REFILL EFFECTIVENESS USING HIGH-BOILING-POINT EMERGENCY COOLANT

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ABSTRACT

This paper presents the results of a study to estimate the effect of coolant boiling temperature on the refilling of hot, vapour-filled pipes. The study used a prototype transient analysis code containing a subroutine library developed to compute the required fluid properties.

Simulations are presented that use the prototype code to examine flashing, quench, rewet and refill in four different, increasingly complex geometries. The studies indicate that the derived fluid properties are thermodynamically consistent, and refill times are dramatically reduced when boiling is avoided.

INTRODUCTION

Currently, following a postulated LOCA in a CANDU, pressurized light water is injected into the heat transport piping to refill and cool the reactor core. Analyses of LOCA transients have shown that vapour generated by the boiling of this water inhibits the refill process, and delays quenching of the fuel elements.

It has been postulated that a fluid with a higher boiling temperature than water, would be much more effective as an emergency coolant. This fluid should not produce large volumes of vapour as it refills the heat transport piping. Using a higher-boiling point emergency coolant also simplifies post-LOCA recovery of the heavy water.

The objective of the present study is to investigate the effectiveness of a high-boiling-point emergency coolant in rewetting and refilling hot piping similar to the heat transport system of a CANDU under the conditions expected following a postulated LOCA. The approach taken is to use the known properties of HB-40[1] in a prototype transient thermalhydraulics code. HB-40 was used as the primary heat transport medium in the WR-1 research reactor that operated at Whiteshell Laboratories from 1965 to 1985 [1]. HB-40 was also used in the NRU U-3 loop at CRL. The prototype code is then used to estimate the refill behaviour in various transients of increasing complexity.

The prototype code is based on CATHENA, an advanced thermalhydraulic computer code developed to simulate postulated upset conditions in CANDU® nuclear reactors [2]. At the present time, CATHENA can model up to six fluids: liquid and vapour phases of water (H_2O or D_2O) and up to four non-condensable gases. Interphase mass, momentum and energy transfer between the two water components are calculated. The CATHENA code has been applied to a wide range of thermalhydraulic problems. The development, modification and distribution of CATHENA is under strict control of a comprehensive quality assurance plan.

The simulations completed indicate that raising the boiling point of the coolant above the temperature of the pipe walls (thus eliminating vapour production) does result in much quicker refill. However, if the local pressure is low enough to allow the organic coolant to boil, the refill transient is comparable with water.

COOLANT PROPERTIES

The properties exhibited by the ideal CANDU emergency coolant are currently the subject of some discussion. For the purpose of this paper, it is sufficient to consider a coolant that has a high boiling point (> 300°C at typical post-LOCA pressures), such as the organic coolant HB-40. Reliable functions describing the thermodynamic and transport properties of HB-40 are available [3].

HB-40 is actually a mixture of compounds with molecular weights ranging from 2 to over 1500. In reality, each of these individual components has its

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[1] HB-40 is a Monsanto Chemical Company trade name for a mixture of partially hydrogenated terphenyls.

own unique thermodynamic properties. For practical purposes, the fluid in its equilibrium form used in WR-1 can be assumed to consist of two components known as high-boilers (HB) and low-boilers (LB). Fresh HB-40 contains less than 1% HB. Due to long-term exposure to heat (pyrolysis) and high neutron flux (radiolysis), higher-molecular weight compounds are formed, increasing the HB content. Using a feed-and-bleed system, an equilibrium high-boiler content of 30% was maintained in WR-1.

A series of FORTRAN function and subroutine subprograms was created, based on the available thermodynamic and transport property data. The new subprogram elements, named the ORGPH library, were written to mimic, as much as possible, the functions and subroutines in the HLWP property library [4] used by CATHENA. In this way, a prototype thermalhydraulic code could be constructed, in which the organic routines replace the water routines normally used in CATHENA.

The variation of saturation pressures with temperature is shown in Figure 1 for HB-40 LB and H_2O. Three regions are immediately apparent from this figure. Under low temperature, high pressure conditions, (the area above the H_2O saturation line) both H_2O and HB-40 exist as liquids. Under high-temperature, low-pressure conditions (the area under the HB-40 saturation line) both exist as vapour. In these two regions, there is likely very little advantage of one coolant over the other (as an emergency coolant). In the intermediate region between the saturation lines, H_2O exists as a vapour, and HB-40 exists as liquid. It is within this region that HB-40 may exhibit superior refill capabilities.

It should be noted that large LOCA simulations (i.e., those that provide the greatest challenge to the existing ECCS) predict system pressures between 200 kPa and 1 MPa during the refill phase. As shown in Figure 1, at these pressures, the boiling temperature of HB-40 is between 130 and 270°C higher than that of H_2O.

The flammability of HB-40 is one characteristic that may be an obstacle to its acceptance as an emergency coolant (although it is irrelevant to the quench and refill thermalhydraulics). However, the flammability of HB-40 was easily managed during the 19.5 years WR-1 operated [1], and was not a major problem.

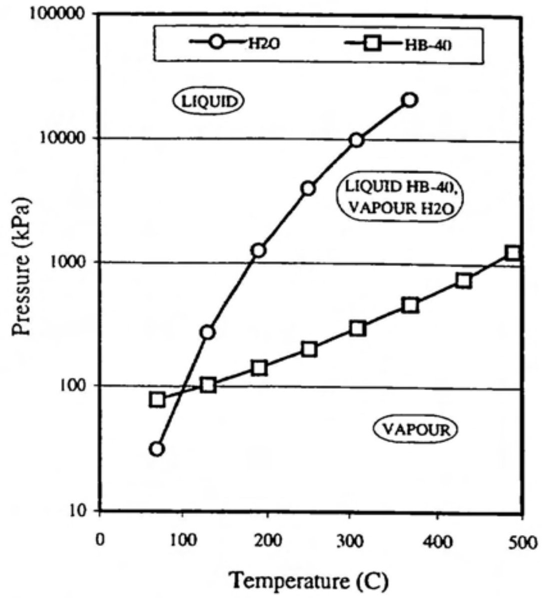

Figure 1: Saturation pressures for water (H_2O) and HB-40 organic.

PROTOTYPE CODE

From a programming point of view, CATHENA was developed using a highly structured and modular approach. This allows substitution of specific parts of the code, while the remaining features are retained to produce a prototype code that is functionally very similar to CATHENA. Taking advantage of this structure, a prototype code was assembled in which the subroutines providing water properties are replaced by identically-named ones returning HB-40 properties.

Of course, the validation that has been completed for CATHENA will largely not apply to the prototype code. In addition, the prototype code exists outside the control of the CATHENA quality assurance plan. In spite of these limitations, the prototype code provides a useful tool to investigate parametrically the refill effectiveness of an alternate coolant.

In addition to the prototype code, several smaller utilities were created. One example of these utilities is a program that automates the conversion of CATHENA input (containing pressures and enthalpies representative of physical states of H_2O) to prototype-code input (containing pressures and enthalpies of equivalent states of HB-40).

SIMULATION RESULTS

Four sets of simulations have been performed using the prototype code. The first set examines the flashing of a volume of superheated liquid. The remaining three sets of simulations examine the effect of coolant boiling point on the refill of three increasingly-complex geometries. Each of these sets of simulations is summarized below.

Flashing of Superheated Liquid

This simulation was devised as a test of the ORGPH property library. The geometry used is shown in Figure 2. A tank is initially half-filled with liquid at a temperature slightly below the local saturation pressure. The transient begins by decreasing the pressure at the reservoir boundary condition, causing the liquid to begin to flash, and allowing the system to approach a new steady-state at a decreased pressure. Throughout the transient, the total mass and energy in the system are monitored. Since the prototype code predicts conservation of mass and energy throughout the transient, this simulation demonstrates that the fluid properties provided by the ORGPH library are thermodynamically consistent.

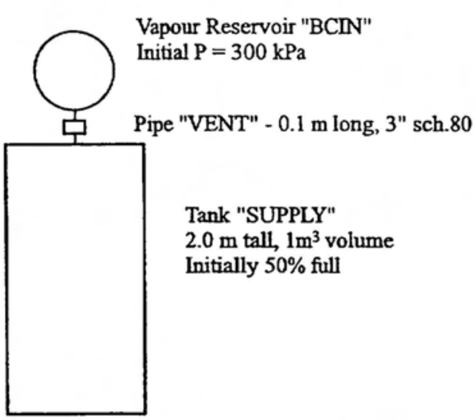

Figure 2: Geometry for flashing liquid simulation

Refill of a Hot Horizontal Tube

The quench and refill transient in a 25-mm ID, 3-m long horizontal zircaloy tube was extensively studied experimentally by Abdul-Razzak [5]. The simple geometry of these tests provides a logical first step in investigating quench and refill using HB-40.

One of the tests reported by Abdul-Razzak, AAA017, was selected to estimate the refill behaviour using CATHENA MOD-3.5b/Rev 0 and the prototype code. Prior to the experiment, the tube was drained, and its 2-mm thick wall was heated electrically to 390°C. The transient began with the injection of 23.4°C water, at a constant flow, into the inlet end of the tube. The outlet end of the tube was open to atmosphere. About 4.9 seconds were required to rewet the tube, starting from the first indication of water at the bottom surface of the tube inlet, until the upper outlet surface reached saturation temperature (100°C).

Horizontal-tube refill using H_2O

The nodalization of the test facility is shown in Figure 3. Wall heat transfer was modelled by dividing the tube into twelve axial segments, and six circumferential sectors.

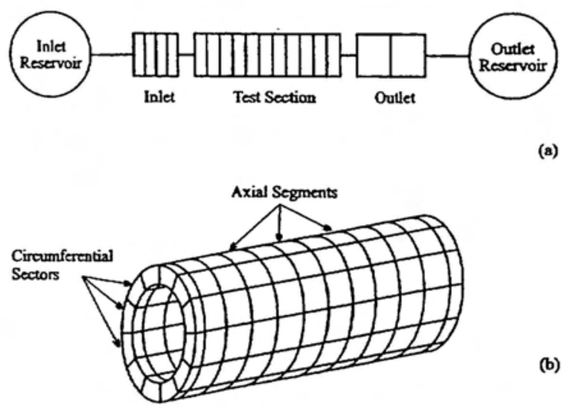

Figure 3: Idealization of horizontal tube refill experimental facility: a) Thermalhydraulic nodalization; b) Wall nodalization

In the CATHENA simulation, the tube rewet time was slightly overpredicted, requiring 5.1 seconds. The quench and rewet phenomena, including stratification of the quench front, were accurately reproduced by CATHENA. By t = 10 s, the tube was completely refilled and the tube wall was cooled to close to the ambient water temperature.

Horizontal-tube refill using HB-40

The CATHENA input file used to simulate test AAA017 was obtained. Minor changes were made to the idealization to account for the fluid property differences (enthalpy and density), and to monitor the overall mass and energy balance during the simulation.

Similar to the water case, the wall temperatures predicted by the prototype code decreased rapidly to the local saturation temperature as the rewet front progressed along the tube. Rewet progressed slightly more quickly than in the water case, and was complete in about 4.0 s. At the end of the simulation (i.e., at t = 10 s), the tube wall was cooled to about 115°C. This temperature was below the local saturation temperature, but still well above the ambient liquid temperature. Thus while the tube refilled slightly more quickly, significantly less energy was removed from the tube wall.

The refill transient in this case was not significantly different from that predicted for water for several reasons. First, the flow boundary condition at the inlet forced a continuous supply of coolant into the tube, while the atmospheric condition at the outlet allowed any vapour generated during the quench and rewet to easily escape. Further, at atmospheric pressure, the boiling points of water and HB-40 are similar, so a significant quantity of vapour was produced in either case.

A slightly more complex geometry, in which the vapour produced during quench and rewet inhibits ingress of the liquid coolant, should better illustrate any potential advantages of the alternate coolant for CANDU refill. This leads to the second refill geometry investigated.

Refill Of A Hot Vertical Pipe

The next case considers the refilling of a closed-ended piping network that includes a vertical pipe. The nodalization for this case is shown in Figure 4. This idealization is not representative of any known experimental apparatus; rather it is the simplest geometry imagined that would capture the phenomena expected during the quench and refill of a CANDU feeder pipe. In particular, the objective was to examine a geometry in which vapour initially in the pipe and produced during the rewet process had to be vented (or condensed) back through the incoming coolant.

The imaginary apparatus consists of a 3-m long, 3 inch (nominal), sch-80, vertical carbon steel pipe whose walls are initially at 300°C. The bottom of the hot pipe is connected to a short length (1 m) of horizontal, adiabatic pipe closed at one end. The top of the hot pipe is also connected to a 1-m long horizontal adiabatic pipe. All three pipe branches are initially vapour filled at 300°C The top horizontal pipe connects to the bottom of a large (1 m^3) tank initially half-filled with liquid at 20°C. The top of this tank is connected to a reservoir boundary condition used to maintain (relatively) constant pressure during the simulation.

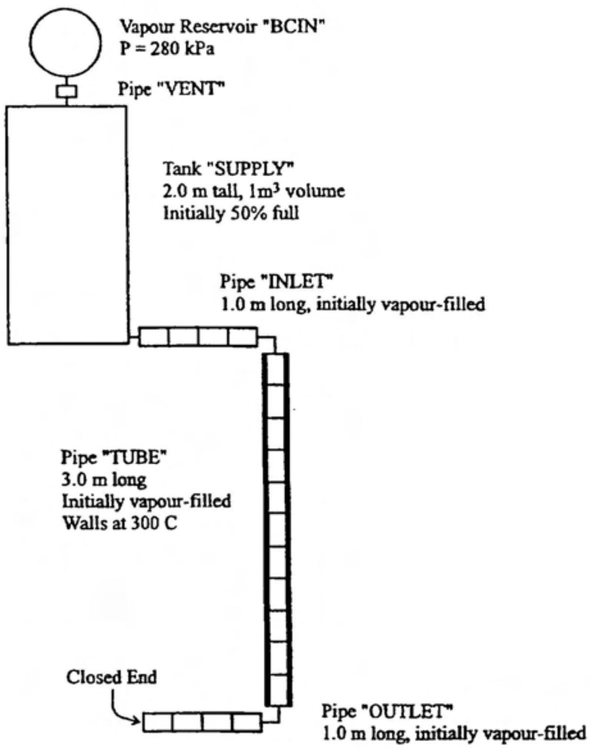

Figure 4: Idealization used for vertical pipe refilling transients

To simplify the transient (by preventing vapour condensation on the liquid surface in the tank), the tank inter-region heat transfer coefficient was set to zero. To monitor the mass and energy balance during the transient, system control models similar to those used in the horizontal refill case were included in the idealization.

At the start of the simulation, liquid immediately begins flowing from the tank into the upper horizontal pipe, with the vapour condensing onto the subcooled incoming liquid. Different behaviours were observed in the vertical pipe, depending on the fluid and conditions.

Vertical-Pipe Refill Using H_2O at 280 kPa

The refill transient in the geometry shown in Figure 4 was simulated using CATHENA MOD-3.5b/Rev 0.

The upper boundary condition pressure of 280 kPa was chosen because it is the boiling point of HB-40 at the pipe wall temperature (300°C). The predicted void transient at the top, middle and bottom of the vertical pipe is shown in Figure 5. This behaviour is typical of the intermittent refilling pattern predicted for CANDU feeders. Liquid penetrates into the top of the vertical pipe, where it encounters the hot wall. A large volume of steam is produced, which causes the pipe to re-void. This cycle repeats several times, with liquid penetrating progressively further into the pipe. Finally, in this case at about 25 s, liquid finally refills the pipe.

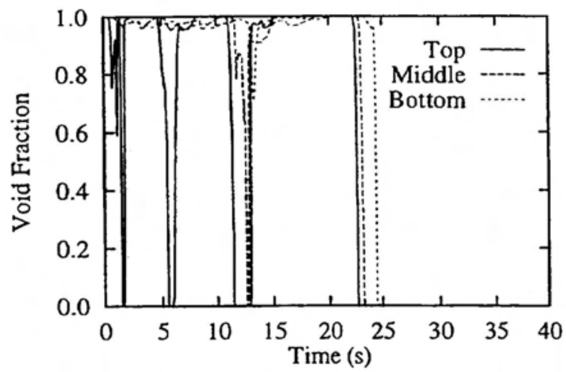

Figure 5: Void transient predicted by CATHENA for vertical pipe refill case using H_2O

The predicted temperature profile along the outside surface of the vertical pipe is shown in Figure 6. The wall temperatures decrease in steps corresponding to the penetration of slugs of liquid. In the final state, the hottest part of the pipe wall is slightly below the saturation temperature. Once the pipe fills there is no further flow, and so no further significant cooling is possible.

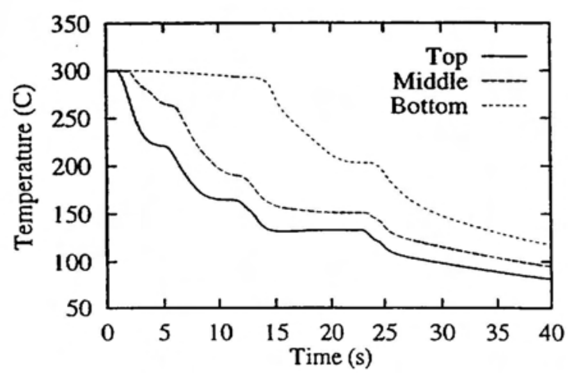

Figure 6: Pipe wall outside surface temperature predicted by CATHENA for vertical pipe refilling case using H_2O

Vertical-Pipe Refill Using HB-40 at 280 kPa

In this case, the HB-40 vapour was initially at 300°C, the saturation temperature for HB-40 at 280 kPa. The predicted void transient is shown in Figure 7. The pipe completely fills in about 2.5 s, about 1/10th the time required using water. There is little or no vapour production, and the initial vapour is condensed onto the incoming subcooled liquid.

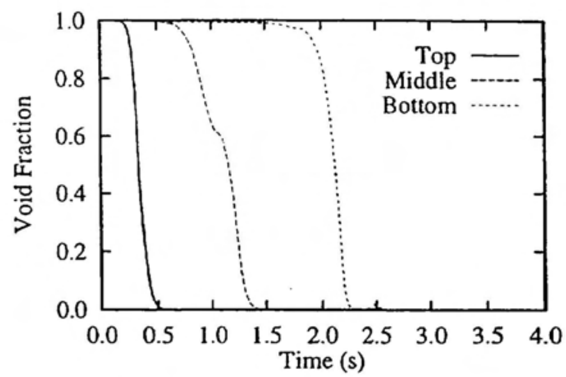

Figure 7: Void transient predicted by prototype code for vertical pipe refill case using HB-40 at 280 kPa

The predicted pipe wall temperatures remain almost constant during the refill transient. Since the pipe wall is initially at the HB-40 saturation temperature, there is almost no heat transfer to the fluid during refill.

Vertical-Pipe Refill Using HB-40 at 103 kPa

The conditions of this case were chosen to demonstrate the refill transient when the pipe wall temperature is greater than the local saturation temperature of the organic coolant. For comparison with the CATHENA case described above, a reservoir pressure of 103 kPa was chosen. At this pressure, the saturation temperature of HB-40 is about 131°C, the same as that of water at 280 kPa.

The predicted void transient for this case is shown in Figure 8. Refill of the vertical pipe is very slow, requiring about 80 s to complete. The specific heat and the latent heat of vaporization of HB-40 are much smaller than that for water. Thus significantly more void is produced in rewetting the hot pipe wall.

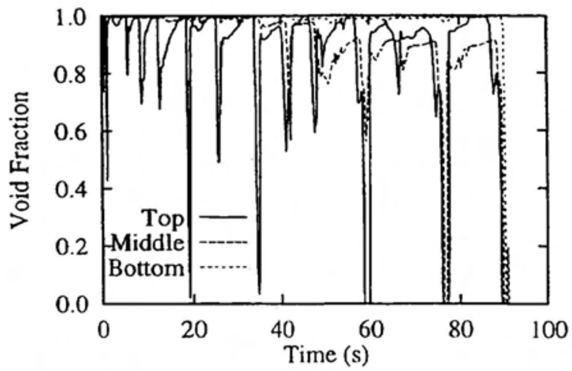

Figure 8: Void transient predicted by prototype code for vertical pipe refill case using HB-40 at 103 kPa

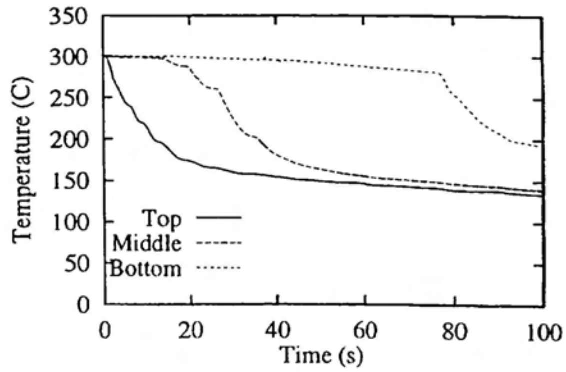

Figure 9: Pipe wall surface temperatures predicted by prototype code for vertical pipe refill case using HB-40 at 103 kPa

The predicted outside wall temperatures are shown in Figure 9. The final temperatures are similar to those predicted for the water case, indicating that a similar quantity of heat was removed from the pipe wall. However, the time required to remove this heat is approximately doubled.

Refill Of A Candu-Typical Header-Feeder-Channel

The next series of simulations examine refill transients in the Cold Water Injection Test (CWIT) facility, located at Stern Laboratories, in Hamilton, Ontario. The CWIT facility is shown schematically in Figure 10. Experiments conducted in this facility are funded by the CANDU Owners Group through the Safety Thermalhydraulics Working Party.

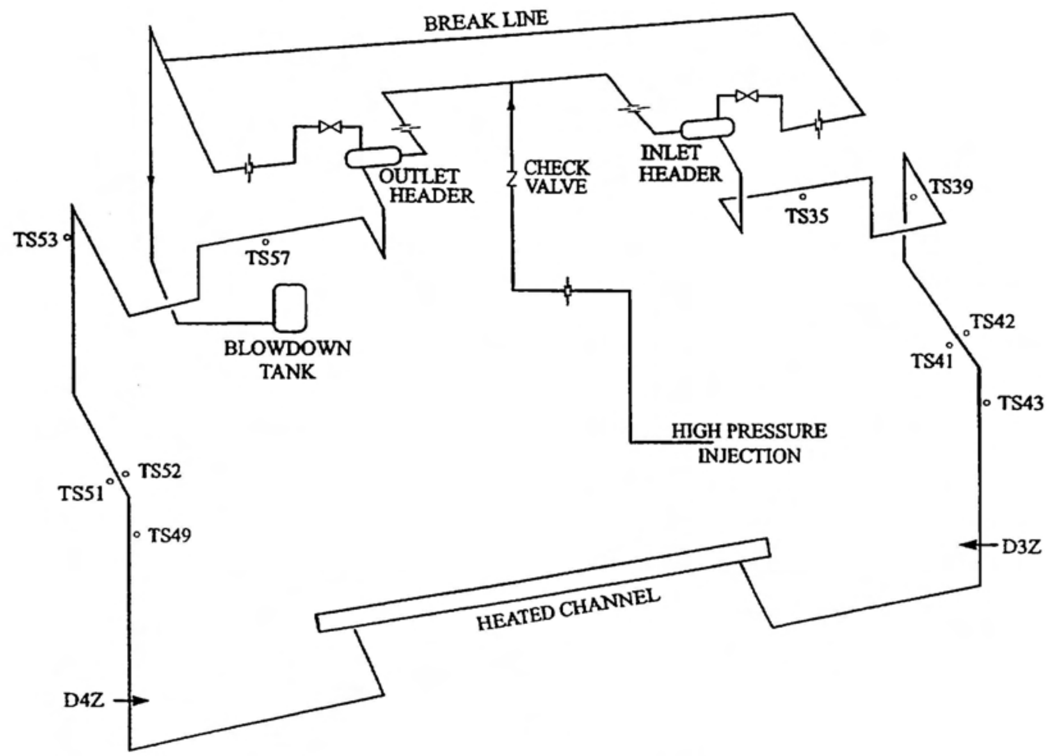

Figure 10: CWIT facility schematic

The CWIT facility, the most complex geometry modelled in the present study, consists of a CANDU-representative channel containing 37, electrically-heated fuel element simulators (FES). The FES have approximately the same geometry and thermal characteristics as CANDU fuel. The electrical resistance of the elements varies along their axial length to produce a reactor-typical, cosine-shaped power distribution. The channel is connected via actual CANDU-6 end fittings to feeders containing the geometric features of CANDU feeders (i.e., several vertical and horizontal sections, significant wall thickness). These feeders are connected to headers, which also connect to blowdown and injection systems. This facility has been used extensively over a (roughly) 20-year period to study the refill behaviour of the CANDU header-feeder-channel system under various conditions.

Description of CWIT Refill Test 1518

Experiment 1518 is one of the most recent blowdown/refill tests conducted in the CWIT program. In this test, both blowdown valves were opened, and cold water was injected to both headers. This arrangement produces highly symmetric header-to-header conditions, and is considered representative of the conditions in the unbroken core pass following a large header break in CANDU. Prior to the test, superheated steam was circulated through the facility to raise the feeder pipe wall temperature to approximately 300°C.

The test began with a steady-state period of about 71 s during which the vapour-filled piping remained at about 5 MPa, and the temperature of the FES slowly increased due to electrical heating. The total power applied to the FES bundle was approximately 50 kW. After the blowdown valves were opened, the system pressure rapidly decreased. When the pressure dropped below 1.5 MPa, a check valve in the injection piping opened allowing cold water to enter the headers and begin to refill the piping.

In the test, liquid finished quenching the inlet feeder and was able to reach the heated section at about 280 s. The FES sheath temperatures peaked at about 485°C before quenching, finally rewetting at about 490 s. The experiment was terminated after 600 s, when the heated section and both feeders were finally completely refilled.

Simulation of CWIT 1518 using H_2O

A detailed simulation of CWIT test 1518 was recently completed using CATHENA MOD-3.5a/Rev 0. The nodalization for this case is shown in Figure 11. The CATHENA-predicted time of first-feeder quench was within 10 s of the experiment, although the refill direction was counter to that observed in the experiment. It should be noted that the experimental conditions are sufficiently symmetric that the refill direction can be considered random. The CATHENA-predicted peak FES temperature was about 20°C below the observed value. The channel rewet time was significantly overpredicted (by about 100 s) by CATHENA.

Simulation of CWIT 1518 Using HB-40

The CATHENA input deck used in the successful simulation of CWIT 1518 was obtained, and used as a basis for a simulation of the refill transient using the higher boiling-point HB-40. The CATHENA simulation was started (using MOD-3.5b/Rev 0) from t = 0 s, and stopped at t = 71.5679 s, the time step immediately prior to the injection check valve beginning to open. The CATHENA-calculated conditions at this time were used as 'initial conditions' to start the simulation using the prototype code and HB-40.

The calculated void fractions in the feeders close to the heated channel are shown in Figure 12. The prototype code predicts first feeder refill at about 180 s. This is more than 120 s earlier than was observed experimentally or predicted by CATHENA.

The calculated surface temperatures at the inlet, middle and outlet of the upper-elevation FES are shown in Figure 13. The temperature rises more quickly in the middle than at the ends because of the axial-cosine power distribution. The sudden increase in temperature at about 70 s is due to the change in fluid properties from H_2O to HB-40 (The "equivalent state" criteria result in a roughly 300°C increase in vapour temperature). The inlet end of the FES begins to rewet at about 190 s, followed by the middle at 210 s and the outlet at 230 s. By 250 s, the heated channel is completely refilled.

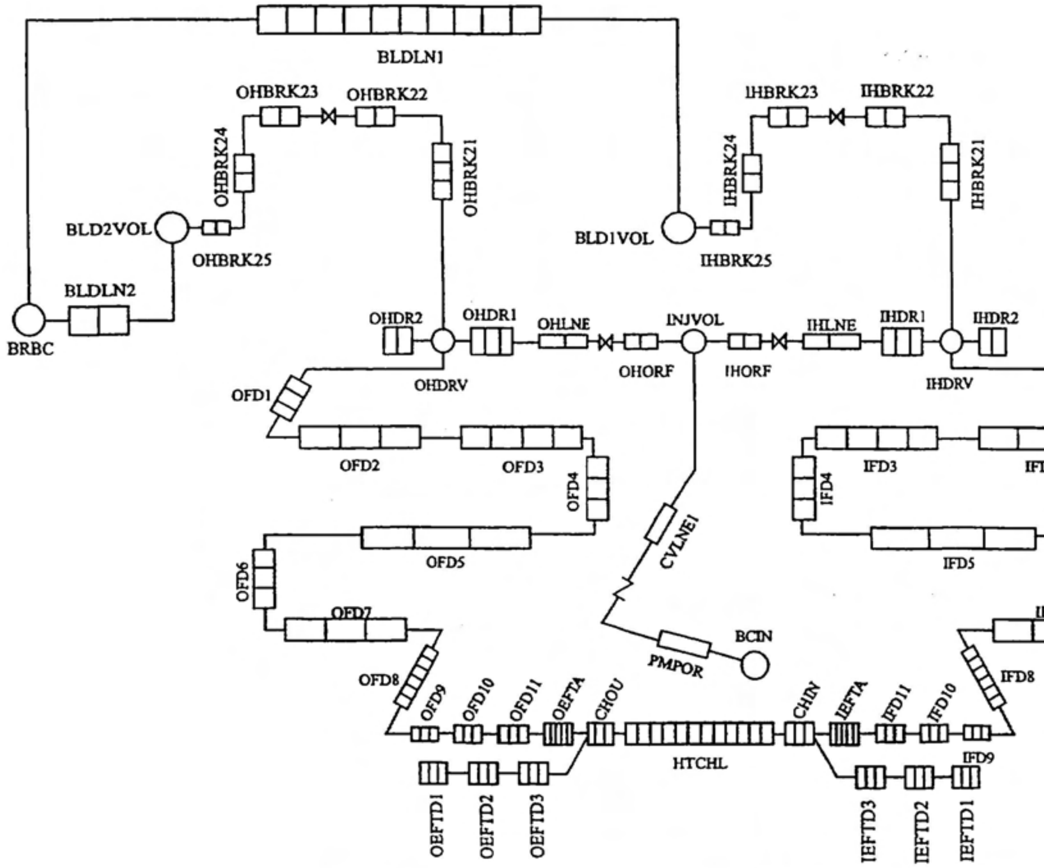

Figure 11: CATHENA idealization of the CWIT facility

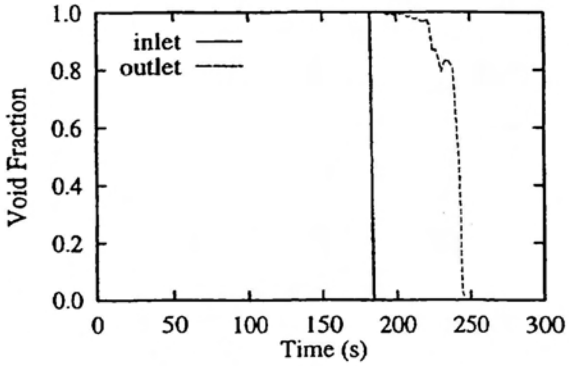

Figure 12: CWIT feeder void fractions predicted using prototype code and experimentally-measured boundary conditions

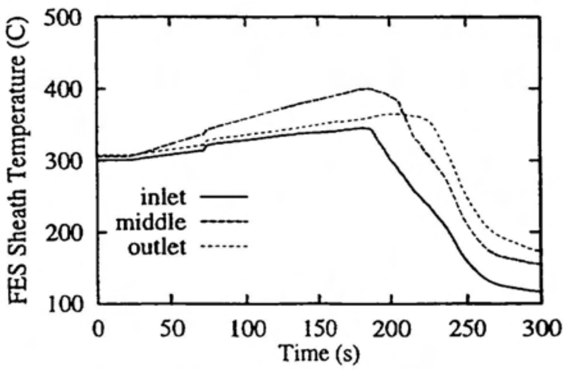

Figure 13: CWIT upper-element sheath temperatures predicted using prototype code and experimentally-measured boundary conditions

Using HB-40, the CWIT facility is predicted to refill about 240 s faster than was observed using H_2O. There are two main reasons for this. First, less heat is removed from the feeder pipe walls, resulting in reduced vapour production during feeder quench. Second, the early arrival of liquid at the heated section limits the heat stored in the FES (that must be removed prior to FES rewet).

The saturation temperature of HB-40 during the quench and refill phase of test 1518 is in the range 200 to 250°C. Thus some boiling does occur during the feeder quench phase of the transient, resulting in some vapour production. It is conjectured that this vapour is still delaying the refill transient. Presumably, if the system pressure during refill were above 300 kPa, the HB-40 boiling point would be above the feeder wall temperature, resulting in even faster refill.

CWIT Refill Using HB-40, Higher Heater Power

In the HB-40 case using the experimentally observed boundary conditions, the peak FES temperatures (and therefore the stored heat to be removed during channel rewet) were much lower than was observed in the experiment, due to the early feeder refill. Another case was set up and run in which the heated section power was increased to 125 kW. This higher power resulted in much higher FES temperatures at the point of feeder refill. These more realistic FES temperatures and provide a better comparison of channel refill with the experiment.

The upper-elevation FES temperatures for this case are shown in Figure 14. The higher power resulted in a higher peak temperature at the middle of the element (about 530°C vs 480°C with low power and water, and 400°C with low power and HB-40). This peak is reached at about the same time as in the low-power case. The time required to quench and refill the heated section is significantly longer than was required in the low power case using HB-40 and is comparable to the channel refill time observed using water.

This case illustrates the sensitivity of refill rate to wall temperature. The feeder wall temperature is slightly above the boiling point of the injected coolant, resulting in relatively quick quench and refill of the feeders. The heated section is significantly above the boiling point, resulting in large volumes of vapour production and refill timing similar to that of water.

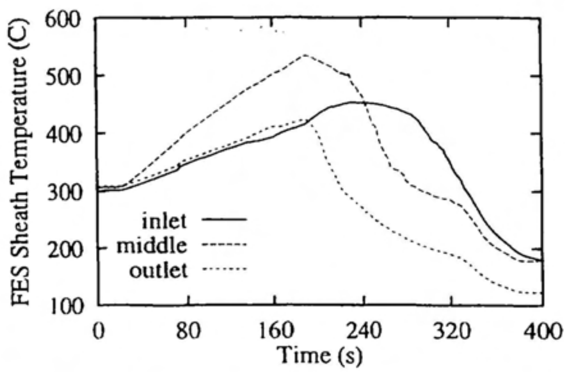

Figure 14: CWIT upper-element sheath temperatures predicted using prototype code and increased heater power

SUMMARY

A study of the effect of coolant boiling point on the quench, rewet and refill of hot piping has been completed. The impetus for this study is the concept that vapour generation during feeder rewet and refill contributes significantly to delaying post-LOCA rewetting of the reactor fuel in CANDU. By eliminating this vapour production, liquid coolant could reach the reactor core earlier, resulting in reduced uncertainties in the predicted consequences.

While a specific, optimum emergency coolant has not been formally selected, the organic fluid HB-40 was selected for the purpose of this study. This coolant was used as the primary heat transport fluid in the WR-1 research reactor, so its behaviour and properties are well known and documented.

In the absence of a qualified, purpose-developed analytical tool to evaluate refill using HB-40, a prototype code based on CATHENA was created. The program elements within CATHENA that provide the thermodynamic and transport properties for water (H_2O) were replaced with ones providing those properties for HB-40. The resulting prototype code was used to estimate a range of transients that illustrate the potential advantages of a higher-boiling-point coolant.

The simulations completed indicate that, raising the boiling point of the coolant above the temperature of the pipe walls (thus eliminating vapour production) does result in much quicker refill. However, if the local pressure is low enough to allow the organic coolant to boil, the refill transient is at least as slow as with water. The lower specific heat of the liquid, and lower latent heat of vaporization in the organic could be detrimental under some conditions.

The conclusions of the study are of course approximations. The uncertainty surrounding the results must include consideration of the approximations made (or implied) in generating the prototype code. The prototype code correctly calculates most of the thermal and transport properties of the organic, but a large number of empirical correlations that were developed specifically for water remain. These include constitutive relations for interphase mass, momentum and energy transfer, fluid-wall momentum and heat transfer correlations.

Future work towards evaluating the effectiveness of an alternate emergency coolant should include a simulation of a large LOCA using the full CANDU primary heat transport system, in as much detail as possible. Further refinements to the prototype code are required to reduce the uncertainties associated with empirical correlations. Ultimately, a program of refill experiments will be required to demonstrate the advantages of the alternate coolant.

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- F.W. Gilbert for embracing the vision that organic coolants have certain advantages over water, leading to the construction of the Whiteshell site and the WR-1 research reactor.

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