A STRONGLY COUPLED REACTOR CORE ISOLATION COOLING SYSTEM MODEL FOR EXTENDED STATION BLACK-OUT ANALYSES

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ABSTRACT

The reactor core isolation cooling (RCIC) system in a boiling water reactor (BWR) provides makeup cooling water to the reactor pressure vessel (RPV) when the main steam lines are isolated and the normal supply of water to the reactor vessel is lost. As part of the effort to develop the new reactor system safety analysis code RELAP-7, we have developed a strongly coupled RCIC system model, which consists of a turbine model, a pump model, a check valve model, a wet well model, and their coupling models. Unlike the traditional SBO simulations where mass flow rates are typically given in the input file through time dependent functions, the real mass flow rates through the turbine and the pump loops in our model are dynamically calculated according to conservation laws and turbine operation curve. A simplified SBO demonstration RELAP-7 model with this RCIC model has been successfully developed. The demonstration model includes the major components for the primary system of a BWR, as well as the safety system components such as the safety relief valve (SRV), the RCIC system, the wet well, and the dry well. The results show reasonable system behaviors while exhibiting rich dynamics such as variable flow rates through RCIC turbine and pump during the SBO transient. The model has the potential to resolve the Fukushima RCIC mystery after adding the off-design two-phase turbine operation model and other additional improvements.

KEYWORDS
SBO, RCIC, RELAP-7, Strongly Coupled

1. INTRODUCTION

The reactor core isolation cooling (RCIC) system in a boiling water reactor (BWR) provides makeup cooling water to the reactor pressure vessel (RPV) when the main steam lines are isolated and the normal supply of water to the reactor vessel is lost. The RCIC system operates independently of AC power, service air, or external cooling water systems. The only required external energy source is from the battery to maintain the logic circuits to control the opening and/or closure of valves in the RCIC systems in order to control the RPV water level by shutting down the RCIC pump to avoid overfilling the RPV and flooding the steam line to the RCIC turbine. It was one of the very few safety systems still available during the Fukushima Daiichi accidents after the tsunami hit the plants and the system successfully delayed the core meltdown for a few days for unit 2 & 3 [1, 2].

The RCIC system, as shown in Figure 1 [3], consists of a turbine and a turbine-driven pump, piping and valves necessary to deliver water to the reactor vessel at accident conditions. The turbine is driven by high-temperature and high-pressure steam and is designed to rapidly accelerate from standby to the full load condition within a pre-prescribed time period. The turbine exhaust steam is routed to the suppression pool. The turbine-driven pump supplies makeup water from the condensate storage tank or the suppression pool, to the reactor vessel via the feedwater piping. The wet well of a BWR containment consists of the suppression pool and the gas space above it. The suppression pool is the alternate source of water for the RCIC pump and it condenses steam from the turbine exhaust or from safety relief valves.

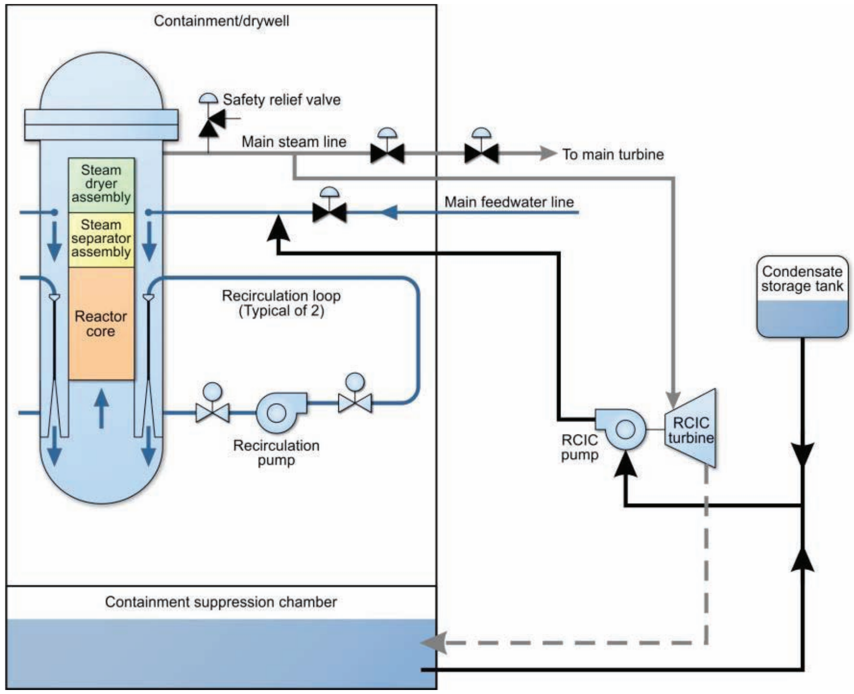

Figure 1. Reactor Core Isolation Cooling (RCIC) system (Credit of U.S. NRC [3]).

It is generally considered in almost all the existing station black-out accidents (SBO) analyses [2, 4-7] that loss of the DC power would result in overfilling the steam line and allowing liquid water to flow into the RCIC turbine, where it is assumed that the turbine would then be disabled. This behavior, however, was not observed in the Fukushima Daiichi accidents, where the Unit 2 RCIC functioned without DC power for nearly three days. Moreover, almost all these analyses replace dynamical physics with given boundary conditions, which are based on limited knowledge and assumptions. For example, in the TRAC model for Fukushima accidents [2], the RCIC was actuated under the assumption that the steam flow rate to the RCIC turbine and the injection flow rate from the RCIC pump were both balanced with the reactor decay heat power. In MAPP models [5], the flow rate through RCIC system is through user input tables. Therefore, more detailed mechanistic models for RCIC system components are needed to understand the extended SBO for BWRs.

The RELAP-7 code [8-10] is a new nuclear reactor system safety analysis code currently being developed at the Idaho National Laboratory (INL). All the physics are integrated into a single fully coupled nonlinear equation system in RELAP-7. The nonlinear equation system is solved with Newton's method such as Jacobian free Newton Krylov (JFNK) method. Unlike traditional system codes, all the physics in RELAP-7 are fully coupled and the errors resulted from the traditional operator splitting approach are eliminated.

Reactor systems are very complex and contain hundreds of different physical components. Therefore, it is impractical to resolve the geometry of the whole system. Instead, like all the existing reactor system codes, simplified thermal hydraulic models are used in RELAP-7 to represent the major physical components and describe major physical processes such as fluid flow and heat transfer. There are three main types of components developed in RELAP-7: one-dimensional (1-D) components, zero-dimensional (0-D) components for setting boundary conditions (BC) for the 1-D components, and 0-D components for connecting 1-D components and describing additional 0-D averaged physics processes. 1-D components, such as pipe, heat exchanger, and core channel, describe 1-D fluid flow model and additional heat conduction model. Zou et al. [8] described the single-phase fluid flow model and several 1-D component models developed in RELAP-7. For 1-D single-phase fluid subsonic flow, two boundary conditions such as momentum and temperature or pressure and temperature are needed for the in-flow boundary and one boundary condition such as pressure is needed for the out-flow boundary. 0-D components will provide those boundary conditions for 1-D fluid flow models. Zhao et al. [9] described related 0-D components for simulating a simplified RCIC system and wet well in RELAP-7, in which a dynamic RCIC turbine was used but a user given time dependent mass flow rate was used to simulate the RCIC pump behavior.

In this paper, an improved RCIC system model is presented, which is based on fully coupled models. Instead of using an ideal pump component whose flow rate was manually set by the user input in the previous SBO demonstration simulation [9-10] (this method was also used by all the existing BWR SBO analyses with RELAP5, MELCOR, or MAAP), the pump flow rate in the new model is dynamically determined by the driving turbine and flow resistance in the RCIC pump loop. In order to prevent primary water reversely flowing out from the RCIC pump to the suppression pool, a check valve at the RCIC pump outlet is simulated.

The paper is organized in the following way: section 2 will summarize the major component models for the strongly coupled RCIC system; section 3 will present the BWR SBO model with the RCIC system model; section 4 shows major simulation result; section 5 presents the conclusion and future works.

2. SUMMARY OF MAJOR RCIC COMPONENT MODELS

For the simplified SBO simulations, we assume that pure steam flows through the discharging pipelines to the suppression pool and pure water is drawn from the suppression pool into reactor vessel. Therefore, the single phase 1-D fluid flow model can be used for RCIC system simulation. The detailed 1-D fluid flow models and 0-D models had been discussed in our previous publications [8-9, 11] and will not be repeated here. This section summarizes the major 0-D safety component models involved to simulate a strongly coupled RCIC system under design conditions. Additional model development will be needed in the future to simulate the off-design situations when battery power is not available and the steam discharge line may be flooded.

2.1. RCIC Turbine Model

A turbine is a device that converts energy contained in high-pressure and high-temperature fluid into mechanical work. The complicated configuration of a turbine precludes a complete first-principle model, at least for the purpose of system transient calculations. In RELAP5 [12], quasi-steady state mass, momentum, and energy conservation equations are used for flow across a turbine stage. However, several questionable assumptions, such as constant density across the turbine blade stage, are used to derive the momentum equation. For a complex curved flow path, it is almost impossible to derive an accurate 0-D momentum equation. The force between the junction solid wall and the fluid is unknown due to the lack of geometric definition in 0-D and no simple assumptions could be made. This is why Bernoulli's equation (or mechanical energy conservation equation) is used instead for 0-D junction or branch models in current reactor safety system codes such as RELAP5 [12], TRAC [13], and TRACE [14]. However, for compressible flow in a turbine, Bernoulli's equation for isentropic compressible flow is identical to the total energy conservation equation. Hence, the Bernoulli's equation cannot be used for momentum.

Lacking an equation for momentum, we instead use turbine characteristics curves for momentum, which is based on actual dynamical turbine performance data. Turbine characteristics curves reflect the complex relationships of the non-dimensional turbine mass flow rate and turbine efficiency with pressure ratio and the non-dimensional rotational speed. Figure 2 shows one example of turbine characteristics curves [15]. In the figure, subscript 01 indicates upstream stagnation condition, subscript 02 indicates downstream stagnation condition and N is the rotational speed. Note that the curves dynamically capture the choking behavior. To further simplify the curves, we make several assumptions: (1) Turbine thermal efficiency is constant; (2) Non-dimensional mass flow rate is not a function of non-dimensional rotational speed by noting that all the curves for different rotational speeds tend to collapse together. With these assumptions, we do not need an equation for rotational speed; and only one characteristics curve for mass flow rate is enough to establish the equation for momentum.

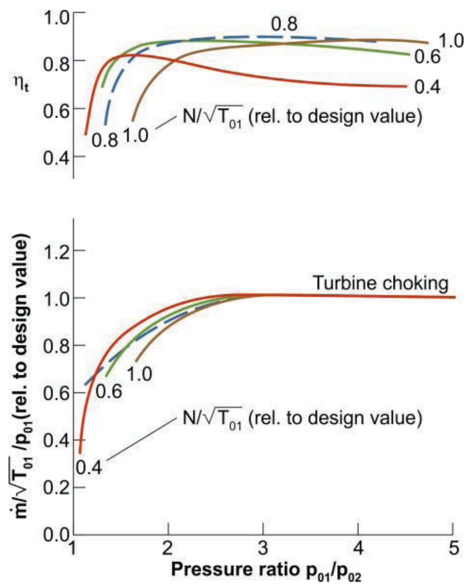

Figure 2. Turbine characteristics curves.

Based upon the aforementioned discussion, we developed a new simple turbine component model as a junction without volume. Thermal inertia in the solid structures and fluid is ignored, similar to that in RELAP-5. Figure 3 shows the T-s diagram for a thermodynamical process in a turbine. Point 1 represents inlet static condition and point 2 represents outlet static condition; point 2s is the end point for a revisable process; point 01, 02, and 02s represent the stagnation conditions corresponding to points 1, 2, and 02, respectively.

Since a quasi-steady state turbine is a 0-D component which provides:

- one BC for inlet pipe: p_1 – inlet pressure
- two BCs for outlet pipe: p_2 – outlet pressure, ρ_2 – outlet density
- turbine shaft power: $\dot{W}_t$,

we need four equations to close the system.

The first one is mass conservation, the same one as used in RELAP5

$$(\rho u)_1 A_1 \hat{n}_1 + (\rho u)_2 A_2 \hat{n}_2 = 0 \tag{1}$$

where ρu is the momentum for connecting pipe, A the cross-section area, and $\hat{n}$ direction normal ($\hat{n}$ =1 for turbine inlet and $\hat{n}$ = -1 for turbine outlet). Mass flow rate $\dot{m} = \rho u A$.

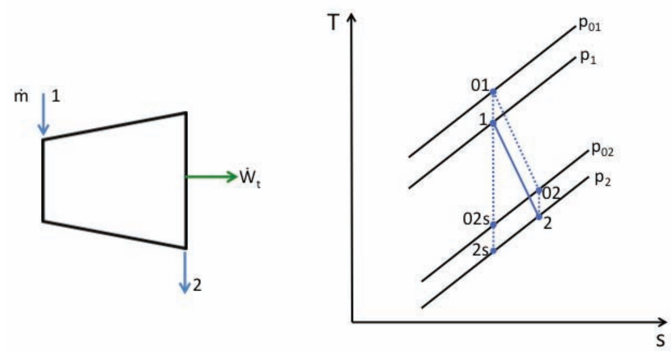

Figure 3. T-s diagram for a turbine.

As discussed before, we use turbine characteristics for momentum equation. Assuming constant thermal efficiency and ignoring rotational speed effect, we have

$$\frac{\frac{\dot{m}\sqrt{T_{01}}}{p_{01}}}{\frac{\dot{m}_{\max}\sqrt{T_{01r}}}{p_{01r}}} = f(p_{01}/p_{02}) \tag{2}$$

The subscript r denotes nominal design reference value and 0 denotes stagnation condition. $\dot{m}_{max}$ is the nominal maximum design mass flow rate through the turbine. The turbine characteristic curve $f(p_{01}/p_{02})$ should come from turbine vendors.

The energy equation for turbine is

$$\eta = \frac{h_{01}-h_{02}}{h_{01}-h_{02s}} \tag{3}$$

where η is the turbine thermal efficiency, and h the enthalpy. Figure 3 shows the locations of the thermodynamic states on a T-s diagram.

Turbine shaft work is calculated by

$$\dot{W}_t = \dot{m}(h_{01} - h_{02}) \tag{4}$$

We use Eq. (1) to (3) to solve for p_1, p_2, and ρ_2, and use Eq. (4) to compute turbine power. When the stagnation pressure at the inlet is less than the stagnation pressure at the outlet, the turbine is treated as a closed valve. Major physical parameters for the turbine model include thermal efficiency, nominal mass flow rate, design pressure ratio, and design stagnation inlet temperature and pressure.

2.2. Pump Model

The simplified pump model is based on three assumptions:

- quasi-steady state,
- incompressible flow,
- and 100% pump efficiency.

We designed the pump as one 0-D junction component which provides:

- one BC for upstream pipe: pressure
- two BCs for downstream pipe: pressure and total energy.

Only one scalar variable – pump pressure p_J is defined as the unknown for the pump model, which uses the mass balance Eq. (1) as the nonlinear equation. Assuming internal energy does not change through a pump. Pressures at inlet and outlet are calculated with incompressible flow Bernoulli's equation. We assume that the pump work is added to the fluid only in the entrance segment and the loss in the exit segment is ignored. For normal flow

$$p_1 = \left(p_J + \frac{1}{2}\rho_J u_J^2\right) - \rho_1 g H - \frac{1}{2}\rho_1 u_1^2 \tag{5}$$

$$p_2 = \left(p_J + \frac{1}{2}\rho_J u_J^2\right) - \frac{1}{2}\rho_2 u_2^2 \tag{6}$$

where

$$u_J = \frac{\rho_1 u_1 A_1}{\rho_J A_J}. \tag{7}$$

g is the gravity constant and H is the pump head. H can be set as an input parameter which can be changed through the control system to simulate dynamic process such as coastdown or H can be calculated by coupling with a shaft work, i.e., provided by a turbine,

$$H = \frac{\dot{W}_t}{\rho_1 u_1 A_1 g} \tag{8}$$

For reverse flow, the pump is treated as a resistance junction. The reverse form loss coefficients for inlet (K_1) and outlet (K_2) are given by users.

2.3. Check Valve Model

The check valve model is needed to prevent the reverse flow through the RCIC pump line (or loss of water from the primary system to the wet well). The check valve component is a simplified model to simulate the fundamental functions (i.e. open and close) of check valves. It is triggered by a trigger condition to open or close. In its opening status, either fully open or partially open, it serves as a regular flow junction with form losses calculated by the abrupt area change model. In its fully closed status, the connected two pipes are physically isolated. The check valve model also includes the gradually open/close capability to simulate the physical response time. It has the benefit of avoiding spurious numerical oscillations that are caused by an instantaneous open/close procedure.

For a closed valve, the valve will open within the given response time when:

$$(P_{in} - P_{out}) + \rho g (z_{in} - z_{out}) > P_{back} \tag{9}$$

For an opened valve, the valve will close within the given response time according to one of three available check valve types when:

$$(P_{in} - P_{out}) + \rho g (z_{in} - z_{out}) < P_{back} \;\; for\ static\ pressure\ controlled\ check\ valve \tag{10}$$

$$u_J < 0 \;\; for\ flow\ controlled\ check\ valve \tag{11}$$

$$(P_{in} - P_{out}) + \rho g(z_{in} - z_{out}) + \frac{1}{2} \;\; u_J^2 < P_{back} \;\; for\ dynamic\ pressure\ controlled\ check\ valve \tag{12}$$

The flow controlled check valve model is used for the SBO simulation model discussed later.

2.4. Wet Well Model

The wet well refers the suppression chamber, which is composed of water space and gas space. The 0-D wet well model simulates both spaces. Figure 4 shows the schematic of the simplified model. Major assumptions include: (1) the suppression pool is well mixed; (2) ignore the kinetic energy in both spaces therefore the water space pressure follows hydrostatic distribution; (3) no mass transfer between water and gas space; (4) gas space is filled with 100% nitrogen gas; (5) the geometry of the wet well is rectangular; and (6) no steam venting from dry well to the suppression pool. The wet well model developed with these assumptions is adequate to simulate slow transients such as extended station black-out transients. However, the current model is not suitable for LOCA analysis.

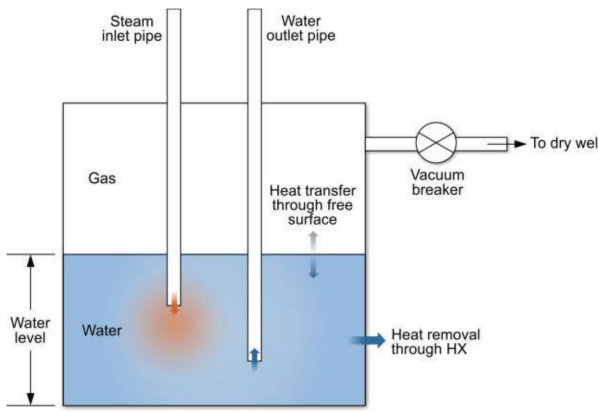

Figure 4. A simplified wet well model.

With those assumptions, we have mass and energy conservation for both gas and water spaces. Assuming one pressure for gas space, we have another equation for the water level. Mass conservation equation for the gas space is

$$\frac{\mathrm{d}m_g}{\mathrm{dt}} = -\dot{m}_v \tag{13}$$

where m_g is the gas mass and $\dot{m}_v$ is the venting mass flow rate to the dry well and is obtained from the connected pipe controlled by the vacuum breaker.

Energy conservation equation for the gas space is

$$\frac{d(me)_g}{dt} = A_c\alpha\left(T_w - T_g\right) - \dot{m}_v H_v \tag{14}$$

where $(me)_g$ is the total internal energy (also total energy since kinetic energy is assumed to be 0) for the gas space, A_c the average cross section area for the wet well, α the effective heat transfer coefficient given by user input, T_w and T_g are temperatures for water and gas, respectively. H_v is the total enthalpy from upstream. The small pressure work due to the change of the volume is ignored since the change of water volume is slow and small due to its tremendous volume. The gravity change inside the volume is ignored due to low density.

Mass conservation equation for water space is

$$\frac{dm_w}{dt} = \sum_i \dot{m}_{in\_i} - \dot{m}_{out} \tag{15}$$

where m_w is the total mass of water; $\dot{m}_{in\_i}$ is the ith inlet steam mass flow rate and obtained from the connected steam pipe; and $\dot{m}_{out}$ is the outlet water mass flow rate.

Total energy conservation equation for water space is

$$\frac{d(me)_w}{dt} = \sum_i \dot{m}_{in\_i}\left(H_{in\_i} + \left(z_{i\_i} - 0.5L_w\right)g\right) - \dot{m}_{out}\left(H_{out} + (z_o - 0.5L_w)g\right) - A_c\alpha\left(T_w - T_g\right) - \dot{q} \tag{16}$$

where $(me)_w$ is the total internal energy for the water space, H_{in_i} the total enthalpy coupled from the connecting steam pipe i, z_{i_i} the ith inlet steam pipe end elevation relative to the pool bottom, L_w the pool water level, z_o the outlet water pipe end elevation relative to the pool bottom, $\dot{q}$ the active heat removal rate from the immerged heat exchanger, and H_{out} the total enthalpy for the outlet water pipe.
The methods to calculate the average water density ρ_w and specific volume energy ρe_w will be introduced shortly. u_{out} is the exit speed and is obtained from coupled water pipe end. For inflow condition, H_{out} will be coupled from the pipe end. In Eq. (16), we assume that the gravity center is at the half depth of the water pool.

Reference pressure in the water space is defined at the middle elevation of the pool

$$p_w = p_g + \frac{1}{2} L_w \rho_w g \tag{17}$$

where p_w is the reference water pressure and p_g the gas pressure. Pressure and temperature are calculated from EOS relationships.

In the code implementation of the wet well model, we define m_g, $(me)_g$, m_w, $(me)_w$, and L_w as the primary variables to solve, with corresponding equations (13)-(17). We also define another set of auxiliary variables to close the system, which include gas density ρ_g and water density ρ_w. Gas density is calculated according to

$$\rho_g = \frac{m_g}{A_c(L_t - L_w)} \tag{18}$$

where L_t is the total effective height of the wet well. Similarly, the average water density is calculated according to

$$\rho_w = \frac{m_w}{A_c L_w} \tag{19}$$

3. SIMPLIFIED BWR SBO MODEL

A simplified BWR plant system model was developed for the SBO simulations, based on the parameters specified in the Organization for Economic Cooperation and Development (OECD) turbine trip benchmark problem [16]. The reference design for the OECD BWR Turbine Trip benchmark problem is derived from the Peach Botom-2, which is a General Electric-designed BWR-4 nuclear power plant, with a rated thermal power of 3293 MW.

Figure 5 shows the schematic of the RELAP-7 SBO model. The plant system model consists: (1) The reactor vessel model which consists of the down comer model, the lower plenum model, the reactor core model, the upper plenum model, the separator dryer model, the steam dome model. The primary pump model is used to simulate the functions of the jet pump and recirculation loops; (2) The main steam line model which is connected to the steam dome. A time dependent volume is attached to the main steam line to provide the necessary boundary conditions for the steam flow; (3) The feedwater line model which is connected to the down comer model. A time dependent volume is attached to the feedwater line to provide the necessary boundary conditions for the feedwater flow; (4) The safety injection system which includes the RCIC turbine, RCIC pump, pump line check valve, as well as the containment wet well and dry well; (5) The safety relief system which includes the safety relief valves and the associated piping system. Detailed model data can be found in our previous publications [10, 17].

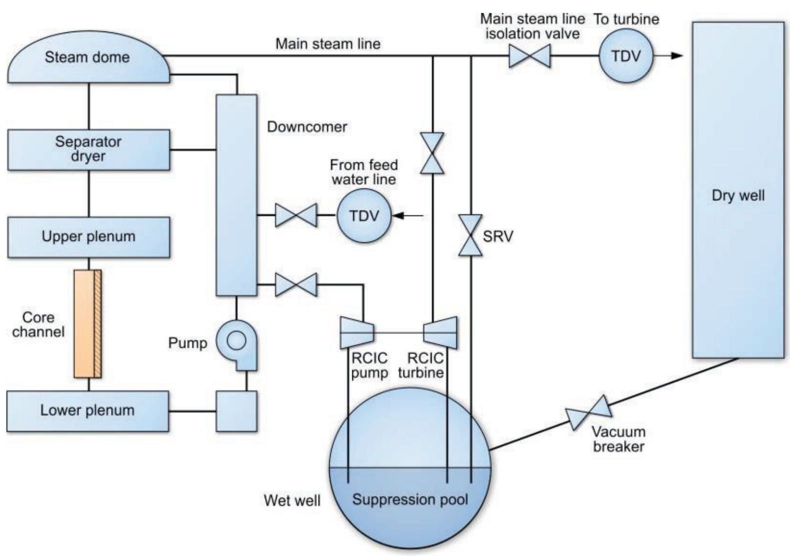

Figure 5. Schematics of a boiling water reactor plant system model for SBO simulation.

4. SBO SIMULATION RESULTS

In the simulation, the steady state is achieved and the SBO accident starts at time zero. Major control actions and sequences include: (1) at time = 0 s, the reactor is scrammed and the decay heat is turned on; the primary pump starts to coast down with a half-time of 1 s. (2) At time = 1 s, the primary system starts to be isolated with feed water line valve closed within 1 s and main steam isolation valves closed within 3 s. (3) The SRV will open when the pressure is higher than 8.17 MPa and close when pressure is lower than 6.38 MPa. (4) Between 1 minute and 6 hours, the RCIC system is turned on when the down comer water level is less than 9 m and turned off when the level is higher than 11.2 m. the RCIC system transition time is 30 s. (5) After 6 hours, the assumed battery energy is exhausted. Only SRV is cycled on or off according to the pressure setting points to control the system pressure. (6) The simulation stops when the PCT (Peak Clad Temperature) reaches 1200 K.

The RCIC turbine nominal flow rate is 4 kg/s. The real flow rate through the turbine is dynamically determined by this nominal flow rate, the pressure ratio and upstream temperature. The RCIC pump flow rate is also dynamically determined and is about 10 times higher than the turbine flow rate. An efficiency of 0.1 is used for the turbine to simulate the combined net efficiency of the turbine, shaft, and pump, which is consistent with the numbers in a study on the Fukushima Unit 2 RCIC pump [18]. For the Fukushima Unit 2 RCIC system, the net efficiency is about 0.11 (= 0.21 turbine efficiency × 0.9 shaft efficiency × 0.58 pump efficiency).

Figure 6 shows the down comer water level variation with time. Figure 7 shows the RCIC mass flow rates through the turbine and pump. The RCIC system turns on and off six times during the first 6 hours when battery power is available. When the RCIC system is on, more water is injected into the reactor vessel than the steam discharged into the suppression pool as shown in the figure. Due to the frequent steam discharge through SRVs as shown in Figure 8, the water level drops again, although the level will rapidly grow when the system pressure as shown in Figure 9 rapidly decreases during the SRVs opening time. After the assumed RCIC battery time is up, the SRVs are the only passive component to control the system pressure by occasionally opening to release steam into the suppression pool in the wet well. Note that we lump 12 SRVs together into one group. More detailed study can use 6 groups of SRVs with different pressure settings.

Figure 10 shows the peak clad temperature during the simulation. The PCT follows the system pressure until dry-out happens. Opening the SRVs can cause the so called steam cooling effect to reduce PCT and bring more water into the core. These two effects can explain the oscillating PCT in the later stage of the transient. However, with the reducing down comer water level, the PCT finally reaches the fuel clad damage temperature at 30819 s and the simulation is stopped.

Figure 11 shows the pressure at the wet well gas space and dry well. When the vacuum breaker pressure difference setting point (back pressure) is met, the wet well gas will rapidly flow into dry well. The back pressure value 3.45 kPa is according to the reference [19]. Figure 12 shows the suppression pool average temperate, and Figure 13 shows suppression pool water level. These parameters are very important for the RCIC pump performance and are all dynamically calculated.

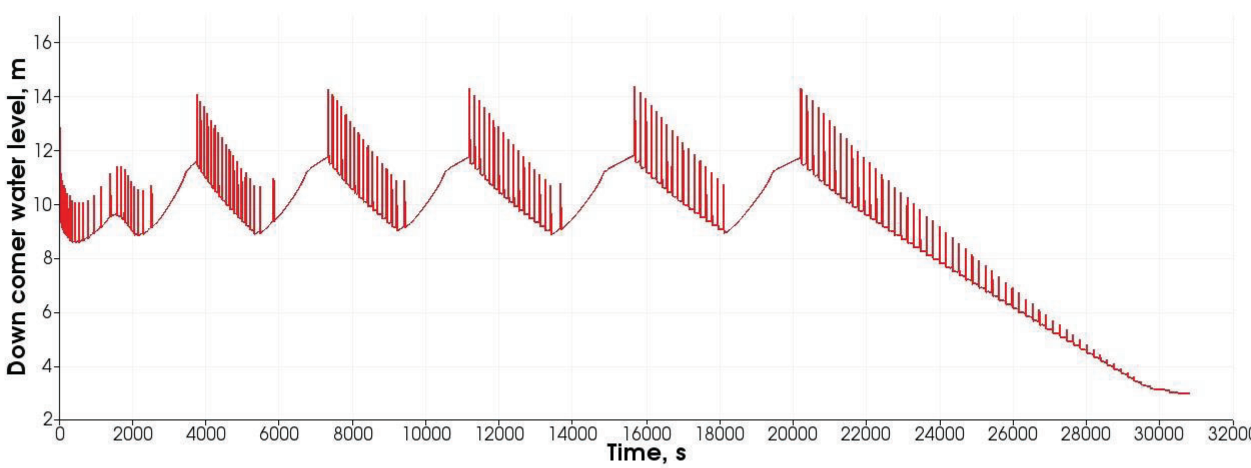

Figure 6. RELAP-7 calculated down comer water level during station blackout.

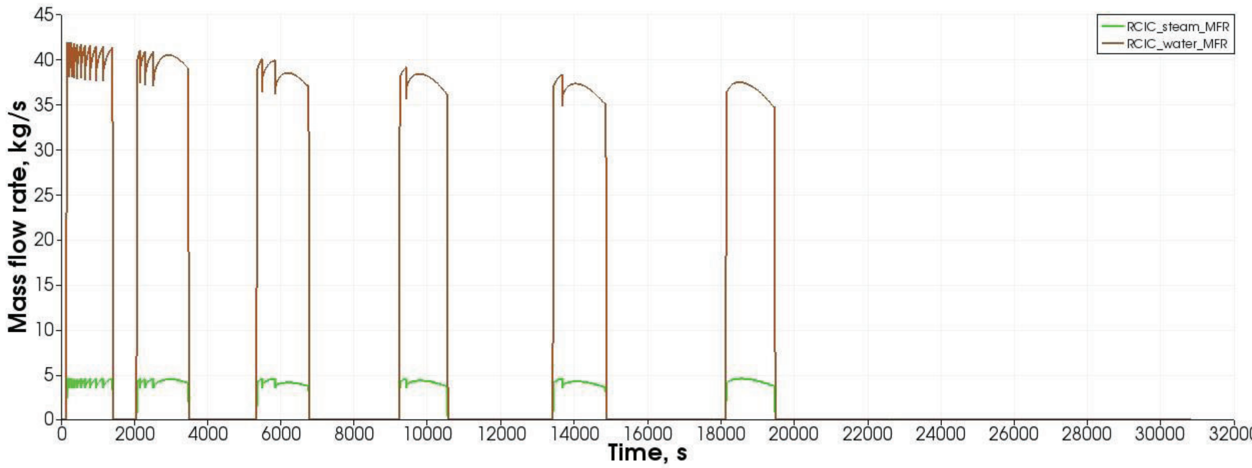

Figure 7. RELAP-7 calculated RCIC mass flow rates through the turbine and the pump during station blackout.

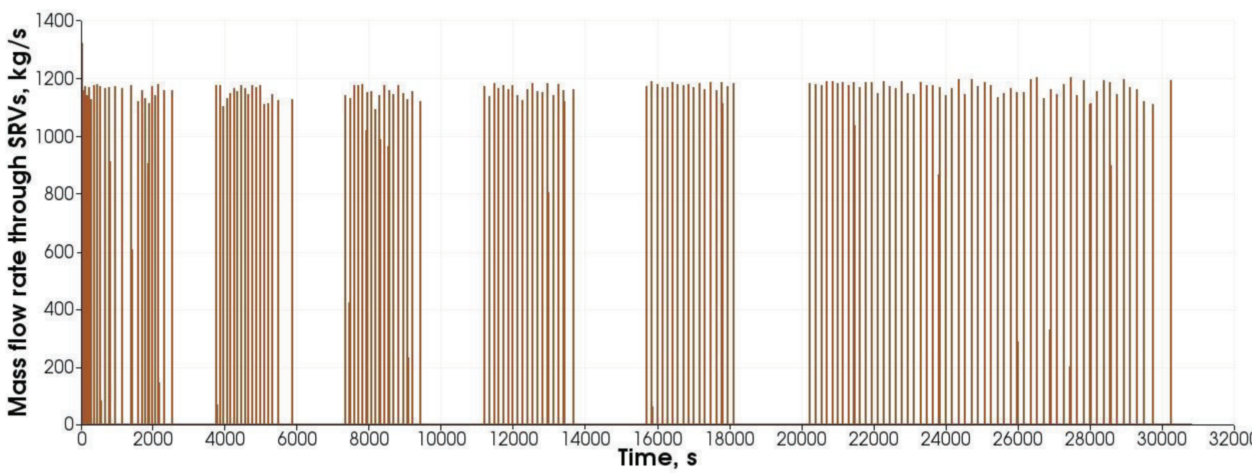

Figure 8. RELAP-7 calculated mass flow rate through SRVs during station blackout.

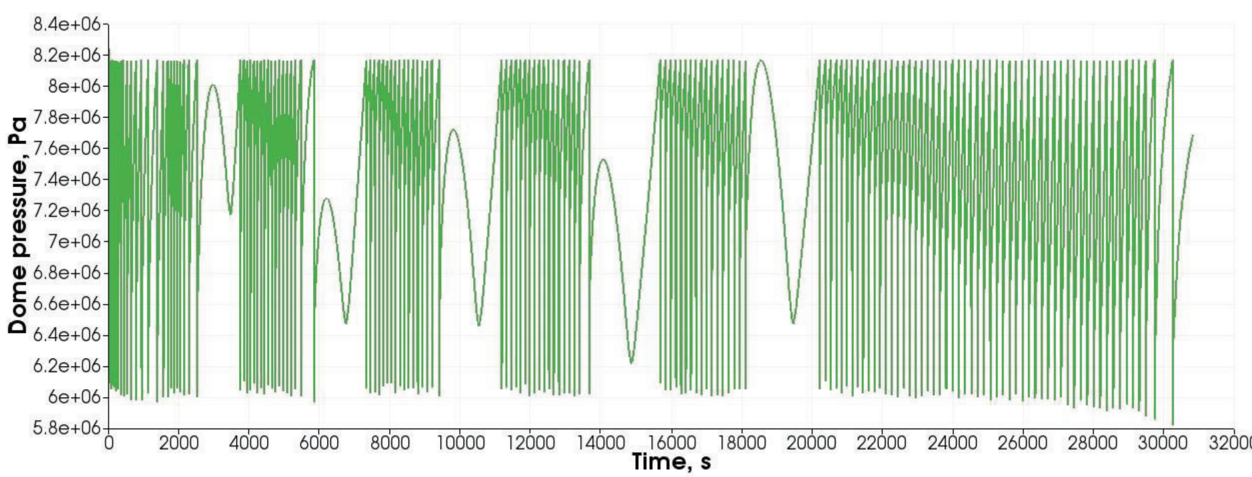

Figure 9. RELAP-7 calculated system pressure during station blackout.

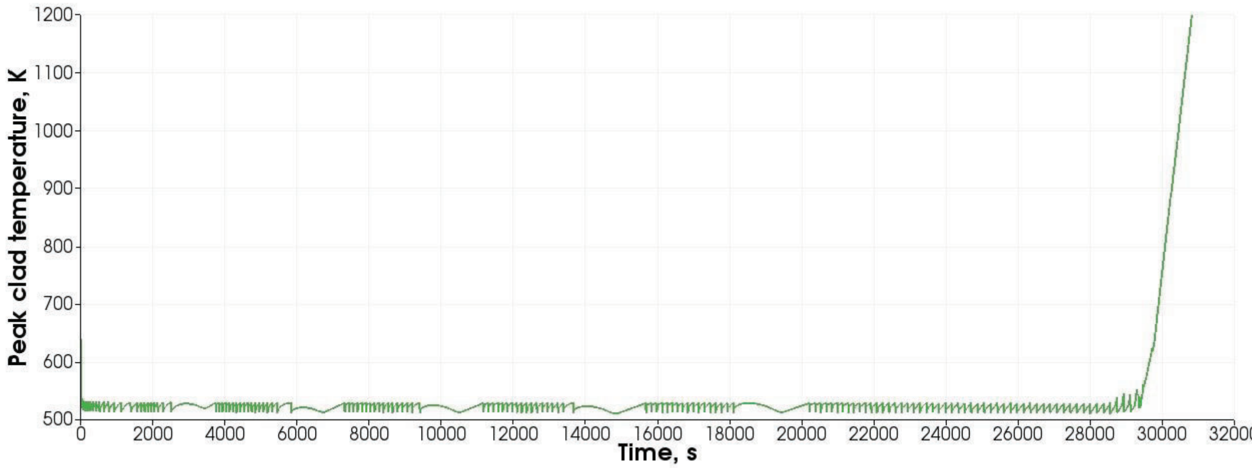

Figure 10. RELAP-7 calculated peak clad temperature during station blackout.

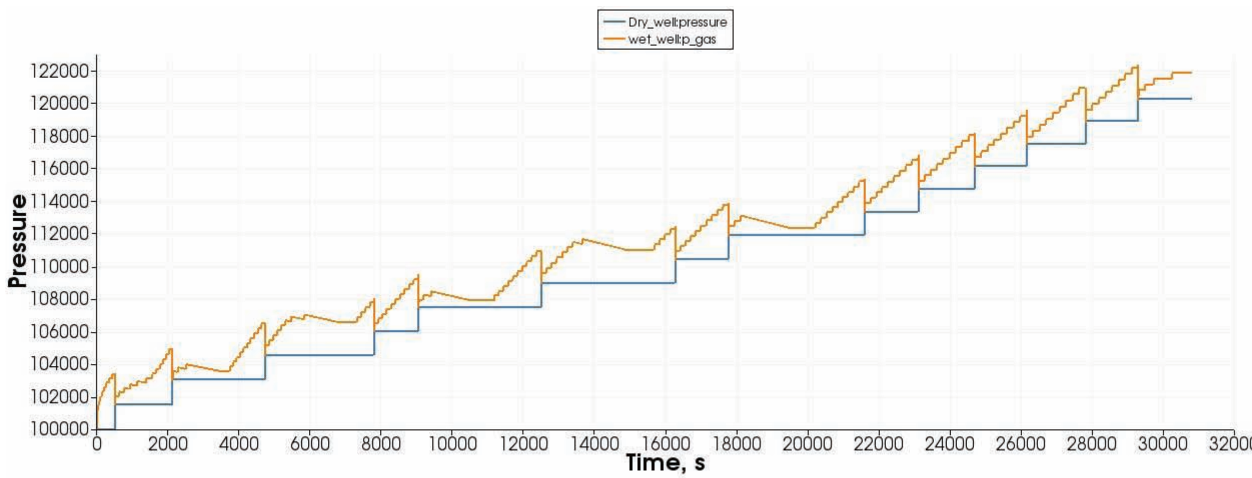

Figure 11. RELAP-7 calculated pressures at wet well gas space and dry well during station blackout.

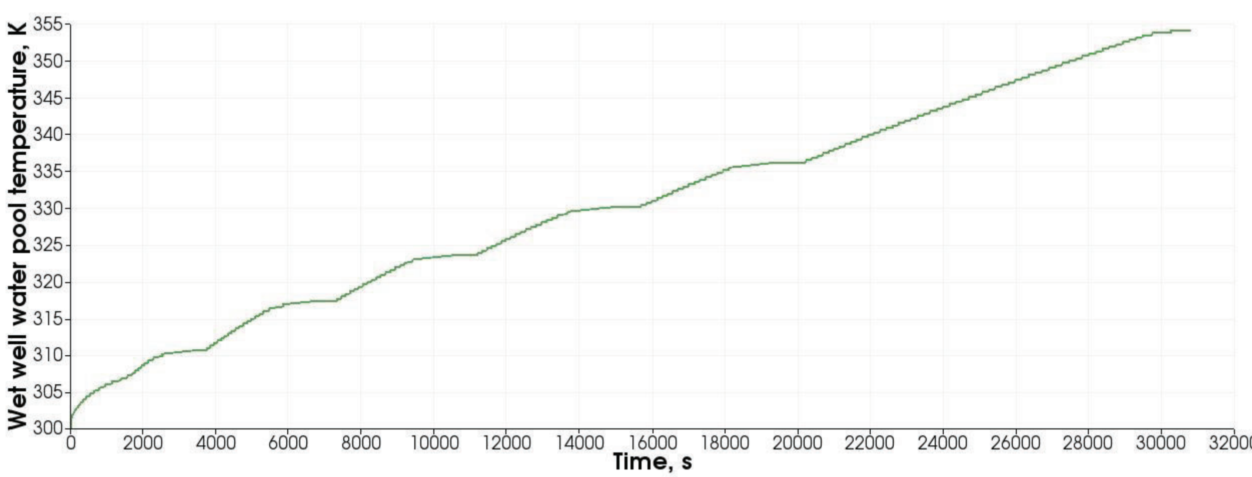

Figure 12. RELAP-7 calculated wet well water temperature during station.

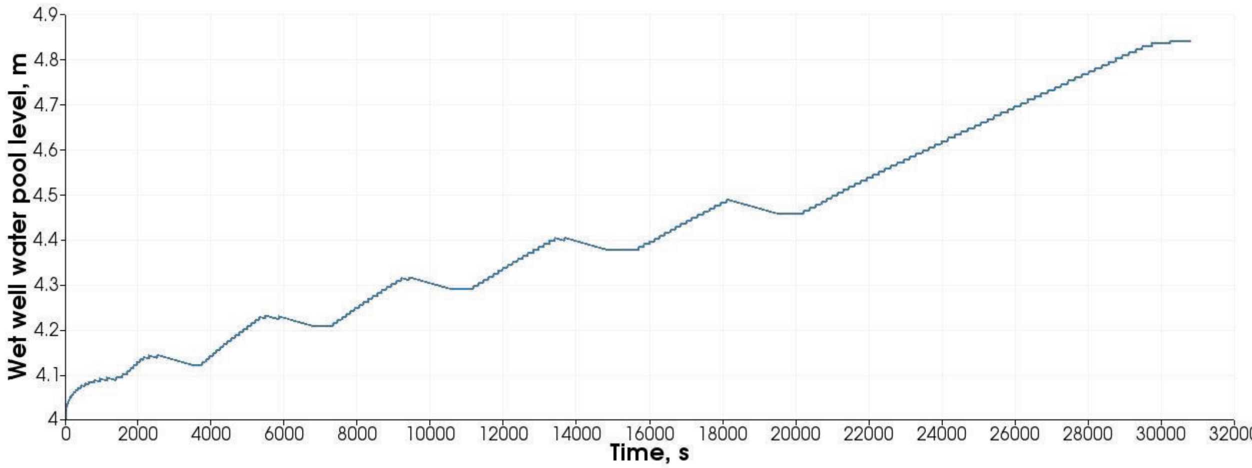

Figure 13. RELAP-7 calculated wet well water level during station.

5. CONCLUSIONS

To fully understand the complex system behavior during extended SBO for a BWR reactor, it is important to include detailed dynamical models for safety-important components and systems in the system analysis codes and models. By fully coupling all these dynamical models together at the system level, the complex interaction between different physics and physical components can be better revealed and predicted. Although not realized in this paper, it is a necessary to include off-design models for the RCIC system in order to predict the system behavior when active control is lost. We believe this is a viable method to resolve the unexpected Fukushima unit 2 & 3 RCIC behaviors. The demonstration RELAP-7 simulation for the simplified SBO scenario shows the importance of the safety relief valves, the RCIC system, and the wet well system to the reactor safety during extended SBO accidents. It also shows that it is doable to implement fully implicit and fully coupled RCIC system models in advanced system codes without resorting pre-determined user input information such as time dependent mass flow rates through the RCIC system. More detailed turbine models including off-design turbine characteristic curves should be implemented in the future, which will enable SBO simulations similar to Fukushima Daiichi types accidents.

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