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PASSIVE HEAT REMOVAL IN CANDU

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Abstract

The Three Mile Island accident spurred a world-wide interest in severe accidents. The initial reaction was to increase the *preventative* measures in existing designs, followed by development of predictive capabilities to improve the *management* of severe accidents[1]. Recently, emphasis has been placed in new designs on *mitigative* measures which slow down or contain the progression of a severe accident. U.S. requirements for Advanced Light Water Reactor designs must now:

- provide reactor cavity floor space to enhance debris spreading
- provide a means to flood the reactor cavity to assist in the cooling process[2]

This paper describes how CANDU Pressurized Heavy Water Reactors (PHWRs) have severe accident prevention and mitigation[3] inherent in the design; in particular, the U.S. severe accident requirements can be met without significant change to the design of current CANDUs.

2. AVAILABLE WATER NEAR THE FUEL

CANDU is a horizontal pressure-tube reactor, with the fuel bundles located inside several hundred 10.5-cm diameter, 0.48-cm thick pressure tubes[1]. Twelve 0.5 m-long fuel bundles reside within each pressure-tube. The 37-element fuel bundle is in close proximity to the pressure tube, separated from it by means of 1.1-mm high bearing pads on the outer fuel elements. The heavy-water coolant flows over and through the fuel bundles and is contained by the pressure tubes within the core.

Since the pressure-tube operates at approximately the coolant temperature (300°C), it is thermally insulated during normal operation from the heavy water moderator (65°C) by the carbon dioxide filled annulus formed between the concentric pressure tubes and calandria tubes. The calandria tube forms the outer boundary between the gas and the moderator (Figure 1). The assembly of fuel, pressure-tube, gas annulus and calandria tube is collectively called the fuel channel. The total radial distance between the fuel and the moderator is 1.5 cm.

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[1] Unless otherwise specified, specific numerical values refer to the CANDU 9 reactor. However the relationships between the values and the conclusions are generic to all CANDUs.

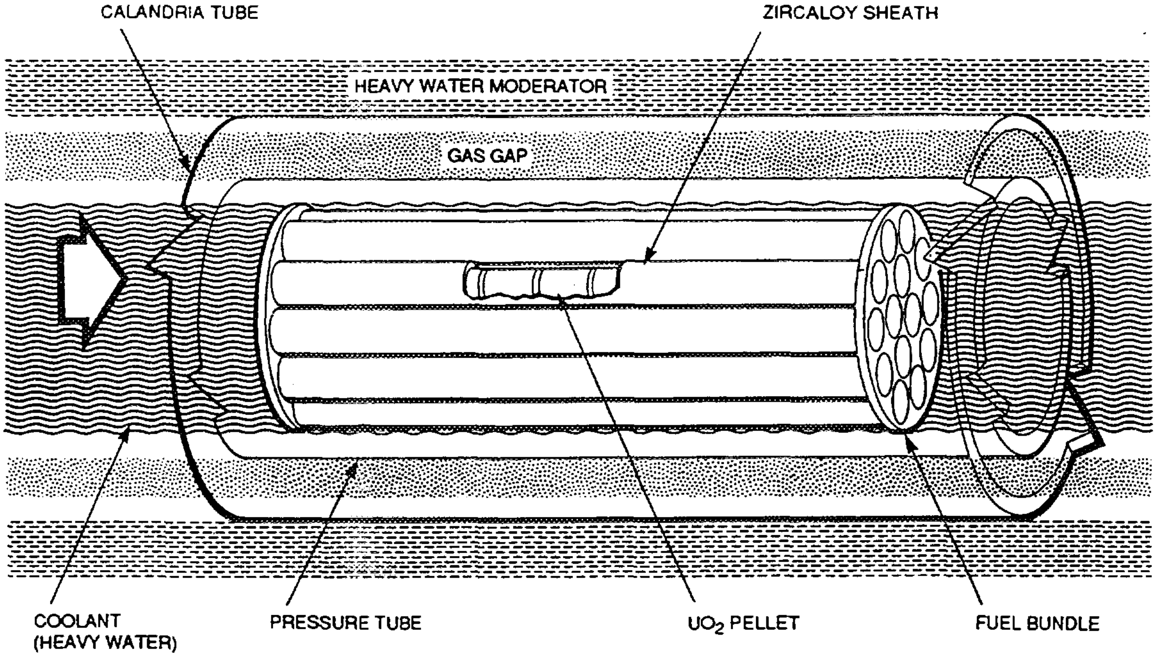


FIGURE 1: Separation of coolant and moderator

The moderator is contained within a low-pressure tank, called the calandria. During normal operation, about 4.4 % of the thermal output of the core is deposited in the moderator, a small amount by conduction from the channels, but mostly by direct deposition of fission gamma rays. This heat is removed via dedicated external moderator heat exchangers; external pumps circulate the moderator through the heat exchangers and provide momentum to mix the moderator within the calandria. They are powered by normal Class IV electrical power, backed up by Class III emergency diesel power when required.

The moderator role as an emergency heat sink for the fuel in a severe accident is discussed below. In this role, its active heat removal capability is enough to continuously remove all fuel decay heat following 15 seconds after reactor shutdown. The moderator specific volume is typically 8 litres/kW(th) at 1% decay power, or enough to absorb (through heat-up and boil-off) over 5 hours of decay heat from the fuel, assuming no heat removal from the moderator fluid.

The calandria vessel is in turn contained within a shield tank, which provides biological shielding during normal operation and maintenance (Figure 2). It is a large steel or concrete tank filled with ordinary water. During normal operation, about 0.4 % of the thermal output of the core is deposited in the shield tank and end shields, through conduction from the calandria structure and fission heating. This heat is removed via the end shield cooling system, consisting of pumps and heat exchangers.

The shield tank's role as an emergency heat sink for the fuel in a severe core damage accident is discussed below. In this role, its active heat removal capability is enough to continuously remove all fuel decay heat a few days after reactor shutdown. The shield tank specific volume is typically 16 litres/kW(th) at 1% decay power, or enough to absorb (through heat-up and boil-off) more then ten hours of decay heat from the fuel, assuming no heat removal from the shield tank water.

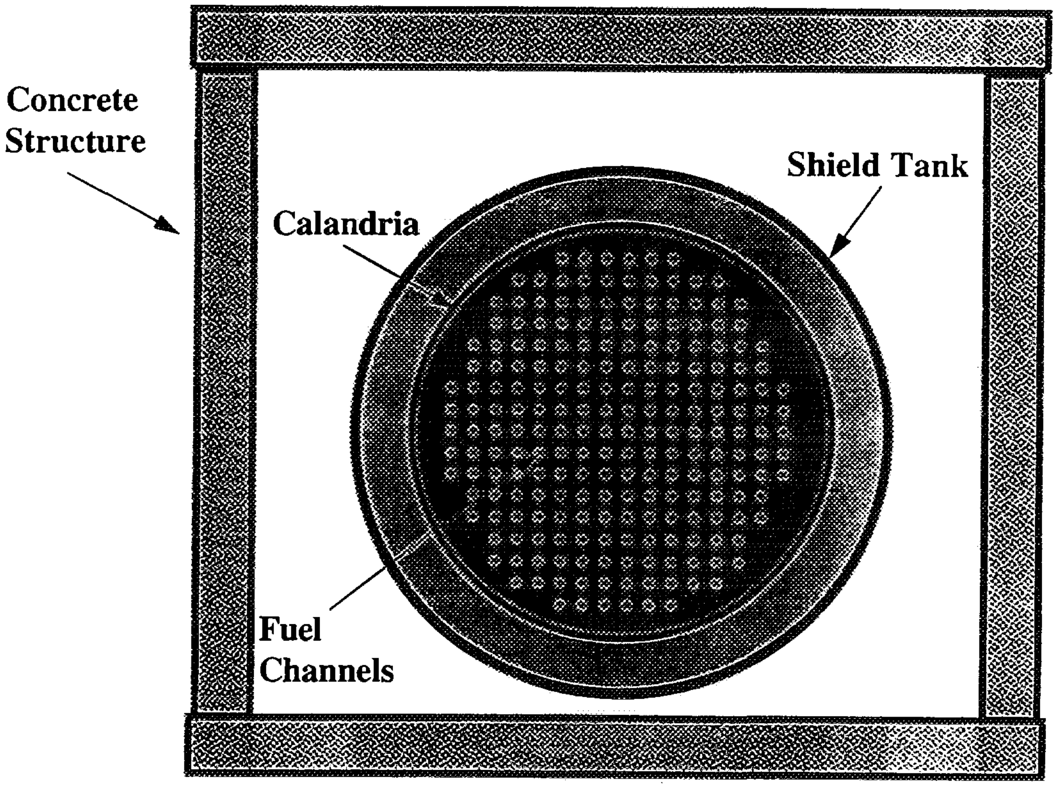


FIGURE 2: Shield tank as core catcher

TABLE I
CAPABILITIES OF MODERATOR AND SHIELD TANK
IN SEVERE ACCIDENTS

System	Continuous Heat Removal Capability (% full thermal reactor power)	Specific Fluid Volume at Decay Power	Time to Heat Up and Boil off All Fluid By Fuel Decay Power, No Heat Removal
Moderator	4.4 %	8 litres/kW @1%	> 5 hours
Shield tank	0.4 %	16 litres/kW @ 1% 32 litres/kW @ 0.5%	>10 hours > 20 hours

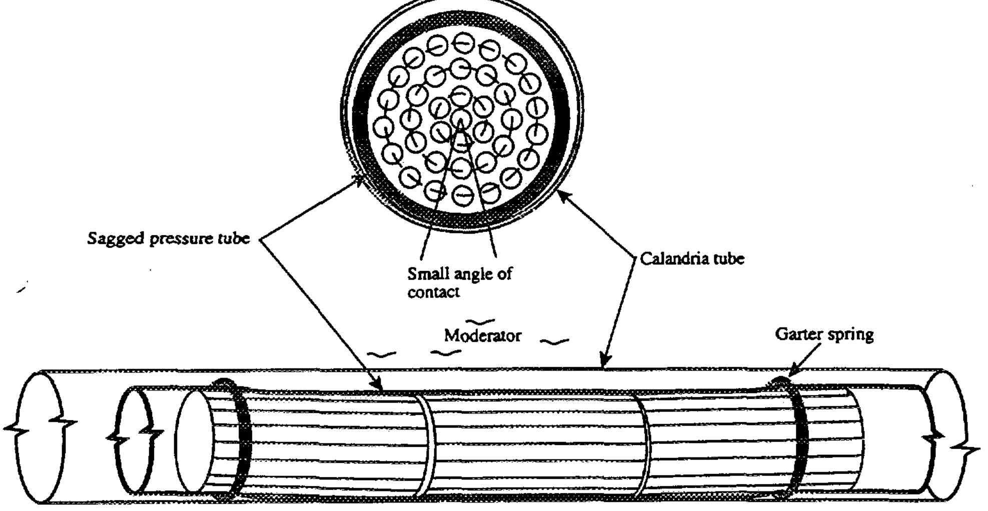
3. MODERATOR AS HEAT SINK FOR THE CHANNEL

All large pipes in the CANDU Reactor Coolant System (RCS) are above the core. They consist of headers, or collectors, to which each channel is connected via a 6-cm to 8-cm diameter inlet and outlet feeder pipe; plus pump suction and discharge piping and steam generator inlet and outlet piping. A large break in one of these pipes would cause rapid voiding of the pressure tubes. As with other water-reactor designs, the emergency core cooling system (ECC) provides high-pressure injection of water to refill the core. In CANDU ECC water is supplied to all the reactor headers.

A failure of ECC in light-water reactors, will, if uncorrected, lead to a meltdown of the core. In CANDU, a loss of coolant with a failure of ECC will be arrested by the moderator short of UO_2 melting. The mechanism is as follows[4]:

The fuel will heat up due to decay power, since no heat is being removed by the RCS. Since the pressure-tube is close by, it will also heat up, by conduction and radiation from the fuel, and convection by the steam remaining in the channel. At about 800°C, the pressure tube will start to plastically deform under the loads from the weight of the fuel and any residual coolant pressure. If the coolant pressure is high (for example, for medium-sized breaks with failure of ECC), typically above 1 MPa, the pressure tube will strain radially outward until it contacts the cool calandria tube (Figure 3). If the pressure is below 1 MPa, the pressure tube will preferentially sag, until again it contacts the cool calandria tube. As long as the calandria tube remains cool, it

a) Pressure Tube Sag



b) Pressure Tube Ballooning

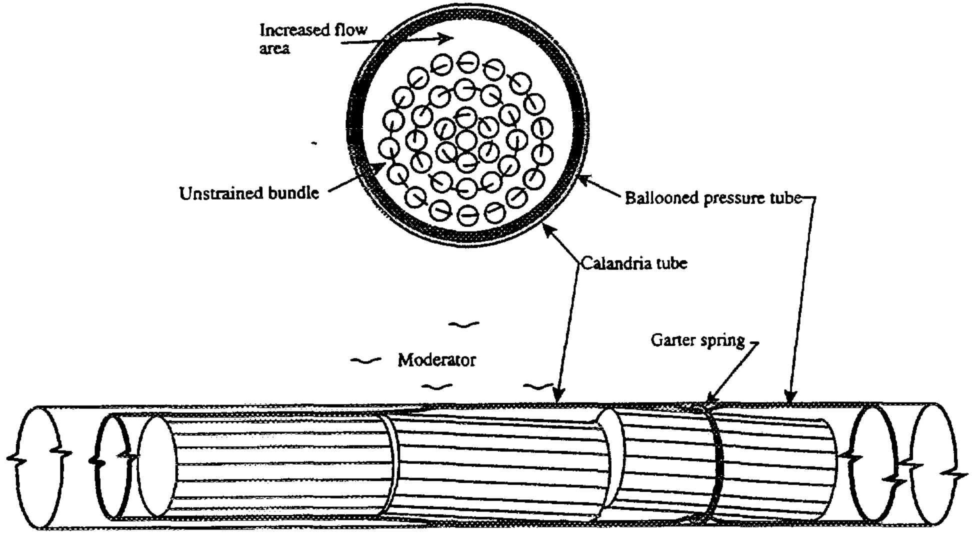


FIGURE 3: Pressure Tube Deformation Modes During a Postulated Loss-of-coolant Accident: a) Sagging, b) Ballooning

is strong enough to arrest the deformation of the pressure tube. Heat can then be removed from the fuel, by conduction and radiation to the pressure tube and calandria tube, and then by convection to the bulk moderator. From there it is removed by the moderator cooling system. The pressure-tube thus acts as a passive **fuse**, deforming only when it overheats in an accident, and so creating a low-resistance heat transfer path to the moderator. This path can remove decay heat from the fuel without the UO_2 melting even with no coolant in the pressure-tube. This is due to the short physical distance from the fuel to the pressure-tube, the relatively thin walls of the pressure-tube and calandria tube, and the enhanced heat transfer through the two tubes when they touch.

The calandria tube can be kept cold by preventing dryout on the outside surface at the time of pressure-tube contact. The surface heat flux at contact is determined by the pressure-tube temperature, the interface heat transfer coefficient and the moderator subcooling. The former cannot practically be controlled, but the latter two can. For existing CANDU reactors, a moderator temperature of about 70^0C is sufficient to prevent calandria tube dryout.

The pressure-tube "fuse" is sensitive to moderator temperature, but NOT to active moderator heat removal - it is truly passive. However the moderator pumps and heat exchangers are used to bring the severe accident to a controlled steady-state.

Measures are taken to assure that the pressure tube does not fail before it reaches the calandria tube. Although such failure would not prevent the moderator from performing its emergency role, the sequence is less complex if the pressure tube remains intact. Pressure tube integrity depends on the pressure at which the pressure-tube strains - the higher the pressure, the more sensitive is the strain to non-uniformities in pressure tube temperature, and the higher the chance of failure before contact with the calandria tube. The pressure parameter varies slightly with the design of the RCS.

Another severe accident results from assuming *all* heat sinks for the RCS are lost. This is an unlikely sequence because the following systems are each capable of removing decay heat from an intact RCS:

- the main feedwater system
- the auxiliary feedwater system
- the shutdown cooling system (which can be brought in at full RCS temperature and pressure)
- the Group II emergency feedwater system (this is a separate means of adding water to the steam generators, taking its supplies from a separate seismically qualified source and using independent seismically-qualified power)
- A gravity supply of water to the steam generator from the high level dousing or reserve water tanks

If however they are all lost, the RCS will pressurize and the fluid will gradually be lost through the relief valves, and the fuel will overheat. Since this sequence occurs at or above operating pressure, typically 10 MPa, the overheated pressure tubes will start to fail before they contact their respective calandria tubes. The higher powered channels will fail first, and the pressure tubes will relieve the rest of the RCS fluid. This will reduce the RCS pressure and allow the moderator to act as an emergency heat sink as described above.

Section 6 describe the Research programme which develops and verifies the models for these sequences[5].

4. SHIELD TANK AS HEAT SINK FOR THE CALANDRIA

Use of the moderator as an emergency heat sink for severe accidents has been extensively studied in Canada both theoretically and experimentally. The driving force has been the AECB requirement that certain severe accidents be considered within the Design Basis. This set includes all combinations of a reactor system failure *and* the unavailability of a safety system - for example, the previous example of a large LOCA and failure of ECC injection. **Severe accidents** within this set, i.e., those for which the fuel heat is not removed by the RCS, result in damaged fuel, but do not lead to loss of pressure-tube geometry. Accidents which combine yet further failures are generally outside the design basis. They may result in loss of core geometry, in which case they are called **severe core damage** accidents. The two types of accidents are usually synonymous in other reactor types, but because the moderator can arrest severe accidents before the core geometry is lost, in CANDU they are distinct.

Severe core damage accidents in CANDU include sequences such as:

- loss of all feedwater and loss of cooling to all alternate heat sinks including the moderator
- loss of coolant, loss of ECC injection, and loss of moderator cooling.

The frequencies of such combinations[6] are of the order of 10^{-7}/year, and are thus not within the scope of licensing analysis. They are, however, examined in the context of Probabilistic Risk Assessment[7]. Because of the low frequency, the emphasis has been on scoping calculations[8] rather than extensive experimental verification of detailed codes.

For such sequences, the moderator water will heat up and boil off. This will take some hours, during which time the pressure tubes will start to fail and the debris will collect in the bottom of the calandria. As long as there is water in the shield tank, the calandria shell will remain intact; the heat generated by the debris is less than the critical heat flux on the outer surface of the calandria[9]. However as is apparent from Table I, the shield tank heat removal rate is insufficient to keep up with the decay power until a few days have passed, so the shield tank water will boil off and the calandria shell will be penetrated. Nonetheless, the heat-up and boil-off of the moderator and shield tank buys valuable time, up to 24 hours, so that accident management can be put into effect before the debris even reaches the concrete floor of the containment.

5. DESIGN ENHANCEMENTS TO IMPROVE PASSIVE HEAT SINKS[10]

Based on the previous description, it is obvious how to extend the passive heat sinks provided by the moderator and the shield tank - simply add water. The advanced evolutionary CANDU 9 family[11] (single unit plants in the power range from 900 - 1300 MWe) has done just that. An elevated reserve water storage tank in containment provides emergency makeup water to the moderator and permits passive heat removal by thermosyphoning from the shield tank (Figure 4). The amount of water is sufficient for more than 40 hours of decay heat removal. During or after that time, a recovery pump collects water from the building sumps and returns it to the reserve water tank. The heat is removed from containment through a combination of passive conduction through the

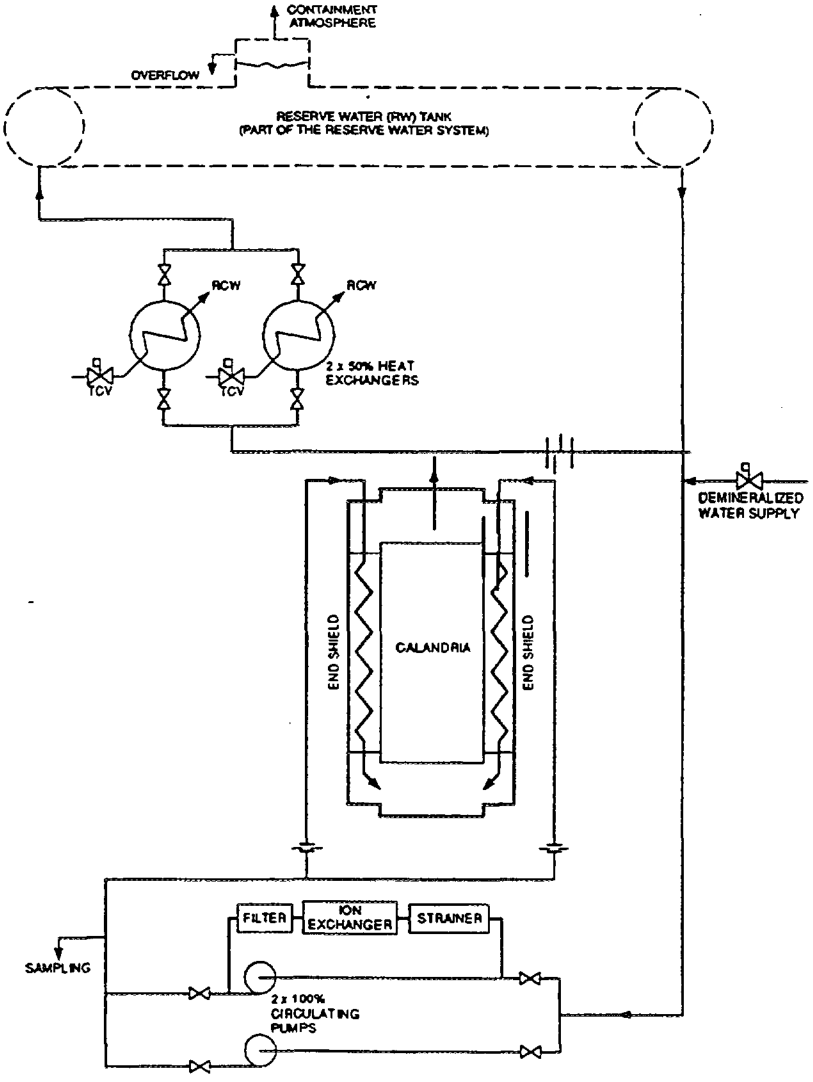


FIGURE 4: Shield cooling system flow diagram

building walls and actively by containment air coolers. A severe accident can thus be arrested either by the moderator or by the shield tank, contained therein, and stabilized. The same approach is being considered for the smaller CANDU 3 (a single-unit 450 MWe plant)[12].

To ensure that steam is adequately relieved from the shield tank without overpressurizing the vessel, engineered relief paths have been provided on the newer designs, sized to take the steam flow generated by decay heat removal.

Finally the pressure-tube/calandria-tube heat transfer has been fine-tuned. First, to reduce the sensitivity to initial moderator subcooling: When the two tubes contact in an accident, the stored heat in the pressure tube is transferred in a "pulse" through the calandria tube. To reduce the magnitude of this pulse, which sets the margin to CHF of the calandria tube, the inner surface of the latter has been roughened slightly (50 micron ridges). This "smears out" the heat transfer over a longer period of time and reduces the peak inter-tube heat flux. Second, to enhance the heat transfer after sag contact, and so to reduce the quasi-steady-state fuel temperatures, the inside of the calandria tube has been blackened.

In short, the provision of emergency water to the moderator and shield tanks gives an effective, and cost-effective, way of arresting severe accidents. Moreover the U.S. requirements for severe accidents, described in Section 1, are met inherently by existing CANDU structures -the calandria shell (backed up by the shield tank) provides both the "floor" area for spreading of debris **and** passive debris cooling through the shield tank water.

6. R&D IN SUPPORT OF PASSIVE HEAT REMOVAL

6.1 General Methodology

The operation of the moderator as a heat sink when normal and emergency cooling is lost to the fuel has been described above. The verification of such behaviour under a wide range of accident scenarios has been provided by an extensive and on-going research programme. This research programme covers fuel channel behaviour throughout the LOCA transient. Phenomena such as coolant boiloff in the channel, thermal-chemical behaviour of the fuel channel at elevated temperatures and pressure-tube deformation have all been extensively studied. The general methodology used in the research programme has been to perform small scale separate-effects experiments to develop and validate mathematical models to describe the phenomena. These validated models are then integrated into a code linking the various phenomena to characterize the fuel channel response to a loss of coolant accident.

For example, small scale experiments have been performed to study pressure-tube deformation at elevated temperatures. These high-temperature creep experiments characterized the plastic deformation mechanisms which control the ballooning and sag behaviour of the pressure tubes when they heat up. The end product was a set of constitutive equations describing transverse and longitudinal pressure-tube deformation[13][14].

The small scale experiments permitted the development of pressure-tube deformation models to describe the ballooning behaviour of a full size fuel channel. These models were validated through experiments on full size sections of pressure tubes in a simulated fuel channel mock-up including a calandria tube and a surrounding water tank to simulate the moderator[15] [16] [17]. Experiments covered both sag and ballooning of the pressure tubes (Figure 3).

6.2 Moderator as a Heat Sink

When an overheated pressure tube deforms and contacts its surrounding moderator-cooled calandria tube, the thermal and mechanical responses of both tubes change rapidly. Prior to contact, the pressure tube is at a much higher temperature than the calandria tube. Upon contact, stored heat in the pressure tube is transferred across the interface of the contacting tubes, through the calandria tube and then to the surrounding moderator. This process results in a large increase in the heat flux to the outside surface of the calandria tube. The magnitude of this heat flux is determined by the internal pressure, pressure-tube contact temperature and the interface thermal contact conductance. The magnitude of the peak heat flux relative to the critical heat flux governs the type of boiling which would occur at a given location on the calandria tube surface.

If the sudden rise in surface heat flux does not initiate film boiling on the outside surface of the calandria tube, the stored heat in the pressure tube is transferred to the moderator. If the critical heat flux on the surface of the calandria tube is exceeded in a particular area, the surface will dry out and film boiling will occur. Since film boiling is less efficient at heat removal than nucleate boiling, the stored heat in the pressure tube is only partially removed, and the calandria tube heats up. If the incident heat flux to the pressure tube is high, the tubes could overheat sufficiently to jeopardize fuel channel integrity.

The relationship between subcooling and critical heat flux on the outside surface of the calandria tube has been investigated over the years through small scale pool-boiling experiments with horizontal banks of tubes. Information from these small-scale experiments fed into full-scale contact boiling experiments using reactor-typical pressure and calandria tubes. These contact boiling experiments covered a wide range of moderator subcooling, pressure-tube internal pressures and pressure-tube heatup rates[18]. The current moderator subcooling requirements are specified for CANDU reactors to avoid the calandria tube being forced into film boiling upon contact with its deforming pressure tube. Figure 5 schematically represents a collection of experimental data from several contact boiling experiments. The broad hatched line marks the boundary separating the film and nucleate boiling regimes. From this, it is apparent that a moderator local subcooling of 26 to 28°C is sufficient to prevent extensive dryout on the calandria tube external surface during ballooning.

This moderator subcooling requirement may be reduced significantly by reducing the pressure-tube to calandria-tube thermal contact conductance as demonstrated by Sanderson et. al.[19] In this experiment, the tube to tube contact conductance was

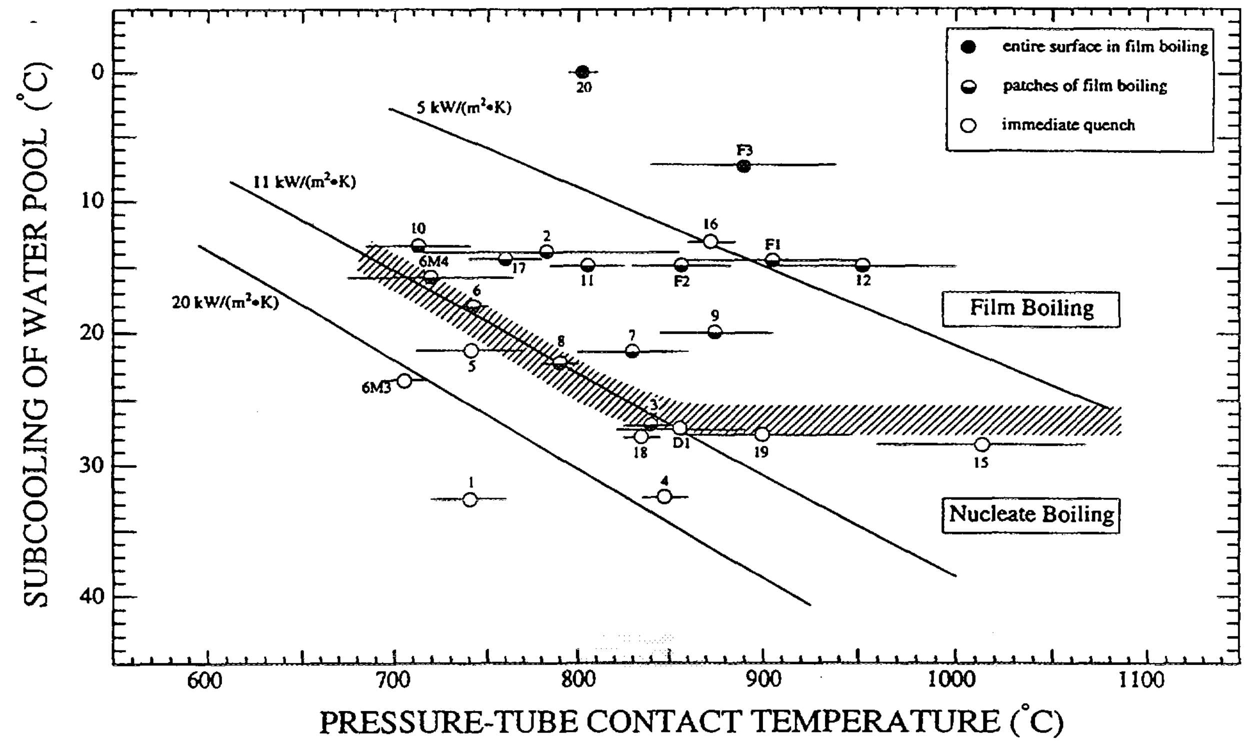


FIGURE 5: Moderator Subcooling Requirements as a Function of Pressure-tube Contact Temperature. The hashed line marks the boundary between film and nucleate boiling regimes.

reduced from its nominal value of 11 kW/(m^{2}K) upon ballooning contact to less than 1 kW/(m^{2}K) through contact limiters placed between the two tubes. This reduction in contact conduction has the potential to significantly reduced the moderator subcooling requirements.

Having demonstrated the sufficient conditions for good heat transfer following ballooning contact, the R&D programme focussed on determining if there were any mechanisms by which the pressure tube would fail prior to coming into contact with the calandria tube or cause the ballooned fuel channel itself to fail after contact in spite of general nucleate boiling.

The likelihood of pressure-tube failure prior to ballooning-contact involves both thermal and mechanical considerations. Since Zr-2.5 Nb pressure tube material is ductile at high temperatures, failure only occurs as a result of severe necking or thinning of the material at a given location. Given the geometric configuration of a pressure tube and its surrounding calandria tube, this is possible only if the pressure tube experiences a highly localized strain before it contacts its calandria tube. Such conditions could arise from either stratified coolant conditions in which the top half of the pressure tube is exposed to steam while the bottom is kept relatively cool by the presence of liquid, or by contact with the fuel element. The latter case can result from conduction through the bearing pad or by contact with bowed, sagged or melted cladding.

6.3 Fuel Channel Behaviour Subjected to Stratified Flow

Water in the horizontal fuel channels of a CANDU reactor may boil off slowly in some postulated LOCA scenarios. This would expose the upper portion of the fuel bundle and pressure tube to superheated steam as the water level drops (Figure 6). The pressure tube would become hot at the top because of thermal radiation and steam convection while it remained near the saturation temperature below the liquid level. The resulting pressure-tube circumferential temperature gradient would induce localized thermal stresses and plastic deformation at the top of the tube. Such conditions may cause nonuniform pressure-tube ballooning and the pressure tube could possibly rupture before coming into contact with the surrounding moderator cooled calandria tube.

A series of experiments have been performed to investigate the circumferential temperature distribution and resultant deformation that may develop around the pressure

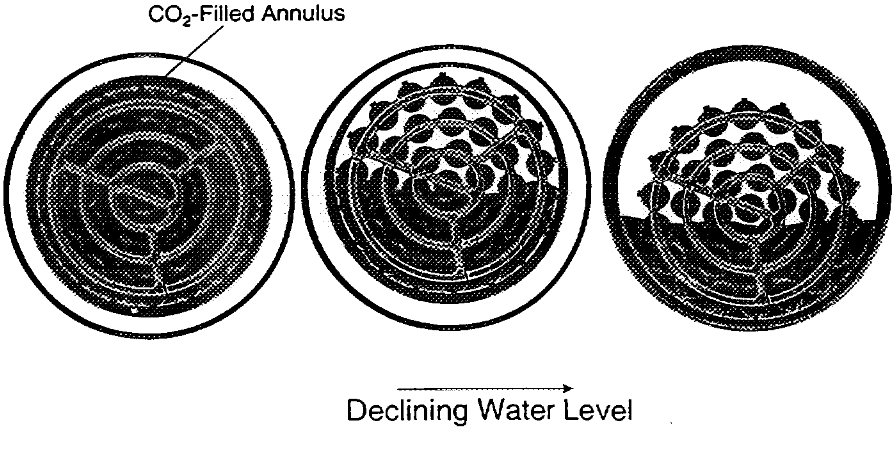


FIGURE 6: Schematic Showing Pressure-tube Behaviour Under Coolant Boiloff Conditions

tube of a CANDU fuel channel under such conditions[20] [21]. These experiments have shown the benefit of steam flow in the uncovered portion of the fuel channel. The steam helps distribute heat circumferentially across the top of the pressure tube, reducing thermal gradients and the likelihood of localized hot spots. The reduction of localized hot spots limits localized strain and the likelihood of a pressure tube failure. These full-scale experiments have provided a substantial data base of experimental results for use in the validation of fuel channel codes used in the analysis of fuel channel behaviour during a LOCA.

6.4 Fuel Channel Behaviour Subjected to Localized Hot Spots

In some postulated LOCAs, the interior of the pressure tube can become completely dry in a matter of seconds after flow stagnation occurs. As the RCS depressurizes, the surface temperature of the fuel bundle can exceed 1000°C. Most of the pressure tube circumference will be heated by thermal radiation, except at locations where the bearing pads are in contact with the pressure tube. Here, conduction and thermal radiation are the dominant modes of heat transfer. Therefore, local hot spots can develop on the pressure tube under the bearing pads. Whether the pressure tube would fail at these hot spots before contacting the calandria tube depends on the temperature and pressure transients it experiences.

An extensive series of small[22] and full[23] [24] scale experiments have been performed to investigate this phenomenon. These experiments demonstrated that the interaction between adjacent bearing pads in contact with the pressure tube tended to smooth out the circumferential temperature gradients. During heatup, the pressure-tube temperature increased more rapidly opposite the ring of bearing pads. This resulted in greater axial temperature gradients than circumferential gradients. The thermal contact conductance between the bearing pad and the pressure tube increases during heatup then decreases during ballooning. This decrease in conductance during ballooning helps minimize the magnitude of the bearing-pad induced hotspot, minimizing the risk of pressure tube failure under the bearing pad.

Another recent series of experiments[25] looked at the effect of molten zirconium that might be created by an overheated fuel bundle end plate if it were to fall onto the surface of a ballooned pressure tube and create a hot spot. The experiments and subsequent analysis demonstrated the resilience of the fuel channel to intense localized hot spots, as might occur in a severe accident. The ballooned fuel channel was resilient if the outside surface of the calandria tube was well cooled (i.e. it was in nucleate boiling) prior to molten Zr-4 (up to 90 g) making contact with the ballooned pressure tube. This in turn required sufficient moderator subcooling to prevent the critical heat flux from being exceeded, on the outside of the calandria tube during the ballooning transient. Fuel channel integrity was maintained in all experiments where the subcooling was adequate to prevent film boiling upon ballooning contact. Figure 7 shows typical calandria tube temperature transients from one of these experiments.

6.5 High Temperature Thermal-Chemical Behaviour of the Fuel Channel

Several small and large scale experiments have been performed over the years to investigate the high-temperature thermal-chemical behaviour of a CANDU fuel channel. These experiments have provided data on the high-temperature thermal properties (emissivity, thermal conductivity and solid to solid heat transfer)[26] [27], material interactions[28] and oxidation characteristics[29] [30] of various fuel channel

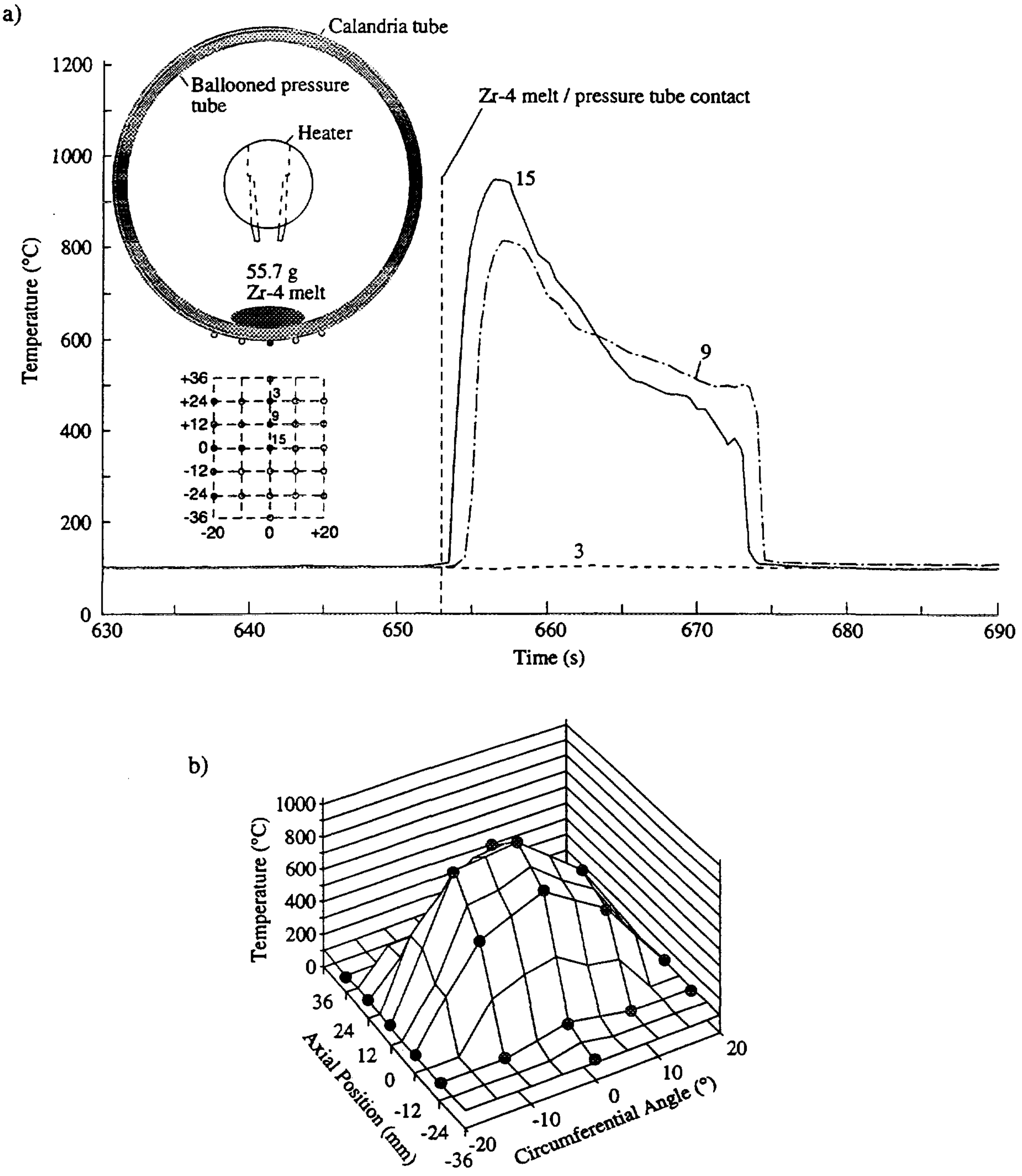


FIGURE 7 a) Calandria-Tube Temperatures Recorded Beneath the Zr-4 Melt, During Test 13 of the Molten Zr-4/Fuel Channel Interaction Program [25]. b) A Three-Dimensional Representation of Maximum Calandria-Tube Temperatures Beneath the Molten Zr-4.

components. Data from the single-effect tests were used to develop mathematical models describing the underlying phenomena. These models are then coupled into an integrated code to predict fuel channel behaviour under accident conditions. Data for validation of the integrated codes come from various full-scale experiments involving the complex interaction of pressure, temperature, material properties, heat transfer and oxidation kinetics on fuel channel components subjected to severe temperature transients.

In one such validation exercise[31], data from a high-temperature (>1600°C) thermal-chemical experiment was used to validate the multi-purpose code CATHENA. The validation exercise demonstrated the capability of CATHENA to model the thermal-chemical behaviour of a 28-element fuel channel when high-temperature steam was the only coolant available within the channel.

6.6 Core Melt Retention

A number of severe accident sequences involving loss of core geometry and core melting have been analyzed by Rogers[32]. They involve sequences where along with loss of normal and emergency cooling the moderator heat sink becomes unavailable. The level in the calandria will drop as the moderator boils and the fuel channels will heat up and collapse onto channels below that are still submerged. As the moderator level continues to drop, more channels will collapse, resulting in a pile of debris at the bottom of the vessel. Roger's analysis shows that at this stage, molten debris may exist but the shield tank water which surrounds the calandria vessel will be able to cool the debris sufficiently that the melt will be contained in the vessel. The peak heat flux into the shield tank for the sequences studied was 50 W/cm^2, well below the estimated critical heat flux of 280 W/cm^2.

The light water reactor community is now showing interest in this concept and are considering the merits of containing a core melt in a severe accident by external flooding of the pressure vessel. A research programme at the Kurchatov institute in Russia has been initiated to develop data and codes to verify this concept for pressure vessel reactors. It is cost shared 50% by Russia and 50% by fourteen OECD countries including Canada. Canada is participating since the technology derived from this study will be useful in improving our capability to analyze the shield tank capability to contain a melt.

7. SUMMARY

CANDU reactors possess two supplies of water surrounding the core - the moderator which surrounds the fuel channels and the shielding water which surrounds the calandria, that can function in emergencies to prevent or contain severe core damage. The moderator capability has been verified by small-scale and full-scale channel tests; the shield tank capability has been assessed analytically, and will be supported by international tests in which Canada is participating. The capability to stop severe accidents can be enhanced by the provision of emergency water to the moderator and shield tanks. This capability exceeds developing international requirements on the mitigation of severe accidents.

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