MAAP5-CANDU DEVELOPMENT

J. Kennedy[1], P. Maka[1] and M. Chai[1]
[1] Amec Foster Wheeler, Toronto, Ontario, Canada
john.r.kennedy@amecfw.com, peter.maka@amecfw.com, michael.chai@amecfw.com

Abstract

MAAP-CANDU is an integral system analysis code for assessing the consequence of a severe accident in CANDU nuclear power plants. The current version of the code features simplifications, such as lumped models and coarse nodalization that enable a fast running code. Increased computer processing speeds now permit improved resolution in the code with less impact on run times. As a response to the Fukushima Daiichi accident, initiatives to improve severe accident modeling for different reactor types in various severe accident codes are currently underway internationally. Similarly, a development program was initiated by the CANDU Owners Group (COG) to enhance the MAAP5-CANDU tool suite.

This paper provides an overview of the code improvements currently in progress. Specific requirements for each development item are discussed along with the challenges associated with implementing each item into the code. The benefits of these improved models to CANDU severe accident analysis are also highlighted.

Keywords: Code development, MAAP-CANDU, Level 2 PSA, MAAP5, Severe Accident Analysis, Beyond Design Basis Accident (BDBA).

1. Introduction

MAAP-CANDU is a computer code that simulates the integrated response of a CANDU nuclear power plant to a postulated severe accident sequence. MAAP-CANDU includes models of important severe accident phenomena that may occur within the reactor core, containment and/or the service buildings. The code has been used to support the development of Level 2 Probabilistic Safety Assessments (PSA). The code calculates releases to the environment to support the categorization of releases. It is used to support sensitivity and uncertainty analysis on the release categorization and to support the development and branch point quantification of Containment Event Trees (CETs). MAAP-CANDU has also been informative when developing Severe Accident Management Guidelines (SAMG). The code has supported operator training on the SAMGs by generating training data for severe accident drills at several CANDU stations.

Following the events at Fukushima Daiichi, the Canadian Nuclear Safety Commission (CNSC) issued numerous action items to the Canadian nuclear industry. Several of these pertained to severe accident analysis. These included the assessment of SAMG instrumentation and equipment survivability and plant habitability assessment following a severe accident. MAAP-CANDU was successfully applied in these novel applications to close the items for several CANDU stations [1] [2].

The Modular Accident Analysis Program (MAAP) forms the basis of MAAP-CANDU. The code was developed by the U.S. power nuclear industry following the Three Mile Island (TMI) accident. The MAAP code was developed by Fauske and Associates, LLC (FAI) and is owned by the Electric Power Research Institute (EPRI). The code suite includes a Pressurized Water Reactor (PWR) version and a Boiling Water Reactor (BWR) version.

A CANDU version was later developed to represent the horizontal fuel channel and heavy water moderated design of Ontario Hydro (now Ontario Power Generation (OPG)). Models of the CANDU reactor core were developed by OPG. These models are referred to as the “Channels Systems” code. The code is currently developed and maintained by the CANDU Owners Group (COG). The MAAP-CANDU code also included MAAP’s generalized containment model as well as adaptions of many MAAP-PWR models to the CANDU design. As such, MAAP4-CANDU is a combination of “generic” MAAP4-LWR models, CANDU-specific component models, and the Channels Systems code. MAAP-CANDU v4.0.4A+ was the first COG Industry Standard Toolset (IST) version of the code.

The Channels Systems code models the core components between the inlet and outlet headers, and models the behaviour of these components within the calandria vessel as the fuel channels disassemble into suspended debris. The debris behaviour is modelled by the Channels System code until the debris forms the terminal debris bed at the bottom the calandria vessel.

Currently, EPRI has invested in improving the MAAP code suite by releasing MAAP5. MAAP5-CANDU is scheduled to be issued in 2017 with funding from EPRI and COG. This paper summarizes the COG MAAP5-CANDU development program with emphasis on the improvements to the MAAP5-CANDU Channels Systems code.

2. Development Program

A multi-year development program for MAAP5-CANDU was initiated through the COG IST work program. To serve as a guide with regard to the program development, a development plan (DEV-PLN) was created which serves the following purpose:

- Identification of Development Items: Feedback was obtained from the MAAP-CANDU users group (CMUG) in order to identify important enhancements to the current code (i.e., development items) and to generate a qualitative assessment regarding the path forward.
- Ranking of Development Items: Code users were asked to rank each development item identified with regard to the need/urgency of enhancement. Feedback from all users was collated and an overall ranking for each item was developed.
- Software Requirements: For issues that were ranked highly by the users, high level software requirements were prepared and reviewed by users. The requirements helped to assist with the estimation of the effort involved in the development of the item.
- Software Description: For those items that obtain development funding, detailed descriptions of the changes to be made were generated from the software requirements.

The focus of this paper is on two development items, namely reactor core and channel nodalization and core collapse modelling. These items both deal with the disassembly/relocation of the reactor core which is of primary importance to severe accident modelling. In addition, these two items are inter-related which meant that it would be more efficient to address these issues together.

3. Software Development Method

The waterfall model for software development is utilized as recommended by Canadian Standard Association (CSA) Standard N286.7-99. The model is described in the flow chart shown in Figure 1.

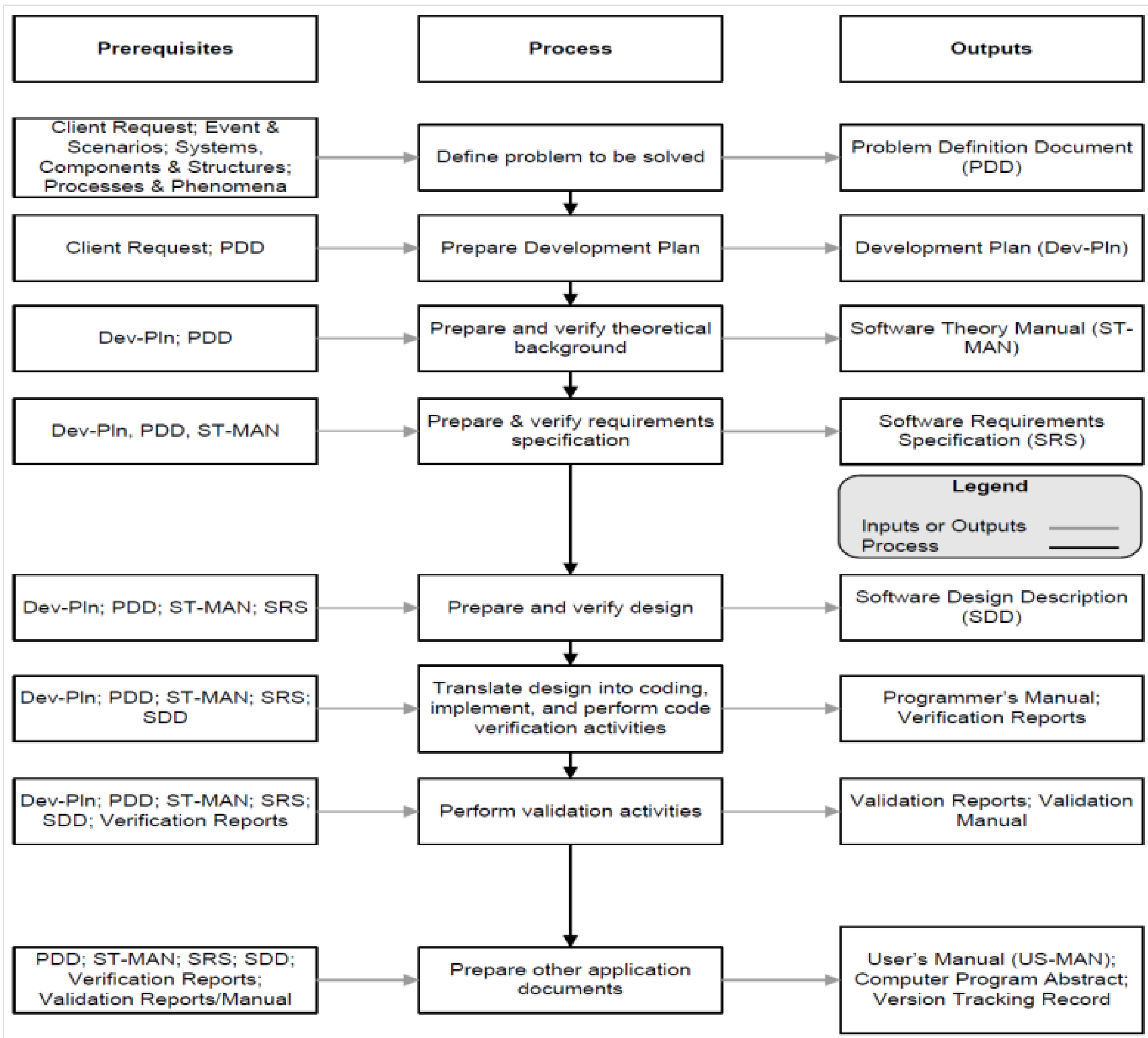

Figure 1: Development and Documentation Processes, Requirements and Outputs [1]

Coding activities followed the recommended programming practices outlined in Appendix A of CSA N286.7-99 [1]. MAAP5-CANDU was developed using the FORTRAN programming language. All development will employ consistent methods.

Software development was performed in the Microsoft Visual Studios Integrated Development Environment (IDE). The Intel Visual Fortran compiler for Windows was used for compilations. Development was performed on the Windows 7 Professional 64-bit operating system. The IDE and compiler version were consistent with that used by the MAAP code developer, FAI. This is an important consideration as the revised Channel Systems code will have to be incorporated into the MAAP5-CANDU code base prior to issuing a new version of the integrated code.

4. Reactor Core and Channel Nodalization

4.1 Background

The current MAAP-CANDU core model represents the 380 to 480 channels in a CANDU core with 18 representative channels per PHTS loop. For the purpose of tracking the formation and motion of molten core debris, the reactor core is conceptually divided into 6 vertical core nodes and 5 horizontal core nodes for each PHTS loop by slicing the core horizontally along its axis. Refer to Figure 2 for an illustration of the CANDU core as modelled in MAAP-CANDU.

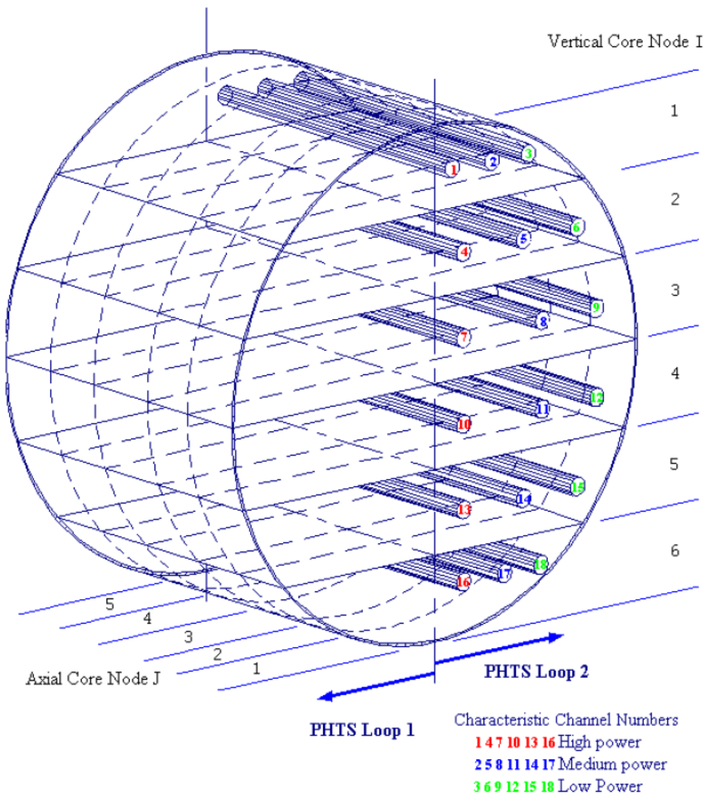

Figure 2: Idealization of a CANDU Core [4]

User documentation states that, at most, 146 characteristic channels can be modelled but hard-coding in certain areas of Channels Systems code restricts this number to 18 per HTS loop. Furthermore, hard-coding imposes three characteristic channels per characteristic channel row and one power profile that is applied to all characteristic channels.

4.2 Motivation

The resolution of channel characteristics is clearly simplified in the current modelling of core disassembly and collapse as noted in the previous section. Increased channel/core resolution is expected to reduce uncertainty in core disassembly and collapse predictions.

The current suspended core debris model is two dimensional. A dimension defined parallel to the long axis of the calandria vessel, and perpendicular to vertical reactivity devices such as control absorber and liquid zone controllers, is currently lacking (refer to Figure 2). This additional dimension, referred to as the lateral dimension, would allow for a 3-dimensional representation of the CANDU core and would significantly enhance core disassembly and collapse modelling (refer to Figure 3 for sample lateral nodalization scheme).

In addition, as there is significant variance in the power profile amongst fuel channels, it is desirable to increase the number of power profiles that can be modelled.

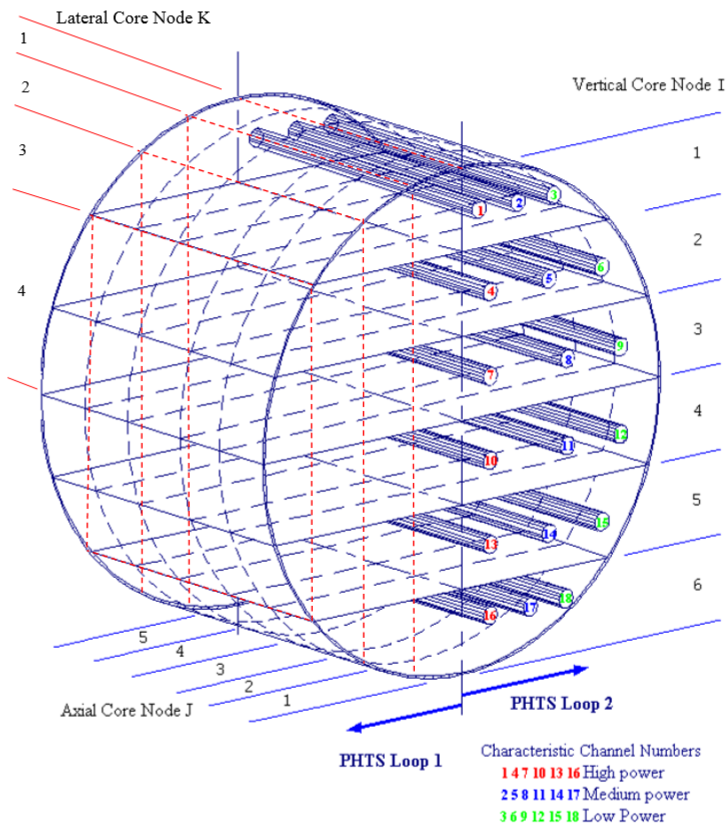

Figure 3: CANDU Core Idealization Including Proposed Lateral Dimension

4.3 Requirements

The following functional requirements were set:

1. Increase the axial core nodalization from 5 to 13,
2. Increase the vertical core nodalization from 6 to 26,
3. Increase the channel nodalization from 18 to 480 per loop,
4. Increase the lateral core nodalization from 1 to 24 per loop, and
5. Increase the number of channel power profiles.

13 axial core nodes were considered sufficient as this number represents the physical maximum number of fuel bundles in a fuel channel. 26 vertical core nodes were considered sufficient to resolve the fuel channel rows for all CANDU designs. 480 fuel channels per HTS loop were considered sufficient to resolve all operating CANDU designs. 24 lateral columns per HTS loop were considered sufficient to resolve all the fuel channel columns for all CANDU core designs. Lastly, up to 480 unique channel power profiles can now be specified.

Note that no changes to the physical models in the Channel Systems code were required as increasing the core and channel nodalization invokes the same physical models except for a greater number of core nodes and channels.

As a modelling constraint, MAAP5-CANDU must retain backwards compatibility with the MAAP4-CANDU.

5. Core Collapse Modelling

5.1 Background

During a severe accident, rows of channels may begin to uncover, heatup, sag and eventually fail. As more channels fail a suspended debris bed will be formed near the top of the reactor. The weight of this debris is supported by channels below that are submerged in the moderator and thus are still relatively strong. Eventually, if the accident progresses without mitigating actions, the mass of the debris will exceed the mass that can be supported by the underlying channels and a cascading set of channel failures will be initiated that continues unabated until all debris has relocated to the bottom of the calandria vessel. This dynamic relocation event is termed core collapse.

MAAP-CANDU models channel disassembly and the collapse of the core in a parametric manner. Channel disassembly continues to be calculated until all three of the core-collapse criteria are met (in the current HTS loop):

1. The number of vertical core nodes uncovered is greater than or equal to user input parameter NDCLPS,
2. The average calandria tube temperature for uncovered axial core bundles in the medium and high power channels is greater than user input parameter TCTCLPS, and
3. Suspended debris mass for each loop is greater than user input parameter MLOAD.

The first two criteria are typically not used, and only increase the time to core collapse, thus MLOAD is the primary core collapse trigger variable. Variation of core collapse timing affects the timing of later events in accident progression (such as calandria vessel failure) and impacts the in-vessel hydrogen production and fission product (FP) releases [5]. It is desirable that this uncertainty be reduced to the extent possible.

5.2 Motivation

Historically, the value of MLOAD has been set to ~25,000 kg for most two loop CANDU plants. This value represents an estimate which was formulated through a combination of static beam loading analysis and also user experience. To make the determination of core collapse more robust it is necessary to include static beam loading calculations directly into the code such that the user is only required to input the ultimate tensile strength (UTS) of a single calandria tube (CT) as a function of temperature and the code will use this information to calculate the load (and also the corresponding mass) that is required to exceed the UTS.

In addition, there is currently no model of a partial or staggered core collapse, which is considered to be possible, given the geometry of the core and the presence of vertical in-core devices (refer to Figure 4).

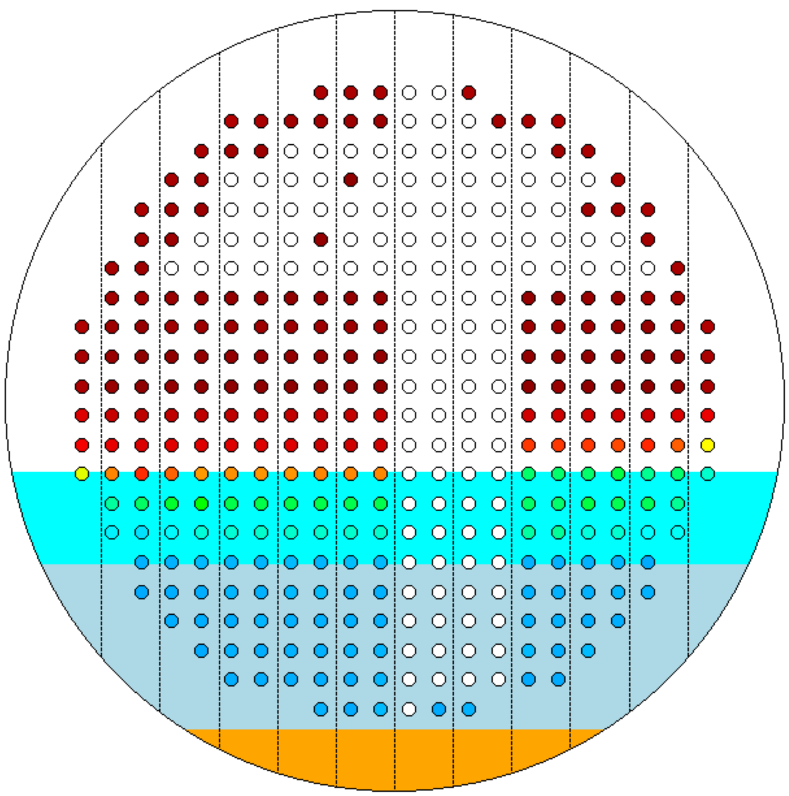

Figure 4: Anticipated CANDU core disassembly and collapse[1]

[1] In the figure, circles indicate fuel channels, with the blue fill indicating cooler channels, red indicating warmer channels and white indicating failed/disassembled channels. The blue level indicates the collapsed water level while the light blue indicates the two-phase water level. The orange level at bottom of the vessel indicates disassembled core debris. Dashed black vertical lines indicate the presence of vertical in-core devices.

5.3 Requirements

From the discussion above the following requirements were set for this development item:

1. Implement a staggered/partial core collapse model, and
2. Implement a dynamic calculation of variable MLOAD that changes the value of the parameter as a function of moderator and debris conditions,
3. Implement an external flag that can be utilized to induce core collapse and is compatible with the above two requirements.

5.4 Theory

For Requirement 1 and 3 above no new theory is required to be implemented into the code. However, to support Requirement 2 a new model is required to translate the strength of cool, irradiated CTs into a load bearing capacity and compare this against the load being applied to the channel from the channel itself, intact sagging channels above and suspended debris. The equations of the model were derived from elastic beam theory. Key aspects of this model are discussed below.

5.4.1 Identifying the Supporting Row

Logic has been added to the code to dynamically determine the channel row which supports the hot sagging channels and suspended debris above. As the moderator water level drops below the current supporting row, the CT in this row will begin to heatup. Once the average CT temperature in the current supporting row exceeds a user defined value, the supporting row is moved down to the next row.

5.4.2 Ultimate Tensile Strength

The ultimate tensile strength (UTS) of a calandria tube at a given temperature (in ^{o}C) is calculated based on the correlation shown in Equation (1). This correlation is based on Equation 2.1.3-4 in Reference [6]. In Reference [6], a coefficient of 1.08 was used which is based on an interpretation of a series of CT pressure burst tests at different temperatures documented in Reference [7]. To make the correlation more flexible a user defined coefficient (FUTSCOEFF) was introduced.

$$\sigma_{UTS_{i,k}} = \sigma_{UTS_0} - FUTSCOEFF \times (TCT_{Ave_{i,k}} - 273.15)\ \{\text{MPa}\} \qquad (1)$$

In Equation (1), σ_{UTS_0} is the ultimate tensile strength of a CT when at 0^{o}C, FUTSCOEFF is a user defined coefficient, $TCT_{Ave_{i,k}}$ is the average CT temperature within a vertical core node i and lateral column k.

5.4.3 Maximum Supportable Load

Given the ultimate tensile stress, the maximum load on a single CT in a given vertical/lateral core node, $W_{chanmax}$, can be evaluated using Equation (2) (Equation 2.1.4-2 of Reference [6]) below:

$$W_{chan\max i,k} = \frac{I_o \sigma uts_{i,k}}{R_{CTo}} \left[\frac{12L}{L^2 + 2aL - 2a^2} \right] \{N\} \tag{2}$$

Where L is the length of the calandria tube, a is the length of one side of the calandria tube which is assumed to be unloaded (refer to Figure 5), R_{CTo} is the outside CT radius, I_o is the moment of inertia of an area. In the case of a calandria tube with inside and outside diameters D_{CTi} and D_{CTo}, the moment of inertia of an area I_o is [8]:

$$I_o = (\pi/64)\,(D_{CTo}{}^4 - D_{CTi}{}^4) \tag{3}$$

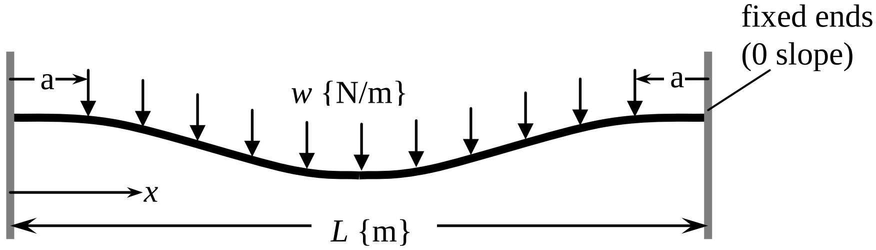

Figure 5: Assumed Loading Profile of Calandria Tube [6]

5.4.4 Maximum Total Supportable Mass

The maximum total supportable mass in a specific vertical/lateral core node is calculated by multiplying the maximum total supportable load from a single channel (which is a function of the average CT temperature of the channels in the vertical/lateral node) by the number of supporting channels in the node and dividing by the acceleration of gravity (g), as shown in Equation (4):

$$M_{Sup_{i,k}} = W_{chan\max i,k} \times N_{Sup_{i,k}} / g \ \{kg\} \tag{4}$$

Where $N_{Sup_{i,k}}$ is the number of supporting channels in a given vertical core i and lateral core node k.

5.4.5 Mass of Intact Channels on Supporting Row

To calculate the load of intact channel segments which have sagged into contact with the supporting row the temperature of each axial channel node in the channels that are located above the supporting row is compared to a user specified input temperature above which the CT strength is significantly reduced. If the temperature of the axial channel node exceeds the user defined temperature then the mass of this axial segment is added to the total load that needs to be supported. Another user specified input limits the number of channel rows that can contribute to the total load. This value should typically be on the order of 2 or 3 actual lattice pitches as it is not feasible for a channel to sag more than this distance without breaking apart.

5.4.6 Mass of Internal Supporting Row

In addition to the mass of suspended debris and mass of intact sagging channels, the load of the supporting row itself must be accounted for. A reduction in the supporting row load due to buoyancy forces has not been considered as it is significantly smaller than the sum of the internal and external loads [6].

5.4.7 Determination of Core Collapse

The final step is to compare the total supportable mass to the mass of the suspended debris, mass of the intact sagging channels and internal mass. If the total mass exceeds the supportable mass then a core collapse is triggered. This calculation is performed for each lateral column in each loop as per the core nodalization chosen by the user.

6. Conclusions and Future Work

A development program for MAAP5-CANDU has been initiated through the COG IST work program with the goal to enhance key models in the MAAP5-CANDU tool suite. Enhancement items have been identified by MAAP-CANDU users and ranked with regard to the need/urgency of the enhancement. Two enhancement items (Reactor Core and Channel Nodalization and Core Collapse Modelling) were chosen for development. The two development items described in this paper are currently being completed under the COG IST work program. These items both deal with the disassembly/relocation of the reactor core which is of primary importance to severe accident modelling. The modifications will allow the user to create more detailed core nodalization which utilizes a more refined collapse model.

Once the changes to the Channels System code have been finalized, they will be handed over to the code developer, FAI, to incorporate into the MAAP5-CANDU code base.

7. References

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