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DEPARTMENT OF MECHANICAL AND NUCLEAR ENGINEERING

CODE-TO-CODE VERIFICATION OF COBRA-TF AND TRACE

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ABSTRACT

The purpose of this project is to perform code-to-code verification of the point kinetics models in both COBRA-TF and TRACE and to verify TRACE’s ability to perform sub-channel analysis. This is important to perform to ensure the validity and accuracy of these widely used codes. Additionally, the point kinetics model is relatively new to COBRA-TF and has not been completely verified. On the other hand, the point kinetics model is very mature in TRACE as it has been in place for more than 30 years. Furthermore, COBRA-TF is a sub-channel based code while TRACE is not; the channel component of TRACE only models entire BWR fuel bundles. This project is split into two main parts, analysis of a base model and a modified model. The base model includes nine components each representing a subsection of a quarter core. One of the smallest components represents the hottest channel in the core and the largest represents the entire quarter core. This base model showed substantial differences between COBRA-TF and TRACE, especially during a transient. These differences were exacerbated by inconsistent input between COBRA-TF and TRACE. Since the focus of this work was to verify the point kinetics model and sub-channel analysis, it was decided to create simplified models that contained strong feedback mechanisms. To complete the analysis, two new models were built based on this base model for COBRA-TF and based off of a simple, one pipe TRACE model of a pressure wave propagating through the primary side of a BWR. This means that only one sub-channel is used on COBRA-TF to mirror the single pipe on TRACE. Both of these models use identical point kinetics models. The new models also correct many of the modeling errors found on the base model, such as inconsistent fuel dimensions between both codes. Running these two models is still in progress since incomplete results have been gathered from both codes. Currently, TRACE does not have all reactivity feedback mechanisms turned on, and they must be activated in order to see changes to thermal hydraulic parameters. Additionally, COBRA-TF is not running any calculations with a transient pressure case as there may be issues with the FORTRAN source code of the COBRA-TF executable that is being used.
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LIST OF VARIABLES

\( \alpha = \) void fraction of gas
\( \rho = \) density
\( g = \) acceleration due to gravity
\( U = \) internal energy
\( P = \) pressure
\( \tau = \) shear stress
\( M = \) momentum
\( \Gamma = \) net volumetric vapor-production rate caused by phase change
\( S = \) net entrainment
\( W = \) mass transfer
\( q = \) specific heat transfer
\( Q = \) heat transfer
\( h = \) enthalpy
\( e = \) internal energy
\( v = \) velocity
\( t = \) time
\( K = \) frictional loss term
\( \theta = \) Azimuthal coordinate in cylindrical geometry
\( x = \) Coordinate for one-dimensional geometry
\( T = \) temperature
\( A = \) area
\( V = \) volume
LIST OF SUBSCRIPTS

\( w \) = wall
\( m \) = mixture
\( l \) = liquid phase
\( v \) = vapor phase
\( g \) = gas phase
\( i \) = interface of pipe
\( r \) = relative quantity or variable
\( s \) = entrainment
LIST OF TERMS

\[ \frac{\partial}{\partial t} (\alpha \rho \vec{v}) = \text{Volumetric change in momentum with time} \]
\[ \nabla (\alpha \rho \vec{v}) = \text{Advection of momentum} \]
\[ \alpha \rho \vec{g} = \text{Gravitational force} \]
\[ \alpha \nabla P = \text{Pressure force} \]
\[ \nabla (\alpha \tau) = \text{Viscous shear stress} \]
\[ M^m = \text{Momentum source or sink due to phase change or entrainment} \]
\[ M^d = \text{Interfacial drag force} \]
\[ M^T = \text{Momentum transfer due to turbulent mixing} \]
\[ \tau'''' = \text{Volumetric drag force} \]
\[ \Gamma'''' \vec{v} = \text{Expanded momentum source or sink due to phase change or entrainment} \]
\[ S'''' \vec{v} = \text{Energy added to the system due to volumetric entrainment} \]
\[ \frac{\partial}{\partial t} (\alpha \rho) = \text{Change in mass with time} \]
\[ \nabla (\alpha \rho \vec{v}) = \text{Advection of mass} \]
\[ \Gamma = \text{Mass transfer due to phase change} \]
\[ W^T = \text{Mass transfer in the mesh cell due to turbulent mixing and void drift} \]
\[ S'''' = \text{Volumetric entrainment rate} \]
\[ \frac{\partial}{\partial t} (\alpha \rho h) = \text{Change in energy with respect to time} \]
\[ \nabla (\alpha \rho h \vec{v}) = \text{Advection of energy} \]
\[ -\nabla (\alpha Q) = \text{Conduction and turbulent heat flux} \]
\[ \Gamma h^t = \text{Energy transfer due to phase change} \]
\[ q'''' = \text{Volumetric heat transfer} \]
\[ \alpha \left( \frac{\partial h}{\partial t} \right) = \text{Pressure work} \]
\[ Q^T = \text{Total heat generation} \]
\[ Q'''' = \text{Volumetric heat generation} \]
\[ 1 - \alpha = \text{Liquid void fraction} \]
\[ \Gamma = \text{Vapor generation rate (TRACE only)} \]
\[ q = \text{Specific energy source} \]
\[ P \nabla \cdot (\alpha \vec{v}) = \text{Pressure work} \]
\[ -\frac{\rho \partial a}{\partial t} = \text{Pressure source} \]
\[ \Gamma h_s = \text{Energy source from phase change} \]
\[ \phi(\vec{r}, E, t) = \text{Neutron flux} \]
\[ p(t) = \text{Flux amplitude} \]
\[ \psi(\vec{r}, E, t) = \text{Flux shape} \]
\[ w(\vec{r}, E) = \phi_0(\vec{r}, E) = \text{Flux weight function} \]
\[ \rho(t) = \text{Reactivity} \]
\[ \beta(t) = \text{Delayed neutron function} \]
\[ \Lambda = \text{Neutron lifetime} \]
\[ \lambda = \text{Delayed neutron decay constant} \]
**ACRONYMS**

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
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</thead>
<tbody>
<tr>
<td>PWR</td>
<td>Pressurized Water Reactor</td>
</tr>
<tr>
<td>BWR</td>
<td>Boiling Water Reactor</td>
</tr>
<tr>
<td>LWR</td>
<td>Light Water Reactor</td>
</tr>
<tr>
<td>TRACE</td>
<td>TRAC RELAP Advanced Computation Engine</td>
</tr>
<tr>
<td>CTF</td>
<td>COBRA-TF = Coolant boiling in rod arrays, the two-fluid version</td>
</tr>
<tr>
<td>LOCA</td>
<td>Loss of Coolant Accident</td>
</tr>
<tr>
<td>NRC</td>
<td>United States Nuclear Regulatory Commission</td>
</tr>
<tr>
<td>HEM</td>
<td>Homogenous Equilibrium Model</td>
</tr>
<tr>
<td>RELAP</td>
<td>Reactor Excursion and Leak Analysis Program</td>
</tr>
<tr>
<td>TRAC</td>
<td>Transient Reactor Analysis Code</td>
</tr>
<tr>
<td>PKE</td>
<td>Point Kinetics Equations</td>
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ACKNOWLEDGEMENTS

I would like to thank Dr. Avramova for providing the starting points of this project and answering specific CTF questions. I would also like to thank Faisal Raja for letting me critique his data and letting me use it as a starting, base model and Caleb Jernigan for providing guidance on critiquing the CTF code. Finally, I would like to thank Dr. Watson for taking up this project with me and answering my lengthy, frequent emails. Without his guidance, this project would not have been possible.
Chapter 1

Introduction

Everyday nuclear engineers use a variety of computer programs to carry out their work. They must use computer programs because physical experiments are often unsafe, expensive, and time consuming. This is especially relevant when transient or accident conditions are under evaluation. This allows nuclear engineers to better understand the conditions associated with potential accidents. This process allows the nuclear industry to predict what may happen during a nuclear accident meaning that these conditions can likely be prevented. Therefore, nuclear engineers will want to use the most accurate nuclear simulation tool to predict these accidents. The most effective nuclear simulation code will make the industry safer.

Two of the more prominent nuclear simulation codes are the TRAC RELAP Advanced Computational Engine (TRACE) and Coolant Boiling in Rod Arrays, the Two Fluid Version (COBRA-TF or just CTF). Both of these are thermal hydraulic codes that were derived using a finite volume analysis. Both of them have been used by different companies or institutions to simulate a variety of conditions including normal operating conditions (steady state conditions) and nuclear accidents conditions (transient conditions). Both of these codes have demonstrated similar yet different behavior when analyzing a transient situation. This thesis verifies this assumption by completing a code-to-code verification of TRACE and CTF. The verification will include a simplified steady state and transient model that compares the point kinetics model (PKM) in both CTF and TRACE along with the sub-channel modeling capabilities of TRACE. Both steady state and transient conditions will be simulated with the transient being the
conditions associated with a turbine trip. If any differences are found between the codes, potential reasons behind the differences will be investigated and explained.

Before diving into the actual workings of the codes, some of past work that utilized CTF and TRACE are analyzed. First, CTF is presented with an example of a turbine trip. The data given next is from a NUPEC, BWR full-size fine-mesh bundle test. This test calculated the void fraction at the exit of a BWR’s turbine following a turbine trip [1]. Figure 1.1 below shows the results of this test and compares the simulated values (labeled as calculated) to those that were measured. The calculated void fraction was done using CTF.

![Void Fraction at Turbine Exit for Both Measured Values and CTF Simulation](image)

**Figure 1.1: Void Fraction at Turbine Exit for Both Measured Values and CTF Simulation [1]**

Figure 1.1 shows the void fraction at turbine exit, but it is important to note that this turbine exit is the inlet of a sub-channel. There are some consistent differences between CTF and the measured data. There is about a ten percent difference between the simulation and measured values throughout all times given in Figure 1.1. Additionally, CTF’s data is well extrapolated beyond the turbine trip initiation at about 12 s. This gives a sense of what happens later on after the transient. The biggest issue with Figure 1.1 is that the differences between reality and CTF
are rather different. A question raised from this data is what is the cause of the large difference? How have its authors entered data? This may be something that hinders the accuracy of CTF.

From the same NUPEC set of tests, the authors measured the temperature of select fuel rods of the reactor core before, during, and after a turbine trip simulation. CORBRA-TF was then used to simulate the same conditions [1]. Figure 1.2 shows these results plotted against time. Again, the label “calculated” represents the CTF simulation.

Figure 1.2: Fuel Rod Surface Temperatures before, during, and after a Turbine Trip with CTF and Actual Data [1]

Figure 1.2 clearly shows the rapid rise in fuel rod temperature as the turbine trip starts and its subsequent drop due to the Doppler Effect. It then shows how the fuel rods return to a steady state temperature, this time being due to decay heat. As for comparing CTF to actual data, steady state shows good alignment with the measured values. The alignment is not as clean during the turbine trip. The CTF values seem to exceed the measured temperatures for all of the fuel rods during the spike in temperature. The author of this data gives no clear indication as to why this has happened. This is another point that this thesis will attempt to answer. Is CTF more accurate in a steady state or transient situation?
Similar data is now analyzed from TRACE. The set of data shown here is from Peach Bottom where a turbine trip simulation was done in April 1977. Later, the same simulation was done on TRACE in 2010. Figure 1.3 shows a comparison between data obtained with the 1977 turbine trip simulation and the 2010 TRACE simulation from Peach Bottom [2]. This data is of the normalized axial power distribution of the Peach Bottom II Reactor during steady state. The “PBTT” acronym in Figure 1.3’s legend represents actual data from the plant.

![Figure 1.3: Normalized Power Distribution from TRACE and Measured Data [2]](image)

Figure 1.3 shows descent alignment between the actual data and that obtained by TRACE. The largest difference is at the peak of the power profile with better alignment at the endpoints. However, the alignment is still not perfect, but it is an improvement over the data seen from CTF. It is important to note that the comparison between the last two mentioned figures is not exactly “apples to apples” since one is a steady state and the other is a transient. Nonetheless, one should expect simulated data to be slightly inaccurate in comparison with analytical data. This is because computer modeling can never capture every single intricacy that goes on within a reactor, but it still paints an accurate picture.

To further compare TRACE with actual data, one more source is evaluated. The next set of data is from the Maanshan PWR Nuclear Power Plant, the first PWR in Taiwan [3]. Although
this data is from a PWR while this project focuses on a BWR, it is still relevant especially since the data, shown in Figure 1.4, shows information before, during, and after a turbine trip.

Figure 1.4: Normalized Power and Core Average Temperature before, during, and after a Turbine Trip Using Measured and TRACE Values [3]

More specifically, Figure 1.4 shows the results of a SCRAM, the reactor operation that automatically occurs after a turbine trip that inserts all control rods into the core to stop the fission reaction. The graph shows very good alignment between the measured data and that obtained by TRACE before and during the SCRAM. There are noticeable differences afterwards as the normalized power and average temperature approach steady state. The differences are not substantial; only about an average difference of five Kelvin with average temperature and roughly a difference of 0.1 for the normalized power between plant and TRACE data. The differences in the data sets are less profound than that seen by data obtained with CTF. This implies that TRACE more accurately simulates a transient, namely a turbine trip, as compared to CTF. All of the figures have also shown that simulated values never exactly match what was
measured. This is because all nuclear simulation codes are approximations to reality. This is why
the code that more effectively depicts reality will be desired.

Although this literature review implies that TRACE depicts reality more accurately than
CTF, more information must be analyzed. This section has included very limited data without
ever comparing TRACE and CTF side-by-side which is the only way to complete a code-to-code
verification. This must be done because any nuclear simulation code will not exactly depict
reality perfectly. However, one may do so better than the other. Consistency between the two
codes under evaluation must also be displayed. This comparison will determine if there are any
significant differences between CTF and TRACE. If both codes are shown to be consistent and
accurately depict actual conditions, then both codes are verified.

The next set of data reviewed does compare TRACE with CTF. It does not use a turbine
trip as a transient, but simulates a loss of flow accident. The upcoming data was compiled by a
graduate colleague, Faisal Raja. Raja’s purpose was to implement TRACE’s point kinetics model
onto CTF and to observe the accuracy of that implementation. In order to obtain data, Raja made
a nine sub-channel model on CTF and a nine pipe model on TRACE. Both codes were to have
identical inputs and nodalizations. For example, Figure 1.5 shows one of the pipes created on
TRACE. The 40 nodes are somewhat visible as cells on the diagram.

Figure 1.5: Channel 9 TRACE Pipe [4]

Figure 1.5 also shows a fill component towards the right and a break component to the left. The
fill component contains a mass flow rate table that alters the mass flow rate at different points in
time when a transient is initiated. Figure 1.6 shows the TRACE menu used to compile the mass flow rate table [4]. The loss of flow accident is clearly discernable as mass flow is nearly cut in half.

![Mass Flow Rate Fill Table](image)

**Figure 1.6: Mass Flow Rate Fill Table [4]**

In order to more fully show the nodalization for this TRACE model, Figure 1.7 shows the geometry used per each node or cell. All 40 cells are not shown since that would be too exhaustive of a menu to show. The figure shows that all of the geometric parameters are equally divided into all of the cells. The menu for initial conditions, like temperature and pressure, are placed into a similar menu.
The last few figures show the basics of Raja’s TRACE model. The second half of his project was on CTF where nearly all of the input from TRACE was placed onto CTF. CTF does not have a graphical interface but has ASCII text files as the only option to input data. The nodalization is identical on CTF to that of TRACE. All input conditions, such as geometries and initial thermal hydraulic parameters are also identical. The PKM on CTF is also the same as that of TRACE. Moreover, a similar table was used on CTF to describe the changes in mass flow rate. This table was based on multiplying the initial mass flow rate by a fraction in order to
obtain the desired mass flow rate. The variable ABSC is the problem time and ORDINT is the fraction multiplying the mass flow rate. This is shown in Figure 1.8.

<table>
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<td>21.8</td>
<td>0.5413</td>
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</tr>
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</table>

**Figure 1.8: CTF Mass Flow Rate Table [4]**

The next important aspect of Raja’s model is how the CTF sub-channels and TRACE pipes were modeled. These were modeled based on a quarter core of a PWR. Figure 1.9 shows the core mapping of this quarter core with the different sub-channels designated. The ninth sub-channel (or just channel since it contains many channels) encompasses the entire quarter core.

**Figure 1.9: Quarter Core Mapping [4]**
The two most important sub-channels are the third, which is the hottest sub-channel, and the ninth, which is the largest. The third sub-channel is the hottest sub-channel because it is bordered by a complete fuel rod at close proximity. The ninth channel has more fuel rods associated with it but the amount of non-fuel regions is so great that it is not the hottest sub-channel. These sub-channels all have a different power fraction associated with them, which proved to be an issue on TRACE. There was also some inconsistent input associated with the codes that is explained in detail later.

Now that Raja’s model has been introduced, its steady state data is presented. An example is shown in Figure 1.10. This plot shows the steady state pressure throughout a reactor in the axial direction [4]. The initial pressure is shown at an axial location of 2.5 m, the top of the reactor core. It is also important to note that the author also included a point kinetics model (PKM) of steady state conditions. The PKM is not shown since it yielded nearly identical results as the standard steady state, as expected.

![Figure 1.10: Axial Pressure Profile Comparison between CTF and TRACE [4]](image)
The “steps” in Figure 1.10 show the pressure losses due to the spacer grids of the fuel assembly. These pressure losses do make sense because the presence of spacer grids and structure cause abrupt changes in pressure. For the most part, the pressures between the codes are the same and start at the same starting point at the top of the reactor at 2.5 m. The pressure profiles should align since identical loss coefficients were entered onto both CTF and TRACE. Spacer grids could have been modeled on CTF, but they were not, likely because TRACE does not have a spacer grid component when pipes are in use. The slight variation in pressure must be due to some other reason.

The next two figures come from two different channels used in the data analysis [4]. The two channels are shown for the same conditions because the data from each is different, one being the hottest channel the other being the largest channel. The channels are technically called sub-channels, the smallest flow areas surrounded by different fuel rods [5]. Figures 1.11 and 1.12 show the cladding surface temperature of a fuel rod in the modeled reactor. Figure 1.11 shows the cladding surface temperature of Channel 3 (the hottest channel) while Figure 1.12 shows the cladding surface temperature of Channel 9 (the largest channel) [4].
Both of the figures are undergoing constant power. Figure 1.12 more closely represents the expected axial power distribution in a reactor, similar to what was shown earlier with TRACE versus measured data. Figure 1.11 shows a similar shape, but its TRACE data is flat lining when it should be reaching its peak power profile. This likely means that something is wrong with
Channel 3 and the author suggests that this is caused by a heat structure initialization on TRACE for Channel 3 [4]. Nonetheless, there is a pronounced difference between TRACE and CTF near the center of the axial locations. This thesis will seek an answer to this problem by first recreating and editing this older model that produced the above data.

Now the codes are analyzed during a transient situation. This transient is a drop in reactor core power which shows more pronounced differences between the two codes. More specifically, the transient that is modeled is a 50% loss of flow accident [4]. Additionally, 1.8 s after the loss of flow accident, the power drops by 80% over a 10 s period [4].

The first set of transient plots describes the above actions without using point kinetics. The transient set of data is run for 31.8 s with data collected at that time [4]. Figure 1.13 shows the results of the pressure throughout the axial direction of the core with the loss of flow accident applied. There are noticeable differences between the pressure results of CTF and TRACE that are not due to spacer grids. The models still start at the same point of around 2.5 m.

![Figure 1.13: Axial Core Pressure during Transient [4]](image-url)
To see if this is an error with other data, more information is analyzed. This time the temperature of the coolant when moving in the axial direction of the core is presented. The differences between both codes are still significant. This is shown in Figure 1.14 where TRACE is presented as having a constant coolant temperature. The data was taken after 21.8 s, or the time the TRACE code was allowed to run to achieve steady state.

![Figure 1.14: Coolant Temperature Comparison in the Axial Direction during a Transient](image)

There seems to be extensive differences between CTF and TRACE in a transient situation. Sometimes the results do not even resemble one another in a qualitative fashion as seen in Figure 1.14. Perhaps the issue is that one of the codes was not set up correctly. This is a good assumption based off of Figure 1.14 where TRACE and CTF show drastically different results. This was due to the steady state TRACE case not being run to a true steady state, also known as poor model initialization. This has been corrected by running the steady state TRACE case to 100 s allowing the model to converge to a steady state at about 50 s. Making the run time longer made the plots appear like a proper transient; however they still did not align. This may have
been caused by an improperly input power model. However, this model cannot be altered as it was empirically given data [4].

The series of plots shown demonstrate that the results of TRACE are somewhat different than those for CTF especially in transient conditions. They are even different when solely compared to the theoretical or measured values. These differences must be explained in order for nuclear engineers to understand the full capabilities of TRACE and CTF. This may even imply that one code is better to use than the other in specific applications. This means that CTF might be able to do sub-channel analysis better than TRACE since CTF is a sub-channel code. This can only be concluded after code-to-code verification is complete. Therefore, the remainder of this report will be a verification of TRACE’s and CTF’s point kinetics model and TRACE’s ability to do sub-channel analysis. This will be done in two main parts. The first part involves an analytical evaluation of the codes’ equations and will seek to discover fundamental differences in how each code was derived. The second part will use new modeling data of running first a steady then transient with both CTF and TRACE to see if differences still exist. Raja’s data will be used as a base model. The base model will be changed to represent consistent input between both codes and will include a turbine trip transient. Furthermore, the feedback mechanisms associated with a turbine trip are of interest since both codes may respond differently to them. Some of this feedback is Doppler and void fraction, for instance. This base model will only be used for CTF while a simple, single pipe TRACE model that is setup for a turbine trip will be used as the final TRACE model with PKM activated. If the results of the codes are not consistent, then the code-to-code verification signals that one code is more accurate than the other under certain circumstances.
Chapter 2

Code Derivations

CTF Code

One type of sub-channel analysis computer code is the Coolant Boiling in Rod Arrays, the Two-fluid Version, or COBRA-TF (also abbreviated as just CTF). As it name implies CTF uses a two-fluid model that considers the three independent flow fields of fluid film, vapor, and liquid droplets. CTF also has a large array of thermal hydraulic models which are essential in performing Light Water Reactor (LWR) sub-channel safety analysis. The program is also powerful enough to analyze a whole vessel Loss of Coolant Accident (LOCA), although only a single sub-channel will be analyzed here. A sub-channel is defined as the smallest flow area bounded by a combination of fuel rods. This is further broken down into three categories: interior, edge, or corner sub-channel [5]. The type of sub-channel used in this work is an interior sub-channel as this type represents a location in a reactor core surrounded by four fuel rods. An interior sub-channel is also more indicative of the actual conditions of a core since the power profile of a core will have power peaks away from core boundaries.

In addition, the two-fluid model utilizes an array of conservation equations which are explained below. These conservation equations represent three fields: mass, momentum, and energy. First, conservation of momentum is presented. It is important to list the conservation of momentum equations for each phase analyzed with CTF. These will include conservation of momentum for a vapor, continuous liquid, and entrained liquid [6]. The vapor phase represents
momentum with all vapor conditions. The continuous liquid phase is when only liquid exists throughout the volume being analyzed. Finally, an entrained liquid is a two-phase situation where liquid droplets are trapped within a gas flow [6]. The liquid field is ultimately divided into the continuous liquid and entrained liquid forms to show that both equations have different velocities. The conservation equations are now listed and explained below. These are shown in Cartesian coordinates.

**Vapor:**

\[
\frac{\partial}{\partial t} (\alpha_g \rho_g \tilde{v}_g) + \nabla (\alpha_g \rho_{vg} \tilde{v}_g) = \alpha_g \rho_g \tilde{g} - \alpha_g \nabla P - \tau'''_{w,g} - \tau''_{l,g} - \tau'_{l} + \Gamma''' \tilde{v}_g + M^T \quad (2.1)
\]

This equation basically presents a balance of forces in the vapor phase. The left hand side shows the time rate of change of momentum and advection of momentum which equate to force. The right hand side sums up surface and body forces. An example of a surface force would be the pressure force term while a body force would be the gravitational force term [7].

**Continuous Liquid:**

\[
\frac{\partial}{\partial t} (\alpha_l \rho_l \tilde{v}_l) + \nabla (\alpha_l \rho_{l} \tilde{v}_l) = \alpha_l \rho_l \tilde{g} - \alpha_l \nabla P - \tau'''_{w,l} + \tau''_{l,g} - \Gamma'' \tilde{v}_s - S''' \tilde{v}_s + M^T_l \quad (2.2)
\]

The equation here is very similar to is vapor phase counterpart with a few nuances. It now includes energy added due to volumetric entrainment, due to the fact that liquid can be trapped in gas flow.

**Entrained Liquid:**

\[
\frac{\partial}{\partial t} (\alpha_s \rho_l \tilde{v}_s) + \nabla (\alpha_s \rho_{l} \tilde{v}_s) = \alpha_s \rho_l \tilde{g} - \alpha_s \nabla P - \tau''_{w,s} + \tau''_{s,g} - \Gamma'' \tilde{v}_s - S''' \tilde{v}_s + M^T_s \mid_{\alpha \leq 0.8} \quad (2.3)
\]
The entrained liquid form is very similar to the continuous liquid equation. The difference is with the momentum transfer due to turbulent mixing, which has a void fraction restriction. This restriction means that the momentum transfer term will only remain in the equation for void fractions of less than or equal to 0.8, or flows that are not in the annular mist flow regime [8].

The remaining CTF field equations are related to one another and deal with conservation of mass and conservation of energy. Three assumptions are used to obtain these equations. They are as follows:

1. The continuous liquid and the entrained liquid fields are assumed to be at thermal equilibrium
2. The conduction heat flux can be partitioned into a wall term and a fluid-fluid conduction term; the latter is assumed negligible in the entrained liquid
3. All mass entering or leaving a phase interface is at saturation [6]

As with conservation of momentum, conservation of mass will be described in all phases, vapor, continuous liquid, and entrained liquid [6].

Vapor:

\[
\frac{\partial}{\partial t} (\alpha_g \rho_g) + \nabla (\alpha_g \rho_g \bar{v}_g) = \Gamma''' + W_g^T \tag{2.4}
\]

This conservation of vapor mass describes how the change in mass plus the advection of mass is equal to the volumetric mass transfer and mass transfer due to turbulence. The equation basically represents a balance of mass transfer throughout the vapor.

Continuous Liquid:
\[ \frac{\partial}{\partial t} (\alpha_l \rho_l) + \nabla (\alpha_l \rho_l \vec{v}_l) = \Gamma_{l}^{\prime\prime\prime} - S_{l}^{\prime\prime\prime} + W_{l}^{T} \] (2.5)

This equation is essentially the same as the one in the vapor form with the exception that the phase is now a continuous liquid. Also, the volumetric entrainment \( S_{l}^{\prime\prime\prime} \) has been introduced for the same reason why it was introduced in the momentum equation for a continuous liquid. Once again, there is the potential for two-phase flow which will cause liquid droplets in a gas medium.

Entrained Liquid:

\[ \frac{\partial}{\partial t} (\alpha_s \rho_l) + \nabla (\alpha_s \rho_l \vec{v}_s) = -\Gamma_{s}^{\prime\prime\prime} + S_{s}^{\prime\prime\prime} + W_{s}^{T} \] (2.6)

Aside from accounting for entrainment, this equation is essentially the same as its continuous liquid version. The only difference is with the signs in front of the volumetric mass transfer and volumetric entrainment terms. Being an entrained liquid, the signs make sense as entrainment is being added per unit volume.

Just as with the other conservation equations, conservation of energy will be described in all phasic forms [6].

Vapor:

\[ \frac{\partial}{\partial t} (\alpha_g \rho_g h_g) + \nabla (\alpha_g \rho_g h_g \vec{v}_g) = -\nabla (\alpha_g q_g) + \Gamma_{g}^{\prime\prime\prime} h_{g}^{\text{sat}} + q_{i,g}^{\prime\prime\prime} + q_{w}^{\prime\prime\prime} + \alpha_g \left( \frac{\partial p}{\partial t} \right) + Q_g^{T} \] (2.7)

The vapor balance of energy shows a balance of energy terms, including all possible terms that could contribute energy to the vapor phase. These terms, in a broad sense, are conduction, turbulent heat flux, energy transfer, work, and heat generation.

Continuous and Entrained Liquid:
\[
\frac{\partial}{\partial t} \left((\alpha_l + \alpha_s)\rho_l h_l\right) + \nabla (\alpha_l \rho_l h_l \bar{v}_l) + \nabla (\alpha_s \rho_l h_l \bar{v}_s) = -\nabla (\alpha_l q_l) + \Gamma'''' h_l^{\text{sat}} + q_l''' + \\
Q''''_{wl} + (\alpha_l + \alpha_s) \left(\frac{\partial p}{\partial t}\right) + Q_l''''''
\]

This equation is unique as the continuous and entrained liquid are now combined. This is a reasonable combination to make as the continuous and entrained phases are related to one another. This may also be done because the liquid and entrained fields are assumed to be in thermal equilibrium [7]. For example, in the continuous and entrained equations for mass and momentum, entrained terms found their way into the continuous liquid equation. This implies that the two forms can be combined, which is what this equation does. This equation does bring up a unique term, that being the void fraction of an entrained liquid. CTF defines void fractions for each of its modeled phases. At the most basic level, each of the void fractions is defined as the volume of a given phase divided by the total volume. As an example, the liquid void fraction would be defined as the volume of liquid in a control volume divided by the total volume within a control volume.

It is also important to reiterate that all of these conservation equations are presented in Cartesian coordinates. They could have been presented in sub-channel coordinates. Sub-Channel Coordinates are sometimes easier to use as they only consider axial and lateral flow directions (Cartesian Coordinates considers the orthogonal flow direction as well). In addition, lateral flow is not fixed and has no direction after it leaves a gap. This means that lateral flow can enter a sub-channel volume through a gap between one sub-channel volume and another. Lateral flow also does not cause too much momentum change across the sub-channel volumes. Therefore, one less momentum equation is needed with sub-channel analysis [7]
CTF Numerical Methods

CTF solves its field equations simultaneously using the Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) [7]. This solution method can be used in several fluid flow situations, such as the Navier-Stokes Equations. The following are general guidelines used to solve problems with SIMPLE [7]:

1. Guess a new pressure term, \( p^* \)
2. Correct pressure and velocity. i.e. \( p = p^* + p' \), where \( p' \) is the corrected pressure
3. Substitute the relations found in Step 2 into the momentum equations. i.e. \( v = v^* + f(p') \)
4. Substitute the relationship from Step 3 into the mass equations. Solve for \( p' \) and then \( v \).
5. Solve for the energy equation.
6. Check the original guess of pressure for convergence.

With SIMPLE completed, the equations can now be put into a finite difference form and solved over a mesh. This is a mesh grid of 3-D volumes. The conservation equations are set up into two meshes, one for scalar quantities, such as \( \alpha \), \( p \), \( h \), etc., and one for momentum [7]. The momentum mesh is used to define the fluid velocity field and is broken into transverse and axial cells. This is shown in Figure 2.1.
Referring to Figure 2.1, the scalar mesh is centered on the momentum cells. Furthermore, the CTF user must enter conditions in order to set up the mesh. Some of these parameters are number of model section, channels per section, scalar mesh cells per channel, and channel connection data. With the mesh initialized, finite differencing can begin.

Since Cartesian coordinates were used earlier to define CTF’s equations, gaps must be defined on CTF or else the transverse cells will not be created. A gap is how different sub-channels laterally communicate [7]. Next, the field equations are written in finite difference form. Here, only the vapor mass equation is shown as an example. First, the conservation of mass equation is expanded into all directions [7].

\[
\frac{\partial}{\partial t} (\alpha_v \rho_v) + \frac{\partial}{\partial x} (\alpha_v \rho_v u_v) + \frac{\partial}{\partial y} (\alpha_v \rho_v v_v) + \frac{\partial}{\partial z} (\alpha_v \rho_v w_v) = \Gamma'''' + \sum_{k=1}^{n_k} (M_v^T)_{k}''''
\]  

(2.9)

All of the cell volumes are now multiplied into the terms on the left hand side [7].

\[
\frac{\partial}{\partial t} (\alpha_v \rho_v) \Delta X \Delta Y \Delta Z + \frac{\partial}{\partial x} (\alpha_v \rho_v u_v) \Delta X \Delta Y \Delta Z + \frac{\partial}{\partial y} (\alpha_v \rho_v v_v) \Delta X \Delta Y \Delta Z + \\
\frac{\partial}{\partial z} (\alpha_v \rho_v w_v) \Delta X \Delta Y \Delta Z = \Gamma + \sum_{k=1}^{n_k} (M_v^T)_{k}
\]  

(2.10)
Now the partial derivatives are expanded by taking the difference in mass change over time and over the control volume spatial directions [7].

\[
\begin{align*}
\frac{[(\alpha_v \rho_v)_{j} - (\alpha_v \rho_v)_{j}^n]}{\Delta t} \Delta X \Delta Y \Delta Z \\
+ \sum_{ib}^{nb} \frac{[(\alpha_v \rho_v)_{j}^n u_{v,j-1} \Delta Y \Delta Z]_{ib}}{\Delta X} - \sum_{ia}^{na} \frac{[(\alpha_v \rho_v)_{j}^n u_{v,j} \Delta Y \Delta Z]_{ia}}{\Delta X} \\
+ \sum_{k_y=1}^{nk_y} \frac{[(\alpha_v \rho_v)_{j}^n v_{v,k_y} \Delta Z \Delta X]_{k_y}}{\Delta Y} - \sum_{k_y=1}^{nk_y+\Delta y} \frac{[(\alpha_v \rho_v)_{j}^n v_{v,k_y+\Delta y} \Delta Z \Delta X]_{k_y+\Delta y}}{\Delta Y} \\
+ \sum_{k_z=1}^{nk_z} \frac{[(\alpha_v \rho_v)_{j}^n v_{v,k_z} \Delta Y \Delta X]_{k_z}}{\Delta Z} - \sum_{k_z=1}^{nk_z+\Delta z} \frac{[(\alpha_v \rho_v)_{j}^n v_{v,k_z+\Delta z} \Delta Y \Delta X]_{k_z+\Delta z}}{\Delta Z}
\end{align*}
\]

(2.11)

\[= \Gamma + \sum_{k=1}^{nk} \left( M^T_v \right)_k \]

In the above formulation the old time step mass (represented with superscript n) is subtracted from the new time step mass. The advection terms are now represented with summations because they have multiple connections with other cells. \( \bar{n} \) has been introduced in the advection terms because the scalar cell from which the terms come from is dependent on flow direction [7].

Finally, a series of simplifications take place to make the above formula more elegant. These include canceling terms, scalar cross-sectional areas are used, gap width \( L_k \) is used, transverse velocity \( w_k \) is used, and a source term is added. Below is the simplified finite difference equation read by CTF for conservation of vapor mass [7].

\[
\begin{align*}
\frac{[(\alpha_v \rho_v)_{j} - (\alpha_v \rho_v)_{j}^n]}{\Delta t} \Delta X \Delta Y \Delta Z \\
+ \sum_{ib}^{nb} \frac{[(\alpha_v \rho_v)_{j}^n u_{v,j-1} A_{c,j}]_{ib}}{\Delta X} - \sum_{ia}^{na} \frac{[(\alpha_v \rho_v)_{j}^n u_{v,j} A_{m,ia}]_{ia}}{\Delta X} \\
+ \sum_{k=1}^{nk} \frac{[(\alpha_v \rho_v)_{j}^n w_{k,v} L_k]_{j} \Delta X \Delta Y}{\Delta X} = \Gamma + \sum_{k=1}^{nk} \left( M^T_v \right)_k + \text{Source}
\end{align*}
\]

(2.12)
TRACE Code

The other computer simulation code used in this project is the TRAC RELAP Advanced Computation Engine, or TRACE. This code is a modern version and grouping of the United States Nuclear Regulatory Commission’s (NRC’s) old codes TRAC-P, TRAC-B and RELAP. TRACE is the NRC’s thermal hydraulic safety analysis code used to check vendor calculations for a range of design basis accidents [8]. This program can simulate LOCA and system transients in both PWRs and BWRs. TRACE also has 1-D and 3-D modeling abilities making it the NRC’s top simulation tool. Finally, TRACE uses a finite volume method to perform reactor simulation that will be explained in detail later [8].

Conservation equations are also at the forefront of the TRACE code. These equations are all similar to their counterparts in the CTF code. The three conservation equations that are evaluated by TRACE are described in detail below. TRACE uses the Two-Fluid Model. This model assumes non-equilibrium and non-homogenous fluid states. Separate mass, momentum, and energy equations will be needed for each phase [8]. In addition, these equations are adequate for use in TRACE as finite-volume approximations can be applied to them. The equations of the Two-Fluid Model are presented in detail next. First, the conservation of mass equations are described.

Liquid Mass:

\[
\frac{\partial}{\partial t} [(1 - \alpha)\rho_l] + \nabla \cdot [(1 - \alpha)\rho_l\nu_l] = -\Gamma
\]  

(2.13)
This equation represents conservation of mass for the liquid phase. It is very similar to its counterpart seen in CTF. One of the big differences is that \( 1 - \alpha \) has been used to represent the liquid void fraction instead of \( \alpha_l \), which was used for the CTF equations. This is because TRACE uses one definition for void fraction, that being the volume of the gaseous phase over the total volume. If one takes \( 1 - \alpha \), then the liquid void fraction is found on TRACE. The other difference is with \( \Gamma \). In TRACE, \( \Gamma \) represents the vapor generation rate. The negative sign in front of the vapor generation rate means that this vapor generation rate is for condensation. This makes sense in this case since the equation is a balance of liquid mass.

Gas Mass:

\[
\frac{\partial}{\partial t}(\rho_g \alpha_g) + \nabla \cdot (\rho_g \alpha_g \vec{v}_g) = \Gamma
\]  

(2.14)

This equation is nearly identical to the previous one. As expected, \( \alpha \) stands alone and is defined as the vapor void fraction. The other difference is with the sign in front of the vapor generation rate. The sign is positive meaning that this term refers to boiling.

Next, the energy equations for TRACE are described. Again, there will be similarities and differences with their CTF counterparts [8].

Total Energy:

\[
\frac{\partial}{\partial t}[\rho_g e_g + (1 - \alpha) \rho_l e_l] + \nabla \cdot \left[ \rho_g e_g \vec{v}_g + (1 - \alpha) \rho_l e_l \vec{v}_l \right] = P \nabla \cdot \left[ (1 - \alpha) \vec{v}_l + \alpha \vec{v}_g \right] + q_{wg} + q_{wl} \]  

(2.15)

Where \( \frac{\partial}{\partial t}[\rho_g e_g + (1 - \alpha) \rho_l e_l] \) is the rate of change of total energy,

\( \nabla \cdot \left[ \rho_g e_g \vec{v}_g + (1 - \alpha) \rho_l e_l \vec{v}_l \right] \) is the advection of total energy,

\( P \nabla \cdot \left[ (1 - \alpha) \vec{v}_l + \alpha \vec{v}_g \right] \) is the pressure work term
Because the above equation is for total energy, both vapor and liquid terms are presented. This is why for any series of liquid parameters, one minus the void fraction of gas precedes it. The last two terms on the right hand side are both energy source terms due to the presence of a wall in the flow channel.

Gas Energy:

$$\frac{\partial [\alpha \rho_g e_g]}{\partial t} + \nabla \cdot [\alpha \rho_g e_g \tilde{v}_g] = -\frac{p \partial \alpha}{\partial t} - p \nabla \cdot (\alpha \tilde{v}_g) + q_{wg} + q_{lg} + \Gamma h_{sg} \tag{2.16}$$

This equation is nearly identical to the one for total energy. A few new terms have been added due to the presence of vapor. For example, $\Gamma h_{sg}$ represents an energy source from the droplet to vapor phase change.

The upcoming equations are labeled as the equations of motion, as they are in literature, but they are also known as momentum equations.

Liquid Equation of Motion:

$$\frac{\partial \tilde{v}_l}{\partial t} + \tilde{v}_l \nabla \cdot \tilde{v}_l = -\frac{1}{\rho_l} \cdot \nabla P + \frac{c_i}{(1-\alpha)\rho_l} (\tilde{v}_g - \tilde{v}_l) |\tilde{v}_g - \tilde{v}_l| - \frac{\Gamma^-}{(1-\alpha)\rho_l} (\tilde{v}_g - \tilde{v}_l) - \frac{c_{wl}}{(1-\alpha)\rho_l} |\tilde{v}_l| |\tilde{v}_l| + \tilde{g} \tag{2.17}$$

Where $\frac{c_i}{(1-\alpha)\rho_l} (\tilde{v}_g - \tilde{v}_l) |\tilde{v}_g - \tilde{v}_l|$ is the interfacial friction term,

$\frac{\Gamma^-}{(1-\alpha)\rho_l} (\tilde{v}_g - \tilde{v}_l)$ is the momentum source term based on a phase change,

$\frac{c_{wl}}{(1-\alpha)\rho_l} |\tilde{v}_l| |\tilde{v}_l|$ is the wall friction term

Any momentum equation represents a balance of forces. The liquid equations of motion of TRACE have two different frictional force terms, one caused by the wall and the other by the
interface. Similar to the momentum source term, the interfacial friction term is based off of a phase change from gas to liquid. In the momentum source term, the vapor generation rate is presented to the negative power as it represents condensation here, which makes sense because this is a liquid equation. It also represents a minimum vapor generation rate for this equation.

Gas Equation of Motion:

\[
\frac{\partial \vec{v}_g}{\partial t} + \vec{v}_g \cdot \nabla \vec{v}_g = -\frac{1}{\rho_g} \nabla P - \frac{c_i}{a\rho_g} (\vec{v}_g - \vec{v}_l)|\vec{v}_g - \vec{v}_l| - \frac{r^+}{a\rho_g} (\vec{v}_g - \vec{v}_l) - \frac{c_{wg}}{a\rho_g} \vec{v}_g |\vec{v}_g| + \vec{g} \tag{2.18}
\]

Where \( r^+ (\vec{v}_g - \vec{v}_l) \) is the vapor generation rate with momentum added or removed and \( \frac{c_{wg}}{a\rho_g} \vec{v}_g |\vec{v}_g| \) is the wall friction term.

The equation for the vapor energy is very similar to that given for liquid. One difference is with the subscript sign of the vapor generation rate. It is positive here meaning that it represents boiling, which makes sense for the vapor phase. In this case it is also a maximum vapor generation rate. Now that the basic equations that TRACE interprets have been introduced, the way that TRACE interprets them is described next.

**TRACE Numerical Methods**

The above fluid equations are approximated in TRACE by using two numerical methods, semi-implicit and SETS numerics. SETS (Stability Enhanced Two-Step) numerics is nearly an implicit method meaning that its equations are solved using a semi-implicit method with a stabilizer set of equations [8]. The best way to show this is with a specific example, like what was done with CTF. The gas mass equation for TRACE will be expanded out into its finite
difference form as it is a simple example to use. Any of TRACE’s field equations can be expanded out in a similar way. First, the gas mass equation is integrated over the volume of a mesh set up around a region of a pipe that undergoes 1-D flow [8]. This is the standard mesh used in TRACE analysis. This is also referred to as cell center and edge indexing [8]. Figure 2.2 shows the mesh followed by the equation development.

\[ \frac{\partial}{\partial t} \int_{V_j} (\alpha \rho g) \, dV + \int_{V_j} \nabla \cdot (\alpha \rho g V_g) \, dV = \int_{V_j} \Gamma_j dV_j \] (2.19)

Apply Gauss’ Theorem to the advection term.

\[ \frac{\partial}{\partial t} \int_{V_j} (\alpha \rho g) \, dV + \oint_{S_j} (\alpha \rho g V_g) \, ds = \int_{V_j} \Gamma_j dV_j \] (2.20)

Now transform the surface integral into two area integrals at the mesh boundaries.

\[ \frac{\partial}{\partial t} \int_{V_j} (\alpha \rho g) \, dV + \int_{A_{j+\frac{1}{2}}} (\alpha \rho g V_g) \, dA_{j+\frac{1}{2}} + \int_{A_{j-\frac{1}{2}}} (\alpha \rho g V_g) \, dA_{j-\frac{1}{2}} = \int_{V_j} \Gamma_j dV_j \] (2.21)

To further simplify the above relationship, the volume average of a function \( F \) is defined.

\[ \bar{F} = \frac{\int_V F \, dV}{V} \] (2.22)

Also defined is the area average of a function \( F \).

\[ <F> = \frac{\int_A F \, dA}{A} \] (2.23)
These two relations are now substituted as appropriate into Equation (2.23).

\[
\frac{\partial}{\partial t} (\alpha \rho_g V_g) J_j + <\alpha \rho_g V_g> j+\frac{1}{2} A_{j+\frac{1}{2}} - <\alpha \rho_g V_g> j-\frac{1}{2} A_{j-\frac{1}{2}} = \bar{\Gamma}_j V_j
\]  

(2.24)

Next, divide through by the volume, \(V\).

\[
\frac{\partial}{\partial t} (\alpha \rho_g) J_j + \frac{<\alpha \rho_j V_g> j+\frac{1}{2} - <\alpha \rho_j V_g> j-\frac{1}{2}}{\Delta x_j} = \bar{\Gamma}_j
\]  

(2.25)

Finally, an important assumption must be made in order to place this equation in a semi-implicit form. This assumption is as follows:

\[
\frac{\partial F}{\partial t} \approx \frac{F^{n+1} - F^n}{\Delta t}
\]  

(2.26)

Applying the assumption to Equation (2.26) leads to the final equation that is in semi-implicit form and interpreted by TRACE.

\[
\frac{\alpha \rho_g^{n+1} - \alpha \rho_g^n}{\Delta t} + \frac{<\alpha \rho_j V_g> j+\frac{1}{2} - <\alpha \rho_j V_g> j-\frac{1}{2}}{\Delta x_j} = \bar{\Gamma}_j
\]  

(2.27)

**COBRA-TF and TRACE Analytical Comparison**

Now that some of the basic field equations and finite volume interpretations of both COBRA-TF and TRACE have been presented, the two codes can be compared to one another. Any differences between the codes may explain why their results during a simulation are different, as seen in Chapter 1 of this report. Some differences may seem subtle, but upon detailed analysis these small differences may be the reason why the codes behave slightly differently in certain situations. If the later verification work of this report shows that there are differences between the two codes, then the reasons described here are the likely explanations of the potential differences.
One of the most notable differences is in both codes’ depictions of the void fraction. TRACE defines one void fraction, the volume of the vapor phase over the total volume in the system. This means that the Greek letter alpha is used by itself to represent the gaseous void fraction and one minus alpha represents the liquid void fraction. CTF is nearly identical. There is a separate definition of the void fraction for each of the three phases modeled by CTF. This means that there is a separate alpha for the liquid, vapor, and entrained phases. This is why a different subscript is used for CTF’s void fractions in each of the three phases. However, the original CTF programmers could have just as easily defined the void fraction as TRACE does, but they chose separate variables to represent each phase. Therefore, this difference in the presentation of the void fraction should make little difference in the two codes’ calculations. The codes are using the same definition for void fraction, just presented differently. However, one definite modeling difference is with how each code simulates entrainment or the liquid droplet phase. TRACE does not model the liquid droplet phase while CTF does. TRACE has no way of modeling entrainment alone at this time meaning that CTF has an advantage in this aspect. Work is currently in progress to develop a liquid droplet model for TRACE, but in the one used in this project is not available. This factor gives a hint as to why there are some differences between CTF and TRACE during a simulation. This reason will be verified in the experimental portion of this report.

Another potential structural difference between CTF and TRACE is with the modeling of spacer grids. The CTF model used in the base simulation (Chapter 1 data) uses spacer grids while the one for TRACE does not since a pipe component was used. Modeling of the spacer grids on CTF grants a more accurate treatment of reality with the pressure losses associated with core spacer grids. This implies that CTF may be more accurate than TRACE when analyzing
reactor pressure. To counter this, the programmer can input loss coefficients into TRACE to mimic the spacer grids of a fuel assembly within the core of a reactor. This is what was done by Raja with both of his CTF and TRACE models. Therefore, both codes have identical loss coefficient input meaning that spacer grids and loss coefficients do not impact the results of running each code.

The most profound differences between CTF and TRACE are in how data was input into the codes. This is caused when the user does not truly understand the physics or conditions that they are inputting into their model. One such inconsistent and poor input was with the fuel material, dimensions, and nodalization on Raja’s TRACE model. Raja’s CTF model has reasonable data for these three categories but TRACE did not. For example, the fuel on TRACE was of an incorrect material, likely leading to the slightly inaccurate results for the fuel centerline temperature TRACE profile. The fuel will be corrected to UO₂ along with a thicker, more reasonable cladding that was observed on Raja’s CTF model but not on the TRACE model. The nodes across the fuel region were also altered to ten in the fuel region, one in the gas gap, and two in the cladding region.

The next inconsistent parameter was in the time domain of Raja’s TRACE model. He only ran his TRACE model to 21.8 s, the same amount of time that it took his CTF model to reach steady state. This time was likely input into TRACE because CTF is a steady state code that requires forcing functions to cause a transient. Therefore, CTF does not need to be run for longer periods of time to acquire steady state. TRACE is both a steady state and transient code meaning that it must be allowed to converge to a steady state before a transient can be completed. Therefore, all codes run calculations slightly differently meaning that their time
domains will almost always be different. To remedy this problem, the run time was extended to 100 s on TRACE and the code converged to steady state at around 50 s.

A final issue is in the axial power distribution on Raja’s TRACE model. This profile was given as empirical data meaning that it really cannot be altered. The profile was exactly the same on Raja’s CTF and TRACE models, but it caused the TRACE model to have the highest fuel centerline temperature on the largest sub-channel. This sub-channel had a fuel centerline temperature at 2200 K while all others were around 600 K. On CTF, the hottest sub-channel which has a relatively small area carried the highest temperature. On the other hand, all sub-channels on CTF had reasonable temperatures meaning that it is functioning correctly here. Recalculating the power profile would be lengthy, so an alternative solution is to use a simpler TRACE model that already has the transient conditions input on it.

There are some less obvious characteristics that may lead to differences between the codes’ results. For example, the finite differencing scheme between the two codes is slightly different (see the previous section for more details). These differences cause a slightly different interpretation of the control volume being analyzed. A different finite volume size will yield slightly different results (i.e. slightly different dimensions are used). Moreover, the basic layout of both CTF and TRACE may lead to differences in simulation. CTF models all parameters at the sub-channel level while TRACE expands out to nearly every component of a nuclear reactor. The finite volume scheme would then be applied to either the sub-channels for CTF or the reactor system components (pipes, downcomers, etc.) for TRACE. This means that TRACE has added functionality when compared to CTF. This added functionality expands outside of reactor components to being able to model expansive control systems to control various reactor conditions. More specifically, in the base model shown in Chapter 1, the Raja decided to use
pipes on TRACE to model the sub-channels from CTF. The added functionality of TRACE gives one the option to do this. However, TRACE does have a channel option that could have been used if a BWR was being modeled. However, this is not necessarily that easy since using the channel component on TRACE requires modeling most of the core. A pipe is not quite a sub-channel, meaning that there will likely be differences between results of both codes.

The principle reason why Raja had inconsistent results for a transient simulated on CTF and TRACE was due to inconsistent input. To further expand this argument, it is necessary to input data onto CTF and TRACE to verify that there are still differences between the codes. This data must be simplified in order to make sure that modeling differences are not the cause of poor code comparison. This would verify that inconsistent input prevents a good comparison of CTF and TRACE. Furthermore, understanding an accident scenario is essential in code-to-code verification because the codes will likely be used in accident simulations. This accident scenario for the new model will be a turbine trip. Analyzing an accident that may readily occur is important because the industry will better understand the conditions associated with the accident in order to prevent them from happening again. However, the real reason why a turbine trip is simulated is because this transient causes feedback due to the point kinetics modeling of both codes. The next chapter of this report details the turbine trip simulation done to both CTF and TRACE. This would complete the code-to-code verification between CTF and TRACE.
Chapter 3
Revised Model Conditions

Point Kinetics Modeling

One of the ways that reactor dynamics can be modeled is with the point kinetics equations (PKE). Reactor dynamics represent the actions inside of a reactor during transient situations. Using the point kinetics equations allows one to model feedback and decay heat. The feedback mechanisms that dominate reactor activity are those due to the Doppler Effect and the moderator. The decay heat mechanisms to be modeled are those due to fission products and actinide decay heat [4]. In order to understand all parts of the PKE equations, a brief derivation of it is completed.

The derivation that is presented is of the approximate PKE with simplifying assumptions. First, an amplitude function, $p(t)$, is multiplied by a shape function, $\psi(\vec{r}, E, t)$, that is dependent on space, energy, and time. When multiplied together, these functions represent the flux of a reactor, its amplitude and general shape [4].

$$\phi(\vec{r}, E, t) = p(t)\psi(\vec{r}, E, t)$$  \hspace{1cm} (3.1)

In order to obtain the desired PKE, this function must be integrated. This is referred to as the shape constraint. This means that one of the variables will be held constant, this being $\psi$. Additionally, a time independent weight function must be added as the exponent of both the amplitude and space function. The weight function is defined as follows [4]:

$$w(\vec{r}, E) = \phi_0(\vec{r}, E)$$  \hspace{1cm} (3.2)
Now the weight function, which is a weighted flux, is multiplied by the shape function for integration to take place. The combined function is now divided by the velocity of the neutrons in the reactor and integrated over the energy spectrum and volume of the reactor. This is a constraint necessary for the shape function to accurately represent the desired PKE. $K_0$ is a constant here [4].

$$
\int_V \int_0^\infty \frac{\phi_0(\vec{r},E)\psi(\vec{r},E,t)}{v(E)} dEdV = K_0
$$

(3.3)

With this complete, the point kinetics equations can be written out in the following forms:

$$
\dot{p}(t) = \frac{\rho(t) - \beta(t)}{\Lambda(t)} p(t) + \frac{1}{\Lambda_0} \sum_k \lambda_k \zeta_k(t) \quad (3.4)
$$

$$
\dot{\zeta}_k(t) = -\lambda_k \zeta_k(t) + \frac{F(t)}{F_0} \beta_k(t)p(t) \quad (3.5)
$$

Where the equation with $p(t)$ represents reactor power and $\zeta(t)$ represents the impact on power due to delayed neutrons. These equations are the exact point kinetics equations.

The point kinetics equations are still not complete for implementation into the computer codes. Two simplifying assumptions need to be made. First, the shape of the flux as a function of space, energy, and time is approximately equal to the initial flux as a function of space and energy [4]. This is only valid if the initial power of the reactor is equal to unity. The other assumption is that the time dependence of the flux is separable from the spatial and energy dependences [4]. This is why the flux is so often reported as only being a function of space and energy. With these assumptions in place, the approximated PKE can be written.

$$
\dot{p}(t) = \frac{\rho - \beta(t)}{\Lambda} p(t) + \frac{1}{\Lambda_0} \sum_k \lambda_k \zeta_k(t) \quad (3.6)
$$

$$
\dot{\zeta}_k(t) = -\lambda_k \zeta_k(t) + \beta_k p(t) \quad (3.7)
$$

Now that the PKE has been developed analytically, the equations can be input into both CTF and TRACE. There are two general methods of imputing reactor power into the codes, with
a power table or using PKE. The variable power is usually set by a table which is a function of a system signal-variable parameter or a constant-block output-signal parameter. Any values between entries in any of the tables are determined by linear interpolation [4]. This is the simplest method but cannot be used here because it does not include any of the PKE.

The second method determines the power from the solution of the point kinetics equations with reactivity feedback. In this case, the time behavior of the core power level with neutron reactivity is specified. This neutron reactivity is the sum of the programmed reactivity and feedback reactivity. Similar to the first method, the programmed reactivity is input by the user in a tabular method [4]. The code will then evaluate the feedback reactivity based on changes in the several reactor parameters such as core averaged fuel temperature, coolant temperature, and boron concentration which all changed with the changes in reactivity. Furthermore, the programmed reactivity accounts for both fuel reactivity and control rod movement [4]. The code then has the ability to determine the power by evaluating the PKE. The specific PKE that the code evaluates is a coupled set of (I+1), first order, differential equations that define fission power and the delayed neutron precursor content. This sounds very similar to the PKE mentioned above and it is, with a few minor changes, including the precursor concentration given as $C_i$. This is the “traditional” set of PKE that are frequently used in other Penn State courses.

$$\frac{dp}{dt} = \frac{ρ - ρ_0}{\lambda} p + \sum_{i=1}^{I} \lambda_i C_i + \frac{S}{\lambda(1-\rho)}$$  \hspace{1cm} (3.8)$$

$$\frac{dC_i}{dt} = -\lambda_i C_i + \frac{\beta_i p}{\lambda}$$ \hspace{1cm} (3.9)$$

Here, the term with $S$ is a source term.
With the basics of the PKE introduced, some of their implementation into both CTF and TRACE are now explained. This begins by solving the equations, not a trivial task. The overall method used to solve the point kinetics equations is the Kaganove method. This begins by making some approximations that make the equations manageable to solve. First, the reactor power, $p$, is approximated as a second order polynomial, the reactivity, $\rho$, is approximated as a first order polynomial, and the neutron generation time, $\Lambda$, is approximated as a constant. The polynomials just mentioned take the following form [4]:

\[
p(t) = p(0) + p_1 t + p_2 t^2 \quad (3.10)
\]

\[
\rho(t) = \rho(0) + \rho_1 t \quad (3.11)
\]

where $p(0)$, $\rho(0)$, and $\rho_1$ are constants. Next, the second PKE (the one for precursor concentration) is solved for $C_i(t)$ in terms of $\dot{p}(t)$. This is done by integrating the function over the time step $\Delta t$. The new equation will then be evaluated with $\frac{\Delta t^n}{\Delta t}$ and $\Delta t^n$ represents the fluid dynamic time step [4]. Performing the integration leads to a solution for the concentration equation of the point kinetics model [4].

\[
C_i(t) = C_i(0) \exp(-\lambda_i t) + \frac{\beta_i}{\Lambda} \int_0^t \exp[-\lambda_i(t - \tau)] p(\tau) d\tau \quad (3.12)
\]

Next, the previous assumptions are substituted into the first PKE (the one that solves for power) and the function is integrated over time resulting in the following solution. The base PKE used here is slightly different from the one presented earlier because this one includes a neutron source term [4].

\[
p(t) = p(0) + \int_0^t \frac{\rho(\tau)p(\tau)}{\Lambda} d\tau - \sum_{l=1}^l \frac{\beta_l}{\Lambda} \int_0^t \exp[-\lambda_l(t - \tau)] p(\tau) d\tau + \sum_{l=1}^l C_l(0) [1 - \exp[-\lambda_l(t)]] + \frac{s}{\Lambda} [1 - p(0)t - \frac{\rho_1 t^2}{2}] \quad (3.13)
\]

The two above equations now have solutions that fit the following forms [4].
\[ a_1(t)p_1 + a_2(t)p_2 = q(t) \]  \hspace{1cm} (3.14)

Where,

\[ a_1(t) = t \Lambda - t^2 \left[ \frac{1}{2} \rho(0) + \frac{1}{3} \rho_1(t) \right] + \sum_{i=1}^{l} \beta_i t^2 I_{i_1}(t) \]  \hspace{1cm} (3.15)

\[ a_2(t) = t^2 \Lambda - t^3 \left[ \frac{1}{3} \rho(0) + \frac{1}{4} \rho_1(t) \right] + \sum_{i=1}^{l} \beta_i t^3 I_{i_2}(t) \]  \hspace{1cm} (3.16)

\[ q(t) = S + t \left[ \rho(0) + \frac{1}{2} \rho_1(t) \right] \left[ p(0) - S \right] + \sum_{i=1}^{l} \left[ \Lambda \lambda_i C_i(0) - \beta_i p(0) \right] t I_{l_0}(t) \]  \hspace{1cm} (3.17)

\[ t^{m+1} I_{l_m}(t) = \int_0^t \exp\left[ -\lambda_i(t - \tau) \right] t^m d\tau \text{ for } m = 0, 1, 2, \ldots \]  \hspace{1cm} (3.18)

With this information in mind, the PKE are solved on both CTF and TRACE. Delta t is now brought in because the integrals must be evaluated at the end of the integration time step. They can also be solved at the midpoint \((\Delta t/2)\) or the quarter point \((\Delta t/4)\) \([4]\). Incorporating these time steps will increase the accuracy of the final solution. In fact, both codes will use series expansions to solve the equations at different time steps. For example, a Maclaurin expansion can be used with the code halving the time steps to converge to a more accurate answer \([4]\). This is the basic outline of how the computer codes solve the PKE.

**Input Data and Conditions**

The PKE are now modeled on CTF and TRACE. The results of running these are shown in the literature review in Chapter 1. This includes just a handful of the complete results, however, it does show some of the thermal hydraulic parameters produced in the output of CTF and TRACE in graphical form. The data was input into the models in a multifaceted way: with and without the PKE model during steady state reactor conditions and then with and without the PKE model during transient reactor conditions. More specifically, the transient modeled is a 50%
loss of flow accident. Moreover, 1.8 seconds after this change is implemented the power is dropped by 80% over a ten second period [4]. In order for the drop in power to occur, a ramp reactivity insertion is done to the reactor. This means that control rods are inserted into the core by a certain amount to obtain an 80% fall in the initial power level. This also causes an exponential drop in the multiplication factor before this parameter of reactor stability levels off. The point kinetics model is then introduced as a means of obtaining more accurate results by adding feedback mechanisms into the calculations.

Data is not input into CTF and TRACE in the same way. As mentioned earlier, CTF is a sub-channel based code while TRACE takes a holistic view of a reactor and its individual components. Raja’s data referenced throughout this report was input as nine channels of varying sizes on CTF and as nine pipes of unique sizes on TRACE [4]. The pipes and sub-channels are modeled without any cross flow. This modeling is sufficient for the type of calculation used in Raja’s work. Data can now be implemented into CTF’s input deck for each sub-channel. On TRACE, the data can either be entered in a similar fashion as an input deck or it can be entered graphically. Graphical data input is done on TRACE’s model editor called SNAP. This is where the pipes would be constructed with the appropriate sizes, nodalizations, and conditions. To make these TRACE pipes more closely resemble the CTF sub-channels, heat structures with power components are added to the pipes. These modeling differences could easily cause the differences seen in this data as shown in Chapter 1. However, the ultimate reason is inconsistent input between Raja’s codes and improper power fractions assigned to the TRACE model’s heat structures.

Before the unique TRACE and CTF models could be built, Raja’s models showed quite a few inconsistencies and errors. First, the fuel was not dimensioned correctly. The fuel had an
abnormally thick cladding on the TRACE model that did not match its sister input from CTF. This has now been corrected. Additionally, TRACE models pipes while CTF models sub-channels. This has been done because CTF is a sub-channel analysis code while TRACE is not. Pipes were used on TRACE to mimic CTF’s sub-channels as both were dimensioned in a similar way. However, a pipe is never going to exactly represent a sub-channel. Since Raja modeled the quarter core of a PWR, his TRACE and CTF models are likely as accurate as they are going to get by using pipes and sub-channels. TRACE does have a channel option available but it can only be applied to BWRs. However, the most profound difference between Raja’s TRACE and CTF models is that their power structures do not align. This is because CTF shows reasonable values for the fuel centerline temperatures on all nine channels while the sister pipes on TRACE do not. In fact, the largest channel on TRACE shows the hottest temperature of about 2200 K while all other channels hover around 600 K. This means that a large fraction of the power on TRACE is being distributed to the largest channel when the hottest channel should have the majority of power flowing to it. These modeling differences were first corrected before the next leg of the project could be completed.

To make this thesis unique, Raja’s model is simplified. It is simplified to only represent one sub-channel (on CTF) and one pipe (on TRACE) with the same type of PKE calculations taking place. For the TRACE model, a base model completed by Watson in his PhD will be used by inserting Raja’s PKE [9]. The pipe could have been switched to the channel component on TRACE, but this would add appreciable complexity to the model since the TRACE channel requires most other components of a complete BWR core including the core shroud [9]. This project will also alter the initial conditions of a turbine trip in a BWR. More details will be listed in the TRACE chapter but the conditions will be for a turbine trip, the turbine trip that occurred
during a test at the Peach Bottom Nuclear Generation Station. Table 3.1 shows the initial conditions that were input into CTF and TRACE [10].

### Table 3.1: CTF and TRACE Turbine Trip Initial Conditions [10]

<table>
<thead>
<tr>
<th>Condition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet Pressure</td>
<td>68.8405 bar</td>
</tr>
<tr>
<td>Outlet Pressure</td>
<td>38.5989 bar</td>
</tr>
<tr>
<td>Mass Flow Rate</td>
<td>7.5 kg/s</td>
</tr>
<tr>
<td>Inlet Enthalpy</td>
<td>1209.700 kJ/kg</td>
</tr>
<tr>
<td>Outlet Enthalpy</td>
<td>1262.4 kJ/kg</td>
</tr>
<tr>
<td>Inlet Temperature</td>
<td>274.85 °C</td>
</tr>
<tr>
<td>Outlet Temperature</td>
<td>284.85 °C</td>
</tr>
<tr>
<td>Linear Heat Rate</td>
<td>20.94 kW/m</td>
</tr>
<tr>
<td>Initial Power</td>
<td>4.3102E3 kW</td>
</tr>
</tbody>
</table>

On both CTF and TRACE, the new models have an active fuel length of 4.2 m with five axial cells/nodes. These revised models also only have three nodes in the fuel region and one in the cladding. The gas gap is not being modeled. In contrast to the earlier presented models, the new ones do have a constant power profile in both the axial and radial directions. The revised models also have different fuel dimensions. Table 3.2 shows these new dimensions including those for the sub-channel around the fuel [10].
Table 3.2: New Fuel and Sub-channel Dimensions for Both CTF and TRACE [10]

<table>
<thead>
<tr>
<th>Fuel Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outside Fuel Rod Diameter</td>
<td>0.0143 m</td>
</tr>
<tr>
<td>Fuel Pellet Diameter</td>
<td>0.0121 m</td>
</tr>
<tr>
<td>Cladding Thickness</td>
<td>0.00109 m</td>
</tr>
<tr>
<td>Theoretical UO₂ Fuel Density</td>
<td>1.0</td>
</tr>
<tr>
<td>Sub-channel/Pipe Flow Area</td>
<td>0.01 m²</td>
</tr>
<tr>
<td>Wetter Perimeter</td>
<td>0.02857 m</td>
</tr>
</tbody>
</table>

Additionally, for the transient cases, a table of varying pressures is used to run the turbine trip on both of the codes. This is done instead of varying power. Table 3.3 shows the different values of pressure that vary during different times of the transient. When these pressures are input onto both codes they simulate a pressure wave propagating through the primary side of a BWR [11]

Table 3.3: Transient Pressure Table [10]

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Pressure (bar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>68.8405</td>
</tr>
<tr>
<td>1.0</td>
<td>68.8405</td>
</tr>
<tr>
<td>1.5</td>
<td>76.9017</td>
</tr>
<tr>
<td>5.0</td>
<td>68.8405</td>
</tr>
<tr>
<td>50.0</td>
<td>38.5989</td>
</tr>
</tbody>
</table>

The next input into CTF and TRACE is the point kinetics model. The PKM on CTF is left unaltered since it is the same one that is inserted on TRACE. The transfer of PKM
parameters onto TRACE has caused some problems. The issue has been that all feedback parameters must be activated on TRACE. This will be explained in detail in the next section.

As for actual implementation of the new CTF and TRACE models, CTF is changed by implementing the new values from TRACE. Its nodalization is reduced down to five axial nodes like in the companion TRACE model. The CTF model is also reduced down to one sub-channel. However, all reactivity feedback variables are kept constant on CTF. Next, the TRACE model takes much less adjustments. The only adjustment made is that point kinetics is activated and all feedback is changed to match that on CTF. The TRACE model also has a break pressure table that will drive the eventual transient. The TRACE model is shown in Figure 3.1 below.

![Figure 3.1: TRACE Model with Break Pressure](image)

All parameters are now set within both codes for steady state and then transient to be run.
Chapter 4

CTF and TRACE Code Comparison

With the parameters from Chapter 3 entered on CTF and TRACE, these models were first run to steady state. This meant that the forcing functions on CTF and TRACE are not activated at this time since both pressure and mass flow rate must remain constant. On TRACE, steady state behaved as expected even with point kinetics activated since point kinetics really only comes into play during a transient. For example, Figure 4.1 shows the fuel centerline temperature of the TRACE model over time. Keep in mind that this TRACE model is only one pipe, much simpler than the data that Raja presented. Figure 4.1 also shows that a steady temperature is reached rather quickly on TRACE. This steady temperature is at about 770.4 K, lower than that of a PWR but a BWR generally operates at lower temperatures when compared to a PWR.

Figure 4.1: TRACE Steady State Fuel Centerline Temperature
The next step in the verification process is to run TRACE as a transient. This transient will include the pressure table presented in Chapter 3. The pressure table will be placed on the break component of TRACE, essentially putting it on the outlet boundary of the TRACE single pipe model. Additionally, this transient on TRACE was saved as a restart model. A restart model is a simulation very similar to the steady state case that is restarted right after the steady state results are processed. A new job stream must also be implemented on the input model in order to read in this external restart file. Lastly, the external job file is solely run because the regular job file has already calculated steady state results and it would only be redundant to run the steady state case again. The results from this turbine trip situation are presented next.

One of the first checks to ensure that the transient case has worked properly on TRACE is to check the outlet pressure. This should just equate the transient pressure table used to simulate a pressure wave associated with a turbine trip. Figure 4.2 shows the results of the outlet transient pressure from TRACE.
Next, the power must be checked to make sure the proper power spike occurs at the moment the transient is initiated. On the current run of this model, the transient power showed a flat line, obviously not a transient. During a turbine trip, the power should momentarily spike before returning to lower levels once all control rods are inserted into the core [11]. This has not happened here, meaning that the results are inaccurate. Taking a deeper look at the TRACE input model, reactivity feedback was inactive. No reactivity feedback means that the power profile would remain consistent. Therefore, all reactivity feedback mechanisms including decay heat, void fraction, and Doppler feedback must be activated for proper turbine trip results. However, close analysis of the TRACE User’s Manual allowed for input of the reactivity feedback mechanisms. The model was then ran, but showed no clear evidence of reactivity feedback in the model’s plots. However, the ASCII output file did show nonzero feedbacks. It is unclear at this time why the output shows feedback but certain plots, in particular power, do not. One potential reason is that the transient has not been initialized correctly. In fact, when the steady case was ran as a transient (without the restart model), thermal hydraulic parameters took nearly 80 seconds to reach steady values. This means that the restart case should be started after this 80 seconds to insure that initialization is correct. This is currently under investigation and being implemented onto TRACE.

In the meantime, some other data was gathered from the transient. It is important to remember that this data is from the transient case without reactivity feedback and is not the most indicative of a true turbine trip. The first parameter analyzed was the vapor void fraction during the transient. Figure 4.3 shows these results.
Figure 4.3: Vapor Void Fraction during the Transient

Figure 4.3 does show a very quick void collapse during the beginning of the transient which is expected. This void collapse may increase in duration when all reactivity feedback is properly implemented. This is seen with data gathered by Watson when he analyzed a similar scenario. This scenario is not exactly the same as the model with results shown above as it does not have a point kinetics model associated with it [10]. This is shown in Figure 4.4.

Figure 4.4: Expected Gas Void Fraction Distribution
Figure 4.4 also shows that the void fraction should continue to increase at the five second mark, where in Figure 4.3 it begins to sharply decrease right after the 2.7 second mark. Nonetheless, this issue should be corrected with proper implementation of point kinetics feedback. There is also the possibility that pressure feedback is causing slightly different results with the void fraction that cause it to collapse over a much shorter period of time.

Currently work is in progress to fix the power plot to make sure that all feedback mechanisms are processed by TRACE. They are currently all being activated. Once that is corrected, plots of power and fuel centerline temperature will be presented along with a revision of the gas void fraction. Currently it is pointless to show the power plot since it remains at the constant initial power.

Once all parameters are input onto TRACE, the process is repeated for CTF. The base model used for CTF was the same one used by Raja in data presented earlier. This model, however, would be significantly changed to only represent one sub-channel, eliminating all of the data associated with the other eight original sub-channels. The one sub-channel would then take on the dimensions and conditions outlined in Chapter 3 that come directly from the TRACE model. The point kinetics model is also left activated on the CTF model meaning that it will match that on TRACE. However, this point kinetics model will already have all feedback activated as that was completed by Raja. Furthermore, the transient conditions had to be changed from Raja’s model. Raja had a change in mass flow rate forcing function table, which now had to be changed to the pressure break table given in TRACE. However, the forcing function had to be represented as a fraction of the total pressure. For example, Figure 4.5 shows the proper forcing function entered onto CTF to represent the changes in pressure over time. These are the values of
the pressure divided by the initial power. The first number in Figure 4.5 is the time in seconds of
where the pressure fraction is applied while the second number is the pressure fraction.

**Pressure boundary condition**

```
   0.0  1.0000  1.5  1.1171  5.0  1.0000 50.0  0.5607
   *
```

**Figure 4.5: Pressure Boundary Condition Table**

There were some other changes applied to Raja’s model as well. Since loss coefficients were the
same on both codes in the previous data, this model will not simulate the loss coefficients
associated with loss coefficients as well. This will apply to both CTF and TRACE. Additionally,
since only one channel is being used in the revised model, no data is necessary on the CTF group
that deals with channel connection data. Finally, the axial power profile was changed to a
constant power case.

Making these changes on CTF would theoretically allow the model to run and simply
have changes in pressure rather than changes in mass flow rate. However, these changes
prevented the CTF model from working. In fact, the CTF model would run and output all of the
input and place everything in proper tables but it does not show any calculated data for thermal
hydraulic parameters that are necessary for code-to-code verification of CTF and TRACE.

Several attempts have been made to fix the issue of CTF not accepting the new changes. CTF
probably cannot accept a pressure boundary change alone without any other forcing functions.
Therefore, a flow rate forcing function was added to maintain constant mass flow and placed
above the pressure forcing function. This was simply done to replicate what worked on Raja’s
model where mass flow rate was changing. However, this also proved to not work as well. The
current input model for CTF is included in the appendix.
At this time, the CTF model is incomplete as it is still not functioning. One of the potential reasons why it may not work is because the model is being run off of a single executable, or black box. This executable was initially designated for Raja’s case of a loss of flow accident with point kinetics modeling. There is a chance that this executable can only run that particular input deck that Raja created. The only way to confirm this assumption is to look into the FORTRAN source code of the executable to see if there are any lines of code that are written for a specific case, such as only a loss of flow accident. Although this is not an ideal way of programming, it could easily be causing the code not to run since it is only expecting a change in mass flow rate. However, this assumption is inconclusive until the FORTRAN code is analyzed, and at this time there is no access to it. Because the code is not producing any calculations on the output file, there are not plots from CTF that can be analyzed. This means that code-to-code verification cannot be done since the results from CTF are not visible. Obtaining CTF results will be one of the primary aspects of the future work of this project.
Chapter 5

Conclusions

Although this project is still a work in progress, some conclusions can be made using Raja’s CTF and TRACE models. His models showed three major reasons for differences between the two codes’ input; fuel material and associated dimensions, true steady state not reached, and an incorrect power distribution, all of these issues found on TRACE. To fix these errors, the fuel material was properly changed to UO₂ on TRACE with zirconium dioxide cladding as specified by the CTF input deck. An improved fuel area nodalization was also adopted to place more radial nodes in the UO₂ region. Next, the initial TRACE model was ran to a true steady state which would allow the transient to restart from that point. Finally, it was discovered that the axial power distribution on the TRACE model was giving too much power to the largest sub-channel and not enough to the others although the CTF model did not have any of these issues. The power distribution was given as empirical data meaning that it could not be adjusted. This did mean that Raja’s TRACE model could not be adjusted for the new model which is why Watson’s simplified model was used. These changes combined with Watson’s base model laid the foundation for the new model. The new model took on input data from a turbine trip and this data was uploaded onto both TRACE and CTF. Two key adjustments were made to each code: CTF took on a transient pressure table while TRACE had to have its PKM turned on along with all reactivity feedback mechanisms. This adjusted model is currently in progress of troubleshooting, in particular the CTF half of the project which may have issues with its source code.
In the meantime, some preliminary conclusions can be made with Raja’s data. These are only a preliminary portion of the code-to-code verification. Strictly using Raja’s models would lead to the premature conclusion that the two codes cannot be verified. The verification portion of this project must be completed in order to obtain a complete conclusion. However, some differences between the codes may cause the inconsistencies seen in Raja’s data. One distinct difference is that CTF has a liquid droplet model while TRACE does not at this time. This means that CTF may be more accurate in describing two phase flow. This assertion can be verified once the new CTF model is properly functioning. Moreover, the differences in the phase equations of each code could also lead to differences in the results of each code. However, these differences would only be minor since they only deal with using slightly different variables, such as enthalpy on CTF and energy on TRACE for the conservation of energy equations. A substantial difference could be caused by the use of spacer grids on CTF and loss coefficients on TRACE, provided that the loss coefficients associated with CTF spacer grids are calculated using CTF’s formula. However, in Raja’s case the loss coefficients on CTF and TRACE were identical meaning that they do not change any of the conditions associated with the codes’ results. The primary issue that causes inconsistent output from both CTF and TRACE is inconsistent input. This is often referred to as “garbage in, garbage out.” The primary differences were discussed earlier in this section and have been corrected. It is always important to make sure that consistent input is placed into each code when performing code-to-code verification. If not, code-to-code verification is impossible to prove and leads to poor results.
Chapter 6

Future Work

Future work is essential to complete this project. The first objective is to obtain desirable results on TRACE. This should be accomplished by activating all feedback flags on TRACE for reactivity feedback. This is the mechanism that will cause changes in the power profile as the pressure wave propagates through the primary side of the BWR being modeled. Some other thermal hydraulic parameters will also be checked to see how much they respond to the added reactivity feedback. The new plots may change due to the added reactivity feedback and will replace those presented in Chapter 4.

The next portion of upcoming work would need to be focused on finding out why CTF is not calculating any reactivity feedback for the conditions associated with a turbine trip. The data given to represent a turbine trip is in the form of a pressure table as a function of time. There is a chance that CTF cannot read this table since the executable that I am using was made for a case that only uses a mass flow of coolant table. This would mean that the FORTRAN code associated with the executable may be hard coded to only allow a change in mass flow rate and not to any other parameters. In fact, some manipulation has been done to the reference pressure of CTF and the one currently being used causes an error of too low a pressure. This could mean that the CTF executable can only run at PWR pressures which are higher than those of a BWR. This could be verified by analyzing this source code. This source code was not available during the time of this project but should be in the near future. It may turn out that there is nothing wrong with the source code and that something else would be wrong with the new pressure table.
Additionally, using an input deck that is known to work and making small changes to it could also find an issue with the model. This is currently underway on CTF by adding turbine trip data, one parameter at a time, onto Raja’s original input deck that worked. As soon as one parameter causes the model to fail, then that parameter might be the cause of the issues. However, until the code is analyzed not too many conclusions can be made about the CTF code. There is also the chance that the PKM on CTF cannot be used with BWR conditions and a pressure wave. Close analysis on how the PKM has been implemented on CTF is necessary in the near future to find out if any PKM parameters, such as feedback or delayed neutron fractions, need to be changed when modeling a BWR. The majority of work on this project is with analyzing and critiquing CTF. This future work does provide a basis for my upcoming Master’s Thesis.
Appendix A

CTF Input Model

This is the exact input deck being used on CTF at the time of this thesis submission.

* Input related to the point kinetics modeling
* I_POWER
  1
* Read number of delay groups, decay groups and history
  * IRPWTY I_PKM IANS
    1 1 2 0.0
  * NDGX NDHX NHIST
    6 71 1
* Q235 Q239 Q238 QAVG R239PF
  192.5 198.5 193.5 195.0 0.5
* FISPHI RANS FP235 FP238
  1.5 1.0 0.95 0.01
* If IRPWTY = 2
* NRPWTB
  *
  * If NRPWTB > 0
  * Read NRPWTB pairs of entrees for TIMETB and RPWTB
  * TIMETB(1) RPWTB(1) TIMETB(2) RPWTB(2) ... TIMETB(NRPWTB)
  RPWTB(NRPWTB)
  *
  * End if NRPWTB > 0
  * End if IRPWTY = 2
* Read neutron generation time
* REACT TNEUT RRPWMX
  0.0 1.625e-5 1.00e+20
* RPOWRI EXTSOU DTPK
  4.3102e+6 0.0 1.0e-03 1.0
* If I_PKM = 1
* Read
  * IRCJTB(1,1) IRCJTB(2,1) IRCJTB(3,1) IRCJTB(4,1) IBU(1)
    2 1 1 1 0
  * IRCJTB(1,2) IRCJTB(2,2) IRCJTB(3,2) IRCJTB(4,2) IBU(2)
    1 2 1 1 0
  * IRCJTB(1,3) IRCJTB(2,3) IRCJTB(3,3) IRCJTB(4,3) IBU(3)
    1 1 1 1 0
  * IRCJTB(1,4) IRCJTB(2,4) IRCJTB(3,4) IRCJTB(4,4) IBU(4)
    1 1 1 1 -2
  * IRCJFM(1) IRCJFM(2) IRCJFM(3) IRCJFM(4) ISNOTB
* POWEXP  BPP0  BPP1  BCR0  BCR1
  2.0  2.6e-1  -2.0e-3  1.0e-1  -3.0e+1
* Read IRC(1) entrees for RCTF
* RCTF  RCTF  RCTF  RCTF  RCTF ....
  5.5e+02  8.0e+02  0.00e+0  0.00e+0  -2.928e-05  -2.3334e-05
* Read IRC(2) entrees for RCTC
* RCTC  RCTC  RCTC  RCTC  RCTC ....
  0.00e+0  5.5e+02  6.0e+02  0.00e+0  0.00e+0  -9.850e-05  -2.0660e-04
* Read IRC(3) entrees for RCTC
* RCAL  RCAL  RCAL  RCAL  RCAL ....
  0.00e+0  0.00e+0  0.00e+0  0.00e+0  -1.2345e-01
* Read IRC(4) entrees for RCBM
* RCBM  RCBM  RCBM  RCBM  RCBM ....
  0.00e+0  5.50e+02  0.00e+0  0.00e+0  -2.321e-05
* End if I_PKM = 1
 *
* Read precursor beta's and dcdn's (decay constant) for each delay group
* Read NDGX times BETA_PK
* BETA_PK(1)  BETA_PK(2)  BETA_PK(3)  ...  BETA_PK(NDGX)
  1.69e-4  8.32e-4  2.64e-3  1.22e-3  1.38e-3  2.47e-4
*Read NDGX times DCDN
* DCDN(1)  DCDN(2)  DCDN(3)  ...  DCDN(NDGX)
  3.87e+0  1.4e+0  3.11e-1  1.15e-1  3.17e-2  1.27e-2
* If NHIS = 0
* Read precursor concentration CDGN NDGX times
* CDGN(1)  CDGN(2)  CDGN(3)  ...  CDGN(NDGX)
*
* Read decay-heat concentrations CDHN NDHX times
* CDHN(1)  CDHN(2)  CDHN(3)  ...  CDHN(NDHX)
*
* End if NHIS = 0
*
* Read decay group constants DCDH and energy fractions EDH
* If IANS = 0 read DCDH and EDH NDHX times
* DCDH(1)  DCDH(2)  DCDH(3)  ...  DCDH(NDHX)
*
* EDH(1)  EDH(2)  EDH(3)  ...  EDH(NDHX)
*
* End if IANS = 0
*
* If NHIST > 1
* Read THIST and PHIST NHIST times
* THIST(1)  PHIST(1)  THIST(2)  PHIST(2)  ...  THIST(NHIST)  PHIST(NHIST)
*
* Read FP235 (NHIST-1) times
* FP235(1)  FP235(2)  ...  FP235(NHIST-1)
*
* Read FP239 (NHIST-1) times
* FP239(1) FP239(2) ... FP239(NHIST-1)
*
* End if NHIST > 1
*
* END of Point Kinetics Input

**********************************************************************
*********
* GROUP 1 - Calculation Variables and Initial Conditions
* 

* NGAS IRFC EDMD IMIX ISOL NDM6 NDM7 NDM8 NDM9 NM10 NM11 NM12 NM13 NM14
  1 2 1 1 0 0 0 0 0 0 0 0 0 0 0

* GTOT AFLUX DHFRAC
  7.5 20.94 0.0

* PREF HIN HGIN VFRAC1 VFRAC2
  68.8405 1209.70 288.233 1.0 .9999

* GTYPE VFRAC
  air .0001

**********************************************************************
*********

* END GROUP 1
*


*

*


**********
* Group 2 - Channel Description

*
**NGRP**

2

*NCHA NDM2 NDM3 NDM4 NDM5 NDM6 NDM7 NDM8 NDM9 NM10 NM11 NM12 NM13 NM14  
  1 0 0 0 0 0 0 0 0 0 0 0 0

* I AN PW ABOT ATOP NMGP
  1 0.01 0.02857 0 0 0

**END GROUP 2**

**END GROUP 3**

**END GROUP 4**

**NGRP**

4

*NSEC NSIM IREB NDM4 NDM5 NDM6 NDM7 NDM8 NDM9 NM10 NM11 NM12 NM13 NM14
  1 1 0 0 0 0 0 0 0 0 0 0 0

*ISEC NCHN NONO DXS IVAR
  1 1 5 0.84 0

* I KCHA KCHA KCHA KCHA KCHA KCHA KCHA KCHA KCHA KCHA KCHA KCHA KCHA KCHA KCHA KCHA KCHA KCHA KCHA KCHA KCHA
  1 1 0 0 0 0 0 1 0 0 0 0 0 0 0

*IWDE
  1

*MSIM
  5
* END GROUP 4
*

* Group 7 - Local loss coefficient and Grid spacer data
*

* END GROUP 7
*

* Group 8 - Rod and Unheated Conductor Data
*

*NGRP
8

*NRRD NSRD NC NRTB NRAD NLTY NSTA NXF NCAN RADF W3 NM12 NM13 NM14
1 0 1 1 0 0 0 0 0 1 0 0 0

***** Group 8.2
* N IFTY IAXP NRND DAXMIN RMULT HGAP ISEC HTMB TAMB

***** Group 8.3
*NSCH PIE NSCH PIE NSCH PIE NSCH PIE NSCH PIE NSCH PIE NSCH PIE NSCH PIE
  1 1 1 0 0.0 1.0 4600.0 1 0.0 0.0 0 1 1.0 0 0.0 0 0.0 0 0.0 0 0.0

***** Group 8.6
* I NRT1 NST1 NRX1
1 1 0 2

***** Group 8.7
*IRTB
1

*** 0.0820 0.1989

** Group 8.9 Initial heater rod temperature profile
* AXIALT TRINIT
  0.0 274.85
  4.200 284.85
**END GROUP 8**

**END GROUP 9**

**GROUP 10 - Material Properties Tables**

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<th>NTDP</th>
<th>RCOLD</th>
<th>IMATAN</th>
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<td>8470.57</td>
<td>Inconel 600</td>
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**END GROUP 10**
*END GROUP 10*

*NGRP 11*

* Axial Power Distribution/Forcing Functions
* YQ 0.0
* I NAXN 1 2
* Y AXIAL
  0.0000 1.0000
  4.2000 1.0000

* Radial Power Distribution/Forcing Functions
* YQR 0.0
* FQR 1.0000

*END GROUP 11*

*GROUP 12 - Turbulent mixing data*

*NGRP 12*

* Card 12.1
* AAAK   BETA
*   1.0   0.051
***********************************************
**************
* END GROUP 12
*
***********************************************
**************
*

***********************************************
**************
* Group 13 - Boundary Conditions Data
*
***********************************************
**************
*N_GRP
  13
*NBND  NKBD  NFUN  NGBD  NDM5  NDM6  NDM7  NDM8  NDM9  NM10  NM11  NM12  NM13  NM14
  2    0    2    0    0    0    0    0    0    0    0    0    0    0
*NPTS
  3    4
*
*ABSC  ORDINT  ABSC  ORDINT  ABSC  ORDINT
**Flow rate boundary condition
  0.0   0.0000  0.1   1.0000  50.0   1.0000
**Pressure boundary condition
  0.0   1.0000  1.5   1.1171  5.0   1.0000  50.0   0.5607
*
* Inlet b.c. --------------------------------------
*IBD1  IBD2  ISPC  N1FN  N2FN  N3FN  BCVALUE1  BCVALUE2  BCVALUE3  INITGAS
  1    1    2    1    0    0      7.5  1209.700      0.0
1
*
* Outlet b.c. --------------------------------------
*IBD1  IBD2  ISPC  N1FN  N2FN  N3FN  BCVALUE1  BCVALUE2  BCVALUE3
  1    7    1    0    0    2       0.0  1262.400  38.5989
1
***********************************************
**************
* END GROUP 13
*
***********************************************
* Group 14 - Output Options
* *****************************************************
* NGRP
  14
* N1 NOU1 NOU2 NOU3 NOU4 IPRP IOPT IRWR NDM9 NM10 NM11 NM12 NM13 NM14
  5  0  0  0  0  0  2  1  0  0  0  0  0  0
*PRCH
* *PRTG
* *PRTR
* *****************************************************
* END GROUP 14
*
* *****************************************************
* END GROUP 15
*
* *****************************************************
* Group 15 - IME DOMAIN DATA
* *****************************************************
* NGRP
  15
* DTMINT DTMAX TEND EDINT DMPINT RTWFP
  0.000001  0.01  30.0  5.0  10.0  1.0
* DTMINT (if negative stop)
  -1.0  0.0  0.0  0.0  0.0  0.0
*
* *****************************************************
* END GROUP 15
*
* *****************************************************
Appendix B

TRACE Input Model

This is the steady state TRACE model that is currently in place. Since this is the steady state case, it does not show the break pressure information.

free format

*m: SNAP:Symbolic Nuclear Analysis Package, Version 2.2.10, October 30, 2014
*m: PLUGIN:TRACE Version 3.3.7
*m: CODE:TRACE V 5.0 Patch 3
*m: DATE:4/5/16
*
*
*************
* main data *
*************
*
* numtcr  ieos  inopt  nmat  id2o
2  0  1  0  0

This is a test problem for my thesis. It represents a small BWR channel.
*
*
*************
* namelist data *

************************

*

&inopts

cpuflg=1,
dtstrt=-1.0,
graphlevel="full",
ipwr=1,
itdmr=0,
nosets=1,
nsolver=1,
r5fdbk=1,
usesjc=3,
npower=1,
nhtstr=1
&end

*

************************

* Model Flags *

************************

*

*        dstep         timet
0          0.0

*        stdyst        transi        ncomp        njun        ipak
1          0          5          2          1
* epso  epss
  1.0E-3  1.0E-10
* oitmax  sitmax  isolut  ncontr  nccfl
  10   10    0     0     0
* ntsv  ntcb  ntcf  ntrp  ntcp
  1   0    0     1     0
*
******************************************************************************
* component-number data *
******************************************************************************
*
* Component input order (IORDER)
*-- type ---- num -------------- name -------------- +    jun1
  jun2   jun3
* FILL     *      1 s * velocity bc                    +       1
* PIPE     *      2 s * subcooled liquid channel       +       1
3
* BREAK    *      3 s * pressure bc                    +       3
* HTSTR    *      4 s * powered-rod conductor          +
* POWER    *    901 e * power data input test1         +
*
******************************************************************************
* Starting Signal Variable Section of Model      *
******************************************************************************
*                  idsv    isvn    ilcn    icn1    icn2
  1            0            0            0            0            0

*****************************************************************
* Finished Signal Variable Section of Model                         *
*****************************************************************

*

*

*

*****************************************************************
* Starting Trip Section of Model                                 *
*****************************************************************

*

** Trip Storage Count Card **

* ntse    ntct    ntsf    ntdp    ntsd
  0    0    0    0    0    0    0

*

*trip     -2

* idtp    isrt    iset    itst    idsg
  -2    2    0    0    1    1

* setp(1)    setp(2)
  0.0    0.1

* dtsp(1)    dtsp(2)
  0.0    0.0
********* type          num        userid             component name
fill            1            0                   velocity
bc
*       jun1          ifty          ioff
         1            2            0
*       twtold          rfmx        concin          felv
         0.0           0.0           0.0           0.0
*       dxin          volin        alpin          vlin          tlin
         1.0          0.0491           0.0           0.0          548.0
*       pin           pain          flowin           vvin          tvin
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<th>th</th>
<th>houtl</th>
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<th>toutl</th>
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<th>pwoff</th>
<th>rpwmx</th>
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</table>

| dx    | *      | 1.0   | 1.4   | 1.4   | 1.4s  |
| dx    | *      | 1.0e  |
| vol   | *      | 0.0491| 0.0687| 0.0687| 0.0687s|
| vol   | *      | 0.0491e|
| fa    | *      | 0.01  | 0.01  | 0.01  | 0.01s |
| fa    | *      | 0.01  | 0.01e |
| fric  | *      | 0.0   | 0.0   | 0.0   | 0.0s  |
| fric  | *      | 0.0   | 0.0e  |
* grav *  1.0  1.0  1.0  1.0s
* grav *  1.0  1.0e
* hd    *  1.0  1.4  1.4  1.4s
* hd    *  1.4  1.0e
* nff   *  0  0  0  0s
* nff   *  0  0e
* alp   *  0.01  0.01  0.01  0.01s
* alp   *  0.18e
* vl    *  0.0  0.0  0.0  0.0s
* vl    *  0.0  0.0e
* vv    *  0.0  0.0  0.0  0.0s
* vv    *  0.0  0.0e
* tl    *  548.0  558.0  558.0  558.0s
* tl    *  558.0e
* tv    *  548.0  558.0  558.0  558.0s
* tv    *  558.0e
* p     *  6.92E6  6.92E6  6.92E6  6.92E6s
* p     *  6.92E6e
* pa    *  0.0  0.0  0.0  0.0s
* pa    *  0.0e

****** type num userid

componentname
break                      3             0                    pressure
bc
*         jun1          ibty          isat          ioff      adjpress
  3             0             0             0             0
*         dxin         volin         alpin           tin           pin
  1.0        0.0491           1.0         558.0     6.82972E6
*         pain        concin          rbmx          poff          belv
  0.0           0.0           0.0           0.0           0.0
*
*
********************************************************************
* Starting Heat Structure Section of Model *
********************************************************************
*
*******   type           num        userid
  componentname
htstr                      4             1          powered-rod
conductor
*         nzhstr          ittc         hscyl          ichf
  3             0             1             1
*         nofuelrod          plane         liqlev           iaxcnd         pdrat
  0            3             0             0             0.0
*         nmwrx          nfci         nfcil          hdri          hdro
  0             0             0             0.0           0.0
*         nhot        nodes          fmon            nzmax        reflood
<p>| | | | | |</p>
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<td>dznht</td>
<td>hgapo</td>
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</tr>
<tr>
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<td>0.0</td>
<td>100.0</td>
<td>4600.0</td>
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*  
* idbcin *  0  0  0e  
* idbcn *  2  2  2e  
*qflxbc0 |  0.0e  
*qflxbc0 |  0.0e  
*qflxbc0 |  0.0e  
* hcomon2 *  2  2  0  0e  
* hcomon2 *  2  3  0  0e  
* hcomon2 *  2  4  0  0e  
* dhtstrz *  1.4  1.4  1.4e  
* rdx *  49.0e  
* radrd *  0.0  3.6347E-3  6.0579E-3  7.1501E-3e  
* matrd *  1  1  2e  
* nfax *  1  1  1e  
* rftn *  450.0  450.0  450.0  450.0s  
* rftn *  450.0  450.0  450.0  450.0s  
* rftn *  450.0  450.0  450.0  450.0e  
* fpuo2 *  0.0e  
* ftd *  1.0e  
* gmix *  0.0e  
* gmles *  0.0e  
* pgapt *  0.0e  
* plvol *  0.0 e
* pslen *  0.0 e
* clenn *  0.0 e
* burn *  0.0  0.0  0.0e

*************************************************
*       Finished Heat Structure Section of Model *
*************************************************


*************************************************
*     Starting Power Components          *
*************************************************

**********  type           num        userid
componentname
c
power                    901             0         power data input
test1

*  numpwr     chanpow
              1             0

*  htnum *  4 e

*  irpwty        ndgx      ndhx       nrts       nhist
              11            0       71            5           1

*  q235        q239        q238        qavg        r239pf
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* **izpwtr** | **izpwsv** | **nzpwtb** | **nzpwsv** | **nzpwrf** |
| Value          | 3.0    | 1.0    | 0.97   | 0.03   |      |

* **ipwrad** | **ipwdep** | **promheat** | **decaheat** | **wtbypass** |
| Value          | 0      | 0      | 0.0    | 0.0    | 0.0  |

* **nzpwz** | **nzpwi** | **nfbpwt** | **nrpwr** | **nrpwi** |
| Value          | 2      | 0      | 0      | 1      | 0    |

* **react** | **tneut** | **rpowoff** | **rrpwmx** | **rpwscl** |
| Value          | 0.0    | 0.0    | 0.0    | 0.0    | 1.0  |

* **rpowri** | **zpwin** | **zpowff** | **rzpwmx** |
| Value          | 4.3102E6 | 0.0    | 0.0    | 0.0    |

* **extsou** | **pldr** | **pdrat** | **fucrac** |
| Value          | 0.0    | 0.0    | 1.0    | 1.0    |

* **ircjtb 1,0** | **ircjtb 2,0** | **ircjtb 3,0** | **ircjtb 4,0** | **ibu 0** |
| Value          | 2      | 2      | 2      | 1      | 0    |

* **ircjtb 1,1** | **ircjtb 2,1** | **ircjtb 3,1** | **ircjtb 4,1** | **ibu 1** |
| Value          | 2      | 2      | 2      | 1      | 0    |

* **ircjtb 1,2** | **ircjtb 2,2** | **ircjtb 3,2** | **ircjtb 4,2** | **ibu 2** |
| Value          | 2      | 2      | 2      | 1      | 0    |

* **ircjtb 1,3** | **ircjtb 2,3** | **ircjtb 3,3** | **ircjtb 4,3** | **ibu 3** |
| Value          | 1      | 1      | 1      | 1      | 0    |

* **ifbtyp1** | **ifbtyp2** | **ifbtyp3** |
<p>| Value          | 0      | 0      | 1      |</p>
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<td>900.0s</td>
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<td>-2.928E-5s</td>
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<td>550.0</td>
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<td>900.0s</td>
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<td>0.0</td>
<td>0.0</td>
<td>0.0s</td>
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<td>0.0</td>
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<td>800.0</td>
<td>550.0</td>
<td>600.0</td>
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* Finished Power Components *

*******************************************************************************

*  *

*  *

*
end
*

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* Timestep Data *
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</tr>
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*

* endflag

-1.0
BIBLIOGRAPHY


ACADEMIC VITA

Adrian M. Leandro
aml5803@psu.edu

Education:
Bachelor of Science in Nuclear Engineering, May 2016
Schreyer Honors College
The Pennsylvania State University, University Park, PA

Work Experience:
Teaching Intern, Penn State University   University Park, PA
(August 2015-Present)
- Grade assignments, quizzes, and exams for core design, fluid mechanics, nuclear writing, and nuclear calc.
- Conduct weekly office hours with nearly a dozen students for help with homework and exam questions
- Demonstrate fluid mechanics experiments weekly to a class to better reinforce concepts for the students

Mechanical Engineering Intern, LL Kurtz Inc.   Erie, PA
(June 2015-August 2015)
- Created and edited nearly 50 process and quality engineering forms for new and old products
- Completed engineering summary reports (calculations, instructions, etc.) for products in a slideshow format
- Drafted 3-D models for new or revised products using ProE Software

Project Experience:
Capstone Design Project, Penn State University   University Park, PA
(January 2016-Present)
- Redesign the fuel pattern of a Westinghouse simulated quarter core
- Shuffle fuel assemblies in order to obtain high burnup, low FDH, and negative MTC
- Prepare, with a group of three, weekly progress reports, bi-weekly technical presentations, and two major technical reports

PWR Simulation, Penn State University   University Park, PA
(October 2015-December 2015)
- Calculated several core, steam generator, and coolant parameters needed for a 30K change in temperature
- Implement a finite volume nodalization on TRACE for all components (pipes, downcomers, fuel rods, etc.)
- Formed a detailed report with design rationale (reactor and controllers) and results (steady and transient)

Honors and Awards:
Schultz Monty Memorial Scholarship in Nuclear Engineering
Exelon Corporation Endowed Scholarship in Nuclear Engineering
Weimert Family Scholarship in Engineering
American Nuclear Society Undergraduate Scholarship

Activities:
2016 ANS Student Conference Presentation
Penn State Department of Mechanical and Nuclear Engineering Faculty Search Committee
Alpha Nu Sigma Honor Society
Member of the American Nuclear Society