SIMULATION OF A SBLOCA IN A HOT LEG. SCALING CONSIDERATIONS AND APPLICATION TO A NUCLEAR POWER PLANT

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ABSTRACT

The main goal of this work is to study the physical phenomena observed during a Small Break Loss-Of-Coolant Accident transient performed in a small-scale Integral Test Facility and to determine the capability of the thermal hydraulic code TRACE5 to reproduce these phenomena in a scale-up model. The accident scenario analyzed is based on Test 1.2 in the frame of the OECD/NEA ROSA Project, which simulates a 1% hot leg Small Break Loss-Of-Coolant Accident in the Large Scale Test Facility of the Japan Atomic Energy Agency. During this test, natural circulation in primary loops occurs, cooling the core during some minutes. This is an important phenomenon, which needs to be checked by means of different TRACE5 models. With this aim, Test 1-2 has been simulated using a TRACE5 model reproducing the geometrical and thermal hydraulic features of Large Scale Test Facility. In order to determine if this phenomenon can be reliably extrapolated to a scale-up plant, a new TRACE5 model has been developed. The geometrical features of this scale-up model are determined using a fixed scaling ratio respect to the original LSTF features. On the other hand, 4 and 3-loop standard Westinghouse PWR models are used in order to simulate the same transient and compare the behaviour of the main thermalhydraulic variables with those obtained in the Large Scale Test Facility model and in the Large Scale Test Facility scale-up model. Results show that both Large Scale Test Facility and the scale-up models present the same behaviour during the whole transient. Important discrepancies are found in the results corresponding to 4 and 3-loop PWR TRACE5 models. In both models, natural circulation is not properly reproduced. Trying to improve the simulation results, the nodalizations of U-tubes and pressure vessel were tested. Results state that the nodalization of U-tubes clearly affects the natural circulation simulation. However, the vessel nodalization effect is not as important.

KEYWORDS: Large Scale Test Facility, Small Break Loss-Of-Coolant Accident, TRACE5, Full-Height Full-Pressure facility, Power-to-volume scaling.

1. INTRODUCTION

The origin of the scaling-issue is the impossibility to obtain measured data in case of an accident in nuclear reactors. The knowledge of thermal hydraulic phenomena occurring in Nuclear Power Plants (NPP) during an accident is very important in nuclear safety. As full-scale testing is usually impossible to perform it, thus, a number of small-scale Integral Test Facilities (ITF) of prototype systems have been built to investigate the physical phenomena of transients or possible accidents in NPPs.

Experiments performed on these ITFs allow identifying and characterizing relevant phenomena during abnormal conditions. Experimental data are usually compared with simulations achieved with thermal hydraulic codes, such as TRACE [1, 2], TRAC-P, TRAC-B, RELAP or RAMONA to test their capability to reproduce experimental conditions. ITFs can be classified into three groups:

- Full-Height, Full-Pressure (FHFP) facilities, such as Semi scale [3], Multiple Loop Integral System (MIST) [4], Large Scale Test Facility (LSTF) [5], and BETHSY [6].
- Full-Height, Reduced-Pressure (FHRP) facilities, such as Primärkreislauf-Versuchsanlage (PKL) [7].
- Reduced-Height, Reduced-Pressure (RHRP) facilities, such as the University of Maryland at College Park facility (UMPC) [8] and the Institute of Nuclear Energy Research (INER) Integral System Test (IIST) [9].

Before the Three Mile Island (TMI) accident, the behaviour of a NPP during a Large Break Loss-Off-Coolant Accident (LBLOCA) was of greatest concern, being considered as a Design Basis Accident (DBA). After the TMI accident, it became evident through Probabilistic Risk Analysis (PRA) studies that a Small Break LOCA (SBLOCA) was far more likely to occur and its consequences could be sufficiently severe to warrant safety concerns. Thus, the attention of reactor safety research was focused on SBLOCA behaviour. During a SBLOCA accident, it is very important to simulate natural circulation in primary loops. In addition, in this type of transients, depressurization can be slow enough to delay the Accumulator Injection System (AIS) entry for a long time. Actuation of High Pressure Injection (HPI) system is then necessary to maintain the core temperature low enough to avoid core boil off, and consequently, avoiding the core level to fall below fuel rods level, thus producing a temperature excursion in the fuel cladding. Several publications on this subject can be found [10, 11, 12].

Among the FHFP facilities, LSTF of the Japan Atomic Energy Agency (JAEA) was used in the frame of the OECD/NEA ROSA Project. The main objectives of this project are two: (1) solving issues in thermal hydraulic analyses relevant to reactor safety providing an experimental database. This database is useful to validate thermal hydraulic codes predictive capability and accuracy. (2) Clarifying the predictability of codes currently used for thermal hydraulic safety analyses as well as other advanced codes presently under development [5]. LSTF was designed to simulate typical thermal hydraulic phenomena during a LOCA and operational/abnormal transients of a typical 4-loop Westinghouse PWR.

In this frame, the purpose of this work is to analyse if the physical phenomena observed in the experiment Test 1-2 of OECD/NEA ROSA Project [13] performed in LSTF can be reproduced using different scale-up models. Test 1.2 consists of a hot leg SBLOCA transient assuming HPI and AIS actuation. Scale-up models were performed using TRACE5, the latest best-estimate system code developed by the United States Nuclear Regulatory Commission (US-NRC). Specifically, in this work four TRACE5 models are used to simulate LSTF and actual NPPs. 1) LSTF model developed and tested by authors in previous works [14, 15, 16]. 2) Scale-up LSTF model conserving the power-to-volume scaling ratios of the original components of LSTF, initial and boundary conditions of the experiment. 3) A 4-loop Westinghouse PWR model simulating Tsuruga NPP (PWR reference of LSTF) and 4) a 3-loop Westinghouse PWR model.

A comparison of the simulation results between these TRACE5 models is provided throughout some graphs, which represent the main thermal hydraulic variables, such as, system pressures (primary and secondary), break mass flow rates, discharged coolant inventories and collapsed liquid levels of Pressure Vessel (PV), hot legs and the Steam Generator (SG) U-tubes.

In order to reproduce the same phenomena occurring in Test 1-2, the nodalization of the SG U-tubes and the PV has been studied in four TRACE5 models.

2. SCALING CONSIDERATIONS

During last years, many studies based on thermal hydraulic scaling laws were developed to obtain small-scale ITF designs of NPPs for water reactor safety research. Among these studies the following could be remarkable:

- Rose [17] examined the scaling criteria associated with the loss of fluid test (LOFT),
- Carbiener and Cudnik [18] performed studies for modelling nuclear reactor blow-downs,
- Ishii and Jones [19] obtained a set of dimensionless parameters to define the two-phase flow,
- Nahavandi et al. [20] developed alternative scaling laws for modelling nuclear reactor systems (linear scaling method),
- Mayinger [21] assessed the scaling and modelling laws in two-phase flow and boiling heat transfer and
- Ishii and Kataoka [22] developed the scaling criteria related to the cooling loops of PWRs under single and two-phase natural circulation.

Results of these studies give a high variety of scaling methods. Linear scaling, power-to-volume scaling and power-to-mass scaling are the most used methods. The suitability of each ones depends on the facility considered.

Linear scaling logic implies the reduction of the linear dimensions of the prototype by a given factor and, in transient conditions, the reduction of time by the same factor. In this case, the amount of power transferred to the fluid is reduced as the square of the linear dimension factor [23].

In SBLOCA scenarios, the most important consideration of the scaling criteria is to preserve both the power and the coolant mass inventory during the transient. The power-to-volume scaling criterion is frequently used to preserve time, power and mass inventory in FHFP facilities regarding the reference's NPPs because of the same fluid properties at full pressure. However, in RHRP facilities, the power-to-volume scaling is not able to preserve the mass inventory because the fluid properties and the simulated parameters can not be completely preserved at a reduced pressure. In this case, a power-to-mass scaling method is recommended to determine equivalent test conditions [24].

As LSTF is a FHFP facility of an actual NPP (Tsuruga unit II) and the scenario is a SBLOCA in the hot leg, the power-to-volume scaling criterion has been chosen to develop a scale-up TRACE5 model of LSTF. This criterion resulting from the application of conservation equations (1) to (4) under some requirements and implications [25]:

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_i)}{\partial x_i} = 0 \tag{1}$$

Momentum equation:

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = F_i - \frac{1}{\rho}\frac{\partial p}{\partial x_i} - \frac{1}{\rho}\frac{\partial \overline{(\rho u_i' u_j')}}{\partial x_j} \tag{2}$$

Energy equation:

$$\rho\left(\frac{\partial h}{\partial t}+u_j\frac{\partial h}{\partial x_j}\right)=-\frac{\partial(\rho C_p\overline{u_j'T'})}{\partial x_j}+T\beta\left(\frac{\partial p}{\partial t}+u_j\frac{\partial p}{\partial x_j}\right)+\dot{q}^m \tag{3}$$

State equation:

$$\rho=\rho(h,p) \tag{4}$$

Where ρ is the density, u is the velocity, x is the coordinate, t is the time, p is the pressure, F is the friction coefficient, h is the enthalpy, C_p is the specific heat, T is the temperature, β is the thermal expansion coefficient and $\dot{q}^m$ is the power density.

Substituting the next dimensionless parameters (denoted by an asterisk) in equations (1) to (4):

$$x_i^*=\frac{x_i}{l_0},\ u_i^*=\frac{u_i}{u_0},t^*=\frac{tu_0}{l_0},\quad F_i^*=\frac{F_i}{g},\ \ p^*=\frac{p}{\Delta p_0},\ \ \rho^*=\frac{\rho}{\rho_0},T^*=\frac{T}{\Delta T_0},$$

$$h^*=\frac{h}{C_p\Delta T_0},\qquad \beta^*=\beta\Delta T_0$$

gives a set of nondimensionalized equations (5) to (8):

$$\frac{\partial\rho^*}{\partial t^*}+\frac{\partial(\rho^*{u_i}^*)}{\partial {x_i}^*}=0 \tag{5}$$

$$\frac{\partial {u_i}^*}{\partial t^*}+{u_j}^*\frac{\partial {u_i}^*}{\partial {x_j}^*}=\frac{gd_0}{u_0^2}{F_i}^*-\frac{\Delta p_0}{\rho_0u_0^2}\frac{1}{\rho^*}\frac{\partial p^*}{\partial {x_i}^*}-\frac{1}{\rho^*}\frac{\partial(\rho^*\overline{{u_i'}^*{u_j'}^*})}{\partial {x_j}^*} \tag{6}$$

$$\frac{\partial h^*}{\partial t^*}+{u_j}^*\frac{\partial h^*}{\partial {x_j}^*}=\frac{\partial(\rho^*\overline{{u_j'}^*{T'}^*})}{\partial x_j}+\frac{\Delta p_0}{\rho_0C_p\Delta T_0}\beta^*T^*\left(\frac{\partial p^*}{\partial t^*}+{u_j}^*\frac{\partial p^*}{\partial {x_j}^*}\right)+\frac{\dot{q}^ml_0}{\rho_0u_0C_p\Delta T_0} \tag{7}$$

$$\rho^*=\rho(h^*,p^*) \tag{8}$$

These equations contain other dimensionless parameters such as $\frac{u_0^2}{gd_0},\frac{\Delta p_0}{\rho_0u_0^2}$ and $\frac{\dot{q}^ml_0}{\rho_0u_0C_p\Delta T_0}$. The first two parameters are Froude and Euler numbers, respectively. The third is known as heat source number following Ishii and Kataoka [22] terminology.

Power-to-volume scaling method requires that all dimensionless parameters included in equations (5) to (8) have to be equal between LSTF model and scale-up LSTF model. If the pressure, water properties, lengths and time are preserved

$$\frac{P_{scaled-up}}{P_{LSTF}}=\frac{\rho_{scaled-up}}{\rho_{LSTF}}=\frac{l_{scaled-up}}{l_{LSTF}}=\frac{t_{scaled-up}}{t_{LSTF}}=1 \tag{9}$$

and considering that similarity between both systems has been achieved, the following power-to-volume relations are obtained:

$$\frac{\emptyset_{scaled-up}}{\emptyset_{LSTF}}=\frac{Q_{scaled-up}}{Q_{LSTF}}=\frac{V_{scaled-up}}{V_{LSTF}}=\frac{A_{scaled-up}}{A_{LSTF}}=K_v \tag{10}$$

being ϕ power, *Q* mass flow rate, *V* volume, *A* area and K_V the volumetric scaling factor.

Furthermore, in the scale-up model the Froude number [26] is conserved in horizontal components. It implies varying the diameter and length of these components. Trying to conserve the Froude number, from the scale-up mass flow rate calculated as Eq. (11), the scale-up diameter, *D*, can be obtained as Eq. (12):

$$U\frac{\pi \cdot D^2}{4} \cdot \rho = u\frac{\pi \cdot d^2}{4} \cdot \rho \cdot K_v \tag{11}$$

$$D = d \cdot {K_v}^{2/5} \tag{12}$$

where U is velocity in the scale-up model, ρ is the coolant density and d is LSTF diameter. Furthermore, from the volume equation Eq. (13) and trying to conserve the Froude number, lengths of the scale-up piping system are obtained as Eq. (14):

$$\frac{\pi \cdot D^2}{4} \cdot L = \frac{\pi \cdot d^2}{4} \cdot l \cdot K_v \tag{13}$$

$$L = l \cdot {K_v}^{1/5} \tag{14}$$

being *l* and *L*, LSTF and scale-up length, respectively.

3. TRACE5 MODELS DESCRIPTION

TRACE (TRAC/RELAP Advanced Computational Engine), developed by the US-NRC, is an advanced best estimate reactor code for analysing thermal hydraulic behaviour in Light Water Reactors. A graphic user interface program, Symbolic Nuclear Analysis Package, (SNAP), is available for conveniently creating and editing the input decks. In this work, TRACE5 patch 2 [1, 2] and SNAP version 2.1.2 [27] have been used in all calculations. Next paragraphs present a description of four TRACE5 models used in this work: 1) LSTF model, 2) scale-up LSTF model, 3) 4-loop Westinghouse PWR model (Tsuruga NPP) and 4) 3-loop Westinghouse PWR model.

3.1 LSTF model

LSTF is a FHFP facility reproducing Tsuruga Unit-II NPP, which is a Westinghouse PWR type of 4 loops and 3423 MWt. LSTF [5] is a 1/48 volumetrically scaled two-loop system. Each loop is sized to conserve the volumetric factor 2/48 and the relation L/√D to reproduce the same flow regime transition in horizontal legs. The maximum core power is 10 MW that corresponds to 14% of the volumetrically scaled-down Tsuruga (reference PWR) nominal power.

LSTF has been modelled with 81 hydraulic components (7 BREAKs, 11 FILLs, 23 PIPEs, 2 PUMPs, 1 PRIZER, 22 TEEs, 14 VALVEs and 1 VESSEL). Figure 1 shows the nodalization of LSTF using SNAP.

LSTF TRACE5 model contains the two loops of the system each one provided with primary and secondary side. The primary side comprises the PV, pumps, cold and hot legs, loop seals, a pressurizer in loop A, the U-tubes of both Steams Generators (SG) and the Emergency Core Cooling System (ECCS).

The Pressure Vessel (PV) has been modelled using a 3-D VESSEL component divided into 20 axial levels, 4 radial rings and 4 azimuthal sectors. Levels 1 and 2 correspond to the lower plenum. Active core is located between levels 3 and 11. Level 12 simulates the upper core plate.

Levels 13 to 16 characterize the vessel Upper Plenum. In level 17, the upper core support plate is located. Finally, the Upper Head is defined between levels 18 to 20. The three inner rings characterize the core region and the fourth ring represents the downcomer. 3-D VESSEL is connected to different 1-D components: 8 Control Rod Guide Tubes (CRGT), hot leg A and B (level 16), cold leg A and B (level 16) and a bypass channel (level 15). CRGT have been simulated by 8 PIPEs components, connecting levels 14 and 20 and allowing the flow between upper head and upper plenum.

The axial power profile is a chopped-cosine with 9 divisions. The axial peaking factor is 1.495. The radial power distribution in the active core is given by 3 peaking factors (0.66, 1.0 and 1.51) assigned to each ring of the core [5]. 12 HTSTRs simulate 1008 fuel assemblies located in the active core. A POWER component manages the power supplied by each HTSTR to the 3-D VESSEL. In the experiment, the core power has been estimated by dividing into 3 power terms, i.e. the delayed neutron fission power term, the fission product decay power term and the actinide decay power term, which contribute much to the PWR core power after a reactor scram. In TRACE5 model it has been simulated by means of a decay curve given in the literature [5].

In LSTF the pump torque characteristics were experimentally obtained for single-phase liquid water flow. The pump torque used to derive the homologous curve was obtained by subtracting the frictional torque from the motor torque [5]. In TRACE5 model, these curves have been modelled using a dimensionless behaviour curves (torque, head, etc.) in single and two-phases. The coast-down curves for the primary coolant pumps have been introduced in the input as the rotation speed ratio versus time.

The pressurizer has been modelled by means of a PRIZER component connected to a VALVE component simulating the Power Operated Relief Valve (PORV) and to the surge line that connects the pressurizer with the hot leg. The pressurizer contains two heaters, a backup heater and a proportional heater, in order to control the primary pressure.

The Emergency Core Cooling System (ECCS) consists of the AIS, HPI and Low Pressure Injection (LPI) systems, which are connected to cold legs. HPI and LPI have been simulated using FILL components while 2 PIPE components type ACCUMULATOR have been used to model the AIS.

Each SG consists of boiler, separator and downcomer. Main and Auxiliary Feedwater (MFW and AFW, respectively) are connected to the top of the SG downcomer. SG separator is connected to the Main Steam Line, where Safety Relief Valves (SRV) and Main Steam Isolation Valves (MSIV) are located.

Each SG has 141 U-tubes, which are simulated by 3 PIPE components depending on the average length of real U-tubes. U-tubes have an inner diameter of 19.7 mm and an outer diameter of 22.24 mm (with 1.27 mm wall thickness). Each node of the U-tubes has an average length of 1.3 m. Boiler and downcomer components of SG secondary side, have been modelled using TEE components. Steam-separator model can be invoked in TRACE5 setting a friction coefficient (FRIC) greater than 10^{22} at a determined cell edge, allowing to flow through the cell interface gas phase only [1, 2]. The boiler nodalization has been performed to correspond with the nodes of SG U-tubes. Heat transfer between primary and secondary sides has been established by using HTSTR components. Cylindrical-shape geometry has been used to best fit heat transmission. Critical heat flux flag has been set in order to use an AECL-IPPE table, and calculating critical quality from Biasi correlation [1, 2]. The level tracking TRACE5 option has been deactivated. SG separator is connected to a TEE component that simulates the Main Steam Line. This line connects the SG to the Relief Valve (RV) and the Main Steam Isolation Valve (MSIV). Each one has been modelled using a VALVE component. The RV is connected to a BREAK component, while the MSIV is connected to a BREAK component, which simulates the turbine. MFW and AFW are simulated using FILL components connected to the top of the downcomer.

The break VALVE is connected to a BREAK component to simulate the atmospheric coolant leakage. The break size is the one specified in Test 1-2 [13], which corresponds to the 1% of the volumetrically scaled cross-sectional area of the reference PWR cold leg. It is located on the hot leg of loop B (without pressurizer) downwards orientation.

Choked flow model, a special TRACE5 issue [1, 2], has been applied in all TRACE5 models described in this work to improve the simulation results when the fluid phase change occurs. Choked flow is a compound of three different models: subcooled single-phase, two-phase and single phase-vapour models. Nevertheless, TRACE5 only allows adjusting two different coefficients: the subcooled and the two-phase multipliers [28]. In all TRACE5 models, these coefficients have been fixed to 1.2 and 1.5, respectively.

The maximum time step in steady state and transient calculations has been set to 0.1 s in all the cases. Furthermore, in all the TRACE5 models a multi-step time-differencing procedure was used for the fluid-dynamics equations in the spatial 1-D and 3-D components that allows the material Courant-limit condition to be exceeded. A more straightforward semi-implicit time-differencing method is also available, but this method supposes higher computational time [1, 2].

LSTF TRACE5 model has been developed and tested with experimental data by authors in previous works [14, 15, 16] simulating different experiments performed in LSTF in the frame of the OECD/NEA ROSA Project.

3.2 Scale-up LSTF model

Based on the LSTF TRACE5 model explained in Section 3.1, a scale-up model has been developed applying the power-to-volume scaling method and trying to preserve the Froude number in horizontal components. As explained in Section 2, this scaling method needs a volumetric scaling factor, Kv, to obtain the scale-up TRACE5 model. Kv, has been fixed to 48 as LSTF is scaled 1:48 in volumes from the reference PWR. The main design factors that characterize the power-to-volume scaling criteria are listed in Table 1.

The scale-up TRACE5 model contains two loops provided by the same components than LSTF with different geometry. The volume of scale-up components is enlarged by the volumetric scaling factor, while heights are the same than LSTF facility. Initial and boundary conditions, temperature, pressure and velocities remain the same as in LSTF model.

In the primary system, the 3-D VESSEL has the same 1-D connections than in LSTF model (8 CRGTs, hot and cold legs and a bypass channel). As it happens in LSTF TRACE5 model, the maximum core power of the scale-up TRACE5 model corresponds to 14% of the nominal reference PWR core power because the scale-up core power decay curve has been obtained from decay curve of LSTF enlarged by Kv. The number of LSTF fuel rods, simulated by HTSTRs, has been multiplied by the same factor.

The scale-up and LSTF pumps use the same dimensionless behaviour curves (torque, head, etc.) in single and two-phases and the same coast-down curves. Regarding horizontal components, such as hot and cold legs, their flow area is scaled to conserve the ratio of the length to the square root of pipe diameter, i.e. $l/\sqrt{d} = L/\sqrt{D}$, to improve the simulation of the flow regime transitions in horizontal pipes. Furthermore, the scale-up model has been built trying to conserve the Froude number [26] in hot and cold legs. It implies modifying lengths and diameters of these components as explained in Section 2. Loop seal and pressurizer have the same nodalization as in LSTF TRACE5 model taking into account Kv to enlarge the volume but maintaining the height. The HPI and LPI mass flow rates have been scale-up using the Kv factor as they are simulated using FILL components. However, in the AIS, which is simulated by means of two PIPE components, Kv has been used to enlarge their volume.

In the secondary side, the number of SG U-tubes and heat structures used to simulate the heat transfer between primary and secondary system are Kv times higher than the LSTF model. Three groups of U-tubes have been maintained in the scale-up LSTF model. The heat transfer model used (AECL-IPPE [1, 2]) is the same as in LSTF model. SG and main steam lines are similar to LSTF model taking into account Kv. MFW and AFW capabilities are enlarged by Kv because they are simulated by means of FILL components.

The break localization, orientation and nodalization is the same than in LSTF model. The scale-up flow area of VALVE component corresponds to 1% of the cold leg flow area, it is using the same Kv as in the LSTF design.

3.3 4-loop PWR model

A TRACE5 model simulating Tsuruga unit II NPP, reference PWR of LSTF, has been developed. Tsuruga is a Westinghouse 4-loop PWR of 3423 MWt, which has been simulated using 125 TRACE5 hydraulic components (10 BREAKs, 21 FILLs, 65 PIPEs, 4 PUMPs, 1 PRIZER, 4 SEPARATORs, 19 VALVEs and 1 VESSEL).

Initial and boundary conditions, temperature, pressure and velocities in primary and secondary system remain the same as in LSTF model. Table 2 shows the main geometrical variables of 4-loop PWR in comparison to LSTF.

Each of the four primary loops was modelled separately, including hot leg, steam generator, loop seal, reactor coolant pump, cold leg and accumulator tanks. The pressurizer and surge line are located in loop 3. The ECCS, which consists of High and Low Pressure Injection (HPI and LPI) and Accumulator Injection Systems (AIS), have been simulated as a boundary condition (pressure dependent). Furthermore, each SG has a Relief Valve and a Main Steam Isolation Valve (MSIV) located in the steam line. In these lines, MFW and AFW systems are connected.

3-D VESSEL nodalization and 1-D connections are the same as in the LSTF model taking into account that Tsuruga has 57 CRGT, 4 hot and cold legs and 4 bypass channels. CRGTs have been simulated by 8 PIPEs components taking into account the total flow area of 57 CRGT. The axial and radial power profiles are the same as in the in LSTF model. In this case, 12 HTSTRs simulate 50952 fuel assemblies located in the active core. A POWER component manages the power supplied by each HTSTR to the 3-D VESSEL. The core power of 4-loop PWR model is defined from the core power decay curve of LSTF model enlarged by 48 because LSTF is a 1/48 volumetrically scale-down system from Tsuruga. As the maximum LSTF core power is 10 MW, which corresponds of 14% of the volumetrically scale-down nominal power of Tsuruga, the maximum 4-loop PWR core power will be limited to 14% of 3423 MW.

Hot legs have been modelled with 4 PIPE components connected to the PV and the SG U-tubes. In loop 3, where the pressurizer is located, hot leg is connected with the surge line of the pressurizer. The pressurizer and its surge line are modelled with two PIPE components.

To simulate the cold legs 4 PIPEs have been used. Cold legs are linked to the vessel, the reactor coolant pumps and the Emergency Core Cooling System (ECCS). In the broken loop (loop 1), cold leg is connected with a VALVE component to simulate the break. The break is simulated with the same orientation as in LSTF. Break size is the 1% of Tsuruga cold leg flow area.

The pumps use the same dimensionless behaviour and coastdown curves as in the LSTF model.

ECCS mass flow rates have been obtained from LSTF model enlarged by 48. In the AIS, which is simulated by means of four PIPE components, the volume has been obtained from the standard 3-loop PWR TRACE5 model explained in Section 3.4.

The secondary side consists of 4 SG. Each of them simulates 3382 U-tubes with an average length of 20.2 m. U-tubes inner diameter and outer diameter are similar to LSTF model. U-tubes have been modelled by means of a PIPE component. The heat transfer between U-tubes and boiler has been simulated by means of the same model as in the LSTF model (AECL-IPPE Biasi [1, 2]).

Ten TRACE5 components have been used to simulate the secondary side of each steam generator and the steam lines. The boiler has been simulated with a PIPE component. Hydraulic diameters were calculated to allow determining the interfacial drag. The SG separators have been modelled using a SEPARATOR component, while the SG downcomer has been simulated with a PIPE component. Appropriate form loss energy coefficients were included in the downcomer and in its connection with the boiler, to get the specified circulation ratio.

The downcomer is connected to a PIPE component that simulates the Main Steam Line, which is formed of the same components as in the LSTF model (RV and MSIV). Each one has been modelled using a VALVE component. The steam generator relief valve is linked to a BREAK component, while the main steam isolation valve is connected to a PIPE component, which simulates the steam line header.

The PIPE component that simulates the steam line header collects the steam from three SG and conducts it to the turbine. Turbine is represented using two VALVE and a BREAK components.

MFW and AFW are simulated using FILL components connected to the top of the SG downcomer.

3.4 3-Loop PWR model

As the Spanish NPPs are 3-loop PWR Westinghouse-type, a standard TRACE5 model of 2686 MWt of rated power has been considered to apply the transient conditions of Test 1-2. Table 3 contains the main characteristics of this model, while Figure 2 shows the nodalization used.

Each of the three primary loops have been modelled separately, including the same components as in other TRACE5 models: hot leg, steam generator, loop seal, reactor coolant pump, cold leg and accumulator tanks.

103 TRACE5 hydraulic components (9 BREAKs, 16 FILLs, 53 PIPEs, 3 PUMPs, 1 PRIZER, 3 SEPARATORs, 17 VALVEs and 1 VESSEL) have been used to model the 3-loop PWR. As in the others models a 3-D VESSEL component has been used to reproduce the PV. The 3-loop PWR PV is divided into 16 axial levels, 4 radial rings and 4 azimuthal sectors. Levels 1 to 2 simulate the lower plenum. Active core is located between levels 3 to 10. Levels 12 to 14 reproduce the upper plenum, while upper head is simulated by levels 15 and 16. As in other models, first three rings are used to simulate the core and the fourth ring simulates the downcomer. In this model, the 3-D VESSEL is connected to 6 CRGT, hot and cold legs and bypass channels. Six PIPEs model the Control Rod Guide Tubes (CRGTs). Three PIPEs allow the flow path between upper plenum and upper head (connect levels 13 to 16), while other 3 connect the core exit (level 11) with upper head (level 16).

Trying to reproduce the same phenomena than in Test 1-2 transient, some parameters of the standard 3-loop PWR model need to be adjusted using a volumetric scaling factor characteristic that relate both models LSTF and 3-loop PWR. This factor has been chosen as the volume relation between both PV (35.77). The power is supplied to the vessel using 12 HTSTRs components, which simulate 36056 fuel rods present in the standard Westinghouse 3-loop PWR model. The axial and radial power profiles are the same as used in LSTF model. A POWER component has been used to manage the power from these HTSTRs to the 3-D VESSEL. The power is defined from the core power decay curve of LSTF model enlarged by the 3-loop PWR Kv, preserving the time. As it happens in all the cases, the maximum core power corresponds to 14% of the nominal 3-loop PWR core power.

Hot and cold legs have been modelled like in 4-loop PWR TRACE5 model, but taking into account that in this case is a 3-loop PWR TRACE5 model. The break unit is simulated such as previous models and located in loop 1. The break size has been scaled from the Test 1-2 using the characteristic 3-loop Kv.

Pumps are simulated similarly as in the other TRACE5 models. Pressurizer and its surge line are located in the hot leg of loop 3. ECCS mass flow rates have been obtained such as in the other TRACE5 models taking into account the 3-loop characteristic Kv.

The secondary side consists of three SGs with 2521 U-tubes (average length of 23.9 m). U-tubes inner and outer diameters are similar as in other models. The secondary side nodalization is equal to the 4-loop PWR TRACE5 model. Heat transfer between primary and secondary sides is simulated using the same model.

4. TRANSIENT DESCRIPTION

Test 1.2 simulates a 1% SBLOCA transient in the hot leg of loop without pressurizer, assuming the actuation of HPI and accumulator systems. The complete control logic of the transient is listed in Table 4.

The experiment started with the break valve opening. The primary pressure began to fall because of the coolant release. When the primary pressure fell below the scram signal set point, pump coastdown and reactor scram were initiated. Reactor scram was simulated by a power decay curve. Simultaneously, in the secondary side, Main Steam Isolation Valves (MSIV) were closed along with the Main Feedwater (MFW) termination.

The transient continued with the Safety Injection (SI) signal activation when primary pressure fell below the SI set point. Some seconds after the SI signal, HPI system was initiated. The accumulators actuated when the primary pressure fell to a predetermined pressure, softening the pressure drop. Test 1.2 finished with the closure of the break valve when the primary and secondary pressures were stabilized.

5. RESULTS AND DISCUSSION

This section presents a brief description of the results obtained using the four TRACE5 models described in previous paragraphs: LSTF, scale-up LSTF, 4 and 3-loop PWR. Steady state results are compared with experimental data. Then, transient results are discussed and some improvements in TRACE5 models are explained.

5.1 Steady State Simulation

A steady-state calculation of 500 s has been performed, with a maximum time step of 0.1 s, to achieve the initial conditions of the transient. Table 5 shows relative errors (%) between experimental and simulated results for different items. In some cases, relative errors have been obtained taking into account the corresponding scale-up value. As it can be seen, the steady state conditions achieved in all simulations are in good agreement with experimental values.

5.2 Transient Simulation

In this section, results corresponding to Test 1-2 using the four TRACE5 models (LSTF, scale-up LSTF, 4 and 3-loop PWR) described in Section 4 are shown in comparison to experimental data. Furthermore, some improvements in the nodalization have been considered. They are related to the number of PIPE components used to simulate the U-tubes and the 3-D VESSEL component. Results shown in this work have been normalized to steady state values.

5.2.1 TRACE5 results

Figure 3 shows experimental and simulated system pressures (primary and secondary) obtained with four TRACE5 models. The transient starts at zero time opening the break valve in the hot leg of corresponding loop for each TRACE5 model and increasing the rotational speed of the coolant pumps. Immediately after the break opening, primary pressure starts to fall caused by the coolant leakage. Few seconds after, when primary pressure reaches a determined value, the scram signal is generated. This signal produces the initiation of the core power decay curve, the initiation of primary coolant pumps coastdown, the turbine trip, the closure of Main Steam Isolation Valves (MSIV) and termination of Main Feedwater (MFW). The primary pressure drop is momentarily stopped when, after falling below the scram pressure set point, MSIV valves are closed. With the MSIV closure, a secondary pressure rise is produced.

Then, the primary pressure continues decreasing near the secondary side pressure, remaining slightly above it. During this time interval, the secondary side keeps removing heat from the primary system while primary loop natural circulation is still on, thus raising secondary pressure. At the same time, the opening/closure cycle of the RV is produced to maintain constant secondary pressure. Once the SG U-tubes are completely empty, natural circulation is finished, secondary pressure stabilizes and primary pressure begins to fall below the secondary side.

In general, the first part of the transient, until the primary pressure decreases below the secondary one, is well reproduced with the four TRACE5 models considered, as it can be seen in Figure 3. Using both LSTF TRACE5 models, the primary pressure becomes lower than the secondary one at 1000 s and it remains quite closer to the experiment during the whole transient. However, using 4 and 3-loop PWR TRACE5 models, the primary pressure is lower than the secondary one around 700 s. From this moment on, 4 and 3-loop PWR TRACE5 results are completely different from the experimental data. Regarding the secondary pressure, slight differences are observed at long term due to discrepancies in the secondary side heat losses.

Figure 4 shows SG U-tube liquid levels. Note that the initial U-tube liquid levels in 4 and 3-loop PWR TRACE5 models are different due to geometrical differences between TRACE5 models (see Tables 1, 2 and 3). U-tubes in 4 and 3-loop PWR TRACE5 models are completely empty 300 s before than in LSTF models. This behaviour is more similar to the experiment than using LSTF TRACE5 models. However, regarding primary pressures, the natural circulation is not well reproduced using 4 and 3-loop PWR TRACE5 models.

Another important parameter in SBLOCA scenarios is the mass flow rate through the break, which is shown in Figure 5. Experimental and LSTF TRACE5 break mass flow rates have been multiplied by the corresponding Kv to be compared between them. As it can be seen, break mass flow rate is entirely one-phase liquid for the beginning of the transient until 100 s. From this moment on, break flow is turned into a two-phase mixture. This two-phase fluid regime is maintained until hot legs are empty at 1000 s, when fluid changes to single-phase vapour and the natural circulation ends. At this moment, primary pressure starts to fall below the secondary side pressure due to the large amount of vapour leaving the system and the relatively high enthalpy loss produced during this period. For this reason, the simulated break mass flow rate shows the same behaviour as primary pressures.

The first part of the transient, until the change to single-phase vapour, is well reproduced with LSTF TRACE5 model. However, the simulated mass flow rate is slightly lower than in the experiment during the two-phase flow. Moreover, the change from two-phase to single-phase vapour is delayed about 60 s. It could be attributed to the lack of a single-phase vapour coefficient in the Choked flow model of TRACE5 code.

The scale-up LSTF TRACE5 model completely agrees with LSTF behaviour during the whole transient. However, in 4 and 3-loop PWR TRACE5 models the change from two-phase mixture to single-phase vapour is advanced in comparison to the experiment. It occurs at the same time when the primary pressure becomes lower than the secondary one, which can be observed in Figure 3.

Discharged inventories, represented in Figure 6, show similar behaviour than the break mass flow rates. Experimental and LSTF TRACE5 discharged inventories have been multiplied by the corresponding Kv. Results show that LSTF and scale-up LSTF TRACE5 models have similar inventories. In both cases, simulated inventories are slightly lower than experimental ones. However, 4 and 3-loop PWR TRACE5 models inventories are still lower.

These results agree with simulated primary pressures pointing out an improper reproduction of the natural circulation using 4 and 3-loop PWR TRACE5 models.

Discrepancies between 4 and 3-loop PWR TRACE5 models in comparison to LSTF models can be attributed to geometrical differences. The number of groups used to simulate U-tubes is different. Moreover, other important fact that can affect the results is the vessel geometry, which is completely different between LSTF, and the 4 or 3-loop PWR TRACE5 models. Results obtained modifying these components are discussed in following sections.

5.2.2 U-tubes nodalization

In both LSTF models, U-tubes are simulated using three PIPE components, while in 4 and 3-loop PWR TRACE5 models only one PIPE component is used. This fact can affect the simulation of the natural circulation. Consequently, both new 4 and 3-loop PWR TRACE5 models have been developed using three groups of U-tubes.

The nodalization of these new PIPE components is the same than the original one. It corresponds to the nodalization of SG boiler for best reproducing the heat transfer between primary and secondary side.

Figure 7 shows the system pressures obtained in comparison to experimental data and the pressures obtained with LSTF and scale-up LSTF TRACE5 models. As it can be seen, using three groups of U-tubes in 4 and 3-loop PWR TRACE5 models, the primary pressure is maintained over the secondary one approximately until 1000 s in agreement with LSTF TRACE5 results and experimental data. Despite this improvement, there are still differences in simulated pressures between LSTF, scale-up LSTF, 4 and 3-loop PWR TRACE5 models. These discrepancies can be attributed to geometrical differences that remain between different TRACE5 models considered.

Figure 8 shows the U-tube liquid levels for all the cases. Now, U-tubes in 4 and 3-loop PWR TRACE5 models are emptied at 1000 s approximately, in agreement with LSTF and scale-up LSTF TRACE5 models.

Concerning the break mass flow rates, results using three groups of U-tubes are shown in Figure 9. As it can be seen, differences are clearly shown in comparison to Figure 5. The change from two-phase mixture to single-phase vapour is delayed. Break mass flow rates reproduced using 4 and 3-loop PWR TRACE5 models with three groups of U-tubes are in good agreement with LSTF model.

Consequently, the discharged inventories agree with simulated LSTF inventory, as it can be seen in Figure 10. However, simulated break mass flow rates and inventories are lower than the experiment.

Despite this improvement in the break mass flow rate and discharged inventory, there are still differences in simulated pressures between LSTF and the 4 or 3-loop PWR TRACE5 models.

5.2.3 3-D VESSEL nodalization

Following the argument that discrepancies in simulated primary pressures can be attributed to geometrical differences between models, it is observed that PV of scale-up LSTF, 4 and 3-loop PWR TRACE5 models are different.

Some differences are observed in the number of axial levels, number and position of CRGTs, volume, flow area fractions, hydraulic diameters, etc. The scale-up LSTF PV model has been developed from LSTF PV nodalization modifying it with the corresponding Kv. On the other hand, 4-loop PWR TRACE5 PV model has been simulated using the available information [5]. Despite of LSTF is a FHFP facility of Tsuruga NPP, there are some volumes in the PV that do not exactly correspond to Kv = 48, used to build LSTF. For this reason, 4-loop PWR TRACE5 model PV is different from the scale-up LSTF TRACE5 model PV. On the other hand, 3-loop PWR TRACE5 PV model is obtained from a standard 3-loop Westinghouse PWR TRACE5 model.

Trying to improve simulated pressures shown in Figure 7, the 3-D VESSEL component used in the scale-up LSTF TRACE5 model has been included in 4 and 3-loop PWR TRACE5 models. The system pressures obtained are shown in Figure 11. As it can be seen, the primary pressures show better agreement with experimental data and LSTF results, at least until 1500 s. From this moment on, the primary pressures obtained with 4 and 3-loop PWR TRACE5 models continue being different in comparison to LSTF models and the experiment.

These discrepancies can be attributed to geometrical differences that still exist between LSTF, 4 and 3-loop PWR TRACE5 models (U-tubes length, SG volume, AIS volume, etc.). In the ITF design there are differences of configuration between the facility and its PWR reference. For this reason, the 4-loop PWR TRACE5 model of Tsuruga is not exactly equal to the scale-up LSTF model. On the other hand, 3-loop PWR TRACE5 model has been obtained from a standard 3-loop Westinghouse PWR TRACE5 model, which is geometrically different from the other models. However, 4 and 3-loop PWR TRACE5 results are quite similar between them, because geometrical characteristics (U-tubes length, SG volume, AIS volume, etc.) of these TRACE5 models are closer (see Tables 1, 2 and 3).

Figure 12 shows a comparison between the break mass flow rates obtained in the experiment and using the LSTF, 4 and 3-loop PWR TRACE5 models, taking into account the corresponding Kv. As it can be seen, in both cases results are not improved respect to Figure 9. These results are confirmed when the discharged mass inventories are compared in Figure 13.

Mass flow rate and discharged inventory through the break are related to the hot leg collapsed liquid level. Figure 14 shows the TRACE5 hot leg liquid levels in comparison to the experiment. As it can be seen, all models present similar behaviour than the experiment. In all cases, the hot legs empty starts slightly after than in the experiment (at 1000 s, approximately), when fluid regime changes to one-phase vapour.

Figures 15 and 16 show the PV core and upper plenum collapsed liquid levels, respectively. All the models reproduce similar behaviour in comparison to the experiment. HPI actuation maintains the core temperature low enough to avoid core boil off, and consequently, avoiding the core level fall below fuel rods level, thus not producing a temperature excursion in the fuel cladding.

The HPI mass flow rates are shown in Figure 17. As it has been said, the HPI mass flow rate is simulated as dependent pressure table, so discrepancies in primary pressure observed between different models produce differences in the HPI mass flow rates.

6. CONCLUSIONS

Test 1-2 of the OECD/NEA ROSA Project, which simulates a 1% hot leg Small Break Loss-Of-Coolant Accident performed in the Large Scale Test Facility, has been applied to different Nuclear Power Plant models developed using the thermal hydraulic code TRACE5. These TRACE5 models are: LSTF, scale-up LSTF, a 4-loop PWR simulating Tsuruga NPP and a 3-loop PWR NPP.

A scale-up LSTF TRACE5 model has been developed from a tested LSTF TRACE5 model applying the power-to-volume scaling method and trying to preserve the Froude number in horizontal components. The suitability of the power-to-volume scaling method to preserve time, power and mass inventory in a scale-up model has been proved. Simulated results have stated that a scale-up LSTF TRACE5 model is able to reproduce the same behaviour observed in LSTF.

Using 4 and 3-loop PWR TRACE5 models, important discrepancies are observed in the main variables. Primary pressure drop is advanced because Steam Generator U-tubes are emptied early, and consequently the natural circulation is not well reproduced.

To improve results, the influence of the nodalization in the Steam Generator U-tubes and Pressure Vessel was tested. The nodalization of U-tubes clearly affects the reproduction of the natural circulation. Increasing the number of PIPE components to simulate the U-tubes, primary pressure drop is reproduced in agreement with LSTF results. The U-tubes emptied are delayed and the simulation of natural circulation is improved. However, varying the Pressure Vessel nodalization does not significantly improve the results.

Discrepancies between different TRACE5 models results can be attributed to geometrical differences that still exist between LSTF, 4 and 3-loop PWR TRACE5 models. The 4-loop PWR TRACE5 model developed to simulate Tsuruga NPP (reference PWR of LSTF) is not exactly equal to the scale-up LSTF model because of differences in the facility design. In the 3-loop PWR TRACE5 model, discrepancies are caused by different design. However, 4 and 3-loop PWR TRACE5 results are quite similar because the geometrical differences between them are slighter in comparison to the scale-up LSTF TRACE5 model.

NOMENCLATURE

1-D: One-dimensional.
3-D: Three-dimensional.
A: Area.
AIS: Accumulator Injection System.
β: Thermal expansion coefficient.
CET: Core Exit Temperature.
Cp: Specific heat.
CRGT: Control Rod Guide Tube.
D: Scale-up diameter.
d: Facility diameter.
ECCS: Emergency Core Cooling System.
F: Friction coefficient.
FHFP: Full-Height, Full-Pressure.
h: Enthalpy.
HPI: High Pressure Injection .
HTSTR: Heat Structure.
ITF: Integral Test Facility.
JAEA: Japan Atomic Energy Agency.
Kv: Volumetric scaling factor.
L: Scale-up length.
l: Facility length.
LPIS: Low Pressure Injection System.
LSTF: Large Scale Test Facility.
MSIV: Main Steam Isolation Valves.
MFW: Main Feed Water.
NEA: Nuclear Energy Agency.
OECD: Organization for Economic Co-operation and Development.
p: Pressure.
PCT: Peak Cladding Temperature.
PORV: Power Operated Relief Valve.
PV: Pressure Vessel.
PWR: Pressurized Water Reactor.
PZR: Pressurizer.
$\dot{q}^{m}$: Power density.
Φ: Power.
Q: Mass flow rate.
RHRP: Reduced-Height, Reduced-Pressure.
ROSA: Rig of Safety Assessment.
RV: Relief Valve.
ρ: Density.
SBLOCA: Small Break Loss-Of-Coolant Accident.
SG: Steam Generator.
SI: Safety Injection.
SNAP: Symbolic Nuclear Analysis Package.
T: Temperature.
t: Time.
TRACE: TRAC/RELAP Advanced Computational Engine.
u: Velocity.
UP: Upper Plenum.
US-NRC: United States Nuclear Regulatory Commission.
V: Volume.

ACKNOWLEDGMENTS

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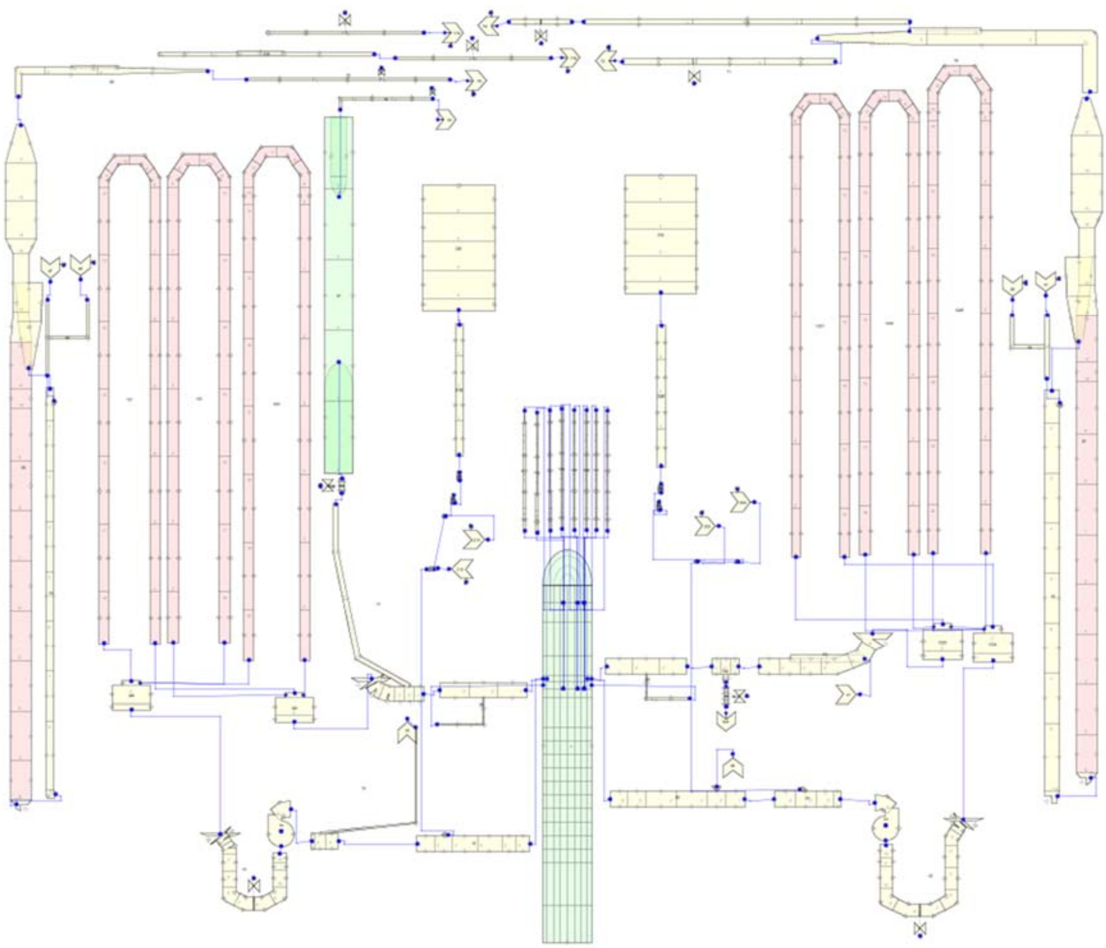

Figure 1. Model nodalization of the LSTF TRACE5 model.

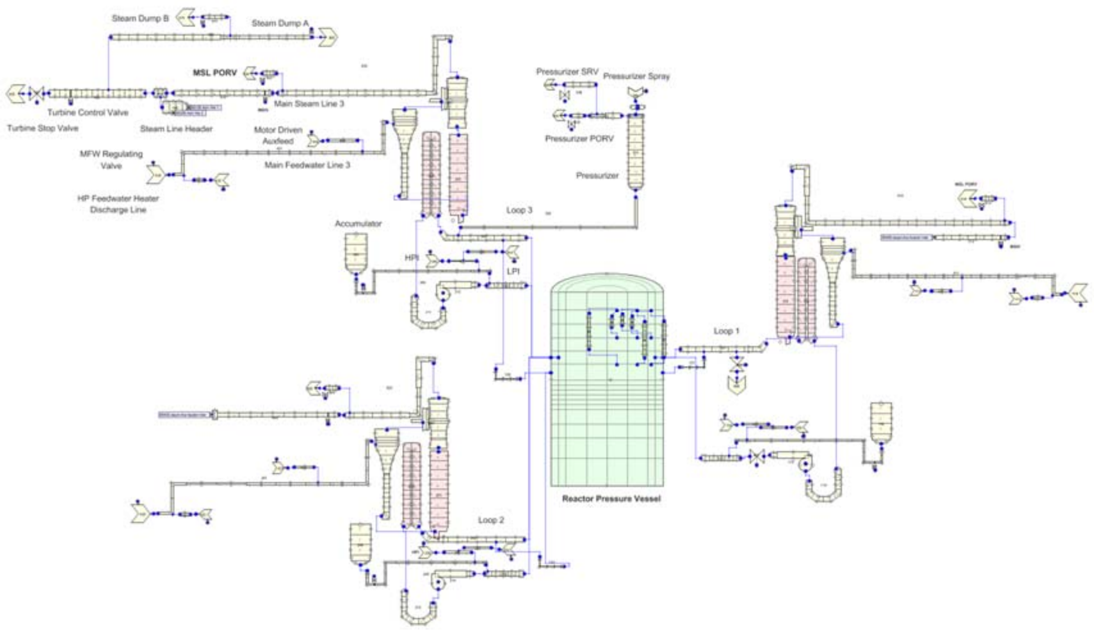

Figure 2. Model nodalization of 3-loop PWR TRACE5 model.

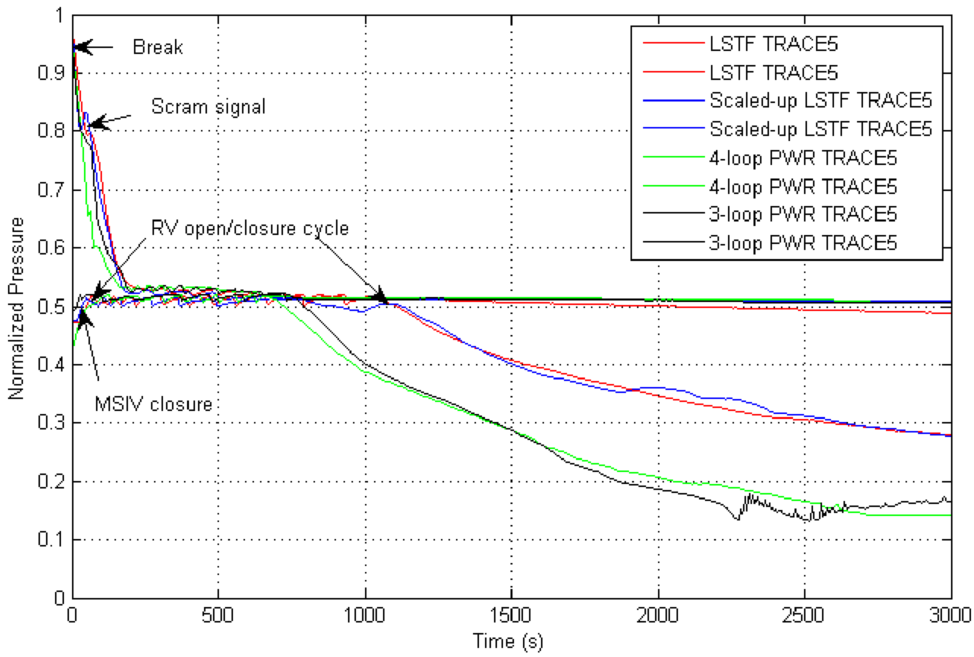

Figure 3. Experimental and simulated primary and secondary pressures.

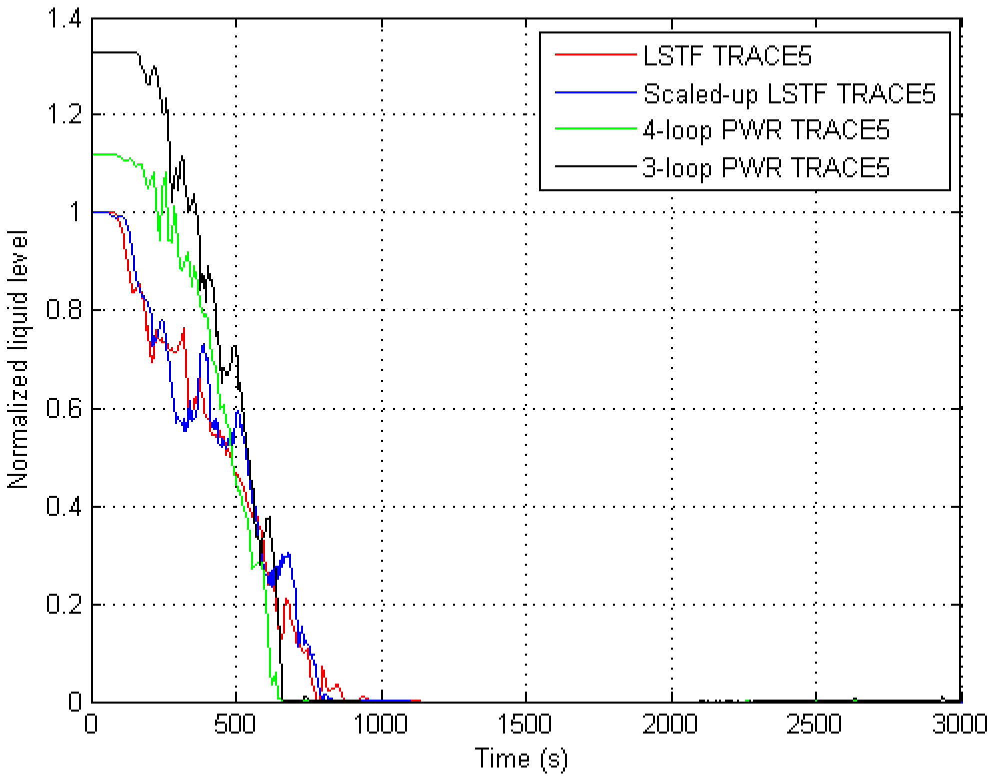

Figure 4. Experimental and simulated collapsed liquid level in SG U-tubes.

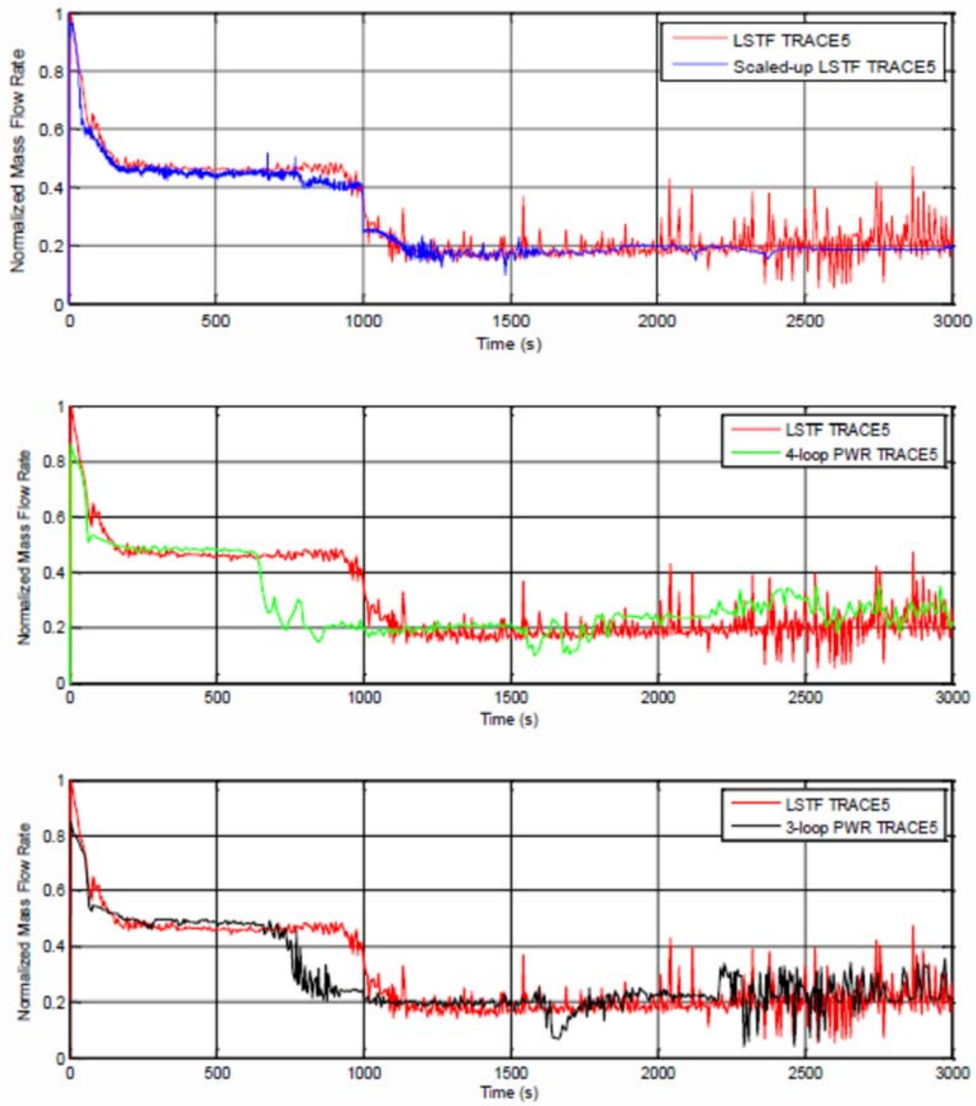

Figure 5. Experimental and simulated break mass flow rate.

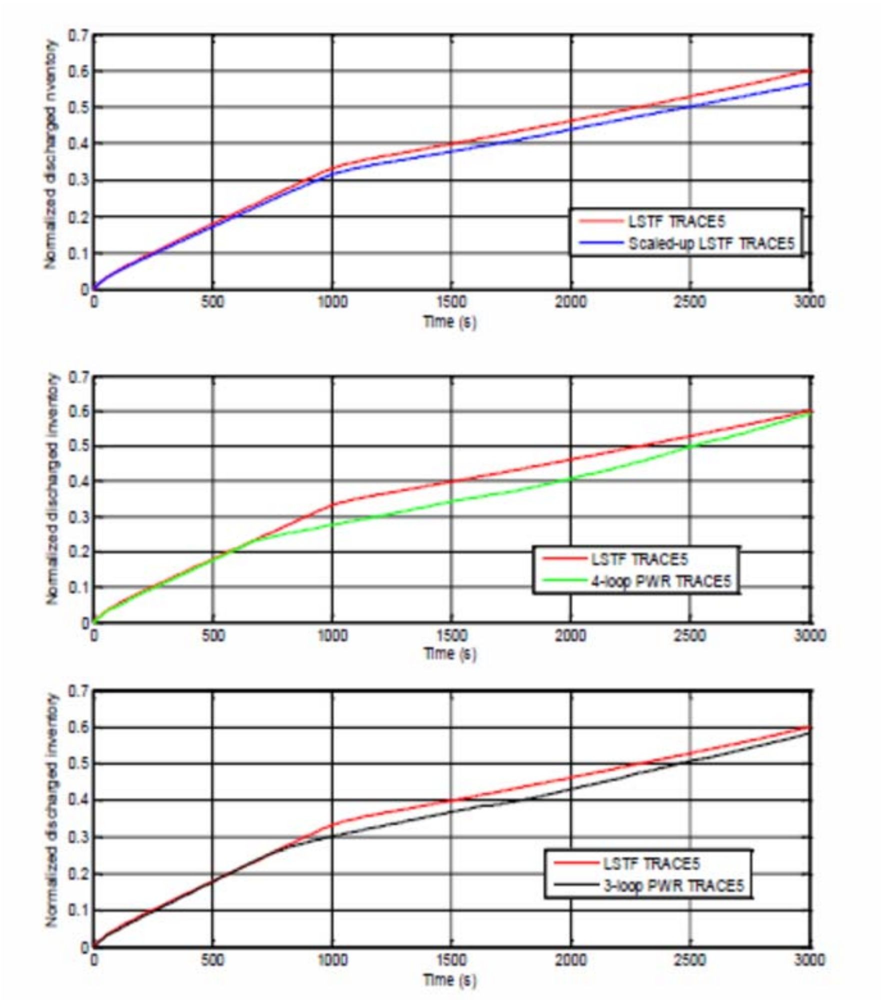

Figure 6. Experimental and simulated discharged inventory.

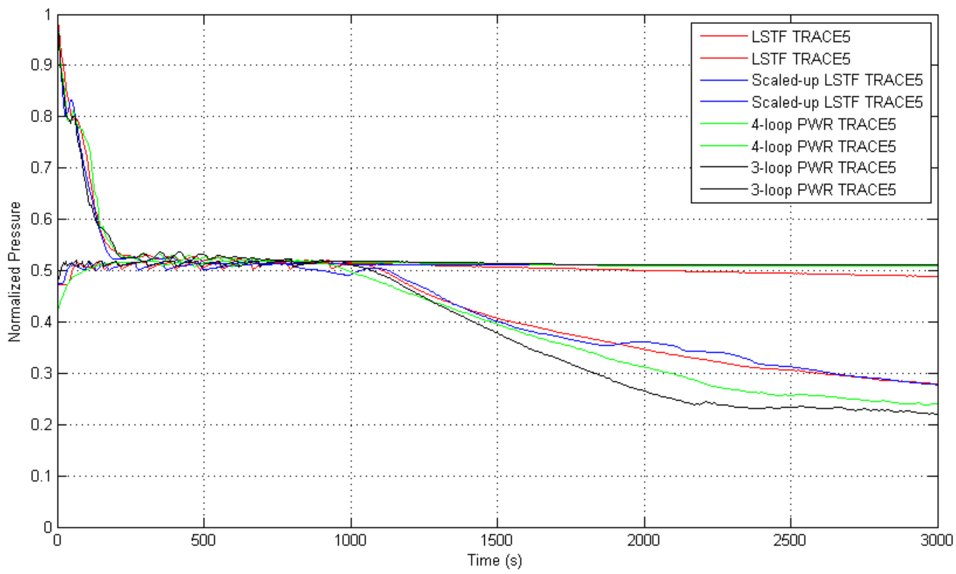

Figure 7. Experimental and simulated primary and secondary pressures using 3 groups of U-tubes.

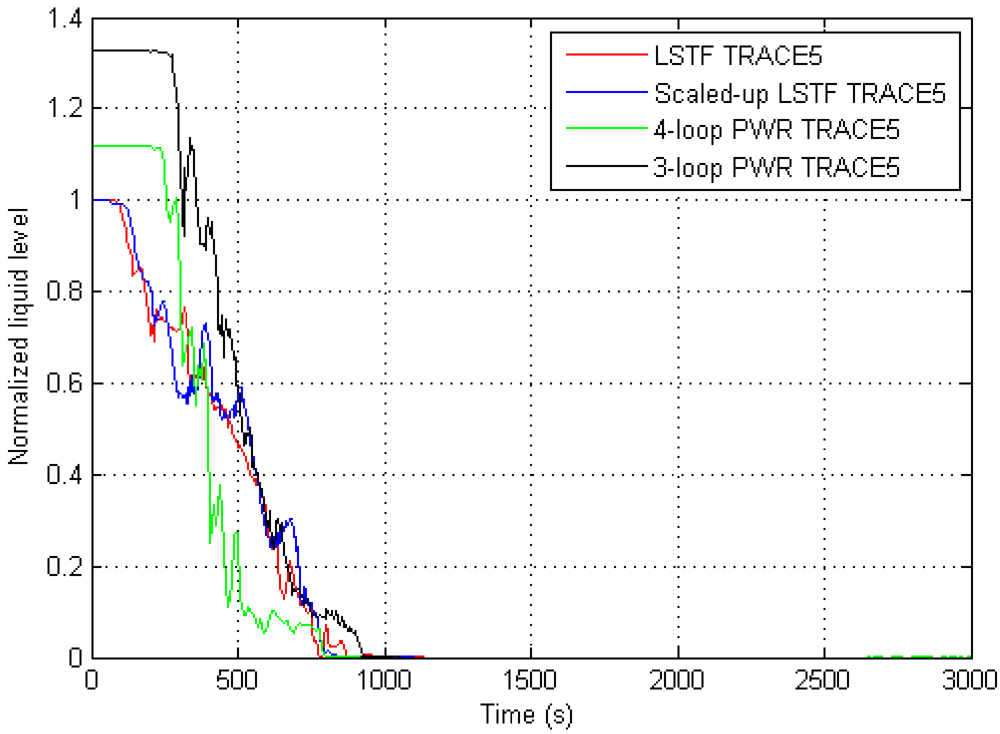

Figure 8. Experimental and simulated collapsed liquid level in SG U-tubes using 3 groups of U-tubes.

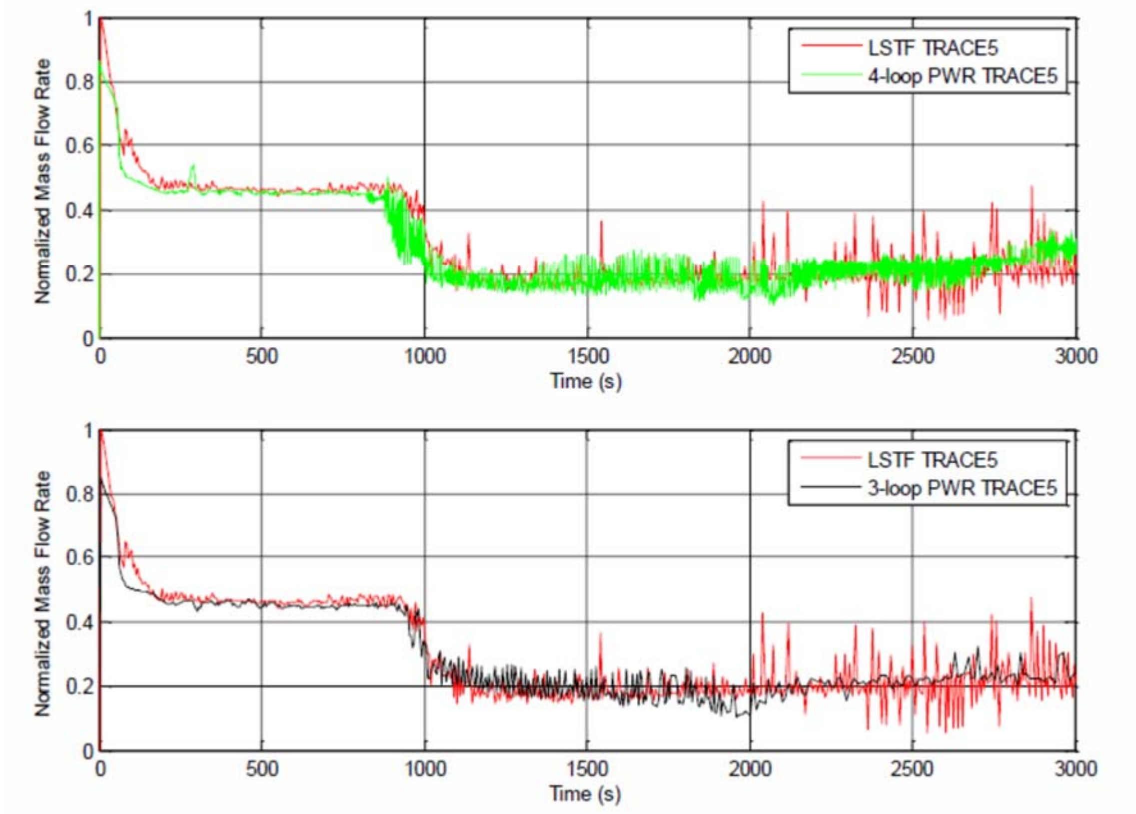

Figure 9. Experimental and simulated break mass flow rates using 3 groups of U-tubes.

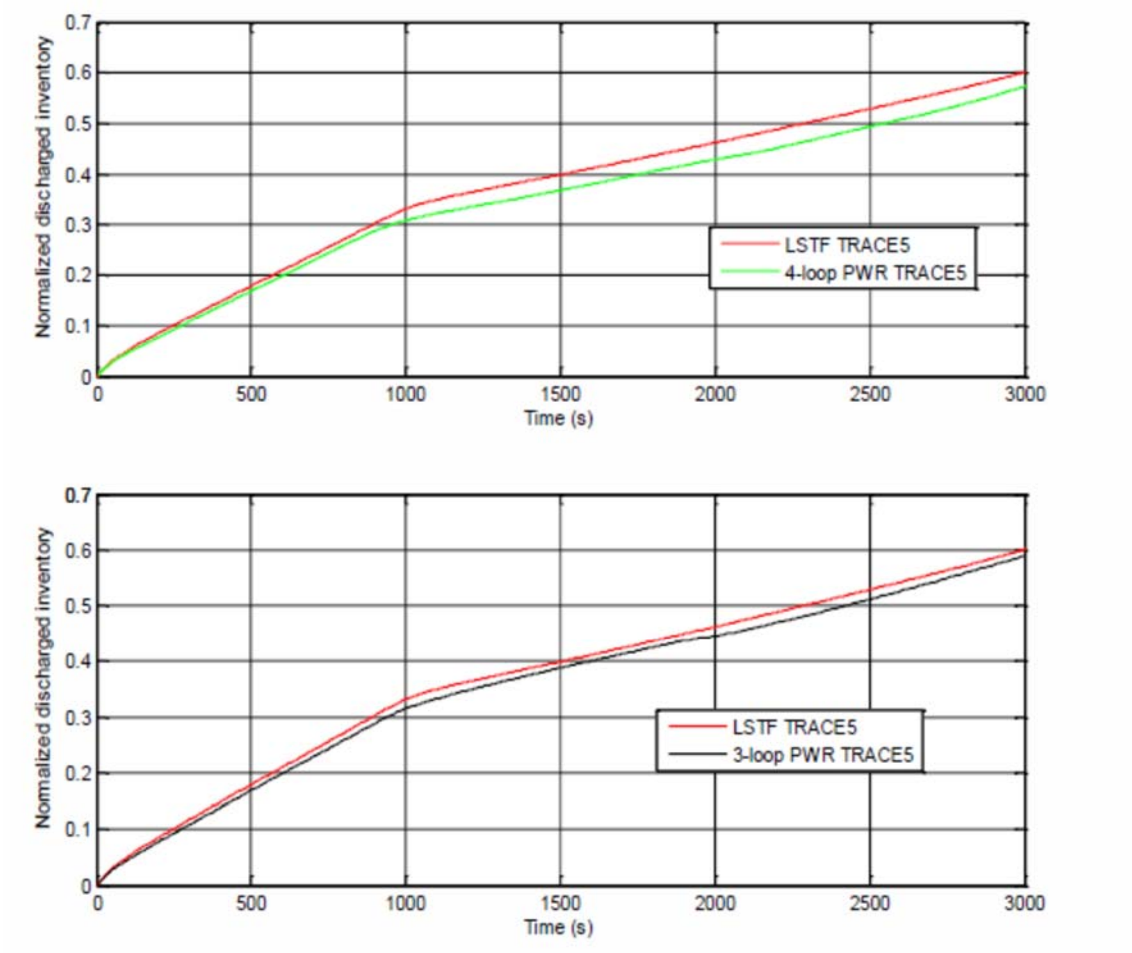

Figure 10. Experimental and simulated discharged inventory using 3 groups of U-tubes.

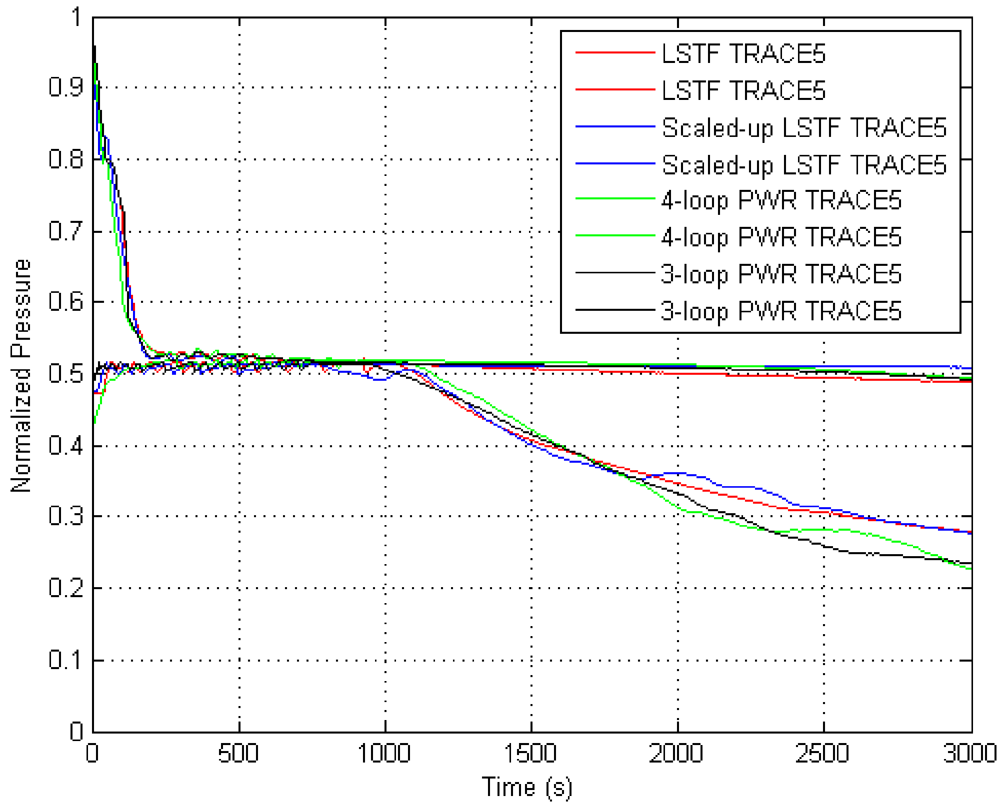

Figure 11. Experimental and simulated system pressures.

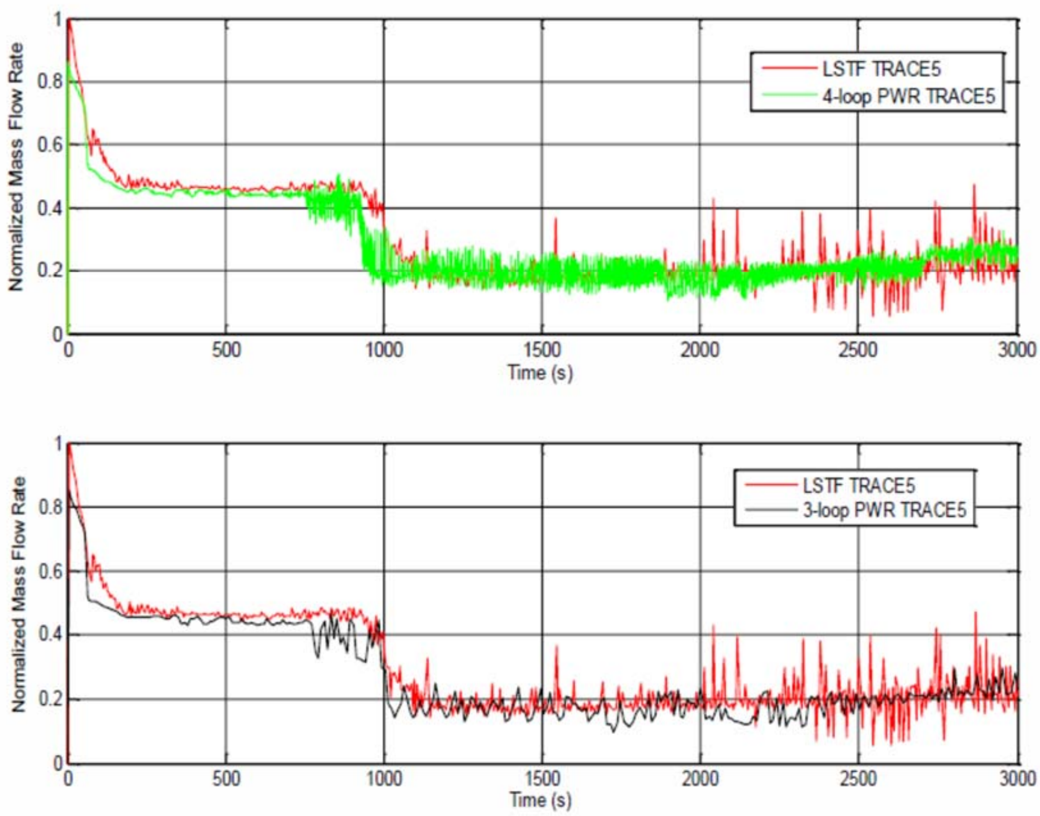

Figure 12. Experimental and simulated break mass flow rate.

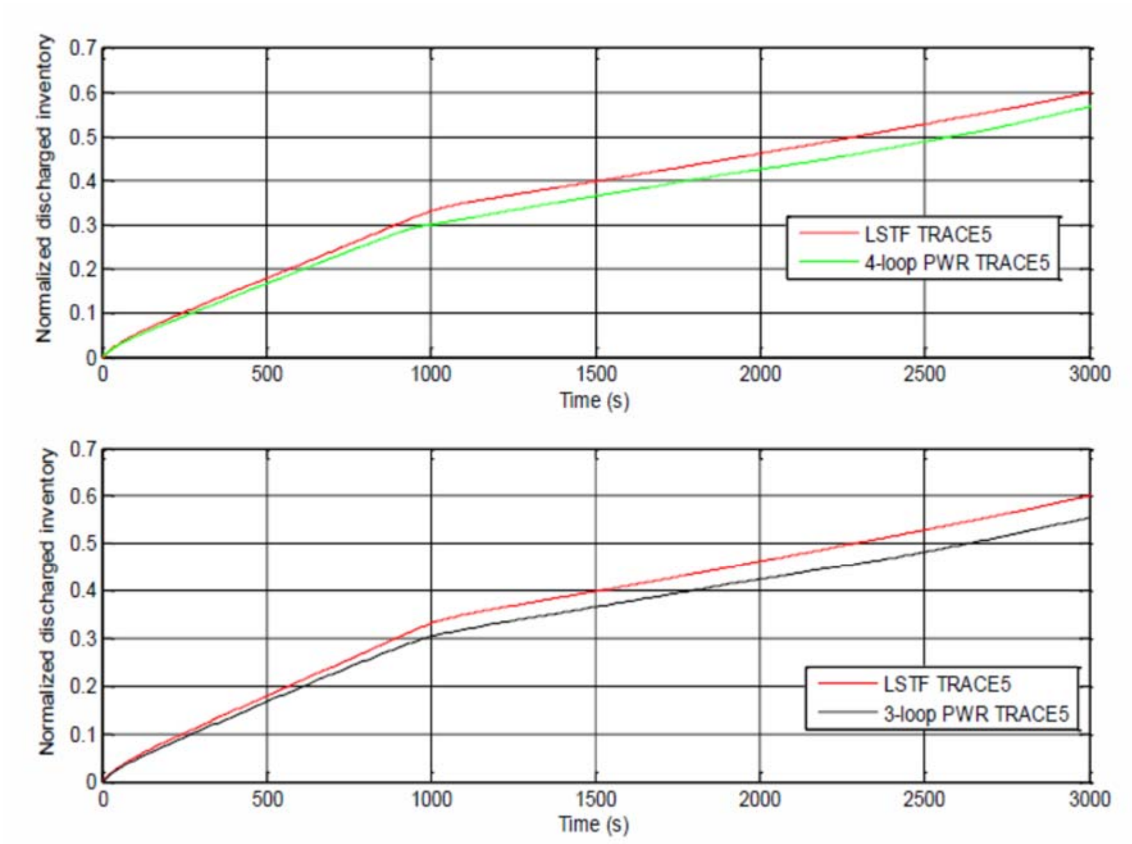

Figure 13. Experimental and simulated discharged inventory.

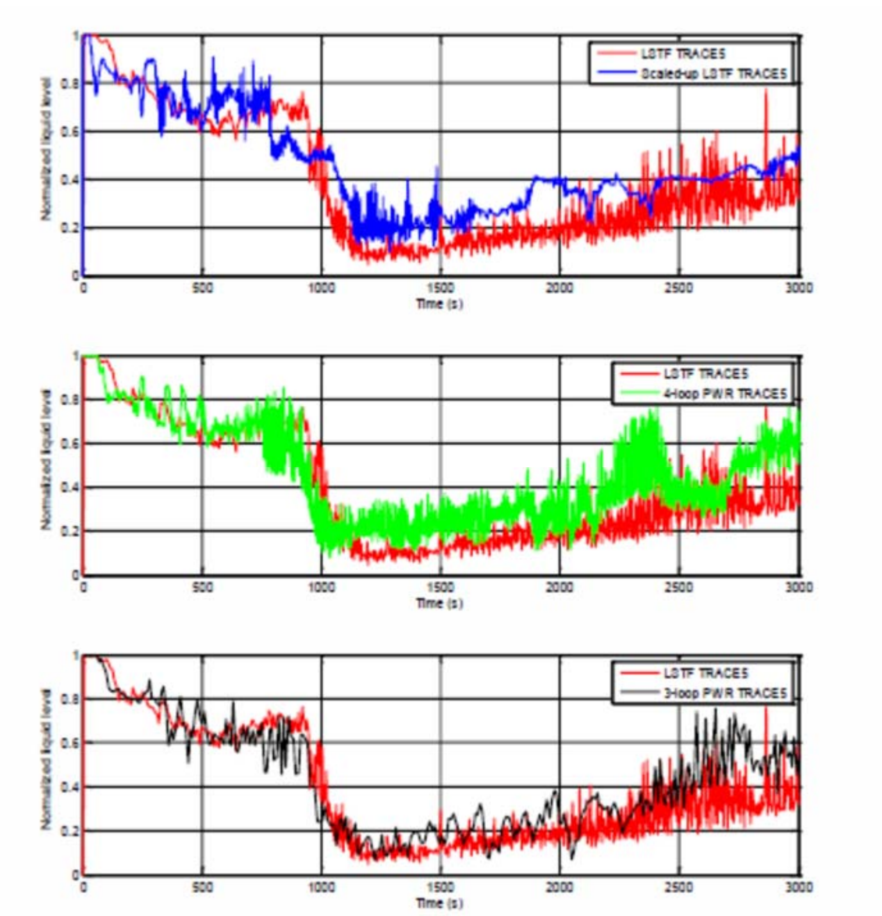

Figure 14. Experimental and simulated collapsed liquid level in hot legs.

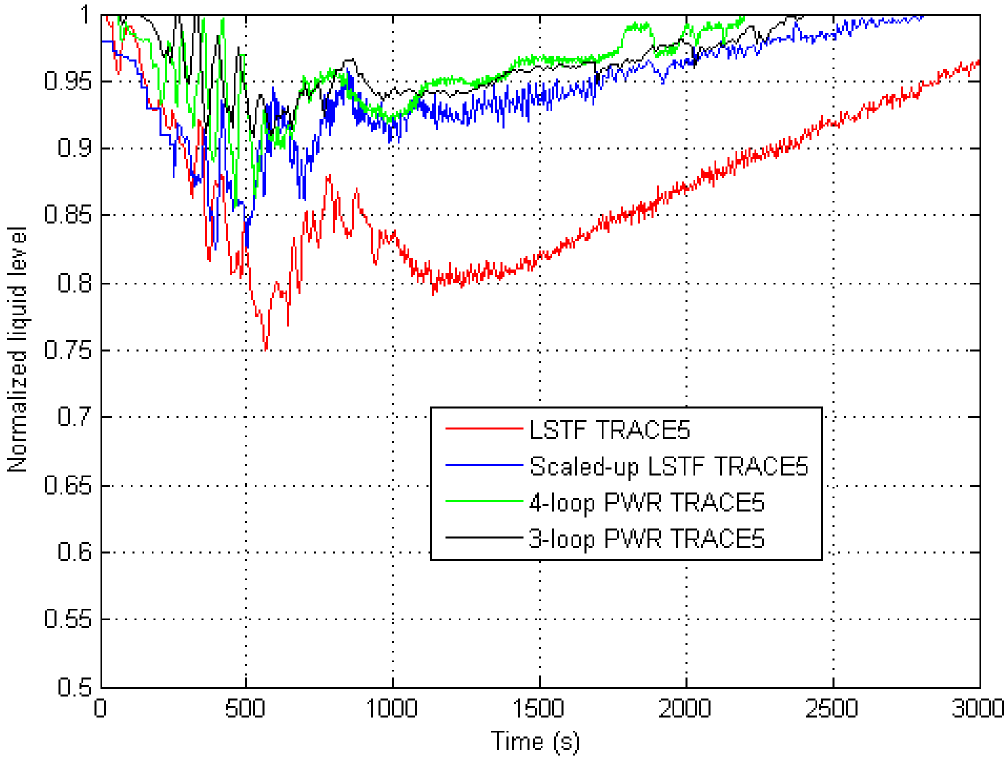

Figure 15. Experimental and simulated core collapsed liquid level.

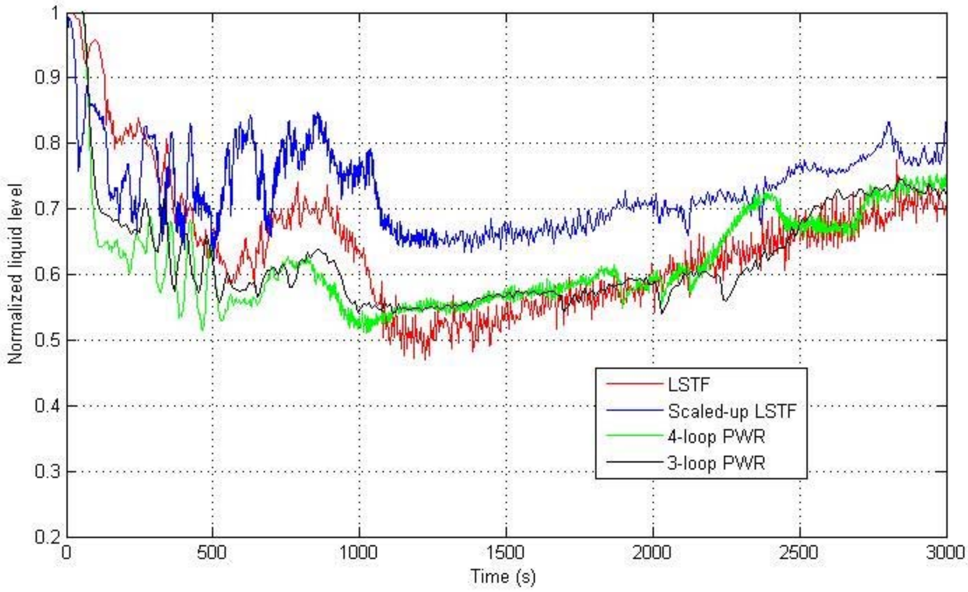

Figure 16. Experimental and simulated upper plenum collapsed liquid level.

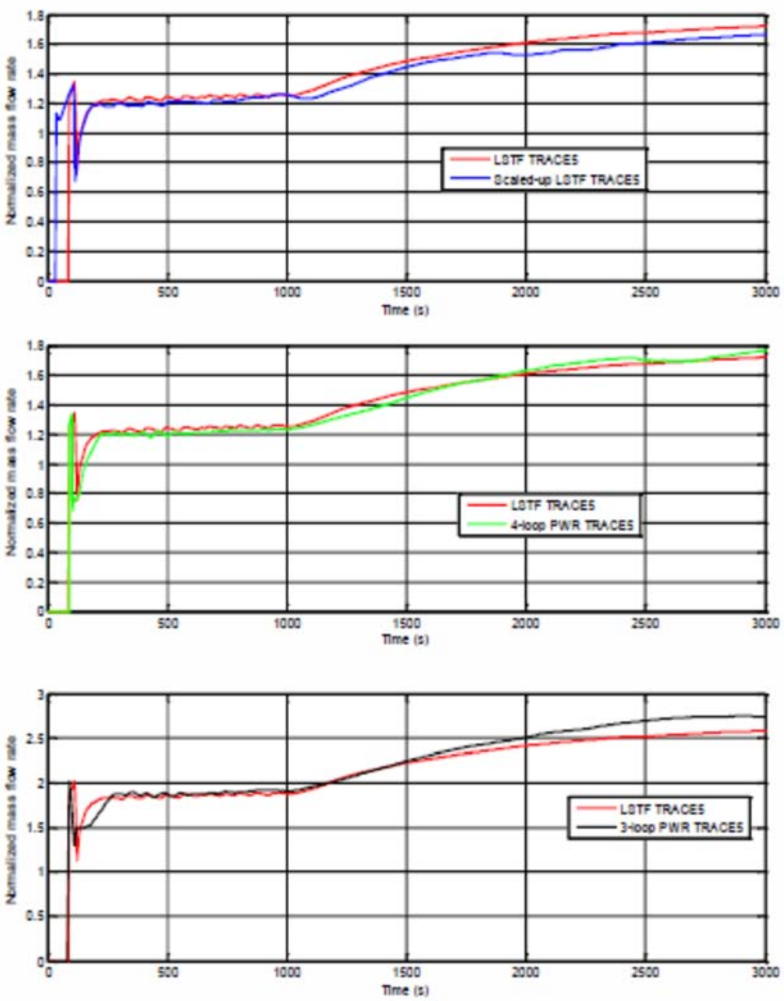

Figure 17. Experimental and simulated High Pressure Injection mass flow rates.

Table 1. The major design characteristics of the LSTF facility versus the scale-up model.

Parameter	LSTF	Scaled-up model	K_v
Primary pressure (MPa)	15.55	15.55	1
Core power (MW)	10	480	48
Number of loops	2	2	1
Vessel Height (m)	10.66	10.66	1
Core height (m)	3.66	3.66	1
Vessel volume (m^3)	2.65	127.2	48
Number of fuel rods	1008	48384	48
Number of U-tubes per SG	141	6768	48
Average length of U-tubes	19.7	19.7	1
Hot leg inner diameter (m)	0.207	0.974	Fr. Num.
Hot leg length (m)	3.7	8	Fr. Num.
$L/\sqrt{D}$	8.1	8.1	1
Cold leg inner diameter (m)	0.207	0.974	Fr. Num.
Cold leg length (m)	3.34	7.44	Fr. Num.
1 % Break area (m^2)	8.02 e-5	3.846 e-3	48
Accumulator volume (m^3)	1.64	78.72	48
SG volume (m^3)	7.93	380.64	48
Main Feedwater flow rate (kg/s)	2.74	131.52	48

Table 2. The major design characteristics of the LSTF facility versus 4-loop PWR model (Tsuruga).

Parameter	LSTF	4-loop PWR Tsuruga	K_v
Primary pressure (MPa)	15.55	15.55	1
Core power (MW)	10	480 (14% of 3423)	48
Number of loops	2	4	
Vessel Height (m)	10.66	10.66	1
Core height (m)	3.66	3.66	1
Vessel volume (m^3)	2.65	137.4	50.1
Number of fuel rods	1008	50952	50.55
Number of U-tubes per SG	141	3382	24
Average length of U-tubes	19.7	20.2	1.025
Hot leg inner diameter (m)	0.207	0.737	
Hot leg length (m)	3.7	6.99	
$L/\sqrt{D}$	8.1	8.1	1
Cold leg inner diameter (m)	0.207	0.6985	
Cold leg length (m)	3.34	7.2465	
1 % Break area (m^2)	8.02 e-5	3.85 e-3	48
Accumulator volume (m^3)	1.64	33.86	20.64
SG volume (m^3)	7.93	140.19	17.67
Main Feedwater flow rate (kg/s)	2.74	68.64	50.1

Table 3. Main characteristics of standard 4 and 3-loop PWR.

Parameter	LSTF	3-loop PWR	K_v
Primary pressure (MPa)	15.55	15.55	
Core power (MW)	10	376 (14 % of 2686)	37.6
Number of loops	2	3	
Vessel Height (m)	10.66	12.24	1.15
Core height (m)	3.66	3.66	1
Vessel volume (m^3)	2.65	94.79	35.77
Number of fuel rods	1008	36056	35.77
Number of U-tubes per SG	141	2521	35.77
Average length of U-tubes	19.7	23.9	1.21
Hot leg inner diameter (m)	0.207	0.737	
Hot leg length (m)	3.7	6.99	
$L/\sqrt{D}$	8.1	8.1	1
Cold leg inner diameter (m)	0.207	0.6985	
Cold leg length (m)	3.34	5.6	
1 % Break area (m^2)	8.02 e-5	$2.87 \cdot 10^{-3}$	35.77
Accumulator volume (m^3)	1.64	33.86	20.64
SG volume (m^3)	7.93	140.19	17.68
Main Feedwater flow rate (kg/s)	2.74	65.34	35.77

Table 4. Control logic and sequence of major events during the Test 1-2 performed in LSTF.

Event	Condition
Break	Time zero
Reactor scram signal	Primary pressure =determined value
Initiation of core power decay curve simulation	Generation of scram signal
Initiation of Primary Coolant Pump coastdown	Generation of scram signal
Closure of Main Steam Isolation Valve (MSIV)	Generation of scram signal
Termination of Main Feedwater (MFW)	Generation of scram signal
Pressurizer (PZR) heater off	Generation of scram signal
Safety Injection (SI) signal	Primary pressure =determined value
High Pressure Injection (HPI)	SI signal + some seconds
Accumulator Injection System (AIS)	Primary pressure =determined value

Table 5. Steady-state condition. Comparison between experimental data and TRACE5 results. Relative error respect to experimental results (%) into brackets.

Item	LSTF model	Scaled-up LSTF model	4-loop PWR Tsuruga model	3-loop PWR model
Core Power (MV)	10 (0.0)	480 (0.0)	480 (0.0)	376 (0.0)
Cold Leg Fluid Temperature (ºC)	564.6 (0.28)	565.4 (0.43)	565.16 (0.38)	565.04 (0.36)
PZR Pressure (MPa)	15.59 (0.32)	15.55 (0.06)	15.50 (-0.26)	15.51 (-0.19)
SG Secondary-side Pressure (MPa)	7.38 (0.68)	7.4 (0.95)	7.47 (1.91)	7.45 (1.64)
Secondary-side liquid level (m)	10.8 (5.26)	10.84 (5.65)	10.02 (2.34)	10.23 (0.29)
Main Feed Water flow rate per loop (kg/s)	2.74 (0.00)	131.52 (0.00)	65.76 (0.00)	65.34 (0.00)
Primary Mass flow rate (kg/s)	25.97 (2.24)	1100 (8.33)	1177 (1.92)	1134 (5.5)
Main steam flow rate per loop (kg/s)	2.67 (2.55)	138.4 (5.25)	67.34 (2.4)	70.8 (8.36)
Total discharged inventory (kg)	$5.09 \cdot 10^3$	$2.44 \cdot 10^5$	$2.44 \cdot 10^5$	$1.92 \cdot 10^5$