A Plan for the Modification and Assessment of TRAC-PF1/MOD2 for Use in Analyzing CANDU 3 Transient Thermal-Hydraulic Phenomena

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ABSTRACT

This report presents the results of the review and planning done for the United States Nuclear Regulatory Commission to identify the thermal-hydraulic phenomena that could occur in the CANDU 3 reactor design during transient conditions, plan modifications to the TRAC-PF1/MOD2 (TRAC) computer code needed to adequately predict CANDU 3 transient thermal-hydraulic phenomena, and identify an assessment program to verify the ability of TRAC, when modified, to predict these phenomena. This work builds on analyses and recommendations produced by the Idaho National Engineering Laboratory (INEL). To identify the thermal-hydraulic phenomena, a large-break loss-of-coolant accident simulation, performed as part of earlier work by INEL with an Atomic Energy of Canada, Limited (AECL) thermal-hydraulic computer code (CATHENA), was analyzed in detail. Other accident scenarios were examined for additional phenomena. A group of Los Alamos National Laboratory reactor thermal-hydraulics experts ranked the phenomena to produce a preliminary phenomena identification and ranking table (PIRT). The preliminary nature of the PIRT was a result of a lack of direct expertise with the unique processes and phenomena of the CANDU 3. Nonetheless, this PIRT provided an adequate foundation for planning a program of code modifications. We believe that this PIRT captured the most important phenomena and that refinements to the PIRT will mainly produce clarification of the relative importance (ranking) of phenomena. A plan for code modifications was developed based on this PIRT and on information about the modeling methodologies for CANDU-specific phenomena used in AECL codes. AECL thermal-hydraulic test facilities and programs were reviewed and the information used in developing an assessment plan to ensure that TRAC-PF1/MOD2, when modified, will adequately predict CANDU 3 phenomena.

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EXECUTIVE SUMMARY

In anticipation of an application for standard design certification by Atomic Energy of Canada, Limited (AECL) for their CANDU 3 reactor design, the US Nuclear Regulatory Commission (USNRC) contracted with Los Alamos National Laboratory for a review and planning activity. This activity consists of five tasks under FIN W6155:

Task 1	Become familiar with the CANDU 3 design, transient behavior, and databases and determine modeling requirements.
Task 2	Develop a draft work plan for modifying the TRAC code for CANDU 3 analysis.
Task 3	Develop a draft work plan for assessing the TRAC code against the CANDU database.
Task 4	Integrate and finalize the work plans for modifying and assessing the TRAC code for CANDU 3 analysis.
Task 5	Provide on-call assistance.

This report is the end product of the integration, finalization, and documentation activities that constitute Task 4. Task 4 integrates and finalizes the work done under Tasks 1 to 3. Database information used in this project was developed and delivered to Los Alamos by the Idaho National Engineering Laboratory (INEL).

As part of Task 1, a large-break loss-of-coolant accident (LBLOCA) simulation was analyzed with an emphasis on key systems and components, and key processes and phenomena. As such, this analysis was done with the goal of providing the information necessary to plan TRAC modifications. This simulation was an LBLOCA run by the INEL with the AECL thermal-hydraulics code CATHENA. In addition, processes and phenomena unique to a small-break loss-of-coolant accident (SBLOCA) were examined. Other transients scenarios were also examined with an emphasis on processes and phenomena that may require code modifications. A panel of thermal-hydraulics experts was assembled to participate in key process/phenomena identification and ranking, as well as discussions of TRAC modifications necessary to simulate CANDU 3 phenomena. A preliminary phenomena identification and ranking table (PIRT) was produced from this effort. We believe that this PIRT captured the most important phenomena and that refinements to the PIRT will mainly produce clarification of the relative importance (ranking) of phenomena.

This was a first effort at applying parts of the applicability portion of the Code Scaling, Applicability, and Uncertainty (CSAU) process to the application of TRAC to CANDU 3 thermal-hydraulics. As work progresses on modifying and assessing TRAC for use in CANDU 3 applications, one or more iterations of the code applicability process, building on the current work on identifying key systems, components, processes, and phenomena and ranking them would be desirable. The NRC is also using the CSAU structure on AP600 and SBWR activities to foster research adequacy and completeness.

As part of work documented in NUREG 1502 and an upcoming NUREG/CR, INEL engineers identified the features of the AECL thermal-hydraulics code CATHENA that differ from the US thermal-hydraulics codes. They also identified the primary phenomenological differences between the CANDU 3 and US pressurized water reactors (PWRs). The INEL investigators recommended a series of modifications to TRAC to enable it to predict CANDU phenomena. Most of these modifications were added capabilities that would match, in some form, the capabilities in CATHENA. As part of Task 1, a group of thermal-hydraulics experts at Los Alamos reviewed the information generated by INEL, as well as the analyses of several transients discussed above. They recommended a set of TRAC code modifications. These code modifications were, for the most part,

the same as the recommendations made by INEL. However, there were differences in priorities, treatment of three-dimensional (3D) component models, and the treatment of reflood and fine mesh models.

The TRAC modification plan developed under Task 2 is based upon the recommendations of the Los Alamos panel of thermal-hydraulics experts. Los Alamos TRAC code developers examined TRAC and its supporting documentation to develop a detailed plan and estimate staffing requirements for implementing the modifications. Developmental assessment will be an integral part of the code modification processes. The AECL test facilities from which data for developmental assessment will probably be utilized were identified. It appears that the database for tests used to validate TRAC modifications is adequate as also found in NUREG-1502.

This plan includes the work to merge 3D neutronics into TRAC. A large part of this activity will be the development of an appropriate cross-section library. This work will be done primarily by personnel specializing in reactor physics rather than TRAC code developers. The 3D neutronics is planned for the initial year-and-a-half of the code development effort.

As part of this project, Los Alamos and NRC personnel traveled to AECL facilities at Sheridan Park, Ontario, and Whiteshell, Manitoba, Canada, to learn more about experimental facilities and programs. The assessment plan (Task 3) included in this report is based largely on the information obtained in those meetings. In a broad sense, assessment includes not only comparisons of code calculations to experiments, but also activities such as a CSAU evaluation; calculations of transients in the full-scale plant that have counterparts in integral facilities tests; and comparisons of code calculations to actual plant transients. The assessment plan presented in this report considers assessment as this broad set of activities. The plan in this report was developed to cover, in as comprehensive a manner as possible, all of the steps needed to use TRAC-PF1/MOD2 for confirmatory calculations on the CANDU 3 design. Code development and assessment are by their nature iterative. At this point, the initial code modification steps and the assessments necessary to verify those steps are identified. As code assessment progresses, it is likely that the need for additional code modifications will be identified. These modifications will require additional assessments. The planning presented in this report reflects this iterative nature.

The plan yielded a staffing estimate of 86 staff member months (smm) for the first year of the activity. The estimated cost is \$1.61 M based on a cost of \$225,000 per 12 smm. Of that 86 smm, 50 smm would be for the TRAC development and CANDU 3 cross-section library development. The remainder would be for information procurement and review, and input deck development for use in assessment work. The second year estimate of 138 smm at \$2.59 M includes 30 smm for code development and related cross-section library development work. The balance is for work related to assessment. The third year estimate total is 103 smm at \$1.94 M. Of this about 19 smm is for code development with the remainder for code assessment activities. The fourth year estimate is 54 smm at \$1.0 M with 5 smm devoted to code development and the balance to assessment activities.

The total for the 4 years is 381 smm at \$7.14 M. Of this amount, 104 smm at \$1.95 M is for code development. The balance is for assessment-related activities including CSAU. Most of the activities discussed in the code modification plan are those required to simulate the unique features of the CANDU 3. Prior experience has shown that additional code modification needs will probably be identified during the code assessment process. Estimated staffing requirements to cover additional modifications are included, though these estimates are by their very nature uncertain.

This estimate does not include a program of calculations to verify the calculations in the AECL submittal. It does include the development of input decks (TRAC models for the CANDU 3 facility) that could be used for confirmatory calculations since these input decks would be needed for activities such as CSAU that are included in this broadly defined assessment plan.

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A PLAN FOR THE MODIFICATION AND ASSESSMENT OF TRAC-PF1/MOD2 FOR USE IN ANALYZING CANDU 3 TRANSIENT THERMAL-HYDRAULIC PHENOMENA

by

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1. INTRODUCTION

This report integrates the work done under FIN W6155, which had as its objective the development of a plan for TRAC-PF1/MOD2 (Ref. 1) modifications and related assessment work that would allow TRAC-PF1/MOD2 (TRAC) to be used for CANDU 3 transient thermal-hydraulic analyses. Before the development of a code modification plan, it was necessary to identify the CANDU 3 thermal-hydraulic phenomena that differ from phenomena in US pressurized water reactors (PWRs). These are the phenomena for which TRAC modifications will be necessary. This was done under Task 1. The code modification plan was developed under Task 2 and the assessment plan under Task 3. Background information used in this project was developed and delivered to Los Alamos by the Idaho National Engineering Laboratory (INEL) under FIN L2445 (to be published as a NUREG/CR report). An assessment of the database information and modeling capabilities for the CANDU 3 design is given by Ref. 2.

The CANDU 3 reactor (Ref. 3) differs significantly from the PWRs in use in the US. The horizontal pressure tube geometry produces thermal-hydraulic phenomena that differ from the phenomena in PWRs. In addition, the CANDU 3 reactor has a positive void reactivity coefficient. During some transients, voiding would occur in parts of the core. Because of the CANDU 3 geometry and cooling system hardware configuration, this voiding would not occur in a symmetrical manner. Thus, a three-dimensional (3D) neutronics capability is needed to accurately predict the power distributions throughout the core during transients. Simulating transients in the CANDU 3 with an existing computer code such as TRAC-PF1/MOD2 will require modifications to the code to implement applicable thermal-hydraulics models and 3D neutronics. Developmental assessment will be required as an integral part of the code development process.

The development of a code modification plan for a thermal-hydraulics computer code required, first of all, that the phenomena to be modeled in the code be identified. A code modification plan was then developed. Developmental assessment is done as part of the code modification process to ensure that a model, as implemented, performs as desired. Developmental assessment usually consists of code/data comparisons for experiments that attempted to isolate the phenomenon of interest. Integral assessment consists of code/data comparisons to integral effects experiments that produced a spectrum of phenomena in a scaled facility, much as these phenomena would occur in a prototypic plant. This ensures that the set of models in the code works adequately for linked phenomena. In a broader sense assessment consists of the set of activities done to ascertain the ability of a code to predict plant performance under transient conditions. This can include code scaling, applicability, and uncertainty (CSAU) determination for certain cases, and plant calculations that may provide insights into the linkages between test facilities, computer codes, and full-scale facilities, as well as code/data comparisons for tests from integral test facilities.

The proposed modifications to TRAC should provide capabilities that are comparable or superior to the unique features of CATHENA, AECL's best-estimate thermal-hydraulics computer code

(Ref. 4). The one-dimensional (1D) capabilities added to TRAC should be comparable to the capabilities of CATHENA, which is a strictly 1D code. Phenomena occurring in the CANDU 3 headers can be 3D. If the 3D capabilities are used in TRAC, this should permit improved modeling of the CANDU 3 headers. In addition, the 3D capabilities of TRAC can be used to produce a detailed, standalone model of a CANDU 3 pressure tube with rod bundles. Modeling a pressure tube in this manner will produce more detailed information on the phenomena occurring in the pressure tubes than can be obtained in 1D models that incorporate stratified flow modeling. A 3D neutronics capability has been developed for TRAC and would be generalized for applicability to the CANDU 3 design. In addition, work will be required to prepare cross sections for the CANDU 3D neutronics.

2. DESCRIPTION OF THE CANDU 3 PRIMARY COOLANT SYSTEM

The CANDU 3 primary cooling system differs in many respects from the PWRs that are the predominant type of nuclear power plant in the US. The CANDU 3 is a heavy-water (D_2O) cooled and moderated horizontal pressure tube reactor design. The core consists of 232 horizontal pressure tubes. Each pressure tube is supplied by an inlet feeder pipe with flow exiting the pressure tube to an outlet feeder pipe. The 232 inlet feeders connect, on their upstream end, to a total of 4 inlet headers, 58 feeders per header. The 232 outlet feeders connect to 2 outlet headers, 116 feeder pipes per header. The outlet and inlet headers are the largest and second largest pipes in the design. The inlet headers are fed by the cold legs. The outlet headers discharge to the hot legs. The loops are similar to the loops in a US PWR with a few important exceptions. The loops are arranged in what is termed a "figure-of-eight" design. The outlet feeder pipes from half the core connect to one of the outlet headers. The loop connecting this outlet header connects to the inlet headers feeding the other half of the core. Thus, the D_2O in the primary coolant system flows in a figure of eight. In addition, the CANDU 3 operates at a pressure that is less than US PWRs, about 10 MPa (1450 psia) compared to the approximately 15-MPa (2200-psia) maximum pressure for a PWR. Piping, pumps, and steam generators are all similar to the corresponding components of US PWRs. Appendix A of Ref. 5 gives a more detailed overview of the CANDU 3 design. Table I, taken from Ref. 5, gives a summary of CANDU 3 unit data. Figure 1, also from Ref. 5, gives a schematic of the heat transport system.

The emergency coolant injection (ECI) system consists of a high-pressure accumulator, which begins injecting when the primary pressure drops to 6 MPa, and a pumped low-pressure injection system. In addition, though not a safety-grade system, the reactor coolant make-up system can perform the function of a high-pressure safety injection system. ECI is injected directly into inlet and outlet headers.

Each of the horizontal pressure tubes is enclosed in a "calandria tube." The pressure tube is separated from the calandria tube by a gas space and spacer springs. These pressure tube/calandria tube assemblies are located in a calandria (moderator) tank filled with cool heavy water. For transients where the rod bundles heat up sufficiently, the horizontal pressure tubes soften and then sag or balloon. This allows the pressure tube to move into contact with the calandria tube, which is in contact with cool heavy water in the moderator tank. The rod bundles can then transfer heat to the pressure tubes by convection (this occurs in a mostly dried out condition), conduction, and thermal radiation heat transfer. The pressure tube then transfers heat to the moderator tank through the region in contact with the calandria tube. Circumferential conduction around the pressure tube to the cooled region becomes important. This mode of heat transfer comes into play only during extreme heat-up conditions such as during a loss-of-coolant accident (LOCA) without ECI.

Table I
CANDU 3 Unit Data (from Ref. 5)

Reactor	
Type	Horizontal pressure tube
Coolant	Pressurized heavy water
Moderator	Heavy water
Number of fuel channels	232
Fuel	
Fuel	Compacted and sintered natural UO ₂ pellets, 12.15-mm diam, clad in 13.08-mm-OD, 0.42- mm-thick Zircaloy-4 sheath
Form	Fuel bundle assembly of 37 elements
Length of bundle	495.3 mm
Outside diameter	102.4 mm
Bundle weight	23.5 kg (includes 19.1 kg U)
Bundles per fuel channel	12
Heat transport system	
Number of steam generators	2
Steam generator type	Vertical U-tube with integral steam drum and preheater
Number of heat transport pumps	4
Heat transport pump type	Vertical, centrifugal, single suction, double discharge
Reactor outlet header pressure (gage)	9.9 MPa
Reactor outlet temperature	310°C
Reactor coolant flow	5.3 Mg/s
Steam temperature (nominal)	260°C
Steam quality (minimum)	99.75%
Steam pressure (gage)	4.6 MPa
Total fission heat	1440.3 MW(th)
Net electrical output (nominal)	450 MW(e) ^a

^a Typical for a cold water site; net electrical output depends on cooling water temperature and turbine generator and condenser design.

Fig. 1.
CANDU 3 heat transport system simplified flow diagram (Ref. 5).

3. LARGE-BREAK (LB) LOCA IN THE CANDU 3 DESIGN

As part of the work supporting the preapplication review of the CANDU 3 for the Nuclear Regulatory Commission (NRC), Idaho National Engineering Laboratory (INEL) ran a series of CANDU 3 transients using the Atomic Energy of Canada, Limited (AECL) thermal-hydraulics computer code CATHENA with input decks supplied by the AECL. Unlike the thermal-hydraulics computer codes developed for the NRC, which put the full set of variables that can be plotted into a graphics file, CATHENA requires a user to specify the parameters to be placed in a plot file as part of the input. The plot files (x-y pairs) for a 100% break of second inlet header LBLOCA transient were obtained from INEL. The number of parameters included in the plot files was limited. Also, the model itself is not sufficiently detailed to resolve all phenomena and is limited by the 1D nature of the CATHENA components. The plots for the transient allow us to define the phenomena occurring in the transient in sufficient detail, so that when taken with an understanding of the nature of two-phase flows, we can develop a reasonable understanding of the major phenomena that could occur during an LBLOCA in a CANDU 3. Additional simulations and analyses, in particular sensitivity studies, would allow us to more thoroughly understand the phenomena.

In analyzing an LBLOCA in the CANDU 3 design, two of the major differences between the CANDU 3 and a PWR produce the major differences in thermal-hydraulic phenomena between the two types of plants. The first of these differences is the header/feeder/horizontal pressure tube design. The second of these differences is the figure-of-eight loop geometry. The headers offer the potential for flow stratification with different amounts of liquid carried into pressure tubes, depending upon the elevation at which the feeder tubes connect to the header (Fig. 2). This is true both for the blowdown phase of a LOCA and the reflood phase where ECI is being injected to the headers. In the horizontal pressure tubes, stratified flow should also exist for a variety of flow conditions. A key in predicting LBLOCA performance in the CANDU 3 will be to correctly predict water quantities, form (mixed two-phase or stratified), and distribution as a function of time. The figure-of-eight loop geometry produces a longer path for most of the water to go through before it reaches the break than occurs in a PWR. As a result of this geometry, water in part of the figure of eight stagnates and then reverses flow direction shortly after the initiation of the break. Once reverse flow toward the break is established, a region develops in the figure of eight where fluid momentum balances and fluid moves away in both directions. Voiding occurs and the voided region expands. This region gets very little cooling from the water pulled toward the break. This region grows as the loops drain. Figure 3a shows a simplified loop schematic for the CANDU 3 primary. The flow arrows show the normal direction of flow through the loops. Figure 3b shows the same figure with the flow directions well after initiation of an LBLOCA. The opening of the inlet header 2 break causes the flow to reverse in the lines connecting outlet header 2 and inlet header 2 via the core, and the lines connecting outlet header 2 and steam generator 2. The break induces voiding, which begins in steam generator 2 and spreads. Initially, liquid in cold-leg 4 flows through pump 4, inlet header 4, and through the core in the normal direction. As this liquid drains, cold-leg 4, then inlet header 4, and finally core channel 4, fill with steam. This steam flows toward the break in the reverse of the normal flow direction. The flow directions are based on the LBLOCA calculation presented below.

For purposes of discussion, the analysis of the LBLOCA will be broken down into two phases: blowdown and reflood. In analyzing PWR LBLOCA transients, three phases have traditionally been used: blowdown, refill, and reflood. Blowdown covers the period when most of the water is expelled from the primary system. The refill phase is designated as the phase during which the lower plenum refills with ECI water. Reflood is the phase beginning when the level of ECI water in the reactor vessel reaches the core and begins quenching the rods. Tests in the 2D/3D program showed that the refill phase is actually concurrent with the later part of the blowdown phase. In the CANDU 3 we also could have defined a refill phase, although for the CANDU 3 it would have been the headers being refilled rather than the lower plenum. The refilling of the headers occurs

Fig. 2.
Schematic of CANDU 3 header cross section—end view showing stratification of water.

Fig. 3.a.
Schematic of CANDU 3 loop with normal flow directions indicated.

Fig. 3b.

Schematic of CANDU 3 loop with flow directions well after initiation of an inlet header 2 LBLOCA indicated.

while blowdown is still going on, and because we expect the same phenomena to occur during the reflood phase as in a refill phase if we had chosen to include one, a separate refill phase was not included in the analysis.

The discussion below reflects the discussion and judgments of the panel of experts that reviewed this transient. In the opinion of the panel, the processes/phenomena that most affect the peak cladding temperature (PCT) are those that determine the water quantities, form, and distribution in the core as a function of time. In ranking the phenomena, the highest rankings were given to the phenomena that have the strongest influence on the quantity and distribution of water in the core. In addition, the most important sources of heat that need to be removed, by transient phases, were considered to be dominant phenomena. Other processes that were considered dominant were those that could significantly affect the heat removal. In the discussion below, components and systems are identified in **bold** type and processes/phenomena are noted in ***bold italic***. The phenomena identification and ranking table (PIRT) should be revisited as further calculations and sensitivity studies are completed and as reviews of CANDU 3 related experimental programs proceed. We believe that this preliminary PIRT captured the most important phenomena and that refinements to the PIRT will mainly produce clarification of the relative importance (ranking) of phenomena.

3.1. Blowdown

For the purposes of this analysis, blowdown is defined as the period of time from the initiation of the break until water from the ECI system begins to be delivered to the core at about 40 s. At the time of initial ECI delivery to the core, the system was still depressurizing and continued to do so. The part of the transient occurring after initial ECI delivery to the core began is included in the reflood phase even though the system was still depressurizing. The system continued to depressurize until about 300 s, which was well after core quenching was completed.

Figure 4 shows the pressures at the inlet and outlet headers. During the initial 10 s of the blowdown, the pressures dropped to about one-half their nominal values. Break flow (Fig. 5) reached its maximum value at about 1 s. This was a 100% break of the second inlet header. Break flow decreased rapidly for about 10 s. After this time break flow decreased more slowly, possibly because of a change from single-phase to two-phase break flow.

At a **break**, there is the potential for ***critical flow***. Liquid flowing through the break would be ***flashing*** and the ***containment pressure*** would rise, increasing the back pressure at the break. Of these phenomena, critical flow was ranked as an important phenomenon because of its effect on the amount of water available for core cooling. As the system begins to depressurize, water in the **pressurizer** would begin to ***flash*** with most of the pressurizer water being driven into the surge line. The large pressure difference that rapidly develops between the pressurizer and the loops would produce the potential for ***critical flow in the surge line***. Water from the pressurizer enters a hot leg and becomes part of the water inventory that helps cool the core before the beginning of ECI delivery. Critical flow in the surge line was also ranked as an important phenomenon for the reasons discussed above.

Figure 6 shows the channel average void fraction. Each "channel" represents 58 pressure tubes fed by a single inlet header. Channel 2, which is connected to the broken inlet header, became highly voided almost immediately. There was enough flow into channel 2 to hold voiding to about 90% during the initial 50 s. It took from about 10 to 20 s for channels 1, 3, and 4 to become mostly voided. Channel 4 was part of the region "opposite" the break that dried out as the loops drained. Channel 4 became completely voided at about 40 s. With different void fractions occurring in different parts of the **core**, and given the positive coolant void reactivity for the CANDU 3 design, the **power** produced during the initial second of the transient is significant and it would not be distributed uniformly throughout the core. Figure 7 shows the lumped power used in the simulation of this transient. After about 1 s, one of the two shutdown systems would have

Fig. 4.
Pressures in headers.

Fig. 5.
Break flow.

Fig. 6.
Average void fraction in channels.

Fig. 7.
Power history.

shut down power generation. After that time, *stored energy* in the fuel and *decay power* become the dominant sources of heating. If the heat up is sufficient, there would be the potential for *steam-cladding reactions*. In determining the temperature of the cladding, the *gap conductance* between the fuel pellets and the cladding would be important. If the fuel pellet-cladding clearances are not tight there could be gap nonuniformities. Because CANDU fuel is designed to maximize the heat transfer from fuel pellets to cladding, this is likely to be a relatively minor effect. Core power was ranked as a dominant phenomenon by the panel because of its direct impact on the PCT. Spatial differences in power during the initial second or two of an LBLOCA would also be important.

Figure 8 shows the channel flows. Flows in channels 1, 3, and 4 coasted down over about 10 s from full flow to flow rates sustained by the "pull" of the break as it drew water through the primary components. Pump coastdown was probably also important. Flow through channel 2 reversed soon after the opening of the break. Significant mass flows were maintained in channels 1, 2, and 3. Channel 4 stagnated beginning at about 20 s. In the CANDU 3 Conceptual Safety Report (Ref. 3), the AECL reports that for a certain break size there can be a balance between the "pull" of the break and the "flow" of the fluid that yields the highest temperatures. This means that there is a break size where the balance of fluid momentum, pressure drops, and momentum imparted by the pumps causes the stagnation in the pressure tubes fed by one inlet header to occur very early in the transient. That is, the point dividing the regions of forward and reverse flow occurs in the core. This would be the worst case with regard to flow stagnation and heat up. In the *core* portion where *stagnation* occurred there would also be a *flow reversal*. The potential exists for *departure from nucleate boiling (DNB)* to occur with a transition to *post critical heat flux (CHF) heat transfer*. With the reduction in convection and boiling heat transfer as a portion of core dries out, *radiation heat transfer* would become important. Under conditions of nearly complete to complete dry-out associated with post CHF heat transfer, the pressure tubes could reach temperatures at which they would sag to touch the calandria tubes. Then *circumferential conduction heat transfer* through the pressure tubes would be important as would the *contact resistance for conduction heat transfer* between the pressure and calandria tubes.

In the core pressure tubes where an extended period of stagnation does not occur, there would be two-phase *stratified flow*. Fuel rods at the top of the bundle could dry out while those at the bottom would be completely submerged. Rods at intermediate elevations would get some cooling from droplets carried upward from *nucleate boiling*. The cooling available at different locations in a bundle would depend on the amount of liquid available at that location. Thus rod temperatures will also depend on the *void generation and distribution* and on *entrainment and deentrainment*.

The *inlet and outlet headers* would also be important in defining the distribution of liquid in the core, and thus the temperatures reached as a function of location. Some of the inlet and outlet headers and feeders would have flow passing through them in the normal direction and some would have flow in the reverse direction. The headers upstream of portions of the core would be outlet or inlet headers depending on their location. These upstream headers would be important factors in determining the distribution of water in the core. *Phase separation* would probably occur during blowdown with some feeder tubes drawing single-phase liquid and some getting a two-phase mixture or single-phase steam. *Entrainment and deentrainment* would also be expected to occur in the headers. There would also be the *flow of two-phase mixture* through the header. All of these phenomena could have significant effects on the distribution of liquid in the core and thus the rod temperatures. There is also an *interconnect between the two outlet headers* that acts to equalize the pressures. Although important primarily to prevent flow oscillations during normal operating conditions, the interconnect could support *two-phase flow* during a transient with the potential for effects on the performance of the headers.

Fig. 8.
Channel flows.

The phenomena in the **feeder tubes** connecting inlet and outlet headers and the core are likely to be less important than the phenomena in the headers. These feeders carry the flow between the headers and the core. This can be *two-phase flow*. Since the hydraulic diameter is relatively small, the *two-phase pressure drop* across the feeder tubes could be a significant contributor to the overall pressure drop through the system. There also could be flashing as the pressure changes through the feeder tubes with some *void generation*.

The components of the CANDU 3 loop are similar to the corresponding components of a PWR. Because of the figure-of-eight loop geometry, the flow path from most locations in the primary system to the break is much less direct than in a PWR. Thus depressurization takes significantly longer (Fig. 4) than in a PWR (25 to 30 s in a PWR). Phenomena occurring in the loop components of the CANDU 3 will be similar to the phenomena occurring in the loop components of a PWR. Because the duration and quantity of cooling available in the core during blowdown are strong functions of loop flows, the phenomena that influence the loop flows may in turn have a greater effect on rod temperatures in the CANDU 3 than in a PWR.

Loop piping would certainly have *two-phase flow* during blowdown. In the simulation, *stagnation and flow reversal* occurred, at least briefly, in part of the piping during the early part of blowdown. In higher void two-phase flow regimes, droplets could be *deentrained*, particularly at bends and expansions. Conversely, droplets could be *entrained* at some locations. As the system depressurized, the potential for flashing would exist and, consequently, *void generation and distribution* should be included in potential phenomena.

The **steam generators** should have a strong influence on the loop flow, primarily because of the *two-phase flow resistances* associated with the turns, expansions, contractions, and small hydraulic diameters. In the CANDU 3, in response to a LOCA signal, the steam generator secondaries blow down. Early in blowdown, there could still be enough thermal energy in the steam generators to cause *flashing of primary fluid* from secondary to primary heat transfer. As the steam generator secondaries blow down, the temperature difference between primary and secondary sides should be small and primary flashing minimized.

The *two-phase performance* of the **primary pumps** would greatly influence the loop flows and was therefore ranked as a dominant phenomenon. The pumps, as they coast down, would impart considerable momentum to the primary fluid. Thus, they are one of the big factors in the momentum balance in the loops. Thus two-phase *flow losses* through the pumps should also be considered as a significant component of the overall flow resistances in the loops.

3.2. Reflood

The ECI is injected directly to the inlet and outlet headers. The CANDU 3 has both a high-pressure accumulator system and low-pressure injection system. As ECI reaches the headers and then portions of the core, the phenomena associated with stratification in the headers and core become the most significant phenomena in determining PCTs. Loop flows will have decreased and will be less important in cooling the core. Thus, loop phenomena should be less important during reflood than blowdown. The reflood phase, as defined here, occurs during the time interval of 40 s, when ECI first reached parts of the core, to about 120 s when all of the core quenched.

Figure 9 shows the ECI delivery to the inlet headers. ECI is also injected into the outlet headers (not shown). ECI reached the headers beginning at about 20 s. ECI delivery to inlet header 2, which was the broken header in this transient, began at about 20 s. Most of this ECI was probably swept out the break. Significant delivery to inlet headers 1 and 3 took until about 25 s. Delivery to inlet header 4, which connected to the stagnant core section, began at about 40 s.

Fig. 9.
ECI flow to inlet headers.

Figure 10 shows the inlet and outlet header void fractions. This plot shows there was a time delay between the time ECI initially reached the headers until the headers filled. Of the headers that were mostly voided at the beginning of ECI delivery, filling took place between 40 and 100 s. This means that feeder tubes that connect to the headers at higher elevations may not get a large amount of liquid until significantly after the beginning of ECI injection.

Figure 11 shows the PCTs. During the initial 20 s of the transient, temperatures dropped for all of the channels defined in the model. This means that, even in channel 4, which eventually stagnated, there was flow initially. The point separating forward and reverse flows must have occurred at some location that was not in the core. Beginning at 20 s, the temperatures in channel 4 began to rise as the dry region "opposite" the break spread to include this portion of the core. Some water did get into channel 4 beginning at about 35 s to yield a brief cooldown. The peak temperature of 680 K occurred at 70 s. At that time, sufficient water was being delivered to quench the hot bundles.

During the reflood period, the **fuel rod** phenomena that affect the PCTs include *stored energy*, *decay heat*, and *gap conductance*. Modeling stored energy and decay heat terms should be similar to modeling the same terms in a PWR. The gap conductance may be different because of the horizontal rather than vertical orientation of the fuel rods causing a nonuniform gap, although CANDU fuel is designed to maximize heat transfer between fuel pellets and cladding. The graphite lubricant used in the CANDU fuel pin/cladding gap also differs from PWRs.

The phenomena that may occur in the **core** during reflood are the same as the phenomena that may occur during blowdown for the most part. The relative importance of the different phenomena are likely to be different. The phenomena associated with film boiling including *DNB* and *post CHF heat transfer*, though possible, are probably less important during reflood. The phenomena associated with the delivery and distribution of water are probably the dominant phenomena during reflood. *Stratified flow* will be important in filling the pressure tubes. *Nucleate boiling* in the water layer will tend to disperse some droplets higher in the bundles and also tend to displace water to higher levels than the collapsed liquid level would indicate. There is also the possibility for droplets to be *entrained* into the steam flow and then *deentrained* at a different location. Because of stratification and filling effects, quenching for a given rod may occur axially and from bottom to top, but for the bundle as a whole, the lower rods will probably quench first with quenching proceeding to higher and higher rods. Before the time when there is significant cooling from water in the hottest pressure tubes, *radiation heat transfer*, pressure tube sagging with consequent *conduction heat transfer to the calandria tubes*, and *circumferential conduction around the pressure tubes* may be important.

ECI injected into the headers must pass through the **feeders** to get to the core. Steam generated in the core that flows toward the break also goes through the feeders. Consequently there is the potential for **counter-current flow limitation (CCFL)** and *two-phase flow*. With cold ECI water contacting steam generated in the core, the *void distribution* may be important to consider.

The phenomena occurring in the **headers**, both inlet and outlet, along with core phenomena are probably the most important phenomena in determining PCTs. *Phase separation* and *void distribution* will be key phenomena in determining how much ECI water gets to the core through which feeder tubes. Since steam exiting the core contacts cold ECI water, there will be considerable *condensation*. The amount of condensation occurring will be important in determining the temperature of the ECI water and its ability to condense more steam in the feeders. There will also be *two-phase flow* entering the headers downstream of the core from the feeders. This may pass through the headers in the space above the liquid filled bottom region.

Fig. 10.
Inlet and outlet header void fractions.

Fig. 11.
Peak cladding temperatures.

During the reflood phase, there would still be flow of two-phase mixture through the loops toward the break. In the judgment of the panel, phenomena occurring in the loops would be less important during reflood than during blowdown. Since ECI is injected to the headers, loop flows would have a small influence on what quantity of ECI water goes into the core at what locations. In **hot and cold legs**, there would probably be two-phase flow with *deentrainment* occurring at bends and expansions. There would also be *entrainment* of liquid off of surfaces into the core flow. In determining two-phase flow regimes and entrainment and deentrainment, the *void distribution* is important.

During reflood, the **steam generators** still constitute a major part of the loop flow resistances. Thus, *two-phase pressure drop* should be considered. Even though the steam generator secondaries depressurize in response to a LOCA signal, there would still be the possibility for *flashing* in the steam generator primaries if the primary depressurizes faster. Flashing in the steam generator primaries can lead to increases in the pressures. This could also have an effect on loop flows. If the secondary side of the steam generators depressurizes faster than the primary, the possibility would exist for *condensation* in the steam generator primary. Then, this condensate could drain back into the primary loops as *reflux*.

The **primary pumps** should have less effect on loop flows during reflood than they did during blowdown. The pumps should have coasted down; therefore, *two-phase pump characteristics* should have only minor effects. The pumps could still be a significant source of *two-phase flow resistance* in the loops because of *form losses*.

The **break** effects are probably much less important during reflood than during blowdown. With the decrease in primary system pressure, *critical flow* through the break is probably unimportant. There will still be *flashing* as the break flow enters the containment with a slow increase in *containment pressure* possible.

The **pressurizer** can continue *flashing* as the primary system depressurizes. Most of the water delivery should have already occurred before the beginning of reflood. Thus the pressurizer is not expected to produce any significant effects on PCTs during reflood.

4. PHENOMENA OCCURRING IN OTHER TYPES OF TRANSIENTS

4.1. Small-Break (SB) LOCA Phenomena

Although we have not examined an SBLOCA in detail, there are several areas where we expect processes or phenomena that differ from those seen in an LBLOCA. *Natural circulation* through the **loops** could occur. There is still the possibility for voiding in the **core** pressure tubes yielding *stratified flows*. Thus the effects of the horizontal pressure tubes, some of which could have stratification, on natural circulation could be very important. As in an LBLOCA, upon generation of a LOCA signal, the **steam generator** secondary sides are depressurized. In an SBLOCA, *primary to secondary heat transfer* and *condensation with reflux* on the primary side of the steam generators are likely to be more important than in an LBLOCA.

4.2. Other Transients

In the Conceptual Safety Report (Ref. 3), brief descriptions are given for several other transients. Steam line break events were examined for their containment overpressurization potential. In PWRs, steam line breaks are of interest because of the positive reactivity insertion resulting from the severe overcooling. In the CANDU 3, a rapid overcooling event such as a steam line break will result in a negative reactivity insertion.

Loss of flow events including the coastdown of a single primary coolant system pump, the seizure of a single primary coolant pump, and the coastdown of all primary coolant pumps as would occur during a loss of Class IV power event were also briefly discussed in Ref. 3. After initiation of the event, there is a power-to-flow mismatch, which can cause *voiding* in the *core*. Thus there is the potential for a brief *power increase* because of the positive void reactivity. The reactor would trip and power would drop to decay heat values. Stored energy in the core and decay power would cause the primary heat transport system to overheat and overpressurize. As the primary heat transport system dumps heat and the core decay power drops, the primary system cools and depressurizes. In the core, the maximum temperatures reached would depend for the most part on the factors already discussed under LBLOCA phenomena.

5. EXPERTS' REVIEW OF CANDU PHENOMENA AND TRAC MODELS FOR CANDU PHENOMENA

A panel of seven Los Alamos experts with a broad range of PWR and thermal-hydraulic test facility experience reviewed the LBLOCA calculation discussed above. The phenomena listed incorporate their comments. It proved difficult to give each phenomenon a 1-9 ranking as has been done for other reactor types. This was because of the lack of experience and available detailed, quantitative information about CANDU 3 phenomena. The panel was able to identify phenomena that are expected to be the dominant phenomena, important phenomena, phenomena that are less important, and phenomena that are relatively unimportant. Table II summarizes the phenomena and the experts' judgments as to relative importance.

The same panel reviewed TRAC models, based on their experiences and knowledge of the code, for applicability to the CANDU 3 phenomena. The following sections summarize the opinions of the panel with regard to TRAC applicability. The panel consisted of people with detailed knowledge of the models in TRAC as well as people with a thorough knowledge of TRAC integral behavior. Thus, the discussion presented below considers both.

5.1. General

The D₂O properties in the existing heavy-water version of TRAC do not go to a high enough pressure range. A table lookup routine using the AECL D₂O tables could be incorporated into TRAC to provide D₂O properties in the appropriate ranges.

5.2. For Blowdown—Fuel and Core

3D neutronics: There has been considerable work on incorporating 3D neutronics into TRAC for specific applications. These efforts need to be generalized to work with the CANDU 3 configuration.

DNB: The existing TRAC correlations may be adequate for initial work, although it would be desirable to incorporate a CHF correlation specifically developed for CANDU 3 conditions.

Post CHF heat transfer: TRAC is probably adequate as it exists.

Stratified flow: TRAC has a horizontal stratified flow model that was developed for unobstructed pipes. Work will be needed to update this model for stratified flow in a horizontal pipe with rod bundles. Updating the fluid mechanics is likely to be straightforward. Coupling heat structures to different conditions in a stratified 1D pipe may require considerable work.

Circumferential conduction heat transfer in the pressure tubes: This is probably not necessary for blowdown.

Table II
CANDU 3 LBLOCA Phenomena

<u>Component</u>	<u>Phenomena</u>	<u>Blowdown</u>	<u>Reflood</u>
Fuel Rods	Stored Energy	B	A
	Power Gen./ Decay Heat	A	A
	Gap Conductance	C	B
Core	DNB	A	B
	Post CHF HT	A	B
	Rad HT	B	B
	Stratified Flow	A	A
	Cond. HT to Cal. Tube/Azimuthal Cond.	C	B
	Nucleate Boiling	B	B
	Void Dist./Void Generation	A	A
	Entrainment/ Deentrainment	A	A
	Flow Stagnation and Reversal	A	C
Outlet Feeders	Two-Phase Flow	C	B
	Void Generation/ Void Distribution	C	B
	CCFL	D	B

A - Dominant Phenomena
 B - Other Important Phenomena
 C - Less Important Phenomena
 D - Relatively Unimportant Phenomena

Table II (cont.)
CANDU 3 LBLOCA Phenomena

<u>Component</u>	<u>Phenomena</u>	<u>Blowdown</u>	<u>Reflood</u>
Outlet Headers	Phase Separation	B	A
	Deentrainment/ Entrainment	B	B
	Two-Phase Flow	B	B
	Condensation	D	B
Outlet Header interconnects	Two-Phase DP	C	C
Hot legs	Entrainment/ Deentrainment	B	C
	Flow Stagnation and Reversal	B	D
	Void Distribution/ Void Generation	B	C
	Two-Phase Flow	B	B
SGs	Two-Phase DP, Form Losses	B	B
	Flashing	B	C
	Reflux Condensation	D	B
Cold legs	Deentrainment/ Entrainment	B	C
	Flow Stagnation and Reversal	B	D
	Void Distribution/ Void Generation	B	C
	Two-Phase Flow	B	B

**Table II (cont.)
CANDU 3 LBLOCA Phenomena**

<u>Component</u>	<u>Phenomena</u>	<u>Blowdown</u>	<u>Reflood</u>
Pumps	Two-Phase Characteristics	A	C
	Two-Phase DP, Form Losses	B	B
Inlet headers	Phase Separation	B	A
	Entrainment/Deentrainment	B	B
	Two-Phase Flow	B	B
	Condensation	D	B
Inlet feeders	Two-Phase Flow	C	B
	Void Distribution/ Void Generation	C	B
	CCFL	D	B
Pressurizer	Flashing/Steam Expansion	B	C
	Critical Flow in Surge Line	B	C
Break	Critical Flow	B	C
	Flashing	C	C
	Containment Pressure	C	C

Void generation and distribution: For blowdown this is mainly flashing. The existing TRAC models may be adequate for blowdown. This issue should be revisited after code/data comparisons are made.

Nucleate boiling: The existing TRAC models may be adequate in the sense that results are not expected to be strongly influenced by changes in the nucleate boiling model.

Entrainment and deentrainment: For blowdown the existing TRAC models are probably adequate.

Flow reversal and stagnation: Again, the existing TRAC models are probably adequate.

5.3. For Blowdown—Feeders and Headers

Two-phase flow, two-phase pressure drop, void distribution, and generation: The existing TRAC models are probably adequate.

Phase separation: The existing vessel model should be tested with the axis of the cylinder in a horizontal rather than vertical orientation as used in previous applications. It may be adequate for header phenomena during blowdown. The existing vessel model will need to be modified to account for stratified flow or an alternative model will need to be developed. It may be possible to add stratification to a TRAC plenum component.

5.4. For Blowdown—Loop Components

Loop components during blowdown: There is no reason to expect any different phenomena than in a PWR. Therefore, the TRAC models are probably adequate.

5.5. For Reflood—Fuel and Rods

Models for fuel: The horizontal orientation of the fuel and the graphite lubricant may produce a nonuniform gap. There may be a need for work on the gap conductance model though this is likely to be a secondary effect. (TRAC incorporates simple fuel heat transfer models in order to correctly couple fuel thermal effects and thermal-hydraulics. These models do not have the level of detail of dedicated fuel behavior models.)

Reflood model for core during reflood: The existing TRAC models may be adequate for the unheated surfaces. For the rods, everything is questionable. This includes all the models related to water distribution. The nucleate boiling model may be adequate. In defining what needs to be worked on, it will be very helpful to do some comparisons of TRAC with existing models to CANDU component data for a pressure tube. It may be desirable to develop a fine mesh model for reflood. This is necessary for good predictions in PWR reflood. The fine mesh model may be necessary in order to do a good job of predicting quenching.

Radiation heat transfer: Radiation heat transfer may be important. Radiation heat transfer models have been developed for specific TRAC applications. These may need to be generalized.

Phenomena associated with the pressure tube sagging into the calandria tube: If TRAC is to model the effects of pressure tube sagging or ballooning on system behavior, a circumferential conduction and contact conduction mode and activation logic is needed so that the model can be activated using control logic. These may be secondary effects and the final decision on whether to implement them may be made later. It may be more practicable to model these phenomena with a severe accident code rather than a thermal-hydraulics code. The models that affect liquid distribution in the core during reflood should have a higher priority.

5.6. For Reflood—Headers

TRAC has a vessel component that can be used in the horizontal orientation. A stratification model is needed.

5.7. For Reflood—Loop Components

Again, there is nothing apparent at this time that makes us think that the phenomena are different than in a PWR. The TRAC models should be adequate.

5.8. Other Transients

Given the limited information available to us, there do not appear to be any processes or phenomena that are not already covered in the above lists that will require TRAC modifications to predict. The key phenomena requiring code modifications for SBLOCAs as well as for LBLOCAs are expected to be stratification. When code modifications are completed, it would be desirable to assess against integral tests for SBLOCAs and other transients. In particular, it would be desirable to test the stratification models with natural circulation.

6. CAPABILITIES OF AECL CATHENA THERMAL-HYDRAULICS COMPUTER CODE

CATHENA capabilities are similar to the capabilities of the US 1D thermal-hydraulics computer code RELAP5 and to the 1D capabilities of TRAC. Information about CATHENA was taken from Refs. 4, 6, and 7. In addition to 1D capabilities similar to the US codes, CATHENA has models to account for the phenomena that are unique to the CANDU design. These are in three major areas. First, models have been developed to account for the horizontally stratified flow regimes occurring within the pressure tubes containing the fuel bundles. When stratified flow occurs in the pressure tubes, CATHENA couples rod models to the region with the appropriate heat transfer regime based on elevation. Second, CATHENA also has the capability to model the header-to-feeder effects (some feeders nozzles may be submersed and some dry) with stratified flow conditions in the headers. Third, the set of phenomena associated with the sagging of the pressure tube into the calandria tube and subsequent heat transfer to the moderator is another area where CATHENA has models with no counterpart in TRAC or RELAP.

The following description of CATHENA was taken from Ref. 6.

CATHENA is a one-dimensional thermalhydraulics computer code developed at Whiteshell Nuclear Research Establishment primarily to analyze postulated loss-of-coolant accident scenarios for CANDU nuclear reactors. The code uses a nonequilibrium, two-fluid thermalhydraulic model to describe two-phase fluid flow. Conservation equations for mass, momentum and energy are solved for each phase (liquid and vapour). Interphase transfer of mass, momentum and energy is handled by a set of flow regime dependent constitutive relations. As well, flow regime dependent constitutive relations for wall shear specify momentum transfer between the fluid and the pipe surfaces. CATHENA, being a two-fluid code, is able to simulate countercurrent flow.

Like the US codes TRAC and RELAP, CATHENA has component models that may be combined in a modular manner to model an entire plant or test facility. Also, like the US codes, CATHENA has extensive control system modeling capabilities.

CATHENA does not have some of the capabilities of TRAC. In particular, TRAC has a 3D hydrodynamics capability, using the VESSEL component, where the VESSEL can have any orientation, a fine mesh model for following quench progression, and a special reflood model. The VESSEL component is not limited to modeling a reactor vessel with core, but is sufficiently general to model other components where a 3D representation may be appropriate—such as a CANDU header. Appropriate versions of a 3D VESSEL, fine mesh model, and reflood model may be desirable for CANDU 3 analyses. Though TRAC has these models, all of them would require at least some modification to be applicable to the CANDU 3 geometry.

7. CODE DEVELOPMENT PLAN FOR PREPARING TRAC-PF1/MOD2 FOR CANDU 3 CONFIRMATORY CALCULATIONS

Figure 12 shows a preliminary time line for initial CANDU 3 related TRAC-PF1/MOD2 code development. Table III provides summary information for the activities listed in Figure 12. The following sections contain additional detail and discussion about the proposed activities from Fig. 12 and Table III. The priorities given in Table III are based on the results of Task 1.

7.1. D₂O Properties

TRAC-PF1/MOD2 currently has only light-water thermodynamic and transport properties modeled. There is a heavy-water version of TRAC-PF1 that was used for Savannah River analyses that has low-pressure D₂O properties. Both of these versions use curve fits to generate the properties. An alternative approach is used in RELAP5. Table lookup and interpolation routines are used with tabulated properties to obtain thermodynamic and transport properties. Good property tabulations are available for heavy water (Ref. 8). The leader of the project to produce this D₂O property tabulation, P.G. Hill, was a participant in the development of the widely used Keenan, Keyes, Hill, and Moore steam tables (Ref. 9) for light water. The methodology used in the production of these two tables is therefore similar. The NRC has invested considerable resources in the development of the methodology used in RELAP5. The methodology used in RELAP5 can be transferred to TRAC with a relatively modest effort. This appears to be more cost effective than extending the approach used in TRAC-PF1/MOD2 to reproduce the high-pressure D₂O properties. There may be a slight penalty in computer run times in using this table lookup approach.

7.2. Incorporate 3D Neutronics Capability into TRAC

The CANDU 3 reactor has a positive void reactivity coefficient. During some transients, voiding would occur in parts of the core. Because of the CANDU 3 geometry and cooling system hardware configuration, this voiding would not occur in a symmetrical manner. Thus a 3D neutronics capability is needed to accurately predict the power distributions throughout the core during transients.

CATHENA has been externally coupled to a 3D neutronics code to calculate thermal-hydraulic transients with coupled 3D neutronics. This type of external coupling was accomplished using the scripting capabilities of workstations so that the codes could be run iteratively with output from one code becoming part of the input of another code.

TRAC has been coupled to a 3D neutronics code in a special DOE version (TRAC/NEM, now called TRAC/NESTLE) that is applicable to a single facility (Savannah River K Reactor). Thus much of the work to incorporate 3D neutronics into TRAC has already been done. Additional work will be required to generalize the 3D neutronics for applicability to the CANDU 3 design and to ensure that quality assurance and documentation are adequate. In addition, work will be required to prepare cross sections for the CANDU 3D neutronics.

Fig. 12.
Preliminary time line for initial CANDU 3-related TRAC code development.

Table III
Tasks, Estimates and Schedules
Initial TRAC-PF1/MOD2 Development Needs for CANDU Reactor Applications

Priority	TRAC/PF1/MOD2 Development Activities			
	Description	Effort staff months	Duration months	Justification/Notes
High	D ₂ O Properties	2.0	2.0	Key feature of CANDU system. MOD3 ^a currently has low-pressure D ₂ O properties. May implement RELAP5 high-pressure tables
High	Incorporate 3D neutronics into TRAC.	8.0	8.0	A 3D neutronics capability will be necessary for predicting core power distributions during transients. 3D neutronics have been added to TRAC for specialized DOE applications. It will be necessary to modify the 3D neutronics package and install it in the NRC version of TRAC.
High	Develop cross-section library for TRAC 3D neutronics for CANDU 3, test and validate.	21.0	18.0	An accurate cross-section library will be needed to resolve the details of the assymetric power distribution caused by the positive void reactivity during the early phase of transients.
High	Stratified, quasi-1D pressure tube flow including coupling heat structures to regions with different void fractions.	12.0	12.0	Revision of existing models (e.g., stratification and flow in and out of horizontal pressure tubes). Provide capabilities parallel to those in CATHENA. ^b The models will permit faster running than using fully 3D models. The models will expedite sensitivity studies.
High	Stratified flow for 3D horizontal VESSEL component (a) Headers (b) Pressure tube	6.0	10.0	LANL and INEL identified stratified flow in inlet and outlet headers as a key phenomenon. Header modeling would also be applicable to pressure tube. A standalone, 3D pressure tube model could be used to benchmark the stratified, quasi-1D pressure tube model in the full-plant CANDU model.

Table III (Cont.)
Tasks, Estimates and Schedules
Initial TRAC-PF1/MOD2 Development Needs for CANDU Reactor Applications

Priority	TRAC/PF1/MOD2 Development Activities			
	Description	Effort staff months	Duration months	Justification/Notes
High	CANDU CHF correlation	2.0	4.0	Important to calculation of key acceptance parameter, PCT, but level of importance is currently unknown.
Medium	Radiation heat transfer in pressure tube	4.0	12.0	INEL identified incorporation of rod-to-rod radiation heat transfer models as a high priority and rod-to-structure radiation heat transfer as a medium priority. LANL staff currently believe both are medium priority.
Medium	Incorporate boiling heat transfer correlations having a horizontal data base.	3.0	13.0	The current correlations do not have the needed pedigree and demonstrated applicability. The assessment of need is based on past reviews of TRAC where "purity" of code correlations was required.
Low	Circumferential pressure tube conduction	3.0	16.0	CATHENA currently has this capability. INEL identified this effort as a development priority. LANL staff believes that the model may have a small impact on the calculated PCT.
Low	Pressure tube sagging and contact conductance	3.0	15.0	It is not clear, at present, whether accidents within the design basis will result in this phenomena occurring. Meeting notes by Shotkin and Meyer, "Meeting on CANDU Thermal-Hydraulics at Whiteshell" dated November 29, 1993, suggest that a single pipe break in the current design may lead to this phenomena (item 9a). The LANL-assigned priority may be low if it is determined that such events are within the design basis.

Table III (Cont.)
Tasks, Estimates and Schedules
Initial TRAC-PF1/MOD2 Development Needs for CANDU Reactor Applications

Priority	TRAC/PF1/MOD2 Development Activities			
	Description	Effort staff months	Duration months	Justification/Notes
Low	Reflood model improvements	10.0	22.0	LANL believes that CATHENA does not have such models. It is unclear whether such models are needed.
Low	Fine mesh model	6.0	21.0	LANL believes that CATHENA does not have such models. It is unclear whether such models are needed.

Notes:

- a TRAC-PF1/MOD3 limited, thermal-hydraulic analysis code.
b Atomic Energy of Canada, Ltd. thermal-hydraulic analysis code.

The external coupling of thermal-hydraulics and 3D neutronics codes, as done with CATHENA, is certainly viable. We believe that coupling TRAC with a 3D neutronics code internally, as proposed here, is superior. We expect that the internally coupled codes will be easier to use with fewer problems. Also, the 3D neutronics capability can be coupled to TRAC's existing 3D hydrodynamics, allowing an integrated, self-consistent, 3D analysis. Proposed plans for use of TRAC's 3D hydrodynamics for CANDU 3 analysis are discussed below in Sec. 7.4.

7.3. Develop Cross-Section Library for TRAC 3D Neutronics for the CANDU 3, Test and Validate

An appropriate cross-section library will be needed to resolve the details of the asymmetric power distribution caused by the positive void reactivity during the early phase of a transient. This is not TRAC code development per se, but rather part of the CANDU 3 specific input that TRAC/NESTLE will use. This will be done by using a 2D lattice cell model with a many-group cross-section library to generate the few-group cross-section library needed by TRAC/NESTLE for the heavy-water, natural uranium fueled CANDU 3.

7.4. Stratified, Quasi-1D Pressure Tube Flow Including Coupling Heat Structures to Regions with Different Void Fractions

Although the capability exists in TRAC to model the pressure tubes and bundles with 3D VESSEL models, the computational time to run transients would be large relative to using a quasi-1D approach. TRAC currently has a 1D stratified pipe flow model. This model was developed for unobstructed pipes. To model the CANDU 3 pressure tubes, it will be necessary to modify the TRAC 1D stratified flow model to hydrodynamically account for the fuel bundles in the pressure tubes. In addition, a significant effort is expected to be required to couple TRAC heat-structure components with the appropriate regions in stratified horizontal flow. This will give the capability to model CANDU 3 fuel bundles in appropriate groupings so that each group gets the correct heat transfer condition as a function of where the group is relative to the stratified flow interface.

Adding this capability to TRAC will give TRAC a quasi-1D pressure tube/fuel bundle modeling capability similar to the capability of CATHENA. The following section describes development of a standalone 3D pressure tube model that will give a major enhancement to CANDU 3 analysis.

7.5. Stratified Flow for 3D Horizontal TRAC VESSEL Component

Two aspects of CANDU 3 analysis that will certainly benefit from TRAC's 3D hydrodynamics capability are modeling of the headers and modeling of the pressure tubes. (It is also possible that multidimensional effects in the calandria will emerge as an important issue for TRAC analysis, but at least our initial efforts would most likely treat the calandria as essentially a constant boundary condition.)

Both INEL and Los Alamos identified stratified flow in inlet and outlet headers as a key phenomenon. When flow is stratified in the headers, some of the feeders, and consequently the rod bundles cooled by flow through those feeders, will receive very little liquid. The amount of liquid available to cool fuel bundles is very important in determining peak temperatures. Thus, prediction of header stratification and consequent flow differences to feeders connecting at different elevations is crucial.

Use of the 3D hydrodynamics capabilities of TRAC should provide a header modeling capability that is superior to the header modeling capability in CATHENA. TRAC-PF1/MOD2 currently has the numerical capability for a 3D VESSEL component to be oriented in any direction, including horizontally. This means that the acceleration of gravity is handled properly in the 3D momentum equations. TRAC also has models for flow stratification in the VESSEL. However, the flow

stratification logic still assumes a vertical VESSEL, which is adequate for a modest tilt. Currently, there is no stratified flow model for a horizontal VESSEL. (By a "horizontal VESSEL" we mean a TRAC VESSEL component modeled in cylindrical coordinates with its main axis at 90° from the direction of gravity.) The proposed plan is to adapt the present TRAC-P stratification logic to the horizontal orientation. The work plan does not presently include development of a level tracker (such as found in TRAC-B) per se.

We have also considered three other approaches to TRAC modeling of the CANDU 3 headers:

- Use of the 3D VESSEL component with the presently available option of Cartesian coordinates (instead of cylindrical coordinates). This may provide advantages in modeling stratification phenomena. However, Cartesian coordinates do not naturally map onto the header geometry (without extremely fine nodalization). This approach is an alternative which would be further considered if unforeseen difficulties emerge with the cylindrical VESSEL.
- Use of TRAC's existing offtake model for the 1D TEE component. The TEE offtake model was developed to predict flow quality at small breaks in large pipes undergoing horizontal stratified flow. This approach has the advantage of faster running time. However, in addition to the drawbacks inherent in the 1D representation, considerable new development work would be required, because the present offtake model only treats flow from/to the top, side (centered), and bottom of the TEE component.
- The capabilities of TRAC's current PLENUM component could be extended to allow multiple piping connections (essentially the PLENUM is a "zero-dimensional" component), to include stratification modeling. This approach shares both the advantage (fast running time) and drawbacks (lack of dimensionality and new modeling requirements) of using the offtake model.

A standalone 3D TRAC model can simulate details of pressure tube/fuel bundle flow phenomena under partially voided conditions. This would provide additional insight into phenomena as well as provide a useful check on results obtained using the quasi-1D bundle model for CANDU 3 simulations. This model could be driven by appropriate boundary conditions, as could the 1D pressure tube. Also, development of a 3D pressure tube model will be necessary to accommodate most of the reflood-model improvements and the quench front improvements discussed in Secs. 7.11 and 7.12 below.

Alternatively, a single 3D pressure tube model could replace one of the 1D models in the TRAC input deck, running in parallel (geometrically speaking) with the remaining 1D pressure tubes. It is not likely this approach could be extended to many more pressure tubes, as computation time would become prohibitive.

If transient scenarios are to be considered where multidimensional effects in the calandria tank are potentially important (e.g., pressure tube rupture), it would be a straightforward extension of the above ideas to include a 3D VESSEL component to model the calandria tank. In fact, the resulting arrangement would bear considerable resemblance to the TRAC model Los Alamos developed for the Savannah River K Reactor, with the exception that it would be tipped over on its side. In that model, two VESSEL components were used, one for the upper (inlet) plenum and the other for the moderator tank. Connecting these VESSELS are 18 assembly models, each comprised of 1D PIPE components and HEAT STRUCTURE components.

Task 1 did not identify the precise timing of gadolinium arrival at points in the calandria tank as an issue. However, Los Alamos has developed a High Order Godunov (HOG) numerical method for anti-diffusive solute tracking for the Savannah River (DOE) version of TRAC. The HOG

numerics (1D and 3D) were implemented in TRAC and tested against Savannah River experimental data, using TRAC 1D and 3D components. Results were excellent. Incorporation of the HOG numerics in TRAC-PF1/MOD2 is not included in this TRAC development plan. The CANDU 3 version of TRAC would use the existing MOD2 numerics for any solute tracking. If precise gadolinium tracking ever does become an important question for the CANDU 3, the anti-diffusive solute tracking could be incorporated into MOD2.

7.6. CANDU Critical Heat Flux (CHF) Correlation

Implementation of a CHF correlation based on the CANDU fuel bundle geometry, particularly the horizontal orientation, is highly desirable. Although we are uncertain about the effects different CHF correlations may have on peak cladding temperatures (PCT), incorporating a CHF correlation with demonstrated applicability and pedigree for the CANDU 3 geometry is very desirable. Doing this will give a capability that is similar to CATHENA.

7.7. Radiation Heat Transfer in Pressure Tubes

Radiation heat transfer may be important in certain scenarios. A radiation heat transfer model has been developed for a version of TRAC used for the analysis of DOE reactor facilities. Implementation of this model will require that it be reviewed, generalized, and documented. CATHENA has a radiation heat transfer capability to allow simulation of cases where the rod bundle is mostly dry, and radiation heat transfer from rod to rod and from rods to pressure tubes become important. This task will give TRAC a capability similar to the capability of CATHENA. In the context of a 3D pressure tube model, the final capability will more closely model physical processes than the 1D modeling capability in CATHENA.

7.8. Incorporate Boiling Heat Transfer Correlations Having a Horizontal Database

The current TRAC correlations do not have the needed pedigree and demonstrated applicability for the horizontal geometry of the CANDU 3 pressure tubes. The assessment of need is based on past reviews of TRAC where "purity" of code correlations was required.

7.9. Circumferential Heat Conduction

CATHENA has the capability to calculate heat conduction in both radial and azimuthal (circumferential) coordinates. The capability for circumferential conduction was driven by CANDU's horizontal geometry and related stratification effects. TRAC-PF1/MOD2's HEAT STRUCTURE component can calculate heat conduction in radial and axial directions, but not azimuthally. We have assigned circumferential heat conduction a relatively low priority for the TRAC/CANDU development effort (see Tables II and III), but we recognize its potential importance. TRAC modifications may or may not be needed depending upon the scope of transients to be run with a severe accident code, and the desirability for some overlap in thermal-hydraulic code/severe accident code cases.

For extreme transients when the pressure tube sags into contact with the calandria tube, circumferential conduction must be considered. Its impact on other transients should be considered as well. Rather than extend development of the current TRAC HEAT STRUCTURE capability to a third dimension, work already done at Los Alamos for TRAC Savannah River K Reactor modeling could be utilized. Azimuthal conduction can be an important factor in the behavior of the K Reactor assemblies. Los Alamos developed a 3D standalone heat conduction code called HERA, which was integrated into TRAC for 3D heat conduction modeling of the assemblies. It would be most cost effective to generalize this work on the integrated TRAC/HERA code done for DOE to the CANDU 3 development effort.

7.10. Pressure Tube Sagging and Contact Conductance

Again, this is important only for the extreme transients when the pressure tube sags or balloons into contact with the calandria tube. CATHENA currently has this capability. A code calculating pressure tube sagging and contact area was incorporated into CATHENA. In TRAC the capability to model the effects of pressure tube sagging or ballooning on rod heat transfer could be implemented differently (and more simply). This would require a straightforward extension of the existing HEAT STRUCTURE capability. Conductivity and affected surface area could be input to the HEAT STRUCTURE as a function of axial location and temperature, with an appropriate lag function, if necessary. This would allow results from a mechanistic code predicting the heat transfer phenomena associated with sagging or ballooning to be utilized in TRAC to extend the thermal-hydraulic systems analyses into this severe accident regime. This is not intended to replace analyses with a severe accident code. Rather, this could be used to supplement and verify results of a severe accident code for the important case where the transient is expected to be terminated by fuel to moderator heat transfer before the onset of fuel damage. The present work plan does not consider implementation of pressure tube sagging/ballooning in a TRAC/HERA 3D heat conduction model (see Sec. 7.9), but clearly that would be an attractive follow-on effort if funding were adequate.

7.11. Reflood Model Improvements

Reflood models are necessary to obtain good predictions in US PWR reflood cases. It is not currently known whether these will be needed for CANDU 3 LBLOCA calculations. Our understanding of CATHENA is that it does not have such a model. If assessment calculations show the desirability of having a special reflood model, one could be incorporated. The effort estimate is based on Los Alamos' experience in developing the two separate reflood models that are currently in TRAC. Reflood improvements for CANDU 3 would primarily be intended for use with TRAC's 3D hydrodynamics.

7.12. Fine Mesh Model

To predict quench front progression in US PWR reflood, a fine mesh model is necessary. Our understanding of CATHENA is that it does not currently have this capability. It is uncertain at this time whether or not a fine mesh model will be needed. If assessment calculations show the desirability of having a fine mesh model, one can be incorporated. TRAC's HEAT STRUCTURE component currently has the capability of adding extra nodalization (fine mesh) only in the axial direction to resolve the quench front in US PWRs. An analogous capability for CANDU 3 would require a fine mesh nodalization azimuthally, as well as axially.

7.13. Additional Work to Incorporate Code Changes Identified as Necessary During Assessment Activities

Prior experience has shown that the code modification and assessment processes require iterative changes. Thus, we expect that additional code modifications needs will be identified as the program to assess code modification progresses. This activity accounts for that likelihood.

8. DEVELOPMENTAL ASSESSMENT PLAN

A plan for initial code modifications has been developed. The term "developmental assessments" as used here means those assessment calculations, primarily code/data comparisons, done for initial testing and validation, as code modifications are developed. Developmental assessments are usually done using separate-effects or component test data. For CANDU-specific code modifications, the developmental assessments will primarily be against component test data. Component tests, as defined by the AECL, consist of tests of an actual or large-scale model of a particular component with carefully controlled initial and boundary conditions. Appendix A provides descriptions of the AECL test facilities.

TRAC developmental assessment will probably be done against two to three of the more basic tests from the CWIT Facility, and two to three from the LASH facility. The most basic tests from these facilities were similar to separate-effects tests, and appear to provide information suited to fundamental model development and testing. As developmental assessments, the costs of assessment calculations against these tests are included in the code modification plan discussed above.

9. WORK PLAN FOR PREPARATIONS FOR USING TRAC-PF1/MOD2 TO PERFORM CANDU 3 CONFIRMATORY CALCULATIONS

The assessment plan presented in this section considers assessment in a broad sense, including all of the activities needed to prepare TRAC for confirmatory calculations. The plan in this report was developed to cover, in as comprehensive a manner as possible, all of the steps needed to use TRAC-PF1/MOD2 for confirmatory calculations on the CANDU 3 design. This includes database acquisition and review activities, PIRT and CSAU activities, a summary of code modifications to show linkages, CANDU 3 and other CANDU plant calculations related to code assessment, code/data comparisons for experiments done in the AECL component and integral facilities, and NRC support and issue resolution. Figure 13 shows a summary of the schedule and estimated costs in preparation for using TRAC-PF1/MOD2 to perform confirmatory calculations for the CANDU 3. Activities are shown by solid lines and linkages between activities by dashed lines. Table IV provides summary information for the activities listed in Fig. 13. The following sections contain additional detail and discussion about the proposed activities from Fig. 13 and Table IV. Code development and assessment are by their nature iterative. At this point, the initial code modification steps and the assessments necessary to verify those steps have been identified. As code assessment progresses, it is likely that the need for additional code modifications will be identified. These modifications will require additional assessments. The planning presented in this report reflects this iterative nature.

As part of this project, Los Alamos and NRC personnel traveled to AECL facilities at Sheridan Park, Ontario, and Whiteshell, Manitoba, Canada, to learn more about experimental facilities and programs. This assessment plan is based largely on the information obtained in those meetings. Appendix A summarizes information about the AECL test facilities. The AECL test facilities are not CANDU 3 specific, but rather are intended to reproduce phenomena possible in various CANDU plants. Appendix B presents a statement defining the AECL's code validation philosophy as we interpreted it. We believe that this is a satisfactory approach to code validation for CANDU 3 applications given that these test facilities are not CANDU 3 specific. We anticipate using a similar approach to TRAC validation for CANDU 3 confirmatory calculations. In proceeding along this path, questions about process or phenomena specific to CANDU 3 may arise that can only be addressed in a specific manner.

Fig. 13
Summary of schedule and costs.

Table IV
Tasks and Estimates for Preparing
TRAC-PF1/MOD2 for CANDU 3 Reactor Applications

Activities related to the use of TRAC-PF1/MOD2 for CANDU 3 Confirmatory Calculations					
Activity Description	Justification/Need	Interfaces	Basis for estimate	Staff est.	Time frame

Section 7. Code Development Plan for Preparing TRAC-PF1/MOD2 for CANDU 3 Confirmatory Calculations

Code Modifications yielding TRAC-PF1/MOD2 v5.6	These code modifications are detailed separately. The modifications to be made include modifications identified at INEL and LANL. This task includes developing the CANDU 3 cross-section library to be used with TRAC.	This activity is fed by work performed under FINs L2445 and W6155. This activity feeds all of the calculational activities.	The estimates are detailed separately in Ref. 2, the Task 2 report. The 3D neutronics effort is included in this estimate.	55 staff- months	1st year
Code Modifications yielding TRAC-PF1/MOD2 v5.7	Changes to be made include items from the initial work plan, which is included as a separate attachment, code changes that have been previously identified and that can be done if a need for them is established, and changes identified by the preliminary PIRT.	The sources of input for this activity are identified above. The Preliminary PIRT feeds this activity. This activity feeds all of the calculational work done after the completion of this activity.	The estimates are detailed separately in Ref. 2, the Task 2 report.	25 staff- months	2nd year
Code Modifications yielding TRAC-PF1/MOD2 v5.8	This includes code changes identified as needed in the assessment calculations. Prior experience has shown the code modification and assessment process to require iterative changes. This activity accounts for this fact.	Incorporate updates as determined from assessments and support CSAU.	The estimates assume that additional code modification work will be identified during assessment activities.	24 staff- months	3rd and 4th years

Table IV (Cont.)
Tasks and Estimates for Preparing
TRAC-PF1/MOD2 for CANDU 3 Reactor Applications

Activities related to the use of TRAC-PF1/MOD2 for CANDU 3 Confirmatory Calculations					
Activity Description	Justification/Need	Interfaces	Basis for estimate	Staff est.	Time frame

Section 9.1. Acquire, Review, and Understand Plant and Experimental Databases

Review test facilities and data, SAR, supporting documentation, facility drawings; assemble data-base and catalog.	Developing a thorough understanding of the test facilities and test data, both SETs and IETs, and the relationship between these facilities and the CANDU 3 is necessary groundwork for code assessment, PIRT activities, CSAU, and code development. To be useful, the information must be assembled and cataloged.	This activity feeds into almost all of the remaining activities, either directly or indirectly.	We expect that a significant effort will be necessary at the beginning of the program with a lower level of activity through FY 95 and 96 to support other activities.	8 staff-months	1st and 2nd years
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Section 9.2. PIRT and CSAU

Preliminary Phenomena Identification, and Ranking Tabulation (PIRT).	This would be a PIRT containing information about key systems, components, processes and phenomena from AECL documentation. A lack of code sensitivity calculations would limit the completeness of this PIRT. It would still be very useful to the initial phases of the code modification process.	This activity feeds the code development process and a more complete PIRT included in the CSAU process.	Requires development of detailed facility and transient descriptions and sensitivity evaluations. The use of consultants with CANDU experience, the NRC/RES Project Manager, and an ACRS consultant would be desirable.	4 staff-months	1st year
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Table IV (Cont.)
Tasks and Estimates for Preparing
TRAC-PF1/MOD2 for CANDU 3 Reactor Applications

Activities related to the use of TRAC-PF1/MOD2 for CANDU 3 Confirmatory Calculations					
Activity Description	Justification/Need	Interfaces	Basis for estimate	Staff est.	Time frame

Section 9.2. PIRT and CSAU (cont.)

CSAU PIRT	This PIRT would occur late enough in the program that some plant calculations would be available. In addition, increased US experience with the CANDU 3 and related facilities should allow a more accurate evaluation and ranking of key systems, components, processes and phenomena. This more thorough PIRT will be a necessary part of the CSAU.	This activity is fed by the calculations utilizing the TRAC CANDU 3 deck developed from AECL CATHENA input decks as well as the preliminary PIRT. This activity feeds the CSAU activity.	The AP600 and SBWR PIRTs. This could be confirmed with the appropriate NRC Project Manager.	4 staff-months	3rd years
CSAU Study	The CSAU process is a key step in determining margins.	This activity is fed by a number of the other activities including the data-base activity, the PIRT activities, code modifications, and code calculations.	The pioneering LBLOCA CSAU effort cost ~\$2M and the SBLOCA CSAU was \$600-800K (est) but seemed to need more resources. Assumes quantify uncertainty for 1 key transient.	60 staff-months	3rd and 4th years

Table IV (Cont.)
Tasks and Estimates for Preparing
TRAC-PF1/MOD2 for CANDU 3 Reactor Applications

Activities related to the use of TRAC-PF1/MOD2 for CANDU 3 Confirmatory Calculations					
Activity Description	Justification/Need	Interfaces	Basis for estimate	Staff est.	Time frame

Section 9.3. CANDU 3 Input Deck Development and Assessment-Related Plant Calculations

Complete CANDU 3 TRAC input deck based on CATHENA input deck.	INEL personnel, as part of their CANDU 3 preapplication activities, are preparing the portion of a TRAC input deck that contains the geometrical information. This is being done by taking information from the CATHENA input decks supplied by AECL. To complete this input deck, it will be necessary to add control systems and debug.	It is desirable to have an input deck that can be used for testing during the initial code development process. Also, having the capability to make one-to-one CATHENA-TRAC comparisons is desirable.	This estimate is based on prior experience.	3 staff-months	1st year
Quality assurance for the TRAC input deck based on CATHENA input.	In order to verify the TRAC input deck, it will be necessary to create an audit notebook in which the data extracted from the database is organized into the form needed for model development.	This activity is a necessary step in assuring the quality of calculations using this input deck.	This estimate is based on prior experience.	3 staff-months	1st year
Run test cases and sensitivity calculations with 1D CANDU 3 deck, make comparisons to CATHENA calculations.	This will provide feedback to the code developers allowing a more complete understanding of the necessary changes. In order to more fully understand the phenomena involved, including sensitivities, it will be necessary to run a series of calculations.	Results of these calculations will support the code development process and the PIRTs.	We have assumed a small effort.	9 staff-months	2nd year

Table IV (Cont.)
Tasks and Estimates for Preparing
TRAC-PF1/MOD2 for CANDU 3 Reactor Applications

Activities related to the use of TRAC-PF1/MOD2 for CANDU 3 Confirmatory Calculations					
Activity Description	Justification/Need	Interfaces	Basis for estimate	Staff est.	Time frame

Section 9.3. CANDU 3 Input Deck Development and Assessment-Related Plant Calculations (cont.)

Production 1D TRAC model for CANDU 3	It will be desirable to have a 1D TRAC deck that complements the 3D TRAC deck. This deck would serve the need for a fast running deck for running large numbers of cases for use in parametric studies for example.	This deck would be used for some of the SAR counterpart calculations.	The estimate assumes that the 3D TRAC deck has already been created.	6 staff-months	2nd and 3rd years
Quality assurance (QA) for the 1D TRAC input deck to be used for detailed design certification related calculations.	QA activity can overlap the deck development activity somewhat. The schedule estimates reflect this.	This activity is a necessary step in assuring the quality of calculations using this input deck.	Deck QA takes about one-third the time of deck development based on our experience.	2 staff-months	3rd year
Develop the TRAC input deck for the CANDU 3 to be used for design certification related calculations.	A TRAC deck that is finely noded and uses 3D components in some locations will be needed for some design certification related calculations. This input deck will be used where detailed resolution of phenomena is important. This input deck should have noding similar to the RD14 M deck used for integral assessment.	This activity is necessary for the SAR counterpart calculations and plant counterpart calculations.	We have recently completed a TRAC input deck, with appropriate QA, for the AP600 and the cost estimate is consistent with that effort.	12 staff-months	1st and 2nd years
Quality assurance for the TRAC input deck to be used for detailed design certification related calculations.	QA activity can overlap the deck development activity somewhat. The schedule estimates reflect this.	This activity is a necessary step in assuring the quality of calculations using this input deck.	Deck QA takes about one-third the time of deck development based on our experience.	4 staff-months	2nd year

Table IV (Cont.)
Tasks and Estimates for Preparing
TRAC-PF1/MOD2 for CANDU 3 Reactor Applications

Activities related to the use of TRAC-PF1/MOD2 for CANDU 3 Confirmatory Calculations					
Activity Description	Justification/Need	Interfaces	Basis for estimate	Staff est.	Time frame

Section 9.3. CANDU 3 Input Deck Development and Assessment-Related Plant Calculations (cont.)

Set up, run, and document CANDU 3 counterpart transients for two of the RD14/RD14M transient cases.	Plant counterpart calculations are important for understanding integral test facility/plant phenomenological similarities and differences.	This activity supports code assessment and PIRT activities.	We estimate 6 staff-months for the first calculation and 4 staff-months for the second calculation.	10 staff-months	2nd and 3rd years
Develop TRAC input deck for Wolsung plant.	Plant transients are one of the most valuable sources of scaling information. AECL has used a small-break LOCA in the Wolsung plant for code assessment. If conditions during the plant transient are adequately known, we believe that the effort to develop the input deck and run the transient will be worthwhile.	This set of activities provides information that can be useful for code assessment and CSAU.	The estimate reflects a factor for experience. Also having audit notebooks for CANDU 3 in electronic form will facilitate developing an input deck for another CANDU plant.	9 staff-months	2nd year
QA Wolsung deck.	Verification of an input deck is a necessary part of developing a deck.	This activity is a necessary step in assuring the quality of calculations using this input deck.	Deck QA takes about one-third the time of deck development based on our experience.	3 staff-months	2nd year
Wolsung transient calculation.	This calculation should provide valuable scaling information and a check between integral facility and plant phenomena.	This activity produces information useful to code assessment and CSAU.	The staffing estimate assumes an experience factor.	3 staff-months	3rd year

Table IV (Cont.)
Tasks and Estimates for Preparing
TRAC-PF1/MOD2 for CANDU 3 Reactor Applications

Activities related to the use of TRAC-PF1/MOD2 for CANDU 3 Confirmatory Calculations					
Activity Description	Justification/Need	Interfaces	Basis for estimate	Staff est.	Time frame

Section 9.3. CANDU 3 Input Deck Development and Assessment-Related Plant Calculations (cont.)

Develop and QA detailed, 3D bundle model.	This deck would consist of a detailed 3D bundle model with inlet and outlet feeder tubes. The conditions at the feeders would be taken from plant calculations.	This activity would provide a check on the results from simpler models during partially voided conditions.	This should be a relatively straight-forward model to develop and QA.	4 staff-months	2nd and 3rd years
Detailed bundle calculations using stand-alone 3D bundle model.	This activity would provide a check on results from other calculations for a variety of partially voided conditions.	Information from these calculations would be a useful check on other calculational results.	This activity may require a large number of relatively simple runs.	6 staff-months	4th year

Section 9.4. Code/Data Comparisons for Component and Integral Effects Tests

Develop CWIT and LASH input decks.	Component transient tests provide a link between large scale components and integral tests. These will be the base input decks for the assessments against component tests. Development of an audit notebook will be part of this activity.	This activity is an important part of the assessment activities.	These input decks should be simple to develop relative to an integral test facility.	2 staff-months	1st year
TRAC input deck quality assurance for CWIT and LASH decks.	Input deck verification is an essential step in assuring the quality of calculations.	This is an essential step in assuring the quality of calculations using the input decks.	The estimate reflects the relatively simple nature of the input decks.	1 staff-month	1st and 2nd years

Table IV (Cont.)
Tasks and Estimates for Preparing
TRAC-PF1/MOD2 for CANDU 3 Reactor Applications

Activities related to the use of TRAC-PF1/MOD2 for CANDU 3 Confirmatory Calculations					
Activity Description	Justification/Need	Interfaces	Basis for estimate	Staff est.	Time frame

Section 9.4. Code/Data Comparisons for Component and Integral Effects Tests (cont.)

Set up, run, and analyze CWIT and LASH transient tests chosen for assessment.	Component transient tests provide a link between large scale components and integral tests.	These calculations feed code development, calculations of RD-14 and RD-14M tests and CSAU.	Assumes 10-14 calculations, 1-month effort estimated for 1st of kind calculations, less for subsequent calculations.	8 staff-months	2nd year
Develop RD14 and RD14M TRAC input decks.	These will be the base input decks for the assessments against integral tests. Development of an audit notebook that contains the information extracted from the database will be part of this activity.	This activity is an essential part of the assessment activities.	Development of an input deck for an integral effects facility is generally simpler than for a plant.	9 staff-months	1st and 2nd years
RD14 and RD14M TRAC input deck quality assurance.	Verification of an input deck generally takes about one-third as long as to originally create the input deck. This task can overlap the input deck development. The elapsed time reflects this.	This is an essential step in assuring the quality of calculations using the input decks.	Reflects a time of about one-third the development time.	3 staff-months	2nd year
Set up, run, and analyze RD14 and RD 14M transient tests chosen for assessment from AECL tests.	We anticipate running 13-18 transients. The selection of transients is detailed in the report body.	This is the heart of the assessment activities and would feed code development and CSAU.	Four months are estimated for first of kind transients and three months for additional transients.	60 staff-months	2nd and 3rd years

Table IV (Cont.)
Tasks and Estimates for Preparing
TRAC-PF1/MOD2 for CANDU 3 Reactor Applications

Activities related to the use of TRAC-PF1/MOD2 for CANDU 3 Confirmatory Calculations					
Activity Description	Justification/Need	Interfaces	Basis for estimate	Staff est.	Time frame

Section 9.4. Code/Data Comparisons for Component and Integral Effects Tests (cont.)

Set up, run, and analyze RD14 and RD 14M transient tests dedicated to NRC design certification.	We anticipate the potential need for tests that address specific NRC concerns. Code calculations would be desirable for these tests.	These would probably feed issue resolution.	We have assumed 4 tests and an experience benefit.	12 staff-months	3rd and 4th years
Develop TRAC input deck for AECL Pressure Tube Circumferential Temperature Distribution test apparatus.	This will be the base input decks for the assessments against AECL Pressure Tube Circumferential Temperature Distribution tests. Development of an audit notebook will be part of this activity.	This activity depends upon the decision of whether or not to proceed with modifying TRAC to handle pressure tube sagging/ballooning conditions.	This input deck should be simple to develop relative to an integral test facility deck.	2 staff-months	2nd year
AECL Pressure Tube Circumferential Temperature Distribution test apparatus TRAC input deck QA.	Input deck verification is an essential step in assuring the quality of calculations.	This is an essential step in assuring the quality of calculations using the input deck.	The estimate reflects the relatively simple nature of the input decks.	1 staff-month	2nd year
Set up, run, and analyze AECL Pressure Tube Circumferential Temperature Distribution test apparatus tests chosen for assessment.	Component transient tests provide a link between large-scale components and integral tests.	If we analyze cases with pressure tube sagging, ballooning conditions these tests provide the data for code verification.	Assumes 4 calculations, 2-month effort estimated for 1st of kind calculations, 1 for subsequent calculations. Phenomena are assumed to be relatively complex.	5 staff-months	3rd year

Table IV (Cont.)
Tasks and Estimates for Preparing
TRAC-PF1/MOD2 for CANDU 3 Reactor Applications

Activities related to the use of TRAC-PF1/MOD2 for CANDU 3 Confirmatory Calculations					
Activity Description	Justification/Need	Interfaces	Basis for estimate	Staff est.	Time frame

Section 9.5. NRC Support and Issue Resolution

NRC Support and Issue Resolution.	We anticipate the need for NRC support and time devoted to the resolution of unforeseen issues.	Tasks under this activity could feed any of the other activities.	The estimate is based on experience with other programs.	24 staff-months	1st - 4th years
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9.1. Acquire, Review, and Understand Plant and Experimental Databases

To modify a thermal-hydraulics computer code for a particular application, assess the modifications, develop input decks, and quantify margins, it is necessary to have considerable knowledge about the facility and related test facilities. The initial task in the proposed work plan is a review of test facilities and data, the Safety Analysis Report (SAR), supporting documentation, and facility drawings. To use these materials they must be assembled and cataloged. The purpose of this activity is to develop a thorough understanding of the test facilities and test data and the relationship between these facilities and the CANDU 3. The test facilities include separate-effects test facilities, component test facilities, and integral test facilities. We obtained some preliminary insight regarding several of these facilities and test programs from meetings with the AECL. A detailed appraisal of the suitability of specific tests for assessment purposes would be a part of this task. An appraisal of this type would include a review of phenomena in the test facility and linkages between phenomena in the test facility and the CANDU 3 plant. Completeness of test data and procedures would also be reviewed. Although an initial and preliminary appraisal of tests was done for this report and is reflected in later sections of this report, another, more in-depth iteration will be required to develop the detailed information needed to accurately estimate programmatic costs. This database acquisition and review activity is necessary ground work for code assessment, PIRT activities, CSAU analysis, and code development. This activity feeds almost all of the other tasks, either directly or indirectly. We expect that a significant effort will be needed at the start of the program with a lower level of effort running through the remainder of the initial 2 years of the program.

9.2. PIRT and CSAU

PIRT development activities are identified at two times during the project. The information generated in a PIRT process is needed throughout the program. However, the accuracy of a PIRT is a reflection of the plant-specific expertise of the participants in the PIRT process. Developing a PIRT that is accurate requires detailed knowledge of the plant, the key systems and components, and the key processes and phenomena. This knowledge comes from experience in the analysis of the plant, including sensitivity calculations, and analysis of related experiments. Early in a program the expertise is limited. Thus, it is desirable to repeat the PIRT activity at several points in the program. With each iteration it should become more refined. The initial code modification plan presented previously used a preliminary PIRT prepared as part of the planning activities in Task 1. This PIRT was not particularly discriminating in the identification of the most important phenomena, yet provided useful information for planning initial code modifications. We believe the initial PIRT has identified several areas of needed code improvement (e.g., stratified flow models and coupled 3D neutronics and thermal-hydraulics) and that these initial findings will not change in subsequent PIRT revisions. After these modifications are completed and assessed, another PIRT, which should be more accurate because of increasing experience with the CANDU 3, when coupled with assessment results, will provide a sound basis for planning additional code modifications. The PIRT identified at the beginning of the CSAU task is intended to provide necessary input to the CSAU. In carrying out these PIRT activities, it would be very desirable to utilize outside expertise. The use of consultants with CANDU experience, the NRC/RES Project Manager, and an ACRS consultant would be desirable, particularly for the final PIRT done to support the CSAU. In addition, we are hopeful that the extensive insight of AECL staff, and perhaps staff of members of the CANDU Owners Group, might be structured into PIRT-like documentation that can be used to compare and check the NRC-sponsored phenomena and ranking efforts.

The CSAU methodology was developed by the NRC and its contractors and consultants to quantify uncertainties for a given code for a particular facility and a particular scenario. As noted in Ref. 10, "The methodology is structured, traceable, and practical, as is needed in the regulatory

arena. The methodology is systematic and comprehensive as it addresses and integrates the scenario, experiments, code, and plant to resolve questions concerned with: (a) code capability to scale-up processes from test facility to full-scale nuclear power plants; (b) code applicability to safety studies of a postulated accident scenario in a specified nuclear power plant; and (c) quantifying uncertainties of calculated results."

The CSAU process is a key step in determining margins. Doing a CSAU requires a significant effort. Many of the other tasks defined in the proposed work plan feed the CSAU task. Thus, the CSAU activity must occur toward the end of the program.

9.3. CANDU 3 Input Deck Development and Assessment-Related Plant Calculations

The development of input decks for full-scale plants and the use of these decks for plant calculations is an important part of the broader process of code assessment. The process of preparing input decks is valuable beyond the obvious end product. Preparation of an input deck requires the preparer to understand the details of the plant. Plant calculations are important as a way of testing code modifications. Plant calculations are also important for developing an understanding of phenomena. Plant calculations that have counterparts in an integral effects test program are useful for relating plant and test facility phenomena. Sensitivity calculations using a plant model are needed to provide the information necessary for obtaining good discrimination of the importance of phenomena in a PIRT. Calculations using plant decks are also an essential part of the PIRT process. Calculations of actual plant transients can be valuable sources of information on how phenomena and code predictions of those phenomena change with scale. The input deck development and assessment related plant calculation tasks are detailed below.

9.3.1. Complete CATHENA Equivalent CANDU 3 TRAC 1D Input Deck

As part of their CANDU 3 preapplication activities, INEL personnel prepared the portion of a TRAC input deck that contains the geometrical information. This was done by taking information from the CATHENA input decks supplied by AECL. To complete this input deck, it will be necessary to add control systems and to debug. In testing during the initial part of the code development process, it will be desirable to have a plant deck. This input deck will also be used for sensitivity calculations to support the CSAU PIRT. In addition, having the capability to make one-to-one TRAC-to-CATHENA comparisons may be desirable at some point.

9.3.2. Quality Assurance (QA) for the TRAC Input Deck Based on CATHENA Input

Checking an input deck is a necessary step in assuring the quality of calculations using the input deck. Because the input deck produced from CATHENA input was not developed from plant drawings and supporting documentation, with the intermediate step of producing an audit notebook, it will be necessary to review plant drawings and documentation and produce an audit notebook as part of the QA process. Thus, the QA process will take longer relative to the complexity of the input deck than for other input decks.

9.3.3. Run Test Cases and Sensitivity Calculations with 1D CANDU 3 Deck and Make Comparisons to CATHENA Calculations

The initial set of code modifications is designed to give TRAC capabilities that are at least equivalent to CATHENA capabilities. To verify the adequacy of the models put into TRAC, a useful initial step is to compare to CATHENA results.

To produce a PIRT with good discrimination in the relative importance of phenomena, it is necessary that the expert analysts have sufficient information. Sensitivity calculations can provide much of this information. Thus, it is important to have an input deck that can be used for CANDU 3 calculations early in the program.

9.3.4. Produce Production 1D TRAC Model for CANDU 3

We currently envision the need for several TRAC input decks for the CANDU 3 to use in performing calculations related to design certification. One of these decks would be a relatively detailed model with 3D vessel components used for the headers. The other input deck would use all 1D components. This deck would be faster running and thus better suited for running scoping and sensitivity calculations. In estimating the time needed to complete this input deck, we have assumed that the more detailed input deck with 3D headers will be completed and the QA on it finished before beginning the input deck with 1D components.

9.3.5. QA for the Production 1D TRAC Input Deck

In the schedule for this we have assumed that deck QA can begin before the completion of the input deck.

9.3.6. Develop the Detailed TRAC Input Deck with 3D Headers

A detailed TRAC input deck will be required for key calculations related to code assessment and for design certification related calculations. In estimating the development time for this input deck, we have assumed that this will be a first of kind input deck and that even seemingly minor details will be incorporated. Modeling compromises will be avoided to the extent possible, even though additional modeling complexity will result.

9.3.7. QA for the Detailed TRAC Input Deck with 3D Headers

This activity is a necessary step in assuring the quality of calculations using this input deck. The time estimate is based on experience with a relatively complicated and detailed AP 600 TRAC input deck. The time estimate also assumes that the audit notebook will be in electronic form.

9.3.8. Plant Counterpart Calculations

Plant counterpart calculations, where plant transients are run that have counterparts in integral facility tests, can be very useful for determining similarities and differences between phenomena occurring in a full-scale plant and those occurring in a scaled integral test facility. These calculations support code assessment and PIRT activities.

9.3.9. Develop TRAC Input Deck for Wolsung Plant

One of the more useful forms of assessment information, when available, are plant transients. Plant transients are valuable supplements to integral facilities tests. Integral facilities tests typically have much better instrumentation and cover a much broader spectrum of events. Plant transients have the advantage of being at full scale. Thus, calculations of plant transients can be helpful in resolving scaling issues between full-scale plants and integral test facilities. Wolsung is a plant that experienced a small-break loss-of-coolant event when a liquid relief valve opened at full power. In developing this input deck we have assumed that experience in developing a CANDU 3 input, and the availability of an audit notebook for the CANDU 3, will speed the development of the Wolsung input deck.

9.3.10. QA Wolsung Input Deck

This step is the necessary verification of the Wolsung input deck needed to assure the quality of calculations using the deck. The staff estimate is based on experience with other complex input decks.

9.3.11. Wolsung Transient Calculation

The justification for doing this transient is discussed in Sec. 9.3.9 above. Results of this calculation provide a link between a full-scale plant and integral facility tests. Results from this calculation will be valuable for code assessment and for the CSAU.

9.3.12. Develop and QA Detailed, 3D, Standalone Bundle Model

As a supplement to plant calculations, we believe that the development and use of a detailed 3D bundle model is desirable. This model would use a 3D TRAC VESSEL component to represent a pressure tube with relatively fine noding. Each of the rods would be represented by a TRAC heat structure component. Inlet and exit conditions would be extracted from plant calculations. This model would be particularly useful as a check on calculations for the bundles using simpler models during partially voided conditions. It should allow a more detailed understanding of pressure tube/bundle phenomena for partially voided conditions to be attained. These conditions prevail through most design basis events so a more thorough understanding of the phenomena and their effects on system behavior is desirable.

9.3.13. Detailed Bundle Calculations Using 3D Standalone Model

These calculations will be a useful check on modeling of the bundles.

9.4 Code/Data Comparisons for Component and Integral Effects Tests

Code assessment is sometimes regarded primarily as code/data comparisons for integral effects tests. In this report we have taken a broad view of code assessment, including all of the activities, with the exception of code modifications, which were dealt with separately as Task 2, needed to prepare TRAC to perform confirmatory calculations related to design certification for the CANDU 3 design. In this section the tasks related to code/data comparisons for component tests and integral effects tests are discussed. Given the database available, assessments against transient component tests, as well as integral tests, are included. Because the tests available from RD-14 and RD-14M are not CANDU 3 specific, we believe that it is desirable to follow a code validation philosophy similar to the AECL philosophy given in App. B, and use both transient component tests and integral tests for code validation.

9.4.1. Develop Input Decks for the AECL Component Test Facilities Related to Design Basis Events

A description of the component test facilities was given in App. A. Tests from the CWIT and LASH facilities provide full-scale validation for the stratification phenomena that can occur in fuel channels and headers during transients with ECI.

Model development will be done for the CWIT and LASH facilities. The development of an audit notebook will be part of the TRAC input deck development. The audit notebook is an intermediate step between data extraction and input deck development where data extracted from facility drawings and supporting facility documentation is reduced to the form needed for the TRAC input deck. The audit notebook will be produced in a computerized form.

9.4.2. Component Test Facility TRAC Input Deck QA

This is an essential step in assuring the quality of calculations using the input decks.

9.4.3. Set Up, Run, and Analyze Component Transient Tests Chosen for Assessment

Six to eight transients from the CWIT facility and four to six from the LASH facility will be selected to produce adequate depth and breadth coverage of phenomena. Before we finalize selections, it will be necessary to examine the pertinent data reports. Sufficient tests will be selected to provide coverage for the key processes and phenomena identified in the PIRT activity.

9.4.4. Develop Input Decks for the AECL Integral Test Facilities RD-14 and RD-14M

A description of the RD-14 and RD-14M facilities is given in App. A. Model development will be done for both RD-14 and RD-14M. Use of tests from both facilities will probably be required to obtain the breadth of tests desired, i.e., processes and phenomena. Because the differences between these two facilities are in the headers, feeders, and channels, there will be considerable overlap between input models for RD-14 and RD-14M. The development of an audit notebook will be part of the TRAC input deck development. The audit notebook is an intermediate step between data extraction and input deck development where data extracted from facility drawings and supporting facility documentation is reduced to the form needed for the TRAC input deck. The audit notebook will be produced in a computerized form. Development of an input deck for an integral effects test facility is generally simpler than for a plant. In estimating staff requirements we regarded the two input decks as being the equivalent to one and one-half new input decks because of the commonality between the two decks. The estimate was based on our experience in developing input decks for other integral test facilities.

9.4.5. RD-14 and RD-14M TRAC Input Deck QA

This is an essential step in assuring the quality of calculations using the input decks.

9.4.6. Set Up, Run, and Analyze RD-14 and RD-14M Transient Tests Chosen for Assessment from AECL Tests

We anticipate running 13 to 18 transients plus steam generator and pump characterization tests. Before finalizing selections it will be necessary to examine the pertinent data reports. Sufficient tests will be selected to provide coverage for the key processes and phenomena identified in the PIRT activity.

9.4.7. Set Up, Run, and Analyze RD-14 and RD-14M Transient Tests Dedicated to NRC Design Certification

The potential exists for tests designed to address specific NRC concerns. Code calculations would be desirable for these tests. These tests and calculations for these tests would be in support of issue resolution.

9.4.8. Develop Input Decks for the AECL Pressure Tube Circumferential Temperature Distribution Test Apparatus—A Component Test Facility

A description of the component test facilities was given in App. A. Assessment against data from this test facility will be done if needed. The phenomena investigated in this test facility apply to transients without ECI. If the decision is made to modify TRAC to model the phenomena associated with pressure tube sagging/ballooning, assessment will be done against the tests from this facility.

9.4.9. TRAC Input Deck QA for AECL Pressure Tube Circumferential Temperature Distribution Test Apparatus

This is an essential step in assuring the quality of calculations using the input decks.

9.4.10. Set Up, Run, and Analyze Tests from AECL Pressure Tube Circumferential Temperature Distribution Test Apparatus

If the decision is made to modify TRAC to model the phenomena associated with pressure tube sagging/ballooning, TRAC should be assessed against the four tests from this test facility.

9.5. NRC Support and Issue Resolution

We have included NRC support and issue resolution in this code validation plan. Although not a direct part of the code validation program, it is included as an essential part of the total program. Including NRC support and issue resolution allows us to more accurately estimate the total cost of the program.

10. CONCLUSIONS

A detailed work plan for modifying and assessing TRAC-PF1/MOD2 for CANDU 3 analysis has been developed under FIN W6155. This modification and assessment plan includes descriptions of specific tasks needed to address the TRAC modification and assessment requirements, and schedule and staffing estimates for those tasks. There remain uncertainties as to the ultimate need for some of the tasks; the code modification and development plans take into account the uncertainties and clearly identify them. This plan considers assessment in a broad sense, including not only comparisons of code calculations to experiments, but also activities such as a CSAU evaluation; calculations of transients in the full-scale plant that have counterparts in integral facilities tests; and comparisons of code calculations to actual plant transients. Information was provided by the AECL about their test facilities. We believe, based on our interactions with the AECL and the documentation provided to us, that the data from AECL test facilities will be adequate for code assessment for the CANDU 3 application. The AECL test facilities and test programs are of high quality and provide an extensive database suitable for code assessment. This plan includes assessment calculations against data from AECL component and integral test facilities.

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APPENDIX A

CANDU-RELATED EXPERIMENTAL FACILITIES

AECL has facilities for separate-effects tests, component tests, and integral effects tests (Ref. 6). Separate-effects test facilities are used to produce fundamental information about, at most, a few phenomena. Typically, separate-effects test facilities are designed so that initial and boundary conditions can be directly controlled. Component test facilities use large-scale models of actual plant components. Most of the AECL component effects test facilities simulate not just a single component, but in some form, connecting components, as well. Test programs include both tests designed to produce quasi-steady phenomena, similar to what might be obtained in a separate-effects test facility, and transient tests that simulate the performance of the modeled components under plant-like transient conditions. Quasi-steady data from component tests will be used primarily for developmental assessment. Some data from component transient tests will be used for component assessment and these are identified in the code/test comparison part of the assessment plan presented in this report. Integral test facilities include RD-14 and RD-14M, the latter being a multichannel modification of the former. The AECL philosophy for validating codes is also discussed.

A.1. Facilities and Test Programs for Assessment

The initial code modifications planned for TRAC-PF1/MOD2 deal largely with problems associated with horizontally stratified flow—both in the pressure tubes and in the headers, as discussed previously. Thus most of the assessment calculations will be simulations of tests from the appropriate component test facilities transient tests and from integral effects test facilities RD-14 and RD-14M. The component test facilities are the Cold Water Injection Test (CWIT) Facility and the Large-Scale Header (LASH) facility. Under conditions of extreme heating in the pressure tubes, sagging of the pressure tubes, radiation heat transfer, and circumferential conduction become important. The models for these phenomena will be verified against tests from the Pressure Tube Circumferential Temperature Distribution Tests apparatus. Brief descriptions of these test facilities as taken from AECL documentation follow.

A.1.1. Cold Water Injection Test Facility

The overall objectives of the CWIT testing, as presented by the AECL, are to (1) study two-phase phenomena that may occur in CANDU reactor feeders and channels under upset scenarios such as emergency coolant injection under LOCA conditions and fuel cooling in the absence of forced flow, and (2) to provide a data base for the development and verification of the channel ECI models in LOCA codes.

The following description of the CWIT facility was taken from Ref. 6:

The CWIT test facility at Stern Labs Inc. consists of two 6-m long horizontally mounted heated channels, at different elevations, connected to inlet and outlet headers by 50-mm and 75-mm steel pipes representing CANDU feeders. The channels are connected to the feeder piping through "off-set" end-fitting simulators. Each channel consists of a 100 mm diameter Zircaloy tube surrounding a 6-m long fuel element simulator comprised of thirty-seven 13 mm diameter indirectly heated rods. Blowdown and refill by emergency coolant injection can be initiated from one or both headers and varied by selecting different sized blowdown and injection orifices.

There are over 250 channels of instrumentation in the facility consisting of thermocouples, differential and absolute pressure transducers, flowmeters, and a three-beam gamma densitometer.

The facility is a full geometrical scale model of a CANDU reactor channel-feeder system. One of the channels is located at the minimum header to channel vertical elevation change and one of the channels is located at the maximum header to channel vertical elevation change for an existing CANDU plant. Both axial and radial power distributions within the fuel bundles are based on plant values.

A variety of tests have been performed in the CWIT facility. These include channel/feeder refill, flow stratification, and single-channel flow stability tests. Break location and size, the location for coolant injection and injection rate and power were varied in a series of tests in the CWIT facility.

A.1.2. Large-Scale Header Test Facility

The overall objective of tests in the LASH facility, as presented by the AECL, is to study the behavior that may occur in a CANDU header/feeder system under two-phase flow conditions and blowdown/refill conditions. This was done to (1) provide an improved understanding of the flow behavior of a CANDU header/feeder system under postulated accident conditions, (2) identify phenomena that occur during postulated accident conditions, (3) use this information in deriving header models, and (4) provide a database for code validation.

The following description of the LASH facility was taken from Ref. 6:

The LASH test facility at Stern Laboratories Inc. consists of an inlet and an outlet horizontal header connected by 30 feeders. The inlet and outlet horizontal headers are 325 mm ID and 4.2 m long, half-length Pickering nuclear generating station headers. Vertical turrets (0.325-m I.D.) are attached to the ends of each header and connected to the top of each turret is a mixing device that is supplied with steam and water mixtures. Injection can be to either or both turrets of the inlet header. The feeders consist of vertical and horizontal sections of 50-mm I.D. pipe connected along the length of the headers in six groups of feeder banks. Each bank has five feeders connected at different angular orientations to the headers; two feeders are attached at 90°, two at 45°, and one is downward oriented. Different angular arrangements are present in some CANDU header/feeder systems, but this facility was expected to produce similar phenomena. Each feeder has an unheated horizontal section located between 8.6 and 10 m below the header elevation to hydraulically simulate the channels. The unheated horizontal sections within the same bank are each at different elevations.

The facility was instrumented extensively, with over 300 measurement channels available. Water level in headers was inferred using differential pressure rakes and conductivity probe assemblies installed in the headers. There were 20 single-beam gamma-densitometers located near the top of the inlet feeders at four of the feeder banks. The feeder volumetric flows were measured by turbine flow meters installed in the horizontal feeder sections. The steam flow to the inlet header was measured using a venturi meter, and the injected water flow rate was measured by an orifice plate. Fluid and surface temperatures were measured at various locations in the loop. As well, the header-to-header differential pressure and the differential pressures across the horizontal and selected vertical feeder sections were monitored.

Test series include (1) two-phase injection tests, which had as their purpose to (a) study the flow behavior with steady-state or near steady-state two-phase injection into the inlet header, and (b) obtain data for the onset of vapor pull-through and liquid entrainment in an inlet feeder; and (2) blowdown/refill tests, which had as their purpose to (a) simulate conditions that may occur in a

CANDU header/feeder system during certain accident scenarios, and (b) study the refill behavior during cold-water injection with various break sizes and locations.

A.1.3. Pressure Tube Circumferential Temperature Distribution Tests 1-4

The objective of these tests was to study the behavior of CANDU fuel channels for postulated accident conditions where pressure tube to moderator heat transfer is important. The following description of the Pressure Tube Circumferential Temperature Distribution test apparatus was taken from Ref. 6. Tests from this facility are applicable to conditions that may arise for transients with an assumed ECI system failure.

The tests were performed to measure the circumferential temperature distribution developed on the pressure tube of a heated CANDU-type channel subjected to stagnated flow. The apparatus consisted of a 2.29 meter horizontal CANDU-type channel with one end closed to ensure flow stagnation. The other end was connected to a vertical 24.3 mm ID pipe linked to a surge tank which provided pressure regulation. The channel contained 36 indirect heaters grouped into 3 rings surrounding a central tube. The ring power distribution roughly corresponded to that of a reactor fuel bundle. The pressure tube was surrounded by a calandria tube and the entire arrangement submerged in water to simulate conditions in the calandria. Two different moderator temperatures, two different primary pressures and two different channel powers were used for the four tests that were conducted.

A.1.4. AECL Integral Test Facilities RD-14 and RD-14M

The objectives of testing in RD14-M, as presented by the AECL, are to (1) provide integrated experimental data on thermal-hydraulic behavior in a multiple-channel test facility; (2) improve understanding of the underlying physical phenomena governing behavior, (3) facilitate verification of computer codes, and (4) enhance the ability to predict behavior in reactor specific geometries.

The following description of the RD14 facility comes from Ref. 6:

The RD14 facility is a pressurized-water loop (10. MPa nominal) with the basic "figure-of-eight" geometry of a CANDU reactor at full (1:1) vertical scale. It has two 6 metre long, 5.5 MW (max) horizontal channels connected to end-fitting simulators representing two passes through a reactor core. Each channel contains 37 electrically heated fuel-element simulators with almost the same heat capacity as reactor fuel.

The RD-14M facility was created by replacing the two RD-14 pressure tubes containing 37 simulated fuel pins each with 10 fuel channels containing 7 pins each. Each of the 10 channels has individual inlet and outlet feeders connected to the headers. The elevations of the channels and the axial and azimuthal locations of the header to feeder connections were chosen to simulate header stratified flow effects of the full-scale CANDU. This was done so that interactions between parallel channels could be studied in thermosiphoning (natural circulation) and LOCA transients. Design features of the RD-14M facility include full elevation changes between major components, 10 full-length electrically heated channels, simulated end fittings, full-length feeder pipes, full-height steam generators, blowdown/ECI and natural circulation simulation, extensive instrumentation, and dedicated data-acquisition system. The facility is heavily instrumented with two-beam, three-beam, and single-beam gamma densitometers, conductivity and fiber optic probes for local measurements, pressure drop and pressure measurements, turbine flow meters, orifice plate flow meters, thermocouples, and resistance temperature detectors.

The RD-14M facility is a full-height, full-pressure facility. It was designed to preserve dynamic similarity with a full-scale CANDU primary heat transport system based on a developed set of scaling criteria. Where scaling criteria could not be applied, past experience and engineering judgment were used to provide a conservative component design. Test series have included (1) natural circulation tests, for (a) partial inventory, and (b) transition to thermosiphoning (natural circulation); (2) LOCAs, including (a) small-break, (b) critical-break, and (c) large-break sizes; and (3) flow stability tests. All tests have been extensively documented although only selected tests have been analyzed.

In addition, the AECL has done significant work to characterize RD-14M pumps, steam generators, and end fittings. When modeling this facility, it will be very useful to perform model validation against data from these characterization tests.

APPENDIX B

CODE VALIDATION PHILOSOPHY

AECL explicitly rejects the concept that the RD-14M facility is "prototypic" of any CANDU reactor. This is contrary to US practice where facility prototypicity is promoted. The AECL does state that information from RD-14M improves "understanding of underlying physical phenomena governing behavior." The CATHENA (AECL's best-estimate thermal-hydraulics code) adequacy logic consists of the following elements. First, closure models and correlations having appropriate pedigree, applicability, and fidelity are used. These are based, in part, on CANDU specific geometries and tests, e.g., horizontal fuel channels. Second, full-size component tests are conducted for CANDU-unique components, i.e., the fuel channel, headers, and end fittings. Although atypicalities exist, efforts are made to characterize them. CATHENA is assessed against data from the component facilities and modified as necessary until acceptable assessment results are obtained. AECL has devoted significant resources to the component test program. In this regard, the AECL component test program is similar to the Westinghouse-sponsored AP600 component test program. Third, a broad spectrum of integral tests are run in the RD-14M integral test facility. CATHENA is assessed against RD-14M data to demonstrate that the code successfully integrates the various component models and successfully predicts the integral behavior of the integral facility. Fourth, AECL argues that (a) full-scale models of the CANDU components have been validated, (b) the models have been successfully integrated into the CATHENA code as demonstrated by successful assessment calculations of integral phenomena in a reduced scale facility that, although it is not prototypic of any given CANDU reactor, simulates the key systems, components, processes, and phenomena, and (c) the governing equations for mass, momentum, and energy automatically scale to full reactor size. It should be noted that there are some RD-14M specific correlations that are used for different applications, e.g., the CATHENA "pipe" component accesses different two-fluid correlations for an empty pipe of circular cross section, square channel, 7-rod bundle, and 37-rod bundle.

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