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# DEVELOPING A FULLY IMPLICIT COMPRESSIBLE FLOW VALVE MODEL IN RELAP-7 AND ITS APPLICATION IN SHORT TERM BWR STATION BLACK-OUT ANALYSES

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*This paper presents a set of dynamical models for compressible flow valve simulation in the RELAP-7 code, a new reactor system analysis code currently being developed at Idaho National Laboratory. The compressible flow valve model covers three different sets of models: fully closed case, subsonic case, and choking case. The RELAP-7 is a fully implicit code and the preconditioned Jacobian-free Newton-Krylov (JFNK) method is used to solve the discretized nonlinear problem. The JFNK method needs a good preconditioning scheme to be effective and efficient. Due to the strong discontinuity in the residual vector space when the compressible flow valve model switches from one set of model to another, accurate analytical Jacobian terms are required for preconditioning. With this method, the compressible flow valve model can be solved efficiently. The developed model has been used for safety relief valve (SRV) component simulation in simplified short-term BWR Station Black-Out (SBO) simulations in which all the safety systems fail to start and function properly except for SRVs. Two short-term SBO cases will be compared: one with single SRV discharge line which represents all the SRV lines and another case with multi-group SRVs with each represents a group of SRV lines with same pressure setting points.*

## I. INTRODUCTION

RELAP-7 (Ref. 1) is a new nuclear reactor system safety analysis code being developed at the Idaho National Laboratory (INL). It is based on the MOOSE (the Multi-Physics Object-Oriented Simulation Environment) framework (Ref. 2), which provides software development environment and computational framework for RELAP-7. Like all other reactor system analysis codes, the RELAP-7 thermal hydraulics model is composed of a network of one-dimensional (1-D) physical components connected by zero-dimensional (0-D) physical components. There are three main types of

components developed in RELAP-7: 1-D components, 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. (Ref. 3) described the single-phase fluid flow model and several 1-D component models developed for RELAP-7. Zhao et al. (Refs. 4 and 5) presented the relevant 0-D components for realizing strongly coupled reactor core isolation cooling (RCIC) system in a BWR (boiling water reactor) system. Limited two-dimensional (2-D) capability is available, such as the heat conduction model. For 1-D and 2-D components, the physical equation set is solved on the continuous FEM (Finite Element Method) mesh with the 2nd order accuracy in space.

All the physics are integrated into a single fully coupled nonlinear equation system in RELAP-7. The nonlinear equation system is solved with Jacobian free Newton Krylov (JFNK) method (Ref. 6). 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. Moreover, with the JFNK as the numerical solver and using a smart software framework design, numerical methods and physical models can be fully separated, which makes the code much easier to develop, maintain, and evolve with time.

Valves are very common in thermal hydraulics systems. For typical valves only experiencing low speed flow, such as check valve, motor valve, or servo valve, the nearly incompressible flow assumption is valid. Therefore the Bernoulli equation and the form loss coefficient for the abrupt area change model can be used to describe the flow through the valves, as used by RELAP5 (Ref. 7). For the valves experiencing high speed flow, compressible flow models are needed. One such example is a safety/relief valve (SRV), which either is activated by passive setting points such as pressure

(safety valve mode) or by active control actions through an electric motor or compressed air (relief mode). Normally, a SRV would discharge pure gas or steam. However, there are transients in a LWR that can involve the discharge of two-phase mixture or pure liquid through a SRV. As an initial version of the simplified SRV model, only steam/gas is considered in this paper. Since the SRV always has the minimal cross section area along the release line, it is assumed that if choking happens along the release line, it always happens in the throat of the SRV. Also, the steam/gas is treated as an ideal gas.

In section II, the preconditioned Jacobian-free Newton-Krylov method will be summarized. Section III describes the compressible flow valve models. Section IV presents two short-term BWR SBO simulations in which SRVs play a key role: one with single SRV discharge line which represents all the SRV lines and another case with multi-group SRVs with each represents a group of SRV lines and with same setting points.

## II. PRECONDITIONED JACOBIAN-FREE NEWTON-KRYLOV METHOD

For a discretized nonlinear system in the residual form, one solves

$$\mathbf{F}(\mathbf{U}) = 0 \quad (1)$$

for the unknown vector  $\mathbf{U}$ . Each component of the  $\mathbf{F}$  vector represents one discretized residual equation. The solution to the nonlinear system is obtained by iteratively solving a series of Newton's linear correction equations,

$$\mathbf{J}(\mathbf{U}^k)\delta\mathbf{U}^k = -\mathbf{F}(\mathbf{U}^k) \quad (2)$$

where  $\mathbf{J}(\mathbf{U}^k)$  is the Jacobian matrix, the (i, j) element (ith row, jth column) of the Jacobian matrix is

$$J_{ij} = \frac{\partial F_i(\mathbf{U})}{\partial u_j} \quad (3)$$

$\mathbf{U}^k$  is the  $k^{\text{th}}$  nonlinear step solution; and  $\delta\mathbf{U}^k$  is the correction vector. In the JFNK frame, the linear system, equation (2), could be effectively solved with a Krylov's method. In the Krylov's method, only a matrix-vector product is required and thus it does not require the explicit formation of the Jacobian matrix. The matrix-vector product can be approximated as,

$$\mathbf{J}(\mathbf{U}^k)\mathbf{v} \approx \frac{\mathbf{F}(\mathbf{U}^k + \epsilon\mathbf{v}) - \mathbf{F}(\mathbf{U}^k)}{\epsilon} \quad (4)$$

in which,  $\mathbf{v}$  is the Krylov vector and  $\epsilon$  is a small perturbation parameter. After the correction vector,  $\delta\mathbf{U}^k$ ,

is solved from the linear system, the  $(k + 1)^{\text{th}}$  nonlinear step solution could be updated as,

$$\mathbf{U}^{k+1} = \mathbf{U}^k + \delta\mathbf{U}^k \quad (5)$$

The JFNK method generally needs a good preconditioning scheme to be effective and efficient. Using right preconditioning, one solves:

$$(\mathbf{J}(\mathbf{U}^k)\mathbf{P}^{-1})(\mathbf{P}\delta\mathbf{U}^k) = -\mathbf{F}(\mathbf{U}^k) \quad (6)$$

where  $\mathbf{P}$  symbolically represents the preconditioning matrix and  $\mathbf{P}^{-1}$  is the inverse of the preconditioning matrix or the preconditioning process. Right preconditioning is actually realized through a two-step process. First solve

$$(\mathbf{J}(\mathbf{U}^k)\mathbf{P}^{-1})\mathbf{w}^k = -\mathbf{F}(\mathbf{U}^k) \quad (7)$$

for  $\mathbf{w}$ . Then solve

$$\delta\mathbf{U}^k = \mathbf{P}^{-1}\mathbf{w}^k \quad (8)$$

for  $\delta\mathbf{U}^k$ . The matrix-vector product in Eq. (7) is approximated as

$$\mathbf{J}(\mathbf{U}^k)\mathbf{P}^{-1}\mathbf{v} \approx \frac{\mathbf{F}(\mathbf{U}^k + \epsilon\mathbf{P}^{-1}\mathbf{v}) - \mathbf{F}(\mathbf{U}^k)}{\epsilon} \quad (9)$$

This operation is performed once per Krylov iteration, and is actually done in two steps: (1) preconditioning: solve (approximately) for  $\mathbf{y}$  in

$$\mathbf{P}\mathbf{y} = \mathbf{v} \quad (10)$$

and (2) perform matrix-free product

$$\mathbf{J}(\mathbf{U}^k)\mathbf{y} \approx \frac{\mathbf{F}(\mathbf{U}^k + \epsilon\mathbf{y}) - \mathbf{F}(\mathbf{U}^k)}{\epsilon} \quad (11)$$

Only the matrix elements required for the action of  $\mathbf{P}^{-1}$  are formed. There are different ways to precondition the JFNK method, which were reviewed in Ref. [6]. In order to be effective, the preconditioning matrix  $\mathbf{P}$  must be a good approximation to the original Jacobian matrix; In order to be efficient, it must be cheap to solve  $\mathbf{y} = \mathbf{P}^{-1}\mathbf{v}$ .

In RELAP-7, two main options are used to realize the preconditioning process: (1) FDP (Finite Difference Preconditioning) option, which uses the default finite differencing method provided in the PETSc package (Ref. 8). PETSc is the numerical solver software developed by Argonne National Laboratory and used by MOOSE as the numerical solution engine; (2) SMP (Single Matrix Preconditioning) option, which requires code developers

to provide approximate analytical Jacobian inputs for the important diagonal and off-diagonal terms. The FDP option tends to become very expensive when the size of the problem becomes large. If any strong discontinuity exists in the residual vector space, the FDP option becomes ineffective and cannot guarantee convergence. The SMP option in this case can still be effective, although developers need to provide relatively good approximate analytical Jacobian inputs.

### III. COMPRESSIBLE FLOW VALVE COMPONENT MODEL

The compressible flow valve component covers three different sets of models: fully closed case, subsonic case, and choking case. The Compressible Valve component in RELAP-7 is designed as a single 0-D junction component that provides:

- one downstream boundary condition for the inlet pipe:  $p_i$  – the inlet pipe downstream pressure,
- two upstream BCs for the outlet pipe: momentum  $(\rho u)_o$  and total enthalpy  $H_o$ .

Therefore three equations are needed to close the system. Note that the three selected boundary conditions are not the only options, but they are convenient for setting BCs and deriving Jacobian inputs for the conservative form of 1-D fluid equations.

As the simplified models, all the inertial terms such as time derivative terms for mass, energy, and momentum conservations, are ignored. The heat transfer with the valve wall is also omitted.

First consider the case when the valve is open. The  $p_i$  unknown corresponds to the mass conservation:

$$(\rho u)_1 A_1 \hat{n}_1 + (\rho u)_o A_2 \hat{n}_2 = 0 \quad (12)$$

where  $(\rho u)_1$  is the coupled momentum for the connecting inlet pipe end,  $A$  the cross-section area, and  $\hat{n}$  the direction normal ( $\hat{n}_1 = 1$  for the inlet and  $\hat{n}_2 = -1$  for the outlet). In this paper, a “coupled” variable means an unknown or an auxiliary variable as a function of unknowns defined at the boundary of a connected component, such as a pipe. The  $(\rho u)_o$  unknown corresponds to the following equation for the choked condition

$$(\rho u)_o A_2 - \dot{m}_c = 0 \quad (13)$$

where  $\dot{m}_c$  is the critical mass flow rate calculated by the equation for isentropic ideal gas flow (Ref. 9)

$$\dot{m}_c = A_t (\rho u)_c = A_t (\gamma p_c \rho_c)^{1/2} \quad (14)$$

where  $A_t$  is the cross-section area at the valve throat, which can be controlled by the valve action, i.e., from 0 to

the fully open area. The critical pressure  $p_c$  and the critical density  $\rho_c$  are calculated by

$$\frac{p_c}{p_{10}} = \left( \frac{2}{\gamma + 1} \right)^{\frac{\gamma}{\gamma - 1}} \quad (15)$$

$$\frac{\rho_c}{\rho_{10}} = \left( \frac{2}{\gamma + 1} \right)^{\frac{1}{\gamma - 1}} \quad (16)$$

where the subscript 10 indicates the stagnation condition for the inlet.

To derive stagnation states, we first have

$$h_o = h + \frac{1}{2} u^2 \quad (17)$$

where  $u$  is the velocity. Assuming an isentropic process, from the static state, say,  $(h_i, p_i)$ , we can find the stagnation state  $(h_{oi}, p_{oi})$ . For ideal gas, the following equations hold (Ref. 10)

$$p_o = p \left( 1 + \frac{\rho u^2}{2p} \cdot \frac{\gamma - 1}{\gamma} \right)^{\gamma/(\gamma - 1)} \quad (18)$$

$$T_o = T \left( \frac{p_o}{p} \right)^{(\gamma - 1)/\gamma} \quad (19)$$

$$\rho_o = \frac{p_o}{RT_o} \quad (20)$$

where  $R$  is the gas constant.

For the non-ideal choked flow (not to be confused with non-ideal gas) through a valve,  $\dot{m}_c$  can be modified by multiplying the valve coefficient  $C_v$  (Ref. 9) which is defined as the ratio of real mass flow rate over the ideal mass flow rate. The valve coefficient model will be included in the future.

For ideal gas and isentropic flow, the steady state mass flow rate for subsonic condition is calculated as

$$\dot{m}_{sub} = A_2 \left\{ 2 \left( \frac{\gamma}{\gamma - 1} \right) p_{10} \rho_{10} \left( \frac{p_2}{p_{10}} \right)^{2/\gamma} \left[ 1 - \left( \frac{p_2}{p_{10}} \right)^{\frac{\gamma - 1}{\gamma}} \right]^{1/2} \right\} \quad (21)$$

By comparing the subsonic mass flow rate and the choking mass flow rate, we can determine whether choking happens. When  $\dot{m}_{sub} \geq \dot{m}_c$ , Eq. (13) is used for momentum; Otherwise, subsonic flow momentum equation is used:

$$(\rho u)_o A_2 - \dot{m}_{sub} = 0 \quad (22)$$

The  $H_o$  unknown corresponds to the energy conservation:

$$(\rho u)_1 A_1 \hat{n}_1 H_1 + (\rho u)_o A_2 \hat{n}_2 H_o = 0 \quad (23)$$

When the valve is fully closed, the following equations are used for  $p_i$ ,  $(\rho u)_o$ , and  $H_o$ , respectively

$$p_i - p_1 = 0 \quad (24)$$

$$(\rho u)_o - (\rho u)_2 = 0 \quad (25)$$

$$H_o - H_2 = 0 \quad (26)$$

$p_1$ ,  $(\rho u)_2$ , and  $H_2$  are coupled variables from the connecting pipe ends. The pipe end BCs are treated as solid wall conditions when the valve is fully closed.

The following table summarizes the equations used for solving the three primary variables (unknowns) for the compressible flow valve component under different conditions:

TABLE I. Summary of Equations for Different Flow Conditions

Valve Conditions	Mass	Momentum	Energy
Fully closed	Eq. (24)	Eq. (25)	Eq. (26)
Subsonic	Eq. (12)	Eq. (22)	Eq. (23)
Choking	Eq. (12)	Eq. (13)	Eq. (23)

The valve open/close action can either be controlled by the active control system to simulate the release mode of SRVs or is activated by the passive setting points such as pressure or pressure difference to simulate the safety valve mode of SRVs. Both the open and close actions have corresponding response times provided by users. For example, for the open action, the valve throat area changes from 0 to the fully opened area within the response time. The current model uses a linear transition curve. Different curves can be implemented in the future.

Note that when the valve changes from the fully closed status to the fully opened status, different flow conditions such as still, subsonic, or choking, may be experienced, which may require different residual equations as shown in Table I. Due to the discontinuity in the residual vector space when the compressible flow valve model switches from one set of model to another, the FDP preconditioning option cannot guarantee convergence, as shown by numerical experiments. Instead, relatively accurate analytical Jacobian terms are required for the compressible flow valve model.

For the 1-D single phase flow model, the primary variables are  $\rho A$ ,  $\rho u A$ , and  $\rho E A$ .  $E = e + \frac{1}{2}u^2$  is the total energy. Only the primary variables at the inlet pipe end point and the outlet pipe starting point are related to the

valve model. Therefore, we need to consider the Jacobian of each residual equation for the valve model with all the related primary variables:  $p_i$ ,  $(\rho u)_o$ ,  $H_o$ ,  $(\rho A)_1$ ,  $(\rho u A)_1$ ,  $(\rho E A)_1$ ,  $(\rho A)_2$ ,  $(\rho u A)_2$ , and  $(\rho E A)_2$ . Take the mass conservation equation with the corresponding unknown  $p_i$  as an example for deriving Jacobian inputs. Define the residual equation for mass as  $res_{mass}$ . The required Jacobian inputs are

$$\frac{\partial res_{mass}}{\partial p_i} = \begin{cases} 1 & \text{for fully closed case} \\ 0 & \text{for subsonic and choking cases} \end{cases} \quad (27)$$

$$\frac{\partial res_{mass}}{\partial (\rho u)_o} = \begin{cases} 0, & \text{for fully closed case} \\ A_2 \hat{n}_2, & \text{for subsonic and choking cases} \end{cases} \quad (28)$$

$$\frac{\partial res_{mass}}{\partial H_o} = 0 \quad (29)$$

$$\frac{\partial res_{mass}}{\partial (\rho A)_1} = \begin{cases} -\frac{\partial p(\rho_1, (\rho u)_1, (\rho E)_1)}{\partial \rho} \frac{1}{A_1}, & \text{for fully closed case} \\ 0, & \text{for subsonic and choking cases} \end{cases} \quad (30)$$

$$\frac{\partial res_{mass}}{\partial (\rho A)_2} = 0 \quad (31)$$

$$\frac{\partial res_{mass}}{\partial (\rho u A)_1} = \begin{cases} -\frac{\partial p(\rho_1, (\rho u)_1, (\rho E)_1)}{\partial (\rho u)} \frac{1}{A_1}, & \text{for fully closed case} \\ \hat{n}_1, & \text{for subsonic and choking cases} \end{cases} \quad (32)$$

$$\frac{\partial res_{mass}}{\partial (\rho u A)_2} = 0 \quad (33)$$

$$\frac{\partial res_{mass}}{\partial (\rho E A)_1} = \begin{cases} -\frac{\partial p(\rho_1, (\rho u)_1, (\rho E)_1)}{\partial (\rho E)} \frac{1}{A_1}, & \text{for fully closed case} \\ 0, & \text{for subsonic and choking cases} \end{cases} \quad (34)$$

$$\frac{\partial res_{mass}}{\partial (\rho E A)_2} = 0 \quad (35)$$

For the momentum and energy conservation residuals, we can derive all the Jacobian inputs in a similar way, although they become more complex. After

the analytical Jacobian inputs are provided in the model, the compressible flow valve model can be solved efficiently for different transient test cases with the SMP option selected.

The compressible flow valve component had been verified through simple test cases which cover all the possible flow conditions and their transitions from the fully closed case, the subsonic case, to the choking case. The choking mass flow rate calculated from the model matches the design nominal value as shown in next section, which validated the model and its implementation.

#### IV. SHORT-TERM BWR SBO SIMULATIONS

The developed compressible flow valve model has been used for the SRV component simulation in several simplified BWR SBO simulations with RELAP-7 (Refs. 4, 9, and 11). In these previous papers, strongly coupled Reactor Core Isolation Cooling system (RCIC) model along with simplified whole BWR reactor system model were presented and used for demonstration SBO simulations. This paper only presents cases for short-term SBO in which all the safety systems fail to start and function properly when SBO occurs. Consequently, only the SRVs automatically open and close periodically to control the primary system pressure and discharge the high temperature and high pressure steam into the suppression pool. Although simplified, this case is quite similar to what happened in Fukushima Daiichi Unit 1 (Ref. 12). Unit 1 had no RCIC system, while the isolation condenser system was believed to be non-functioning, or only available for a very short period of time during the accident. Therefore, the Unit 1 reactor core reached a fuel failure temperature only a few hours into the accident. Short-term SBO accidents had also been extensively studied by the U.S. NRC sponsored SOARCA (State-of-the-Art Reactor Consequence Analysis) project which used the MELCOR code models to perform a realistic evaluation of SBO accident progression (Ref. 13). Two short-term SBO cases will be compared: one with single SRV discharge line which represents all the SRV lines and another case with five groups of SRVs with each group of SRV lines at the same setting points.

##### IV.A. Short-Term SBO System Models

A simplified BWR plant SBO model has been developed mainly based on the parameters specified in the Organization for Economic Cooperation and Development (OECD) turbine trip benchmark problem (Ref. 14). The reference design for the benchmark problem is derived from Peach Bottom-2, which is a General Electric designed BWR-4 nuclear power plant, with a rated thermal power of 3,293 MW.

Fig. 1 shows the schematics of the one-group-SRV BWR short-term SBO RELAP-7 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 relief system which includes the SRVs and the associated piping system. For the five-group-SRV SBO model, the single safety relief line is replaced with 5 separate relief lines. Ref. 11 has more detailed descriptions of components and parameters used in the simulations.

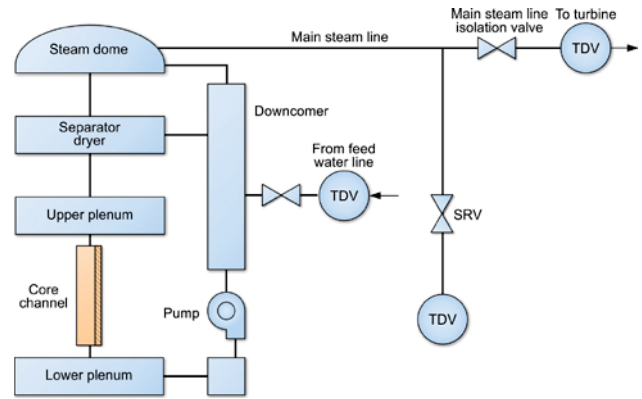


Fig. 1. Schematics of a BWR system short-term SBO model.

SRV parameters taken from the LaSalle Units 1 and 2 Updated Final Safety Analysis Report (Ref. 15) were used for the demonstration simulations. The reference contains detailed pressure setting points and open/close response time information. The SRVs open response time is 0.3 s and the close response time is 1.5 s. A single SRV has a rated release rate of 110 kg/s with a fully opened throat area at 0.011 m<sup>2</sup>. Five groups of SRVs were used in this simulation, with each group representing two SRVs. The following table shows the SRV setting points. The averaged setting points were used for the single group of SRVs model.

TABLE II. SRV Parameters

Group Number	High Pressure Setting Point [Pa]	Low Pressure Setting Point [Pa]
1	7.93E6	6.25E6
2	8.10E6	6.25E6
3	8.17E6	6.38E6
4	8.24E6	6.52E6
5	8.31E6	6.52E6
Average	8.15E6	6.38E6

Steady-state simulation results were obtained by marching transient solutions sufficiently for a long time (200 s for these cases) so that no further changes occurred. The simulation sequence for the SBO scenario is summarized as follows:

- At  $t = 0$  s, SBO initiating event occurred:
  - Reactor scrammed
  - Decay heat was turned on
  - Primary pump coast down started with a half-time of 2 s
- At  $t = 1$  s:
  - Feedwater line valve began to close and became fully closed at  $t = 2$  s
  - Main steam isolation valve began to close and became fully closed at  $t = 4$  s
- Simulation stopped when the peak clad temperature (PCT) approached 1477.6K (2200°F):
  - The SRVs were cycling on and off to control the system pressure and release steam.

#### IV.B. Simulation Results

The results for the model with one group of SRVs and the model with 5 groups of SRVs are presented together for comparison. Fig. 2 shows the evolution of the down comer water level during the transient. The down comer water level indicates the water inventory within the reactor vessel. The relative height for the reactor core top fuel to the bottom of down comer is 6.84 m. Without any makeup water, the water level in the down comer gradually decreases as the SBO accident progresses. The decreasing water level results in a less driving head to drive the coolant through the reactor core and to transport the heat out of the reactor core. Consequently, the natural circulation capability is degraded. The oscillations of the water level are due to the pressure oscillations as shown in Fig. 3, which are caused by the periodic SRV opening and closing cycling. Comparing the results for the one-group-SRV model and the five-group-SRV model, the general trends are similar; however, the oscillation magnitudes of the water level and system pressure for the five-group-SRV model are much lower than the one-group-SRV model.

Fig. 4 shows the mass flow rate through the SRVs for the one-group-SRV model and Fig. 5 shows the zoomed-in mass flow rate for the first 200 s. Note that the SRVs' opening frequency decreases gradually with time, along with the decreasing decay heat. The peak release rate through each SRV is around the rated value – 110 kg/s. The total cycling times is 43 for the group. Fig. 6 shows the mass flow rates through the SRVs for the five-group-SRV model and Fig. 7 shows the zoomed in mass flow rates for the first 200 s. The group 1 SRVs open 32 times; group 2, 3, and 4 SRVs only open once in the beginning; the group 5 SRVs never open. The group 1 SRVs have the lowest high pressure setting point to open. Therefore automatic pressure release for this type of slow pressure transients will mainly be realized through low pressure setting SRVs. In order to avoid early failure of any SRVs such as sticking open or close due to fatigue and to avoid inhomogeneous heating of the suppression pool, manual operation of other SRVs is often mandated in plant-specific operating procedures. Figs. 8 and 9 shows the total steam release through the SRVs for the one-group-SRV model and the five-group-SRV model, respectively. Comparing the results for the one-group-SRV model and the five-group-SRV model, the total accumulated steam release amount is similar as shown in Figs. 8 and 9, although for each cycle, the one-group-SRV model has a much higher release rate and a much shorter release duration as shown in Figs. 5 and 7.

Pressure oscillations cause the oscillations of the core void fraction as shown in Fig. 10. When the core average void fraction approaches 1, dry-out happens. The PCT, as shown in Fig. 11, begins to increase. When the SRVs open, the residual water in the down comer and lower plenum enters the core again; the steam cooling effect (Ref. 16) also reduces the PCT. Finally the core is full of steam and the PCT rapidly increases. Within 1000 s, the fuel clad damage temperature is reached and the simulation is stopped. The timing for PCT to reach 1477.6 K (at around 4390 s for the one-group-SRV model and at 4530 s for the five-group-SRV model) is quite close to a similar case studied by the SOARCA project, which is around 4700 s for the fuel damage at the core middle plan (Ref. 13).

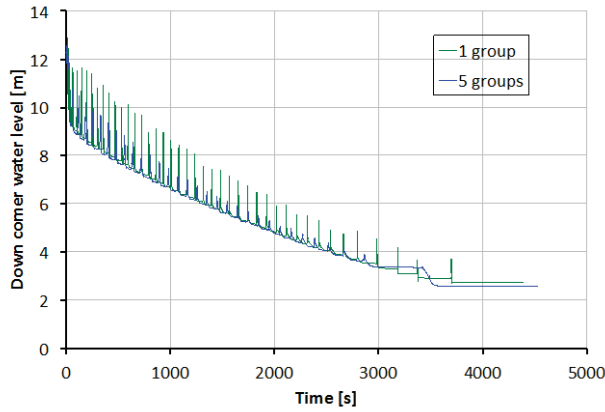


Fig. 2. RELAP-7 calculated down comer water level during the short-term SBO.

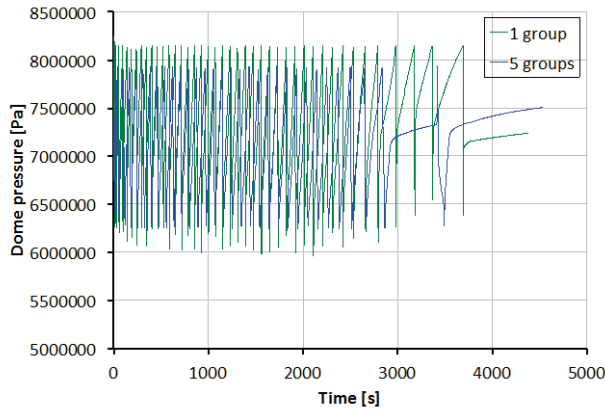


Fig. 3. RELAP-7 calculated steam dome pressure during the short-term SBO.

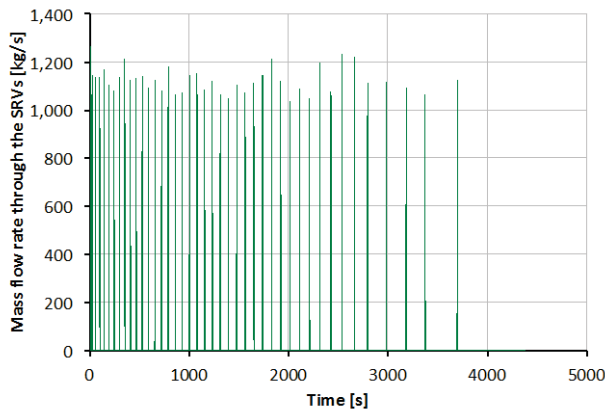


Fig. 4. RELAP-7 calculated SRV mass flow rate for the one-group-SRV SBO model.

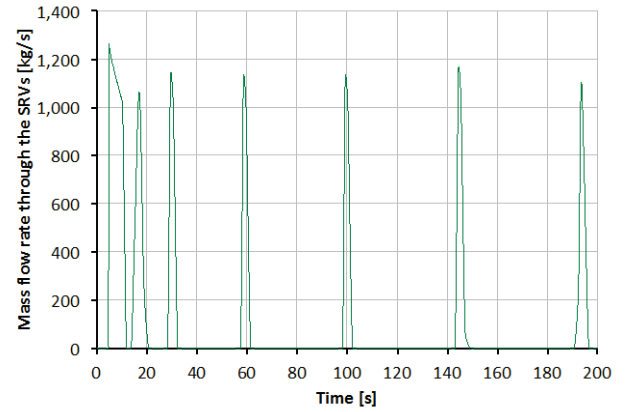


Fig. 5. RELAP-7 calculated SRV mass flow rate for the one-group-SRV SBO model for the first 200 s.

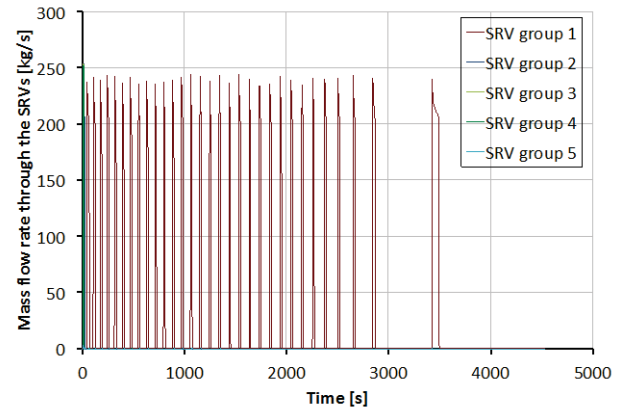


Fig. 6. RELAP-7 calculated SRV mass flow rates for the five-group-SRV SBO model.

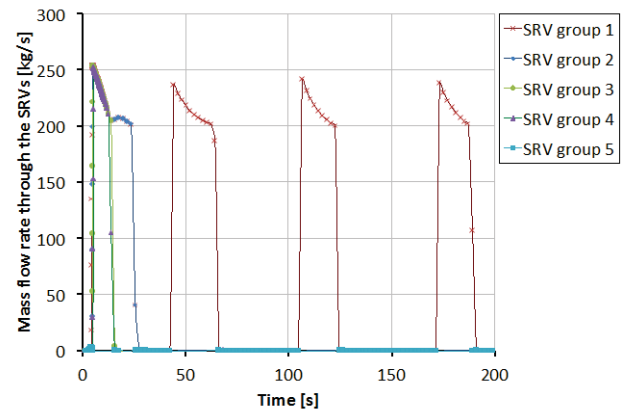


Fig. 7. RELAP-7 calculated SRV mass flow rates for the five-group-SRV SBO model for the first 200 s.

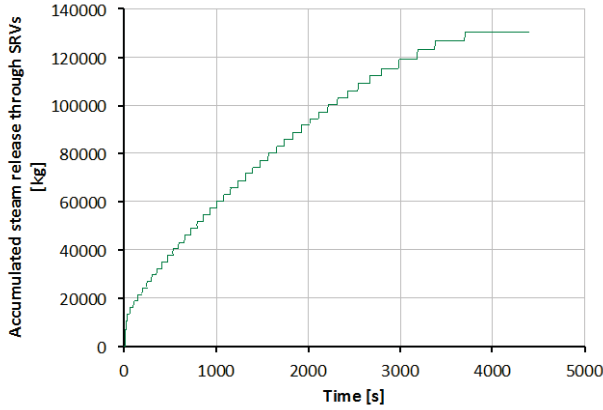


Fig. 8. RELAP-7 calculated accumulated steam release for the one-group-SRV SBO model.

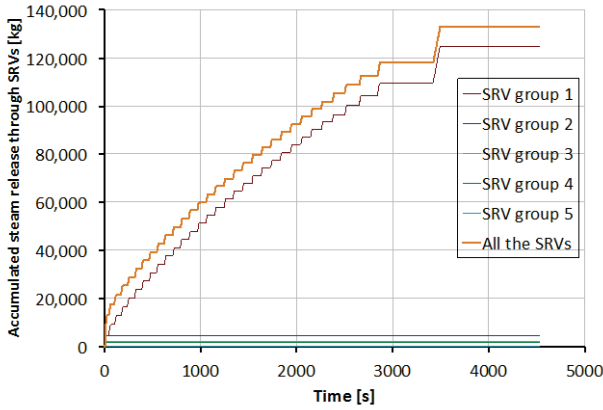


Fig. 9. RELAP-7 calculated accumulated steam release for the five-group-SRV SBO model.

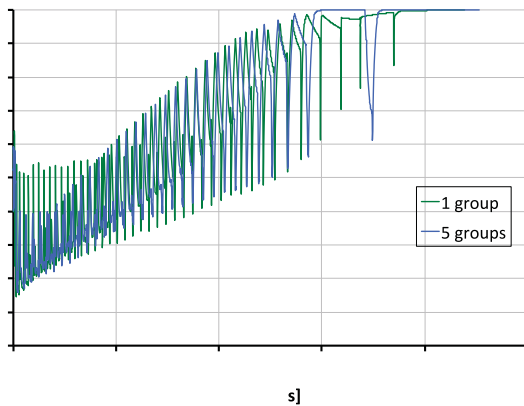


Fig. 10. RELAP-7 calculated reactor core average void fraction during the short-term SBO.

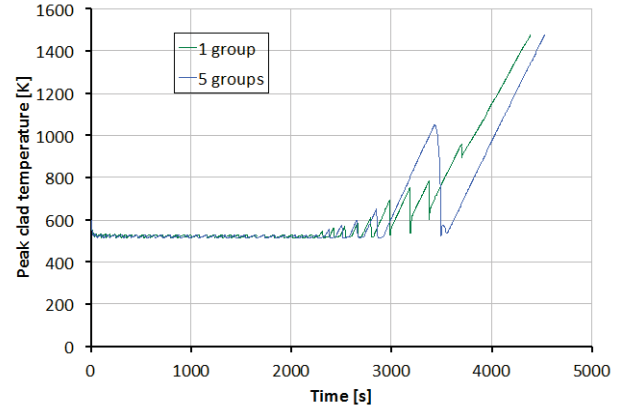


Fig. 11. RELAP-7 calculated fuel peak clad temperature during the short-term SBO.

Table III summarizes the major results from the one-group-SRV model and five-group-SRV model. The time to core damage is one of the most important figure of merits in any SBO analysis. The total steam release into the wet well is important for containment venting strategy. The total times of SRVs' cycling affects SRVs' reliability which is a very important input for risk analysis. From the comparison, it can be concluded that the simplified one-group-SRV model can be sufficiently used for scoping analysis; however, for detailed risk informed safety analysis (Ref. 13), only the multi-group-SRV model can give accurate results and allow the flexibility to simulate real plant control actions.

TABLE III. Summary of Major Results

Figure of Merits	One-Group-SRV Model	Five-Group-SRV Model	Difference
Time to core damage	4390 s	4530 s	- 3.1%
Total steam release	1.31E5 kg	1.33E5 kg	- 1.5%
Times of SRVs' cycling	43 for all SRVs	32 for group 1 SRVs	34%

## V. CONCLUSIONS AND FUTURE WORK

A fully implicit compressible flow valve model has been successfully implemented in a new reactor system analysis code RELAP-7. The model can be used for simulating the SRV component in a BWR or PWR plant. The model covers three different sets of flow conditions: fully closed case, subsonic case, and choking case. With analytical Jacobian terms implemented, the model can be effectively and efficiently solved with the preconditioned JFNK method. The developed compressible flow valve component has been used in short-term BWR SBO analyses in which SRVs play a key role. Two short-term

SBO cases are presented and compared: one with single SRV discharge line which represents the combined SRV lines and another case with five groups of SRVs with each group of SRV lines at the same setting points. The results show that the simplified one-group-SRV SBO model can be used for scoping study without major error and multi-group-SRV SBO model should be used for detailed risk informed safety analyses.

The compressible flow valve model presented in this paper only represents the first step of the model development work. The model needs to be extended for the two-phase flow case. The valve coefficient model should be included. The dynamical models containing transient terms in the mass, energy, and momentum conservation equations and heat transfer effect with the valve wall will be studied. Advanced models retaining the physical time scales may avoid the discontinuity in the residual vector space and therefore eliminate the requirement for providing analytical Jacobian inputs, which is difficult to derive and expensive to compute for more complex engineering models.

## ACKNOWLEDGMENTS

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