Modeling of A Power Conversion System with RELAP5-3D and Associated Application to Feedwater Blowdown Licensing Analysis for the LungMen ABWR Plant

Prepared by: Thomas K.S. Liang

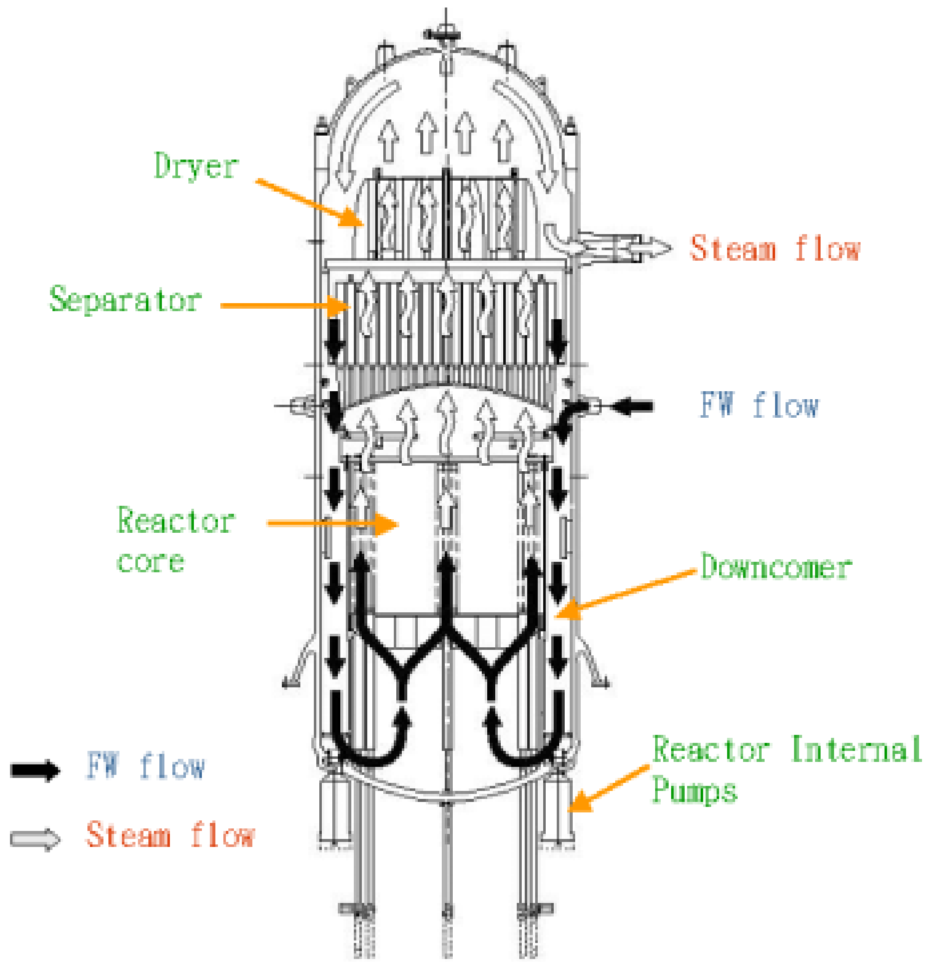
Institute of Nuclear Energy Research, Taiwan

Contents

Introduction

- *Conventionally, the limiting break for BWR containment design is the recirculation line break.*
- *In the ABWR design, the jet pumps driven by the recirculation loops are replaced by the reactor internal pumps (RIPs).*
- *As a result, the limiting break for ABWR containment design shifts to the Feedwater Line Break (FWLB).*

Introduction

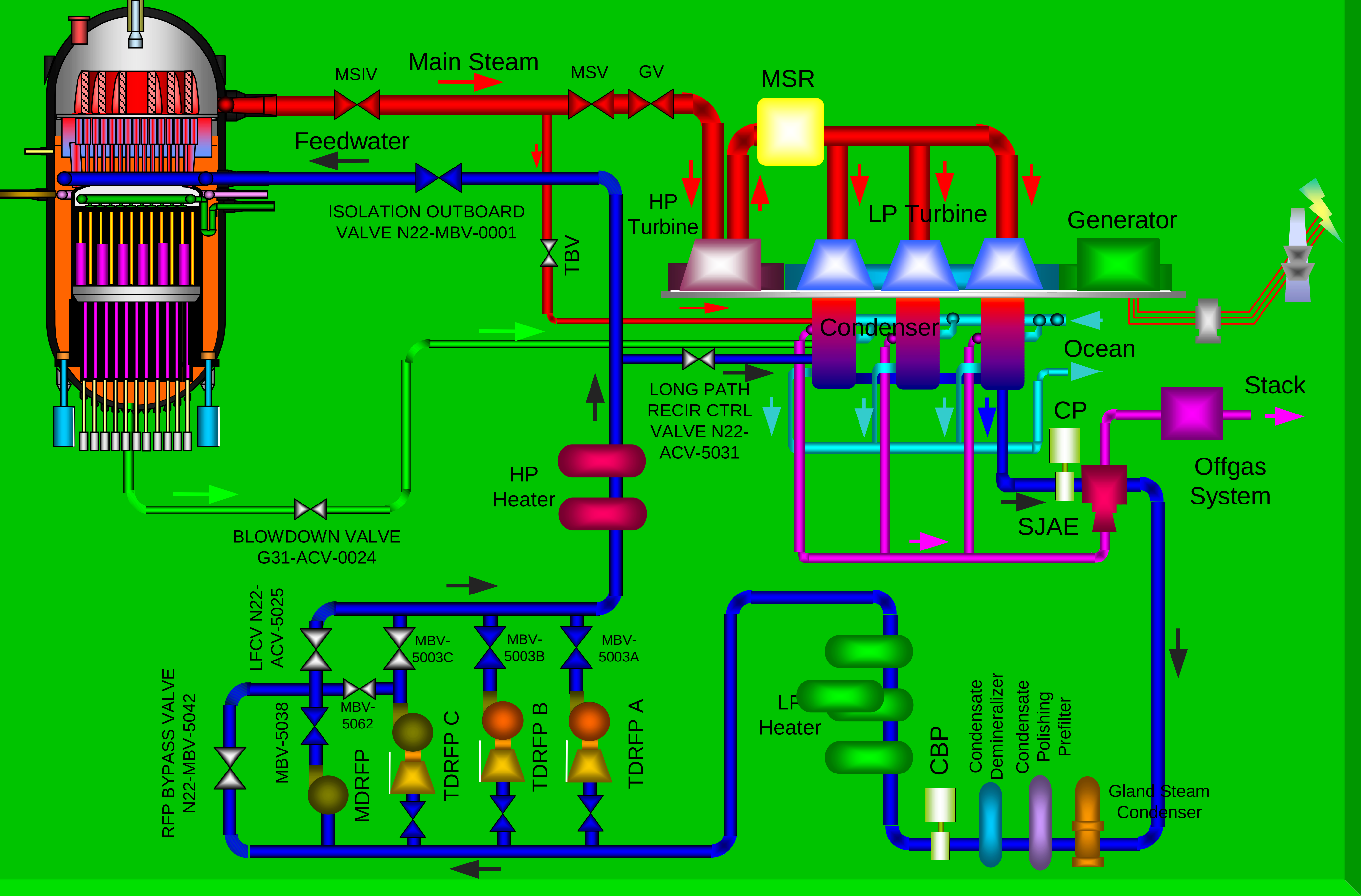


Reactor Design of Typical ABWR

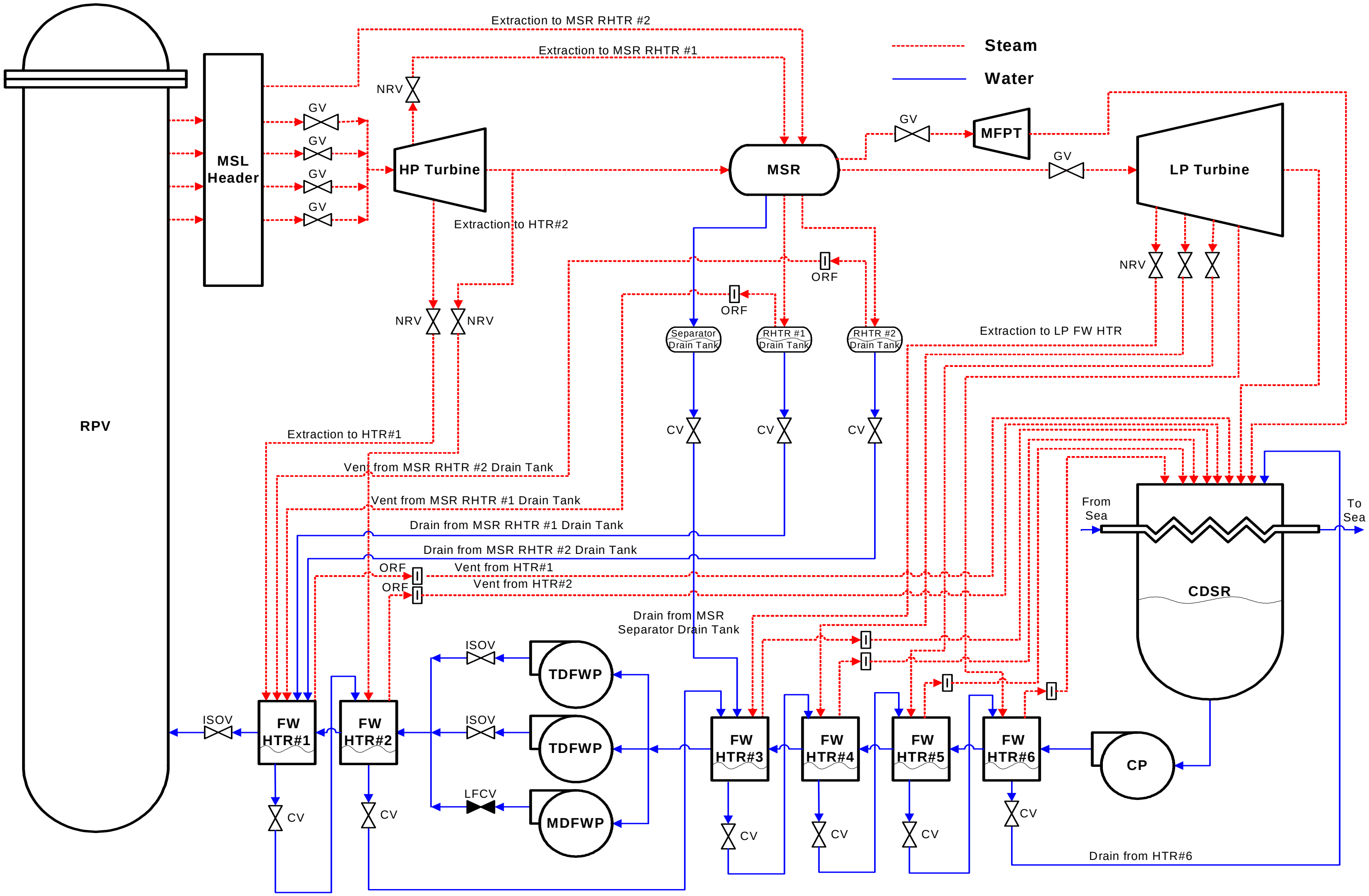
Introduction

- *The licensing analysis of FW line break with RELAP5-3D/K , and the RELAP5-3D/K is an Appendix K version of RELAP5-3D.*
- *To adequately calculate the blowdown flow and enthalpy for the event of FW line inboard break, the BOP modeling scope includes all the necessary components and systems.*
  - Main feedwater system;
  - Main condainson;
  - Main steam system
  - Main turbine system
  - Turbine driven feedwater pumps

Modeling Scope for Feedwater Line Break Analysis



Introduction



NPP4 System Simulation Diagram

Event Description

- *For the event of FWLB, blowdown flow and enthalpy from both RPV & BOP are the most essential parameters to be calculated.*
- *The early BOP blowdown flow will be limited by choking at either the break end or the internal venturi.*
- *The early FW blowdown will drive more extraction steam from MS system to FW heaters.*
- *As a result of MSIV isolation during the early blowdown stage, the steam supply cannot be maintained and steam pressure will drop rapidly.*
- *After the run out and coast down of FW pumps, the condensate and booster pumps will continuously pump water from condenser to the break thereafter by conservative assumption.*

Event Description

- *To adequately analyze the break events, all essential phenomena involved in the FW blowdown process need to be adequately simulated. Those phenomena include :*
  - critical flow at the break and the internal venturi,
  - flashing of FW near the break,
  - run out and coast down of the FW pumps,
  - steam extraction to FW heaters and FWP turbines,
  - flashing of saturated water initially stored inside the FW heater shell sides and drain tanks,
  - energy release from saturated water and system metal to the FW, and
  - cold water transportation from the main condenser to the break.

Modeling Description

- *All components of MS and FW systems are modeled and integrated by system piping to form a completed power conversion system.*
- *Detailed system design data is applied to develop the model for each component and associated piping.*
- *The simulated initial system conditions at rated state will be compared against associated parameters from Thermal Kit and/or Process Flow Diagram (PFD) of Lungmen plant.*
- *Totally 299 nodes and 277 junctions are involved in the entire BOP simulation scope.*

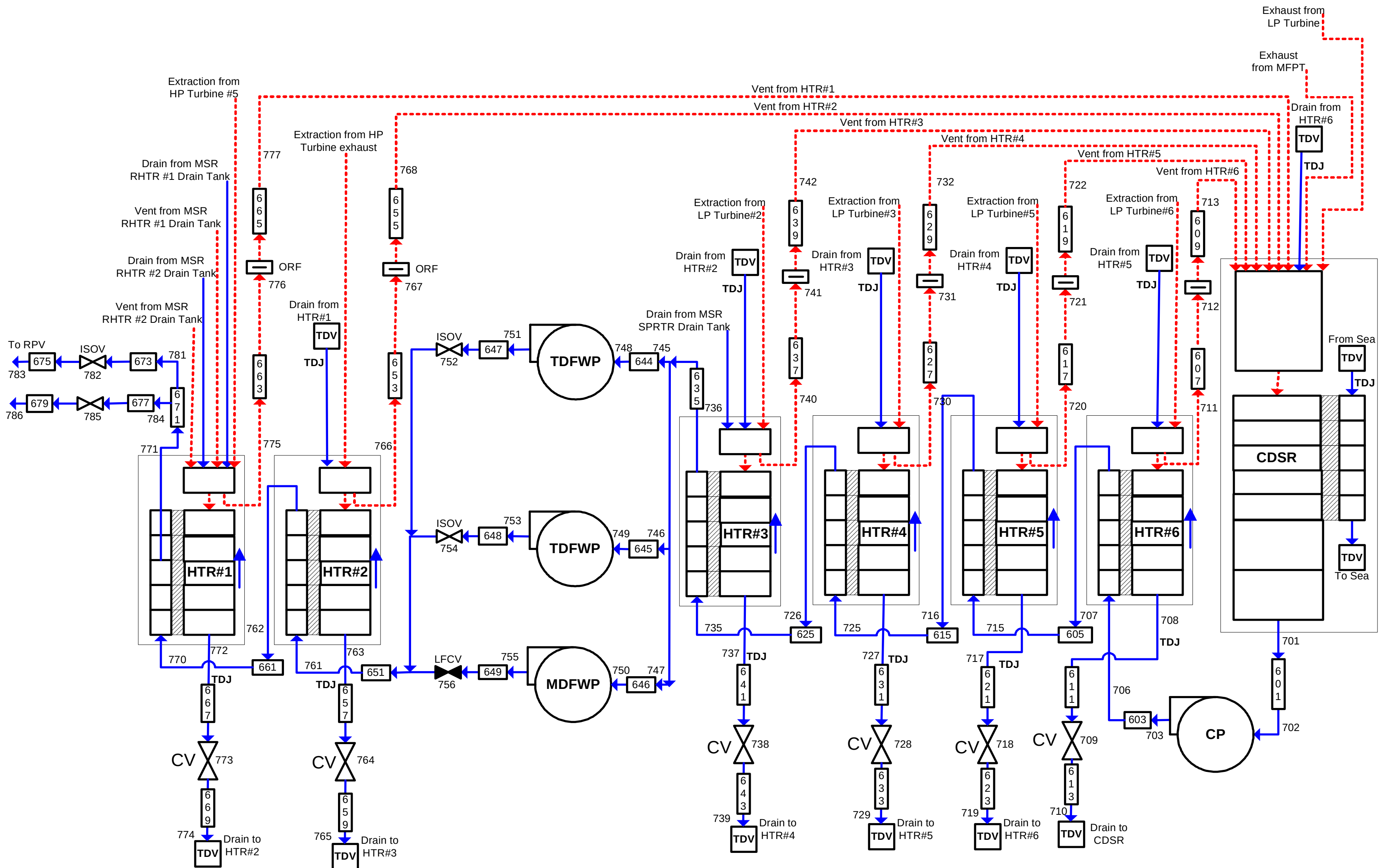
Modeling Description

-FW System Modeling-

- *Total of 158 hydraulic volumes and 151 junctions are involved in modeling of the FW system.*
- *The components of the FW system modeling include :*
  - FW pumps (FWPs) and driving turbines;
  - FW heaters;
  - condensate and booster pump;
  - main condenser; and
  - system piping.

Modeling Description

-FW System Modeling -



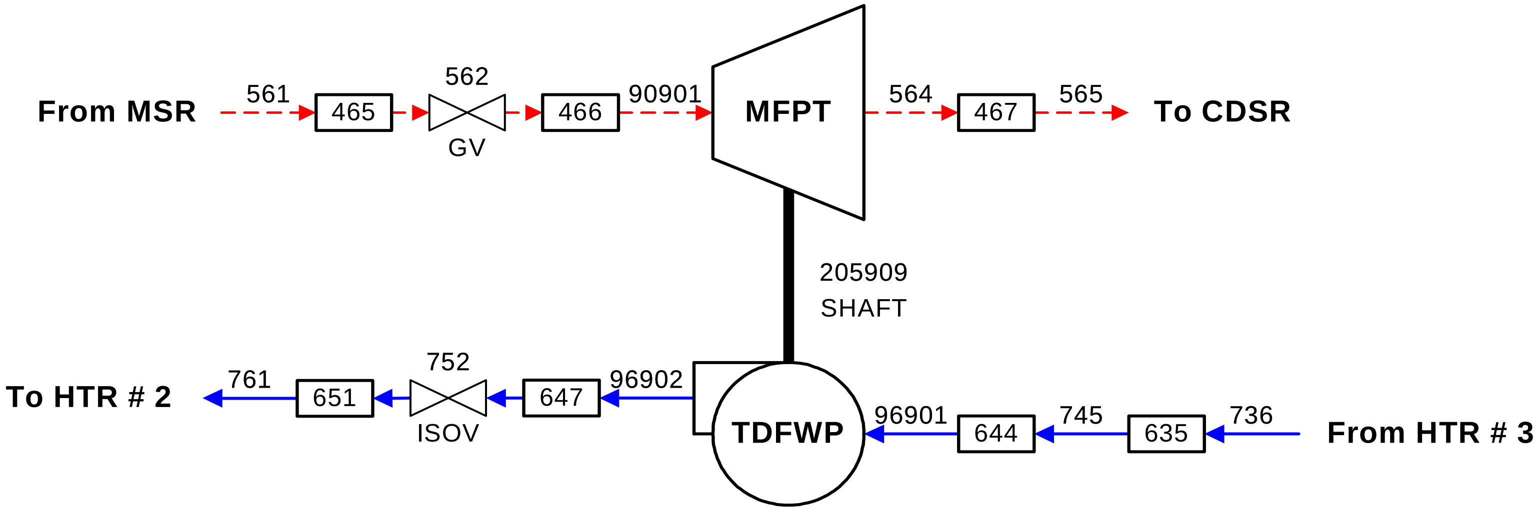
Modeling Description

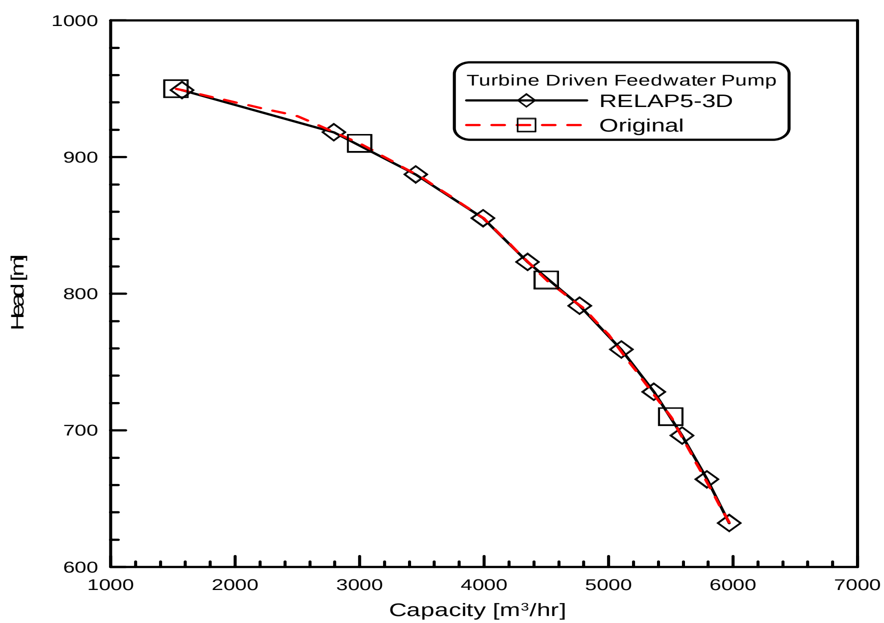
-FW System Modeling -

- *Pump design curves at run out speed 5350 rpm are used to simulate the pump characteristics.*
- *Since each FWP is driven by a FWP turbine, the modeling of FWP turbine with a shaft to connect FWP is also included.*
- *The rotation speed of the whole FWP module will be determined by the angular momentum conservation applied on the shaft connecting associated turbine and pump.*

$$\sum_i I_i \frac{d\omega}{dt} = \tau_T - \tau_P - f * \omega$$

Modeling Description
-FW System Modeling -





Modeling Description

-FW System Modeling -

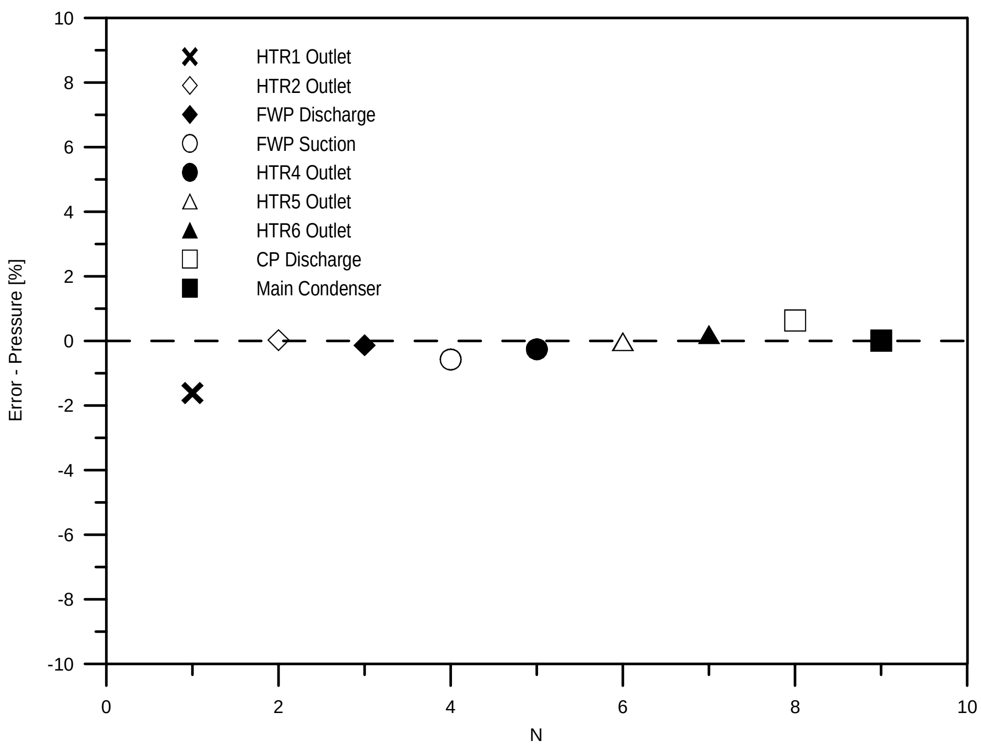
Error Analysis of Initial Conditions of Feedwater System at Rated Condition

Pressure [MPa]	Rated Value	Initial Value	Error [%]
89001 (Main Condenser)	**0.0059260**	**0.0059265**	**0.008**
821 (HTR4 Outlet)	**3.2603000**	**3.2518800**	**-0.258**
651 (FWP Discharge)	**8.1633000**	**8.1523100**	**-0.135**
671 (HTR1 Outlet)	**7.8143000**	**7.6884300**	**-1.611**
Temperature [K]	Rated Value	Initial Value	Error [%]
813 (HTR6 Inlet)	**309.95**	**309.20**	**-0.242**
824 (HTR3 Outlet)	**423.85**	**421.81**	**-0.481**
830 (HTR1 Outlet)	**488.75**	**487.36**	**-0.284**
Mass Flow Rate [kg/s]	Rated Value	Initial Value	Error [%]
706 (HTR6 Inlet)	**2122.306**	**2121.700**	**-0.029**
716 (HTR4 Inlet)	**2122.306**	**2121.700**	**-0.029**
771 (HTR1 Inlet)	**2122.306**	**2121.700**	**-0.029**
Pump Speed [rad/s]	Rated Value	Initial Value	Error [%]
969 (TDFWP-A)	**515.22**	**516.10**	**0.171**

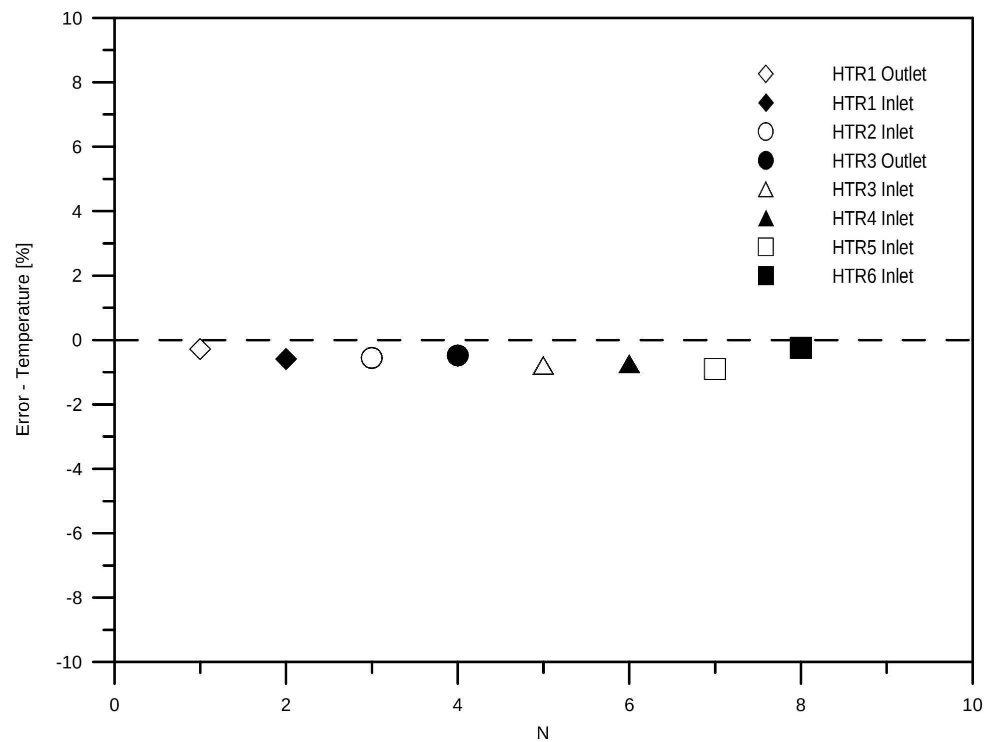
Modeling Description

-FW System modeling -

Error Analysis of Pressure Distribution



Error Analysis of Temperature Distribution



Modeling Description

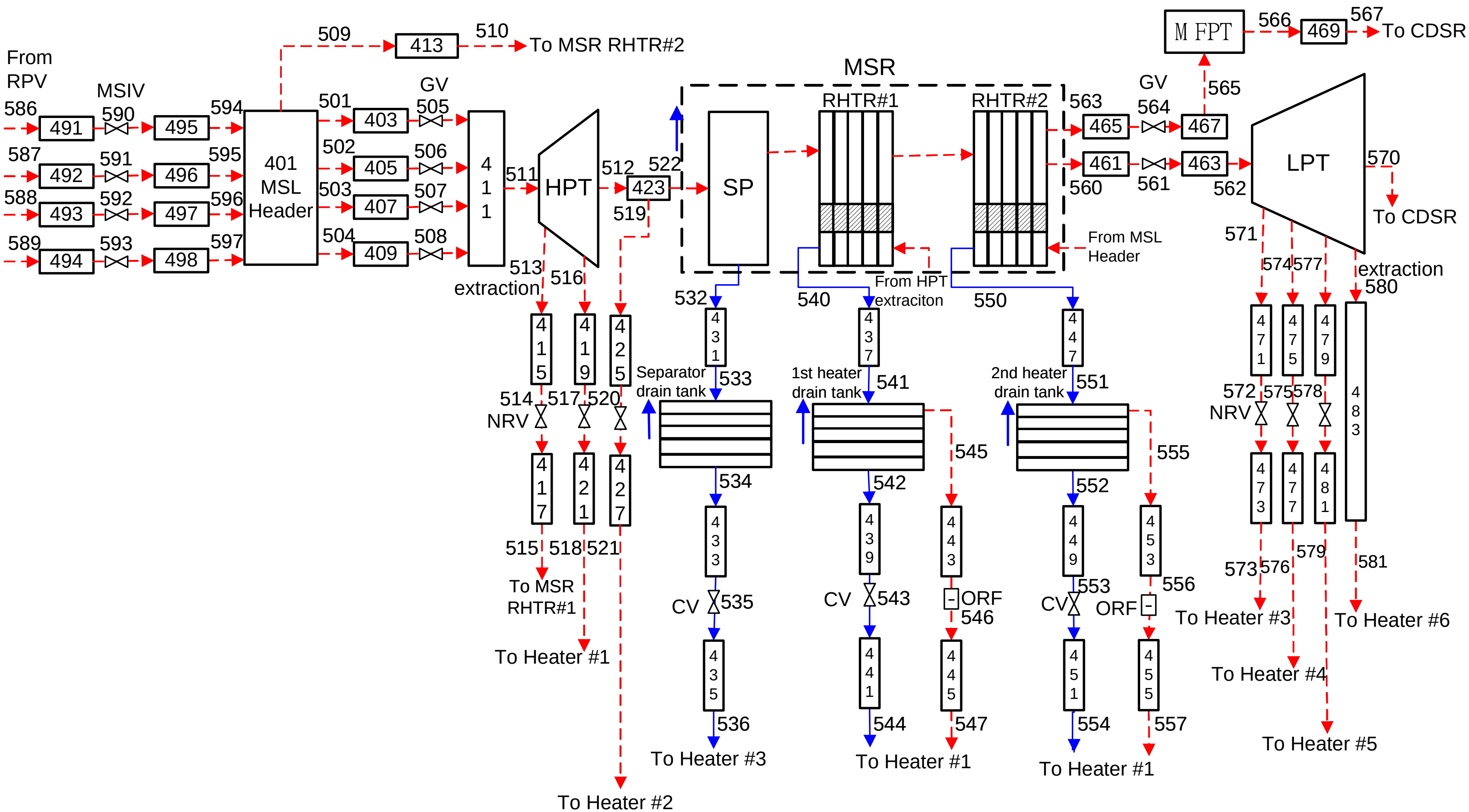
- Modeling of Main Steam System-

- *Total of 141 hydraulic volumes and 126 junctions are involved in modeling of the MS system.*
- *The components of the MS system modeling include*
  - steam header;
  - high pressure and low pressure turbines;
  - MSR and drain tanks; and
  - steam extraction.

All components are connected by piping as design.

Modeling Description

- Modeling of Main Steam System-



Modeling Description

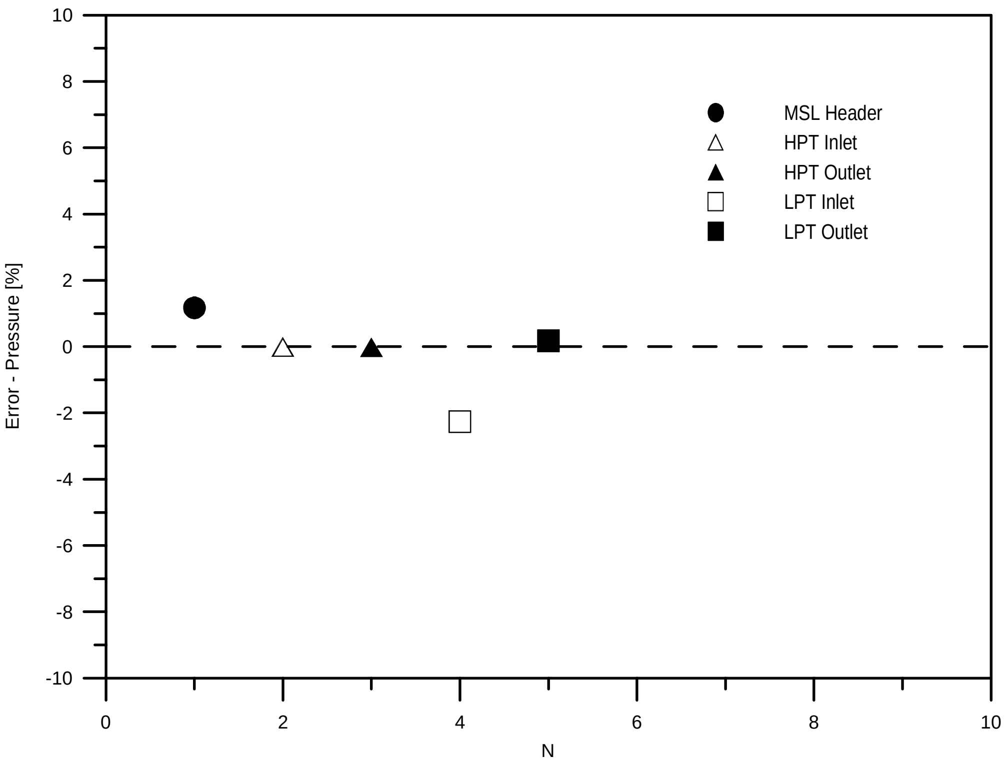
- Modeling of Main Steam System-

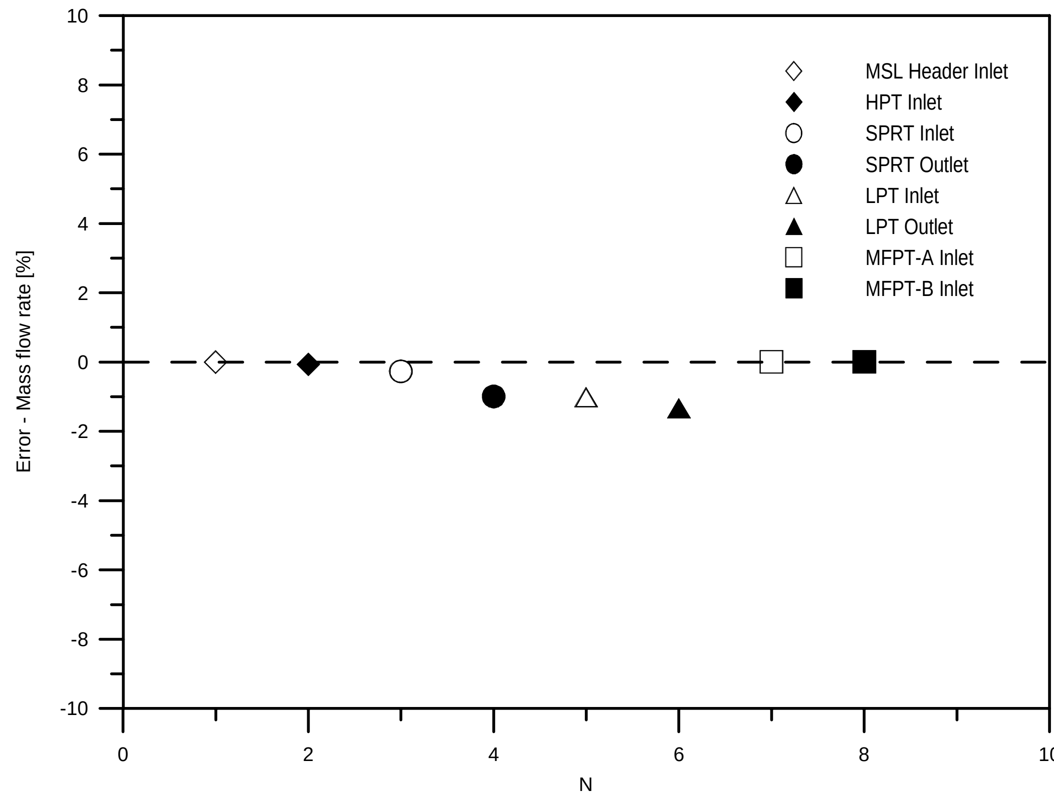
Error Analysis of Initial Condition of Main Steam System

essure [MPa]	Rated Value	Initial Value	Error [%]
1 (MSL Header)	6.7900000	6.8694200	1.170
1 (HPT Inlet)	6.5200000	6.5190700	-0.014
3 (HPT Outlet)	1.3100000	1.3097000	-0.023
3 (LPT Inlet)	1.2300000	1.2020900	-2.269
4 (LPT Outlet)	0.0076000	0.0076133	0.175
ass Flow Rate [kg/s]	**Rated Value**	**Initial Value**	**Error [%]**
0 (MSL Header Inlet)	530.577	530.560	-0.003
1 (HPT Inlet)	506.070	505.730	-0.067
103 (SPRT Inlet)	1677.145	1672.600	-0.271
101 (SPRT Outlet)	1462.336	1447.800	-0.994
8 (LPT Inlet)	1426.776	1412.300	-1.015
0 (LPT Outlet)	1157.997	1142.600	-1.330
901 (MFPT-A Inlet)	17.780	17.781	0.006
001 (MFPT-B Inlet)	17.780	17.781	0.006

Modeling Description

- Modeling of Main Steam System-



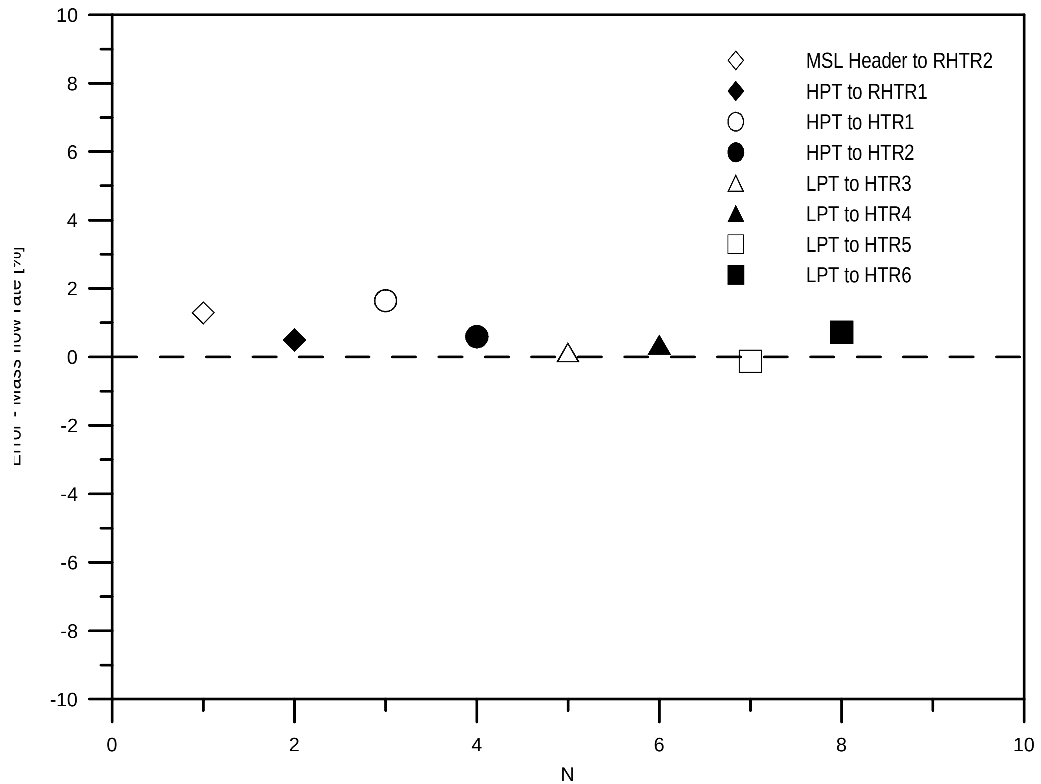


Modeling Description

- Modeling of Main Steam System-

Error Analysis of Initial Condition of Steam Extraction

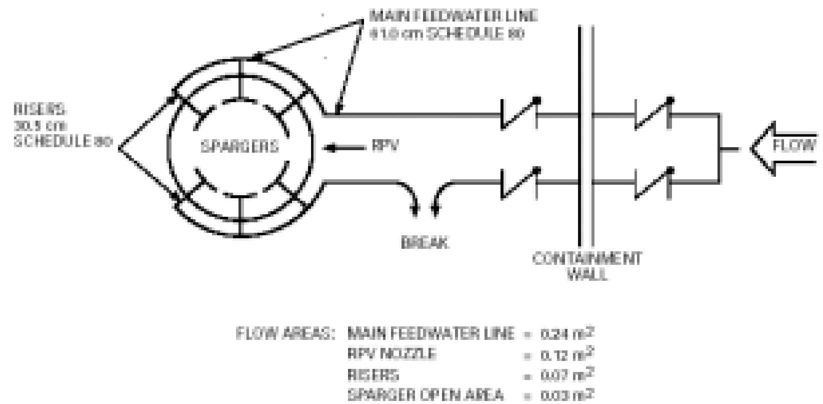
essure [MPa] (Turbine Side)	Rated Value	Initial Value	Error [%]
2 (HP Turbine 5th Stage)	2.370000	2.330480	-1.668
3 (HP Turbine Outlet)	1.320000	1.309700	-0.780
4 (LP Turbine 2nd Stage)	0.548900	0.549262	0.066
5 (LP Turbine 3rd Stage)	0.335700	0.335753	0.016
6 (LP Turbine 5th Stage)	0.126200	0.126830	0.499
7 (LP Turbine 6th Stage)	0.051920	0.052942	1.968
essure [MPa] (Heater Side)	**Rated Value**	**Initial Value**	**Error [%]**
1 (HTR6)	0.049330	0.049584	0.515
3 (HTR5)	0.119800	0.118039	-1.470
5 (HTR4)	0.318900	0.312848	-1.898
7 (HTR3)	0.521500	0.516583	-0.943
9 (HTR2)	1.260000	1.265900	0.468
1 (HTR1)	2.250000	2.198650	-2.282
ass Flow Rate [kg/s]	**Rated Value**	**Initial Value**	**Error [%]**
9 (MSL Header to RHTR2)	98.027	99.289	1.287
3 (HPT to RHTR1)	77.735	78.120	0.495
6 (HPT to HTR1)	119.329	121.290	1.643
9 (HPT to HTR2)	150.070	150.960	0.593
1 (LPT to HTR3)	33.977	34.024	0.138
4 (LPT to HTR4)	81.389	81.679	0.356
7 (LPT to HTR5)	59.962	59.886	-0.127
0 (LPT to HTR6)	93.451	94.128	0.724



Modeling Description

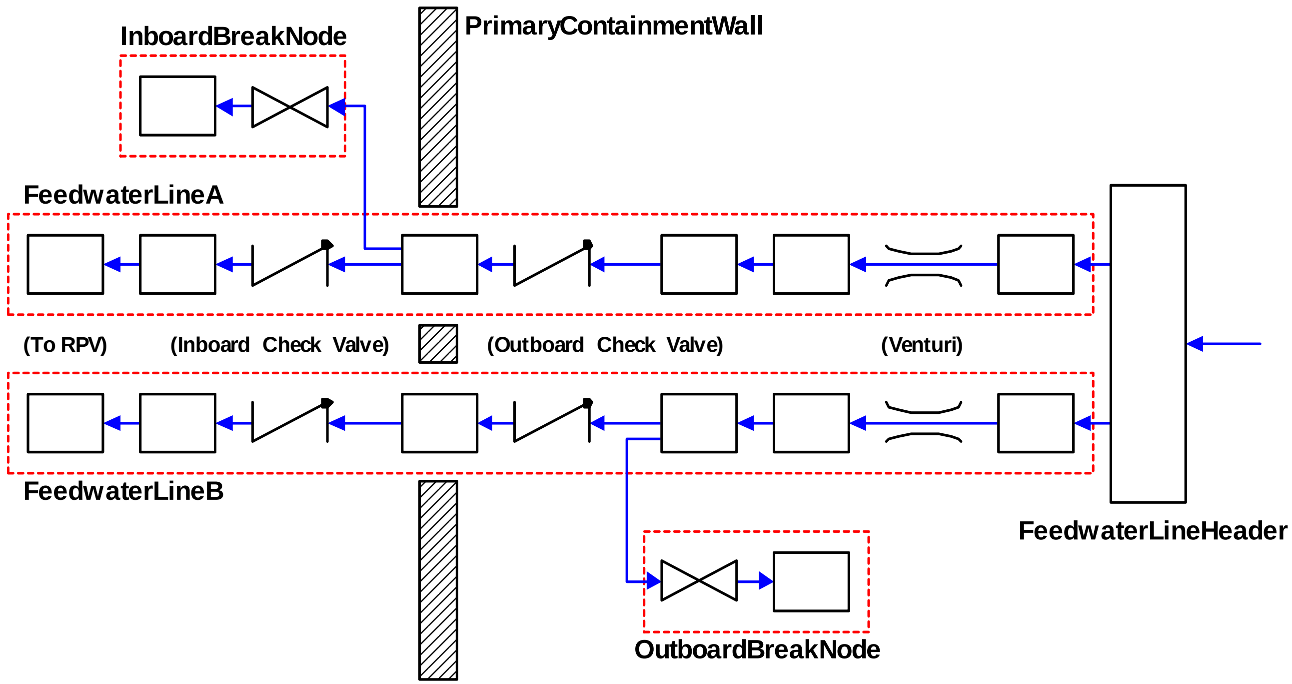
- Modeling of the Feedwater Line Break-

- *Two separated FW lines entering the reactor vessel are simulated.*
- *On each line the venturi is also modeled using junction component with reduced flow area.*
- *To simulate the internal choking, the Moody critical flow model is applied on the break junction as well as the venturi junction.*



Modeling Description

- Modeling of the Feedwater Line Break-



Modeling Sensitivity Study

- To ensure proper or conservative modeling, sensitivity study of five important parameters are performed. Those parameters include
  - inertia of feedwater pumps

    A range of pump inertia (100%, 75% and 50% of the design inertia of FWPT, 930.0 kg-m^2) is studies.
  - Moody critical flow model

    The quantitative effect of using Moody model is verified by comparison against the build-in best estimate choked-flow model
  - size of nodding right before the break

    The node right before the break is subdivided by three different kinds of nodding size in term of L/D (0.34, 0.71 and 1.06).
  - discharge coefficient; and

    As required by the Appendix K, studies of the effect of discharge coefficient ranged from 0.6 to 1.0 were performed.
  - internal choking on Venturi.

    If internal choking occurs on the Venturi, the break flow might be limited by the area of Venturi.

General Assumptions for
Event Licensing Analysis

❑ *Initial Conditions*

Parameter	Initial Value
Reactor Thermal Power [MW_t]	**4005 (102 %)**
Steam and Feedwater Flow [kg/s]	**2164.8 (102 %)**
Feedwater Temperature [°C]	**216.9 (102 %)**
Turbine Driven Feedwater Pump Speed [rpm] (Pump Rated Speed: 4920 rpm)	**4957**

General Assumptions for
Event Licensing Analysis

❑ *Plant Operations*

- The FW pumps go to maximum speed and corresponding flow runs out (maximum controller demand) immediately upon event initiation;
- The FW pumps are continuously running along with the coast down of FW pump turbines;
- MSIV closure time for the inboard break is 5.5 seconds and 14.55 seconds for the outboard break. Information is derived from pressure and steam flow boundaries supported by GE;
- Extraction steam continues to enter the FW heater and the FW pump turbines until steam inventory is depleted or blocked by the non-return valves designed to protect main turbines;

General Assumptions for
Event Licensing Analysis

- ***Plant Operations***
  - Non-safety systems and components are assumed to fail in ways that maximum the amount of water mass and energy blowdown;
  - Condensate pumps and condensate booster pumps continue operating and provide flow to the FW system;
  - Transfer of condensate storage tank inventory available to the condensate system is credited; and
  - FW flow to the vessel through the unbroken line continues intermittently through the event, depending on the FW line and RPV pressures.

General Assumptions for Event Licensing Analysis

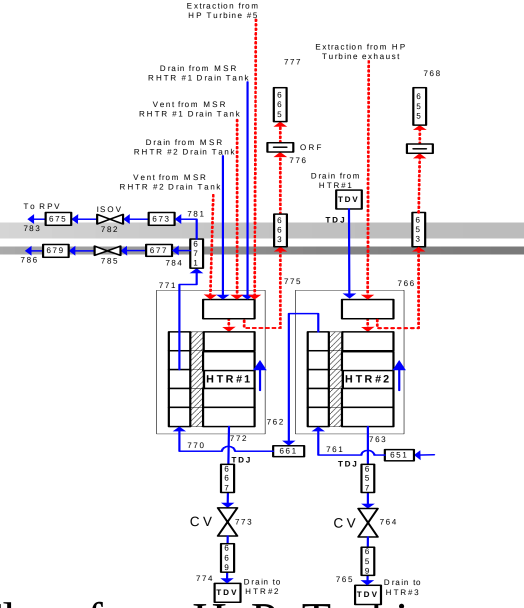
❑ *Modeling Assumptions*

- Homogeneous Moody model is applied to calculate blowdown flow rate;
- The effects of critical flow at various valves, fittings and components are considered;
- Flow losses (piping friction, local losses, and elevation effects) is considered in determining the maximum break flow;
- The pump curves of flow run out are used to model the FWPs;
- Flashing of saturated water and the associated effect of flashing on steam supply are considered;

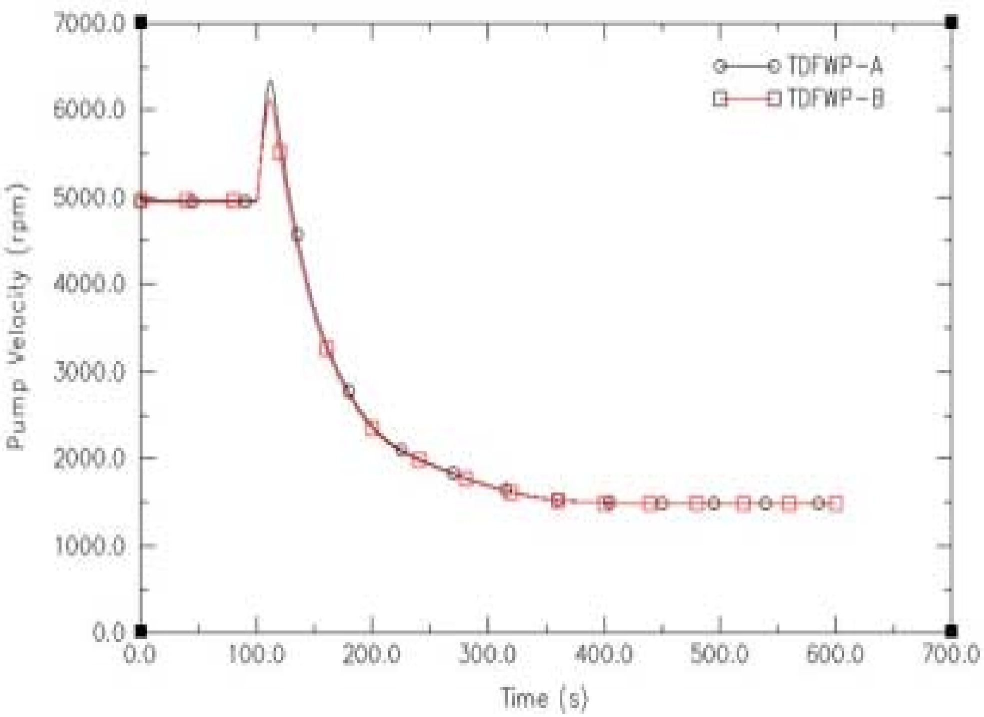
General Assumptions for Event Licensing Analysis

- The effect of stored heat from metal and saturated water stored in FW heater shell sides on the FW heating are considered;
- Calculated extraction steam and drain water to the FW system is multiplied by a factor of 1.05;
- Calculated steam flow entering into the FW pump turbines is multiplied by a factor of 1.05;
- The L/D of nodes right before the break is set to be 0.34 by sensitivity analysis; and
- The discharge coefficient is conservatively set to be 1.0 by sensitivity analysis .

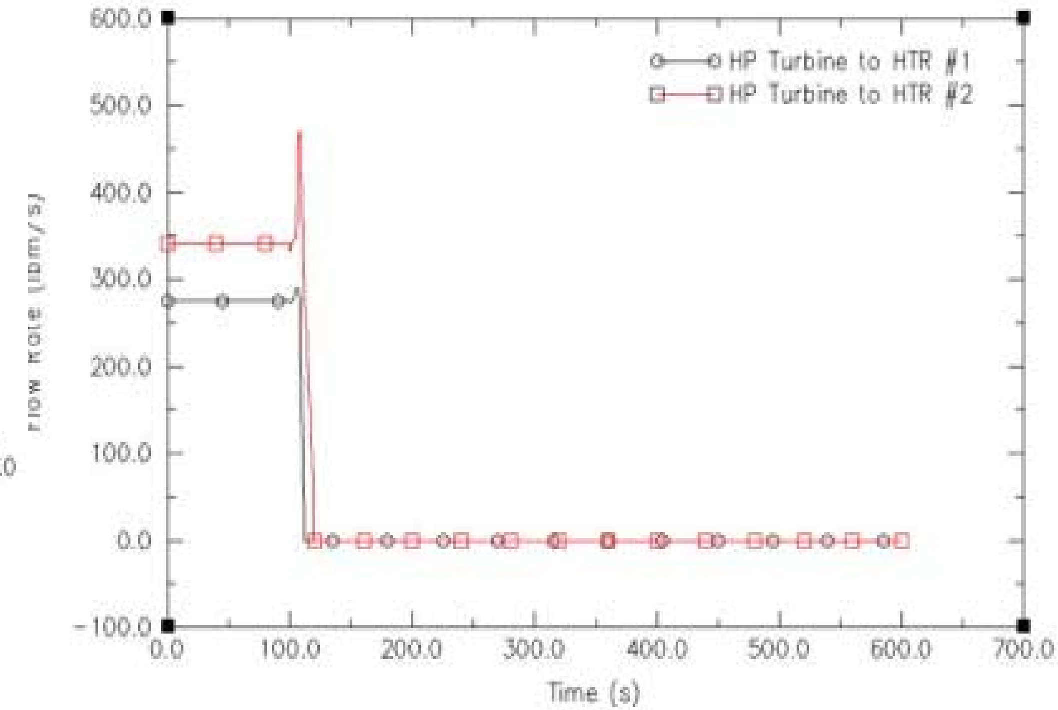
Results



Feedwater Pump Run out Speed

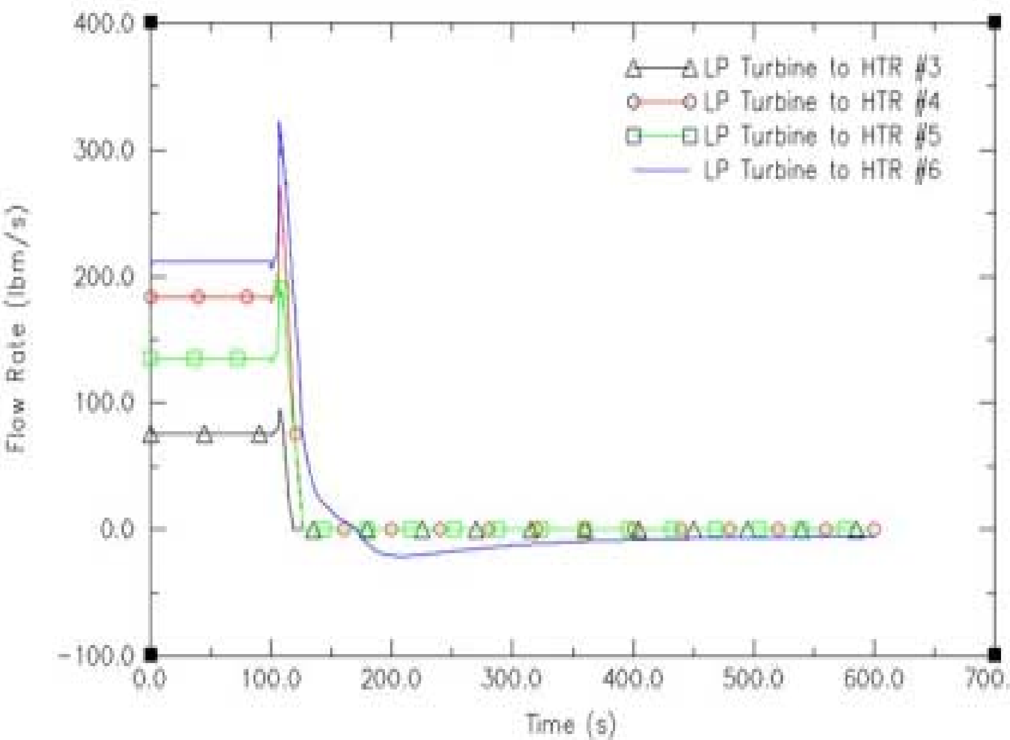


Extraction Steam Flow from H. P. Turbine

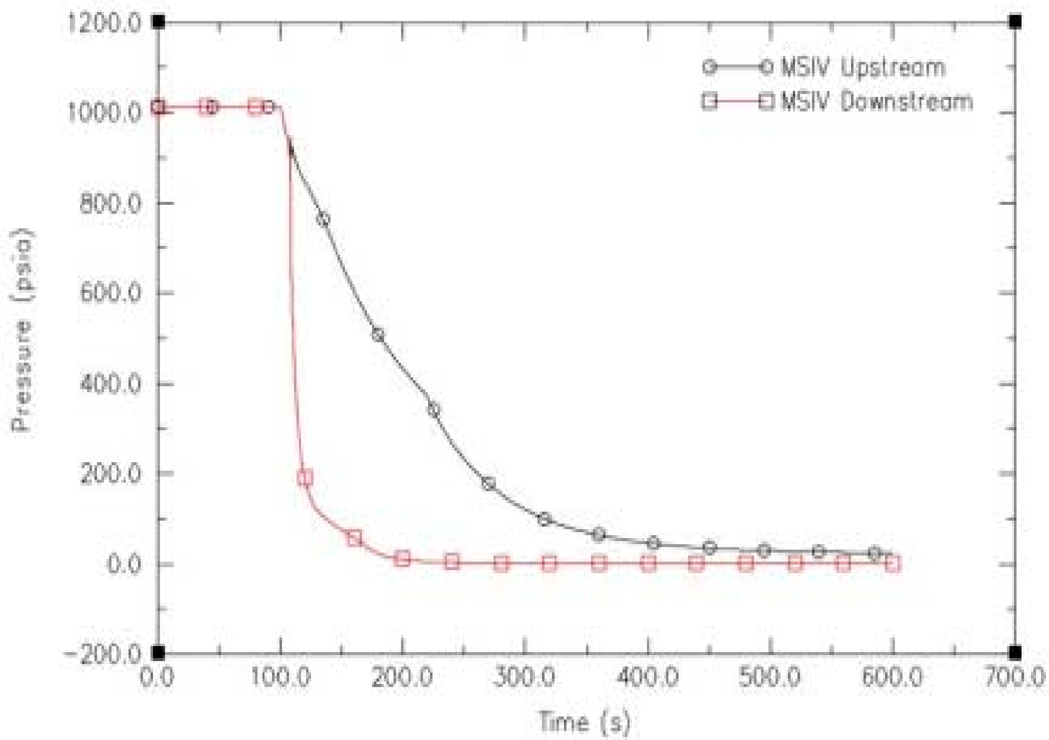


Results

Extraction Steam Flow from L. P. Turbine

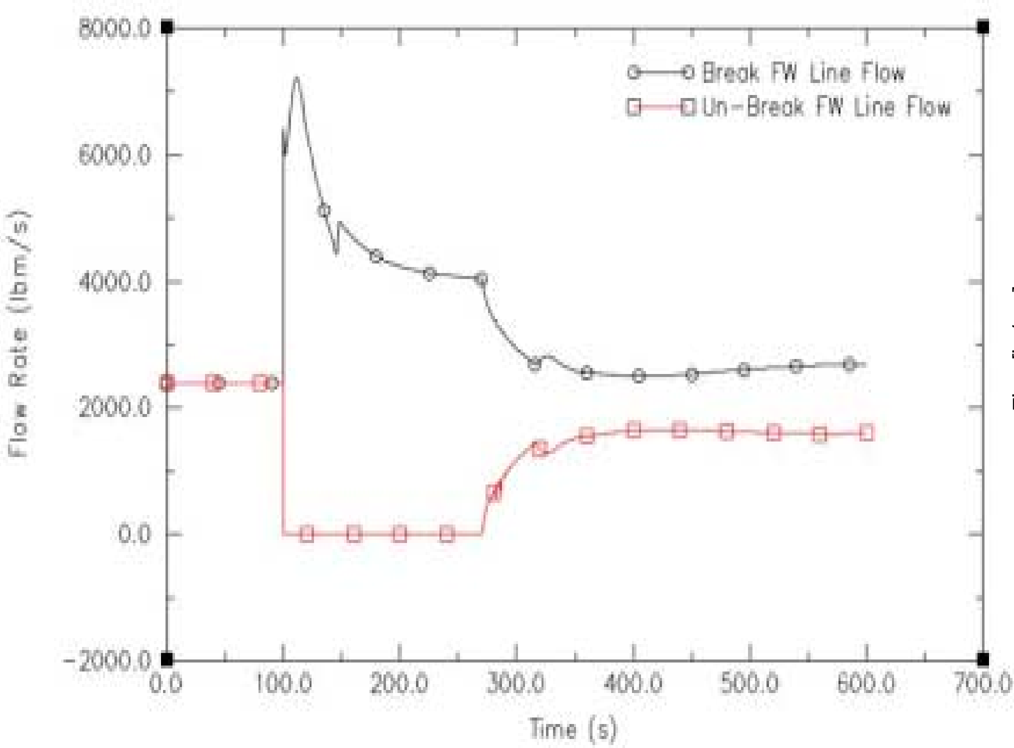


Steam Pressure before and after MSIV

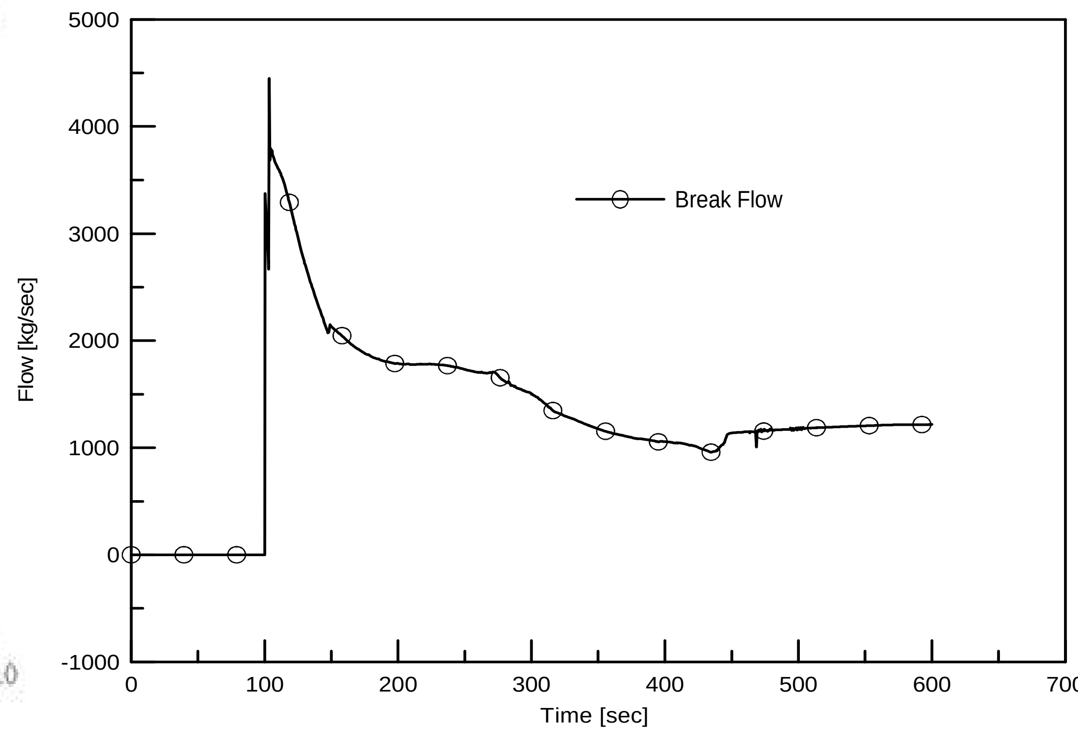


Results

FW Flows of Both Intact and Broken Lines

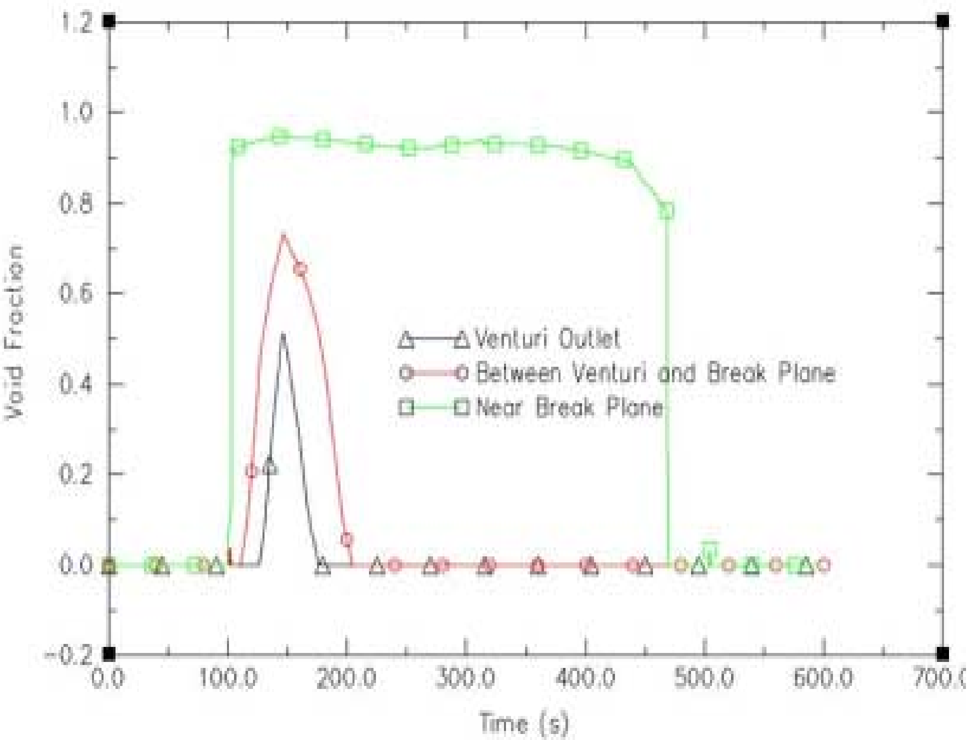


Blowdown Flow Rate

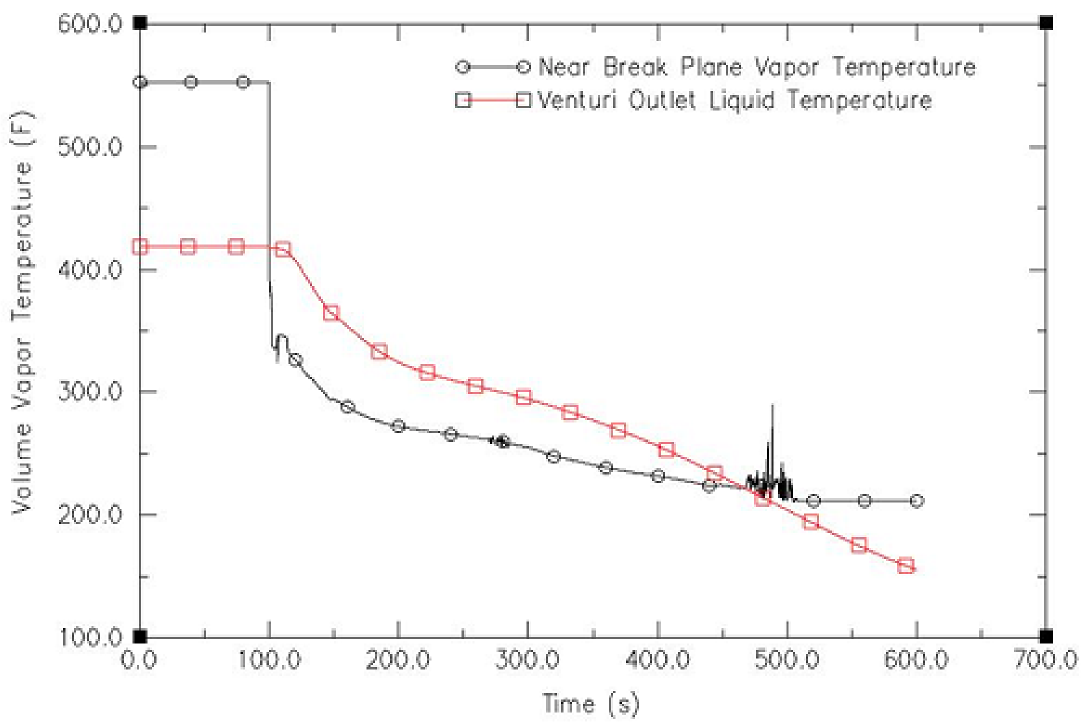


Results

Local voids near the Break

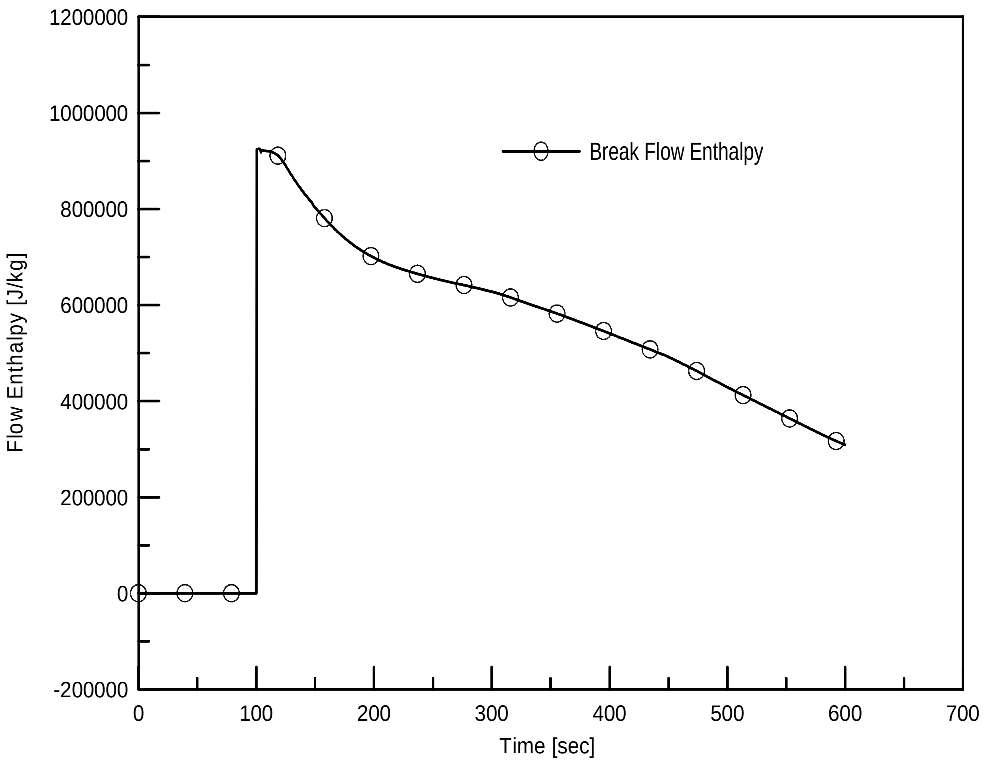


Local T_{sat} v.s. the Coming Water Temperature

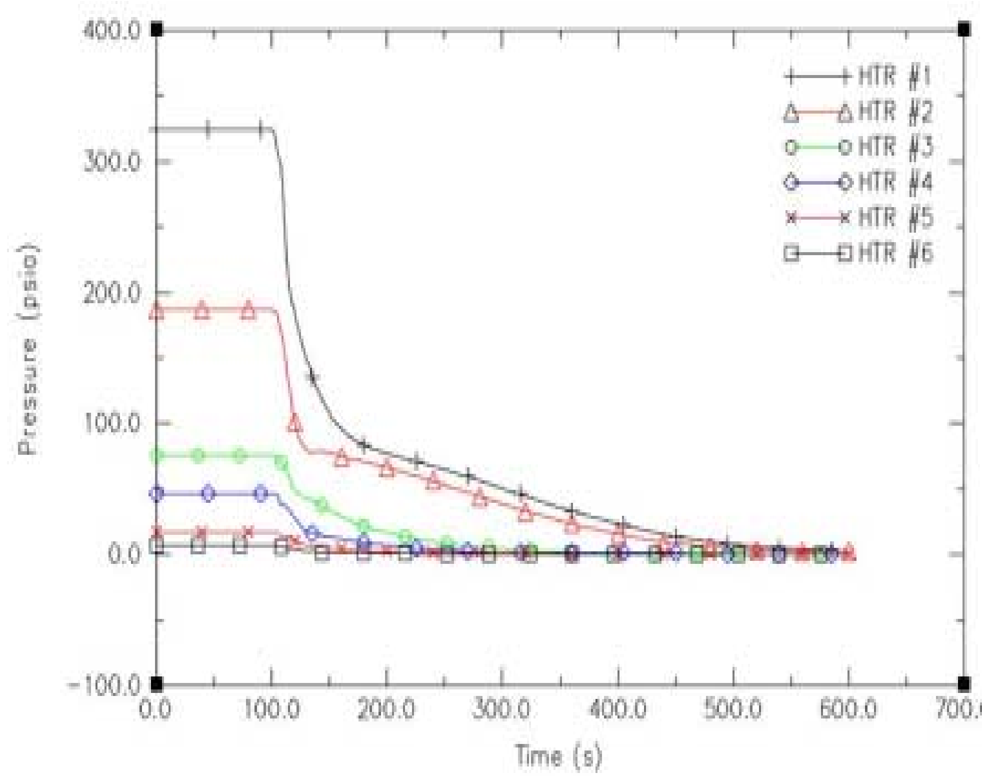


Results

Blowdown Enthalpy

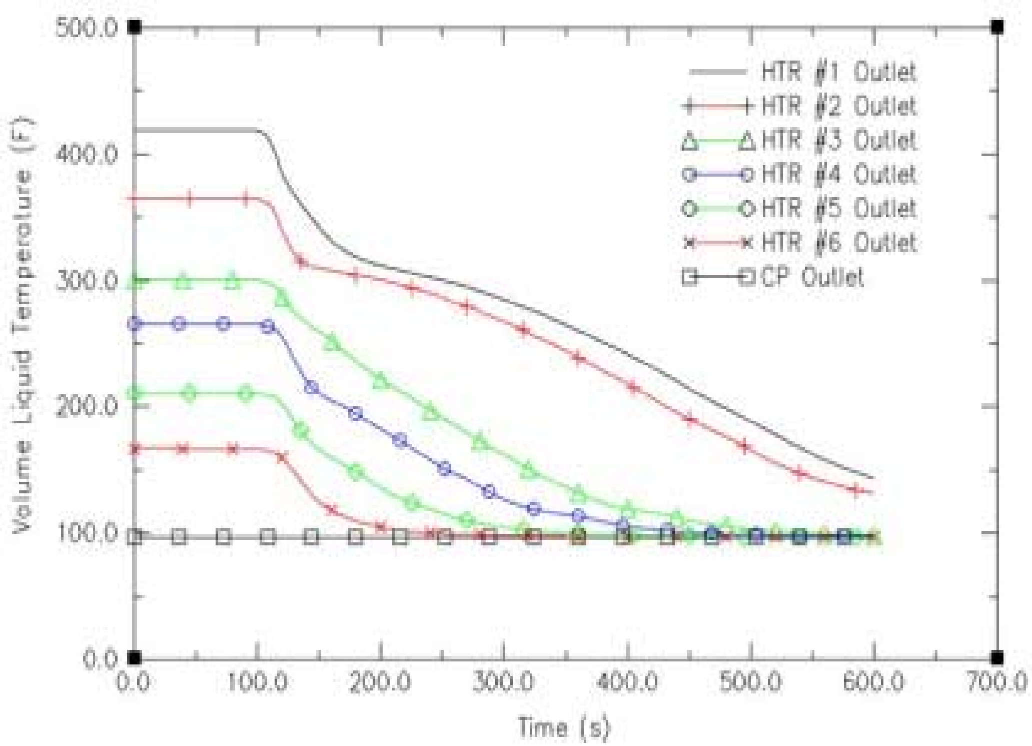


Feewater Heater Shell Side Pressures

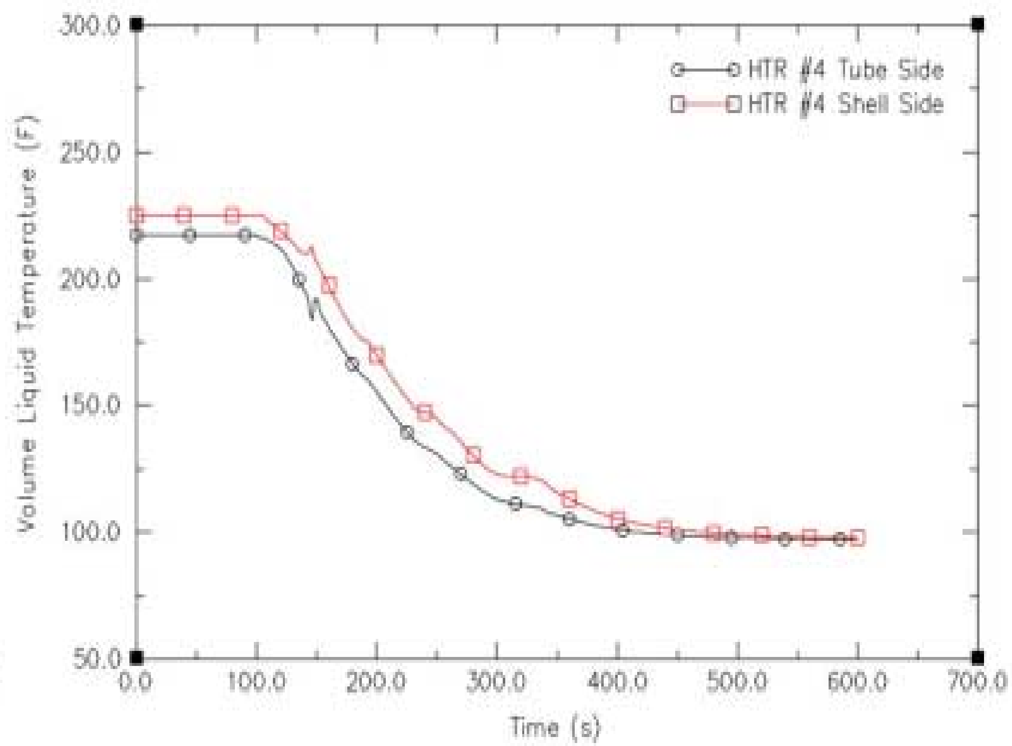


Results

Feewater Heater Shell Side Temperatures

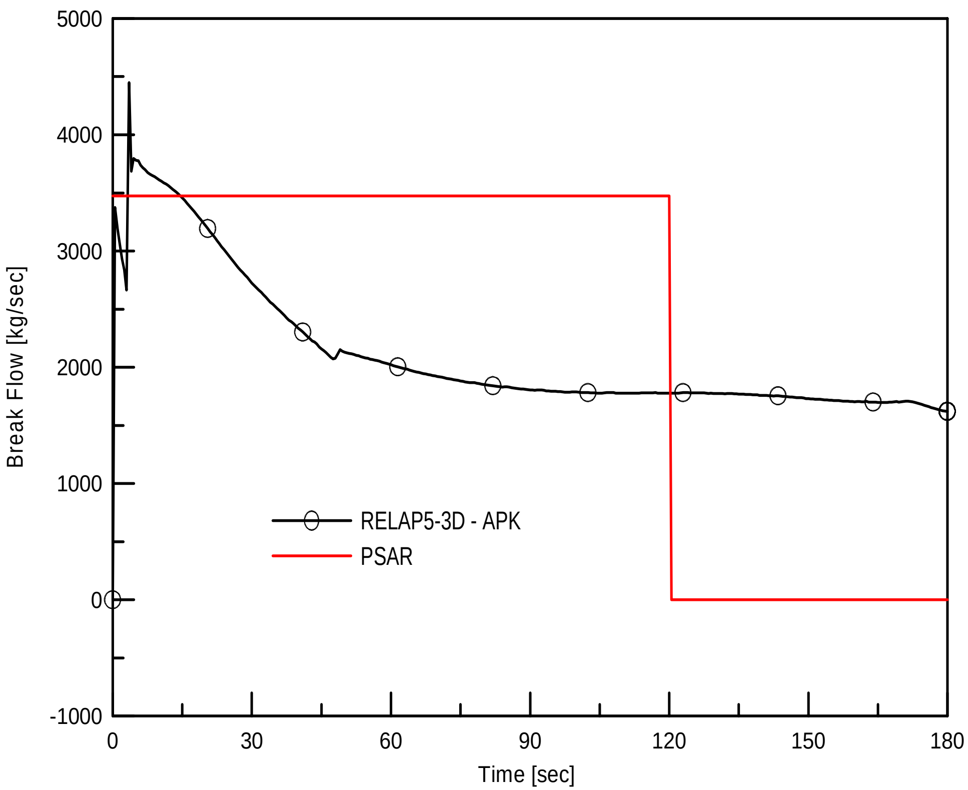


Temperature Change across the L. P. Heater

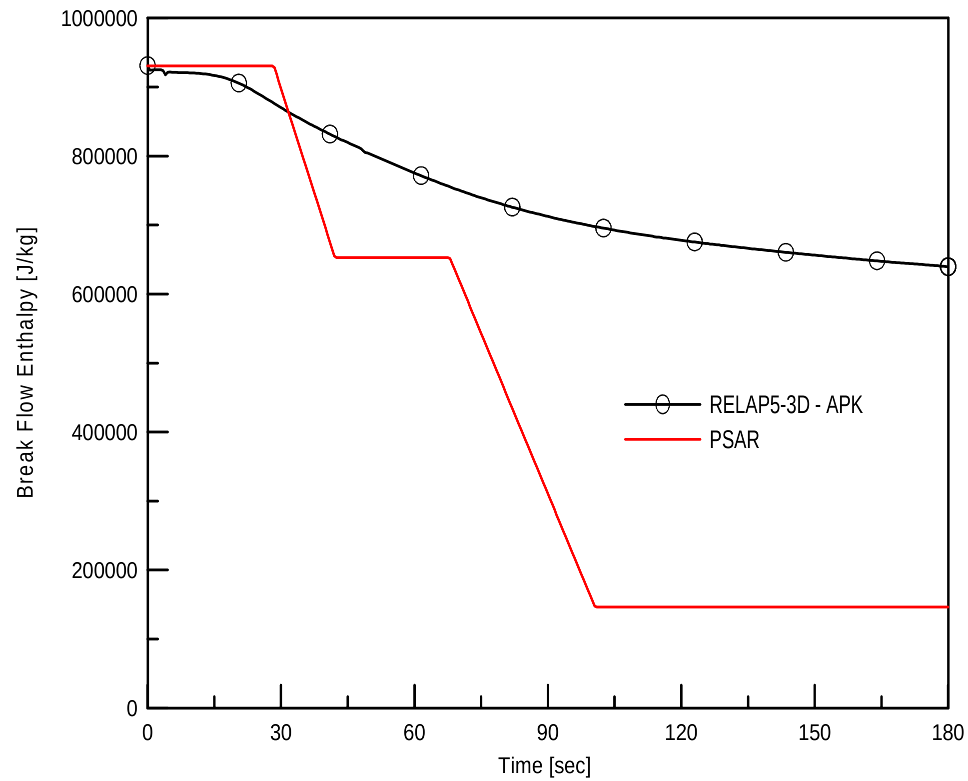


Comparison with PSAR Analysis

Comparison of the Blowdown Flow



Comparison of the Blowdown Enthalpy



Conclusions

- *The blowdown of BOP system caused by the FW line break has been successfully analyzed by the Appendix K version of RELAP5-3D.*
- *The essential components of the BOP simulation scope include*
  - steam header,
  - high pressure and low pressure turbines,
  - MSR,
  - FWP turbines,
  - main condenser,
  - condensate and booster pumps,
  - FW heaters of six stages,
  - steam extraction of seven stages,
  - turbine driven FW pumps.

Conclusions

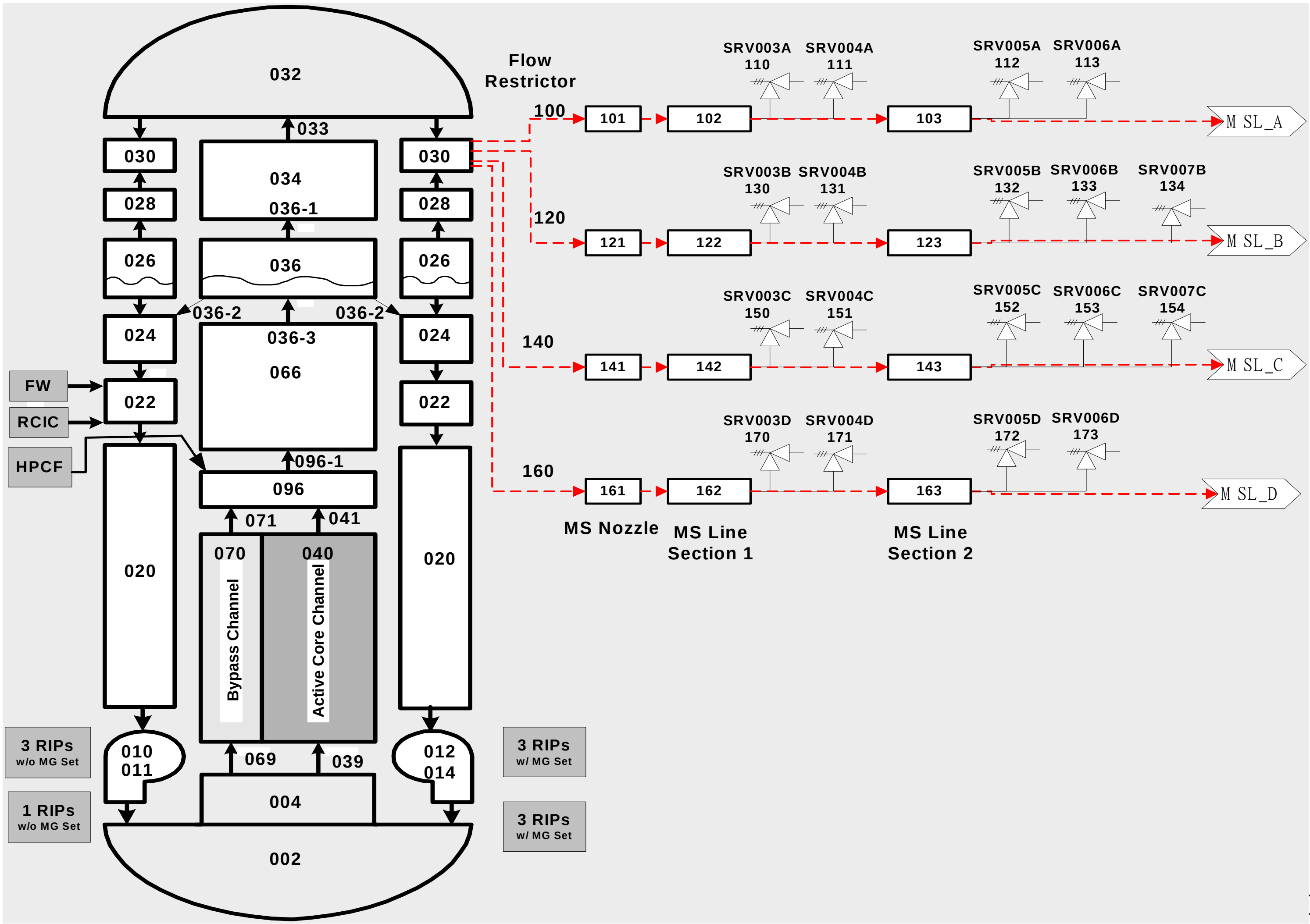
- *Important phenomena involved can be properly simulated by RELAP5-3D. Those phenomena are*
  - critical flow at the break and the internal venturi,
  - flashing of FW near the break,
  - run out and coast down of the FW pumps,
  - steam extraction to FW heaters and FWP turbines,
  - flashing of saturated water initially stored inside the FW heater shell sides and MSR drain tanks,
  - energy release from saturated water and system metal, and
  - cold water transportation from the main condenser to the break.
- *The successful application of the RELAP5 for the FW blowdown analysis indicates that the advanced RELAP5 code can extent it's traditional reactor safety analysis to entire power conversion system simulation.*

Conclusions

- *Through comparisons against the PSAR curves for the inboard break, it was observed that*
  - the blowdown flow rate are generally less than the constant value applied in PSAR in the first 120 seconds;
  - After 120 seconds, the present analysis conservatively assumes continuous operation of the condensate and booster pumps;
  - The accumulated blowdown inventory can be bounded by the PSAR only for the first 180 seconds;
  - the blowdown enthalpy decreases more gradually as compared with the PSAR;
  - It can be seen that accumulated blowdown energy from RELAP5-3D/K calculation was bounded by the PSAR only in the early 120 seconds;
  - The revised blowdown flow and enthalpy using RELAP5-3D/K can provide a new and solid basis for the FSAR containment analysis of the Lungmen nuclear power plant.

Future Work
Phase II Integral Blowdown Analysis

Nodding Diagram for RPV Blowdown



Future Work
Engineering Simulator of LungMen ABWR

RELAP5

Major System Dynamic Simulation

Systems invlove:

(1)Reactor System
- -RPV
- -3-D kientics
- -ADS

(2)Power Conversion System
- -main steam
- -main turbines
- -main condensor
- -main FW

SIMPORT

Simulation environment, contorl systems,secondary BOP & ESF, Man-machine Interface

Systems involve

(1)control systems
- -FW control(FWC)
- -steam bypass & P control(SBPC)
- -recir. Flow control (RFCS)

(2)ESF
- -reactor protection system(RPS)
- -high H core Flood (HPCF)
- -reactor core isolation cooling (RCIC)
- -residual heat removal (RHR)
- -standby boron liquid control (SBLC)

(3)man-machine interface

Hardware Configuration of Engineering Simulation