CHAPTER 15
SAFETY ANALYSIS I: THERMOHYDRAULICS

N.J. Spinks
Thermohydraulics Branch, Safety Analysis Department
Atomic Energy of Canada Limited - Engineering Company
Mississauga, Ontario

ABSTRACT

Safety analysis comprises reactor physics, thermohydraulics, core behaviour and containment studies. This lecture addresses the thermohydraulics part. Generally thermohydraulic studies require information from reactor physics and supply information to fuel behaviour and containment assessments. The end objective is to determine the release, if any, of radioactivity from fuel to primary heat transport system (PHTS) to containment to the public given each scenario as a starting point. Given reactor physics information, the thermohydraulics part is to evaluate system temperatures and pressures — notably fuel temperatures.

15.1 Introduction

The calculation of fuel temperature requires knowledge of the coolant condition at the fuel surface and this generally requires a prediction of coolant condition throughout the primary system.

Theoretically one could use a multi-dimensional two-fluid transient computer code for these studies, however, such a tool is not yet available for practical use. Indeed even the one-dimensional (1D) two-fluid models still need development, see chapter 8.

To date the work horse has been the 1D homogeneous equilibrium code modified by empirical correlations for some two-fluid effects but backed up by semi-scale and full-scale experiments. For example, the homogeneous equilibrium model underpredicts pressure during cold water injection into a voided system. So we empirically modified the pressure calculation until it agreed with a range of fuel-channel cold-water injection experiments. In some situations of low channel flow where the phases stratify we have resorted to firstly, a direct use of full scale experimental data and secondly, separate algebraic models. The homogeneous model remains useful in providing system conditions for these separate models. For example the header conditions (pressure and enthalpy) from the homogeneous model are used as input to a separate channel model. Or the channel fluid conditions (pressure, enthalpy and flow) are used as input to a separate fuel element calculation called the hot pin model.

In the following section, a sample of scenarios will be described. For each case an outline of the method of analysis and its important features will be given. As a general rule, the reader is advised to keep a schematic diagram of the PHTS at his side when studying these scenarios. For example, he could use Figure 1.4 of chapter 1.

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15.2 Accident Scenarios

Accident scenarios can be categorized as overpower, loss of pumping, loss of coolant or loss of heat sink though combinations are also studied. Overpower is commonly called loss of regulation (LOR) which means a loss of control of neutron flux such that the core or core zone power levels are greater than normal. Loss of pumping (LOP) scenarios include a loss of all PHTS pumps as would occur if the class IV electrical supply were lost, a loss of one or more pumps and the seizure of a pump.

Combinations of LOC and LOP scenarios are studied. A reactor trip may conceivably cause a loss of class IV electrical supply so we study LOC with loss of class IV power coincident with the reactor trip. As another example, a loss of electrical power as the initial event may result in primary pressures high enough to activate relief valves. Then it could be postulated that the valves fail to close causing a small LOC.

Below we examine particular scenarios selected because of their significant impact on safety system design.

15.2.1 Overpower or Loss of Regulation

The LOR scenario is the basis for neutronic trip setpoints. The slow LOR sets the overpower (or high n) trip and in so doing puts a limit on reactor power (100% power is chosen to permit a comfortable operating margin below the overpower trip). At low power and for the faster LOR's, the overpower trips become less effective and a rate trip (high rate log n) is used.

The objective of thermohydraulic analysis for the LOR is to demonstrate heat transport system integrity over a range of reactivity insertion rates from zero to greater than the maximum credible. Integrity is ensured if

a) Coolant overpressure is limited

and b) Fuel melting is avoided. This may not be necessary but is a sufficient condition.

The limiting scenario for the overpower trip is the LOR that takes a core region to a power level just below the trip setpoint, where it sits. Fuel centreline temperatures have time to reach equilibrium.

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The thermohydraulic analysis is approached by considering particular channels in turn. Header pressures and enthalpy are held constant at the nominal full power condition as channel power is raised step by step in a series of steady-state calculations. The sequence is terminated when fuel melting is predicted. The power for melting is called the critical channel power (CCP). The overpower trips are set such that the CCP is not exceeded in any channel with due allowance for uncertainties in doing the CCP calculation and in making in-core measurements.

The CCP calculation requires accurate two-phase pressure drop correlations because of the substantial amount of coolant boiling as power is raised. Boiling comes from the increased power and, indirectly, because of reduced flow. The calculation requires critical heat flux (CHF) correlations which are taken from full-scale experiments. Accurate post dryout heat transfer information is also desirable but data are scattered and sparse so we resort to the use of conservatisms. For example, we assume that the hottest fuel pin has dried out around its full circumference even though the CHF correlation is based on the first indication of a localized patch of dryout on any pin. Also we ignore the transition from nucleate to film boiling and use a conservative film boiling heat transfer coefficient.

15.2.2 Loss of Pumping

Classical safety analysis includes the study of several scenarios involving an impairment of the forced circulation of primary coolant. The simplest and most probable is a loss of electrical supply to all the PHTS pumps but we also study the rundown of one or more pumps and the seizure of a pump. Also PHTS flow impairment is common to many postulated scenarios, in particular the primary and secondary LOC scenarios, see 15.2.3 and 4 below.

The PHTS pumps are supplied with flywheels that reduce the head loss in the short term prior to reactor trip and permit a gradual development of thermosyphoning forces in the longer term -- about 2 minutes.

A flow reduction is readily sensed by several regulating and safety system measurements: low flow, low header-to-header pressure drop, high pressure. Thermohydraulic analysis is required to show that power is reduced before fuel cooling is unacceptably impaired. For the more probable events such as a simple loss of class IV power we ensure that dryout is avoided. For the improbable events such as a loss of class IV plus unavailability of regulating system plus unavailability of shutdown system #1 (SDS1) plus unavailability of the primary trip on SDS2, we ensure that fuel channel integrity is maintained. This requires accurate and/or conservative calculation of primary system pressure and fuel post-dryout temperature.

The longer term analysis is simple if single-phase thermosyphoning can be demonstrated but for some low probability events, e.g., loss of class IV plus loss of secondary system feedwater plus a failed open PHTS liquid relief valve the thermosyphoning is two-phase and analysis becomes complicated, see section 15.2.5.

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15.2.3 Primary System LOC Events

We study breaches of the PHTS ranging in size from zero plus to a header rupture. Breaks are considered in several locations, e.g., inlet header and outlet header. Pumps are generally assumed to be running consistent with design but cases of pump rundown are also studied.

15.2.3.1 Small Breaks

Small breaks encompass feeder-size pipe breaks which, because of the lengths involved, are much more probable than large breaks. They include events where PHTS bleed or relief valves fail open. A small break has a significant probability of occurrence during the 30-year life of a reactor, and economics dictate that fuel damage be limited.

Small breaks depressurize the PHTS slowly down to secondary system pressure. The break force is small compared to that generated by the PHTS pumps so a large coolant flow persists. Though the core coolant inventory decreases causing an increase of void reactivity, reactivity rates are within the capability of the regulating system so core power continues to be controlled to the set point. Trips on high building pressure, low primary pressure, and low pressurizer level are set so that the reactor is shutdown before widespread fuel dryout is encountered. Thus fuel damage and activity release to containment is limited.

For a very small break, the break size is insufficient for the discharging coolant to take all the decay power so the boilers continue to be a heat sink. Eventually the boilers have to be depressurized so as to depressurize the PHTS and permit emergency coolant injection (ECI). The PHTS quickly fills and remains at pressures near that of the emergency coolant supply and at a temperature just greater than that of the boilers. This settles out near 100°C.

Thermohydraulic analysis is required to ensure that reactor trips are effective and that ECI takes place prior to the onset of stratified flow in the fuel channel. Again, the latter ensures limited fuel damage and activity release.

15.2.3.2 Large Breaks

For the largest break, substantial core voiding occurs within a second of the event, and reactivity rates are beyond the capacity of the regulating system. Neutronic trips limit the energy of this power pulse. After the trip, energy discharged from the break exceeds that generated in the core so that primary pressure quickly drops below secondary and ECI pressures. A large ECI flow develops that, even for the worst "stagnation" break, refills all channels in time to limit the fuel and pressure tube temperature excursion.

Break location has a significant influence. For reactor outlet header (ROH) breaks, flow, assisted by the pumps, continues in the normal flow direction. However, the unbroken pass sees lower flows than the core pass with the broken header both during the blowdown and during injection. Basically this is because the flow has a direct path through the broken pass to the break whereas flow through the unbroken pass must also go through the broken pass.

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For large reactor inlet header (RIH) breaks, the break force is large enough to cause reverse flow in the broken pass. For small RIH breaks, the flow in both passes continues in the forward direction. For an intermediate size break, low flows can occur prior to injection when the break force balances that of the PHTS pumps. This is called a stagnation break. The stagnation is broken when the pump suction receives injected water and the head recovers.

For the 600 MW reactor, the large ROH break has the worst fuel damage, fuel surface temperatures reaching about 1200°C by the time ECI has penetrated to the fuel of a high powered channel. At this time most of the injected water is vaporized as it contacts the upstream fuel bundles and the steam produced is effective in limiting the temperature of downstream fuel bundles. Eventually, about 2 minutes after the event, the channel is full and the fuel is quenched.

Thermohydraulic analysis is required to calculate the power pulse, the core flows during blowdown -- in particular the flows which precede or follow break stagnation, and the flow split of emergency coolant to the two passes and, in particular, to the high powered channels of the critical pass. Calculations of sheath and pressure-tube temperature and time at temperature are used as input to fuel and pressure tube behaviour studies. Calculations of discharge rate from the break are used as input to containment studies.

The analysis is done in two stages. The first stage is a system calculation which produces header boundary conditions for the second stage, the channel calculation. These are demanding calculations requiring predictions of two-phase flow at flows where the phases tend to separate. This leads to unequal phase temperatures and velocities. For example, cold injected coolant mixes with superheated steam making the calculation of pressure especially difficult. In the channel the steam and water tend to stratify providing a superheated steam environment for the upper fuel pins. The degree of heat transfer is difficult to calculate under these conditions so we resort to doing full-scale channel tests, for code verification.

Most attention is given to stagnation breaks. By a process of trial and error, the break size is found at which stagnation occurs. Though the calculation is especially difficult for the fuel channel, the PHTS calculation is, to some extent, not so difficult. Errors made, for example, in break discharge rate will cause errors in the size of the stagnation break but do not cause significant error in the stagnation condition itself. Again, an incorrect pump head will be offset by an incorrect break force but, at stagnation, the header-to-header pressure drop <u>will</u> be close to zero.

15.2.3.3 <u>Loss of Coolant plus Loss of Pumping</u>

Studies are done of events wherein the PHTS pumps rundown during a LOC. Generally PHTS refill by ECI is complete at the end of pump rundown but stagnation breaks can again be identified. They are of smaller size than the corresponding pumps-running case because coolant circulation is by weaker buoyancy forces and these can be balanced by a smaller break.

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As an example of a stagnation break following pump rundown, take a small break in an inlet header and imagine that pump rundown starts at a time after ECI has refilled the system. Reactor power is at decay power and, with full flow, coolant temperature differences around the PHTS are very small. During the pump rundown, outlet feeder temperatures increase above inlet feeder temperatures but not by much because of the small power level. At the end of the pump rundown the buoyancy force is still small and can be balanced by a small break force. Eventually much larger buoyancy forces will develop but this takes time.

For stagnation breaks, when the pumps have stopped running, the PHTS is generally full of cold stagnant water below the headers. In any particular channel, flow may not get going until the water has been brought to boiling and sufficient steam has been produced to penetrate the cold end fitting thus producing a buoyancy force in the feeder. Ironically, the colder the initial water, the more the fuel channel heats up because it takes longer for steam penetration of the colder end fitting.

As a matter of interest when steam does enter the feeder, the buoyancy force can be so large that large flows develop which flush out both channel and feeder and the buoyancy force is lost again. So the process can repeat to give an intermittent buoyancy induced flow (IBIF). This is an instability common to many thermosyphoning scenarios, see 15.2.5 below.

As usual, thermohydraulic analysis is done in two stages, a system calculation firstly to provide the boundary condition for the channel calculation. An important intermediate parameter in the stagnant channel calculation is the liquid level in the channel. The lower it gets, the smaller the proportion of channel power that goes to produce steam and the longer it takes to heat up the end fitting. Getting the level correct is beyond the current capabilities of our thermohydraulic codes so simple algebraic models are used, supported by full-scale channel tests.

15.2.4 Loss of Heat Sink

As with primary-side LOC's, loss-of-heat-sink scenarios are studied with and without supply of power to the PHTS pumps.

Secondary-side events have no immediate effect on fuel cooling. However, a long-term heat sink has to be provided. The shutdown cooling system and the emergency water supply (EWS) to the steam generators are alternate heat sinks. An important aspect is the time of reactor trip because this affects the total energy to be transferred to an impaired heat sink.

The most demanding event is the design-basis earthquake (DBE). A loss of all electrical power systems is assumed coincident with a large secondary side break. This causes a rundown of the PHTS pumps and a loss of feedwater to the steam generators.

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Secondary system depressurization is more rapid than PHTS pump rundown so EWS, under gravity, starts flowing to the steam generator during pump rundown. Primary system pressure follows secondary system pressure causing a shrinkage of the coolant volume. This is compensated in part by a flow from the pressurizer but pressurizer volume is limited so void appears in the PHTS as it depressurizes towards atmospheric.

The objective of thermohydraulic analysis is to show the adequacy of thermosyphoning under the condition of low pressure and significant void in the PHTS. The results are sensitive to the EWS design. The 600 MW design has a cooling spray concentrated on the down-flow side of the boiler U tubes. This promotes and stabilizes the thermosyphoning flow.

15.2.5 Thermosyphoning

From the above sections we see that there are a variety of scenarios in which the primary coolant flow is not forced but must be buoyancy induced. These range from

a) Loss of electrical power where the PHTS pressure is high (i.e., just above nominal secondary pressure of 4.5 MPa) and the extent of void is small, to

b) the DBE where the system pressure is near atmospheric and a significant degree of boiling is possible.

Generally it is expected that a flow will continue over the top of the boilers induced by the buoyancy force arising from differences in coolant density. This is called thermosyphoning. (Another possibility is a reflux mode of two-phase flow between headers and boilers: steam from the core rises to the boilers where it is condensed and falls back in a countercurrent flow. Within a core pass individual channels would see a buoyancy-induced flow both in the normal and reverse directions.)

Thermosyphoning is of interest over a range of PHTS coolant inventories and secondary-side pressures (or temperatures). Core power is invariably at decay power levels -- no more than 3%. Thermohydraulic analysis is required to evaluate fuel temperatures for conditions under which the coolant boils in the fuel channel and the flow is low enough for the phases to stratify, or even to determine if such conditions exist.

At low pressures, because of flashing, PHTS void is concentrated near the boiler inlet plenum. Very low inventories have to be reached to get boiling within the fuel channel. At high pressures void is more uniformly distributed from fuel channel to boiler, so small losses of inventory can cause boiling within the fuel channel. Also flows are smaller because void in a fuel channel contributes to friction but not to the buoyancy force. So under conditions of high pressure and reduced inventory, we need to study the heat transfer in a stratified channel. Fortunately, heat transfer to steam improves at high pressure.

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Thermohydraulic analyses of thermosyphoning have identified three modes of potential flow instability. These are of interest because they can lead to intervals wherein the coolant in the channel is two-phase and stratified. These analyses need to determine the duration of such intervals and the degree of heat transfer under stratified conditions. Also two of the modes are system instabilities which could conceivably lead to a breakdown of thermosyphoning itself. (It is noted in passing that such a breakdown is yet to be observed experimentally.)

The instability modes are as follows:

a) Out-of-Phase Oscillations. Here the steam volumes at the outlet end of each core pass expand and contract out of phase as do the flows in the two core passes. The period is about one minute and the fuel in a core pass can heat up for about half this time whilst the steam volume is large enough to enter the fuel channel and the flow is low enough to permit stratification. Since the channel is filled during the next half cycle, the degree of heat up is modest.

   These oscillations have been seen in system thermosyphoning experiments and are captured by code simulations of these experiments. For the reactor they are predicted at intermediate pressure but not at high or low pressure.

b) In-Phase Oscillations. System oscillations have been predicted with parameters in both passes in phase.

   They are first noticed when void extends past the top of the boiler. They are gravitationally induced: Given a flow reduction, the additional void tends to penetrate further into the down leg of the boiler causing a loss of head and a further flow reduction.

   There oscillations usually require void from core outlet past the top of the boiler so that the necessary system void fraction is large. However, for some boiler designs, such oscillations have been predicted without core boiling.

c) Channel Oscillatory and Intermittent Flow. Flow oscillations have been observed in channel experiments under conditions of boiling at exit from the outlet feeder. This corresponds with negative header-to-header pressure drop which is invariably the case for two-phase thermosyphoning at high pressure.

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The oscillations grow to a limit cycle which depends on the inlet subcooling. At high inlet subcooling, the limit cycle is characterized by a long interval of low flow followed by a short interval of high flow. During the low flow interval, void develops in the channel and eventually reaches the outlet feeder. A large driving head quickly develops to accelerate the flow and flush the void from channel and feeder. The buoyancy force is lost and the process repeats to produce an intermittent flow. Channel heat up occurs during the low-flow interval and can be significant at high subcooling. At lower inlet subcooling, the low-flow period is shorter and the limit cycle becomes more sinusoidal.

15.3 Conclusion

Though safety analysis of CANDU covers a wide range of scenarios, a general pattern has emerged for the thermohydraulics part. Firstly, a system calculation is performed to determine the boundary conditions for the second phase, the channel calculation.

As a general rule, the system calculation is not too difficult because the critical boundary conditions are known in advance, at least to some extent. Most of the analysis difficulties are in the second phase where for critical cases we have to deal with low pressure drops, low flows and non-equilibrium.

Fortunately, the CANDU design permits full-scale testing of channels so modelling deficiencies can be rectified by adjusting the models to the results of such tests. These are done over a wide variety of header conditions.

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