The major accident scenario that this model will be designed for is a Large Break Loss of Coolant Accident (LB-LOCA). In this LB-LOCA scenario, there is a large break of the major coolant line resulting in a reactor shutdown and the rapid draining of coolant from one of the figure of eight loops of the CANDU reactor heat transport system. In this postulated accident the reactor will still have decay heat from the fuel heating up the coolant while it is draining, and could lead to high temperatures in the fuel, the cladding and the calandria/pressure tubes. These high temperatures could cause issues such as hydrogen formation, fissile material release into containment, and in worst case projected scenarios could lead to core geometry degradation caused by the rupture and destruction of single or multiple channels. To determine whether or not this is a possibility, and the timing of these different steps, a model that describes the behavior of the core must be created. The first part of this model is to describe the operation of the intact calandria tubes with a characteristic channel model.

# MATLAB channel model overview

To begin an analysis of the CANDU reactor under severe accident conditions, a model of the CANDU channel must be created to assess the properties at different times. This channel model will be used to assess the performance of different characteristic channels within the calandria during the progression of the accident. Each of these characteristic channels will be defined by: the power of the channel, the decay heat generation/fuel age of the channel, the flow rate within the channel and the location of the channel in the reactor lattice.

The single channel model is integral to the model as the performance of the calandria tubes within the CANDU reactor determines the overall system response to the accident position. This model will be developed in multiple stages, the first being complete channel models with single phase fluid flow, and the second includes two phase flow within the channel as well.

## Single Phase Model

This is the first model that was created to approximate the behavior of the CANDU fuel channel. This model used basic flow and heat transfer for single phases. This model was extremely simplistic and only describes the channel under a small subset of conditions. It was converted to the two phase model before it was completely finished as the two phase model would cover the same conditions as well as most others the channel. The main outcome of this model was a method of determining the friction factor (Darcy-Weisbach) for the turbulent flow within a CANDU channel.

## Two Phase model

The two phase model that was developed came directly from the single phase as the governing equations are the same, with the difference being the effect on these due to the different properties of vapor and liquid coolant. As the vapor phase has a much lower density, the channel will develop lower flow rates, and there will be different heat transfer effects as well. The effects of the two phases on channel performance will be discussed in the following section.

# Two Phase Channel Model Development and Description.

To determine the performance of a characteristic channel, a major component is the flow of coolant within the channel. This coolant flow is what actually keeps the fuel at reasonable temperatures under normal operation by removing the heat generated by the fuel. The flow through a channel is determined by the effect of friction of the walls and internal elements of the fuel channel on the momentum of the fluid. This friction will cause pressure losses within the system and determine how much mass flow can go through the system at any given time. This friction and friction losses are generally described for pipe sections and enclosed channels with what is known as the Darcy-Weisbach equation in which ΔP is the pressure drop over the section, L is the length of the section, M is the mass flow, Dh is the hydraulic diameter or characteristic diameter of the section, ρ is the density of the fluid flowing in the channel and fd is the Darcy friction factor:

Equation

The Darcy friction factor is a factor that varies for different flow conditions within the channel. For very low flows where the behavior of the fluid is laminar Re, this can be determined by a simple relation the fluids Reynolds number.

Equation

This relation does not work at conditions of turbulent flow (Re<3200) and becomes a function of the roughness and size/shape of the pipe, and the velocity and properties of the fluid. This relation becomes quite complex and is best described for flows with Reynolds numbers above 4000 by the iterative Colebrook-White equation:

Equation

There are other equations that do not require iteration that approximate the results from the Colebrook-White Equation such as the Haaland equation, however for the purpose of this initial channel model, the friction factor was found through a simplified method. The first part of the friction factor was defining a few assumptions: The channel dimensions/roughness will be the same throughout the intact channel, there will always be forced flow (from pump or due to large pressure differences between the atmospheric containment and the pressurized system in the case of a LB-LOCA) leading to the assumption that the pressure drop will be constant and there will be highly turbulent flow. Under fully developed turbulence, the friction factor does not change depending on flow rate, so it was assumed that tis value would not change for the channel section under the flow it will see in the accident scenario. This allowed for the rearrangement of the first equation into a very manageable form…

Equation

Equation

Where k is a combined constant consisting of the characteristic dimensions of the channel (length and hydraulic diameter) as well as channel friction factor and represents the effective resistance of the channel. This equation is only valid under turbulent flow where fd is constant, but as previously stated, it is assumed that the constant flow out of the system as well as the changing states of the coolant will keep the flow in the turbulent region for as long as this model configuration is valid. Should the intact channel develop lower flow rates so as to enter laminar flow regimes or even stagnate, another model will need to be developed as these conditions greatly change the heat transfer and behavior of the reactor channel.

To determine the k value for the evaluated CANDU channel, equation 4 was rearranged, and characteristic data for mass flow, pressure drop and coolant conditions (density) from existing CANDU plants operating at normal capacity were used determine the k. This empirically derived k value was able to be used within the channel model due to the previous assumption that all flow is turbulent and that there is no change of friction factor with change in flow or phase of coolant.

Within higher power channels in the CANDU reactor (approx. >6.5 MW) the thermodynamic quality begins to become positive. This greater than 0 quality results in the formation of vapor and the onset of two phase flow. Two phase flow is a very complex situation in any system due to the interaction of the two phases, and the differences in physical properties (density, heat capacity, thermal conductivity). The interaction of the two phases can vary greatly depending on density differences and velocity differences caused by different combinations of temperature and pressure, as well as heat input, and the behavior of two phase flow is historically very difficult to predict and assess. Many derivations of the behavior of two phase flow from direct physical constants and properties lead to equations and correlations that require lots of information that is not always practical to measure therefore there are many empirical correlations that have been derived from experimental data.

In this model, the two phase flow is determined by two phase flow factor that approximates the flow characteristics based measurable flows of liquid, gas or fluid only. This is known as a two phase flow friction multiplier. For this model the friction multiplier is based on the assumption that the fluid flow is all liquid. This is represented by the following equation.

Equation

For the channel model, as the pressure difference is constant, equation 4 and 6 can be rewritten into the useful form of equation 7 below.

Equation

This equation describes the mass flow of the two phase fluid in reference to the liquid only flow. As the density of the coolant vapor in the fuel channel is much lower for the vapor, there will be a large increase in volume. This increase in volume will reduce the overall mass flow to match the constant pressure drop and leads to lower cooling rates for the fuel.

For this model, an correlation devised by Levy(1967) was used. Levy correlated the two phase friction multiplier with the void fraction of the channel by assuming that vapor and fluid flows are equivalent and that the friction factors are equal for the two phases. These assumptions, along with a derivation from the Bernoulli equation led to the correlation:

Equation

In this correlation, the only system property needed is α, the void fraction of the channel flow. The void fraction of two phase flow is in itself quite complex to determine as it is affected by many factors including, but not exclusively: system temperature and pressure, thermodynamic quality, boiling regime, and the viscosity of the phases. There are many correlations to determine this, some completely empirical and others that are partially derived from physical processes. For this model the Lockhart-Martinelli correlation was used. The Lockhart-Martinelli correlation was based on research done in the 1940’s and uses what is known as the Lockhart-Martinelli correlation factor which is a parameter that is dependent on the viscosity and density of the two phases as well as the thermodynamic quality. This correlation factor is known as Xtt and is present in other void fraction correlations as well.

Equation 9

This correlation factor was correlated with measured values of void fraction and the following empirical correlations were determined for two different conditions of Xtt.

Equation 10

Equation 11

This two part correlation allows for a larger range of possible density differences to be correlated with less error which for the case of the characteristic channel allows for the calculation of void fraction in a good range of pressures, temperatures and heat inputs.

A major issue that can arise in nuclear heat transport systems as well as many other types of applications that involve heat transfer to a fluid is critical heat flux. Critical heat flux is the highest heat flux that a fluid can take from a system. This critical heat flux is caused when the surface is no longer cooled sufficiently by the continuous contact and evaporation of coolant which takes place in the very efficient nucleate boiling, and a layer of vapor forms between the fluid and the surface. This vapor layer has a much greater thermal resistance which reduces the amount of heat transferred. The onset of critical heat flux depends on many factors including the subcooling of the coolant fluid, the surface which through the heat is being transferred, and the amount of heat. In a typical CANDU channel the critical heat flux will only be reached at high power levels which are not expected to be reached as the reactor will be in a state of shut down with power levels decreasing from the typical values of 5.5 to 8 MW per channel.

Temperature profiles for the different elements of the channel need to be calculated to determine the channel behavior. For the fuel pins it was assumed that the bulk flow within the channel was well mixed and that the average bulk temperature could be used to determine the fuel pin temperatures. The temperatures of the outside and inside of the Zircaloy fuel cladding as well as the outside and centerline of the UO2 fuel meat were calculated. As the temperature of UO2 greatly affects the heat transfer capabilities, the centerline temperature was calculated by dividing the fuel meat into 1000 nodes (concentric shells of UO2) and evaluating the thermal conductivity for each at the inner surface temperature of the previous node.

The temperature profiles for the pressure and calandria tubes were determined by using the available data to determine the thermal resistance of the entire pressure tube/calandria tube assembly. The heat transfer coefficient for the contact of the bulk flow and the pressure tube inner wall was determined, thermal conductivity of the inner Zircaloy was calculated using the bulk fluid temperature. The CO2 gap between the calandria tube and pressure tube was assumed to be stagnant and the thermal conductivity was calculated at the mean temperature between the bulk flow and the moderator temperature. The thermal conductivity of the Zircaloy of the calandria tube was calculated at moderator pressure and a natural convection heat transfer coefficient for the exterior of the calandria tube was assumed to be 1000 W/m.K. These values were used to calculate the heat lost from the channel and subsequently the inner and outer temperatures of the PT and CT. The heat loss assumes that the entire channel is at the conditions of final bulk flow, however in the real physical system this would not be the case. This assumption allows for a worst case scenario analysis and will describe the channel at the most vulnerable point which is of great interest to safety analysis.