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Analysis of Design Extension Conditions in a heavy water research reactor

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ABSTRACT

In this study, the core behavior following the reactor vessel lower head rupture together with the moderator system failure in a tank type heavy water research reactor, IHWRR, is analyzed through the MELCOR code. The focus is on the safety assessment of the reactor core for Design Extension Conditions and overall assessment of safety features of the reactor for any residual risk posed by severe accidents. The inherent features of IHWRR provide a broad spectrum of scenarios where the fuel does not melt, even if primary and moderator cooling are lost. Accordingly, coincident with vessel rupture, three different scenarios are considered for moderator failure: i) loss of moderator forced circulation, calandria tube rupture in ii) the upper and iii) the lower parts of the core. The obtained results showed that the vessel rupture that coincides with the tube rupture in the lower part of the core leads to the oxidation of entire Zr cladding and failure of the calandria tubes without core melt or hydrogen explosion in the containment.

1. Introduction

After multi-unit accident at Fukushima Daiichi nuclear power plant in 2011, the nuclear community has been reassessing certain safety assumptions of the nuclear reactor plants design, operation and emergency actions, particularly with respect to extreme events that might occur, and that are beyond current design basis events.

According to IAEA requirements (IAEA, 2016), a set of Design Extension Conditions (DECs) for a research reactor shall be analyzed. DECs are postulated accident conditions not considered in design basis accidents, but are considered in the design process of the facility in accordance with the best estimate methodology. DECs are either initiated by a very unlikely event or include the simultaneous failure of two or more safety systems.

Several computer codes like MELCOR (Gauntt et al., 2005), MAAP (Fauske and Associates Inc., 1994), ASTEC (Chatelard et al., 2014; Van Dorsselaere et al., 2009), SOCRAT (Bolshov and Strizhov, 2006) and SAMPSON (Ujita et al., 1999) can integrally predict the consequences of severe accident scenarios. MELCOR is an advanced computational tool widely used and adoptable in various reactor designs for severe core damage analyses. Using MELCOR, all phenomena that occur during a severe accident in water-cooled nuclear reactor, from the initiating event to the possible release of radioactive products outside the containment can be simulated (Gauntt et al., 2005).

For a tank type heavy water research reactor like the one applied in this study, IHWRR, DECs fall into two classes: those with preserved core geometry, and those with loss core geometry. In both cases, presence of the moderator as a heat sink prevents fuel channels failure and limits core degradation. Similar to pressurized heavy water reactors, here severe core damage is only possible if the heat sink behavior of the moderator is lost (IAEA, 2013).

Vessel rupture in a light water reactor, however rare, would severely damage the reactor core, though it does not have any significant impact on IHWRR reactor fuel integrity. Although, there is no individual emergency core cooling system in IHWRR reactor, heat is removed from the reactor core through the moderator circuit. Accordingly, an assessment is performed to investigate the fuel/channel integrity during reactor vessel rupture with coincident loss of moderator cooling as a DEC.

The objective here is to provide an overview of DECs in a heavy water tank-type research reactor. In this regard, coincide with vessel rupture, three different scenarios are considered for moderator failure: i) loss of moderator forced circulation, calandria tube rupture in ii) upper and iii) lower part of the core. The results of these accident scenarios obtained through MELCOR 1.8.6 calculations covering a wide range of thermal-hydraulic phenomena are discussed.

2. Reactor and primary cooling system identification

The IHWRR is a 40 MW tank type research reactor, with natural uranium dioxide fuel, and heavy water for moderation and cooling. The IHWRR reactor is applied for R&D purposes, and radioisotopes production for medical and industrial applications. The main parameters of the IHWRR reactor are presented in Table 1 (Faghihi et al., 2008;

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Table 1
Main parameters of the IHWRR research reactor.

Parameter	Value
Reactor type	Tank type
Reactor thermal power (MW)	40
Coolant	Heavy water
Moderator	Heavy water
Vessel inner diameter (mm)	4000
Vessel thickness (mm)	16
Calandria inner diameter (mm)	3760
Calandria thickness (mm)	20
Material of the fuel pin cladding	Zr + 1%Nb
Fuel material	UO_2 Natural
Material of channels	Zr + 2.5%Nb
Number of rods per assembly	19
Number of fuel pins per fuel assembly	18
Active fuel rod length	3430
Fuel rod length	3830
Fuel pin diameter (mm)	13.63
Thickness of the fuel pin cladding (mm)	0.9
Fuel assembly channel Inner diameter (mm)	80
Number of primary coolant loop	2
Number of moderator loop	2
Primary coolant loops mass flow rate (kg/s)	220 × 2
Moderator loops mass flow rate (kg/s)	17.5 × 2
Primary coolant Gas pressure (MPa)	0.2
Moderator loop Gas pressure (MPa)	0.2
Coolant temperature at reactor inlet (°C)	50
Moderator temperature at reactor inlet (°C)	50
Coolant temperature at reactor outlet (°C)	70
Moderator temperature at reactor outlet (°C)	70
Maximum fuel temperature (°C)	360
Maximum fuel cladding temperature (°C)	120
Radial Peaking factor at BOL	1.77
Axial Peaking factor at BOL	1.46
Containment free volume (m^3)	30000

Hashemi-Tilehnoee et al., 2010).

The reactor core is located in calandria, which is housed in the reactor vessel (Fig. 1). The reactor core consists of 150 fuel assemblies and a central channel in a hexagonal lattice. Each assembly is placed inside a separate coolant channel. Heavy water coolant flows inside the channels which are immersed within the calandria. The reactor core contains 27 channels for control and protection system: 3 control rod, 12 shimming rod, 6 emergency rod, and 6 emergency light water. Nine vertical channels are provided for radioisotope production, irradiation and activation applications (Faghihi et al., 2008).

The coolant is in liquid phase and does not mix with the moderator. Both the reactor coolant and moderator systems consist of two circulation loops. The primary cooling system is designed to transfer heat from the reactor core to the heat exchangers and then to the main cooling water circuit. The moderator water circulates around the channels and removes the heat produced by moderation and the heat transferred through the channel walls. The residual heat is removed by moderator loop and natural circulation of the primary coolant loop. In emergency conditions, such as LOCA, moderator circuit can be operated as a cooling system to remove heat from the core.

Both the coolant and moderator systems are equipped with a pressurizer, designed to regulate pressure and compensate for the primary coolant volume changes as a result of temperature variations. The helium gas system maintains the pressurizer's pressure and removes the accumulated D_2 and O_2 from the circulation loops. Moreover, it prevents the direct contact of D_2O with air in the technical tanks of the systems. The nominal water level is maintained in the pressurizer during normal operation. When water level drops, the make-up pump is switched on by the regulator signal and water level is brought back to its nominal state. When the water level rise as a result of an increase in water temperature, the coolant is drained through the reactor drainage valve.

In the nominal operation mode, the one-way valves installed on the

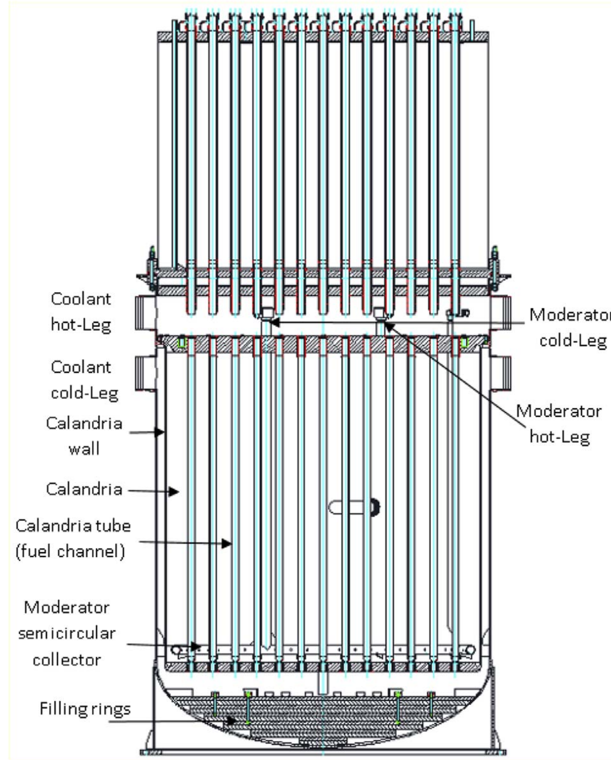

Fig. 1. Reactor vessel and its internal.

pumps bypass lines remain closed. Following the circulation pumps' stoppage, shut gates of the pumps bypasses open automatically by progressing the head of natural circulation. Reliability of natural circulation in reactor cooling mode is assured through the heat exchangers layout, which are installed above the reactor. The scheme of the primary coolant system PFD is shown in Fig. 2.

3. Modeling

3.1. MELCOR model

For modeling IHWRR through MELCOR, a complete data base of IHWRR design data is developed, followed by preparation of the nodalization and input deck. This input model is a coarse node representation of the hydraulic system and structures, consisting of 7 fluid cells for each coolant/moderator loop. The reactor vessel consists of down comer, lower plenum, upper plenum, moderator tank and core region. This core region is divided into 15 control volumes (3 axial levels and 5 radial rings). The reactor core is modeled by invoking COR package of the code which specifies the structural materials in fuel rods, control rods, guide tubes, etc. To represent the core configuration, BWR option is selected where the radial relocation is disabled. According to power distribution and geometry, 7 radial non-uniform rings and 22 axial nodes are considered. The moderator in calandria is modeled as the bypass volume for all of the core cells. The 5 inner rings are assigned to 15 core volumes. Here, opening of a flow area between the channel and bypass during failure of separating channel tubes are of concern. The nodalization of the reactor vessel and loops are shown in Figs. 3 and 4, respectively.

To validate the nodalization, the steady state core parameters, such as thermal power on the primary/secondary sides, core inlet/outlet coolant temperatures, core/calandria mass flow rate are compared with reference data in Table 2. It is seen in this table that there exist a good agreement between the steady-state key parameters calculated from the model and operating conditions of the IHWRR reactor.