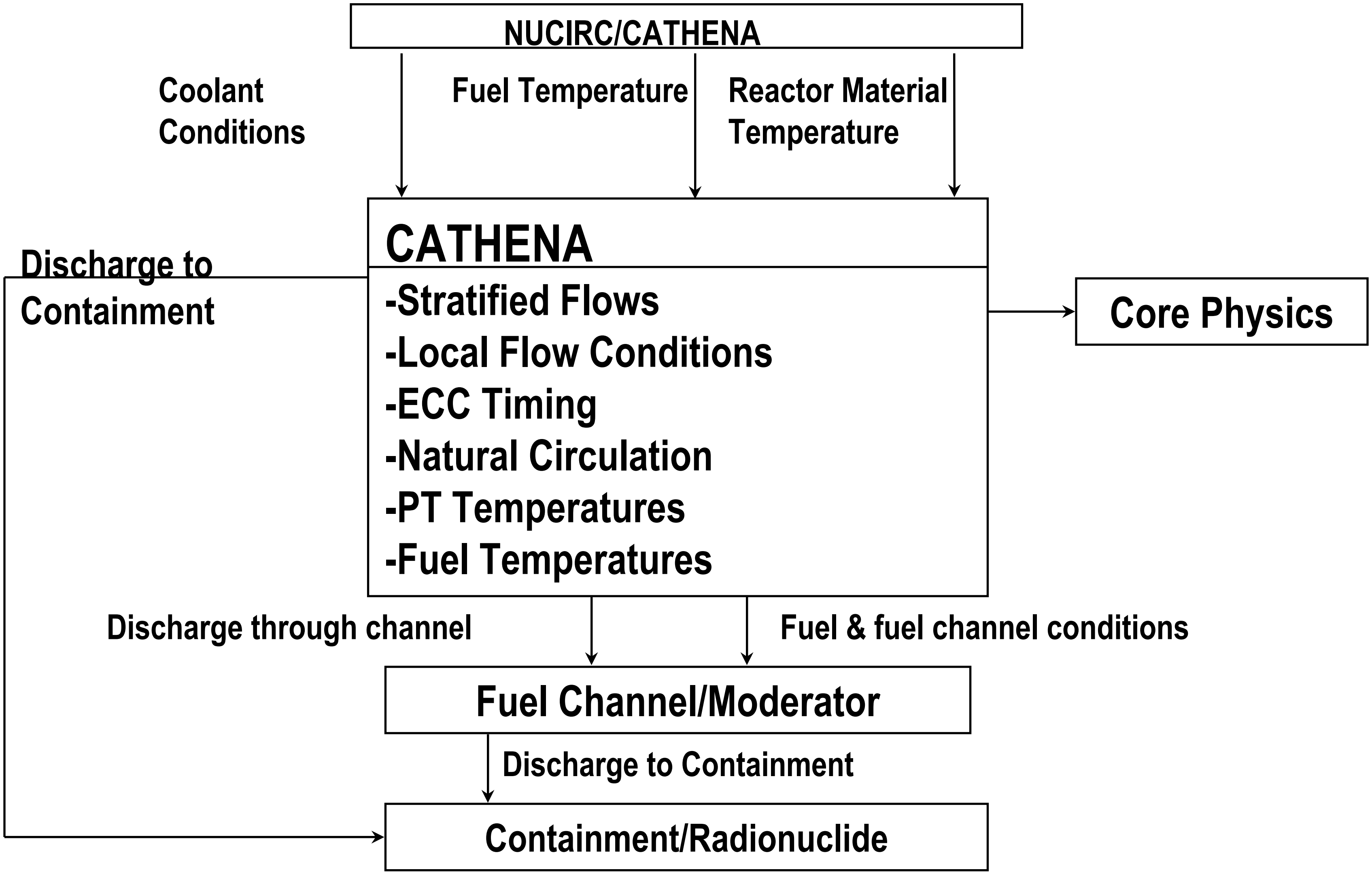
Safety Analysis Codes Interfaces



Safety Analysis Codes



Thermal Hydraulics Codes



CATHENA

- CATHENA is a one-dimensional, two-fluid thermal-hydraulic computer code designed for the analysis of two-phase flow and heat transfer in piping networks
- The acronym CATHENA stands for Canadian Algorithm for THErmal-hydraulic Network Analysis
- The primary focus of the development has been on the analysis of the sequence of events which occur during a postulated loss-of-coolant accident (LOCAs) in a CANDU
- The code has been applied successfully to the simulation of a wide range of thermal-hydraulic problems, from test facilities
- The hydrodynamic model used in CATHENA is a one-dimensional, two-fluid non-equilibrium representation of two-phase fluid flow
- The model consists of individual mass, momentum, and energy equations for the gas and liquid phases together with flow-regime dependent constitutive relations that describe mass and momentum, and energy transfers across the interface and between each phase and the piping walls (energy)

CATHENA – Conservation Equations

Mass equation

$$\frac{\partial}{\partial t}(\alpha_k \rho_k) + \frac{1}{A}\frac{\partial}{\partial z}(A C_{0k} \alpha_k \rho_k v_k) = m_{ki} - \Gamma_{zk}$$

Momentum equation

$$\frac{\partial}{\partial t}(C_{0k}\alpha_k \rho_k v_k) + \frac{1}{A}\frac{\partial}{\partial z}(A C_{1k}\alpha_k \rho_k v_k^2) + \frac{1}{A}\alpha_k \frac{\partial}{\partial z}(A P_k) + \frac{1}{A}(P_k - P_i)\frac{\partial}{\partial z}(A\alpha_k) = \tau_{kw} + \tau_{ki} + m_{ki} v_{ki} + P'_{ki} - \alpha_k \rho_k g_z$$

Energy equation

$$\frac{\partial}{\partial t}\left(\alpha_k \rho_k \left(h_k + \frac{v_k^2}{2}\right)\right) + \frac{1}{A}\frac{\partial}{\partial z}\left(A C_{0k}\alpha_k \rho_k v_k \left(h_k + \frac{v_k^2}{2}\right)\right) - \alpha_k \frac{\partial P_k}{\partial t} - (P_k - P_i)\frac{\partial \alpha_k}{\partial t} = q_{kw} + q_{ki} + \tau_{ki} v_{ki} + v_{ki} P'_{ki} + m_{ki}\left(h_{ki} + \frac{v_{ki}^2}{2}\right) - \alpha_k \rho_k v_k g_z \quad (2.1\text{-}15)$$

CATHENA – Non-condensable Equations

Mass conservation equation

$$\frac{\partial}{\partial t}\left(\alpha_g \rho_g X_{nc}^i\right) + \frac{1}{A}\frac{\partial}{\partial z}\left(A C_{0k} \alpha_g \rho_g v_g X_{nc}^i\right) = \Gamma_{nc}^i$$

$$X_{nc}^i = \frac{\text{mass of } i^{\text{th}} \text{ noncondensable gas}}{\text{total gas mass (including noncondensable gas)}}$$

CATHENA – Horizontal Flow Regime Map

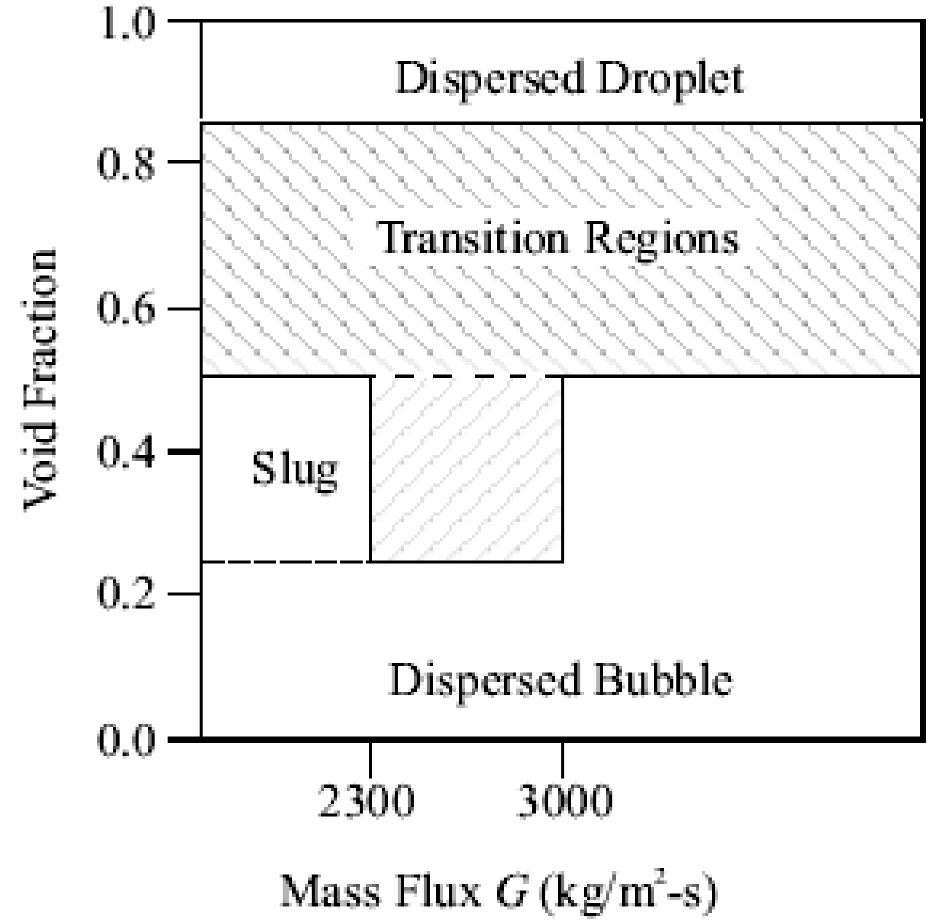
$$F_A = W_s F_S + (1 - W_s) F_M$$

n	$W_n = 1.0$ (stratified)	$1.0 > W_n > 0.0$ (transition)	$W_n = 0.0$ (mixed)
1c	$j^* < 1.0$	$1.0 \le j^* < 10.0$	$j^* \ge 10.0$
1p	$j_f < j_{f,min}$	$j_{f,min} \le j_f < j_{f,max}$	$j_f \ge j_{f,max}$
2	$U_r^* < 0.75$	$0.75 \le U_r^* < 1.0$	$U_r^* \ge 1.0$
3	$\alpha_g > 0.1$	$0.1 \ge \alpha_g > 1 \times 10^{-5}$	$\alpha_g \le 1 \times 10^{-5}$
4	$C_s^* < 1.0$	$1.0 \le C_s^* < 5.0$	$C_s^* \ge 5.0$
5	$U_e^* < 1.0$	$1.0 \le U_e^* < 11.0$	$U_e^* \ge 11.0$
6	$\lvert v_f \rvert \le v_1$	$v_1 < \lvert v_f \rvert < v_2$	$\lvert v_f \rvert \ge v_2$

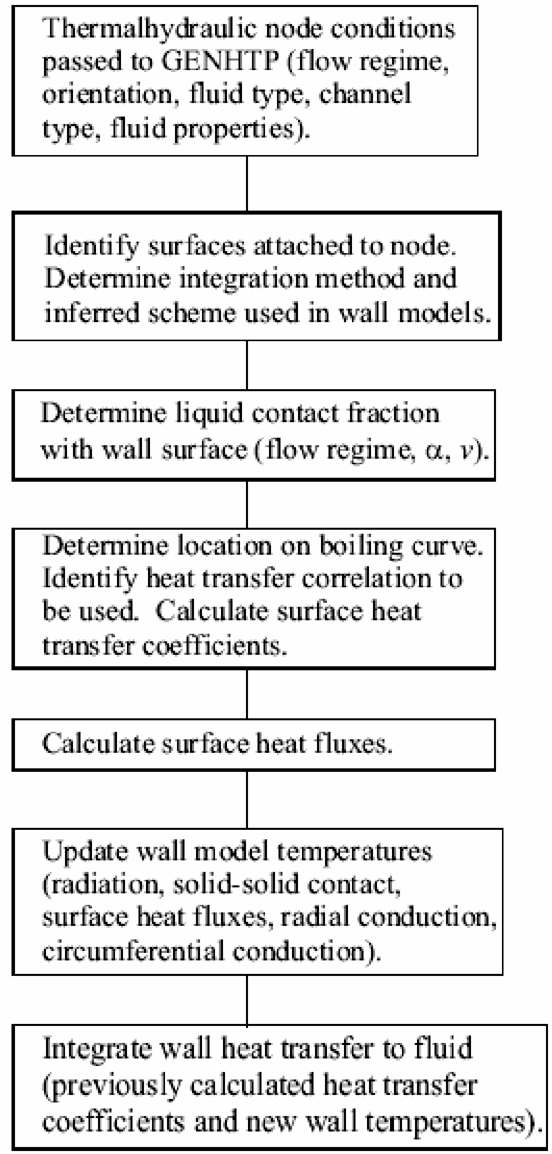
CATHENA – Inclined Flow Regime Map

n	$W_n = 1.0$ (annular)	$1.0 > W_n > 0.0$ (transition)	$W_n = 0.0$ (mixed)
1	$j_f < 3.0$	$3.0 \leq j_f < 5.0$	$j_f \geq 5.0$
2	$\alpha_g > 0.8$	$0.8 \geq \alpha_g > 0.4$	$\alpha_g \leq 0.4$
3	$U_e^* < 1.0$	$1.0 \leq U_e^* < 11.0$	$U_e^* \geq 11.0$
4	$\lvert v_f \rvert \leq v_1$	$v_1 < \lvert v_f \rvert < v_2$	$\lvert v_f \rvert \geq v_2$

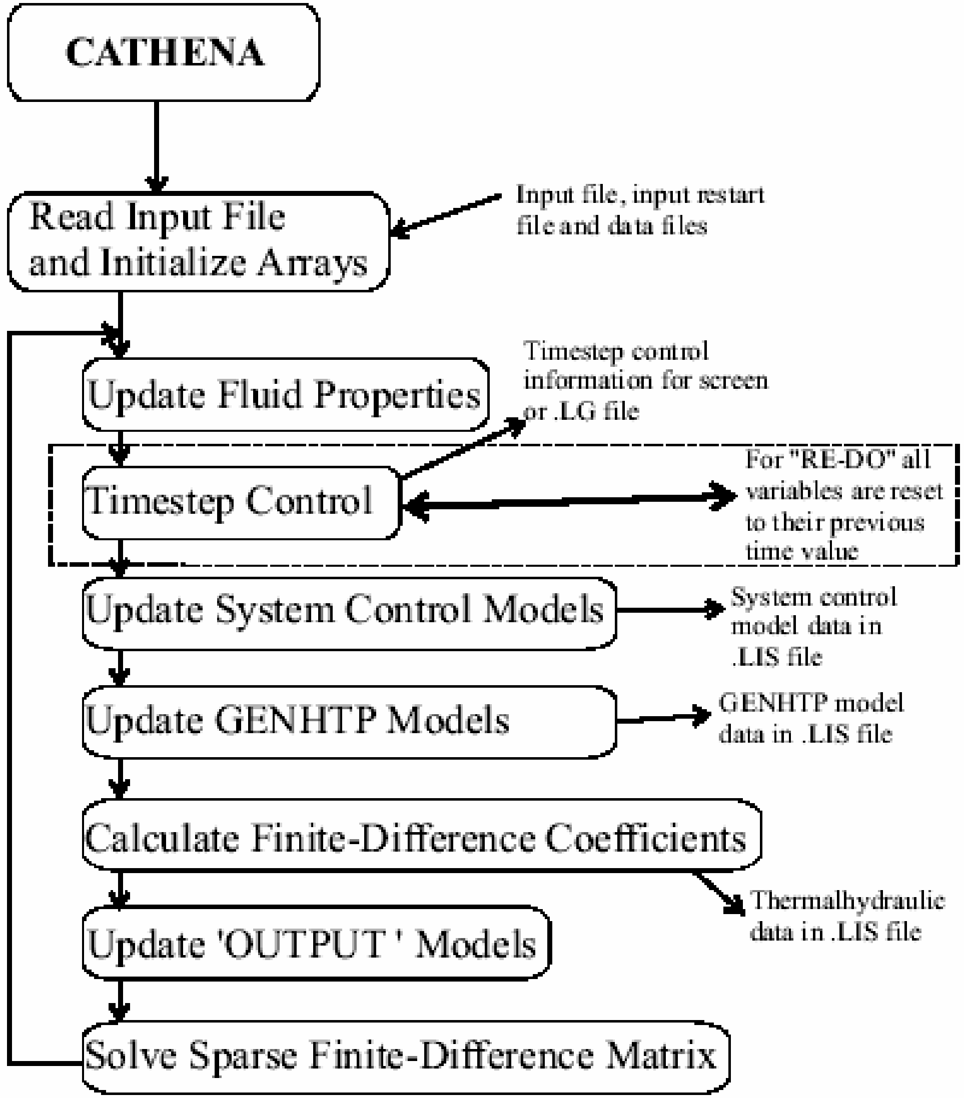
CATHENA – Mixed Flow Regime Map



CATHENA – Heat Transfer Logic Diagram



CATHENA – Calculation Sequence



CATHENA – Gas Mass Equation

$$\chi_1 = (\rho_g)_j^n \left(\alpha_g^{n+1} - \alpha_g^n\right)_j + \left(\left(\frac{\partial \rho_g}{\partial P}\right)^n \left(P_g^{n+1} - P_g^n\right) + \left(\frac{\partial \rho_g}{\partial h_g}\right)^n \left(h_g^{n+1} - h_g^n\right) + \sum_{i=1}^{n} \left(\frac{\partial \rho_g}{\partial X_{nc}^i}\right)^n \left(X_{nc}^{i,n+1} - X_{nc}^{i,n}\right)\right)_j (\alpha_g)_j^n \quad (6.2\text{-}29)$$

$$\chi_2 = \frac{\Delta t}{V_j} \sum_L (AC_{0g})_L \, \mathrm{SGN}_L \left[-(\alpha_g \rho_g)_J^n \, v_{gL}^n + \alpha_{gJ}^n v_{gL}^n \left\{\left(\frac{\partial \rho_g}{\partial P_g}\right)_J^n (P_{gJ}^{n+1} - P_{gJ}^n) + \left(\frac{\partial \rho_g}{\partial h_g}\right)_J^n (h_{gJ}^{n+1} - h_{gJ}^n)\right\} + (\alpha_g \rho_g)_J^n \, v_{gL}^{n+1} + \rho_{gJ}^n v_{gL}^n \alpha_{gJ}^{n+1}\right] \quad (6.2\text{-}30)$$

$$\chi_3 = \Delta t \left(m_{gi}^n + \frac{\partial m_{gi}^n}{\partial P}\left(P_g^{n+1} - P_g^n\right) + \frac{\partial m_{gi}^n}{\partial h_g}\left(h_g^{n+1} - h_g^n\right) + \frac{\partial m_{gi}^n}{\partial h_f}\left(h_f^{n+1} - h_f^n\right) + \sum_{i=1}^{n} \frac{\partial m_{gi}^n}{\partial X_{nc}^i}\left(X_{nc}^{i,n+1} - X_{nc}^{i,n}\right)\right)_j + \varepsilon_g \quad (6.2\text{-}31)$$

CATHENA – Gas Energy Equation

$$\chi_1 = \left(\left(\alpha_g \rho_g\right)^n \left(h_g^{n+1} - h_g^n\right) - \alpha_g^n \left(P_g^{n+1} - P_g^n\right) - \beta_g^n \left(\alpha_g^{n+1} - \alpha_g^n\right) \right)_j$$

$$\chi_2 = \frac{\Delta t}{V_j} \sum_L \left(AC_{0g}\right)_L \mathrm{SGN}_L \Big[- \left(\alpha_g \rho_g\right)_J^n v_{g_L}^n \left(h_{g_J}^{n+1} - h_{g_j}^n\right)$$
$$+ \rho_{g_J}^n \left(h_{g_J} - h_{g_j}\right)^n \left(\alpha_{g_J} \left(v_g^{n+1} - v_g^n\right)_L + v_{g_L}^n \left(\alpha_g^{n+1} - \alpha_g^n\right)_J \right) \Big]$$

$$\chi_3 = \Delta t \left(q_{gw}^{n+1} + \left(\lambda_{gi}^n\right) \left(-h_g^{n+1} + h_{gi}^n + \frac{\partial h_{gi}^n}{\partial P} \left(P_g^{n+1} - P_g^n\right) \right) \right)_j + \Delta t \, Q_{g,PMP}^n$$

CATHENA – Gas Momentum Equation

$$\chi_1 = \Delta z \left((\alpha_g \rho_g)^n \left(v_g^{n+1} - v_g^n \right) \right)_{j+1/2} \tag{6.2-37}$$

$$\chi_2 = \Delta t \Bigg[\left(\frac{\alpha_g \rho_g}{2} \right)^n_{j+1/2} \left(\left(v_g^n v_g^{n+1} \right)_{j+1/2} - \left(v_g^n v_g^{n+1} \right)_J \right) + \alpha_{g_{j+1/2}} \left(P_{g_{j+1}} - P_{g_j} \right)^{n+1} + \beta_{g_{j+1/2}} \left(\alpha_{g_{j+1}} - \alpha_{g_j} \right)^{n+1} \Bigg] \tag{6.2-38}$$

$$\chi_3 = \Delta t \, \Delta z \left[\left(\tau_{gw} + \tau_{gi} \right)^{n+1} + m_{gi}^n \left(v_{gi}^n - v_g^{n+1} \right) - \alpha_g^{n+1} \rho_g^n g_z \right]_{j+1/2} - \rho^n_{AP_{j+1/2}} \left[\Delta z \left(v_g^{n+1} - v_g^n - v_f^{n+1} + v_f^n \right)_{j+1/2} + \Delta t \, v^{*n}_{j+1/2} \left(v_{g_{j+1/2}} - v_{g_J} - v_{f_{j+1/2}} - v_{f_J}^{n+1} \right) \right] + \Delta P_{JNK_g} + \Delta P_{PMP_g} \tag{6.2-39}$$

CATHENA – Liquid Mass Equation

$$\chi_1 = \left(\rho_f - \alpha_f \theta_2 \frac{\partial \rho_f}{\partial P}\right)_j^n \left(\alpha_g^n - \alpha_g^{n+1}\right)_j$$
$$+ \left(\theta_1 \left(\frac{\partial \rho_f}{\partial P}\right)^n \left(P_g^{n+1} - P_g^n\right) + \left(\frac{\partial \rho_f}{\partial h_f}\right)^n \left(h_f^{n+1} - h_f^n\right)\right)_j (\alpha_f)_j^n$$

$$\chi_2 = \frac{\Delta t}{V_j} \sum_L \left(A C_{0f}\right)_L \mathrm{SGN}_L \left[-\left(\alpha_f \rho_f\right)_J^n v_{f_L}^n + \alpha_{f_J}^n v_{f_L}^n \left\{ \left(\frac{\partial \rho_f}{\partial P_f}\right)_J^n \left(\theta_1 (P_{g_J}^{n+1} - P_{g_J}^n)\right.\right.\right.$$
$$\left.\left.\left. + \theta_2 \left(\alpha_{g_J}^{n+1} - \alpha_{g_J}^n\right)\right) + \left(\frac{\partial \rho_f}{\partial h_f}\right)_J^n (h_{f_J}^{n+1} - h_{f_J}^n) \right\} + \left(\alpha_f \rho_f\right)_J^n v_{f_L}^{n+1} + \rho_{f_J}^n v_{f_L}^n \alpha_{f_J}^{n+1} \right]$$

$$\chi_3 = -\Delta t \left(m_{gi}^n + \frac{\partial m_{gi}^n}{\partial P} \left(P_g^{n+1} - P_g^n\right) + \frac{\partial m_{gi}^n}{\partial h_g} \left(h_g^{n+1} - h_g^n\right) + \frac{\partial m_{gi}^n}{\partial h_f} \left(h_f^{n+1} - h_f^n\right)\right.$$
$$\left. + \sum_i \frac{\partial m_{gi}^n}{\partial X_{nc}^i} \left(X_{nc}^{i,n+1} - X_{nc}^{i,n}\right)\right)_j + \varepsilon_{f_j}$$

CATHENA – Liquid Energy Equation

$$\chi_1 = \left((\alpha_f \rho_f)^n \left(h_f^{n+1} - h_f^n \right) - (\alpha_f \theta_1)^n \left(P_g^{n+1} - P_g^n \right) - (\beta_f - \alpha_f \theta_2)^n \left(\alpha_g^n - \alpha_g^{n+1} \right) \right)_j \tag{6.2-46}$$

$$\chi_2 = \frac{\Delta t}{V_j} \sum_L (AC_{0g})_L \, \mathrm{SGN}_L \Big[- (\alpha_f \rho_f)_J^n \, v_{f_L}^n \left(h_{f_J}^{n+1} - h_{f_j}^n \right) + \rho_{f_J}^n \left(h_{f_J} - h_{f_j} \right)^n \left(\alpha_{f_J} \left(v_f^{n+1} - v_f^n \right)_L + v_{f_L}^n \left(\alpha_f^{n+1} - \alpha_f^n \right)_J \right) \Big] \tag{6.2-47}$$

$$\chi_3 = \Delta t \left[q_{fw}^{n+1} + (\lambda_{fi})^n \left(-h_f^{n+1} + h_{fi}^n + \frac{\partial h_{fi}^n}{\partial P} \left(\theta_1 \left(P_g^{n+1} - P_g^n \right) + \theta_2 \left(\alpha_g^{n+1} - \alpha_g^n \right) \right) \right) \right]_j + \Delta t \; Q_{f,PMP}^n \tag{6.2-48}$$

CATHENA – Liquid Momentum Equation

$$\chi_1 = \Delta z \left(\left(\alpha_f \rho_f\right)^n \left(v_f^{n+1} - v_f^n \right) \right)_{j+1/2}$$

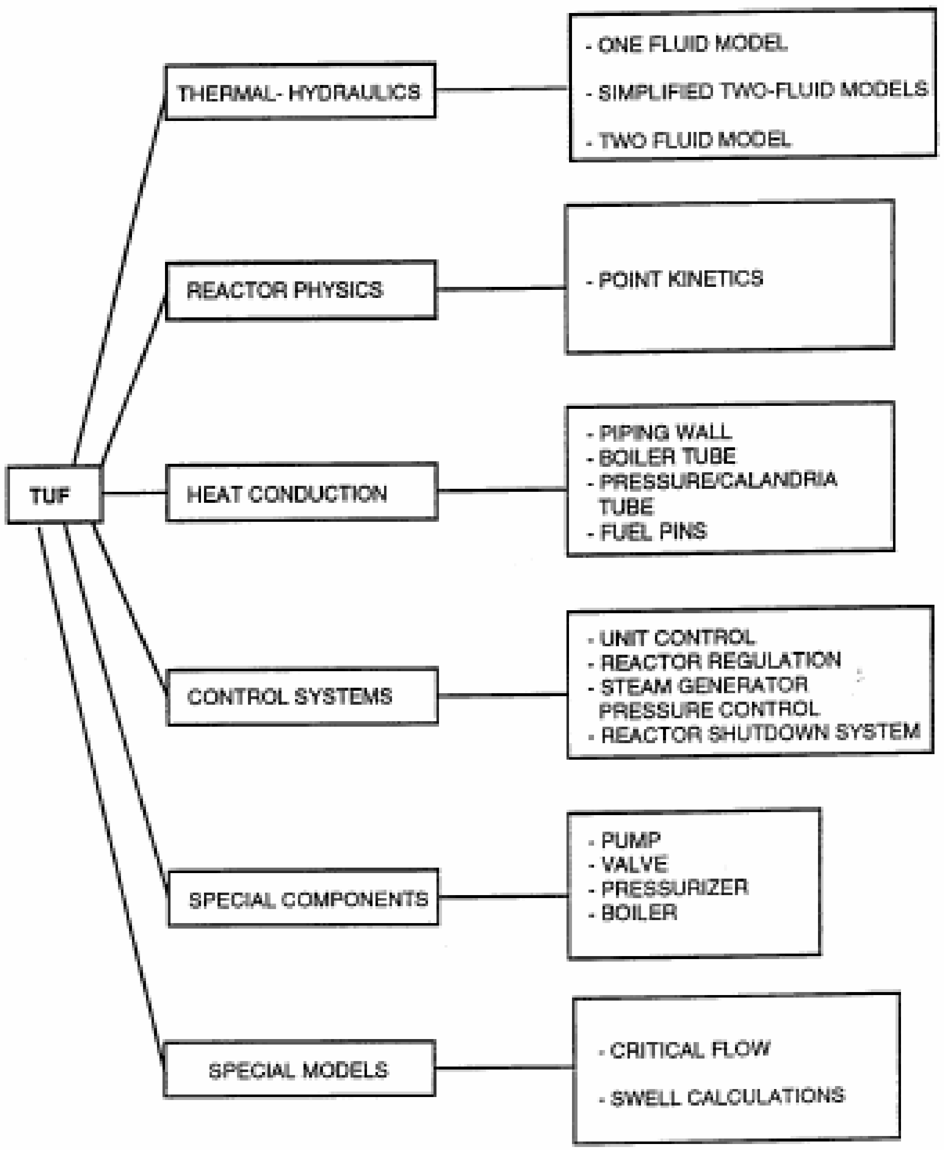
$$\chi_2 = \Delta t \Bigg[\left(\frac{\alpha_f \rho_f}{2} \right)^n_{j+1/2} \left(\left(v_f^n v_f^{n+1} \right)_{j+1/2} - \left(v_f^n v_f^{n+1} \right)_J \right) + \left(\theta_1 \alpha_f\right)^n_{j+1/2} \left(P_{g_{j+1}} - P_{g_j} \right)^{n+1} + \beta_{g_{j+1/2}} \left(\alpha_{g_{j+1}} - \alpha_{g_j} \right)^{n+1} \Bigg]$$

$$\chi_3 = \Delta t \, \Delta z \left(\left(\tau_{fw} + \tau_{fi} \right)^{n+1} - m_{gi}^n \left(v_{gi}^n - v_g^{n+1} \right) - \alpha_f^{n+1} \rho_f^n g_z \right)_{j+1/2} + \rho^n_{AP_{j+1/2}} \Bigg[\Delta z \left(v_g^{n+1} - v_g^n - v_f^{n+1} + v_f^n \right)_{j+1/2} + \Delta t \, v^{*^n}_{j+1/2} \left(v_{g_{j+1/2}} - v_{g_J} - v_{f_{j+1/2}} + v_{f_J}^{n+1} \right) \Bigg] + \Delta P_{JNK_f} + \Delta P_{PMP_f}$$

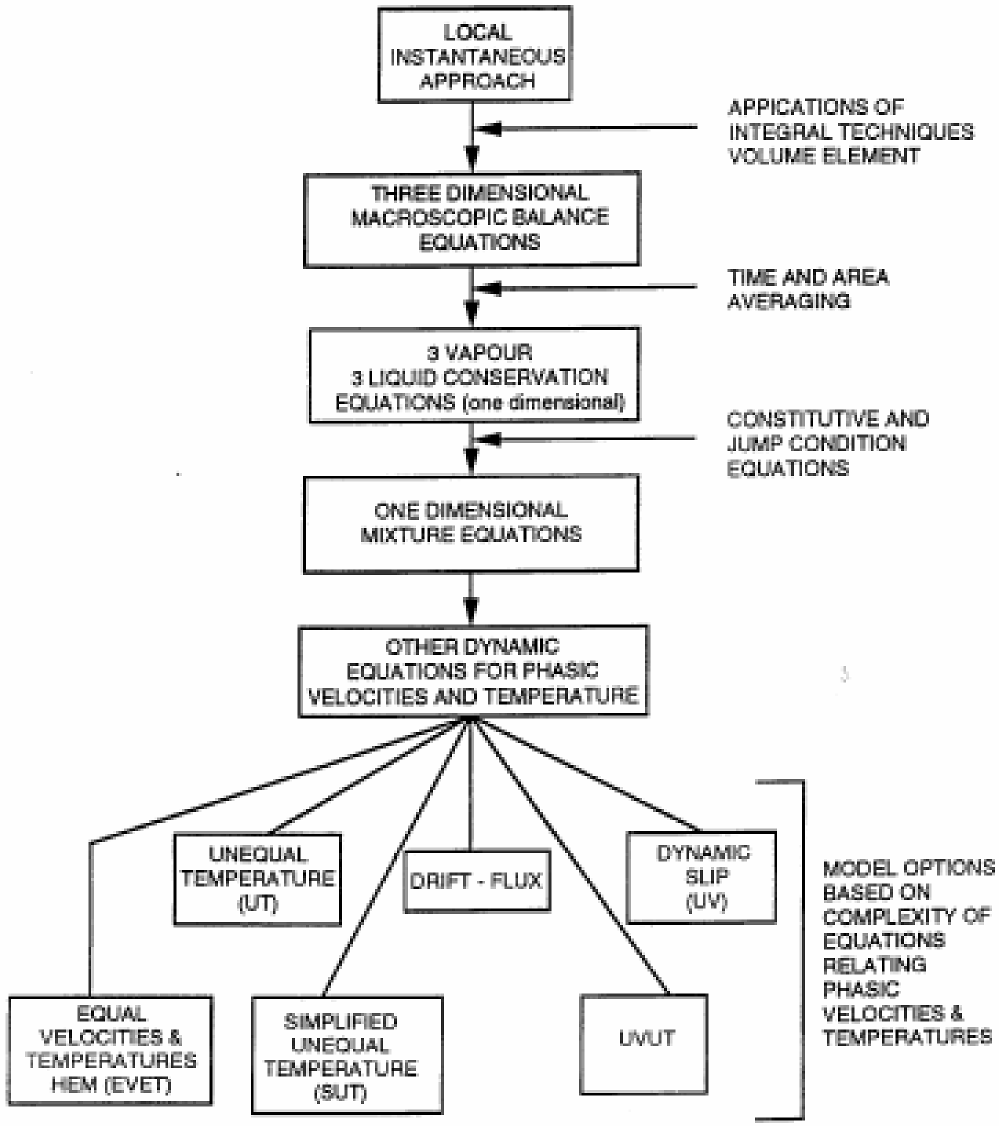
TUF – Two Unequal Fluids Code

- State-of-the-art system thermal-hydraulics code for transient analysis of CANDU Nuclear Generating Stations (OPG and BP owned)
- Uses Eulerian approach, which uses time and space coordinates as independent variables
- One-dimensional conservation equations of mass, momentum and energy obtained by averaging the three-dimensional, instantaneous equations over time and over the cross-sectional area

TUF - Overview



TUF – Modeling Options



TUF – General Conservation Equations

Mass conservation equation

$$\frac{\partial}{\partial t} A\,\alpha_k\,\rho_k + \frac{\partial}{\partial s} A\,\alpha_k\,\rho_k\,v_k = A\,\Delta m_k$$

Momentum conservation equation

$$\frac{\partial}{\partial t}\left(A\,\alpha_k\,\rho_k\,v_k\right) + C_o\,\frac{\partial}{\partial s}\left(A\,\alpha_k\,\rho_k\,v_k^2\right) + A\,\alpha_k\,\frac{\partial p_k}{\partial s} + A\,(p_k - p_i)\,\frac{\partial \alpha_k}{\partial s}$$

$$= -\,A\,\tau_{kw} + A\,\tau_{ki} + A\,\Delta m_k\,v_{ki} - A\,\alpha_k\,\rho_k\,g\,\frac{dZ}{ds} + A\,f_{ki} + A\,\alpha_k\,H_{pump}$$

Energy conservation equation

$$\frac{\partial}{\partial t} A\,\alpha_k\,\rho_k\,H_k + \frac{\partial}{\partial s} A\,\alpha_k\,\rho_k\,v_k\,H_k - A\,\alpha_k\,\frac{\partial p_k}{\partial t} - A\,(p_k - p_i)\,\frac{\partial \alpha_k}{\partial t} + A\,\frac{\partial G_k}{\partial s}$$

$$= A\,q''_{kw} + A\,q_{ki} + A\,q_{kp} + A\,\Delta m_k\,H_{ki} + A\,\tau_{ki}\,v_{ki} - A\,\alpha_k\,\rho_k\,v_k\,g\frac{dZ}{ds} + A\,f_{ki}\,v_{ki}$$

TUF – Jump Conditions & Mixture Equations

$$\sum_k \Delta m_k = 0$$

$$\sum_k \left[\tau_{ki} + \Delta m_k \, v_{ki} + f_{ki} \right] = 0$$

$$\sum_k \left[q_{ki} + q_{kp} + q''_{wk} + \Delta m_k \, H_{ki} + \tau_{ki} \, v_{ki} + f_{ki} \, v_{ki} \right] = q_w$$

$$\frac{\partial}{\partial t} (A \, \rho) + \frac{\partial W}{\partial s} = 0$$

$$\frac{\partial W}{\partial t} + C_o \frac{\partial}{\partial s} \left(\sum_k W_k \, v_k \right) + A \frac{\partial p}{\partial s} = - A \, \tau_w - A \, \rho \, g \frac{dZ}{ds} + A \, H_{pump}$$

$$\frac{\partial}{\partial t} (A \, \rho \, H) + \frac{\partial}{\partial s} \left(\sum_k W_k \, H_k \right) - A \frac{\partial p}{\partial t} = A \, q_w - W \, g \frac{dZ}{ds}$$

TUF – Mixture Mass and Energy Vapor and Non-condensable Equations

Vapor Mass

$$\frac{dM_g}{dt} = \sum_{in} W_g - \sum_{out} W_g + \Gamma - \Gamma_{ga}$$

Vapor Energy

$$\frac{dU_g}{dt} + V\,p\,\frac{d\alpha_g}{dt} = \sum_{in} h_g W_g - \sum_{out} h_g W_g + \Gamma h_{gs} + Q_{gp} + Q_{gi} + \ddot{Q}_{gw} + Q_{ga}$$

Non-condensable Mass

$$\frac{dM_a}{dt} = \sum_{in} W_a - \sum_{out} W_a + \Gamma_{ga} + \Gamma_{fa}$$

Non-condensable Energy

$$\frac{dU_a}{dt} + V\,p\,\frac{d\alpha_a}{dt} = \sum_{in} h_a W_a - \sum_{out} h_a W_a - Q_{ga} - Q_{fa} + Q_{aw}$$

TUF – Mixture Mass and Energy Liquid Equations

Mass equation

$$\frac{dM_f}{dt} = \sum_{in} W_f - \sum_{out} W_f - \Gamma - \Gamma_{fa}$$

Energy equation

$$\frac{dU_f}{dt} + V\, p\, \frac{d\alpha_f}{dt} = \sum_{in} h_f\, W_f - \sum_{out} h_f\, W_f - \Gamma\, h_{fs} + Q_{fp} + Q_{fi} + Q_{fw} + Q_{fa}$$

Jump condition

$$\Gamma\,(h_{gs} - h_{fs}) + Q_{gp} + Q_{fp} + Q_{gi} + Q_{fi} + Q_{gw}^{''} + Q_{fw}^{''} = Q_{gw} + Q_{fw}$$

TUF – Momentum Conservation Equations

Vapor and non-condensable equation

$$\frac{1}{A}\left[\frac{\partial W_v}{\partial t} + C_o \frac{\partial}{\partial s}(W_v v_v)\right] + \alpha_v \frac{\partial p}{\partial s} + \frac{\partial}{\partial s}\alpha_v (p_v - p) + (p - p_i)\frac{\partial \alpha_v}{\partial s} = -F_{vm} + E_v$$

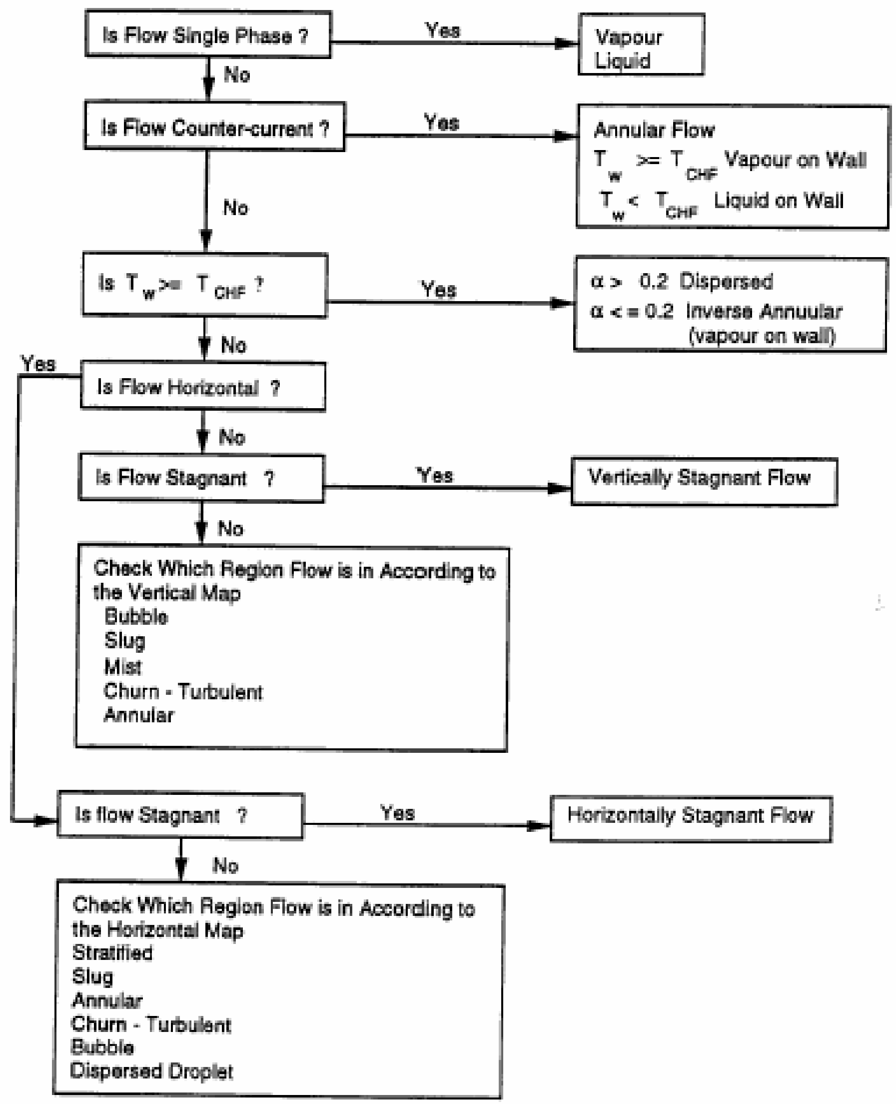
Liquid equation

$$\frac{1}{A}\left[\frac{\partial W_f}{\partial t} + C_o \frac{\partial}{\partial s}(W_f v_f)\right] + \alpha_f \frac{\partial p}{\partial s} + \frac{\partial}{\partial s}\alpha_f (p_f - p) + (p - p_i)\frac{\partial \alpha_f}{\partial s} = F_{vm} + E_f$$

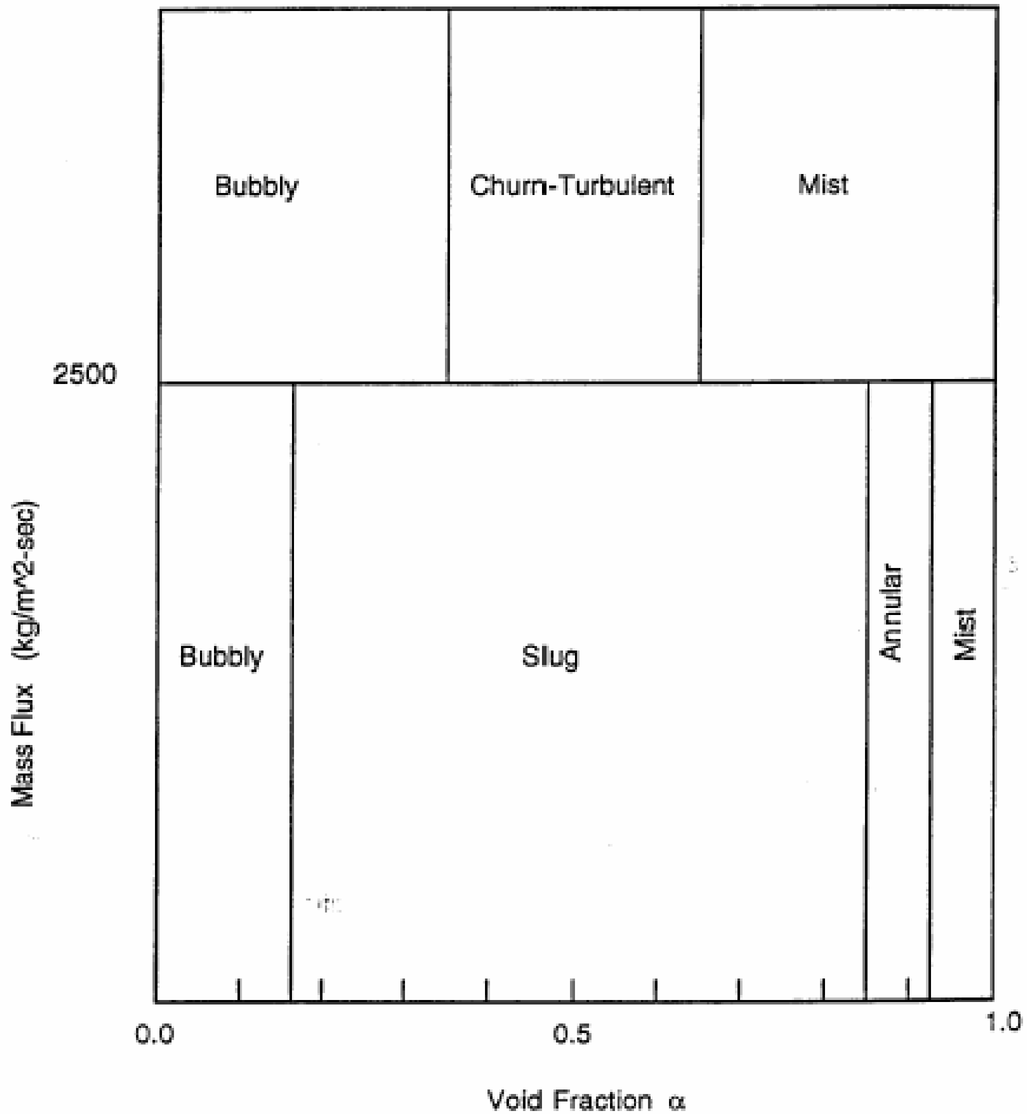
Mixture momentum equation

$$\frac{1}{A}\left[\frac{\partial W}{\partial t} + C_o \frac{\partial}{\partial s}\left(W v + \phi\, v_{gf}^2\right)\right] + \frac{\partial p}{\partial s} = E_v + E_f = -\tau_{vw} - \tau_{fw} - \rho\, g \frac{dZ}{ds} + H_{pump}$$

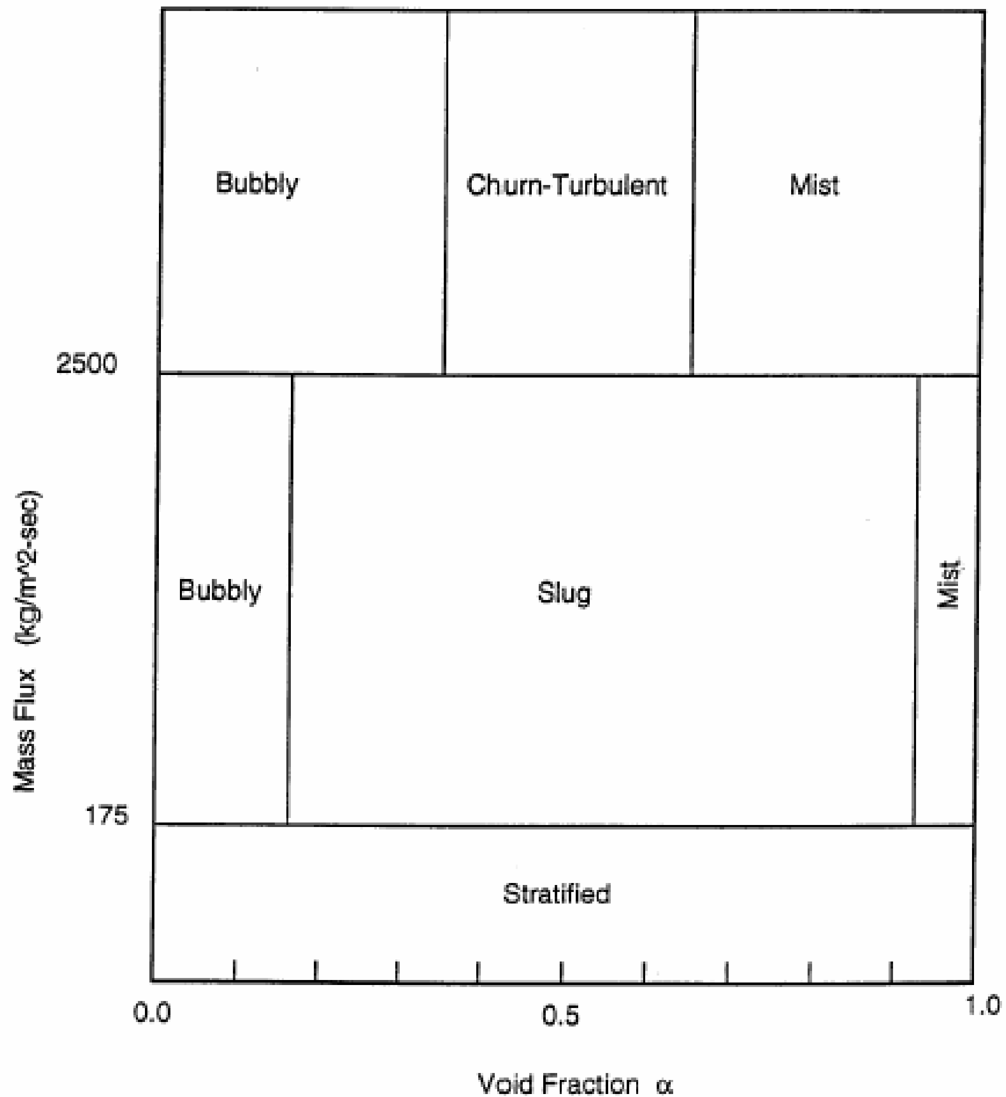
TUF – Flow Regime Selection Logic



TUF – Vertical Flow Regime Map



TUF – Horizontal Flow Regime Map



MODTUR-CLAS: Introduction

<u>MOD</u>erator <u>TUR</u>bulent **<u>C</u>**irculation **<u>C</u>**o-**<u>L</u>**ocated **<u>A</u>**dvanced **<u>S</u>**olution

- Consists of coupling CANDU moderator related specific modules developed by OPG (Ontario Power Generation) with the general purpose CFD code CFX-TASCflow 2.9, a commercial CFD code owned by AEAT ESL (AEA Technology Engineering Software LTD)
- Jointly owned by AEAT ESL and OPG
- One of the IST (Industry Standard Toolset) suite of safety analysis codes specifically used by the Canadian CANDU industry to model three-dimensional moderator flow and temperature distributions in the calandria for different calandria vessel designs
- V2.9 is currently being qualified for nuclear applications (verified, validated and documented)

MODTUR-CLAS: Background

- The functions of the OPG modules are as follows:
  - calculation of pressure losses in the calandria tube array
  - modelling of the buoyancy term in the momentum equation
  - calculation of the volumetric heat load distribution in the calandria vessel using the pre-processor module MODHEAT and input from steady-state and transient neutronic power and radioactive decay distributions
  - calculation of moderator subcooling
  - simulation of the moderator temperature control system
  - modelling of the moderator heat exchangers and associated control valves
  - the setting up of transient boundary conditions (inlet/outlet mass flows, transient poison concentration and other scalar inlet/outlet conditions, and restart capability)

MODTUR-CLAS: Background

- Used in nuclear safety analysis to predict velocity, temperature and/or poison concentration distributions (corresponding to SDS2 activation).
- This information is in turn used

  to determine moderator subcooling availability for the following postulated accident scenarios:
  - large break LOCA’s with and without ECC(involving PT/CT contact heat loads to the moderator)
  - loss of moderator circulation
  - loss of moderator cooling and to determine the poison distribution corresponding to
  - in-core, single-channel breaks in an overpoisoned guaranteed shutdown state

MODTUR-CLAS: Governing Equations

- Porous media approximation - volume-based isotropic porosity and distributed hydraulic resistance.
- Boussinesq approximation of buoyancy in momentum equation.
- Two-equation k- ε epsilon turbulence model.

Mass

$$\nabla \cdot (\gamma V) = 0$$

Momentum

$$\rho_r \frac{\partial V}{\partial t} + \frac{\rho_r}{\gamma} \nabla \cdot (\gamma V V) + \nabla p - \nabla \cdot [(\mu + \mu_t) \nabla V] + \rho_r g \beta (T - T_r)$$

$$+ \frac{\rho_r f \gamma^3}{2 l_{row}} V |V| \ f(\Psi) = 0$$

Energy

$$\rho_r C_p \gamma \frac{\partial T}{\partial t} + \rho_r C_p \nabla \cdot (\gamma V T) - \nabla \cdot \left[C_p \gamma \left(\frac{\mu}{\Pr} + \frac{\mu_t}{\sigma_t} \right) \nabla T \right] - \gamma Q = 0$$

MODTUR-CLAS: Closure Relationship

Thermophysical Properties

Specified to be constant at a selected reference temperature

Volume-Based Porosity

$$\gamma = 1 - \frac{\pi}{4}\left(\frac{d}{p}\right)^2$$

p and d = calandria tube pitch and diameter, respectively

Distributed Hydraulic Resistance

$$f = 4.5626\left(\frac{\rho_r \gamma |V| d}{\mu_r}\right)^{-0.1655}$$

cross-flow friction factor

$$l_{row} = p\cos(\alpha)$$

distance between tube rows

$f(\Psi)$ function that accounts for pressure loss due to flow along tube axis; allows for pressure loss due to both cross flow and parallel flow

MODTUR-CLAS: Closure Relationships

Volumetric Thermal Expansion Coefficient

$$\beta = -\frac{1}{\rho_r}\left(\frac{\partial \rho}{\partial T}\right)_p \cong -\frac{1}{\rho_r}\left(\frac{\rho - \rho_r}{T - T_r}\right)$$

can be specified to be a constant or a function of temperature

Turbulent Viscosity

$$\mu_t = c_\mu \rho_r \frac{k^2}{\varepsilon}$$

k and ε from two-equation turbulence model

Volumetric Heat Source

$$Q = f(Q_n, x, y, z, t)$$

Space and time function of neutron power, fission product decay, and heat transfer from fuel channels, if PT/CT contact occurs

MODTUR-CLAS: Numerical Solution

- Governing equations transformed to control volume equation analogues
- Vector and scalar solution variables co-located using orthogonal/non-orthogonal grid
- Several options for discretization: upwind difference, modified linear profile, physical advection correction, linear profile skew, etc
- Options of coupled and uncoupled multigrid solvers - iteration used to handle non-linearities
- Relaxation during iteration using distorted time step or true time step
- Implicit steady-state or transient solution

MODTUR-CLAS: User Input

Ten input files:

- Solution control parameters
- Grid file generated by TASCgrid pre-processor
- Boundary condition file generated by TASCbob3D pre-processor
- Initial distribution of dependent variables
- Input parameters used by BUNPOW subroutine to create the bundle power map
- File containing axial flux distribution by BUNPOW to create the bundle power map
- File names & input parameters used by MODHEAT pre-processor
- Bundle power map produced by BUNPOW and used by MODHEAT pre-processor
- Volumetric heat source distribution created by MODHEAT
- Time-variation of heat source

MODTUR-CLAS: Applications

Simulation of CANDU 6 Moderator Flow

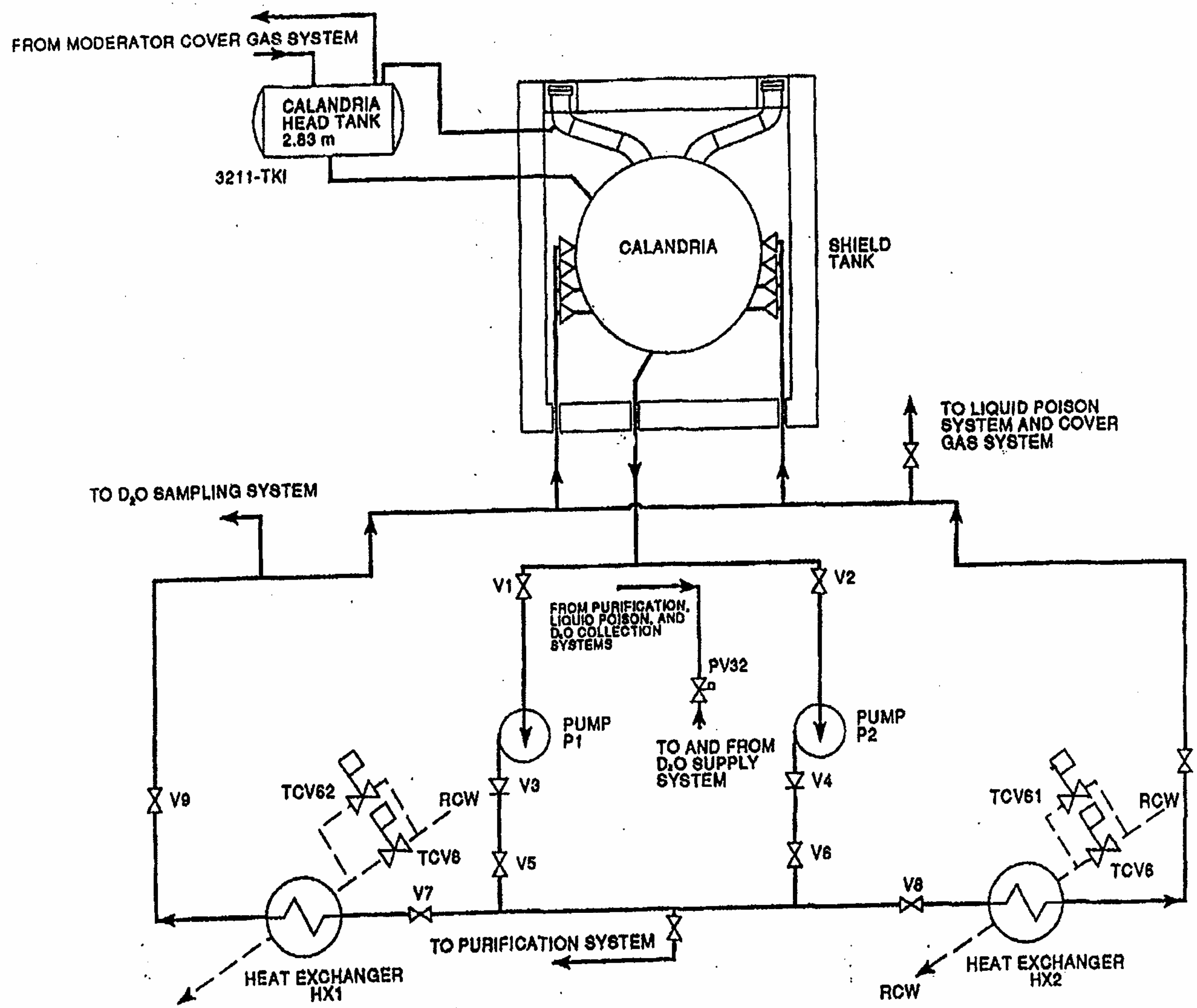
(Steady State and Transient analyses)

Description of the CANDU 6 Moderator System

- Calandria vessel is approximately 6m long and 7.6m in diameter at its widest point
- 380 calandria tubes displacing approximately 17% of the calandria vessel volume
- The moderator fluid is heavy water which is extracted from the vessel through two ports at the bottom of the vessel
- After discharging through the outlet ports, the moderator fluid mixes in a header and passes through one of two 100%pumps to be cooled via two 50% parallel heat exchangers and is returned to the calandria through 8 inlet nozzles located on the circumference of the vessel in the reflector region
- Under nominal operating conditions nuclear heat generation induces approximately 100MW of power to the moderator fluid

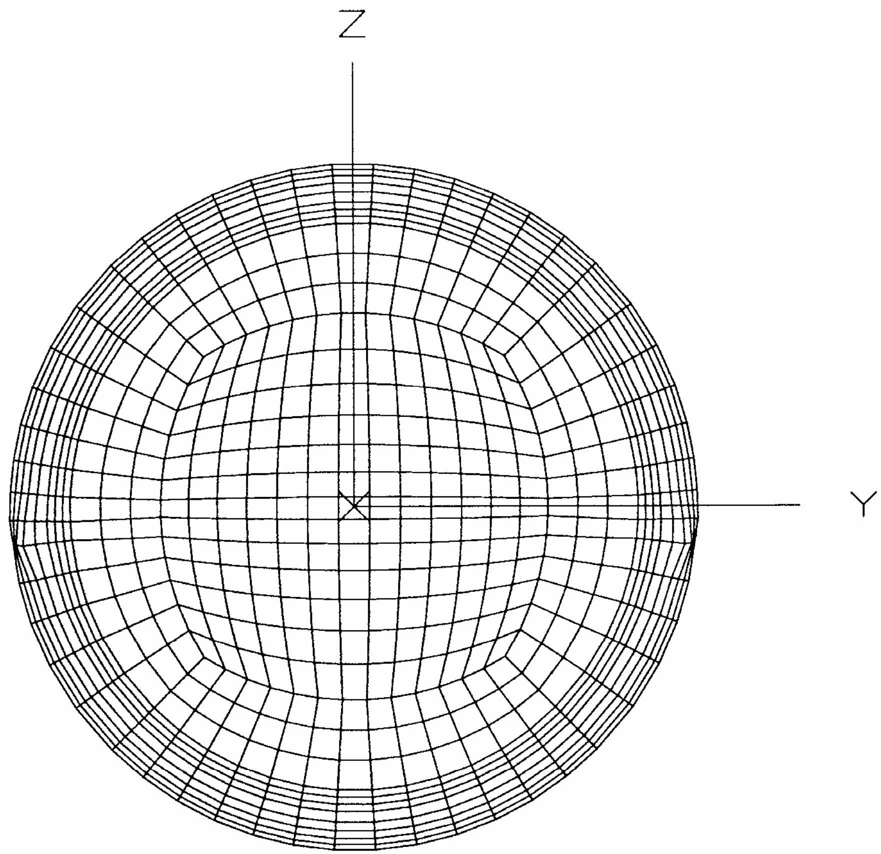
MODTUR-CLAS: CANDU 6 Application

Schematic of CANDU 6 Main Moderator System



MODTUR-CLAS: Nodalization – Cross-Section

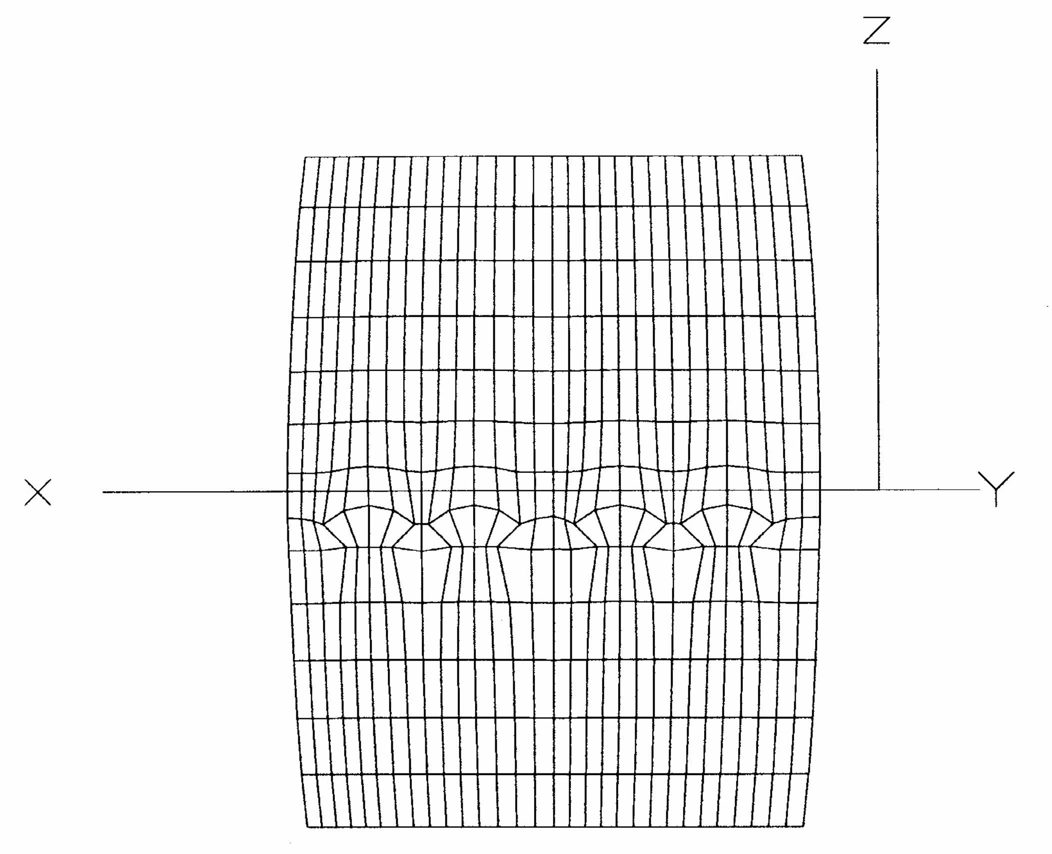
MODTURC_CLAS Butterfly grid representation of the Moderator Cross Section



MODTUR-CLAS: Nodalization – X-Y Plane

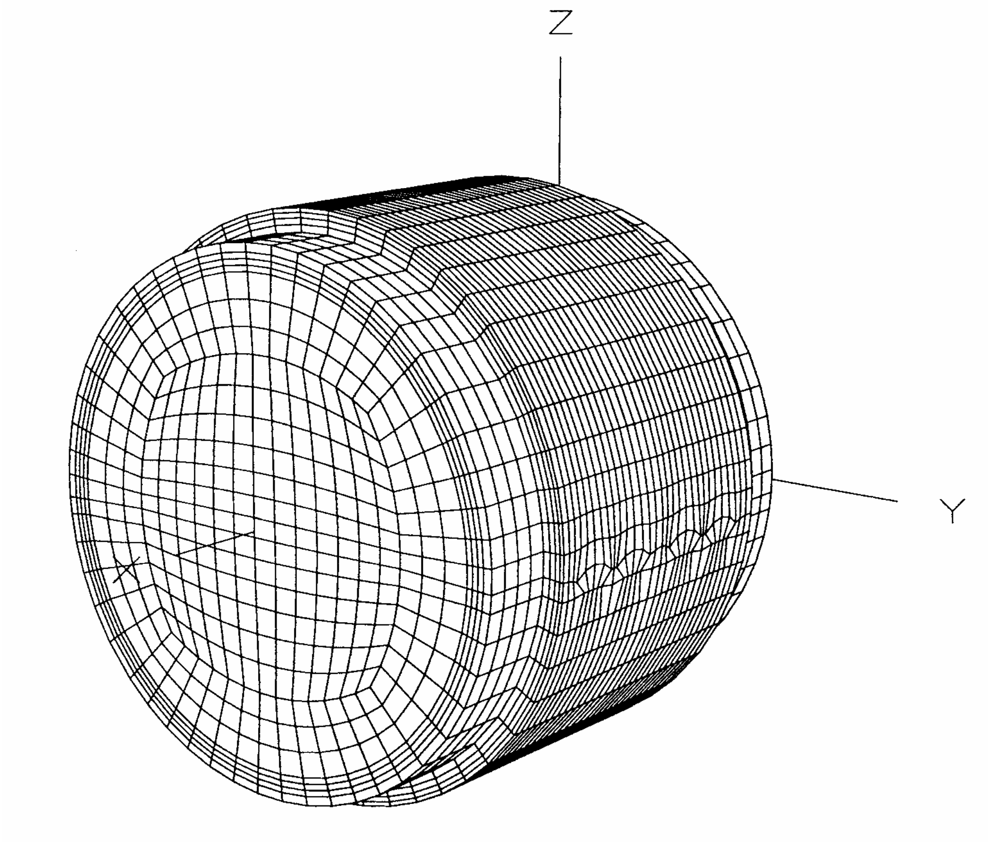
MODTURC_CLAS

Grid representation in the X-Y plane



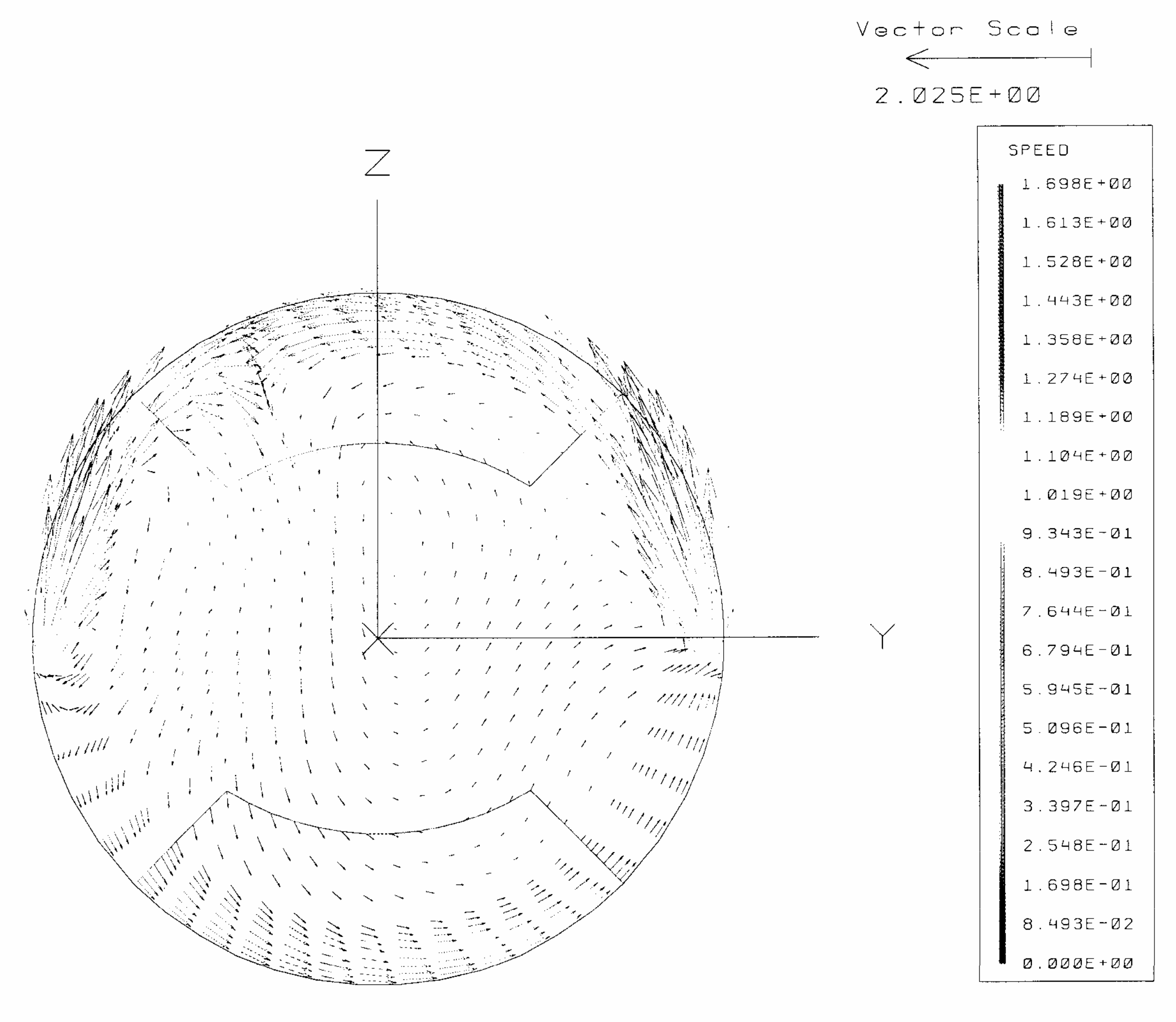
MODTUR-CLAS: Nodalization – Wire Frame

MODTURC_CLAS 3-D
wireframe grid



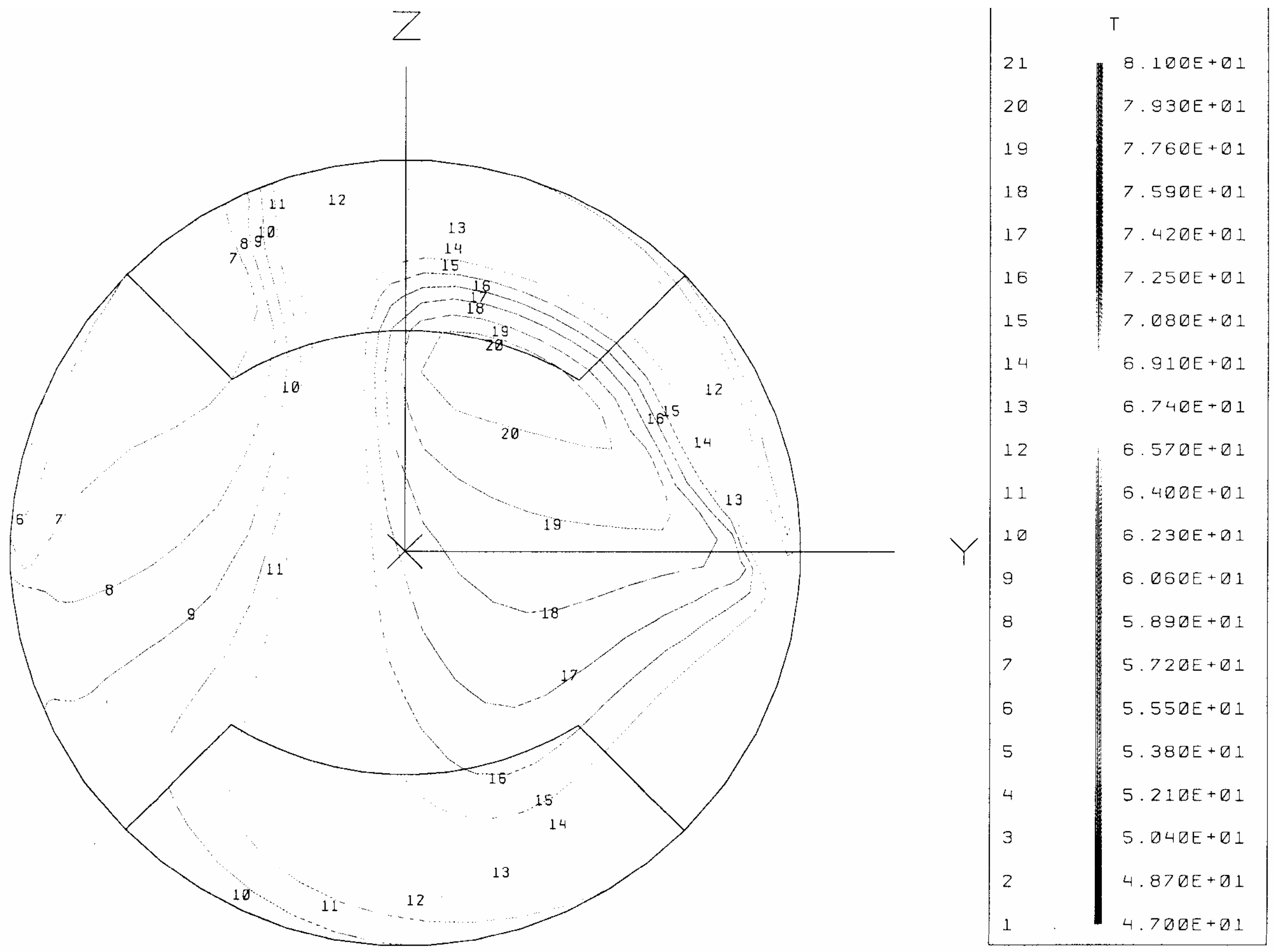
MODTUR-CLAS: Velocity Field

Typical CANDU 6 velocity field in the Mid-Axis plane X=3.0m



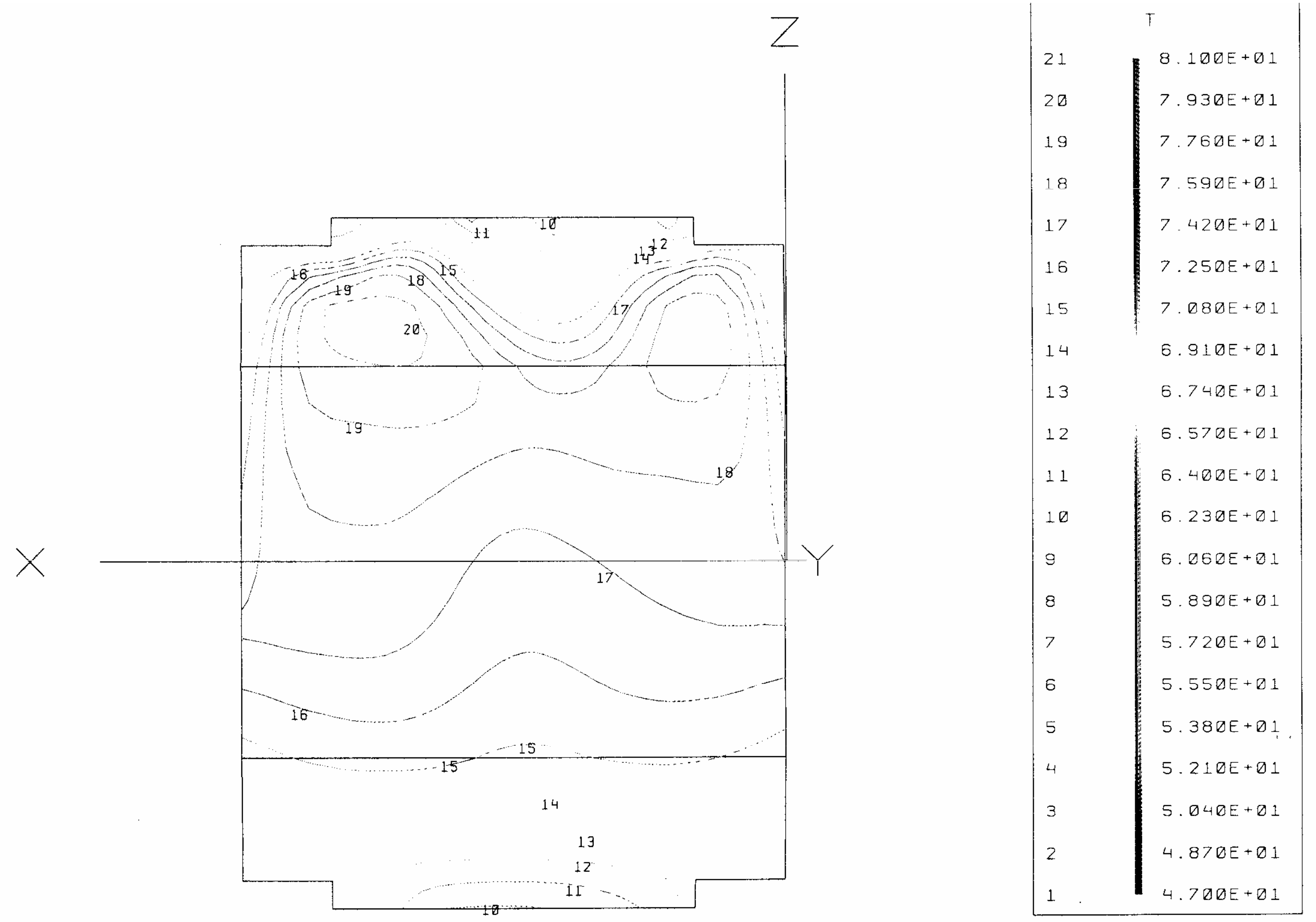
MODTUR-CLAS: Temperature Field

Typical CANDU 6 Temperature contours in the Mid-Axis plane X=3.0m

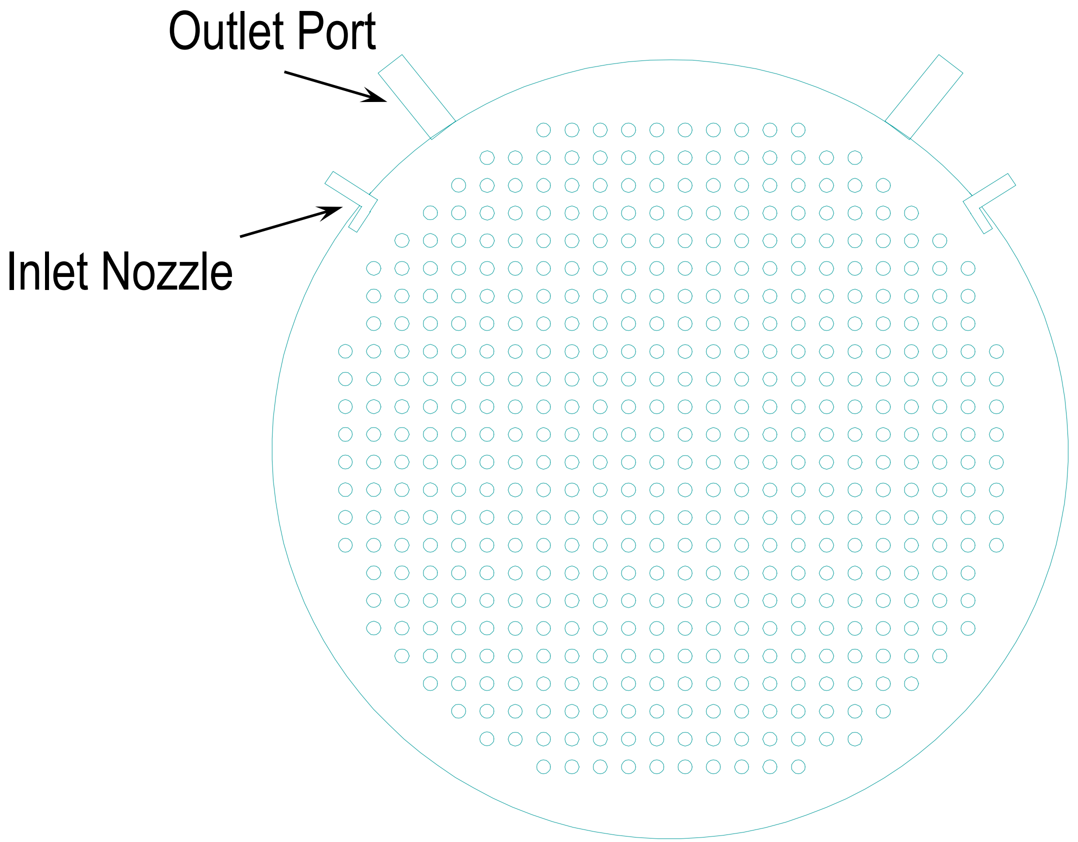


MODTUR-CLAS: Temperature Field

Typical CANDU 6 Temperature contours in the Calandria Axis plane Y=0.0



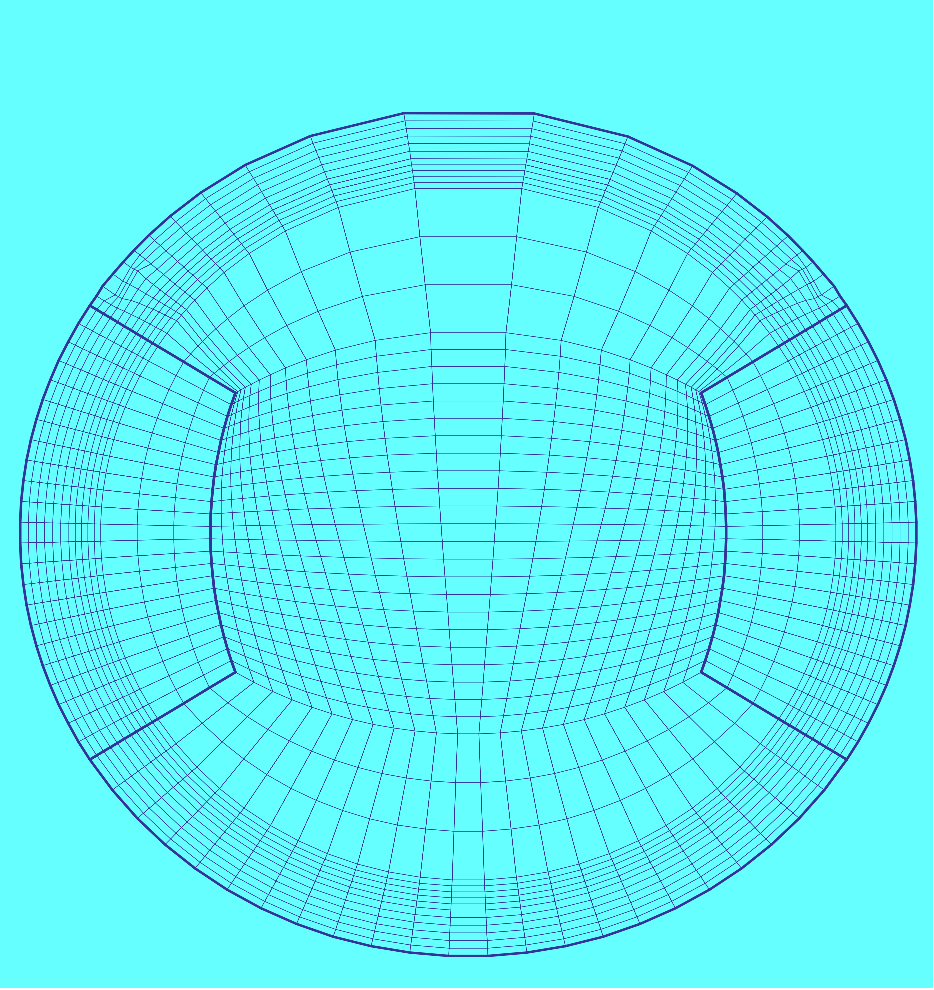
MODTUR-CLAS: CANDU 9 and ACR View



Simplified Cross-Section of CANDU 9 Calandria

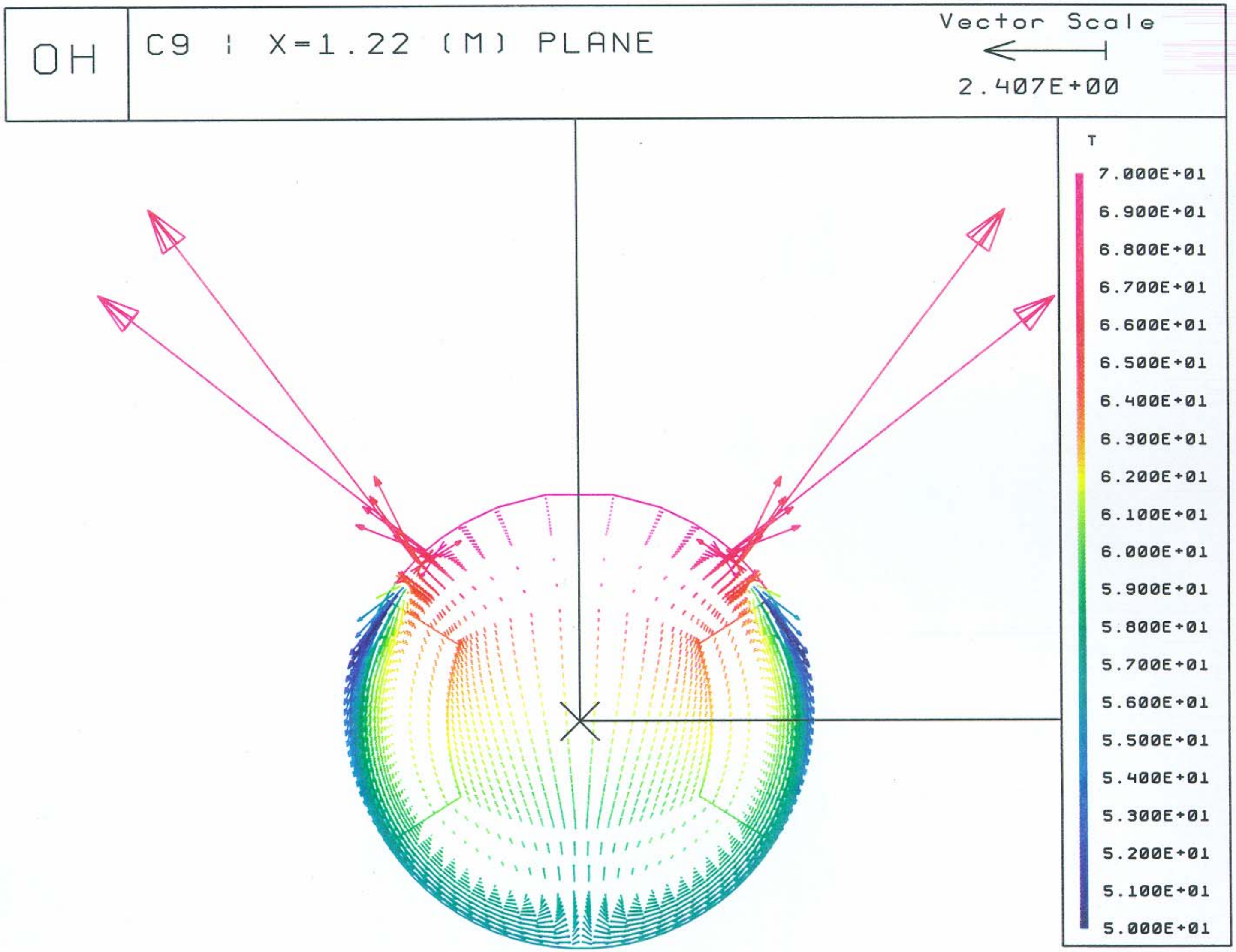
MODTUR-CLAS: Nodalization – Cross-Section

MODTURC_CLAS
Butterfly grid
representation of
the CANDU 9
Moderator Cross
Section



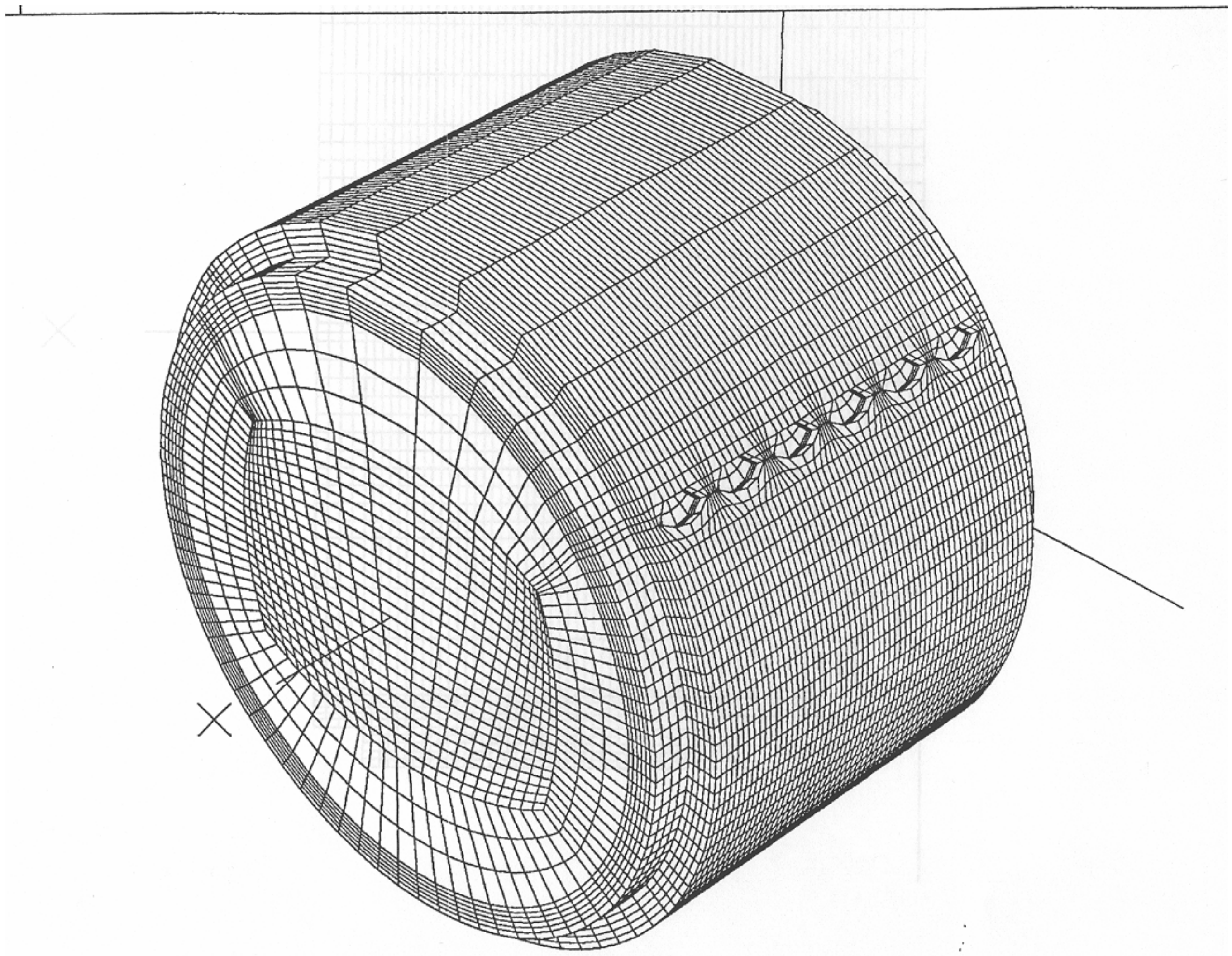
MODTUR-CLAS: Velocity Field

Typical CANDU 9 Velocity field (outlet port plane)



MODTUR-CLAS: Nodalization – Wire Frame

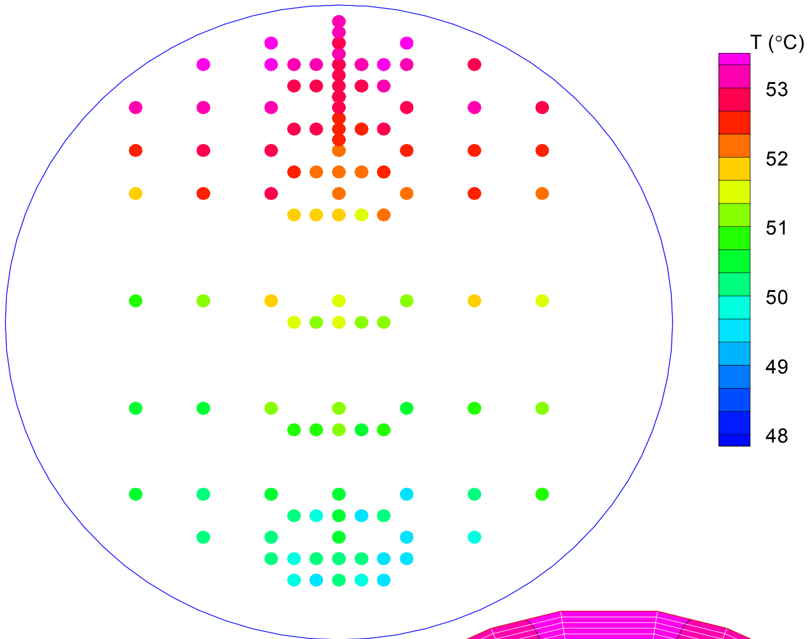
CANDU 9 3D
Wireframe



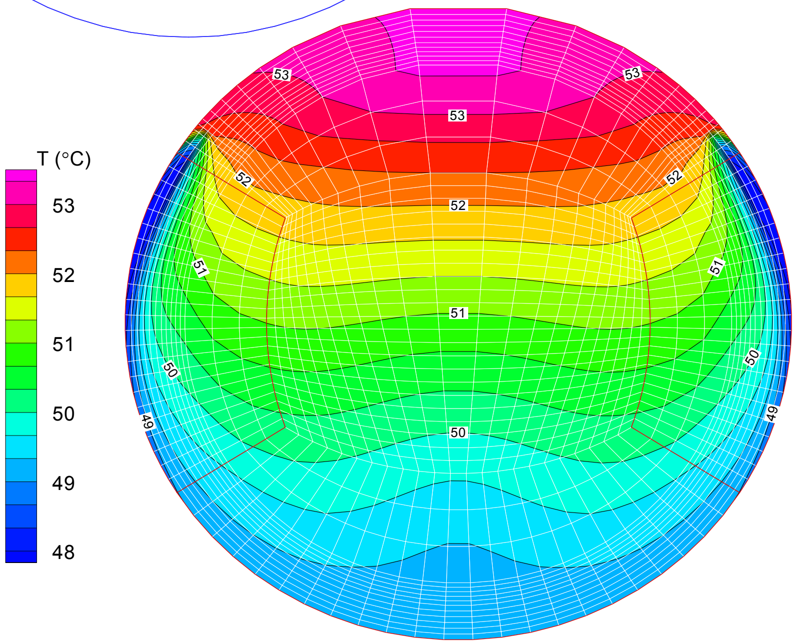
MODTUR-CLAS: Validation

- In order to perform MODTURC_CLAS validation several experiments were conducted in a 1/4 scale 3D moderator test facility (MTF) designed and constructed at CRL
- Both steady state and stylized accident tests were performed
- The following slides show comparisons between the experimental results and code predictions

MODTUR-CLAS: Validation

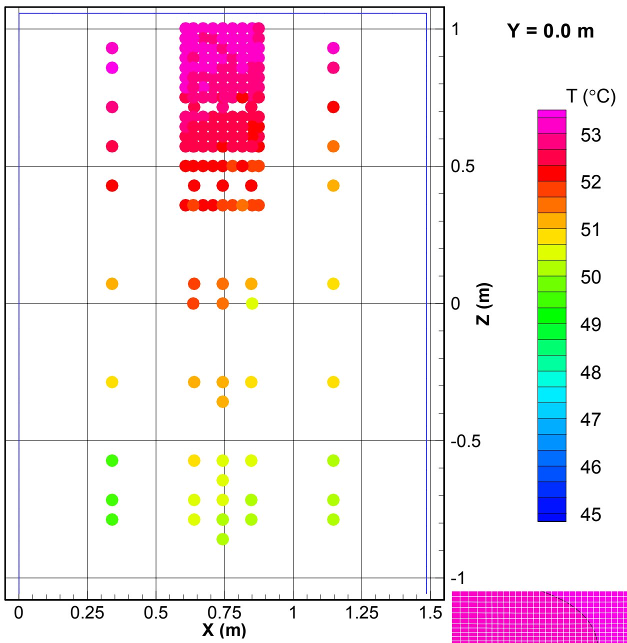


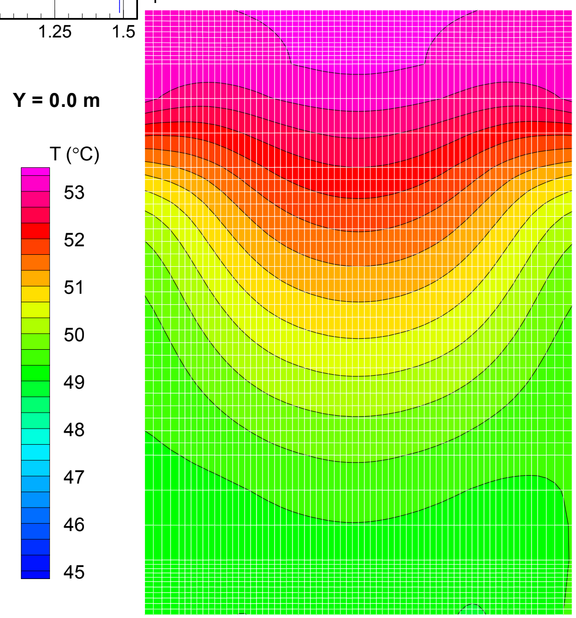
Measured (Top) and Calculated (Bottom) Temperatures in Middle Cross-Section Nominal Steady-State Conditions



MODTUR-CLAS: Validation

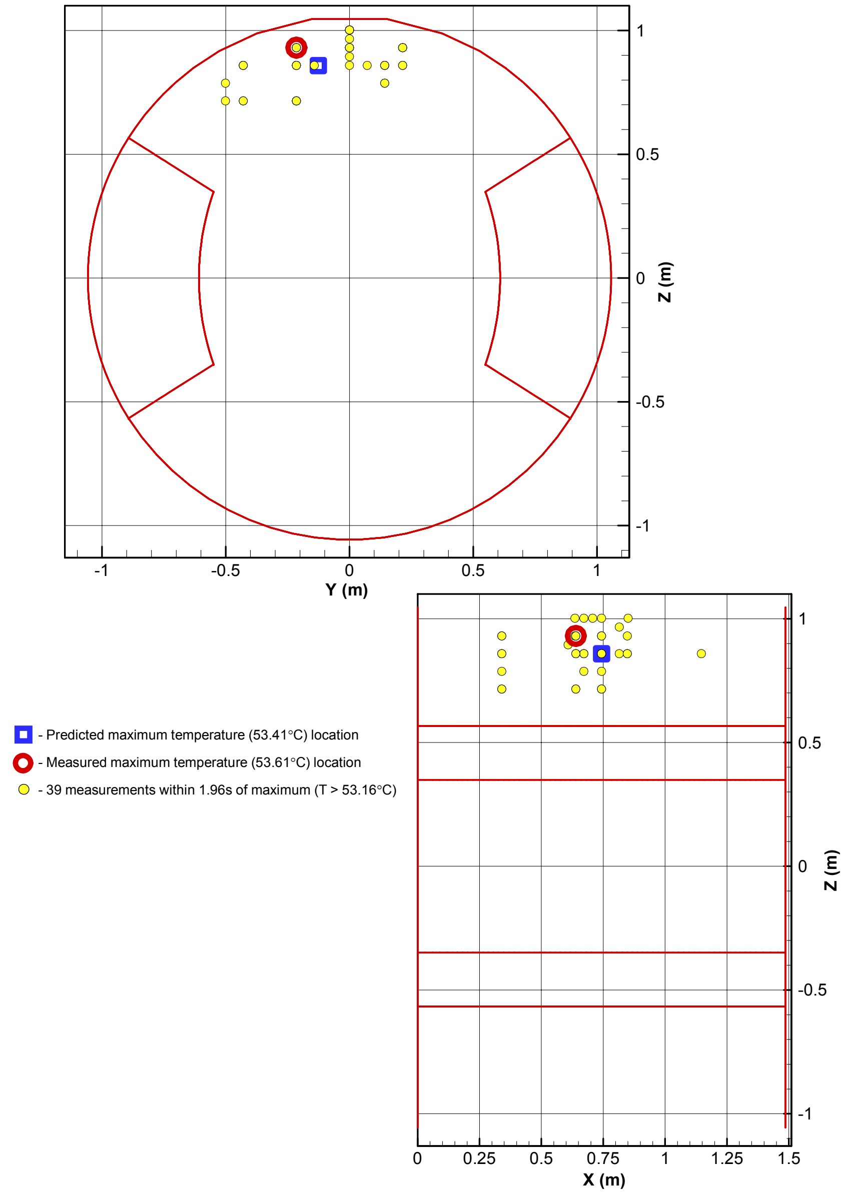
Measured (Top) and Calculated (Bottom) Temperatures in Lateral Centre Plane Nominal Steady-State Conditions





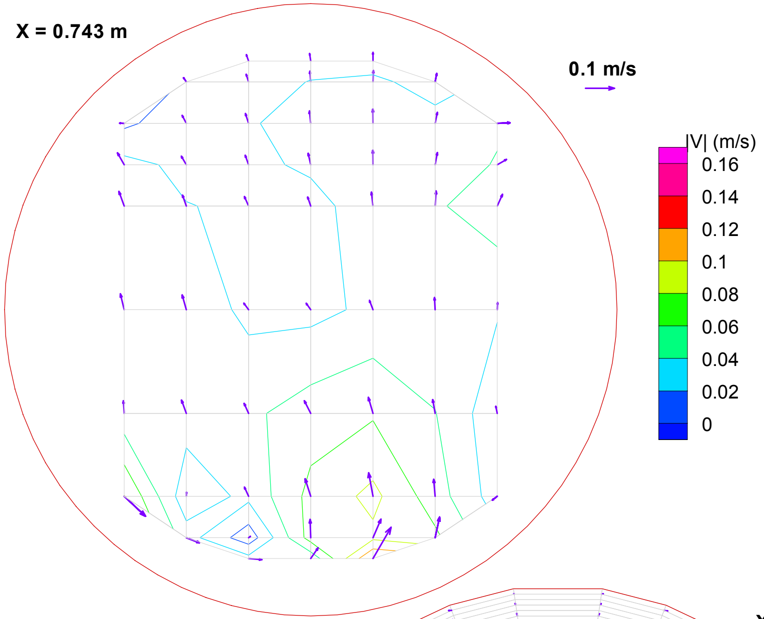
MODTUR-CLAS: Validation

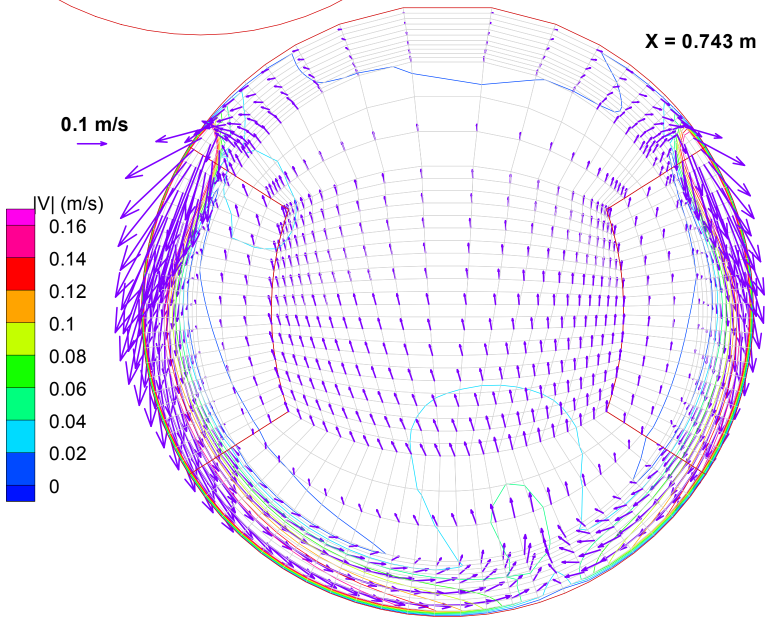
Measured and Calculated
Locations of Maximum
Temperatures
X-Projection (Top)
and Y-Projection (Bottom)
Nominal Steady-State
Conditions



MODTUR-CLAS: Validation

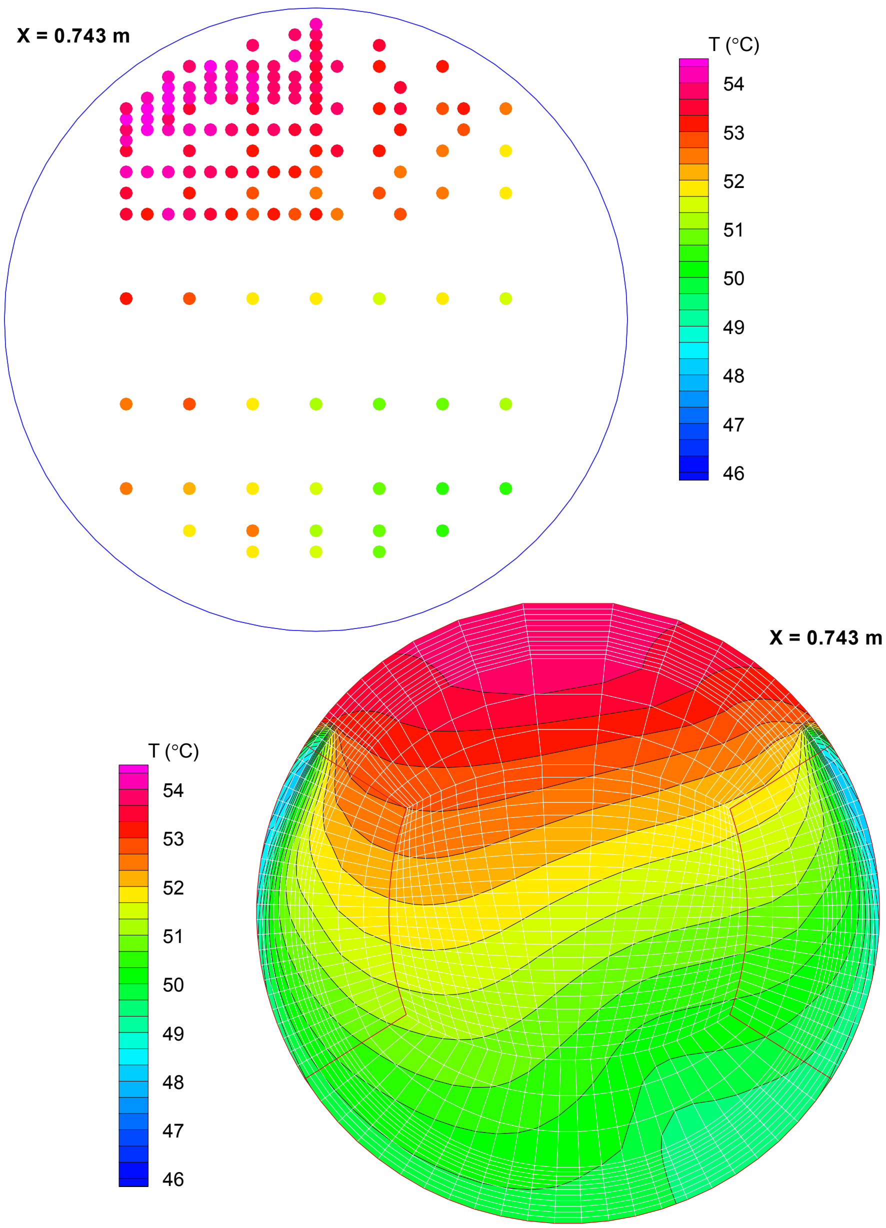
Measured (Top) and
Calculated (Bottom)
Velocities in
Middle Cross-Section
Nominal Steady-State
Conditions with
60% (Left) - 40% (Right)
Inlet Flow Split





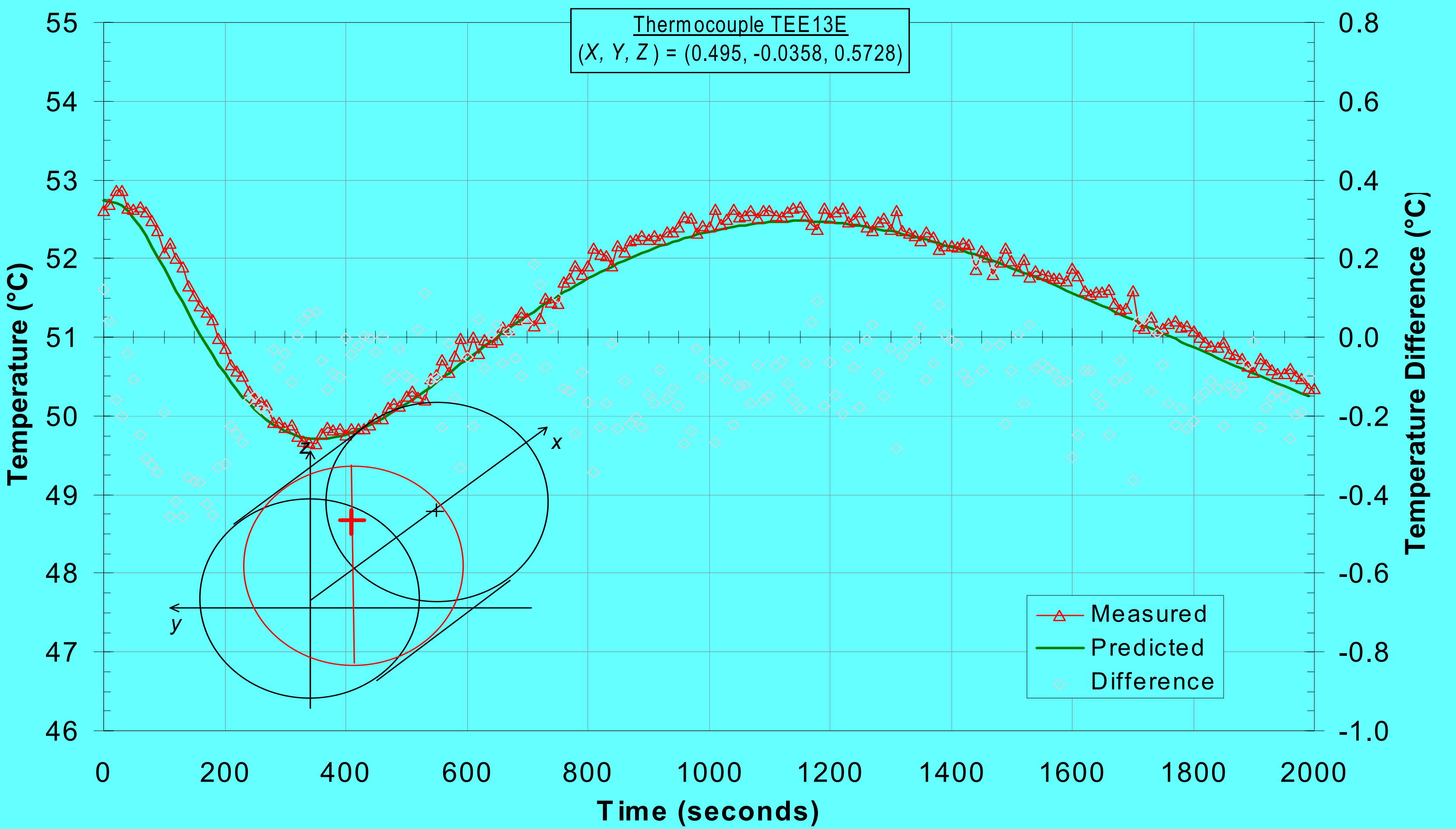
MODTUR-CLAS: Validation

Measured (Top) and Calculated (Bottom) Temperatures in Middle Cross-Section Nominal Steady-State Conditions with 60% (Left) - 40% (Right) Inlet Flow Split

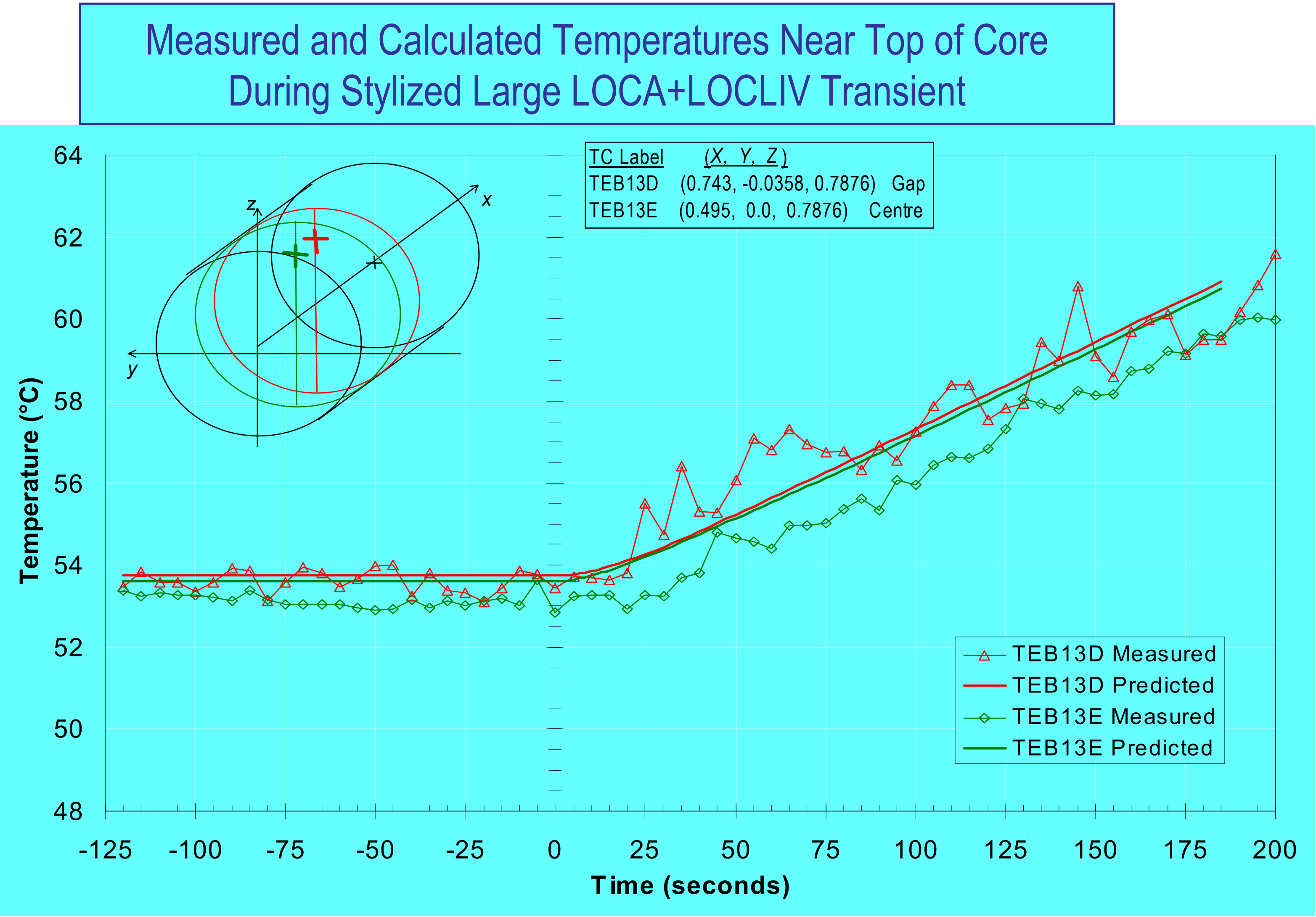


MODTUR-CLAS: Validation

Measured and Calculated Temperatures Near Top of Core During Stylized Large LOCA Transient



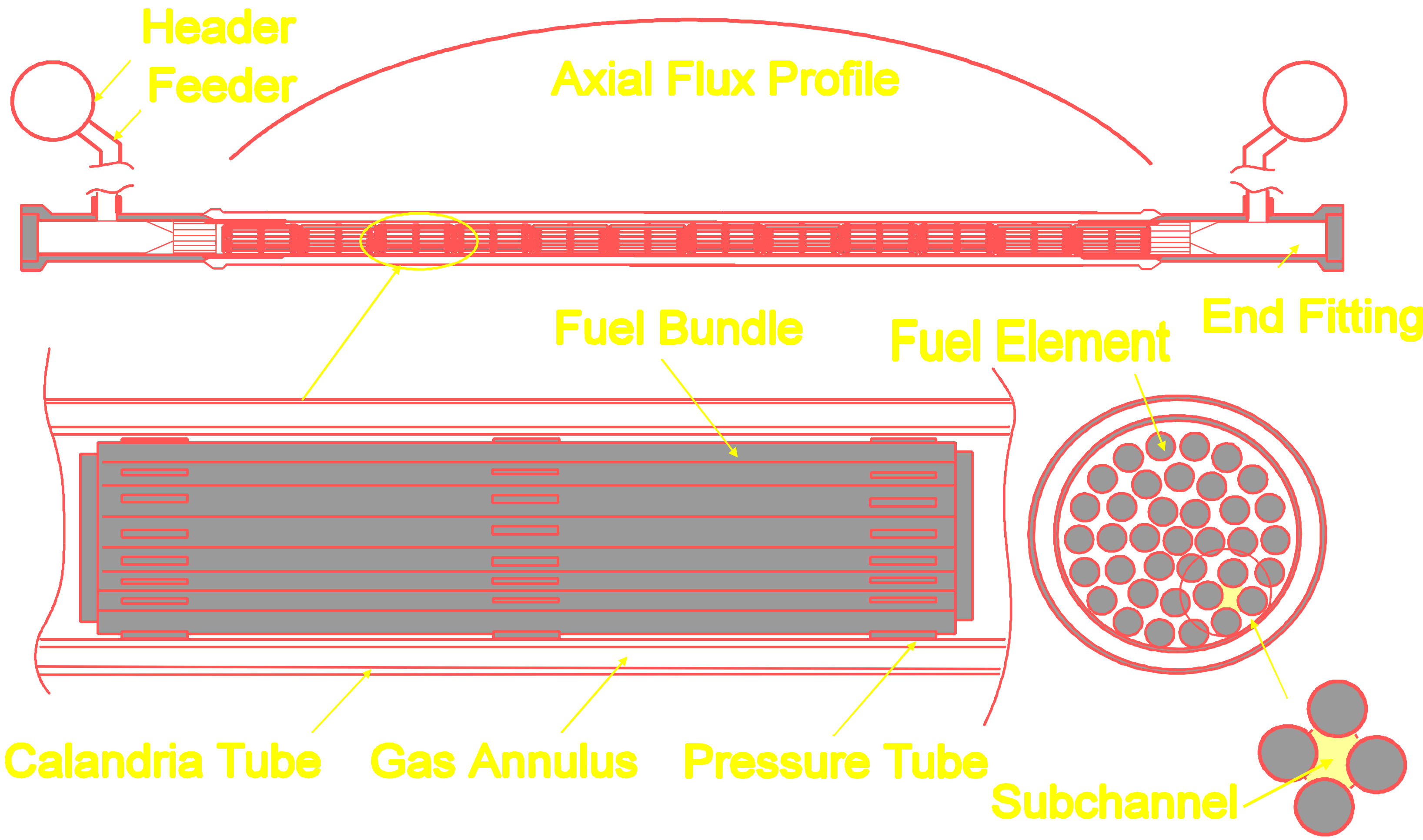
MODTUR-CLAS: Validation



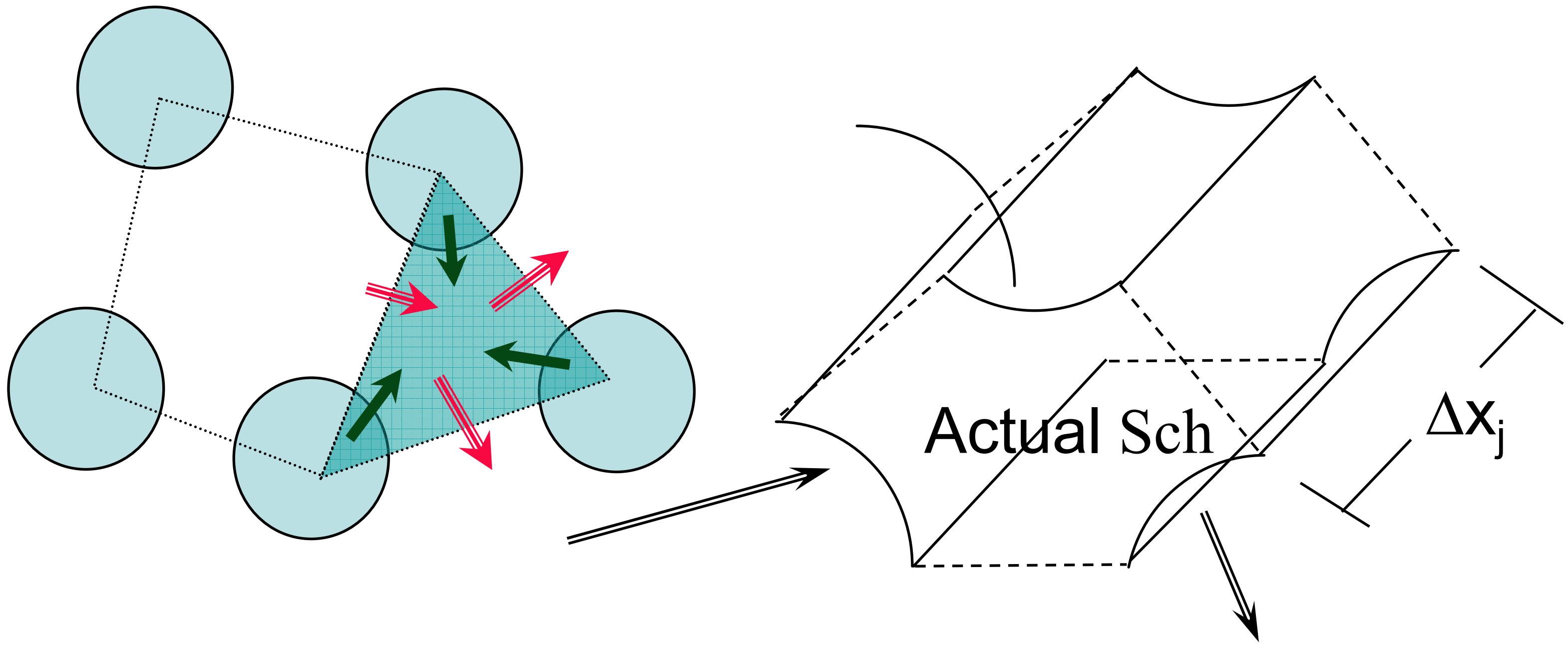
ASSERT-PV: Background

- ASSERT: Advanced Solution of Subchannel Equations in Reactor Thermalhydraulics.
- **Developed by AECL to model flow and phase distributions within horizontal subchannels of CANDU PHWR fuel channels and provide a detailed description of the CHF distribution throughout a fuel bundle.**
- **General enough to be applied to vertical PWR- and BWR-type bundles and in simple geometries ranging from single tubes to multiple interconnected subchannels.**
- **Uses drift flux formulation of governing equations to handle thermal and mechanical non-equilibrium.**
- **Based on the subchannel approach used by the COBRA IV computer code (see next three overheads).**

ASSERT-PV: Background (cont.)



ASSERT-PV: Background (cont.)



Simulated Subch.:

A_i, P_{hi}, P_{wi} , $Vol_i = A_i \Delta x_j$

q_i = diff. heat flux for each rod sector

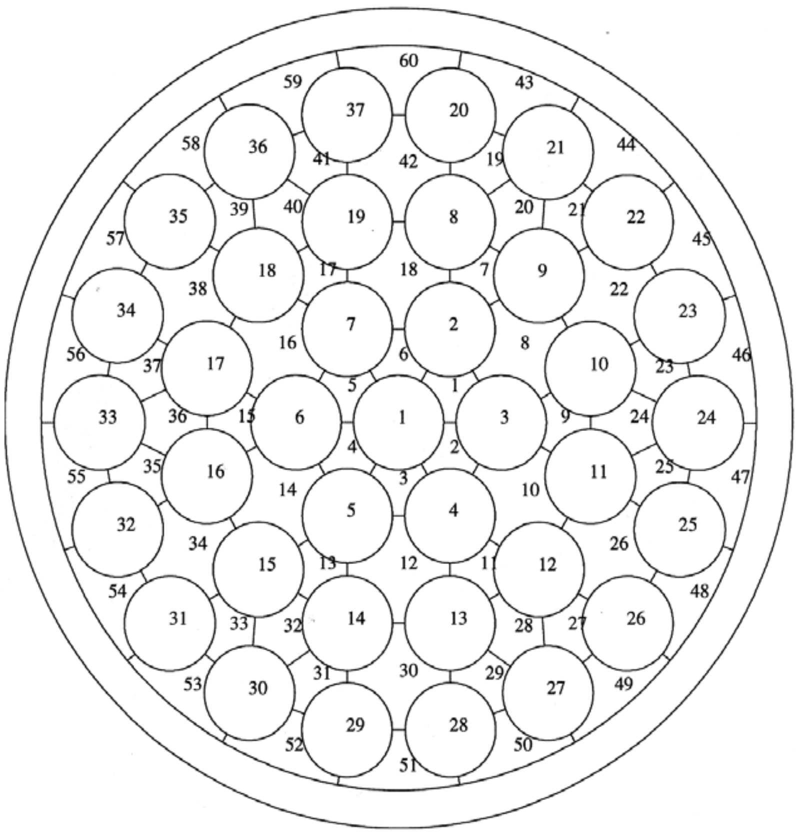
$S_{ii,jj}$ = gap between subchs. ii and jj

$\delta_{ii,jj}$ = centroidal distance between ii and jj

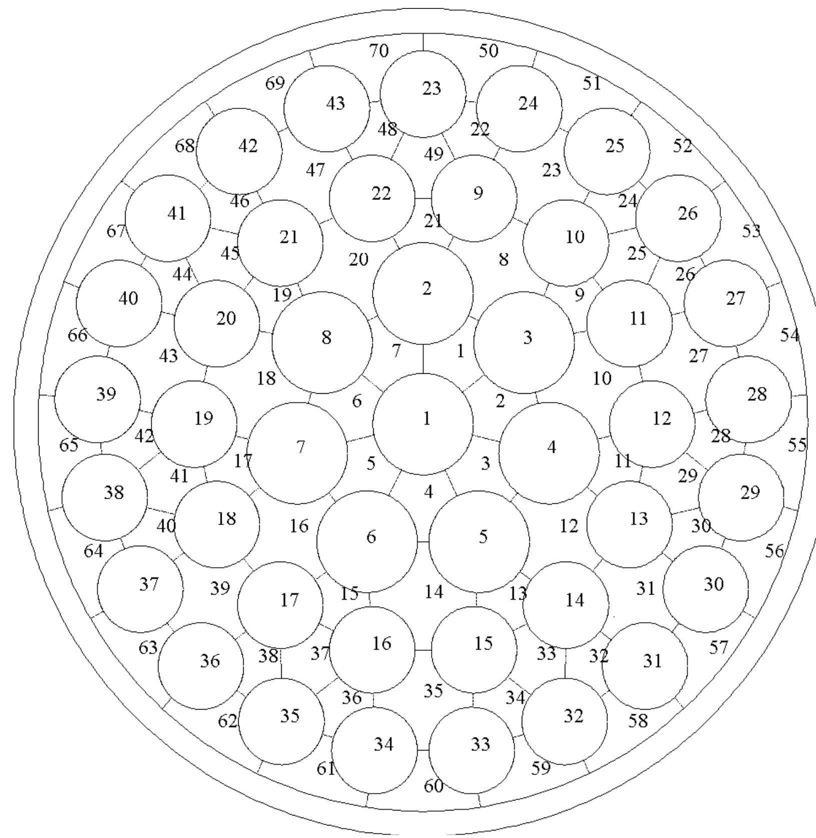
$\phi_{ii,jj}$ = centroidal angle angle

ASSERT-PV: Background (cont.)

Subchannels in a 37-Element Bundle



Subchannels in a 43-Element Bundle



ASSERT-PV: Background (cont.)

- Two different versions developed: ASSERT-IV and more recently, ASSERT-PV.
- ASSERT-IV initially developed to model subchannel thermal hydraulics at nominal or slightly off-nominal reactor flow and power conditions. No further development planned.
- ASSERT-PV solves the same equations as ASSERT-IV and has similar closure relationships. Main difference is the use of a more general numerical solution in PV, which will enable it to handle very low flows, including flow reversals, under both steady and transient conditions.

ASSERT-PV: Background (cont.)

- **Current release version of ASSERT-PV is V2R8m1 used to model the subchannel heat transfer flow and phase distribution up to and including CHF, in uncrept and crept pressure tubes.**
- **During 2000 ASSERT-PV will be formally designated an IST (Industry Standard Toolset) code to be used by the CANDU industry for subchannel thermalhydraulic analysis.**
- **Two new IST versions will be released within next two years:**
  - **V3R0 - and extension of V2R8m1 with the following additional capabilities:**
    - **modelling of the effects of local geometric variations (due to design or operation) of fuel element diameters and offsets from pitch circles, as well as interelement spacer heights and bearing pad heights,**

ASSERT-PV: Backround (cont.)

    - improved header-to-header boundary conditions,
    - new phenomenological CHF models in addition the the currently used tube look-up table for CHF, and
    - improved relationships for intersubchannel single and two-phase mixing, void drift and buoyancy drift.
  - V3R1, an extension of V3R0 with the additional capabilities to model steady-state and transient Loss-of-Flow, Loss-of-Regulation and small LOCA-type scenarios, up to and including post-dryout conditions
- formal validation of each version will be completed approximately one year after its release.

ASSERT-PV: Thermal-hydraulic Equations

- **Based on three-dimensional two-fluid modelling of Ishii (i.e., six equations two-fluid model leads to conservation of mass, energy and momentum vector equations for each phase).**
- **Two-fluid equations combined to obtain a five-equation set: vector equations for mixture mass, energy and momentum, and vector phasic equations for vapour and liquid energy. also referred to as diffusion model of two-phase flow.**
- **Mixture equations used with phasic equations for thermal non-equilibrium analysis.**
- **Relative velocity between phases from semi-empirical correlations.**
- **Time- and volume-averaging concepts used to convert five fundamental vector equations into simplified subchannel equations that follow.**
- **Subchannel control volume: subchannel bounded by rod surfaces and gaps between rods over incremental axial length along channel.**
- **Constant flow or pressure drop boundary conditions with specified outlet pressure.**

ASSERT-PV: Thermal-hydraulic Equations

Mass:

$$\overline{A}_{ij}\Delta x_j \frac{\left(\rho - \rho^n\right)}{\Delta t} + \left(F_{ij} - F_{ij-1}\right) + D_{ik}W_{kj} = 0$$

Axial Momentum (F = axial flow rate, U = axial velocity):

$$\Delta \hat{x}_j \frac{(F - F^n)_{i,j}}{\Delta t} + \left[(\overline{F}_l U_l^*)_{i,j+1} - (\overline{F}_l U_l^*)_{i,j}\right] + \left[(\overline{F}_l U_l^*)_{i,j+1} - (\overline{F}_l U_l^*)_{i,j}\right]$$
$$+ D_{i,k}\left[(\overline{W}_l U_l^*)_{k,j} + (\overline{W}_v U_v^*)_{k,j}\right] + \hat{A}_{ij}\left(P_{ij+1} - P_{ij}\right)$$
$$+ \left(\hat{A}K|F|F\right)_{ij} + g\left(\hat{\rho}\hat{A}\right)_{ij}\Delta\overline{x}_j \cos\theta = 0$$

Transverse/Lateral Momentum (W = transverse flow rate, V = transverse velocity):

$$\Delta y_k \frac{((\overline{\rho^n}\, W)/\overline{\rho} - W^n)_{k,j}}{\Delta t} + (\overline{F}_l V_l^*)_{k,j} - (\overline{F}_l V_l^*)_{k,j-1} + (\overline{F}_v V_v^*)_{k,j} - (\overline{F}_v V_v^*)_{k,j-1}$$
$$- V_{k,j}\left(\overline{F}_{k,j} - \overline{F}_{k,j-1}\right) + \overline{A}_{k,j}\left(P_{j(k)j} - P_{i(k)j}\right) + \left(\overline{A}K|W|W\right)_{k,j} + g(\overline{\rho}\,\overline{A})_{k,j}\Delta y_k \sin\theta \cos\varphi_k = 0$$

ASSERT-PV: Thermal-hydraulic Equations

Liquid Enthalpy:

$$\overline{A}_{i,j}\ \Delta x_j\ (\alpha\rho)^n_{l\,i,j}\ \frac{(h_l - h_l^n)_{i,j}}{\Delta t} + (F_l\, h_l^*)_{i,j} - (F_l\, h_l^*)_{i,j-1} - h_{l_{i,j}}(F_{l_{i,j}} - F_{l_{i,j-1}})$$

$$+ D_{i,k}\ \ (W_l\, h_l^*)_{k,j} - h_{l_{i,j}}\ \ D_{i,k}\ \ W_{l_{k,j}} - q_{il_{i,j}} - \psi_{i,n}\ \ q_{wl_{n,j}} + D_{i,k}\ \ (\alpha_l\, q_{l_{mix}})_{k,j} = 0.$$

Vapour Enthalpy:

$$\overline{A}_{i,j}\ \Delta x_j\ (\alpha\rho)^n_{v\,i,j}\ \frac{(h_v - h_v^n)_{i,j}}{\Delta t} + (F_v\, h_v^*)_{i,j} - (F_v\, h_v^*)_{i,j-1} - h_{v_{i,j}}(F_{v_{i,j}} - F_{v_{i,j-1}})$$

$$+ D_{i,k}\ \ (W_v\, h_v^*)_{k,j} - h_{v_{i,j}}\ \ D_{i,k}\ \ W_{v_{k,j}} - q_{iv_{i,j}} - \psi_{i,n}\ \ q_{wv_{n,j}} + D_{i,k}\ \ (\overline{\alpha}_l\, q_{v_{mix}})_{k,j} = 0.$$

Mixture Enthalpy:

$$\overline{A}_{i,j}\,\Delta x_j\,\rho^n_{i,j}\,\frac{\left(h - h^n\right)_{i,j}}{\Delta t} + (F_l\, h_l^*)_{i,j} - (F_l\, h_l^*)_{i,j-1} + (F_v\, h_v^*)_{i,j} - (F_v\, h_v^*)_{i,j-1} - h_{i,j}(F_{i,j} - F_{i,j-1})$$

$$+ D_{i,k}(W_l\, h_l^* + W_v\, h_v^*)_{k,j} - h_{i,j}\, D_{i,k}\, W_{k,j} - \psi_{i,n}\ \ (q_{w_{n,j}}) + D_{i,k}\, q_{mix_{k,j}} = 0$$

ASSERT-PV: Thermal-hydraulic Equations

General Expression for Gas Velocity:

$$\vec{V}_v = C_o \vec{j} + \vec{V}_{jg} - \frac{\varepsilon_\alpha}{\alpha} \nabla (\alpha - \alpha_{eq})$$

Mixture Volumetric Flux:

$$\vec{j} = \alpha \vec{V}_v + (1 - \alpha) \vec{V}_l$$

General Expression for Relative Velocity (distribution, buoyancy and void diffusion & drift components):

$$\vec{V}_r = \frac{C_o - 1}{1 - \alpha} \vec{j} + \frac{\vec{V}_{gj}}{1 - \alpha} - \frac{\varepsilon_\alpha}{\alpha (1 - \alpha)} \nabla (\alpha - \alpha_{eq}).$$

Simplified Axial Relative Velocity (no void diffusion or void drift):

$$U_r = \frac{(C_o - 1)j + U_{gj}}{1 - \alpha}$$

Simplified Transverse Relative Velocity (distribution parameter, $C_o = 1$)

$$V_r = \frac{V_{gj}}{1 - \alpha} - \frac{\varepsilon_\alpha}{\alpha(1 - \alpha)} \nabla\left(\alpha - \alpha_{eq}\right)$$

ASSERT-PV: Closure Relationship

- **Thermophysical and transport properties:**
  - User-specified tables for air-water and Freons; internal property package for light and heavy -steam-water.
- **Wall-to-fluid single- and two-phase skin friction and form losses:**
  - User-specified single phase friction factor functions and geometry-based form losses; implicit/explicit Colebrook-White.
  - Two-phase multipliers: user-specified polynomials; user-selected models ranging from homogenous to Friedel.

ASSERT-PV: Closure Relationship (cont.)

- **Wall-to-fluid single- and two-phase heat transfer:**
  - Dittus-Boelter for single-phase flow.
  - Six user-selected options for two-phase flow:
    - Chen; Ahmad; Rouhani & Axelsson; Hancox-Nicoll; Maroti; Lahey & Moody.
- **Interphase heat transfer:**
  - Hancox-Nicoll.
- **CHF:**
  - Tube look-up table (default); phenomenological models of Hewitt-Govan (film dryout) and Weisman and Pei (DNB).

ASSERT-PV: Closure Relationships (cont.)

- **Single- and two-phase intersubchannel turbulent mixing:**
  - **Single-phase thermal mixing**
    - **User-specified or Rogers and Tahir.**
- **Two-Phase Mixing Void Mixing/Diffusion**
  - **User-specified coefficients for constant Peclet number model with Okhawa-Lahey multiplier; void-fraction-dependent Rowe model; new void-dependent relationships based on air-water mixing data with flow regime correction factors for higher pressures.**

ASSERT-PV: Closure Relationships (cont.)

- **Equilibrium void:**
  - **To reflect tendency of higher void to occur in larger subchannels.**
    - **Choice of Lahey or Rowe models (both based on the same air-water data)**
- **Buoyancy drift (or phase separation):**
  - **Okhawa-Lahey model in vertical axial flow.**
  - **Choice of Okhawa-Lahey or Wallis-type models for transverse direction in horizontal flow.**
- **Distribution Parameter:**
  - **Okhawa-Lahey model in axial and transverse flow.**
  - **Option of Dix model for axial flow.**

ASSERT-PV: Numerical Solution

Newton Method:

$F(x)$ = conservation equation (momentum, mass, energy)

x = solution vector (for *h*, h_v, h_l, *F*, *W*, *or P*)

$\tilde{x}$ = initial estimate of solution

δx = correction to initial estimate

$\frac{dF(\tilde{x})}{dx}$ = Jacobian derivative matrix

$$F(x)=0 \Rightarrow x=\tilde{x}+\delta x \Rightarrow F(\tilde{x}+\delta x)=0$$

$$\Rightarrow F(\tilde{x})+\frac{dF(\tilde{x})}{dx}\delta x=0 \Rightarrow \left[\frac{dF(\tilde{x})}{dx}\right]\delta x=-F(\tilde{x}) \Rightarrow \delta x=-F(\tilde{x})\left[\frac{dF(\tilde{x})}{dx}\right]^{-1}$$

ASSERT-PV: Numerical Solution (cont.)

Momentum, mass and energy equations solved sequentially using block iteration strategy:

- Over-score indicates values are kept constant while equation is being solved.
- Each equation set is solved directly at a given axial plane.
- Marching technique is used to advance solution in positive (and negative - if reverse flow) axial direction.

transverse momentum

$$M_v(\widetilde{h}, \widetilde{h}_l, \widetilde{h}_v, \widetilde{F}, W, P) = 0$$

axial momentum

$$M_u(\widetilde{h}, \widetilde{h}_l, \widetilde{h}_v, F, \widetilde{W}, P) = 0$$

ASSERT-PV: Numerical Solution (cont.)

mass continuity

$$C\,(\widetilde{h}, \widetilde{h}_l, \widetilde{h}_v, F, W, P) = 0$$

mixture, liquid and vapour energy

$$E_m(h, h_l, h_v, \widetilde{F}, \widetilde{W}, \widetilde{P}\ ) = 0$$

$$E_l(h, h_l, h_v, \widetilde{F}, \widetilde{W}, \widetilde{P}\ ) = 0$$

$$E_v(h, h_l, h_v, \widetilde{F}, \widetilde{W}, \widetilde{P}) = 0$$

ASSERT-PV: Numerical Solution (cont.)

Example - matrix form for simultaneous solution of energy equations in two adjacent subchannels i and j at a given axial plane

$$
\begin{bmatrix}
\left|\begin{matrix}
\frac{\partial E_m}{\partial h} & \frac{\partial E_m}{\partial h_l} & \frac{\partial E_m}{\partial h_v} \\
\frac{\partial E_l}{\partial h} & \frac{\partial E_l}{\partial h_l} & \frac{\partial E_l}{\partial h_v} \\
\frac{\partial E_v}{\partial h} & \frac{\partial E_v}{\partial h_l} & \frac{\partial E_v}{\partial h_v}
\end{matrix}\right|_{i,i} &
\left|\begin{matrix}
\frac{\partial E_m}{\partial h} & \frac{\partial E_m}{\partial h_l} & \frac{\partial E_m}{\partial h_v} \\
\frac{\partial E_l}{\partial h} & \frac{\partial E_l}{\partial h_l} & \frac{\partial E_l}{\partial h_v} \\
\frac{\partial E_v}{\partial h} & \frac{\partial E_v}{\partial h_l} & \frac{\partial E_v}{\partial h_v}
\end{matrix}\right|_{i,i} \\
\left|\begin{matrix}
\frac{\partial E_m}{\partial h} & \frac{\partial E_m}{\partial h_l} & \frac{\partial E_m}{\partial h_v} \\
\frac{\partial E_l}{\partial h} & \frac{\partial E_l}{\partial h_l} & \frac{\partial E_l}{\partial h_v} \\
\frac{\partial E_v}{\partial h} & \frac{\partial E_v}{\partial h_l} & \frac{\partial E_v}{\partial h_v}
\end{matrix}\right|_{j,i} &
\left|\begin{matrix}
\frac{\partial E_m}{\partial h} & \frac{\partial E_m}{\partial h_l} & \frac{\partial E_m}{\partial h_v} \\
\frac{\partial E_l}{\partial h} & \frac{\partial E_l}{\partial h_l} & \frac{\partial E_l}{\partial h_v} \\
\frac{\partial E_v}{\partial h} & \frac{\partial E_v}{\partial h_l} & \frac{\partial E_v}{\partial h_v}
\end{matrix}\right|_{j,j}
\end{bmatrix}
\begin{Bmatrix}
\begin{Bmatrix} \delta h \\ \delta h_l \\ \delta h_v \end{Bmatrix}_i \\
\begin{Bmatrix} \delta h \\ \delta h_l \\ \delta h_v \end{Bmatrix}_j
\end{Bmatrix}
=
\begin{Bmatrix}
\begin{Bmatrix} -E_m \\ -E_l \\ -E_v \end{Bmatrix}_i \\
\begin{Bmatrix} -E_m \\ -E_l \\ -E_v \end{Bmatrix}_j
\end{Bmatrix}
$$

ASSERT-PV: Numerical Solution (cont.)

Fuel Model:

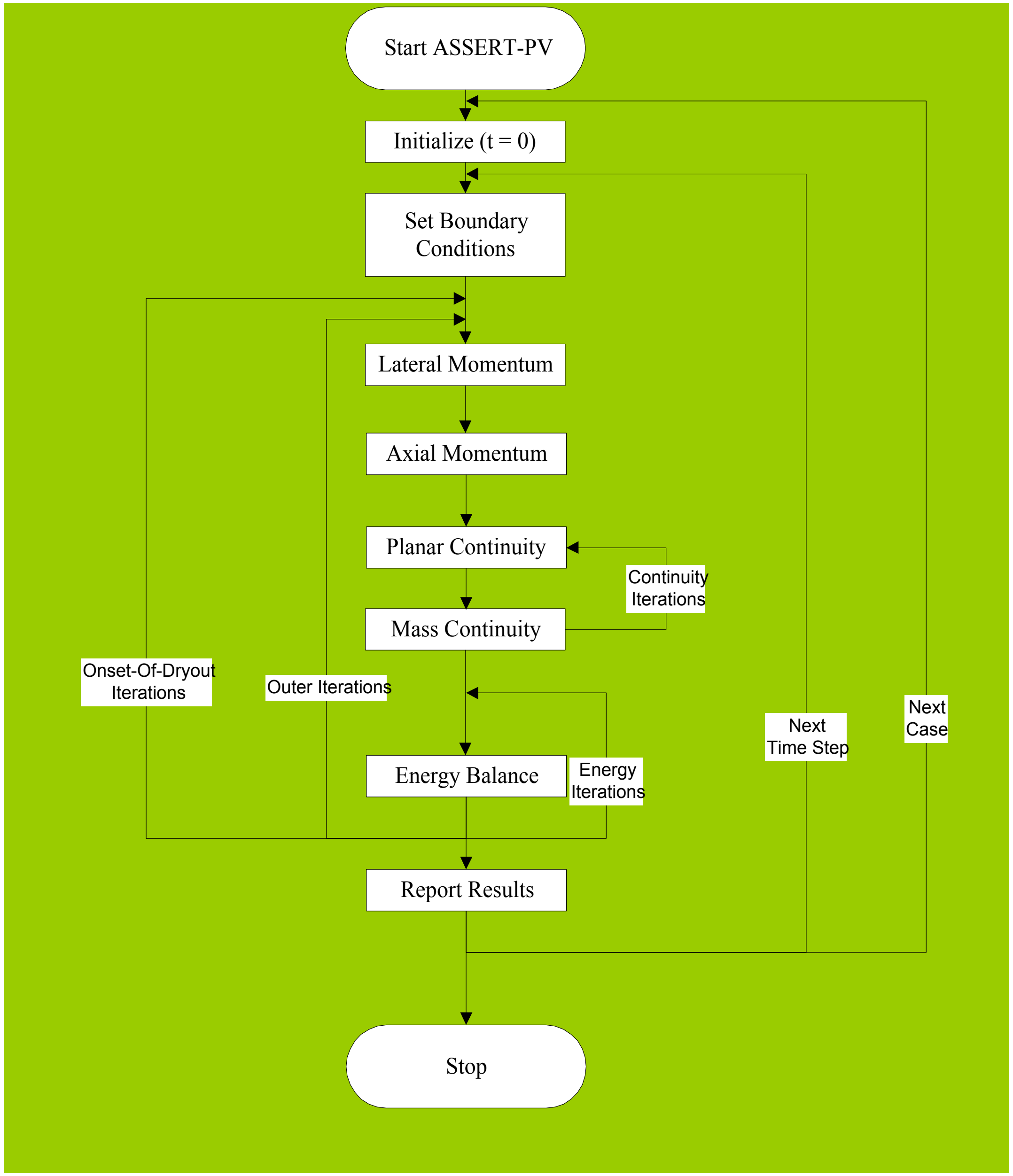
- **Specified surface heat flux on individual rod segments - accommodating axial and transverse variations in bundle power,**

<u>or</u>

- **steady- and transient finite-difference-based heat conduction model, with options for one-D radial, two-D radial circumferential and full three-D discretization. Can accommodate different densities, specific heats and thermal conductivities of fuel and sheath, and different fuel-to-sheath heat transfer coefficients.**

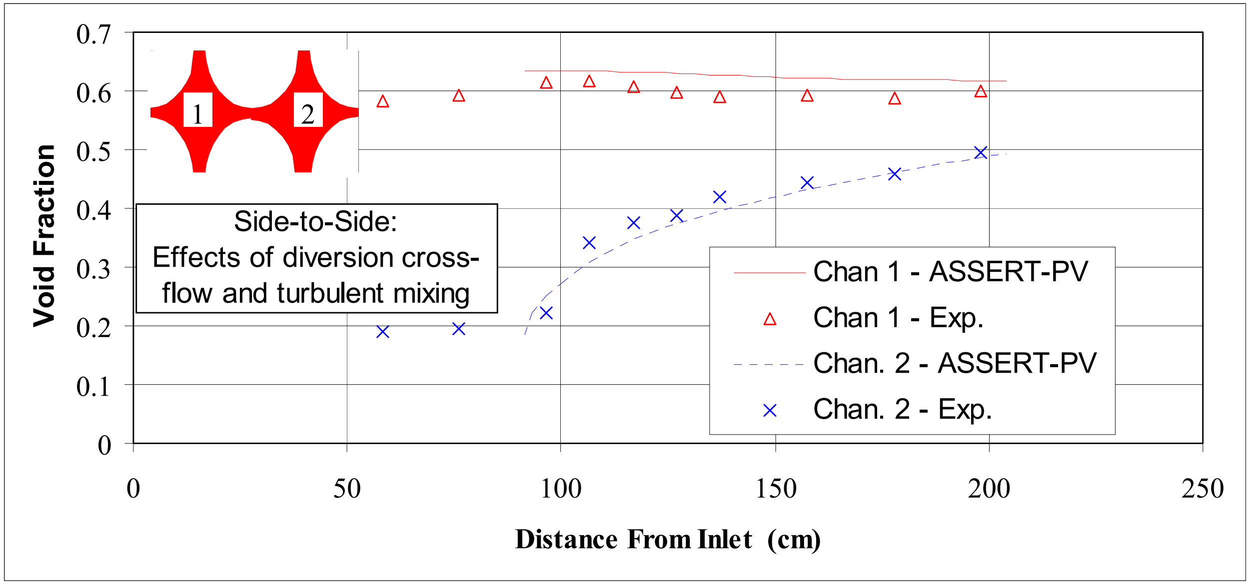
ASSERT-PV: Numerical Solution (cont.)

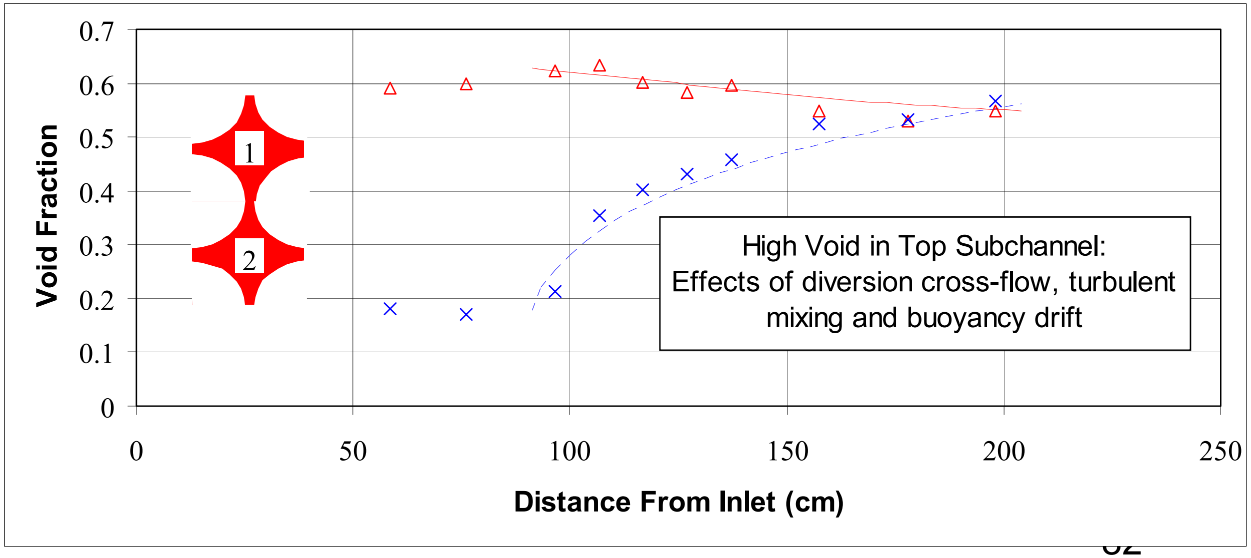
Iterative Solution Procedure



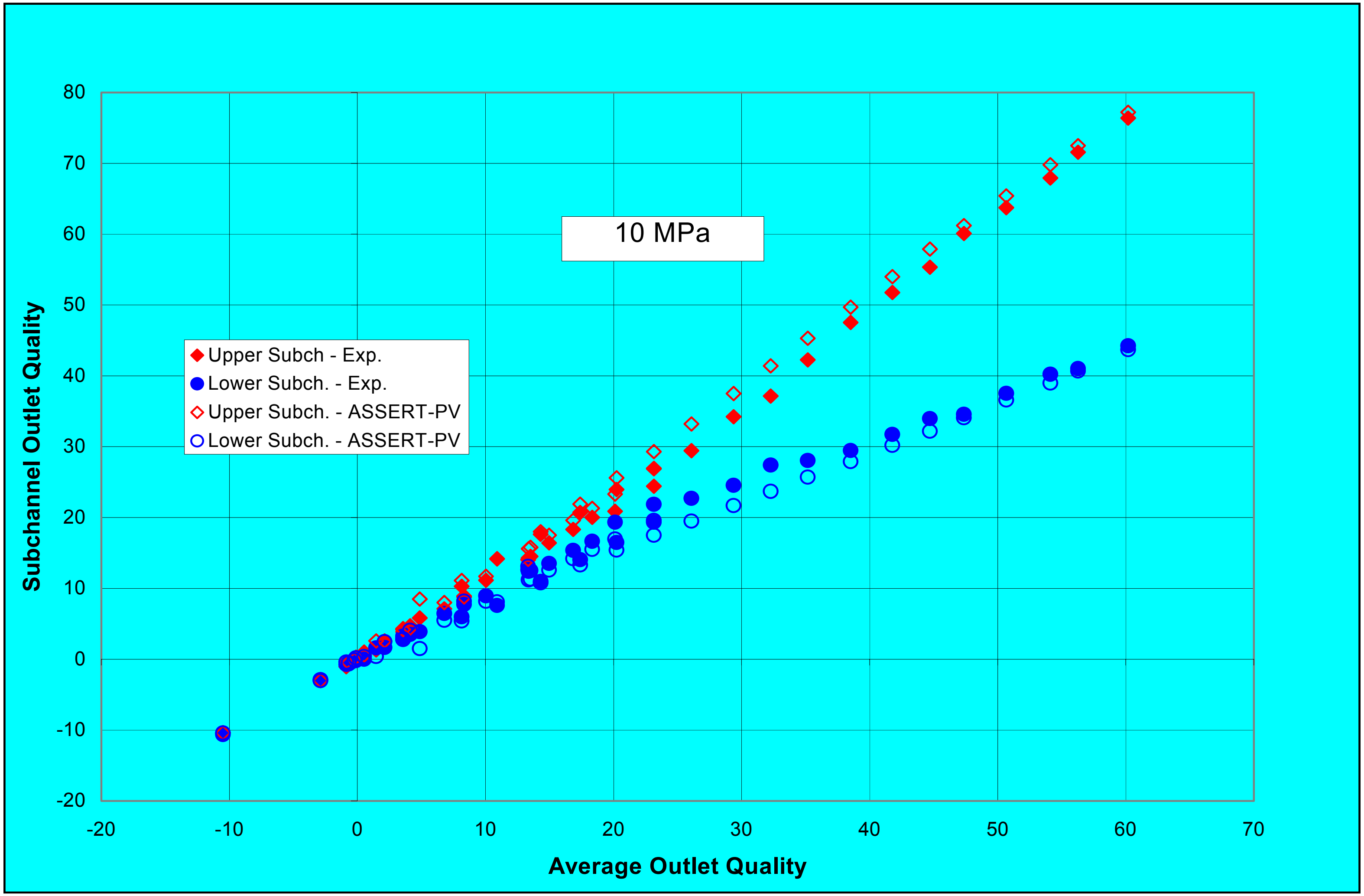
ASSERT-PV: Sample Calculations

Horizontal Two-phase Air-Water Flow in Twin Rectangular Subchannels

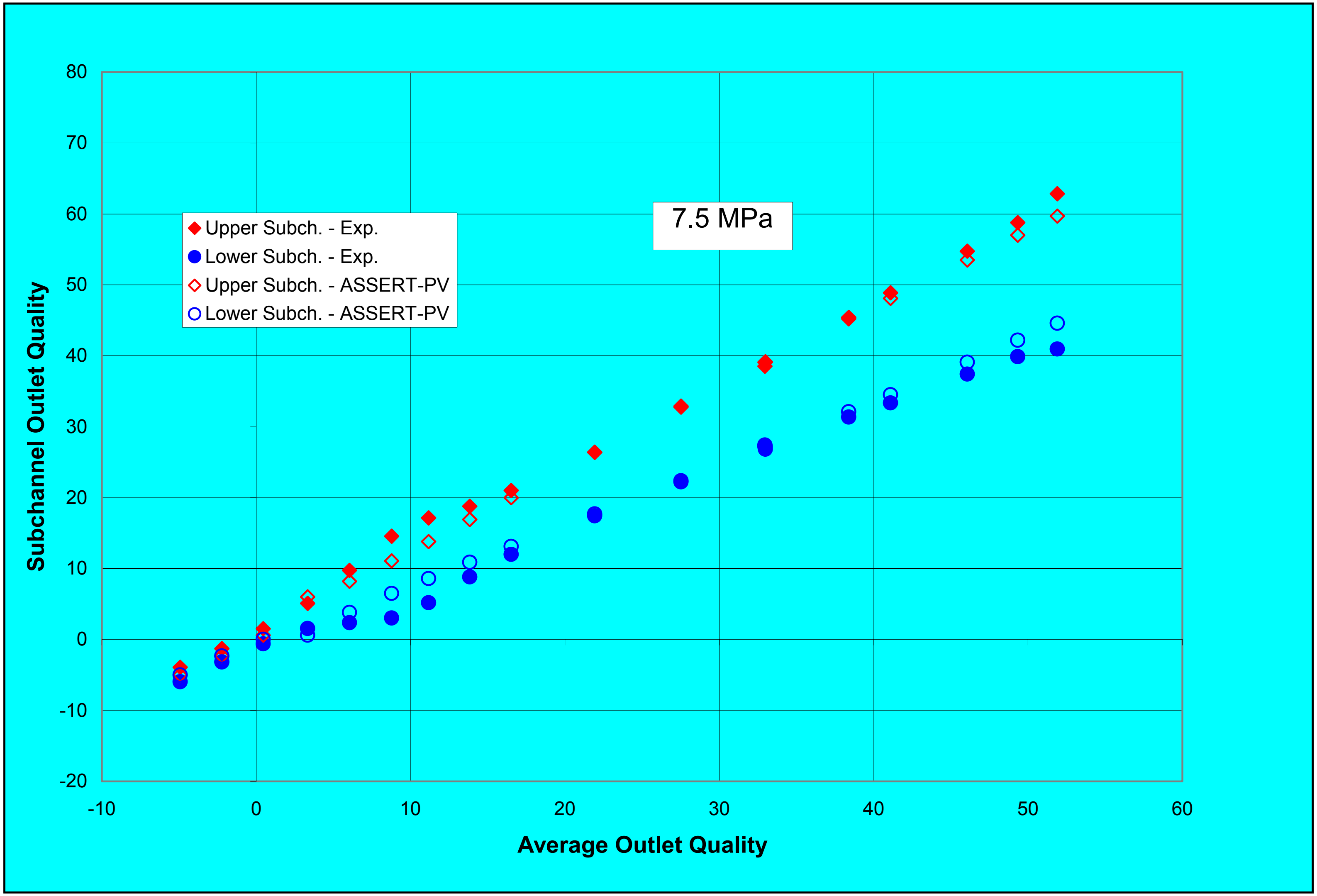




ASSERT-PV: Sample Calculations: Horizontal Twin-Subchannel Enthalpy Migration at High-Pressure Steam-Water Conditions

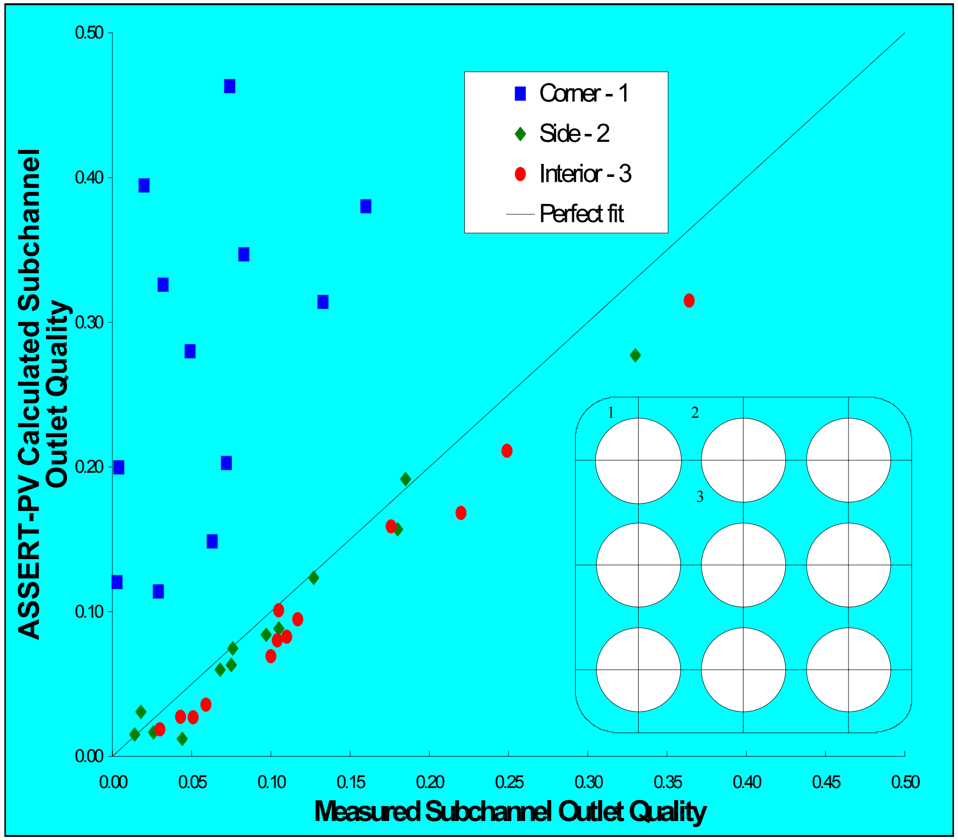


ASSERT-PV: Sample Calculations: Horizontal Twin-Subchannel Enthalpy Migration at High-Pressure Steam-Water Conditions

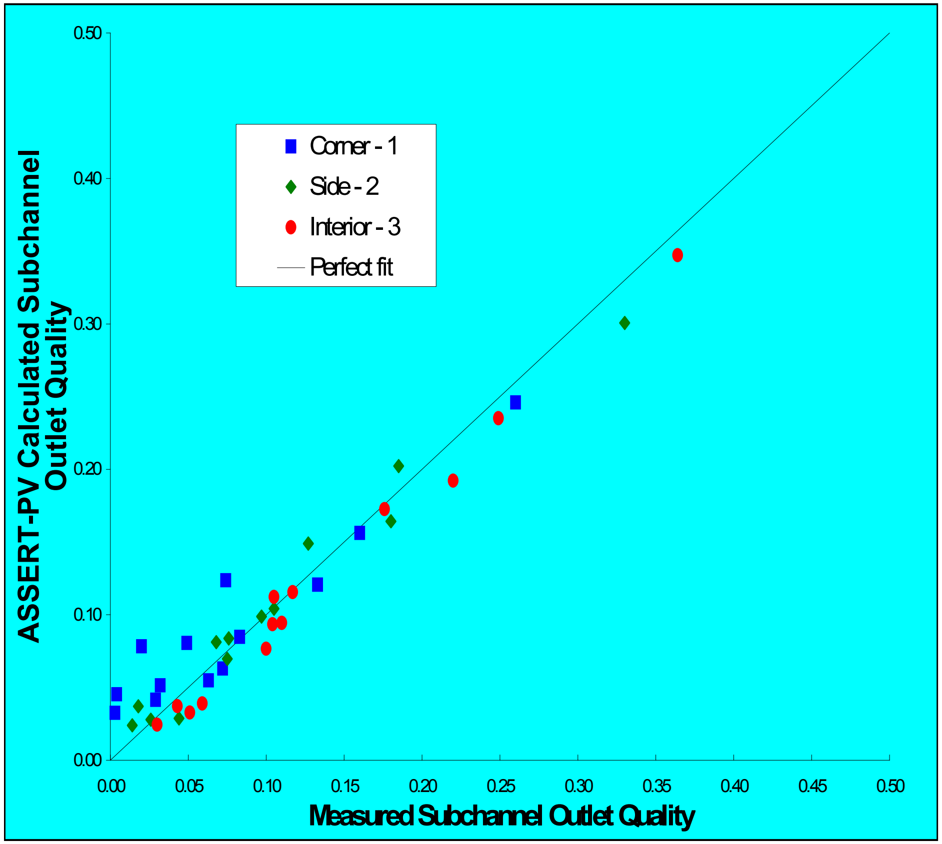


ASSERT-PV: Sample Calculations: Effects of turbulent mixing and void drift in outlet quality distribution in vertical four-rod bundle

(a) without turbulent mixing or void drift



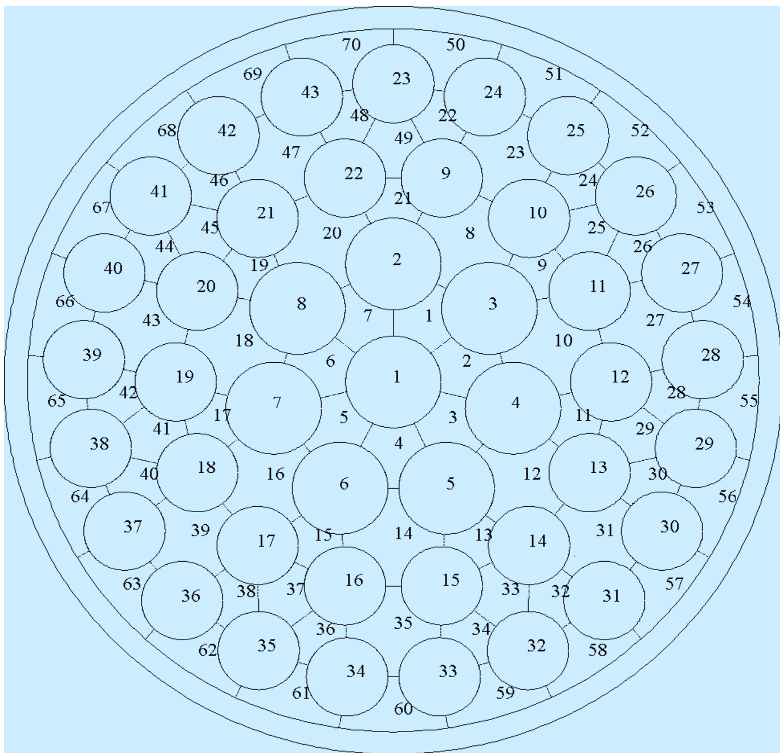
(b) with turbulent mixing and void drift

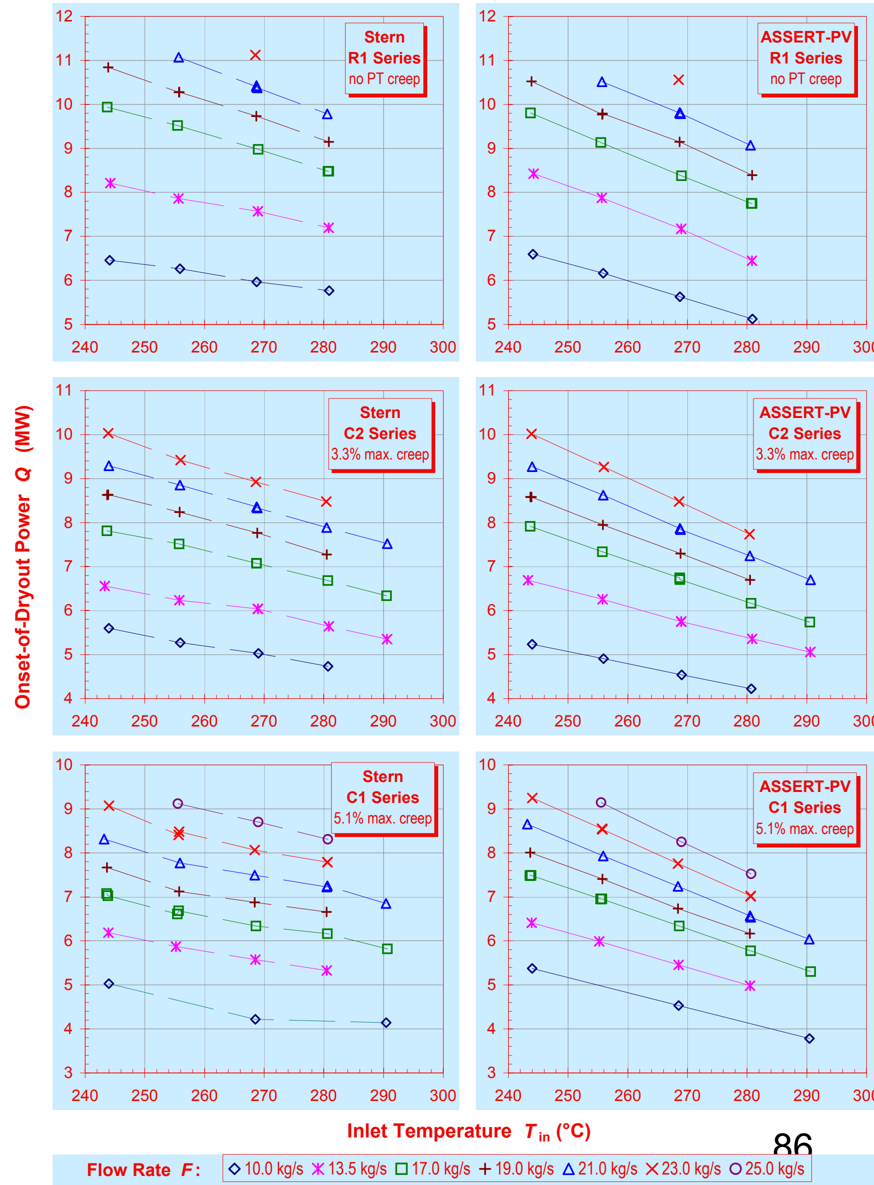


ASSERT-PV: Sample Calculations:

Dryout Power in Uncrept and Crept PTs

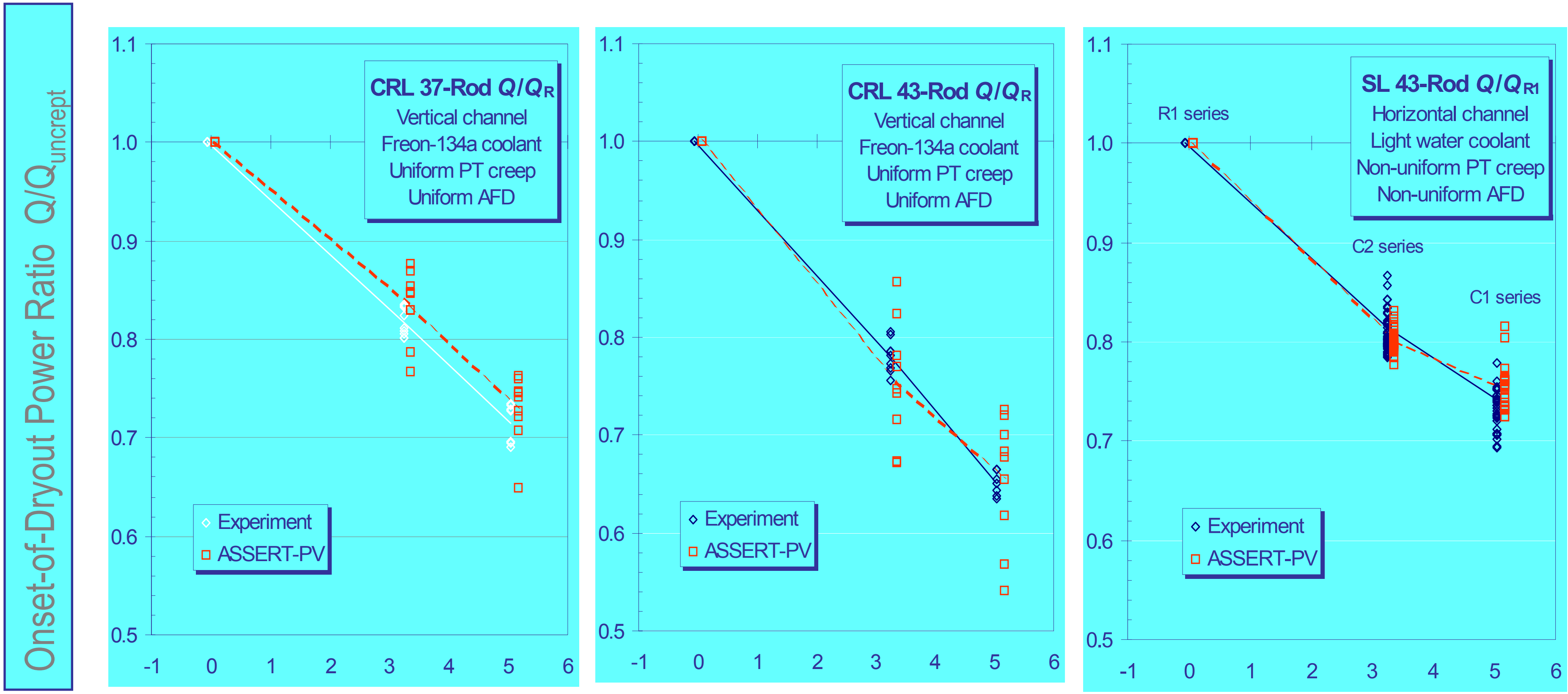
43-element bundle channel at 11 MPa
Left = experiment Right = ASSERT-PV





ASSERT-PV: Sample Calculations:

Effect of Pressure Tube Creep on Dryout Power



ASSERT-PV: Applications

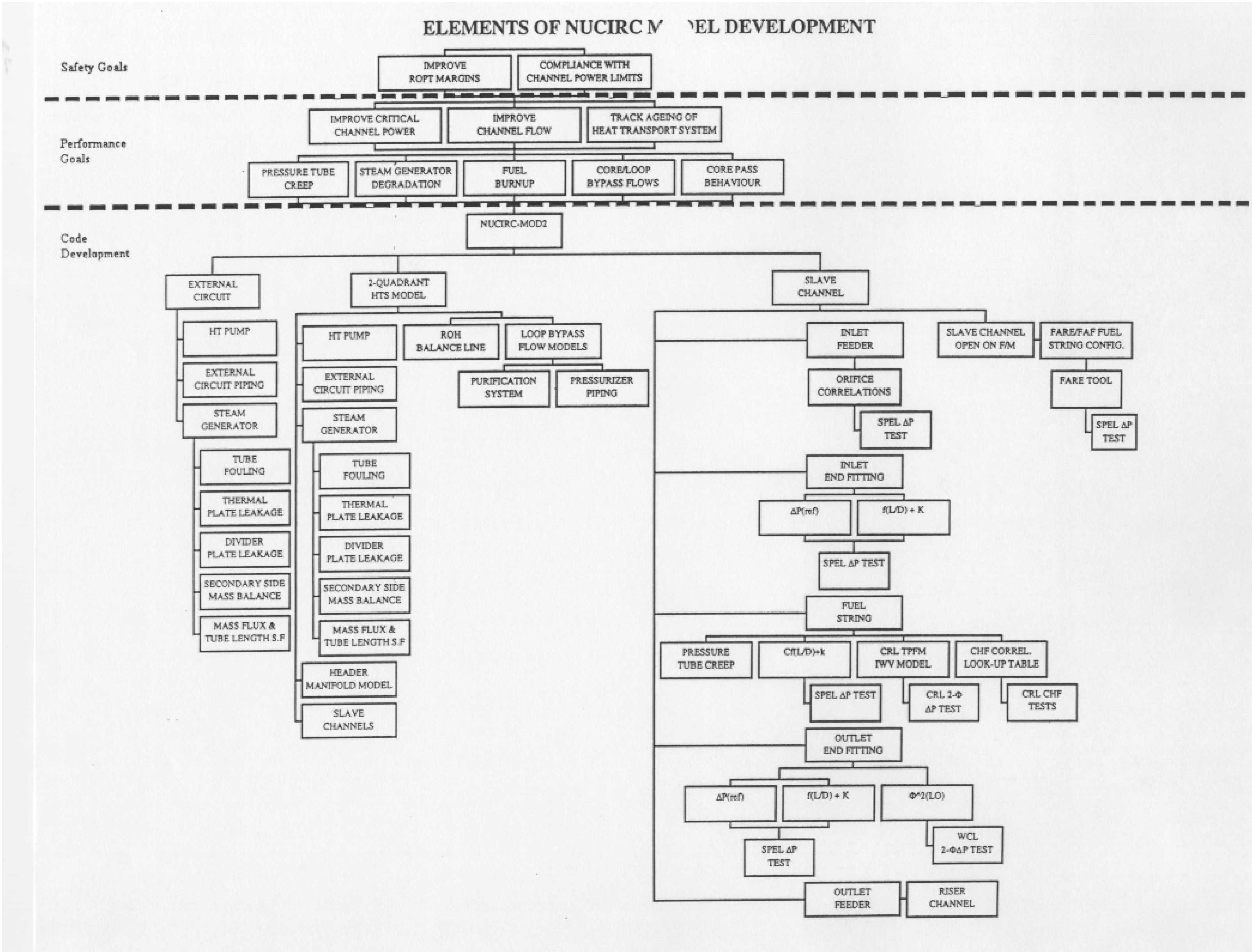
- **Assessment of thermalhydraulic performance of new fuel designs: e.g., effects of different radial (RFDs) and axial heat flux profiles (AFDs); CHF enhancements.**
- **Assessment of effects on thermalhydraulic performance of geometry variations resulting from manufacturing tolerances or operation: e.g., changes in fuel element diameter due to diametral creep or manufacture; changes in interelement spacer and bearing pad heights due to wear or design non-conformances; pressure tube creep.**
- **Sensitivity studies in support of NUCIRC development.**
- **Assessment of operational anomalies on channel thermalhydraulics, such as Point Lepreau wood and screw incident.**

- **Licensing support for CCP analysis.**

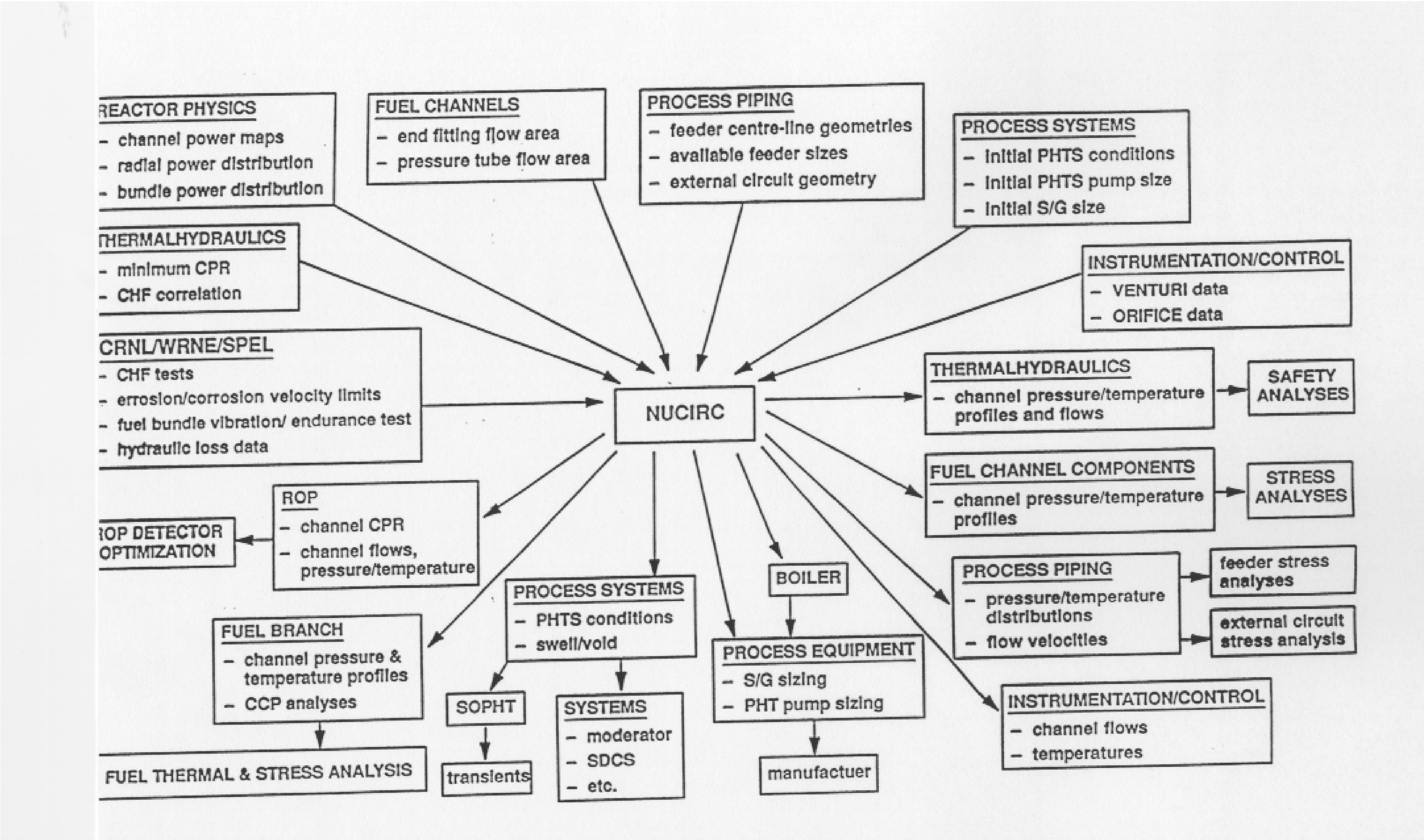
NUCIRC: Objective of NUCIRC Code

- Why do we need it?
  - Process and safety analysis
- What does it do?
  - Predict pressure, temperature, flow and quality for steady-state conditions of Primary Heat Transport System

NUCIRC: Elements of NUCIRC



NUCIRC: Code Interfaces



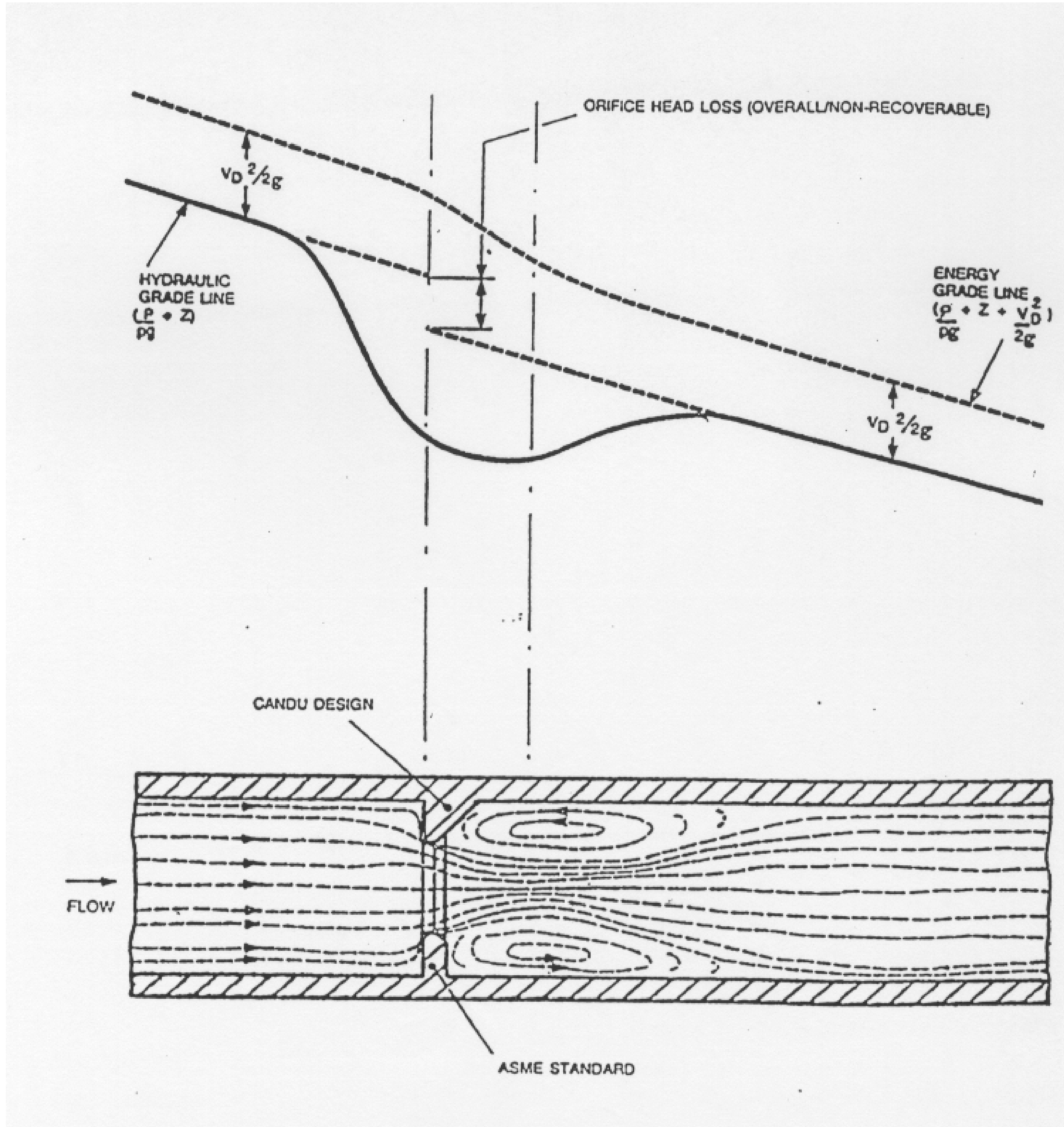
NUCIRC: Description

- 1-D cross-sectional averaged steady-state code
  - Full PHTS circuit model (Full Core including inlet and outlet feeders and channels, Headers, Pumps, Boilers, etc.)
  - Detailed calculation for pressure, flow, and temperature, in the channels
  - Determines Critical Channel Powers (CCP)
  - Capable of addressing BP/CP compliance issues
  - Provides assessment of plant aging issues
  - Provides boundary conditions and input data for other simulation codes (RFSP,THIRST,etc.)

NUCIRC: *CANDU Components*

- Fuel String
- End Fittings
- Feeders
- Headers
- Pumps
- Steam Generators
- Boundary Nodes

NUCIRC: Feeders



NUCIRC: Headers

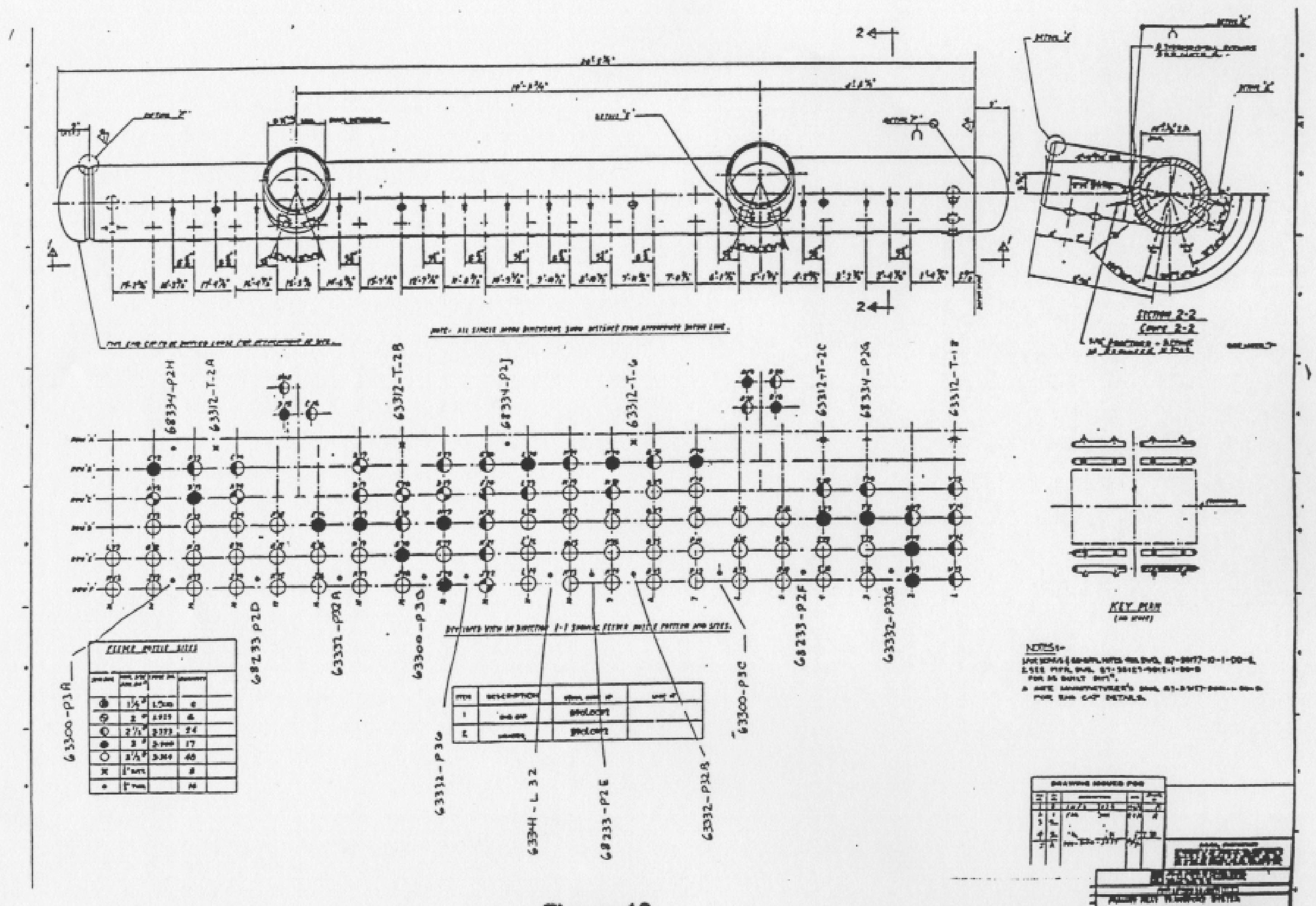
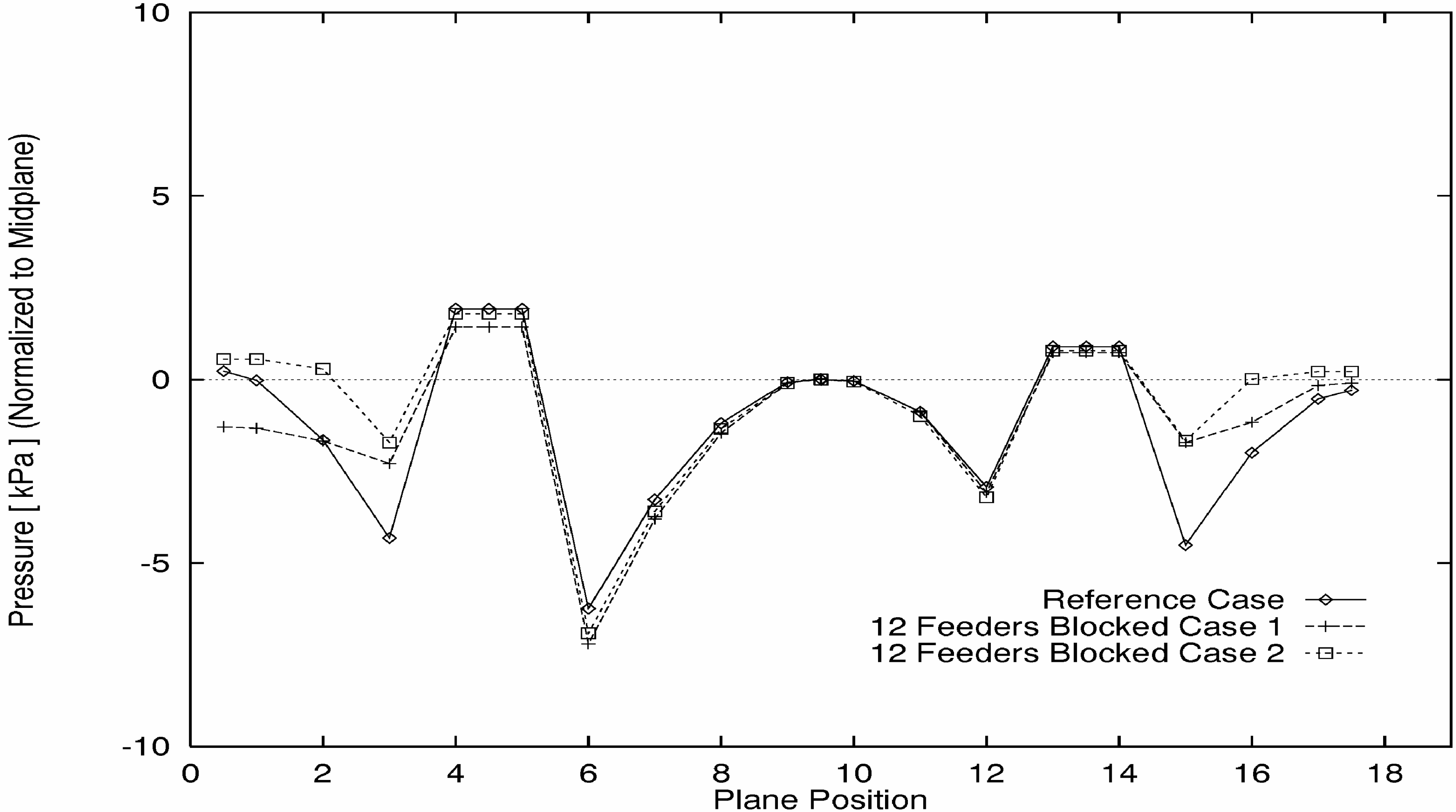


Figure 12
Pressure and Temperature Instrument Tap Locations on Outlet Header ROH3

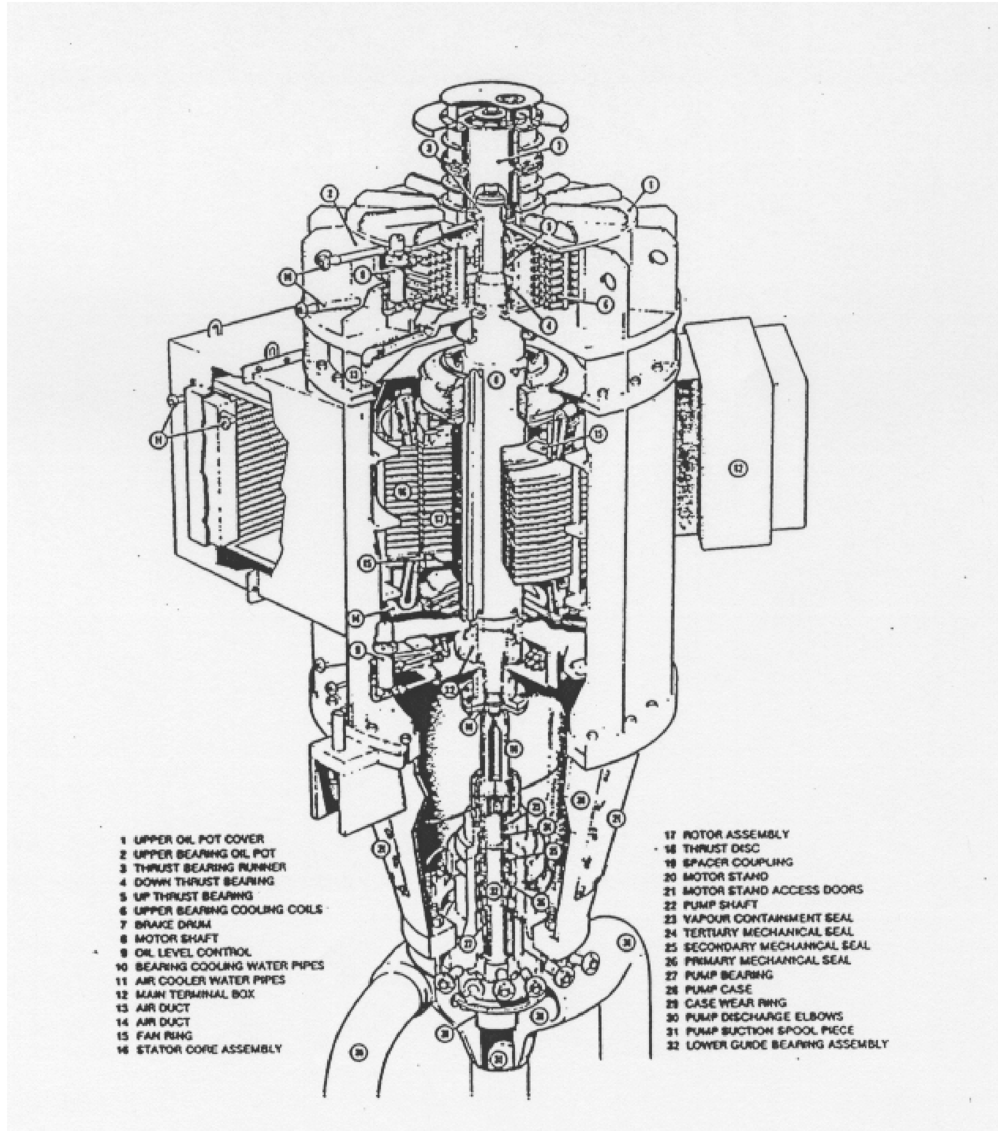
NUCIRC: Headers Manifold Behaviour

- CANDU 6 inlet/outlet headers are not constant pressure reservoirs
  - Constant header-to-header pressure drop for all channels
  - Header flow is irrelevant
- CANDU 6 headers behave as manifolds
  - Significant axial pressure gradients
  - Channel-specific header-to-header pressure drop
  - Skewed 3-D flow velocity distributions are important
- NUCIRC's 1-D header manifold model
  - Momentum-correction factors to account for skewed flow velocity distributions along header
  - Model parameters obtained from literature and/or derived from station data assessment
- CFD code: FLOW3D
  - Simulate CANDU 6 headers and provide detailed data to improve or introduce closure relationships in our 1-D header model

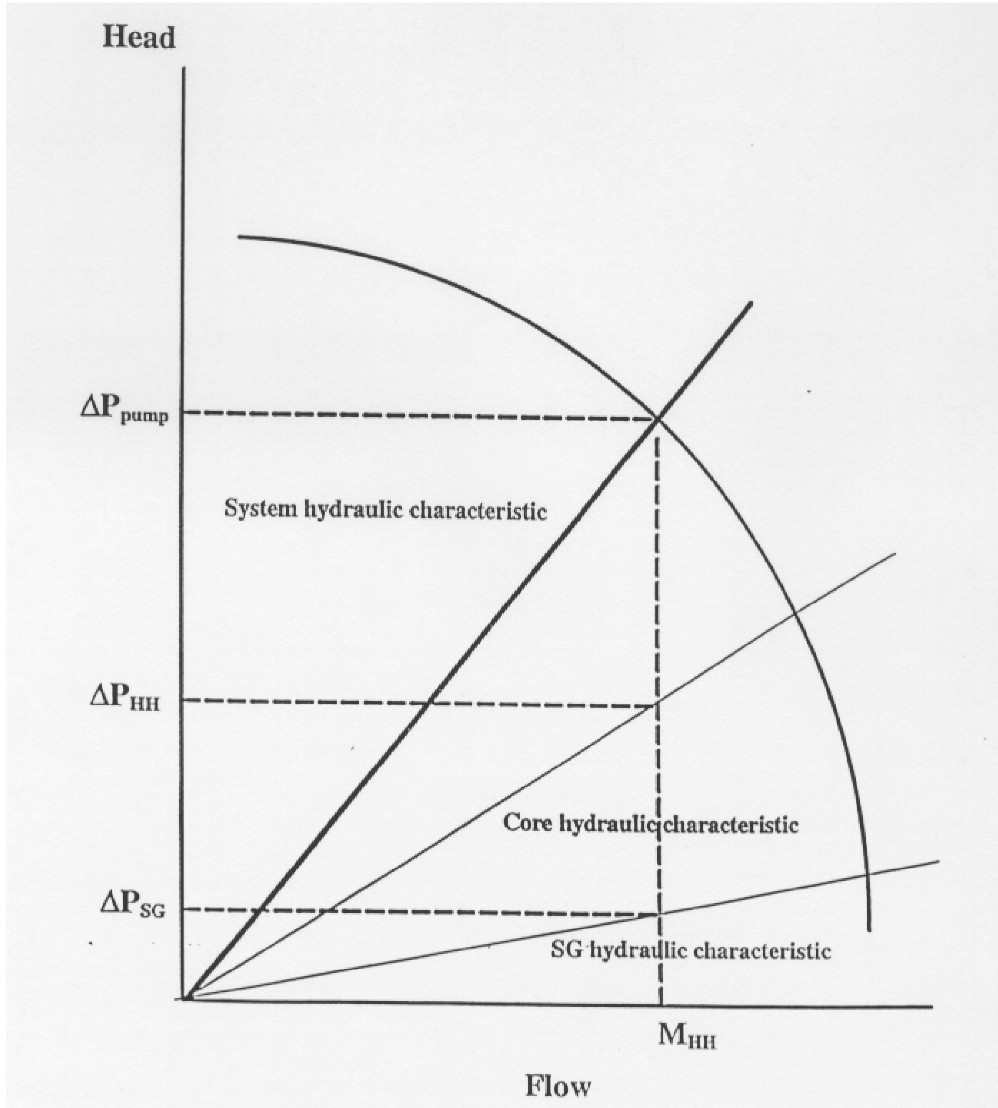
NUCIRC: Effect of Flow Blockage on the Header Axial Pressure Gradient of an Idealized Header



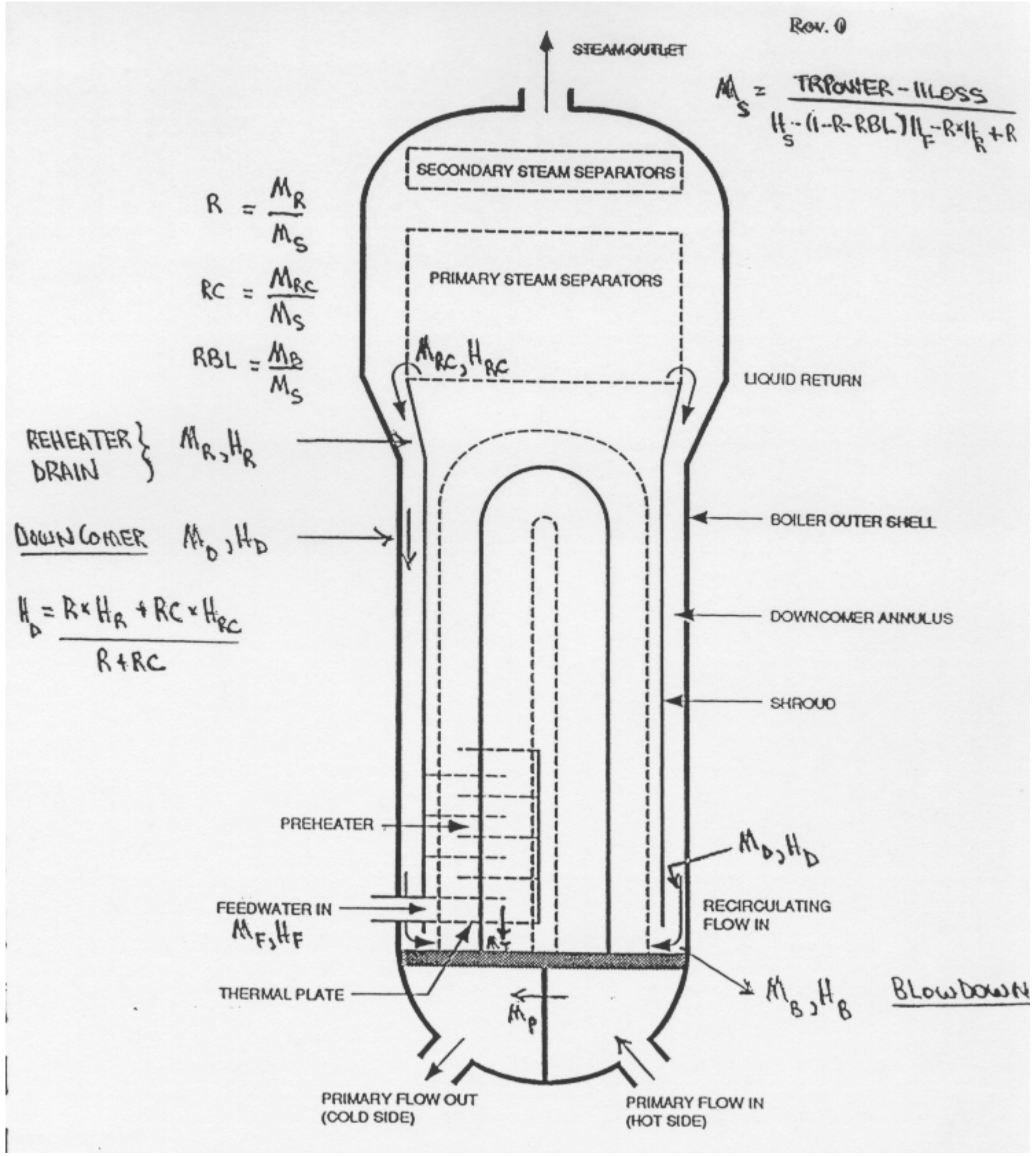
NUCIRC: Pumps



NUCIRC: Pump Behaviour



NUCIRC: Steam Generators



NUCIRC: NUCIRC Modules

- Modules are called “ITYPE”s.
  - Itype 1 : Slave channel for given flow
  - Itype 2 : Slave channel for given pressure drop
  - Itype 3 : Feeder sizing (Design)
  - Itype 4 : 1 Quadrant circuit model (No longer recommended)
  - Itype 5 : Refuelling slave channel
  - Itype 6 : 2 Quadrant circuit model
  - Itype 7 : External circuit model
  - Itype 8 : Purification model
  - Itype 9 : Pressurizer piping model

NUCIRC: Itype 1

- Objectives
  - Calculate Header to Header pressure drop
  - Calculate Critical Channel Flow
- Components
  - Inlet feeder, outlet feeder, fuel channel, and end fittings
- Boundary Conditions
  - feeder geometry
  - channel mass flow rate
  - channel power
  - inlet header temperature
  - outlet header pressure

NUCIRC: Itype 2

- Objectives
  - Calculate Channel Flow
  - Calculate Critical Channel Power
- Components
  - Inlet feeder, outlet feeder, fuel channel, and end fittings
- Boundary Conditions
  - feeder geometry
  - header to header pressure drop
  - channel power
  - inlet header temperature
  - outlet header pressure

NUCIRC: Itype 5

- Objectives
  - Calculate Channel Flow
  - Calculate Critical Channel Power
  - Accounts for refuelling operation
- Components
  - Inlet feeder, outlet feeder, fuel channel, and end fittings
- Boundary Conditions
  - feeder geometry
  - header to header pressure drop
  - channel power
  - inlet header temperature
  - outlet header pressure
  - F/M injection flows and temperatures

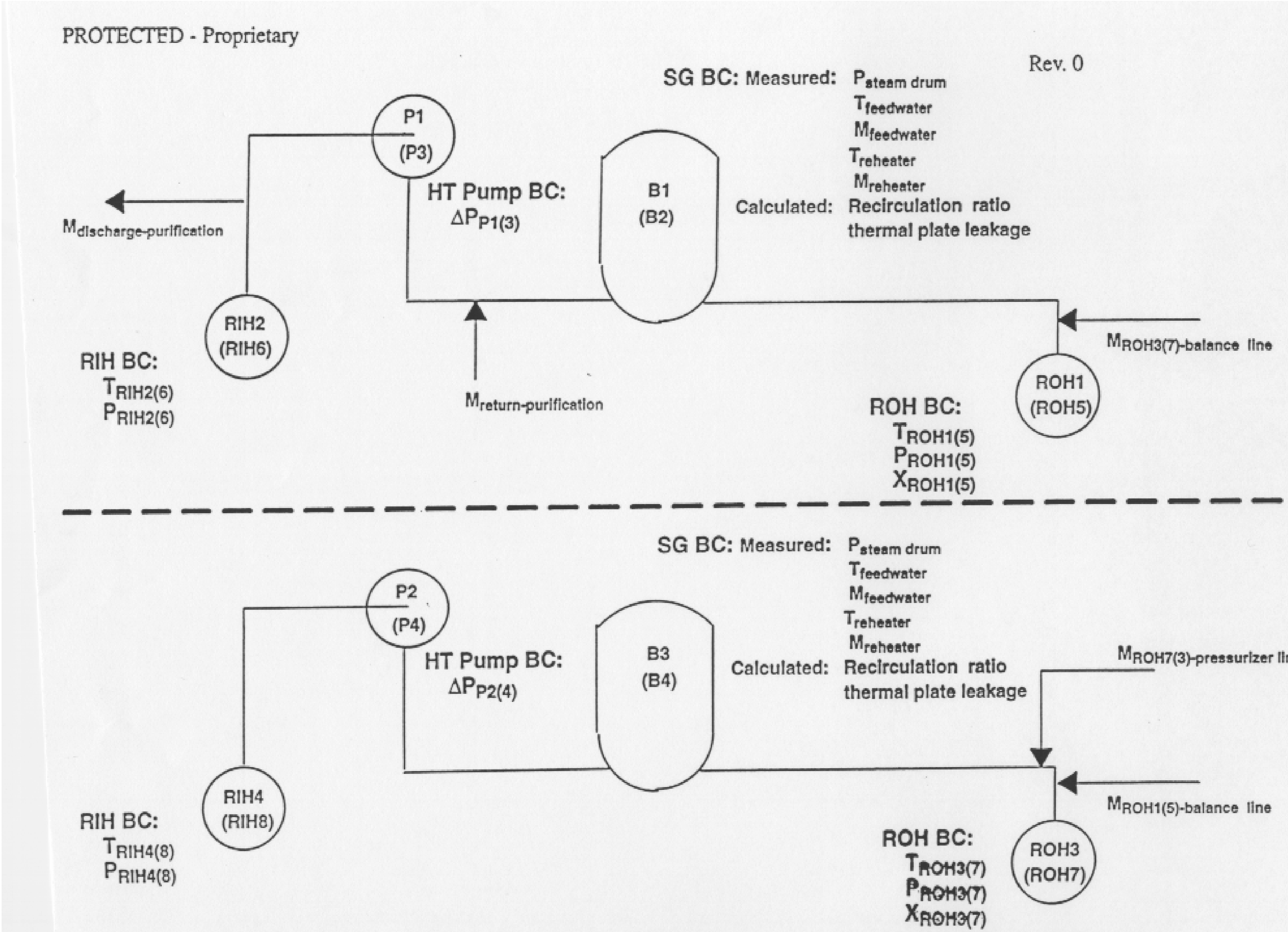
NUCIRC: Itype 6

- Objective
  - Calculate full circuit pressure, temperature, flow, and quality distributions
- Components
  - All main HTS components
- Boundary Conditions
  - HTS geometry
  - Pressurizer junction pressure
  - Steam Generator secondary side conditions
  - Reactor power
  - Auxiliary system boundary conditions

NUCIRC: Itype 7

- Objective
  - Calculate pressure, temperature, flow, and quality distribution from ROH to RIH
- Components
  - Steam Generator
  - Pump
  - External circuit piping
- Boundary Conditions
  - External circuit/SG geometry
  - RIH/ROH pressures and temperatures
  - Steam Generator secondary side conditions
  - Auxiliary system boundary conditions

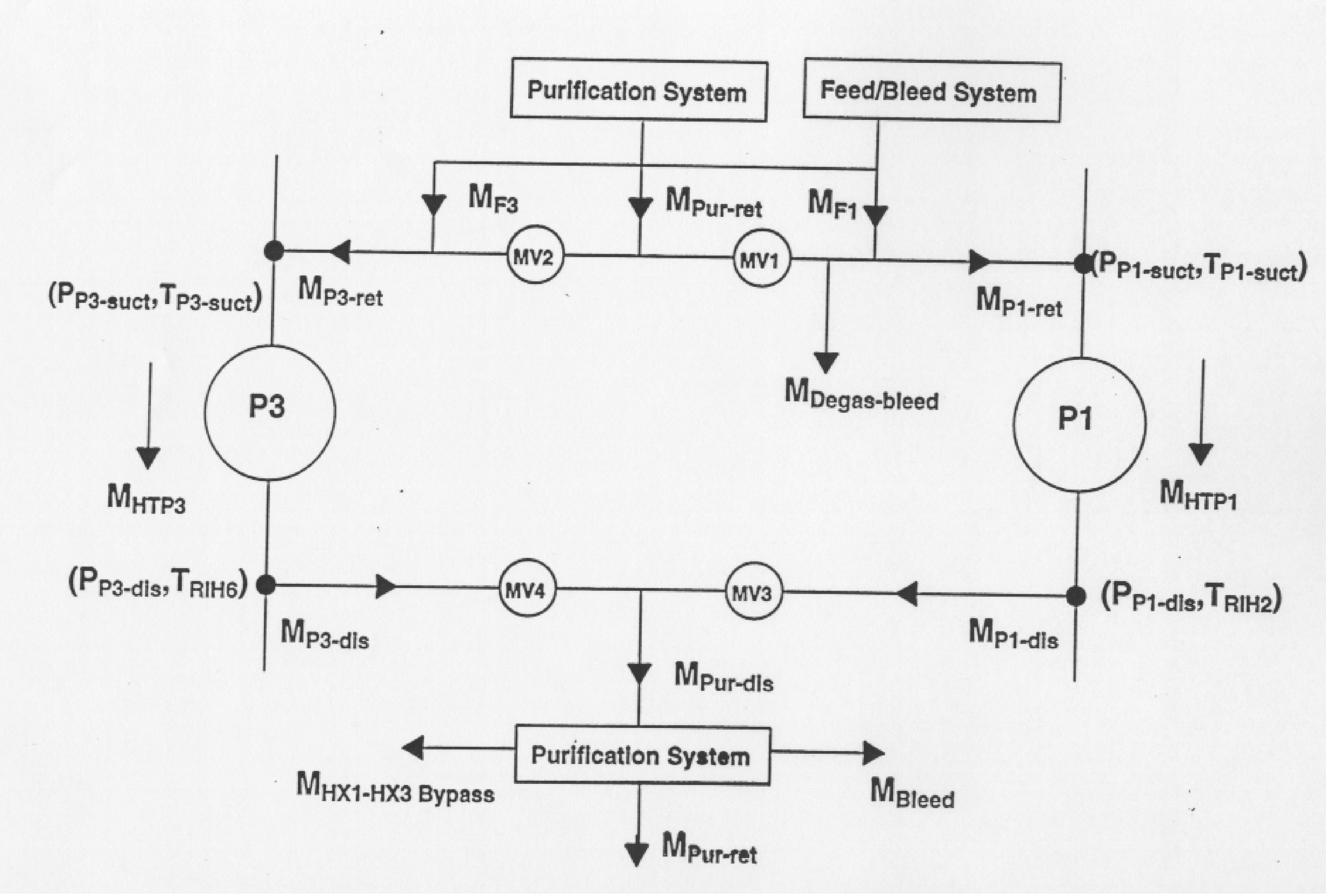
NUCIRC: Itype 7 (cont'd)



NUCIRC: Itype 8

- Objective
  - Calculate flow distribution to and from HTS due to purification
- Components
  - HTS Boundary Nodes
  - Purification piping
- Boundary Conditions
  - Purification piping geometry
  - Pump pressures and temperatures
  - Purification flows and temperatures
  - Feed/bleed and De-gas flows and temperatures

NUCIRC: Itype 8 (cont'd)



NUCIRC: Itype 9

- Objective
  - Calculate flow through pressurizer line
- Components
  - Pressurizer line piping connecting both loops
- Boundary Conditions
  - Pressurizer line geometry
  - ROH pressures and temperatures

NUCIRC: Itype 9 (cont'd)

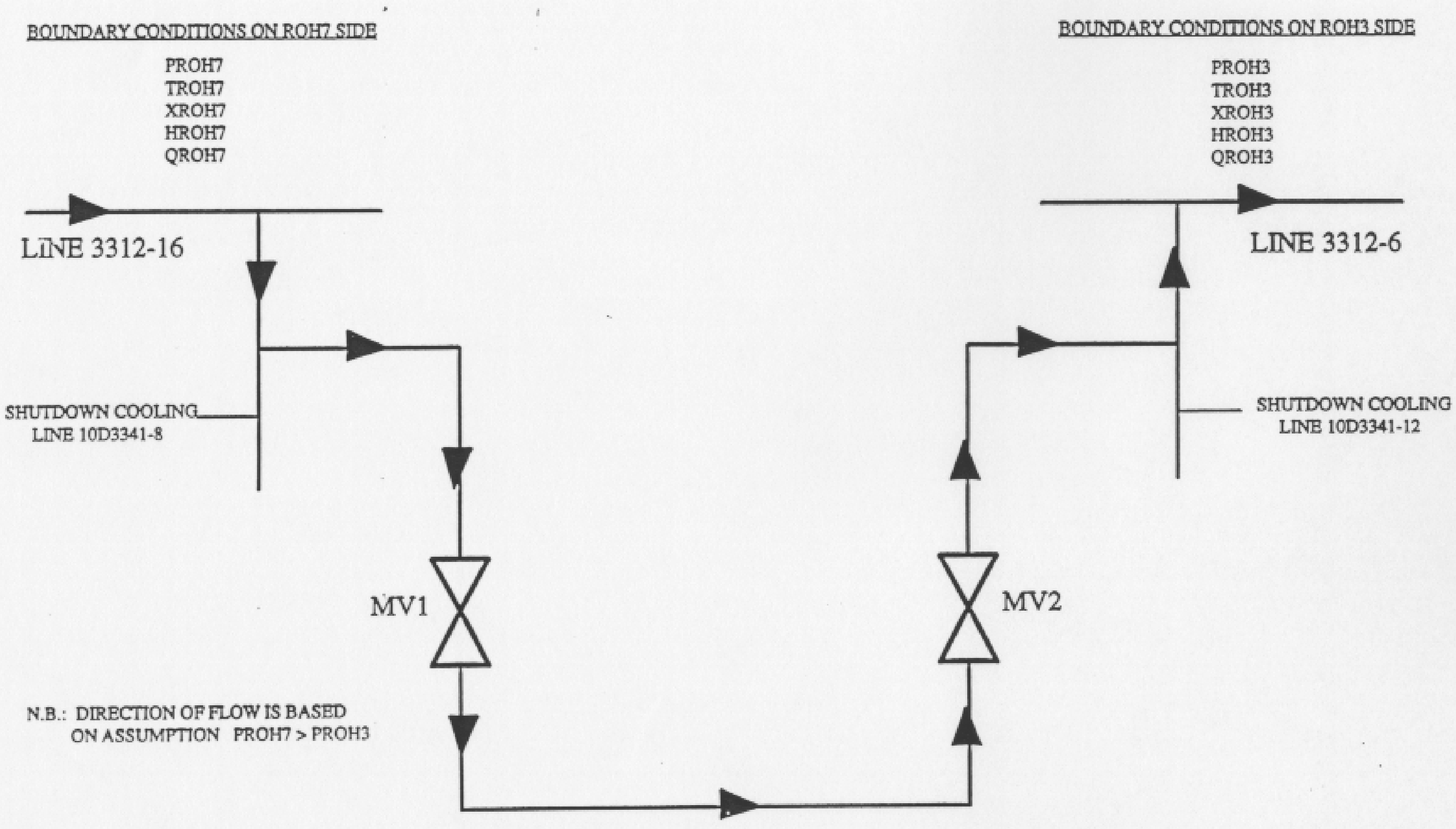


Figure 4 Common Pressurizer Piping Between ROH3 and ROH7

NUCIRC: Operating States

- 0.0% FP Cold
- 0.0% FP Hot
- Reduced Power
- Full Power
- +/- Fuel
- Refuelling

NUCIRC: 0.0%FP Cold

- Entire PHTS at cold condition (~40 C) due to shut down cooling valved in.
- Usual state during which ultrasonic flows are measured.

NUCIRC: 0.0%FP Hot

- Entire PHTS at hot condition (>100 C) due to shut down cooling valved out.
- Usual state just before start-up of reactor core.

NUCIRC: Reduced Power

- Entire PHTS at hot condition (Trih ~ 263 C). Reactor power between 75% and 80%. No boiling in core.
- Usually state used at Gentilly-2 and Point Lepreau for assessment of flow verification. Monthly (G2) or quarterly (PL) power reductions are performed so that the heat balance flows can be determined.
- Power is usually reduced, the system is allowed to stabilize, and then returned to full power.

NUCIRC: Full Power

- Entire PHTS at hot condition (Trih ~ 265 C). Reactor power at or near 100%. Boiling is present in some channels in core.
- Usual operating state for CANDU stations.
- Boundary Conditions for CCP analysis.

NUCIRC: Pre-Requisites

- Site data
  - Process Boundary Conditions
  - Bundle Powers (Physics Code)
  - Diametral creep profiles
- Site model
  - Type of steam generators
  - Pump curves
  - Type of station (CANDU 6 vs. CANDU 9)

NUCIRC: NUPREP (Pre-processor)

- Full circuit and Slave channel models for all 380 channels is a large data file. Most information required in the NUCIRC input deck is generic from case to case.
- NUPREP is a pre-processor code used to generate NUCIRC files from a selection of NUPREP files.

NUCIRC: NUPREP Interfaces

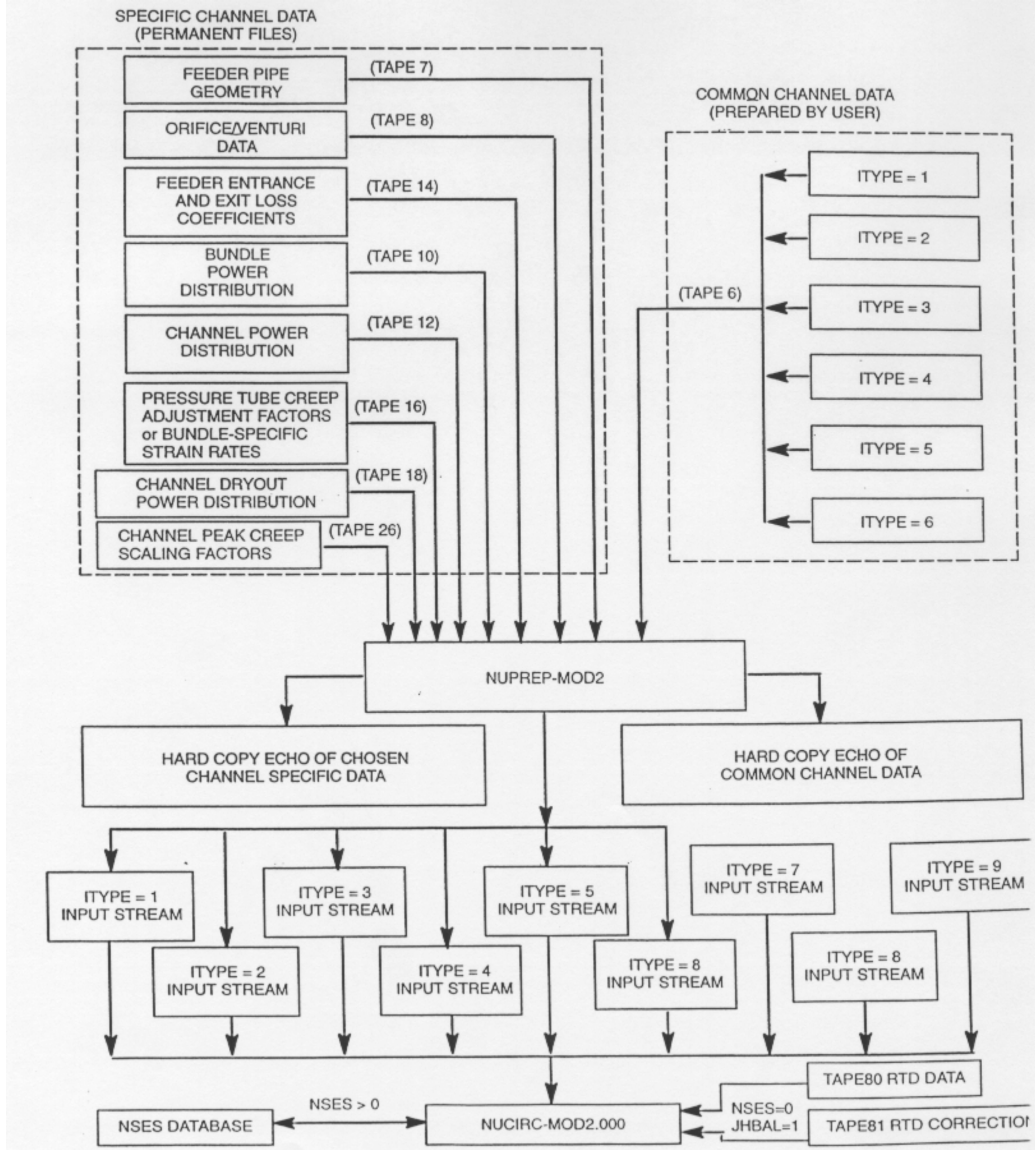


Figure 7
Data Flow Logic Between NUPREP-MOD2.000 and NUCIRC-MOD2.000

Questions?