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Assessment of In-Core Damage for Feeder Stagnation Break in CANDU

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1. Introduction

A feeder break is a single channel accident while the other channels remain intact in the CANDU core. For some ranges of feeder break size, a flow in the channel can become stagnate due to a force balance between the upstream and the downstream ends. In the extreme, this can lead to a rapid fuel heat up and fuel damage, and the failure of a fuel channel. This break scenario is called a feeder stagnation break.

Following the feeder stagnation break, the fuel and pressure tube in the affected channel heat up quickly. The channel fails due to overheating and the channel contents begin to discharge into the moderator. The discharge is composed of steam, some hydrogen produced by possible metal-water reaction, and solid fuel elements of fuel fragments with molten material. The severity of the transient is primarily determined by the amount of molten material discharged into the moderator, and by the interaction between the molten material and the moderator, which determines the rate of energy release.

After a channel rupture (pressure tube and calandria tube) some SOR (Shut-Off Rod) guide tubes, which are located in the vicinity of the break in the core, may be damaged. If the damage to the guide tube is substantial, some SORs may not be able to descend into the moderator, and therefore, not contribute to the shut down of the reactor. The increase in system reactivity, due to factors such as poison dilution from discharging coolant and void formation, may challenge the reactivity worth of the available undamaged SORs. Therefore, an analysis of the reactivity worth of the partially impaired SDS #1 (Shut-Down System #1) is required to determine that it can compensate for the increase in reactivity and shut down the reactor [1].

In this study, the hydrodynamic transient, due to the dispersed molten material and the discharged steam, was calculated following the feeder stagnation break. The timing of the channel failure and the mass of the molten material were provided from the thermal-hydraulic analysis. The energy release from hydrogen and solid fuel elements or fuel fragments were neglected, since the amount of discharged hydrogen was relatively small (the presence of hydrogen would simply displace the steam) and the time constant for energy release of solid fuel elements or fuel fragments was longer by, at least, an order of magnitude than that of the molten material. The amount of steam generated in the fuel channel prior to rupture and the steam generation from molten material was calculated using the TUBRUPT-IST 2.0 code [2]. The hydrodynamic transient was also calculated by using the same code. The SOR guide tubes could be damaged due to the hydrodynamically impulsive loads, jet impingement, and pipe whip. Any guide tubes that could experience a direct impingement by the jet were assumed to be disabled. Additionally, fuel channel damage due to fuel ablation, which occurs due to contact between the calandria tube outer surface and the hot molten material ejected, was considered. If the SOR guide tubes are in the path of the jet, the molten material could solidify on their inner surfaces and prevent the subsequent passage of the SOR. Therefore, any guide tube that could experience a direct impingement by the jet was assumed to be damaged and unavailable for SOR insertion.

2. Analysis Methodology for In-core Damage

2.1 Overview of TUBRUPT-IST Code

The TUBRUPT-IST code was designed to predict the hydrodynamic transients inside two liquid-filled vessels, one inside the other during in-core break accidents in a single fuel-channel. The inner vessel is the calandria vessel (CV) and the outer-vessel is the shield tank (ST). The modeled pressure transients were caused by a sudden and continual discharge of high-pressure and high-temperature primary heat-transport coolant from the broken fuel channel into the CV. The main CANDU reactor application of the TUBRUPT code involves an in-core break from a single fuel channel. This in-core break would follow a calandria tube rupture caused by a pressure-tube rupture. The pressure tube rupture could be either spontaneous or by molten fuel resulting from a severe flow blockage or a feeder stagnation break.

2.2 Preparation of Input Parameters and Assumptions

A longitudinal break of 0.5m long with a crack propagation speed of 200 m/s are assumed, since it accounts for the ductility of the fuel channel material at high initial temperatures. The hydrodynamic transient for this accident requires special consideration since there is the potential for steam and molten material to be discharged into the moderator. The interaction between the molten material and the moderator could result in more severe hydrodynamic transient or more severe in-core damage.

The amount of molten material was obtained from the fuel channel analysis based on two kinds of fuel channel failure criterion, one was the pressure tube (PT) ballooning criterion and the other was sheath melting criterion.

By applying the pressure tube ballooning failure criterion, the fuel channel failed at the time of pressure tube and calandria tube (CT) contact. For this case, a sheath mass of 15 kg and an alloy mass of 7.5 kg were determined as the amount of molten material. The molten materials were considered to be dispersed into the moderator from the broken fuel channel. A bounding temperature of 2273°C for molten sheath and alloy was also used.

For the sheath melting criterion, the fuel channel was assumed to fail due to molten sheath contact with the PT after PT/CT contact occurs. The estimation of the molten mass was generally higher for this criterion than for the PT ballooning failure criterion. Accordingly, in-core damage was assessed using molten masses which bound the results based on the sheath melting criterion. Molten masses of the 30 kg of UO_2, 20 kg of sheath and 10 kg of alloy were determined by the sheath melting criterion. The molten fuel was assumed to be at a bounding temperature of 3273°C.

3. Results of the In-Core Damage Assessment

3.1Refernece Case – Sheath Melting Criterion

The analysis shows that the shutoff rod guide tube damage for the sheath melting criterion was identical to that for the PT ballooning criterion at the most severe damage locations. Table 1 shows the result of the damaged SOR guide tubes. The damaged SORs are 5, 9, 14, 16 and 21 and the next most effective SOR 25 was also assumed unavailable. The calandria pressure transient is given as Case 2 in Fig. 1. It indicates a lower peak pressure compared to the peak pressure for the pressure tube rupture. Short duration pressure spikes have previously been assessed and found not to impart sufficient energy to the large and massive reactor structure to result in significant pressure boundary displacements. The associated stresses were low and were bounded by the stresses resulting from the steady state pressure, therefore, calandria integrity was assumed.

3.2 Result of SDS #1 Depth Assessment

The net reactivity was separated into its constituents (moderator poison displacement, coolant void, coolant temperature, fuel temperature, degrading moderator, moderator temperature and shutoff rods static worth). The system reactivity was -10.4 mk at 15 minutes and -4.3 mk at 20 minutes after the accident.

3.3 Sensitivity Calculations

Two key phenomenological quantities of the longitudinal break size and amount of molten material available for discharge were used for sensitivity calculation. Four different sensitivity calculations were set up as shown in Table 2.

The pressure increase after the calandria tube collapse onto the pressure tube was shown in Fig. 1. From this, it was concluded that the calandria integrity was maintained for the discharge of molten material into the moderator.

4. Conclusions

The effect of the potential discharge of molten material into the moderator was accounted for in the calandria integrity assessment. The analysis shows that calandria integrity was maintained.

The shutdown systems have adequate negative reactivity depth to keep the reactor sub-critical until the operator can act.

Table 1 Number of Impaired SOR Guide Tubes

Break Location (m)		Damage Mechanism			Total Number
X	Y	Hydro-dynamic	Pipe Whip	Fuel Impact	
2.145 (4)	0.0	9(50%), 14(50%), 16(50%)	5, 9, 14, 16, 21,	9, 14, 16	5

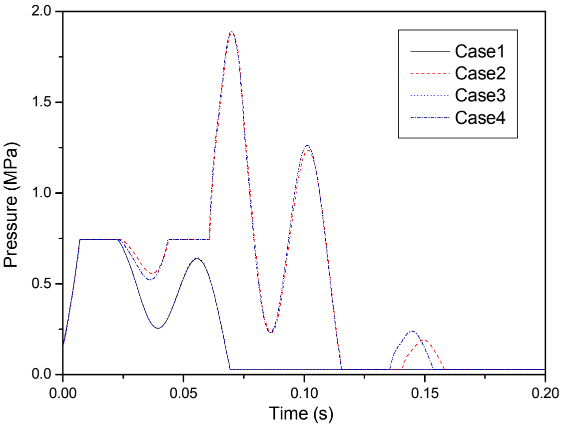

Fig.1 Pressure Transients at Inner Calandria Shell for Stagnation Feeder Break

Table 2 Cases for Sensitivity Calculations

Case	Break Size (m)	Molten Material (kg)	Temperature (k)	Time to open the rupture (s)	Density of Discharged MM (kg/m^3)
1	0.5	20	2273	1.25E-3	6518.25
2	0.5	70	3273	1.25E-3	8865.14
3	2.5	20	2273	6.25E-3	6518.25
4	2.5	70	3273	6.25E-3	8865.14

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