



A thermal structural analysis tool for RPV lower head behavior during severe accidents with core melt

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Abstract

The Fukushima Daiichi Nuclear Power Plant accident showed a significant effect on the environment due to the release of a large amount of radioactive material. To prevent the damage of the reactor pressure vessel (RPV), an in-vessel melt retention (IVR) by external reactor vessel cooling is considered to be a key severe accident management strategy. For its success, investigation of the thermal-mechanical behavior of the RPV lower head is of importance. The main objective of this study is the development of a thermal structural calculation tool for simulating the failure process and the visco-plastic behavior of the RPV lower head wall during the late phase of a core-melt severe accident. OpenFOAM, an open-source toolbox for developing numerical solvers, was used for the calculation platform. Thermal behavior of the molten pool in the RPV lower head is simulated by the phase-change effective connectivity model (PECM). One of the LIVE (Late In-Vessel Phase Experiments) experiments was analyzed for an evaluation purpose and reasonable results were obtained. The solver was then extended to couple PECM with a structural analysis model that considers thermal expansion, plasticity, creep and material damage. Two FOREVER (Failure Of Reactor Vessel Retention) tests, each of which uses different type of steel, were analyzed: EC-FOREVER-2 with French RPV steel 16MND5 and EC-FOREVER-4 with American RPV steel SA533B1. The deformation and failure time agreed reasonably well with the measured data. In addition, the failure mode was also well predicted qualitatively. The numerical analysis showed that the developed tool has a capability of simulating the lower head thermal structural behavior.

Keywords : Model development, In-vessel melt retention, LIVE, FOREVER, RPV, Structural analysis

Nomenclature

<i>Greek symbols</i>		<i>Subscripts and superscripts</i>	
α	thermal diffusivity [m^2/s]	<i>cr</i>	creep
β	thermal expansion coefficient [$1/\text{K}$]	<i>down</i>	down
ϵ	strain [-]	<i>eqv</i>	equivalent
ν_p	Poisson's ratio [-]	<i>frac</i>	fracture
ν_{kin}	kinematic viscosity [m^2/s]	<i>h</i>	hydrostatic
ρ	density [kg/m^3]	<i>local</i>	local
σ	stress [Pa]	<i>pl</i>	plastic
<i>Latin symbols</i>		<i>pool</i>	pool
C_p	specific heat capacity [$\text{J}/(\text{kg}\cdot\text{K})$]	<i>side</i>	side
D	damage parameter [-]	<i>up</i>	up
ϵ	emissivity [-]	<i>x, y, z</i>	coordinate axis directions
g	gravitational constant ($=9.8 [\text{m}/\text{s}^2]$)		

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