An Overview of MAAP4-CANDU Code

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ABSTRACT

MAAP4-CANDU was selected by AECL and the CANDU utilities to be the primary tool for modelling the CANDU station response to a Severe Core Damage accident. MAAP4-CANDU is the current adaptation of the MAAP code, specifically designed for a CANDU station. OPG is the code licensee, and AECL holds a sub-license from OPG. The results from MAAP4-CANDU analyses support Level 2 PSA activities and assist in the development of severe accident management measures. This paper provides an overview of the MAAP4-CANDU Code, which includes the code development history, code capabilities and the current status.

1. INTRODUCTION

Severe Core Damage (SCD) accidents in a CANDU®[1] reactor are postulated very low frequency reactor accidents that lead to the loss of core geometry. SCD accidents are beyond design basis accidents. To ensure there is no health risk to the public or station staff, SCD accidents must be halted in their progress.

Reliable emergency heat sinks are provided in CANDU reactors, to prevent an accident at decay power from entering a severe core damage realm. An SCD accident typically requires a significant loss of moderator, which would otherwise act as a heat sink for voided fuel channels. Postulated SCD accidents begin as design basis accidents (DBA), but are combined with additional loss of safety or process systems (*i.e.,* loss of heat sinks). Examples of SCD accidents include i) a loss-of-coolant accident (LOCA) plus loss-of-emergency-core-coolant (LOECC) and a loss of moderator cooling, ii) a station blackout (SBO) scenario, and iii) a multiple steam generator tube rupture with a LOECC and loss of steam generator feedwater and loss of moderator cooling. Severe core damage progresses through several stages, including: fuel bundle heat up and disassembly; fuel channel heat up, sagging, perforation and melt-through; fuel and fuel channel debris separation (disassembly) from the remaining channel; suspended debris heatup, motion and melting; terminal debris formation within the calandria vessel; calandria vessel failure; interaction of core debris with the concrete calandria vault; and failure of the containment structure. Severe core damage could be halted by accident management measures, such as reflooding the calandria vessel (in-vessel cooling) and maintaining cooling on the outside of the calandria vessel (ex-vessel cooling). An SCD analysis code is required to

[1] CANDU is a registered trademark of Atomic Energy of Canada Ltd.

model the progression of a severe core damage accident in a CANDU reactor.

The overall objectives of an SCD accident consequence analysis are [1]:

- to provide radioisotope source term data for Level 2 Probabilistic Safety Assessments (PSA);
- to provide the timing and duration of significant stages of the accident; and
- to support the development of severe accident management guidelines.

Severe core damage accident simulation requires the ability to model processes such as: primary heat transport system (PHTS) response; fuel uncovery; fuel heat up and subsequent geometry changes; loss of heat sinks (*e.g.,* calandria vessel, end shields and calandria vault water inventory); fuel melting; fuel and fuel channel debris formation; debris heat up and motion; fission product release, deposition and transport; containment response; core-concrete interaction; engineered safety systems (*e.g.,* ECCS); and operator actions; amongst others. The interactions between separate regions or systems (*e.g.,* the PHTS and the calandria vessel, or the calandria vessel and the containment) must be modelled to follow the accident progression and fission products across system boundaries. An integrated computer code is required for SCD accident analysis, to model the total station response.

An SCD accident analysis code does not necessarily need comprehensive and detailed models as in many DBA analysis codes; simpler models are adequate to capture the pertinent accident phenomena (*e.g.,* channel dry out). Much of a severe accident, such as debris behaviour, is dependent upon the presence or absence of heat sinks to determine the accident progression; thus quantifying the amounts and location of mass and energy are important features of an SCD analysis code, but the detailed thermodynamics of the intact PHTS are less important. Since the severe core damage accidents typically begin with a design basis accident, qualified DBA codes can be used to simulate the early stages of an accident. An SCD code should be adjustable to emulate the initial conditions calculated by the DBA analysis code, for the time when the DBA analysis code can no longer simulate the accident (*e.g.,* fuel channel disassembly). Considering the above requirements, Atomic Energy of Canada Ltd. (AECL) and the CANDU utilities selected MAAP4-CANDU to be the primary tool for modelling the CANDU station response to a Severe Core Damage accident.

2. MAAP4-CANDU CODE

MAAP (Modular Accident Analysis Program) is an integral nuclear plant analysis code for modelling severe core damage accidents. The MAAP code was developed for pressurized and boiling light water reactors by Fauske and Associates Incorporated (FAI), and is owned by the Electric Power Research Institute (EPRI) [2]. MAAP-CANDU is the adaptation of the MAAP code, specifically designed for integrated CANDU reactor station severe core damage accident simulation [3].

2.1 MAAP4-CANDU development history

MAAP was extended, from light water reactor designs, to model the Ontario Power Generation (OPG) multi-unit CANDU stations with the development of MAAP-CANDU v2.0. The change from a pressure vessel type of reactor required the coding of several modules, developed by

OPG, to simulate the CANDU reactor core, calandria vessel, and debris formation and movement. The development of MAAP-CANDU also required adaptation of many non-core MAAP models to CANDU station designs.

MAAP4-CANDU was selected by AECL and OPG to be the primary tool for modelling the entire CANDU station response to an SCD accident. OPG is the licensee (code holder), and AECL holds a sub-license from OPG. The code is also used by other utilities and consultants, and it is an Industry Standard Toolset (IST) code within the CANDU Owners Group.

MAAP4-CANDU v4.0.4A+ was developed to model other CANDU reactor designs (*i.e.,* CANDU 6) [1]. The subsequent code version MAAP4-CANDU v4.0.5A is an evolutionary enhancement from the released IST version of the code (v4.0.4A+) and has some new or enhanced models. All the MAAP4-CANDU versions are backwards compatible to model the OPG, Bruce Power multi-unit CANDU stations and the CANDU 6, CANDU 9 and ACR-700 stations. The code is currently undergoing changes mainly for error fixes and the next version is expected to be MAAP4-CANDU v4.0.6.

2.2 MAAP4-CANDU code development strategy

When modelling accidents over the long periods of time until containment failure (*e.g.,* 100,000 s (~28 h) to 500,000 s (~139 h or ~6 days)), which are typical for an SCD accident, the accuracy of event timing during the early stages of the transient (and hence many models) is not as important as for DBA analysis codes. MAAP4-CANDU does not attempt to provide the same degree of accuracy as DBA analysis codes for the early stages of the accident, since those early stages can be modelled by DBA codes with more sophisticated models and higher accuracy. The MAAP4-CANDU does, however, link significant reactor systems together (*e.g.,* PHTS, safety systems, containment, fuel) in an integrated fashion. MAAP4-CANDU models the core disassembly and debris behaviour, which are integrated with fission product release and containment response. The MAAP4-CANDU models are mechanistic where possible, using correlations or theoretical models to determine outcomes. Other models are based on failure criteria, some hard-coded and others reliant upon user input, for phenomena that either lack mechanistic models or have been simplified for use in MAAP4-CANDU. The result is a fast-running SCD accident analysis code.

The top-level control file for operating MAAP4-CANDU is the *input file*. The *parameter file* contains the station-specific data. By changing the input file, the user can perform different runs using the same parameter file. The input file can override variables in the parameter file, introduce or modify operator actions, and determine the length of the simulation. This allows the user to implement a single large parameter file, in conjunction with several input files, to model a series of different accidents for the same reactor design or to perform a parametric study for different model controls but using the same station data.

While MAAP4-CANDU is specific to the CANDU reactor design, there are several thousand user inputs in the station parameter file to adapt the code for the different plant configurations, accident scenarios, modelling assumptions, failure criteria, time step limits and output control. The flexibility of MAAP4-CANDU, as reflected in the parameter file, allows the code to model a wide variety of CANDU designs and accident conditions, or to be run with the same physical inputs but with different modelling assumptions. This latter feature allows the user to perform parametric studies of an accident sequence to determine the significance of certain models or phenomena for which there may be no experimental evidence or operating experience as guidance.

A third input file, the *channel data file* contains the initial temperatures and initial thicknesses of consumed zirconium for each characteristic fuel channel, axial channel node and radial channel node.

The parameter, input and channel data files are in ASCII format and the code is written in FORTRAN 77. The code is distributed as an executable, compiled for a specific computer platform (typically a personal computer running a Microsoft Windows operating system). The executable is stand-alone, requiring no additional software libraries for operation. As long as it has been compiled and verified for a particular computer platform, the code will run correctly on that platform independent of local system configurations.

3. MAAP4-CANDU MODELS

3.1 General description

MAAP4-CANDU is a combination of "generic" MAAP4-LWR models, CANDU-specific component models, and the Channels System suite of CANDU core models (Figure 1).

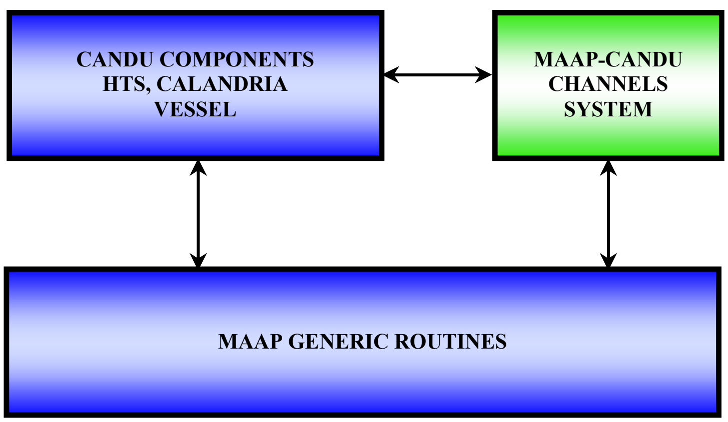

Figure 1: The basic architecture of MAAP4-CANDU code.

The generic models are those used in the MAAP4-LWR code. They include subroutines and functions for fission product behaviour, thermal properties, containment behaviour, steam generators, etc. Some models have been modified slightly to adapt them to the CANDU design features and to integrate with the rest of the MAAP4-CANDU coding, but these models are essentially unchanged from the LWR versions of MAAP4.

The CANDU component models are specific to the CANDU design, and include models for the calandria vessel, pressure and inventory control system, and some of the engineered safety systems.

The Channels System is a large set of MAAP4-CANDU models of the core components between the inlet and outlet headers (*i.e.,* the feeders, end fittings, channels, fuel) and the behaviour of these components within the calandria vessel volume as the fuel channels disassemble into suspended debris. The debris behaviour is modelled by the Channels System subroutines up until the channel debris coalesces into the terminal debris bed within the calandria vessel. The following are some of the phenomena modelled by the MAAP4-CANDU code:

- PHTS coolant circulation, phase separation, blow-down;
- Temperature excursion of fuel and fuel channels;
- Zircaloy-steam reaction;
- Thermal mechanical behaviour of fuel and failures of fuel channels;
- Disassembly of fuel channels and formation of suspended solid debris beds;
- Motion of solid and molten debris bed;
- Debris jet particulation in calandria vessel and containment compartments;
- Interaction of the core debris with coolant and steam;
- Molten corium-concrete interaction;
- Hydrogen burning and steam explosion;
- Iodine chemistry models in the containment; and
- Fission product release, transport and deposition.

The following is a list of the systems modeled in the MAAP4-CANDU code:

- Two-loop or one-loop PHTS including piping, pumps, reactor inlet and outlet headers and feeders;
- Pressurizer and pressure and inventory control system;
- CANDU reactor core;
- Steam generators - primary and secondary sides;
- Containment building including a number of compartments;
- Calandria vessel and calandria vault;
- Shield cooling, moderator cooling and shutdown cooling systems;
- Emergency core cooling system (high, medium and low pressure components);
- Containment dousing spray system and local air coolers;
- Containment ventilation system, and Hydrogen igniters and recombiners; and
- Power operated and passive (spring loaded) relief valves.

3.2 CANDU-specific models

CANDU-specific models are available in MAAP4-CANDU to characterize the following components/systems: fuel and fuel channel, core and debris, calandria vessel, PHTS and steam generator, calandria vault and engineered safety systems. The MAAP4-LWR generic containment and fission product models are used in MAAP4-CANDU.

3.2.1 Fuel and fuel channel models

MAAP4-CANDU models CANDU fuel and fuel channels as a set of nine concentric rings (Figure 2). The rings are continuous along the channel, with no models of end plates, end caps, spacers or bearing pads. Each ring of fuel elements, except the centre element, is transformed into two adjacent, contacting model rings.

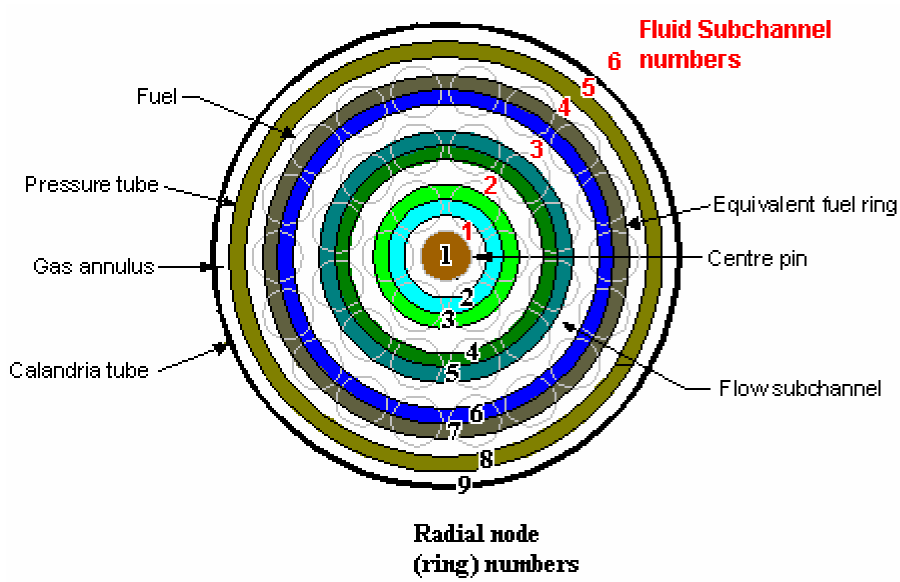

Figure 2: MAAP4-CANDU nodalization of a fuel bundle and fuel channel into a fuel ring model (37-pin fuel bundle).

For a CANDU 6, the fuel and fuel channel is subdivided into 12 axial nodes, representing the total number of fuel bundles in the channel. The fuel bundle rings represent a mixture of UO_2 and zirconium. Each fuel bundle ring has a single uniform temperature for a given axial channel node; there is no circumferential variation or separate sheath temperature. All the zirconium in the fuel bundle is incorporated into the fuel ring model to ensure that all possible zirconium is available for the total heat and hydrogen generation. The zirconium oxidation and related hydrogen production rate depend upon the ring temperature, oxide thickness, and amount of steam. Three sets of zirconium-steam oxidation correlations are available in MAAP4-CANDU. The fuel decay heat, as a function of axial and radial position within a fuel channel, is calculated from the initial channel decay heat and the total core decay heat as a function of time. Calculations of the fuel and fuel channel temperatures in MAAP4-CANDU begin only when the channel is dry; prior to that a global energy balance is used to account for the heat transferred to the surroundings.

MAAP4-CANDU also models fuel-sheath melting and relocation, radial heat transfer from fuel to the calandria vessel fluid (water or gas), and fuel bundle slumping into contact with the pressure tube. The annulus between the calandria tube and the pressure tube is normally filled with CO_2 but, if the calandria tube becomes perforated, steam from the calandria vessel enters the annulus; this increases the oxidation and hydrogen production rates, resulting in higher temperatures and speeding the disassembly of the fuel channel into fuel channel debris. Channel perforation is based on fuel channels sagging into contact with underlying channels. A sagging channel preferentially stretches at the ends of adjacent fuel bundles, and perforates when the calandria tube strain exceeds a user-defined input strain.

A fuel channel rupture model is used in MAAP4-CANDU, to allow the channel to fail at high pressure. The high-pressure fuel channel rupture model in MAAP4-CANDU compares the pressure-tube hoop stress with the maximum sustainable hoop stress at that temperature before breaking, based on experiments performed for isothermal Zr-2.5%Nb tubes. If the calculated stress is greater, the pressure tube balloons into contact with its calandria tube. If the hoop stress of the combined tubes is greater than the maximum sustainable hoop stress (at the temperature of the combined tubes), the fuel channel ruptures. The user can also introduce a channel failure time based on external analyses.

3.2.2 Core and debris models

The CANDU core is nodalized into (1) a channel nodalization scheme to calculate the fuel and fuel channel heat up and the disassembly to core debris, and (2) a calandria vessel nodalization scheme to calculate the calandria vessel heat transfer conditions and the formation, heat up and motion of core debris.

MAAP4-CANDU does not model every single channel in the core, but uses the concept of *characteristic channels*, each representing one or more actual fuel channels (associated channels). Each characteristic channel is modeled as an average of all its associated channels. There are three characteristic channels - high, medium or low decay heat - for each vertical core node of the calandria vessel for each PHTS loop. A two-loop CANDU 6 with six vertical core nodes therefore has $2 \times 6 \times 3 = 36$ characteristic channels.

The calandria vessel volume is nodalized by vertical and axial core nodes, and by the PHTS loop. A two-loop CANDU design has separate PHTS loops, which are symmetrical about the centre vertical plane, dividing the calandria vessel volume into left and right hand sides. Typically, MAAP4-CANDU uses six vertical core nodes and five axial core nodes (Figure 3).

The code uses a failure criterion, based on the pressure and calandria tube temperatures, to determine when a portion of fuel and fuel channel becomes core debris. When the pressure and calandria tube temperatures exceed the melting point of oxygenated zirconium, or a user input temperature, the fuel and fuel channel of that channel node disassemble from the channel to become suspended core debris, which is held up by colder (hence stronger) underlying, submerged channels. The steam/hydrogen flow rate through the suspended core debris is calculated, and any remaining Zr is oxidized, if the debris is above the moderator level and exposed to steam. The energy and fission product inventories of the debris are tracked. Melting can occur; UO_2 –Zr interaction can occur, and molten material can trickle down to the terminal debris bed. The core collapses into the bottom of calandria vessel and forms a terminal debris bed, where it is cooled by the moderator, when the underlying channels can no longer support the overlying debris.

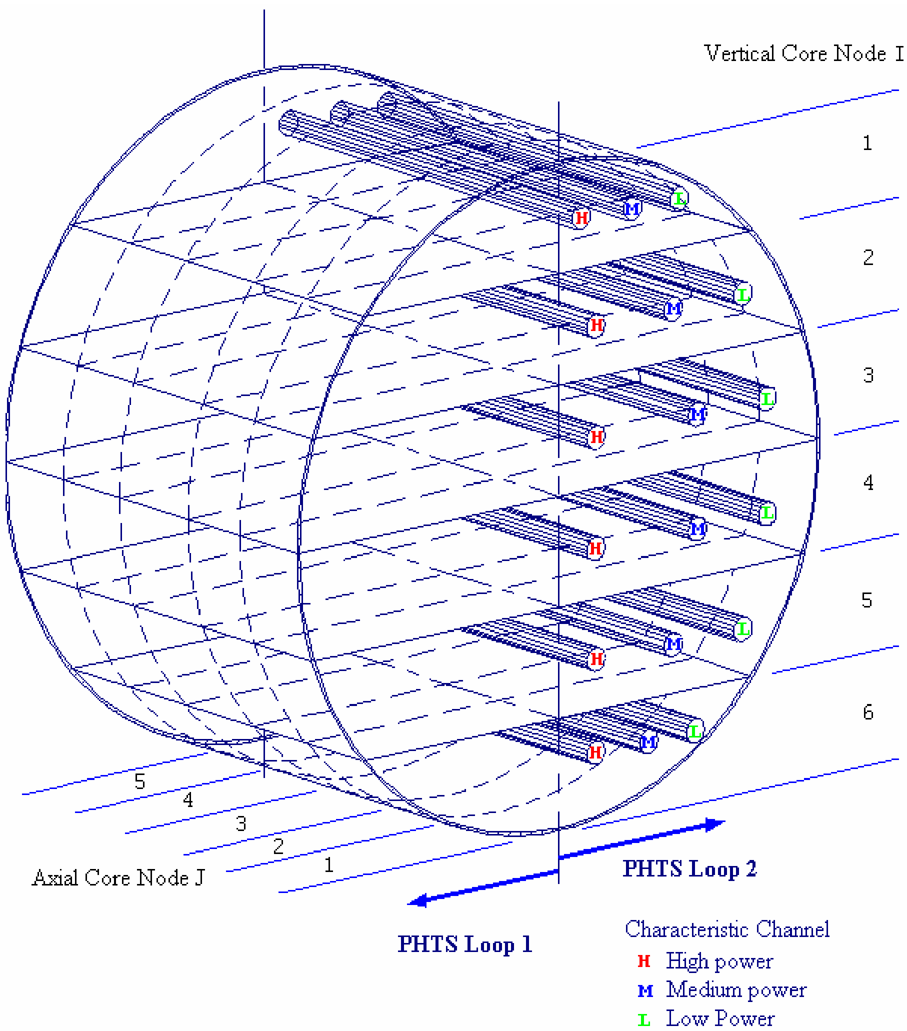

Figure 3: Nodalization of a two-PHTS-loop CANDU reactor core, with six vertical and five axial core nodes for each PHTS loop and the distribution of the characteristic channels in a single PHTS loop.

3.2.3 Calandria vessel model

The calandria vessel model calculates the pressure, gas and water temperatures, water level, steaming, flows in and out, end shield recirculation and cooling, and heat losses to the calandria vault. The rupture disks on the calandria vessel are modelled; they open if the maximum allowed pressure differential, between the calandria vessel and the containment, is exceeded. Water, steam and non-condensables are expelled, and boiling further reduces the calandria vessel water level. The moderator can be cooled via the moderator heat exchanger model.

Natural circulation models of the calandria vessel atmosphere provide heat transfer conditions for uncovered fuel channels. Core debris phenomena modelled in the calandria vessel include a) quenching and entraining molten debris as it relocates into the water pool, b) oxidation of entrained debris, and c) a debris bed model including heat transfer from the debris to the calandria vault water, gas and heat sinks.

The calandria vessel failure mechanisms include a) creep rupture of the calandria vessel wall and tube sheets, b) vessel drain line failure from molten corium, c) calandria vessel wall ablation, d) calandria vessel failure by molten debris impingement on the calandria vessel wall, and e) over-pressure. When the calandria vessel fails, the corium retained in the calandria vessel is allowed to relocate into the calandria vault.

3.2.4 PHTS and steam generator models

MAAP4-CANDU models the CANDU PHTS figure-of-eight loops in a simplified fashion, including the primary pump, wall heat sinks and the steam generator. The pressurizer is modelled as part of the Pressure and Inventory Control system. The fuel channels, fuel and calandria vessel are modelled separately, as previously discussed in sections 3.2.1, 3.2.2 and 3.2.3. The PHTS loop model has 14 nodes, excluding the channel, feeder and end fitting nodes. Figure 4 shows the PHTS nodalization for a CANDU 6 reactor.

MAAP4-CANDU tracks the PHTS masses and energy in one gas space and multiple water pools, at only one pressure, for each loop. Six gases are considered - steam, hydrogen, oxygen, nitrogen, carbon monoxide, and carbon dioxide - and the total energy and mass of each species are conserved. The number of water pools depends on the configuration of the pools and the amount of water in the PHTS. During normal operation, one continuous two-phase mixture circulates in the PHTS. Any local variations in water temperature and void fraction are not considered, and the dispersed gas phase is considered part of the single gas space. Water and gas are in thermal equilibrium in the two-phase mixture.

Natural circulation of two-phase fluid persists after the primary pumps trip. If the total PHTS void fraction increases in a loop, the phases separate at a user input global PHTS loop void fraction, resulting in separate water pools being tracked in each pass of the PHTS loop. The water pools split again as the water level falls, until the water level falls below the headers and the water is divided amongst the channels. If the emergency core coolant refills the primary system, multiple water pools merge into fewer pools.

Decay heat from the fuel heats the PHTS coolant, which transfers some of the heat to the calandria vessel, end shields, steam generator, and containment. The PHTS components have mass, and can store or release heat.

In MAAP4-CANDU the steam generator secondary side is represented as one node. The primary side of the steam generator is represented as two nodes (cold legs and hot legs). A number of parameters for the primary and secondary sides of the steam generator, such as the total volume of the primary and secondary sides, the total number of U-tubes, their dimensions etc., are used in the MAAP4-CANDU input deck to describe the steam generator design.

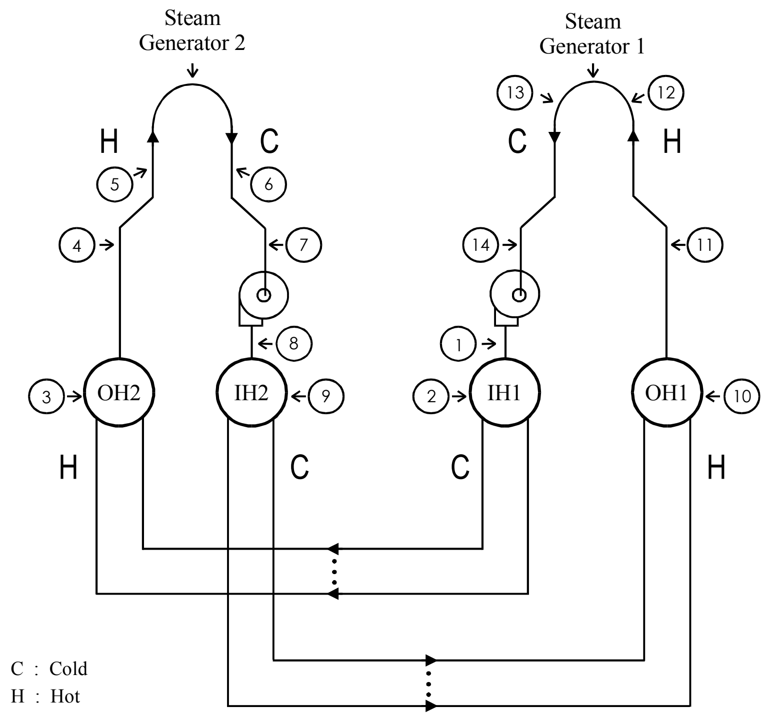

Figure 4: Nodalization scheme for a CANDU-6 PHTS, showing 1 of two PHTS loops. OH and IH are the outlet header and inlet header respectively.

3.2.5 Calandria vault model

The calandria vault surrounds the calandria vessel; the pressure, gas and water temperatures, water level, steaming flows in and out of the shield tank, thermal shield circulation and cooling system, and heat losses to the containment are modelled. The heat from the calandria vessel walls, and the flows of gas, water, and debris from the failed calandria vessel, are calculated. Corium-concrete interaction is modeled in MAAP4-CANDU, which leads to hydrogen generation, fission product release and the subsequent failure of the calandria vault floor.

3.2.6 Containment model

MAAP4-CANDU has a generalized containment model, which allows some flexibility for the user to represent the containment configuration. The containment model can accommodate up to 39 nodes, 120 junctions between the nodes, 200 distributed heat sinks, 200 lumped heat sinks and up to 10 debris pools.

3.2.7 Engineered safety systems

Engineered safety systems are modeled in MAAP4-CANDU: the emergency coolant injection system (ECIS) to supply coolant at elevated pressure to a ruptured PHTS; the post accident cooling system to remove heat during the recirculation mode of ECIS; the shutdown cooling system to remove the decay heat after reactor shutdown. Operator actions can also be implemented.

4. CODE APPLICATION

MAAP4-CANDU runs on a PC platform running a Microsoft Windows operating system. Typical usage data for a CANDU-6 station blackout sequence is as follows:

Input File size:

- Exe File ~5 Mb
- Parameter File ~1 Mb
- Input File ~2 Kb

Typical Output file size:

- Log file ~180 Kb
- Tabular file ~10 Mb
- Plot files ~ 2 Mb each

Run time:

- Station blackout ~20 min.
- Large LOCA ~45 min.
- Small LOCA ~35 min.
- Steam generator tube rupture ~25 min.

The MAAP4-CANDU code has been applied to several reactor types and various accident scenarios successfully [1, 3-7]. Benchmarking, documentation and model enhancement are some of the activities underway for the MAAP4-CANDU code, as it continues to be developed to meet the needs of SCD analysis and new reactors. Future efforts include implementing the necessary models for the Advanced CANDU Reactor.

5. CONCLUSIONS

MAAP4-CANDU is an integrated accident analysis code, used for the analysis of CANDU reactors when they undergo a postulated, low frequency severe core damage accident. MAAP4-CANDU is a combination of the "generic" MAAP4-LWR models, CANDU-specific component models, and the Channels System suite of CANDU core models. MAAP4-CANDU analyses are conducted to support level 2 PSA activities, and to support the development of severe accident management guidelines. The MAAP4-CANDU code is an Industry Standard Toolset code, used by AECL and the CANDU utilities. MAAP4-CANDU models the core disassembly, debris behaviour, which are integrated with fission product release and containment response. The MAAP4-CANDU models are mechanistic where possible, using correlations or theoretical models to determine outcomes. Other models are based on failure criteria, some hard-coded and others reliant upon user input. MAAP4-CANDU is fast running, and the code has been applied to several reactor types and various accident scenarios successfully.

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