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Numerical investigation of in-vessel core coolability of PWR through an effective safety injection flow model using MELCOR simulation

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ABSTRACT

A safety injection (SI) flow model predicting target depressurization was developed in the previous study. The model estimated the sum of the decay heat and oxidation heat using the core exit temperature increase rate and core water level decrease rate during the accident progression. However, in the old model only the heat transfer to the coolant was considered but the heat accumulation in the structures was not included in detail. To resolve this issue, therefore, a new mechanistic model was developed by considering heat sources accumulated in the core heat structures. The accuracy of the new model was validated through the prediction of core total heat using the MELCOR 1.8.6 code. It was confirmed that the new model resulted in a relatively small error less than 10% in almost all sections while the old model exhibited a large error exceeding 50% since the start of oxidation for postulated SBO severe accident scenario. Through the model validation, an improved SI flow map was developed to predict more accurate target depressurization of the reactor coolant system (RCS) needed for maintaining core coolability. This study suggests that new SI flow map can effectively assist operator's execution related to the RCS depressurization and SI injection into the RCS implemented in the severe accident management guideline under various severe accident scenarios.

1. Introduction

In Korea, Severe Accident Management Guideline (SAMG) for Optimized Power Reactor (OPR1000) was developed based on Westinghouse Owner's Group SAMG. Primarily, execution of the SAMG is initiated by the Technical Support Center (TSC) when the core exit temperature (CET) reaches 923 K (Kim et al., 2013; Seo et al., 2015). Fig. 1 shows a schematic flow chart of the SAMG strategies. Among the seven mitigation strategies envisioned, the third management strategy of injecting coolant into Reactor Coolant System (RCS) is a key to fortifying the in-vessel retention capability. The amount of coolant injected using this strategy should correspond to the maximum possible extent to recover the core water level by removing the heat generated from the core (Wang et al., 2004). During a postulated severe accident in Light Water Reactor (LWR), the decay heat as well as a substantial amount of oxidation heat is generated in the reactor core (Schanz et al., 2004; Park et al., 2013; Chatelard et al., 2006). Thus, it is essential to develop an accurate model to predict the possible heat generation to determine a reasonable safety injection (SI) flow rate which facilitates the third strategy and correspondingly to determine the target RCS depressurization.

Previously, the SAMG included a calculating table for SI injection to support the third strategy. However, rather simple formulae in the calculating table (SAMG model) only estimated decay heat in the core without detailed consideration on the oxidation heat prior to the coolant injection. This implies that the SAMG model is limited in predicting the accurate core total heat, which comprises of the decay heat as well as oxidation heat during accident sequences.

Abbreviations: ADV, Atmospheric Dump Valve; AFW, Auxiliary Feed Water; BWR, Boiling Water Reactor; CDV, Condenser Dump Valve; CET, Core Exit Temperature; CV, Control Volume; ECCS, Emergency Core Cooling System; FSAR, Final Safety Analysis Report; HPSI, High Pressure Safety Injection; KWU, Kraftwerk Union AG; LPSI, Low Pressure Safety Injection; LWR, Liquid Water Reactor; MSIV, Main Steam Isolation Valve; MSSV, Main Steam Safety Valve; NPP, Nuclear Power Plant; NSSS, Nuclear Steam Supply System; OPR1000, Optimized Power Reactor 1000 MWe; PKL, Primarkreislauf; PSRV, Pressurizer Safety Relief Valve; PWR, Pressurized Water Reactor; RCS, Reactor Coolant System; RPV, Reactor Pressure Vessel; SAMG, Severe Accident Management Guideline; SBLOCA, Small Break Loss of Coolant Accident; SBO, Station Black Out; SDS, Safety Depressurization System; SGTR, Steam Generator Tube Rupture; SI, Safety Injection; SIT, Safety Injection Tank; TLOFW, Total Loss of Feed Water; TSC, Technical Support Center.

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Nomenclature

A	cross sectional area of the core (m^2)
$c_{p,cl}$	specific heat of the cladding (J/kg K)
$c_{p,core}$	specific heat of the core (J/kg K)
$c_{p,f}$	specific heat of the fuel (J/kg K)
$c_{p,hs}$	specific heat of the heat structure (J/kg K)
$c_{p,st}$	specific heat of the structure (J/kg K)
$c_{p,steam}$	specific heat of steam (J/kg K)
h_{fg}	specific enthalpy of vaporization (J/kg)
h_{inj}	specific enthalpy of the injected coolant (J/kg)
$h_{sat,g}$	specific enthalpy of the saturated steam (J/kg)
L	height of the uncovered core (m)
$\frac{dL}{dt}$	decreasing rate of core water level (m/s)
M_{cl}	mass of the cladding (kg)
M_{core}	mass of the core (kg)
M_f	mass of fuel (kg)
M_g	steam mass in the core (kg)
M_{H_2O}	molecular weight of water (kg)
M_{hs}	mass of the heat structure (kg)
M_{st}	mass of the supporting structure (kg)
$\dot{m}_{min}$	minimum required flow rate (kg/s)
$\dot{m}_{req}$	required flow rate (kg/s)
P_{RCS}	pressure of RCS (Pa)
$\dot{q}_{decay}$	decay heat in the core (W)
$\dot{q}_{oxidation}$	oxidation heat in the core (W)
$\dot{q}_{tot}$	total heat in the core (W)
$\dot{q}_{steam}$	sensible heat of steam (W)
$\dot{q}_{water}$	latent heat of water (W)
$\dot{q}_{hs}$	accumulated heat in heat structure (W)
Q_0	power before the shutdown (W)
Q_{store}	total heat accumulated in the core (W)
R	gas constant (J/mol K)
t	time after shutdown (s)
t_{refill}	refilling time (s)
T_{CET}	core exit temperature (K)
$\frac{dT_{CET}}{dt}$	increasing rate of core exit temperature (K/s)
$\frac{dT_{hs}}{dt}$	increasing rate of heat structure temperature (K/s)
T_{core}	temperature of the core (K)
T_{sat}	saturation temperature of steam (K)
V_0	volume of the upper head (m^3)

Greek letters

ρ_f	density of coolant (kg/m^3)

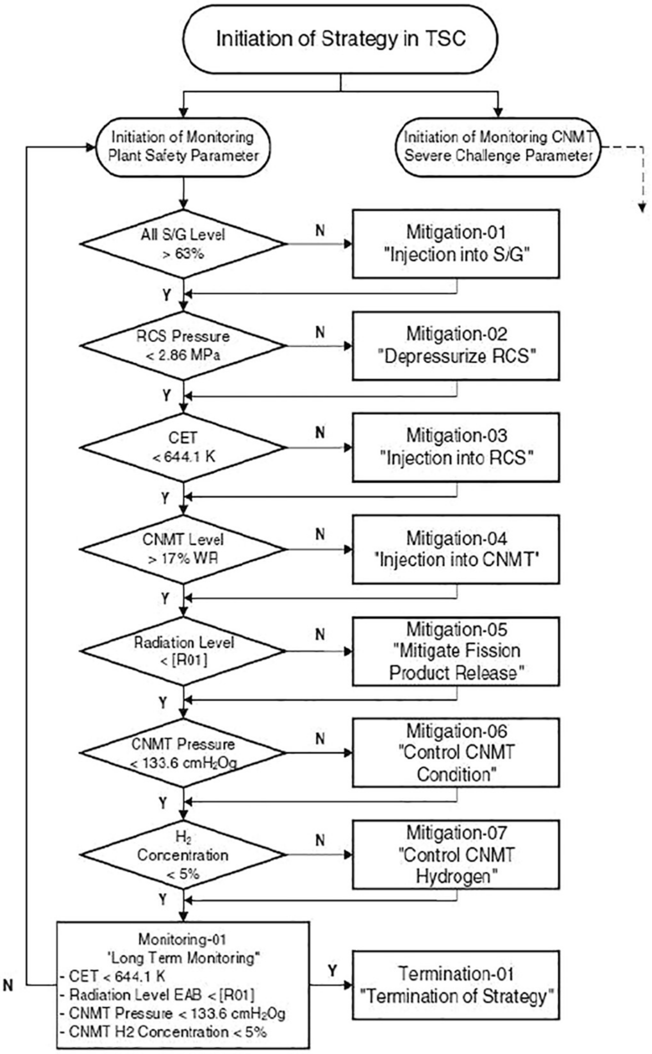

Fig. 1. Schematic flow chart of OPR1000 SAMG.

So the SAMG model takes a rather conservative approach by considering the maximum core temperature and material properties of core, which are implemented into the decay heat since the occurrence of the accident. However, this conservative approach allows unnecessarily large amount of coolant, whose resource is obviously limited during the accident management. After noticing this issue, to estimate the more effective safety injection rate Lee et al. developed a SI flow model adopting two major heat sources of inherent decay heat and exothermic oxidation heat. The mechanistic model employed the CET increase rate and core water level decrease rate reflecting important accident processes (Lee et al., 2016). In contrast to the calculating table in the SAMG, the SI flow model developed by Lee et al. could consider additional heat sources by oxidation reaction between hot steam and metal components such as cladding, supporting structures, and control rods. However, their model exhibited poor accuracy by underestimating total heat removal especially since the start of oxidation. A major reason was because the heat accumulated in the structures (fuel, cladding and supporting structures) was not properly considered (Clément et al., 2003; Zinkle et al., 2014; Guillard et al., 2001).

Therefore, the objective of this study is to improve the SI flow model by implementing detailed heat sources. It is important to mention that the SI flow model is closely associated with target RCS depressurization so that the developed model can assist operators in determining if a sufficient injection flow can be assured to guarantee the in-vessel core coolability during severe accidents (Park et al., 2008). In developing a new model, additional terms were derived with the experimental evidence to calculate accurate heat accumulation using the CET increase rate. The resulting SI flow model led to an SI flow map including the target RCS depressurization that enabled in determining the required flow rate by utilizing the curve of flow rate and pressure by operating two high pressure safety injections (HPSIs) (Park et al., 2008). Furthermore, the accuracy of the new model and map was verified by the recent MELCOR simulation results, in which four major initiating events of small break losses of coolant accident (SBLOCA), station black out (SBO), total loss of feed water (TLOFW), and steam generator tube rupture (SGTR) were considered.