Adding Choking, CCFL, Power Distribution, and Radiation Models

Objective

Counter Current Flow Limitation (CCFL), choked flow, core power distribution, and radiation heat transfer are phenomena that can be important in simulating a realistic Peak Cladding Temperature (PCT) for boiling water reactor (BWR) models. The objective of this exercise is to add CCFL and radiation models, a power profile, as well as choking flags at places in the example BWR model that are identified in a PIRT as having a high impact on PCT for LOCA events.

PIRT Information

A PIRT is a review of the thermal-hydraulic phenomena, processes, and parameters that are significant for analyzing a specific accident in a specific plant configuration. For BWR LBLOCA events, a PIRT[1] ranked the importance of the phenomena indicated above in relation to its anticipated effect on PCT. The ranking of the phenomena discussed in the Objective section is given below for reference. Only cases that had at least one rank of High are included in the table. H, M, L, and 0 indicate High, Medium, Low, and zero impact respectively. A long term cooling phase is not included.

Phase	**Blowdown**			**Refill/Reflood**		
Phenomena ↓ BWR Type →	**2**	**3,4**	**5,6**	**2**	**3,4**	**5,6**
Core – Heat Transfer: radiation	L	L	L	H	M	M
Core – CCFL Upper Tie Plate	L	L	M	H	H	H
Core – CCFL Side Entry Orifice	L	L	H	L	L	H
Core – Power Distribution: radial	M	M	M	H	H	H

1 "BWR PIRT and Assessment Matrices for BWR LOCA and NON-LOCA Events" by M. Straka and L. W. Ward, SCIE-NRC-393-99, Contract NRC-04-96-060 Task 002

Phase	Blowdown			Refill/Reflood		
Bypass – CCFL (top)	M	M	H	H	H	H
Jet Pumps – Flow: critical	0	H	H	0	L	L
Recirc. Line – Flow: critical (break)	H	H	H	M	M	M

The importance of the phenomena depends on the BWR plant type. For example, Core CCFL at the side entry orifice (inlet) is considered to have little impact on PCT in BWR plants of type 2, 3, and 4, but high impact in plant of type 5 or 6. In this exercise, we will update the simplified BWR model to include all of the phenomena identified in the list above.

Setup

1. Open the BWR PBTT_SS.med file in SNAP located in the 'Day4\Afternoon\BWR\' folder.

Make a Steady State Run

Before we start to make changes to the simple BWR model, we will run a steady state simulation in order to become familiar with how the model behaves. An animation of the simulation will automatically load once you submit the simulation so that you can examine the system behavior. As you examine the steady state simulation, review the steady state targets listed in the animation file and note any discrepancies between the target and the actual value. Over the next few exercises we will be modifying the model in order to reach the steady state target values.

1. Submit the steady state simulation using the Job Stream View tab located at the bottom of the View Window in the Model Editor.

   a) Click on the Execute button and assure there is a name that will define the calculation as a BWR steady-state run.

b) Click on the lock button in the upper left-hand corner of the View window and then click on the Execute button to submit the job.

Note the steady state target or expected value and the actual value at the end of the simulation in the table below.

Parameter	Target/Expected Value	Actual Value
Turbine Stop Valve Pressure		
Steam Dome Pressure		
Downcomer Level		
Core Mass Flow		
Total Jet Pump Mass Flow	None Given	
Core Inlet Temperature		
Feedwater Flow	None Given	
Steam Line Flow	None Given	

Adding a CCFL Model

A CCFL flag is added at each cell edge in the model where CCFL is expected to occur. Before the CCFL flags can be added, a CCFL model needs to be defined.

The CCFL model uses a correlation equation of the form:

$$H_g^{1/2} + M\, H_l^{1/2} = C \qquad H_k = j_k \left(\frac{\rho_k}{g\, w\, (\rho_l - \rho_g)} \right)^{1/2} \ : \text{where } k \in g, l$$

$$w = D^{1-E} L^E \qquad L = \left(\frac{\sigma}{g\, (\rho_l - \rho_g)} \right)^{1/2}$$

H_i = Dimensionless Mass Flux where $i \in g, l$
$M \& C$ = Correlation Constants chosen to best fit data
j_i = Phase velocity where $i \in g, l$
ρ_i = Density where $i \in g, l$
D = Hydraulic Diameter of edge where CCFL is applied
σ = Surface Tension
w = Bankoff Interpolated Length Scale
L = Kutateladze Length Scale derived from σ

E is the Bankoff interpolation constant. It is typically a value between 0 and 1, that defines the length scale used to nondimensionalize mass flux. If $E=0$ then hydraulic diameter *D* is used (Wallis scaling). If $E=1$ the Kutateladze length based on Surface Tension is used (Kutateladze scaling).

Add a Kutateladze correlation to the model by doing the following:

1. Locate the CCFL Models box in the Navigator Window and add a new CCFL model.
2. Assuming a slope (M) of 1.24 and a correlation constant (C) of 1.5 complete the CCFL data input in the Properties Window (lower left-hand side of Model Editor) for a Kutateladze correlation.

The following figure shows the CCFL correlation consistent with the above parameters plotted against data. If CCFL conditions are known to match a particular data set well, then the E, M, and C values can be chosen to best match that data set. Note that the 'slope' M is actually the *negative* of the standard definition of slope for a line as seen in Figure 1 below.

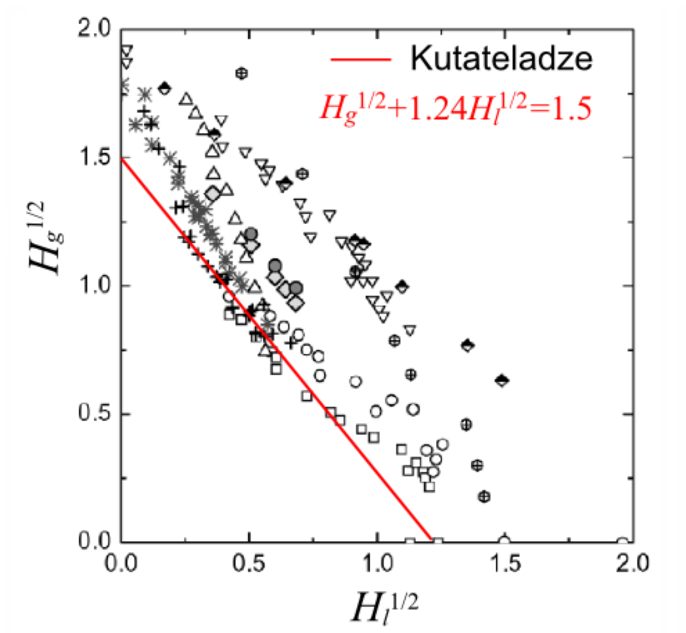


Figure 1: Kutateladze correlation comparison with data

Multiple CCFL models can be added if different correlations are appropriate at different locations. The coefficients for the Kutateladze model added herein were derived for purposes of this exercise in order to get the correlation line shown in Figure 1. Remember CCFL is geometry dependent.

Adding CCFL Flags

A CCFL flag should be applied at the top (upper tie plate) and the bottom (side entry orifice) of the CHAN components, and in the core bypass region. The bypass region is modeled in the vessel component. CCFL is activated in the component geometry input in the SNAP environment. **CCFL is an "edge" input parameter.**

1. For each CHAN component in the BWR input model, activate the CCFL model implemented above to Cell face 1 (side entry orifice) and Cell 28 (upper tie plate).

The top of the CHAN components connect to the bottom edge of VESSEL axial level 6 in rings 1 and 2. This is the top of the bypass region. To activate the CCFL model in the bypass region in the VESSEL component, do the following:

1. Expand the 'Volumetric and Edge Data' box in the Properties Window of the VESSEL component.
2. CCFL input data is entered on the Edges tab for the axial input.
3. Set the CCFL Flags in rings 1 and 2 for level edge 5 (same as the level 6 inlet edge).

The Kutateladze CCFL correlation has now be applied at the top and bottom of the CHANs and at the top of the bypass region, so the CCFL phenomenon should be captured at regions identified as important to the prediction of Peak Cladding Temperature (PCT) for LBLOCAs.

Enabling Choked Flow in the Jet Pump Components

In order for TRACE to capture choked/critical flow phenomenon, a choking flag must be set at the edges where choking is to be enabled. Modeling choked flow at the break is essential for predicting a reasonable break flow. Since break flow is a primary influence on system pressure, and system pressure contributes to many of the important phenomena, the choking flag should always be set at the break for a LOCA. **The PIRT indicates that choking can also be important in the jet pump (nozzle) during the blowdown phase.**

For this part of the exercise, choking at the jet pump nozzle will be applied. The application of choking at the break plane will be done later on in the exercise.

Recall that the JETP component is a special case of a TEE component and contains a primary flow path and a side arm flow path. In modeling a jet pump, the primary flow path is connected to the VESSEL component. The side arm is connected to the recirculation loop. The jet pump nozzle is associated with the recirculation loop flow path and provides the driving flow for the jet pump suction flow. It is noted that the modeled jet pumps contain a total of 5 cells; three cells on the primary side and two cells in the side arm. In modeling the jet pump, the nozzle is the first cell edge of the side arm.

Choking is a cell edge input parameter and in SNAP it is associated with the Friction input parameters. To apply the choking flag at the jet pump nozzle for each jet pump component by doing the following:

1. Locate and expand the Friction dialog box located in the Properties Window.
2. In applying the choking flag, note that there are several options that can be selected for choke flow application. An exploration of implementing the different choke flow options is left as an exercise for the student. For this exercise, the "Choked-flow model using default multipliers" will be used.

3. Apply the choking flag (Choke Flow Model) to the modeled jet pump nozzle..

The choking model is now applied at the jet pump locations indicated by the PIRT as having a high impact on PCT in LBLOCA events, So choking phenomenon should be appropriately captured at these locations in the simulation.

Configure the CHAN Radial Power Distribution

Radial power distribution is configured among the CHANs as well as within each CHAN. In this section the radial power among the CHANs will be configured in the model. **For this exercise it will be assumed that a hot channel bundle is modeled**

with a power fraction of 1.4, The average channels in ring 1 will have a radial power fraction of 1.0 and the average channels in ring 2 will have a radial power fraction of 0.8.

To configure the power distribution among the CHANs:

1. In the Navigator Window, expand Power Components [1] and Powers [1] and select Power 99 (power com). This component contains the plant power parameters.
2. Expand 'Powered Components' in the Properties Window.

> The Power Components dialog shows the list of CHANs. CHANs 1, 2, and 3 are attached to Ring 1 (R1) of the core, while CHANs 4 and 5 are attached to Ring 2 (R2). CHAN 1 contains a single bundle, and will be used to model the **hot bundle**.

> The Radial Power Fractions for each CHAN are specified here. This value is a **Power per Bundle** value, so the number of bundles in a CHAN does not affect the value. The Power Fractions only have meaning in relation to one another. These values are normalized in proportion to distribute the power to the individual CHAN components.

3. In the 'Powered Components' dialog, set the appropriate 'Power Fraction' for the CHANs:
   - Channel 1 (Ring 1) – hot bundle
   - Channels 2 and 3 (Ring 1)
   - Channels 4 and 5 (Ring 2)

   Close the dialog.

The CHAN radial power profile, which was identified in the PIRT as having a high impact on LBLOCA PCT has now been (partially) configured. In particular, there is now a **hot bundle**. Ring 2 CHANs are given a lower power. The power profile inside the channel still needs to be configured. This will be done in the Radiation Model sections that follow.

Configuring the Radiation Model

The radiation power per area emitted from a body is given by $P=\epsilon\sigma T^4$ where ϵ is the emissivity, σ is the Stefan-Boltzmann constant, and T is the temperature. The amount of this emitted power that reaches a second body is given by the view factor.

If the difference in emitted power per area between the rods and/or channel box becomes large enough (by a significant difference in temperature), radiation can become a significant form of heat transfer among the bundle rods and from the rod bundle to the channel wall.

In order to configure the radiation model:

1. The emissivity ϵ of the rods and the channel wall have to be specified.
2. A radial power profile also has to be defined in the bundle in order to have a temperature profile that is used in calculating radiation between rods and from rods to the wall.
3. View Factors need to be defined for the different objects that participate in radiation heat transfer.

The emissivity ϵ of the rods and channel wall (item 1 above) can be assigned in the CHAN Properties Window. The power profile and view factors (items 2 and 3 above) are handled by defining 'rod groups' and specifying these properties for the rod groups.

Radiation and other rod properties are defined by assigning rod groups. Each CHAN starts with one default rod group called the average rod group. Additional 'Non-Average' rod groups can be created. Each rod belongs to one rod group, and properties for the group are calculated by averaging properties for each rod in the group. Different factors can contribute to the selection of rod groups. One such factor is rod power and rod groups can be used to define a bundle cross sectional power profile.

CHAN 1 is the hot bundle, and we will only set up the radiation model for this CHAN in this exercise.

Configure Radiation Model – Set Emissivities

Some of the materials used in a core are carbon steel, stainless steel, inconel, and zircaloy. Typical emissivity ϵ values are given in the table below:

Material	Emissivity	Reference
Carbon Steel (Mild Steels)	0.2-0.35	*Heat Transmission* Chemical Engineering Series W. McAdams 1954
Stainless Steel (Type 301 Cc)	0.51-0.7	
Inconel (Type X)	0.55-0.78	
Zircaloy	~0.4	TRACE Theory Manual

A temperature based quadratic formula $\epsilon_1 + \epsilon_2 T + \epsilon_3 T^2$ is used for emissivity if this information is available. In SNAP, the emissivity coefficients are called Emissivity 1, Emissivity 2, and Emissivity 3. If Emissivity 1 (ϵ_1) value is specified and Emissivities 2 and 3 (ϵ_2 and ϵ_3) are 0, the emissivity is modeled as a constant.

In order to determine what emissivity to use, we will look at what material has been used for the channel or canister wall and for the fuel rod cladding and then set the emissivity accordingly. To do this:

1. In the View Window, select CHAN 1.

2. In the Properties Window, open the ▸ Canister Wall section and Expand the "Wall Material" input box. From the 'Specify Radial Materials' dialog, note that the channel wall material is Zircaloy, so we will use an emissivity of **0.4** for the channel wall. Close the dialog.

3. In the ▸ Canister Wall section set 'Canister Emissivity 1' to **0.4**. Since we assume constant emissivity, verify that Emissivity 2 and 3 are **0.0**.

4. In the ▸ Fuel Rods section, Expand the "Radial Geometry" input box. The 'Define Radial Geometry' dialog that pops up gives the composition of the rod radially outward. Note that the cladding material (intervals 7 and 8) are Zircaloy like the channel box, so an emissivity of **0.4** will be used again.

> The 'Channel Fuel Rod Radial Mesh' dialog is where you specify the material composition of the rod.

5. In the ▸ Fuel Rods section, set 'Rod Emissivity 1' to **0.4**. Again since we assume constant emissivity, so verify that Emissivity 2 and 3 are **0.0**.

Configure Radiation Model – Add Rod Groups

> Each CHAN has a 'Rods per Row' property. If n is the Rods per Row, then there will be $n \times n = n^2$ total rods in the bundle.

The hot bundle is configured as an 8x8 channel (64 fuel rods). The hot rod CHAN model contains one average rod group. Three additional rod groups will be added. One group will be for lower power rods, one for higher power rods, and one group that holds a single hot rod. To set up the Non-Average rod groups do the following:

1. Expand 'Non-Average Rods' in the ▸ Fuel Rods section of the Properties Window.

2. In the 'Edit Non-Average Rods' dialog, click 

three times to add 3 Non-Average rod groups.
    a) When these rod groups are added, there is a glitch in SNAP that will show up as an input error when a 'Check Model' is done. To get around the glitch, while in the the fuel rod section, locate the 'fuel-clad Interaction' box and change it from '[0] dynamic gas-gap model is off' to '[1] dynamic gas, clad rupture off'. Then under "Fuel Properties" expand the 'Gap Gas Mass Fractions' box and set Helium to 1.0 for all of the fuel rods and 0.0 for all of the other gases. After this is done go back to the fuel rod section and reset the dynamic gas-gap model to off ([0]). This glitch will be fixed in the next version of SNAP.

For this exercise, it has been determined that the three Non-Average Rods have no plutonium dioxide, a fuel density of 0.95, and an average gap-gas pressure of 1.0e5 Pa. In addition, the Non-Average rod have following attributes:

- Non-Average Rod: 1 has a power peaking factor of 0.9 and has 12 physical rods.
- Non-Average Rod: 2 has a power peaking factor of 1.1 and has 4 physical rods.
- Non-Average Rod: 3 is the hot rod of the hot channel and has a power peaking factor of 1.25.

3. For each Non-Average Rod apply the above fuel rod input information.

> The **Power Peaking Factors** indicate the relative power of the rod groups, and only have meaning in relation to one another. The values are normalized proportionally so that the total power produced by the CHANs is consistent with the power defined in the power component. The **Physical Rod Multiplier** indicates the number of rods in the group. Later we will assign specific rods in the bundle to each group. The number of rods indicated by Surface Multiplier above will be assigned to the individual rod groups.

Note that the Non-Average rod groups are labeled 1, 2, and 3, but when configuring which rods are in the groups will actually be referred to as groups 2, 3, and 4 when assigning rod groups. The default average rod group will be group 1.

Above we set the Power Peaking Factors and Surface multipliers for the Non-Average Rod groups. Properties for the average rod group are found in the main Properties Window for the CHAN. To set these values for the average rod group (group 1), do the following:

1. In the ▸ Fuel Rods section of the Properties Window, set 'Physical Rod Multiplier' to **47**.

The Surface Multiplier indicates the number rods in the average groups. Some rods were added to the Non-Average groups (12, 4, and 1 for a total of 17). There are 64 rods in the bundle, so 64-17=47.

2. In the Properties Window, click on ▸ Fuel Properties and set the power peaking factor to 0.98

Configure Radiation Model – Assign Rod Groups

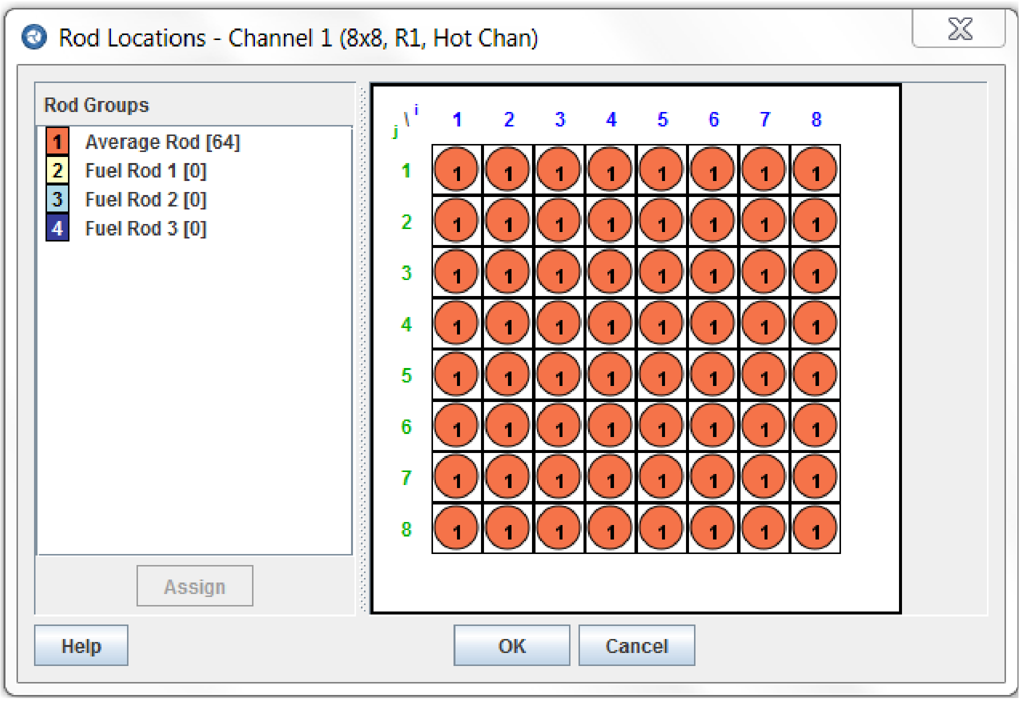
View factors need to be calculated between each rod group, and between each rod group and the channel wall. This can either be done manually, or you can graphically select the rods that are part of each group and have the view factors calculated for you automatically. For this exercise, the graphical method will be used.

To graphically assign the rod groups do the following:

1. With CHAN 1 selected, set 'Use Radiation Enclosure' to **False** in the Properties Window under the ▾ General section. When false is selected, rod groups are assigned graphically and the view fractors are calculated internally in TRACE.

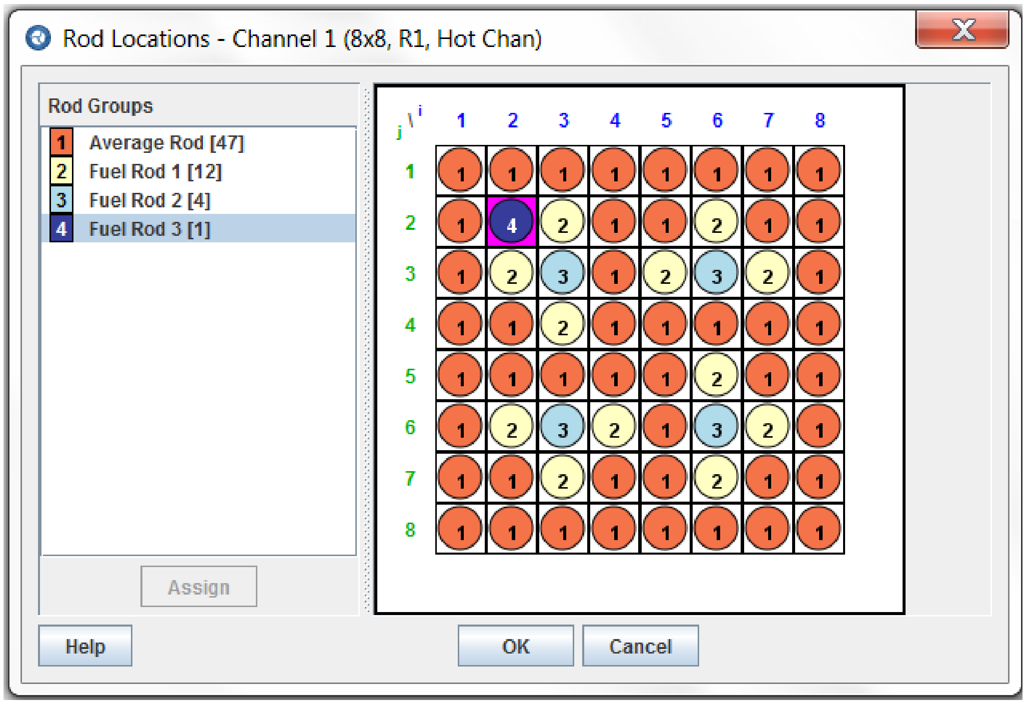
2. Note that when 'Use Radiation Enclosure' is set to **False**, SNAP adds an option to turn the radiation model on or off to the CHAN properties. To verify that the radiation model is on, at the bottom of the ▼ General section of the Properties Window, check that 'Radiation Model' is set to on.

3. To assign the rod groups, Expand 'Rod Locations' under ▼ General and note the following configuration.



4. To assign a fuel rod to a particular rod group, click on the rod in the graphical display, click on the “Assign” button, and then under “Rod Groups” click on the rod group the selected fuel rod is assigned to. Note that multiple fuel rods of a rod group can be selected when assigning to a rod group.

5. Using the method described in Step 4, assign the fuel rods in the hot channel to be consistent with the figure shown below. Note the number of fuel rods assigned to each rod group and assure that the numbers in your model match those shown in the figure.



Normally the process of configuring the radiation model has to be repeated for each of the CHAN components. For purposes of the exercise, this will not be done for the other CHAN components.

With the emissivities set for the rods and the channel wall, the rod groups configured, and rods assigned to rod groups, radiation heat transfer, which the PIRT indicates can have a medium to high impact on PCT for LBLOCAs, is now captured in the model.

With the power configured across the different CHAN components (core wide power profile), and the rod group powers configured within the hot bundle, with rods assigned to the rod groups (CHAN specific power profile), the radial power profile, which the PIRT identifies as having a high impact on PCT during reflood is now configured for the simplified BWR model.

Make a Steady State Run

When you make changes to a model, it is a good idea to keep a backup of the original copy in case errors are introduced that are difficult to find. We use a source control tool to store backups when developing models (there are many good source control tools available such as the freely available svn or git).

It is also a good idea to run a model after you have made a set of changes to verify that it still works. Fixing a model after many changes have been made can be difficult since the number of places where errors might have occurred depends on the number of changes to the model. The likelihood of multiple errors, which complicates debugging, also increases.

Do a model check to verify that SNAP does not detect any errors in the model. If there are no errors to fix, run a steady state simulation by doing the following:

1. Save the SNAP model as PBTT-SS-Ex1.med.
2. Submit the steady state simulation using the Job Stream View tab located at the bottom of the View Window in the Model Editor.
   a) Click on the Execute button and change the name to reflect this exercise (for example BWR-Steady_State-ex1). Note that changing the name of the SNAP job submission will not over-write the calculation made at the beginning of this exercise.
   b) Click on the lock button in the upper left-hand corner of the View window and then click on the Execute button to submit the job.

From the animation window review the steady state target values again. Did any values change significantly?

Parameter	Target/Expected Value	Actual Value
Turbine Stop Valve Pressure		Old: New:
Steam Dome Pressure		Old: New:
Downcomer Level		Old: New:
Core Mass Flow		Old: New:
Total Jet Pump Mass Flow	None Given	Old: New:
Core Inlet Temperature		Old: New:
Feedwater Flow	None Given	Old: New:
Steam Line Flow	None Given	Old: New:

Optional Exercise

Do the 'Phenomena Review' exercise (the BWR-3-Optional-Phenomena.pdf file). This reviews through all the phenomena which is ranked as having a high impact on PCT for BWR LBLOCA events, and has you consider some of the dependencies on steady state parameters.

Conclusion

This exercise stepped through configuring some of the phenomena that are identified by the PIRT as having high impact on Peak Cladding Temperature (PCT). The exercise focused on a few phenomena that are often more significant in BWR accident scenarios than in PWR accident scenarios. Some of the components such as jet pump and CHAN components are unique to BWRs and will briefly be discussed further later in the session.