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COMPREHENSIVE SCALING METHOD WITH VALIDATION FOR APPLICATION TO SB-LOCAS OF A PASSIVE PWR

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ABSTRACT

A comprehensive scaling method is proposed for a scaled-down facility simulating SBLOCA in the CARR passive reactor (CP-1300). The present method consists of two stages: scaling methodology, and validation of scaling methodology and code. The present scaling methodology is based on the integral response scaling method. Through sensitivity study, the condensation of the top of the CMT is identified as one of the little-known phenomenon with high importance which should be addressed for the applicability of the code. Using the similarity of the derived scaling parameters, the major component geometries of the scaled-down facility are determined. In the case of 1/4 height and 1/100 area ratio scaling, it is found out that the power ratio is the same as the area ratio, and the present scaling methodology generates the design parameters of the scaled-down facility without any distortion.

1 Introduction

At Center for Advanced Reactor Research (CARR) in Korea, a passive PWR concept named CARR Passive Reactor (CP-1300) has been developed by adopting a passive engineered safety-feature-system (SangIl, 1995) as shown in Figure 1. The passive engineered safety- feature-system in the CP-1300 are: (1) the Passive Safety Injection System (PSIS), (2) the Secondary Condenser (SC) which functions as passive residual heat removal system, (3) the Passive Containment Cooling System which uses a natural circulation loop with a heat exchanger, (4) the Automatic Depressurization System (ADS). The PSIS consists of Core Makeup Tank (CMT) with a sparger and a pressurizer pressure balance line (PRZ PBL) , accumulators, and In-Containment Refueling Water Storage Tank (IRWST), which are used to supply emergency core cooling water at high, intermediate, and low pressure, respectively.

It is necessary to study the performance of the new safety system and its interactions in order to assess the response of the CP-1300 under postulated accident conditions. Since it is not feasible to build and test a full power prototype system, a scaled integral facility is the best alternative. Therefore, it is necessary to have a rational scaling method that establishes the interrelationship between the important phenomena of the prototype system and the model.

Here a comprehensive scaling method, which can be applied to SBLOCAs in the CP-1300, is proposed,and used for generating scaling criteria. Figures 2 and 3 show the schematic diagrams of the proposed comprehensive scaling method including code validation and scaling methodology validation.

2 Application of the proposed method

2.1 Identification of phenomena and system

To investigate the transient response during SB LOCA in the CP-1300, and identify phenomena where modification of code might be required, the preliminary calculation for 3-inch diameter small break in the cold leg is performed by RELAP5/MOD3.1. The nodalization of the CP-1300 is shown in Figure 4. The input model consists of 416 volumes, 494 junctions and 256 heat structures. The simulated overall system response is indicated by the calculated pressurizer pressure shown in Figure 5.

In the viewpoint of safety, the pressure transient and the core mixture level are selected as the most critical parameters to be preserved in a scale-down test facility. The whole accident scenario is divided into three phases: break-dominant depressurization phase (BDDP), ADS-dominant depressurization phase (ADDP), and long-term cooling phase (LTCP). The identification of phenomena and system in the CP-1300 is summarized in Table 1. Through sensitivity study, the condensation of the top of the CMT is identified as one of the little-known phenomena which should be addressed for the applicability of RELAP5/MOD3.1.

2.2 Derivation of scaling parameters

2.2.1 Break-dominant depressurization (BDD) phase

According to Table 1, the critical flow through the break and the condensation in the CMT are the high important phenomena in this phase. In this phase, the critical flow is mainly the subcooled one. The subcooled break flow has a great influence on the pressure transient and the RCS inventory. During this phase, there is no safety injection, and so the pressurizer plays a role in the inventory source. To predict the pressure and inventory trend in this phase, it is necessary to model properly the pressurizer.

The mass and energy conservation equations for the pressurizer are

$$\frac{dM_{prz}}{dt} = -W_{su}, \tag{1}$$

$$\frac{d(Mh)_{prz}}{dt} = -W_{su}h_{su} + Q_H + V_{prz}\frac{dP}{dt}. \tag{2}$$

The mass and energy conservation equations for the RCS excluding the pressurizer are as follows:

$$\frac{dM_{RCS}}{dt} = -W_{brk} + W_{su} \tag{3}$$

$$\frac{(Mh)_{RCS}}{dt} = W_{su}h_{su} + Q_{in} - Q_{out} - W_{brk}h_{brk} + V_{RCS}\frac{dP}{dt} \tag{4}$$

Assuming that the pressurizer is saturated and the RCS is subcooled, the nondimensional forms of Eqs. 1 through 4 can be obtained using the following nondimensional parameters:

$$\text{inventory volume number} \quad N_{inv} = \frac{V_{inv}}{V_{RCS}}, \tag{5}$$

$$\text{pressurizer volume number} \quad N_{pr} = \frac{V_{prz}}{V_{RCS}}, \tag{6}$$

$$\text{papor volume number} \quad N_{ps} = \frac{V_{prz,vapor}}{V_{prz}}, \tag{7}$$

$$\text{decay heat number} \quad N_d = \frac{Q_{in,o}}{W_{out,o}h_o}, \tag{8}$$

$$\text{heatsinknumber} \quad N_s = \frac{Q_{out,o}}{W_{brk,o}h_o}, \tag{9}$$

$$\text{pressurenumber} \quad N_p = \frac{P_o}{\rho_o h_o}, \tag{10}$$

$$\text{pressureheaternumber} \quad N_{ph} = \frac{Q_H}{W_{out,o}h_o}, \tag{11}$$

The integral response functions of enthalpy, system pressure, and void fraction of pressurizer are expressed in terms of the above nondimensional variables and nondimensional parameters:

$$h^* = 1 + \int_0^{t_f} f(P^*, \alpha^*_{prz}, N_{vol}, N_{pr}, N_d, N_s, N_p, N_{ph}) dt^* \tag{12}$$

$$P^* = 1 + \int_0^{t_f} f(h^*, \alpha^*_{prz}, N_{vol}, N_{pr}, N_d, N_s, N_p, N_{ph}) dt^* \tag{13}$$

$$\alpha^*_{prz} = 1 + \int_0^{t_f} f(P^*, h^*, N_{vol}, N_{pr}, N_d, N_s, N_p, N_{ph}) dt^* \tag{14}$$

$$\tag{15}$$

The BDD phase continues until the CMT injection begins. It is expected that the CMT does not be injected into the DVI pipe as soon as the CMT injection valve is opened because of the pressure drop caused by the sudden condensation in the top of CMT. As the condensation proceeds, the pressure of the CMT increases due to the increase of the CMT temperature. As a result, the CMT begin to inject. The actuation of the ADS is initiated after the CMT injection. To predict the transition between two phases, BDDP and ADDP, in scaled-down system, it is necessary to model properly the transition criterion. From the CMT condensation experiments with a small-scaled facility (Lee, 1996), the following transition criterion is obtained:

$$C_o N_A^{-5/6} N_\rho^{1/6} N_\mu^{-1/2} Pr^{1/2} Re_s^{-1/2} Ja = 1.0, \tag{16}$$

where the coefficient, C_o is dependent on the particular geometry and operating condition of the test facility. From Eq. 16, the following nondimensional parameters are obtained:

$$CMT\ nozzle\ number \quad N_A = \frac{A_{cmt,nozzle}}{A_{CMT}} \tag{17}$$

$$Density\ number \quad N_\rho = \frac{\rho_g}{\rho_f} \tag{18}$$

$$Kinematic\ viscosity\ number \quad N_\nu = \frac{\nu_g}{nu_f} \tag{19}$$

$$Prandle\ number \quad Pr = \frac{\mu c_{pf}}{k_f} \tag{20}$$

$$Steam\ Reynold\ number \quad Re_s = \frac{v_g D_j}{\nu_g} \tag{21}$$

$$Jabcob\ number \quad Ja = \frac{\rho_f c_p (T_g - T_f)}{\rho_g h_{fg}} \tag{22}$$

Steam velocity, v_g of the steam Reynolds number should be properly modeled to predict the transition criterion. By the experimental results (Lee, 1995), the steam velocity approaches the sonic one because of the choked flow resulting from the large pressure difference between the pressurizer and the top of the CMT. The following single phase critical flow model can be used for v_g:

$$v_g = \left\{ \frac{2\gamma}{\gamma - 1} \frac{P_{CMT}}{\rho_{CMT}} [1 - (\frac{P}{P_{CMT}})^{\frac{\gamma - 1}{\gamma}}] \right\}^{1/2} \tag{23}$$

2.2.2 ADS-dominant depressurization(ADD) phase

In ADD phase, the pressurizer is no longer the inventory source and so the control volume is the RCS including the pressurizer. According to Table 1, the important phenomena considered in the present phase are the saturated break flow, the ADS flow, the core mixture level, the CMT gravity injection, and the accumulator injection. These phenomena are related in the RCS inventory. The pressure transient and the RCS inventory are considered as the global parameters which are governed by the global system behavior, but the core mixture level and the fuel temperature are considered as the local parameters.

The mass and energy conservation equation for the RCS are

$$\frac{dM_{RCS}}{dt} = W_{CMT} + W_{acc} - W_{brk} - W_{ADS}, \qquad (24)$$

$$\frac{d(Mh)_{RCS}}{dt} = W_{CMT}h_{CMT} + W_{acc}h_{acc} - W_{brk}h_{brk} - W_{ADS}h_{ADS}. \qquad (25)$$

For obtaining the integral response functions of pressure and RCS void fraction, the following additional nondimensional parameters are used:

$$CMT\ injection\ number \quad N_{CMT,inj} = \frac{W_{CMT,o}}{W_{brk,o}},$$

$$Accumulator\ injection\ number \quad N_{acc,inj} = \frac{W_{acc,o}}{W_{brk,o}},$$

$$ADS\ flow\ number \quad N_{ADS} = \frac{W_{ADS,o}}{W_{brk,o}},$$

$$CMT\ energy\ number \quad N_{CMT,e} = \frac{W_{CMT,o}h_{CMT,o}}{W_{brk,o}h_{brk,o}},$$

$$Accumulator\ energy\ number \quad N_{acc,e} = \frac{W_{acc,o}h_{acc,o}}{W_{brk,o}h_{brk,o}},$$

$$ADS\ energy\ number \quad N_{ADS,e} = \frac{W_{ADS,o}h_{ADS,o}}{W_{brk,o}h_{brk,o}}.$$

For modelings of W^*_{CMT}, W^*_{acc}, W^*_{ADS}, W^*_{brk}, the following nondimensional parameters are used:

$$accumulator\ area\ number \quad N_{acc,A} = \frac{A_{acc}}{A_{brk}},$$

$$accumulator\ pressure\ number \quad N_{acc,pr} = \frac{\rho_{acc}P_{acc,o}}{G^2_{brk,o}},$$

$$acc.nozzle\ pressure\ number \quad N_{acc,pr2} = \frac{\rho_{acc}P_o}{G^2_{brk,o}},$$

$$accumulator\ volume\ number \quad N_{acc,vol} = \frac{V^l_{acc,o}}{V^g_{acc,o}}.,$$

$$accumulator\ time\ constant \quad \tau_{acc} = \frac{M^l_{acc,o}}{W_{brk,o}} = \frac{\rho_{acc}V^l_{acc,o}}{W_{brk,o}}.$$

The nondimensional scaling parameters of the core uncovery and heatup process are as follows

$$phase\ change\ number \quad N_{pch} = \frac{\bar{\bar{\Gamma}}}{\rho_g}\tau,$$

$$density\ number \quad N_\rho = \frac{\rho_g}{\rho_f},$$

$$subcooling\ number \quad N_{sub} = \frac{\Delta h_{sub}}{h_{fgh}},$$

$$core\ inlet\ velocity\ number \quad N_{u_i} = \frac{j_g}{u_{gj}},$$

$$decay\ heating\ number \quad N_{dh} = \frac{\tau q'_d}{aT_s},$$

$$oxidation\ heating\ number \quad N_{ox} = \frac{e\delta_{cl}}{aT_s},$$

$$\textit{convective cooling number} \quad N_c = \frac{\tau}{a} 2\pi R_{cl} h,$$

$$\textit{radiation cooling number} \quad N_{rj} = \frac{\tau}{a} T_s^3 \sigma \frac{A}{n_f} F_j,$$

$$\textit{coolant heating number} \quad N_p = \frac{\tau}{a} \frac{A_f}{n_f} G C_{pv},$$

$$\textit{modified saturation number} \quad N_{T_s} = \frac{T_{sc}}{T_s}.$$

2.3 Long-term cooling phase

Due to depressurization by the ADS, the pressure of the RCS reaches near the atmospheric one, and thereafter the IRWST begins to inject. The following nondimensional equation can express the transition to the IRWST-injection-cooling phase:

$$N_{atm} + N_{IRWST,h} > P^*, \tag{26}$$

nondimensional parameters:

$$\textit{atmoshperic pressure number} \quad N_{atm} = \frac{P_{atm}}{P_o} \tag{27}$$

$$\textit{IRWST head number} \quad N_{IRWST,h} = \frac{\rho g H_{IRWST}}{g_c P_o}. \tag{28}$$

For modeling the IRWST gravity-driven injection flow, the following nondimensional parameter is used:

$$\textit{IRWST injection number} \quad N_{IRWST,inj} = \frac{W_{IRWST,o}}{W_{IRWST,o}}, \tag{29}$$

$$\tag{30}$$

where t^* is nondimensional IRWST injection time defined as $\frac{t}{\tau_{IRWST}}$, and τ_{IRWST} is an IRWST injection time constant defined as $\frac{\rho_{IRWST} H_{IRWST,o} A_{IRWST}}{W_{IRWST,o}}$.

2.4 Application

Let us design a scaled-down model on the basis of the scaling parameters derived previously. The subscript R as the ratio between the model and the prototype is defined as follows:

$$\Psi_R = \frac{\Psi_m}{\Psi_p} \tag{31}$$

Similarity between the model and the prototype requires that Ψ_R should be equal to 1.

To determine the overall size of the scaled-down facility, it is necessary to consider a justifiable rationale for the choice of A_R and L_R. Since the existing integral test facilities for PWR are almost full-height, volume scaling, they fall into the category of thin and tall system, which have some major shortcoming, for example, excessive loop pressure drop. Recently, the PUMA facility (Ishii, 1996) simulating SBWR adopts the ratios of the height and the area as 1/4 and 1/100, respectively. The 1/4 height- and the 1/100 area- ratio scaled facility has the aspect ratio factor of 1/2.5, which is the very close to the prototype system. The aspect ratio provides a simple indication of their ability to produce multidimensional phenomena.

With the 1/4 height and the 1/100 area ratios, the major design parameters of the scaled-down facility can be obtained from the derived scaling criteria. The initial core decay power and the pressurizer heater power can be determined by the break area ratio:

$$(Q_{in,o})_R = (Q_{prz,o})_R = (A_{brk})_R = \frac{1}{100}. \tag{32}$$

The injection pipe areas of the CMT and the IRWST , which are related to the gravity-driven injection, can be obtained from Eqs. (26) and (29):

$$(A_{CMT,inj})_R = {\frac{(A_{brk})_R}{H_{CMT,o}}}^{1/2} = \frac{1}{50}, \tag{33}$$

$$(A_{IRWST,inj})_R = {\frac{(A_{brk})_R}{H_{IRWST}}}^{1/2} = \frac{1}{50}. \tag{34}$$

(35)

Table 2 shows the comparison of major components and dimensions between CP-1300 and the scaled-down facility.

3 Conclusions and recommendations

The comprehensive scaling method including validation of the scaling methodology and the safety code is proposed in the present study. Through the identification of the phenomena and system, the whole scenario of the SBLOCA in the CP-1300 is divided into three phases: break-dominant depressurization phase, ADS-dominant depressurization phase, and long-term cooling phase. The condensation of the top of the CMT is identified as one of the little-known phenomena with high importance. Using the similarity of the derived scaling parameters, the major parameters of the scaled-down facility are determined. It is found out that the power ratio is the same as the break area ratio, and the present methodology generates the design parameters of the scaled-down facility without any distortion when is is applied to scaling analysis of the CP-1300 in the case of the same pressure, the same fluid, and the reduced height. To complete the present method , it is essential that the present method be validated by using the well-validated code.

References

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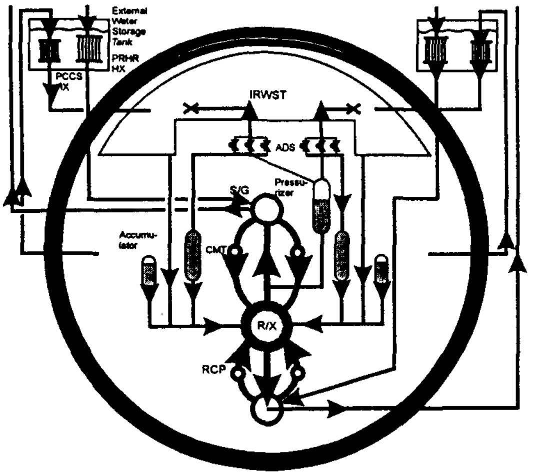

Figure 1. CARR Passive Reactor(CP-1300)

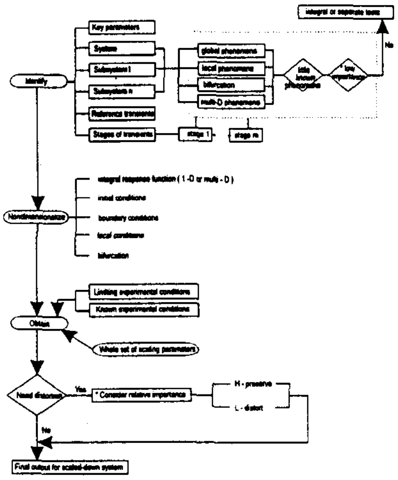

Figure 2. Scaling methodology

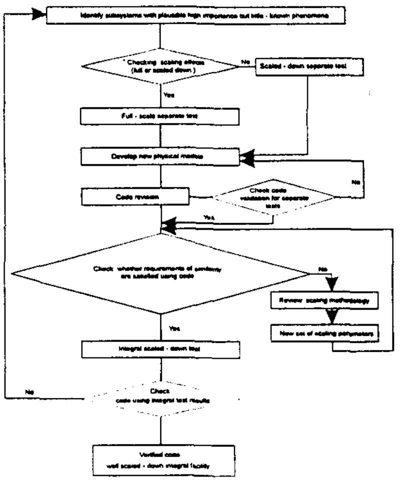

Figure 3. Validation of scaling methodology and code

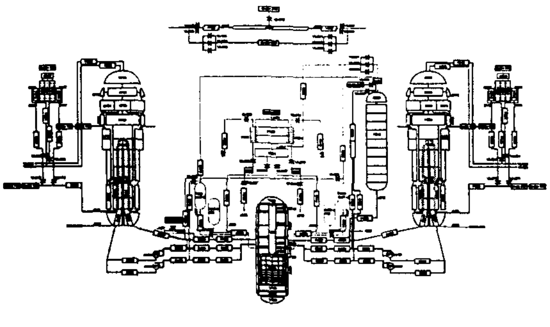

Figure 4. CP-1300 nodalization

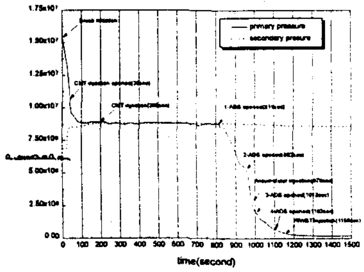

Figure 5. Pressurizer pressure

Table 1. Phenomena and system of CP-1300

component phenomena	*Break-dominant* depressurization phase	ADS-dominant depressurization phase	IRWST-injection cooling phase
Break Critical flow	H	H	M
Vessel/Core Decay heat Core mixture level Uncovery core heat transfer	H H H	H H H	H H H
Pressurizer PRZ fluid level	M	H	L
ADS 1-4 stages Critical flow	N/A	H	H
CMT Vapor condensation Gravity draining injection	H N/A	M H	N/A N/A
Accumulator Injection flow rate	N/A	H	N/A
IRWST Gravity draining injection Vapor condensation rate	N/A N/A	N/A M	H L
Subsystem	RCS, *pressurizer*, CMT	RCS, CMT, ADS Accumulator, Core	IRWST
Most important parameters	Pressure	Pressure, core inventory, T_{clad}	IRWST injection flow

Table 2. Comparison of major parameters

Component	CP-1300	Scaled-down facility
Reactor vessel		
Total height(m)	14.63	3.66
I.D(m)	4.115	0.4115
Core		
Active length(m)	3.81	0.952
Core thermal power(MWt)	3914	39
Initial decay heat power(MWt) (6% of core thermal power)	234.8	2.348
Core equivalent dia.	3.647	0.365
Pressurizer		
Volume(m^3)	67.96	0.169
I.D.(m)	2.44	0.244
Height(m)	16.46	4.115
Core Makeup Tank		
Height(m)	7.9	1.975
Volume(m^3)	113.0	0.2825
Accumulator		
Height(m)	4.5	1.125
Water volume(m^3)	97.6	0.244
Gas volume(m^3)	15.4	0.0385
IRWST		
Water level(m)	10.7	2.68
Water volume(m^3)	3915	9.786
Elevation from DVI pipe (m)	4.2	1.05
ADS valves		
1st stage dia.(m)	0.102	0.00102
2nd stage dia.(m)	0.203	0.00203
3rd stage dia.(m)	0.203	0.00203
4th stage dia.(m)	0.305	0.00305