# MELT EJECTION EXPERIMENTAL PROGRAMS RELEVANT TO CANDU REACTORS

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## SUMMARY

There are three possible channel responses to a severe power/cooling mismatch at full reactor power and high heat transport system pressure following a blockage of primary heat transport coolant flow in a single fuel channel. These responses are:

- *Sufficient convective heat removal is available to avoid pressure tube ballooning* - in this case there is no channel failure, also fuel temperatures remain relatively low.

- *Fuel channel fails early during pressure tube ballooning* - in this case, there is either no molten material in the channel at the time of failure, or any small amount of melt generated is confined within the fuel elements (*i.e.*, no melt pool at the bottom of channel).

- *Pressure tube balloons uniformly into contact with its calandria tube* - in this case, some fuel liquefaction occurs, and channel failure is induced by the relocation of melt from the fuel bundle interior to the composite wall of the ballooned channel.

Although the third type of channel response is highly unlikely, its consequences are more severe than the other types since it may lead to energetic Fuel-Coolant Interactions (FCIs).

Two analysis methodologies are available for the modelling of fuel-coolant interactions following a severe power-cooling mismatch in a single channel of a CANDU reactor. These methodologies simulate forced-interaction, and free-interaction of the melt with liquid water, respectively. The two methodologies address different physical phenomena. The forced interaction model postulates that the melt is ejected from the channel at sufficiently high velocities to be finely fragmented and rapidly quenched within milliseconds of the ejection. The free interaction model postulates that the ejected melt first accumulates outside of the channel as a coarse melt-water-steam mixture. Some time later, this coarse mixture is triggered to finely fragment and rapidly quench.

A number of experimental studies[1-6] have been performed to investigate the process and behaviour of pressurized melt ejection, and they are considered in this work. The experiments may be divided into two categories, namely, Direct Containment Heating (DCH) and Reactivity Initiated Accident (RIA) experiments.

In the DCH process, it is considered that the melt accumulates in the lower head of a Pressurized Water Reactor (PWR) pressure vessel under high pressure coolant conditions. Failure of the vessel at a location in contact with the melt would then lead to gas-pressure-driven ejection of melt into the reactor cavity region and eventual deposition of the melt onto the floor of the containment building. Because of the presence of water in the reactor cavity region, a molten fuel-coolant interaction may occur. The DCH experiments include: Corium-Water Thermal Interaction Experiments (CWTI)[1], System Pressure Injection Tests (SPIT)[1,2], High Pressure Melt Streaming Series (HIPS)[1,2], Limited Flight Path Experiments (LFP)[3], Wet Cavity Experiments (WC)[4], and Integral Effects Tests (IET)[5]. In some of these experiments, molten material was ejected by high pressure steam into a cavity having no, or little water (condensate levels of water). In other experiments, with water in the cavity[2], energetic fuel-coolant interactions that destroyed the cavity were observed. Due to early failure, little data was recorded in these experiments. Other experiments with a robust cavity, designed to withstand large loads, are considered more reliable and relevant to CANDU reactors.

The DCH experimental results suggest that the high-velocity molten jet from the reactor vessel is fragmented while moving to the base of the cavity under the influence of a high velocity and perhaps dissolved gas release[1]. High pressure gases in the reactor pressure vessel (steam and hydrogen), which follow the melt from the vessel, flow at high velocity through the cavity, and fragment the melt into smaller particles. These particles are created from the melt by a combination of mechanisms: melt jet breakup by the action of gases, atomization, entrainment process and Weber breakup.

The results of Integral Effects Tests (IET), indicated that when the molten material was ejected by relatively high pressure into the cavity (about 6.25 MPa), FCI began immediately after the initiation of the high pressure melt ejection and continued throughout the blowdown of the melt (i.e., forced FCI). However, in a similar experiment, where the molten material was essentially dropped into the cavity, a delayed FCI occurred near the end of the molten pour into the cavity resulting in a larger pressure spike (i.e., free FCI).

Some of the DCH tests involved the discharge of melt into shallow water pools at the bottom of a linearly scaled reactor cavity. The mass of water was typically smaller than, or comparable to, the mass of the molten corium simulant. The liquid water depths ranged from a few centimetres to several tens of centimetres (*i.e.*, the pools were very shallow). In these experiments, an energetic melt-water interaction invariably commenced when the molten jet fragmented and dispersed by impacting the cavity floor. This experimental series is relevant to the CANDU single channel events in demonstrating the effectiveness of mechanical melt fragmentation due to impact on the adjacent in-core structures.

Several reactivity initiated experiments performed in Japan by JAERI[6], have initial conditions similar to those postulated in a channel in terms of the high driving pressure, the simultaneous presence of molten and solid $UO_2$ at the time of rupture, and the rapid rupture opening to a limited length. The initial pressures ranged from ambient to 8 MPa. The results of these tests displayed the shape of the hydrodynamic transient characterized by forced interaction (*i.e.*, a single pressure spike occurring immediately after the rupture). Furthermore, the magnitude of the pressure spike was observed to increase as the driving pressure increases, which is consistent with the finer melt fragmentation that occurs as the melt velocities increase.

In some of the Japanese tests, secondary pressure excursions occurred 5 to 10 ms after the first pressure peak. However, upon closer examination of the published results, it is apparent that the experiments which experienced the secondary fuel-coolant interactions actually involved low-velocity *melt pours* in the later stages of tests (*i.e.*, the transient melt generation continued after the fuel element had depressurized).

The objective of this paper is to present a state-of-the-art overview of the available experimental evidence to demonstrate that the free-interaction model is not suited for the high pressure melt ejection phenomena associated with CANDU single channel events. It is more appropriate to employ the forced fuel-coolant interaction methodology in analyzing CANDU single channel severe flow blockage scenarios if some molten fuel is postulated to occur.

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