IAEA ICSP on HWR Moderator Subcooling Requirements to Demonstrate Backup Heat Sink Capabilities of Moderator during Accidents

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Abstract

The IAEA launched a new International Collaborative Standard Problem (ICSP) on "HWR Moderator Subcooling Requirements to Demonstrate Backup Heat Sink Capabilities of Moderator during Accidents". The purpose of the ICSP is to benchmark analysis computer codes in simulating contact boiling experimental data to assess the subcooling requirements for an overheated pressure tube, plastically deforming into contact with the calandria tube during a postulated large break loss of coolant accident. The experimental data obtained for the ICSP blind simulation can be used to assess safety analysis computer codes simulating thermal radiation heat transfer to the pressure tube, pressure tube deformation or failure, pressure tube to calandria tube heat transfer, calandria tube to moderator heat transfer, and calandria tube deformation or failure.

1. Introduction

An important safety feature of HWR is the ability to use the moderator as a backup heat sink during emergencies. The pressure tube in a CANDU fuel channel is normally separated from the surrounding calandria tube by a CO_2-filled gap. This gas-filled gap thermally isolates the pressure tube from the calandria tube during normal operation. The deformation and subsequent ballooning contact of overheated pressure tube with the calandria tube rely on the combined performance of the pressure tube and calandria tube during the post-contact period to maintain channel integrity. The calandria tube, which is submerged in a subcooled pool of moderator water, supports and cools the pressure tube upon contact, arresting the outward deformation. The calandria tubes are thinner than the pressure tubes, but are directly cooled by the surrounding liquid moderator.

Heat transfer between the pressure tube and the calandria tube under normal operating conditions occurs primarily by conduction through the gas and by thermal radiation in an undeformed geometry of the channel. The moderator carries away the heat transferred radially out of the fuel channel. During abnormal accident conditions, however, the pressure tubes undergo plastic deformation and growth [1-2]. Plastic deformation is a permanent dimensional change, which occurs as a result of the interaction of stress and temperature. This deformation is known as pressure tube ballooning. When a pressure tube balloons into contact with the calandria tube, the resultant contact heat transfer significantly increases the rate of heat transfer to the calandria tube, and subsequently, to the moderator. The rate of heat transfer to the calandria tube is determined by the temperature difference between the pressure tube and the calandria tube and by the contact heat transfer coefficient. The temperature of the calandria tube is determined by the moderator subcooling and the heat transfer coefficient between the calandria tube and the moderator.

In a number of postulated loss-of-coolant accident (LOCA) scenarios with or without coincident loss-of-emergency core cooling (LOECC), the fuel may overheat and transfer heat to the pressure tube. As the pressure tube overheats, it loses strength and plastically deforms (balloons) into contact with the surrounding calandria tube. At the time of contact, the calandria tube experiences a large increase in heat flux at the contact locations as stored heat is rejected from the pressure tube to the cooler calandria tube. If the heat flux on the outer surface of the calandria tube exceeds the critical heat flux (CHF), film boiling (dryout) may occur on the surface of the calandria tube. If the area in dryout is sufficiently large and the dryout is prolonged, the pressure-tube/calandria-tube combination can continue to strain radially and may challenge fuel-channel integrity.

The moderator subcooling limits required to avoid dryout conditions that could challenge fuel-channel integrity are defined by the contact boiling curve. The contact boiling curve (Figure 1) generated from data collected in contact boiling experiments performed in the 1980s related moderator subcooling and pressure-tube contact temperature to the occurrence of immediate quench, patchy film boiling or extensive film boiling [3-4]. The boundary between immediate quench and patchy film boiling defined the moderator subcooling limits for CANDU reactors.

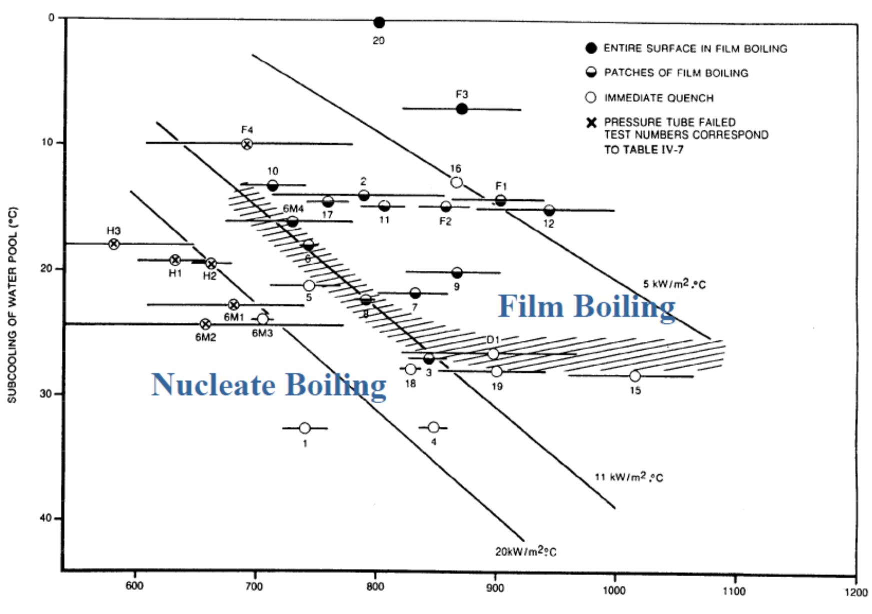

Figure 1 Contact boiling curve showing experiments performed in 1980s

In 2000, the contact boiling curve was updated with data collected from contact boiling experiments performed since the publication of the original contact boiling curve. The new experimental data showed that the occurrence of small patches of film boiling did not necessarily threaten fuel-channel integrity. If the area in dryout was modest (less than 15%) and the time to rewet was short (less than 20 s), fuel-channel integrity was not challenged.

The fuel channel integrity assessments during an accident scenario depend on the simulation of a number of phenomena and their interactions [5-6]. The safety analysis codes are validated against full-scale contact boiling experiments conducted using specific channel power, pressure, and moderator subcooling as pre-test conditions. The pressure tube and calandria tube temperatures, the extent of dryout and failures of the pressure tube or the calandria tube (if any) are the outcome of these experiments.

The purpose of this IAEA ICSP is to provide contact boiling experimental data to assess the subcooling requirements for a heated pressure tube, plastically deforming into contact with the calandria tube during a postulated large break loss of coolant accident condition. The data can be used to assess safety analysis computer codes simulating radiation heat transfer to the pressure tube, pressure tube deformation or failure, pressure tube to calandria tube heat transfer, calandria tube to moderator heat transfer, and calandria tube deformation or failure.

The ICSP participants from IAEA Member States will be able to use safety analysis codes to perform pre-test, blind and open simulations. The initial and boundary conditions for pre-test calculation are typically the internal pressure of the pressure tube, heater power, and moderator subcooling (water temperature). Following the pre-test simulations the contact boiling experiment will be performed with target initial & boundary conditions as close as possible to the pre-test initial & boundary conditions given to the analysts. The test will be completed following the pre-test simulations and then the actual initial & boundary conditions obtained in the test will be provided to participants for a blind simulation. The test data will be distributed to participants once the blind simulation results are obtained.

2. Test Apparatus

The Fuel Channel High Temperature Heat Transfer (FCHTHT) laboratory in AECL's Chalk River Laboratories has an experimental facility designed to study the behaviour of CANDU fuel channels under postulated accident scenarios involving insufficient primary and/or secondary emergency cooling. The facility can conduct full scale experiments and investigate the integrated thermal-chemical-mechanical response of a CANDU fuel channel under normal and abnormal conditions. The experiments in the laboratory investigate the conditions and processes for transferring residual and decay heat from the fuel to the moderator. The laboratory provides data for validation of codes used in the safety analysis of CANDU reactors.

The test section consists of a 1750 mm long section of Zr-2.5Nb pressure tube mounted concentrically inside a 1700 mm long section of Zircaloy 2 calandria tube (Figure 2). Before assembling the test apparatus, the pressure tube and calandria tube surfaces are cleaned with isopropyl alcohol to remove any organic contaminants. The calandria tube inside surface and the pressure tube outside surface receive special attention to ensure that the thermal contact conductance between the tubes during contact is not influenced by surface contamination. Both the pressure tube and calandria tube are free to expand during heating.

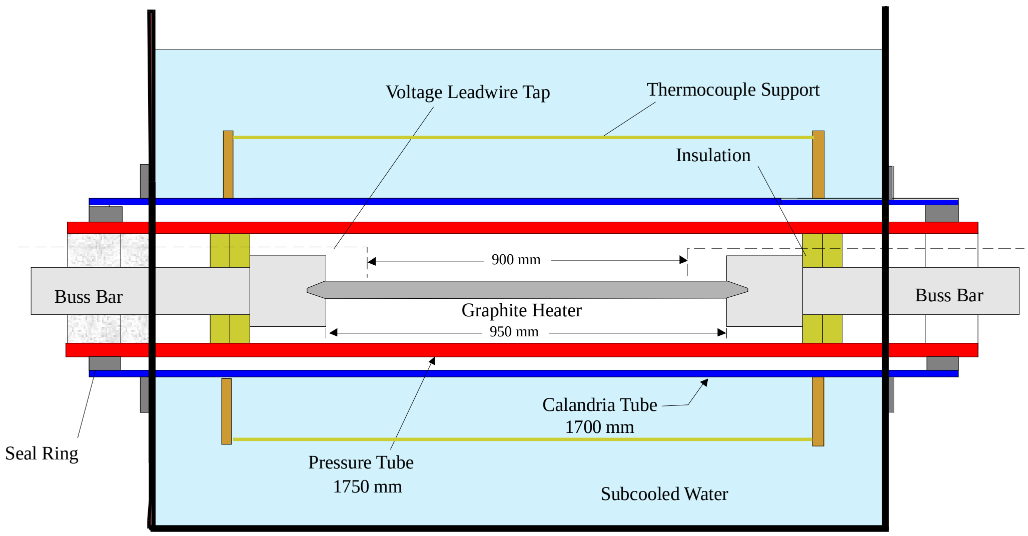

Figure 2 Experimental apparatus for IAEA ICSP test

The test section is surrounded by heated distilled light water in an open tank measuring 750 mm high, 1425 mm long and 600 mm wide. The top of the calandria tube is approximately 425 mm from the bottom of the tank and 180 mm below the surface of the water at the start of the test. The walls of the tank are equipped with Lexan windows to allow observation and video recording of the boiling on the outside surface of the tube during the test.

A uniform 38 mm diameter graphite rod heater, offset 9.5 mm toward the bottom of the pressure tube, is used to heat the test section. The 9.5 mm offset attempts to minimize the free convection induced circumferential temperature gradient on the pressure tube during heating. When the heater is concentric with the tube, convection in the pressurizing gas causes significantly higher temperatures at the top of the tube than at the bottom. The heater is held in place by water-cooled stainless steel buss bars with Zircaloy end fittings. Compression springs are used to keep the buss bars in contact with the ends of the heater, which are tapered in a 60° cone to match the conical receptacles in the buss bars. The heater is free to expand during heating. A gas cylinder is used to equalize the pressure inside the pressure tube and the buss bars. Three 25 mm thick Zirconia disk insulators are placed at the end of each buss bar to thermally insulate the pressure tube end-fitting assembly from the heater.

Argon was supplied to the inside of the pressure tube via a pressure control system with the 30 L surge tank online. The gas in the surge tank was heated to a set point of 300°C. Carbon dioxide was supplied directly from gas cylinders to the pressure-tube/calandria-tube annulus.

The pressure-tube section will be identified for traceability of materials and will have adequate documentation to trace the pedigree from ingot to final product. The nominal wall thickness of the pressure tube is 4.40 mm. The calandria-tube section is from typical calandria tubes available in the laboratory, an as-received seam-welded tube manufactured by Zircatec Precision Industries (ZPI). The seam weld in the test will be oriented at 135° from the top. The nominal wall thickness of the calandria tube is 1.42 mm.

3. Experimental Plan

3.1 Instrumentation

Power is supplied by a 500 kW direct current power supply and controlled using constant power mode with current feedback. The power supplied to the graphite heater is determined using a 10,000 A shunt to measure the current, voltage taps across the buss bars to measure the total circuit voltage and voltage taps on the heater to measure the heater voltage. The voltage taps on the heater are typically 900 mm apart.

Rosemount pressure transducers are used to measure the test section pressure and the LabVIEW data acquisition system will record the pressure as gauge pressure. The pressure is controlled by an automatic pressure control system with the ability to feed and bleed gas as required to maintain set point pressure. The annulus pressure is not measured but is assumed to be near atmospheric since the annulus is not a closed system.

The pressure tube and calandria tube are instrumented with thermocouples at five axial rings spaced 150 mm apart along the test section heated length (Figure 3). Fifty-four thermocouples are used to monitor the test section temperature: fourteen embedded halfway into the pressure tube wall and forty on the outside surface of the calandria tube. The fourteen pressure-tube thermocouples (labelled TC0 to TC13) are special grade, special limits of error, 1 mm diameter, Inconel-clad Type K thermocouples. These thermocouples are swaged to 0.5 mm diameter and inserted into blind holes drilled halfway through the pressure tube wall. The calandria-tube thermocouples, labelled TC14 to TC53, are special grade, special limits of error, Teflon-insulated Type K thermocouples with sensing elements of 0.13 mm diameter. The tips of these thermocouple wires are spot-welded directly onto the outer surface of the calandria tube at five axial rings corresponding to the instrumented locations on the pressure tube.

Four platinum resistance temperature detectors (RTDs) placed inside the water tank are used to measure the water temperature surrounding the calandria tube. Two RTDs are located at the test section axial centreline: one 50 mm above the top surface and the other 50 mm below the bottom surface of the tube. The other two RTDs measured the bulk water temperature near the ends of the test section at a depth of a horizontal plane passing through the calandria-tube centre.

Two video cameras are used to record the entire test through the windows on either side of the water tank (north and south views). This allows the observation of the boiling behaviour on the outside of the calandria tube during the test. Another camera will provide an overhead view of the test enclosure during the experiment.

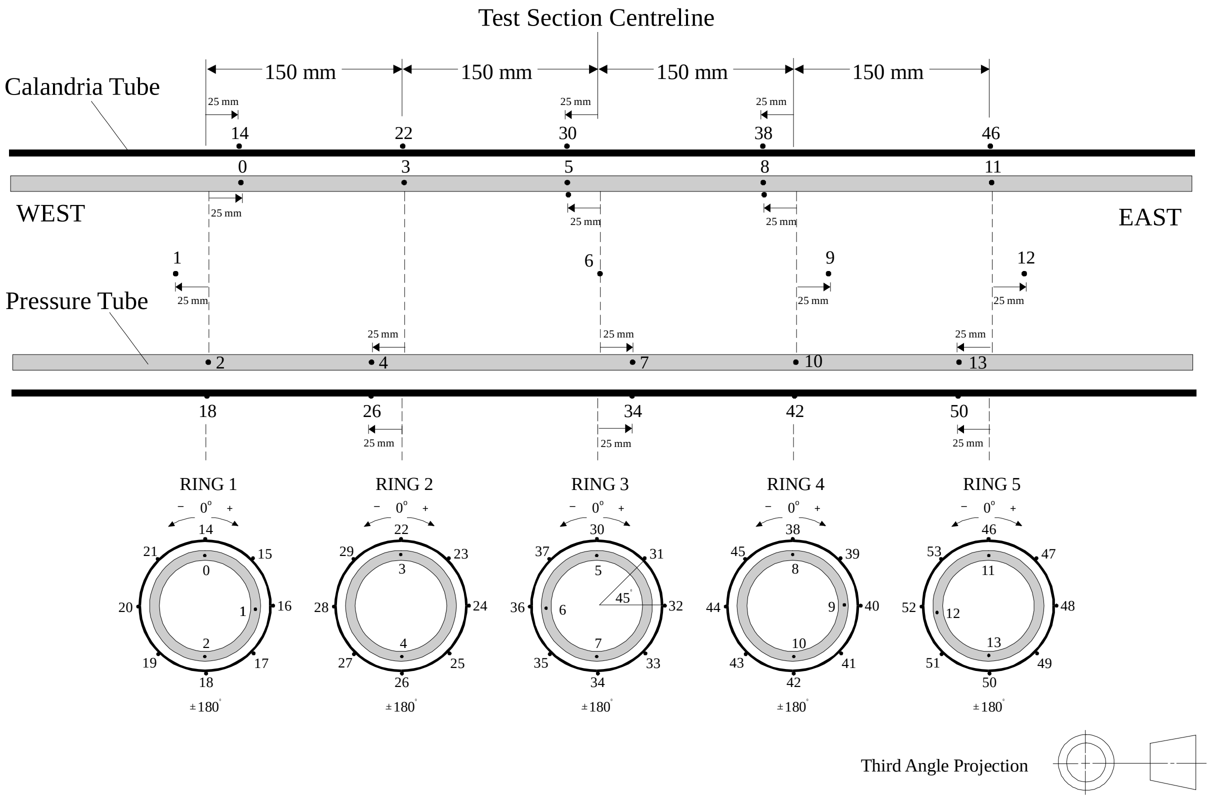

Figure 3 Section through test section showing pressure-tube and calandria-tube thermocouples

3.2 Test Procedure

Prior to the start of the test, the water surrounding the calandria tube is heated to ~10°C above the initial water temperature required to achieve the subcooling specified for the test to partially remove dissolved gases. As the water is heated, it is circulated to ensure a uniform water temperature. During this time, the pressure tube is purged with argon. Just prior to the start of the test, when the water is cooled to the test temperature specified, the circulating pump is turned off, the height of water above the calandria tube is measured and the barometric pressure is recorded. The water will not be mixed during the test. The pressure tube is then pressurized to the test pressure with argon and the annulus is supplied with carbon dioxide at a low flow rate. The power is then increased to its set point over 20 s to start the test. The set point power is one of the test conditions specified for the analysis. The power is maintained as the pressure tube heats, balloons and contacts the calandria tube.

Approximately ~15 s after initial contact, the test section is depressurised and, ~45 s after initial contact, the power is turned off to end the test.

The following generalized procedure will be used for the test:

1. The annulus between the calandria tube and the pressure tube is purged with CO_2.
2. The water surrounding the calandria tube is heated to approximately 10°C higher than the desired tank water temperature to partially degas the water for better visibility. The water is then cooled to the desired subcooling. A small impeller inside the water tank is used to stir the water before the commencement of the test to maintain uniform water temperature.
3. The pressure tube is pressurized to the test pressure.
4. The total power was increased to the test power within 20 s.
5. The test is terminated 60 s after the pressure-tube ballooning into contact with the calandria tube.

3.3 Test Condition for ICSP

The proposed ICSP test conditions are selected with an objective that the test conditions fill an area of the contact boiling curve where more data is desirable. The proposed test conditions are:

- Test Pressure: 3.5 MPa
- Heater Power (V-tap): 140 kW
- Pressure tube heat up rate: 20°C/s
- Subcooling: 30°C

This test conditions are within the LOCA spectrum and expected to belong to the boundary region challenging the fuel channel integrity.

4. Assessment of Computer Codes

4.1 Pre-test Calculation

ICSP participants conduct pre-test calculation with information available from ICSP proposal and ICSP host institute (AECL). There will be some differences in initial and boundary conditions between pre-test (proposed) and real test situations. The purpose of pre-test calculation is to set-up an analysis model including computer codes and to confirm that designed test condition is appropriate to observe the expected phenomena.

4.2 Blind Calculation

Blind calculation is conducted with real initial and boundary conditions from the experiment. Heater power, test pressure, moderator temperature (subcooling), pressure tube heat-up rate, initial temperature of all components and material properties obtained from the experiment will be given to ICSP participants for blind calculation. The experimental data may be utilized to assess each participant's computer codes simulating heat-up of the graphite heater, radiation heat transfer to the pressure tube, pressure tube deformation or failure, pressure tube to calandria tube heat transfer, calandria tube to moderator heat transfer, and calandria tube deformation or failure.

The participants from IAEA Member States will be able to use any design or safety analysis codes to perform a blind simulation using test initial/boundary conditions. The calculated result will be provided by all participants to AECL in an Excel spread sheet for comparison with experiment and other participants. An Excel template will be provided to the participants. Expected parameters for comparison are:

- Pressure tube temperature at thermocouple locations
- Pressure tube deformation - Strain (%) at thermocouple locations
- Calandria tube temperature at thermocouple locations
- Water temperature at RTD locations
- Heater temperature
- Total heat transfer between heater & pressure tube, pressure tube & calandria tube, from calandria tube to moderator
- Pressure tube to calandria tube contact heat transfer coefficient
- Heat transfer coefficient at calandria tube surface

Table 1 Proposed schedule for the ICSP

	2012			2013				2014				2015	
	2Q	3Q	4Q	1Q	2Q	3Q	4Q	1Q	2Q	3Q	4Q	1Q	2Q
Prepare ICSP proposal Select participants													
1st workshop			√										
Perform pre-test calculation with design initial/boundary conditions													
Conduct contact boiling experiment													
Release real initial & boundary conditions													
Perform blind calculation													
2nd workshop Release contact boiling experimental data									√				
Perform open calculation													
Documentation													
Last workshop													√

The code predictions will be assessed against the experiment. The blind simulation will allow ICSP participants to assess safety analysis code capabilities of Member States, determine the range of code uncertainties, assess user effects, identify analysis gaps, and benchmark safety analysis codes.

4.3 Open Calculation

Full experimental data in addition to initial and boundary conditions will be open to all ICSP participants after the collection of blind calculation results. During the phase of open calculation, participants can try to improve the analysis model, including sensitivity study, to produce a better result which is closer to the experimental data. Participants could identify any weakness or strengths of their prediction tools, search a way to overcome any limitations, and also suggest any further experiments or analytical models to fill the gap identified in the ICSP.

5. Conclusion

Recently the IAEA launched an International Collaborative Standard Problem on "HWR Moderator Subcooling Requirements to Demonstrate Backup Heat Sink Capabilities of Moderator during Accidents". Table 1 shows the proposed schedule for the ICSP implementation. The ICSP includes an experiment to study fuel channel behaviour at 3.5 MPa internal pressure, 140 kW heater power, 20°C/s pressure tube heat up rate and 30°C subcooling. The ICSP participants will be simulating the experiments with proposed (pre-test) and real (post-test) initial and boundary conditions using their own analysis tools. This experimental data may be utilized to assess computer codes simulating thermal radiation heat transfer to the pressure tube, pressure tube deformation or failure, pressure tube to calandria tube heat transfer, calandria tube to moderator heat transfer, and calandria tube deformation or failure. Through the ICSP, participants could identify the strengths and weakness of their analysis tools, search for workarounds to overcome limitations, and suggest further experiments or analytical models to fill any gaps identified in the ICSP. Detailed information on the ICSP is available from the IAEA website [7].

6. References

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