

Coupled thermo-structural analysis for in-vessel retention in PHWR using ABAQUS



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ABSTRACT

This paper presents simulations which give insights about the thermo-structural interaction of molten core debris and calandria vessel during severe accident scenario in a pressurised heavy water reactor. The insights developed are required to devise appropriate accident mitigation strategies including in-vessel retention and source term evaluation. Internationally, the severe accident assessment research has been focussed on RPV lower head failure studies and a limited and simplified approach has been attempted for analysing calandria vessel behaviour with core debris in pressurised heavy water reactor. This paper presents a 3D finite element based simulation of the thermo structural interaction of molten debris and calandria vessel.

During a postulated severe accident, core debris would relocate into the lower portion of calandria vessel and may threaten the integrity of calandria vessel. The heat transfer between the molten core debris and the vessel may cause localised overheating (or partial melting) or inelastic strain accumulation which may result in vessel failure. In this paper coupled thermo structural analysis of calandria vessel with debris is carried out in a finite element framework to evaluate integrity of the calandria vessel. In this analysis boundary conditions include availability and non-availability of water outside calandria vessel. Initial conditions assume molten debris with different percentage of zirconium oxidation. Structural behaviour of calandria vessel is simulated considering elasto-plastic material behaviour including creep deformations. A failure criterion based on inelastic strain is used in the simulation.

The analysis shows that the calandria vessel may not undergo inelastic strain failure as long as the calandria vault water is available. The failure of calandria vessel may occur due to the localised melting when the vault water is not available. Further the paper also presents experimental studies planned to investigate the heat transfer from calandria with core debris to calandria vault water. Finite element simulation is presented which is used to design the proposed direct heating arrangement to simulate the debris heat flux.

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1. Introduction

For unmitigated loss of coolant or station blackout accident scenarios, pressure tube contacts with calandria tube and the decay heat is transferred to the moderator. As the moderator is depleted due to boil off, overheating and melting of the core results in debris formation at the calandria bottom. At this stage, the debris is cooled by the remaining inventory in the calandria. Once the calandria inventory is completely boiled off, the significant portion of heat is removed through the calandria wall to the calandria vault inventory. The heat transfer between the molten core debris and

the vessel may cause localised overheating (or partial melting) which may result in vessel failure. As a part of severe accident management guidelines further core degradation must be arrested and molten corium concrete interaction (MCCI) must be averted. The failure of the calandria vessel defines the initial conditions for all ex-vessel events. The knowledge of mechanical behaviour of the calandria vessel defines the possible methods for accident mitigation.

The severe accident assessment research initiated after the accident at Unit 2, Three Mile Island (TMI-2) and since then there has been a significant increase in the ability to understand and model severe accident phenomena. In 1994 US NRC initiated experimental and analytical work at Sandia National Laboratories to investigate the mechanical behaviour of the lower head of a reactor pressure vessel (RPV) under postulated severe accident conditions.

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There have been a number of reactor safety programs dealing with creep rupture of RPV (Hoge and Ott, 1989; Humphries et al., 2002; Autrusson and Combescure, 1998; Chambers, 1989; Devos et al., 1996; Harada et al., October 1997; Sievers et al., 1998; Strub et al., 1996; OECD, 1994; Sehgal et al., 1998). The lower head failure (LHF) experiments were the only such program where experiments were performed with prototypical reactor pressure vessel geometry. The FOREVER experimental work (Sehgal et al., 1998) also dealt with thermal and mechanical behaviour of reactor pressure vessels for small wall temperature differential, and in-vessel melt retention under severe accident conditions. In 1998, the Nuclear Energy Agency of the Organization for Economic Cooperation and Development (NEA_OECD) sponsored the Lower Head Failure program (OLHF) at the Sandia National Laboratories (SNL) to address some of the issues left unresolved by the LHF experiments. However, similar analytical and experimental studies are very limited for in-vessel retention in pressurised heavy water reactor (Prasad et al., 2015; Mukhopadhyay et al., 2014; Kulkarni et al., 2013).

Unlike in case of pressurised water reactors (PWR), only two severe accident codes are available i.e. MAAP4 CANDU and ISAAC (IAEA-TECHDOC-1594., 2008). Generally, codes for simulating severe accident progression are developed for light water reactor and are modified to take into account the horizontal channels in a pressurised heavy water reactor (Mladin et al., 2009). Studies are reported on the interaction of terminal debris bed with calandria vessel following an accident with severe core degradation in a CANDU with SCDAP/RELAP5 (Mladin et al., 2010). Several modifications are reported in COUPLE routines for a proper use of

SCDAP/RELAP5 in cylindrical geometry. Also, the structural behaviour of calandria vessel under the debris load and thermal gradients is done in a simplified manner. Therefore, it is important to develop a 3D coupled thermo-structural model to simulate calandria vessel behaviour under various configuration of corium i.e. layers formed and percentage of zirconium oxidised. A finite element based model also has capability to capture the material behaviour under such extreme loading. Fig. 1 shows a schematic of PHWR core assembly (Bajaj and Gore, 2006).

The current work evaluates the integrity of calandria vessel with molten core debris during a severe accident scenario using a multi-physics finite element method (FEM) based code, ABAQUS (User's Manual and 2013). The simulation evaluates the effectiveness of calandria vessel to transfer heat from corium to vault water under severe accident scenario. The accident scenario considered is loss of coolant accident (LOCA) with simultaneous loss of emergency core cooling (LOECCS) and moderator cooling (LOMODC). It is assumed that whole fuel and structural mass inside the reactor core is slumped into the calandria vessel bottom (Mani Mathew and et al., 1996). In general, a molten corium pool (Barrachin et al., 2004) including metallic materials, such as stainless steel and Zircaloy, and oxide materials, such as UO_2 and ZrO_2 , may form in the initial stage. The corium pool may be stratified into two layers, due to their density differences, an upper metallic layer with no volumetric heat source and a lower oxide layer with a volumetric decay heat source as shown in Fig. 2. Two layer corium pool formation is considered in the analysis.

The analysis is carried out in two parts. First part comprises of heat transfer analysis and second part includes coupled thermal

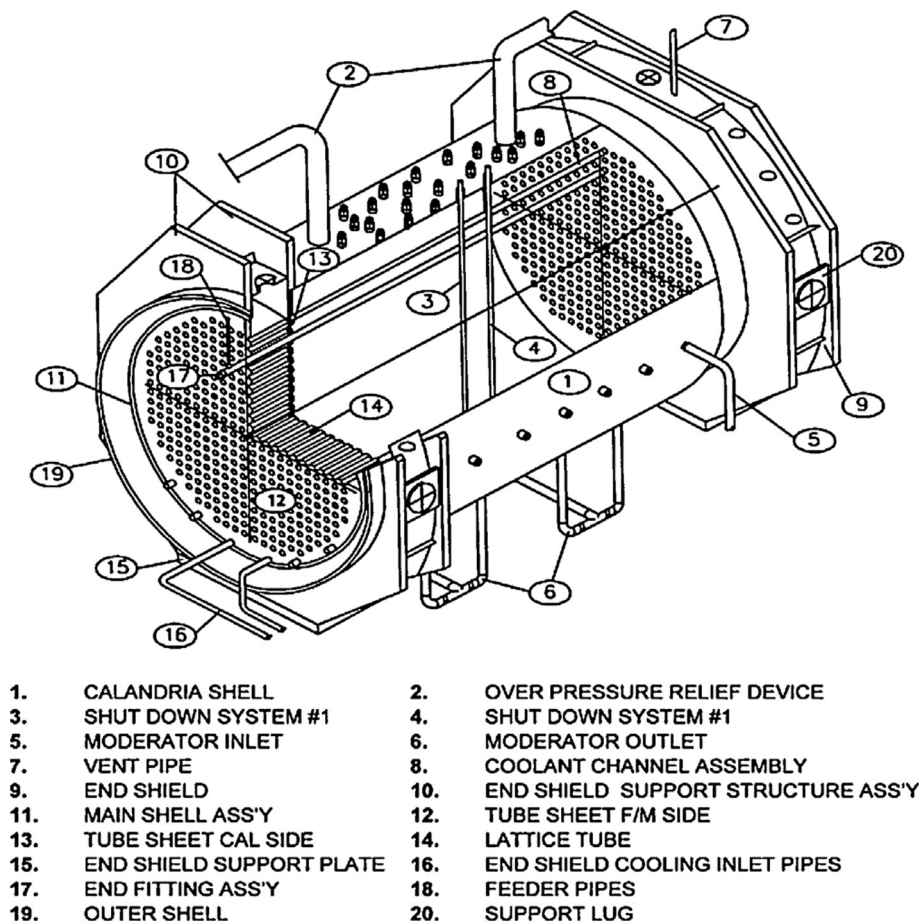


Fig. 1. PHWR core assembly (Bajaj and Gore, 2006).

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