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VERIFICATION OF CTF AND NEM COUPLED CODES

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ABSTRACT

The goal of this project was to explore the accuracy of the Reactor Dynamics and Fuel Management (RDFMG) Group's CTF/NEM coupled codes. This was done to allow for their use in a variety of reactor analysis scenarios, as well as, use in a classroom setting. To accomplish this, the codes were run in three cases: Hot Zero Power steady-state, Hot Full Power steady-state, and a Rod Ejection Accident (REA) scenario using the Purdue PWR MOX Core benchmark. The results from these simulations were then compared to benchmarks from a PARCS predictions for the same Purdue PWR MOX Core benchmark. This report is to analyze and interpret that data and any discrepancies that exist and draw conclusions on the validity of CTF/NEM and verify it for use in reactor analysis.

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Chapter 1

Introduction

Motivation

A computer code to model conditions within a nuclear reactor is only as good as the reliability of the data it provides. For this reason, there has been and always will be a need to verify the accuracy of those models, especially, when they predict something as important as conditions within a nuclear reactor. The motivation for this project is connected to that idea.

The Pennsylvania State University's Reactor Dynamics and Fuel Management Group (RDFMG) has coupled and developed such codes with the intention of accurately generating data for Pressurized Light Water Reactors (PWR). Specifically, CTF [1], an advanced subchannel thermal-hydraulic code, and Nodal Expansion Method (NEM) [2], a three-dimensional (3D) nodal neutron diffusion code, were coupled to more accurately model steady state and transient behavior of a Light Water Reactor (LWR). In order to use these codes for reactor analysis, they should be verified by comparison to other similar codes. NEM, in particular, is useful for analyzing and teaching sensitivity of modeling reactor cores response to changes in size, shape, delayed neutron groups, neutron energy groups, and mesh size. The previous applications of CTF and NEM for analysis of Reactivity Initiated Accidents (RIAs) such as Rod Ejection Accident (REA), boron dilution, and Main Steam Line Break (MSLB) transient are reported in references 3 through 7.

For these reasons, it is important that these codes be accurate. For many nuclear engineering students, these codes will be their first look at modeling of nuclear reactors. At such a critical time to their learning, incorrect results would greatly harm their thinking and development as engineers. This project was born out of a desire to provide a working, error-free code for the students. That motivation is what drove this project from start to finish.

Objectives

Verification of the coupled code system of CTF/NEM is the main goal of this project. In order to achieve it, several smaller, more specific, objectives must be identified and reached. The codes must respond properly in a set of standard operating procedures in order to be verified. This will be accomplished by comparing results from previously verified codes for the well-known Purdue MOX Core Benchmark [8] for a couple different scenarios. Firstly, results will be compared to the benchmark, which comes from PARCS code, at Hot Zero Power (HZP) steady-state conditions. The data to be discussed in this comparison will be the multiplication factor k, the boron concentration, the Power Weighted Error, and the Error Weighted Error. Results at Hot Full Power (HFP) steady-state conditions will be analyzed using the same criteria. Finally, a rod ejection starting at HZP with all control banks in and shutdown banks out will be performed and compared to PARCS data.

A secondary objective, pertaining more to this thesis, is the exploration and definition of those codes. In this paper, the models used, the case studies performed, and the comparison to benchmark results will be explained fully. Finally, from these comparisons, conclusions will be

drawn about the validity of the coupled code system and its suitability for use for reactor analysis and teaching nuclear engineering as described in the motivation.

Chapter 2

Models

Purdue MOX Core

This section will detail the MOX Core's design parameters. As mentioned briefly above, the Purdue MOX/UO_2 core model from the 2007 OECD / NEA PWR MOX/UO_2 Core Transient Benchmark [8] was the subject of this entire project. The Purdue core is a version of a Westinghouse four-loop reactor core. The fuel uses plutonium mixed fuel which is relevant to current plans for plutonium disposition in the United States [8]. Similar programs for use of high grade plutonium are in place in Europe and Japan [8]. The fuel considered ranges from fresh to twice burned with corresponding burnup listed in GWd/t. Figure 1 contains the configuration of the fuel assemblies for a quarter of the core. Though the rest of the core is symmetrical, a full picture can be found in Appendix A. The core was designed with the following additional guidelines in mind [8]:

- no fresh MOX on the periphery;
- no MOX assemblies facing each other;
- no MOX assemblies in control rod position;
- maximum 1/3 of the core loaded with MOX fuel;
- no integral fuel burnable absorbers (IFBA) in MOX assemblies;
- a three-batch equilibrium fuel cycle.

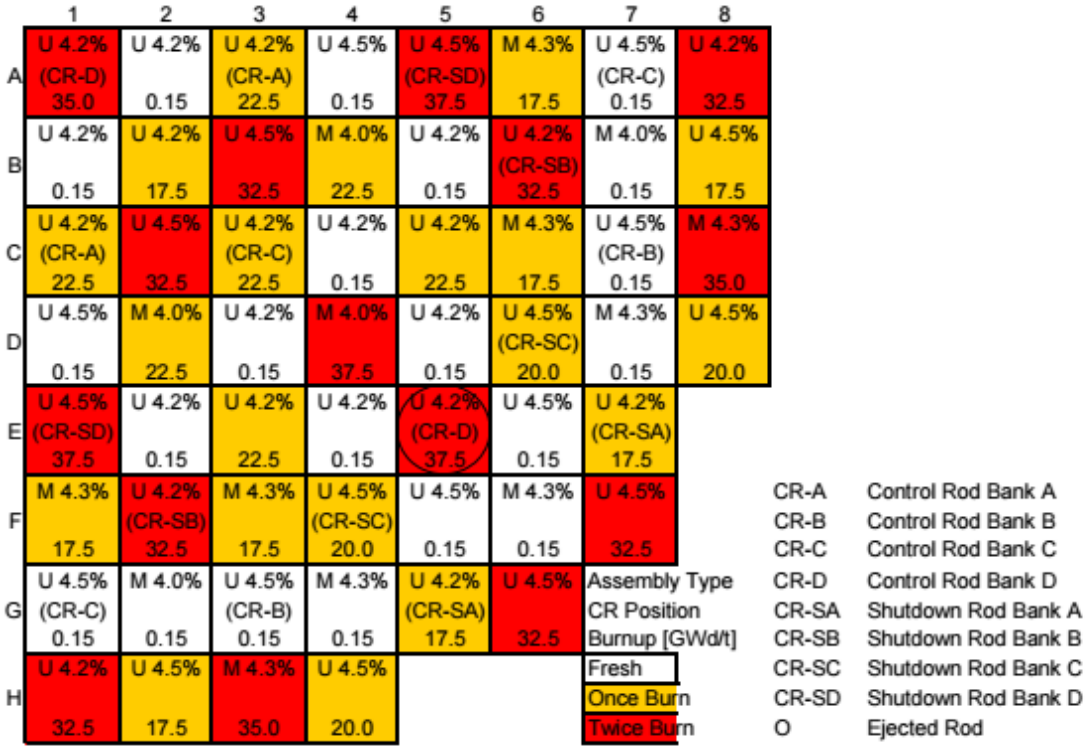

Figure 1. Quarter-Core Configuration Map [8]

The table below contains the core design parameters outlined in the Purdue benchmark [8]. Additional tables containing relevant information about the benchmark core are in Appendix A. All the information provided is important to fully define the problem statement. Only with careful consideration and application of this information will comparison to benchmarks even be useful.

Table 1. Purdue MOX Core Design Parameters [8]

Number of Fuel Assemblies	193
Core Full Power Rating [MWthermal]	3565.0
Nominal Inlet Pressure [MPa]	15.5
HFP Core Average Moderator Temperature [K]	580.0
HZP Core Average Fuel Temperature [K]	560.0
HFP Core Average Fuel Temperature [K]	900.0
Fuel Lattice, Fuel Rods Per Assembly	17x17 Square, 264
Control Rod Guide Tubes Per UO2 Assembly	24
Guide Tubes Per Assembly	1
Total Core Moderator Mass Flow Rate [kg/sec]	15849.4
Active Fuel Length [cm]	365.76
Assembly Pitch [cm]	21.42
Pin Pitch [cm]	1.26
Baffle thickness (cm)	2.52
Design radial pin-peaking (F_H)	1.528
Design point-wise peaking (F_Q)	2.5
Core loading [tHM]	81.6
Target cycle length (GWd/tHM) (months)	21.564 (18)
Capacity factor (%)	90.0
Target effective full power days	493
Target discharge burnup (GWd/tHM)	40.0-50.0
Maximum pin burnup (GWd/tHM)	62.0
Shutdown Margin [%$\Delta\rho$]	1.3

The cross sectional data used in calculations comes from the benchmark specifications, as well. The appropriate cross section is calculated using a multi-dimensional linear surface interpolation based on the thermal hydraulic data supplied to NEM. Moderator density, fuel temperature, and boron concentration are the parameters used to determine cross section in NEM. NEM loads its cross section library from a separate input file called NEMTAB [3].

CTF Code

CTF is an improved version of Coolant Boiling in Rod Arrays – Two Fluid (COBRA-TF) developed and maintained by RDFMG at Penn State. While COBRA-TF [13] originally began as a thermal hydraulic rod-bundle analysis code developed by Pacific Northwest Laboratory [1] it has since been updated and expanded to the form it is today. CTF uses a two-fluid, three-field approach to accurately model subchannels within LWR. In each subchannel node, CTF solves each of the mass, momentum, and energy equations in three dimensions [13]. To satisfy two phase flow conditions, a separated flow model is used for the three fields: fluid film, vapor, and liquid droplets.

CTF makes use of two different sets of flow regime maps to determine momentum and energy transfer. Under most conditions, a normal flow regime map is used. Under extreme conditions, however, CTF will make use of hot-wall flow regime maps. In this way, thermal hydraulic conditions can still be modeled even when wall surface temperature exceeds the Critical Heat Flux temperature. This is a big advantage when modeling reactor conditions during an accident. Additionally, CTF is capable of modeling wall and phase interface shear, wall and phase interface heat transfer, void drift, turbulent mixing, and entrainment of droplets.

Recent updates to CTF have allowed the incorporation of soluble boron tracking in the coolant. This allows for more accurate modeling of LWR. In this project, boron tracking was used to match simulation conditions specified in the benchmarks [10-12].

CTF is controlled by its input deck called DECK.inp. It is here that the user specifies many of the initial and boundary conditions throughout the core's coolant. Conditions are specified for each subchannel. In this project, that means providing initial conditions and inlet and outlet conditions for 194 subchannels. Additional data must be provided for transverse

channel connections also known as gaps. Geometric, thermal, and physical properties about the rods and conductors are also entered. Because this version of CTF/NEM includes boron, its concentration and a forcing function must be specified for each subchannel. Time domain data will also be specified, which becomes more important when running transient calculations. Finally, the user can also use DECK.inp to change what information will be output to DECK.out. For instance, specifying how often to print data sets is very useful. In this project, this was manipulated to obtain data every .01 seconds during transient conditions and every 4.0 seconds while converging to steady state.

For this project, data was printed to DECK.out for all subchannels, rods, gaps, and conductors. This makes the output file rather large and difficult to sort through. Figure 2 below is just a short example of the kind of data provided by DECK.out for a fuel rod.

nuclear fuel rod no. 69 simulation time = 4.00 seconds
surface no. 1 of 1
conducts heat to channels 69 0 0 0 0 0 geometry type = 1
and azimuthally to surfaces 1 and 1 no. of radial nodes = 12

rod node no.		axial location (in.)	fluid temperatures (deg-f) liquid	vapor	surface heat flux (b/h-ft2)	heat transfer mode	-clad temperatures- (deg-f) outside	inside	gap conductance (b/h-ft2-f)	-fuel temperatures- (deg-f) surface	center
28		143.98	618.4	653.2	0.1338E+06	subc	658.35	671.74	1761.1	759.93	1160.96
27	*	141.21	618.5	653.2	0.1499E+06	subc	661.09	676.08	1761.1	774.87	1235.23
26	*	135.68	616.9	653.2	0.1775E+06	subc	664.31	682.02	1761.1	799.00	1367.03
25	*	130.14	614.9	653.2	0.2045E+06	subc	666.85	687.22	1761.1	821.95	1502.25
24	*	124.60	612.5	653.2	0.2199E+06	subc	667.78	689.67	1761.1	834.53	1582.09
23	*	119.06	610.0	653.2	0.2231E+06	subc	667.29	689.51	1761.1	836.53	1598.65
22	*	113.52	607.3	653.2	0.2215E+06	subc	666.17	688.24	1761.1	834.18	1588.76
21	*	107.99	604.7	653.2	0.2182E+06	subc	664.78	686.53	1761.1	830.29	1569.95
20	*	102.45	602.0	653.3	0.2156E+06	subc	663.40	684.90	1761.1	826.95	1554.92
19	*	96.91	599.3	653.3	0.2138E+06	subc	662.00	683.34	1761.1	824.21	1544.14
18	*	91.37	596.7	653.3	0.2126E+06	subc	660.60	681.84	1761.1	821.95	1536.68
17	*	85.84	594.0	653.3	0.2120E+06	subc	659.14	680.32	1761.1	820.00	1531.67
16	*	80.30	591.3	653.3	0.2117E+06	subc	657.56	678.72	1761.1	818.21	1528.34
15	*	74.76	588.6	653.3	0.2116E+06	subc	655.79	676.96	1761.1	816.42	1526.11
14	*	69.22	585.8	653.4	0.2118E+06	subc	653.69	674.89	1761.1	814.46	1524.68
13	*	63.68	583.1	653.4	0.2122E+06	spl	651.29	672.57	1761.1	812.43	1524.13
12	*	58.15	580.4	653.4	0.2129E+06	spl	648.90	670.26	1761.1	810.59	1524.85
11	*	52.61	577.6	653.5	0.2142E+06	spl	646.62	668.12	1761.1	809.26	1528.34
10	*	47.07	574.8	653.5	0.2161E+06	spl	644.56	666.27	1761.1	808.70	1535.83
9	*	41.53	571.9	653.5	0.2184E+06	spl	642.55	664.52	1761.1	808.46	1545.20
8	*	36.00	569.0	653.5	0.2208E+06	spl	640.54	662.76	1761.1	808.28	1555.12
7	*	30.46	566.1	653.5	0.2237E+06	spl	638.63	661.16	1761.1	808.56	1567.54
6	*	24.92	563.1	653.6	0.2267E+06	spl	636.68	659.52	1761.1	808.86	1580.48
5	*	19.38	560.0	653.6	0.2282E+06	spl	634.23	657.25	1761.1	807.62	1585.54
4	*	13.84	556.9	653.6	0.2242E+06	spl	629.94	652.59	1761.1	800.34	1559.46
3	*	8.31	553.8	653.6	0.2068E+06	spl	621.29	642.26	1761.1	778.53	1460.16
2	*	2.77	550.9	653.6	0.1622E+06	spl	603.95	620.53	1761.1	727.38	1226.69
1		0.00	550.9	653.6	0.4232E+05	spl	564.77	569.18	1761.1	597.05	705.78

Figure 2. Sample Fuel Rod CTF Output

As you can see in Figure 2, data is given for each axial rod node all at the current simulation time listed of 4.00 seconds. While fuel rod provides data like fuel temperature, conductance, heat flux, etc, other structures provide different data. For example, gap tables provide crossflows, velocities, void fraction, pressure difference, and flow area. Similarly, channel results provide pressure, velocities, void fraction, flow rate, flow regime, heat added, enthalpy, density, and entrainment data. All the useful data in DECK.out serves to paint a truly comprehensive picture of a reactor core. However, for this project, data from NEM about the power will be relied on more heavily to compare to power distributions from the benchmark.

NEM Code

Penn State's NEM code handles the neutronic and power calculations for this project. RDFMG's NEM is a multi-group, three-dimensional nodal diffusion code used to perform steady-state and transient neutron kinetics calculations. NEM is capable of simulating up to 70 neutron groups but can be modified to allow the simulation of more groups [14]. This section details NEM's capabilities related to iterative processes, coordinate systems, and cross sectional data as well as its input and output.

The traditional inner and outer iteration multigroup diffusion theory method can be used to solve the Nodal Expansion Method. First, inner iterations are performed, sweeping through the mesh with a known internal source in order to invert the within-group diffusion removal matrix [14]. Inner iteration continues until convergence is reached or a set inner iteration limit is reached. The neutron currents given by the final inner iteration is then used to predict neutron fluxes which can be used to calculate new source moments from fission, down-scattering, and

up-scattering. Then, the outer iterations can calculate the problem's eigenvalue (k_{eff}) and the fission neutron source distribution based on space and energy.

After each outer iteration is completed, NEM tests the current iterations values against the previous one to determine if the solution has converged. Typically, the absolute difference in the two most recent k_{eff} values must be less than 10^{-7}. Additionally, the change in the leakage norms (L_2 and L_∞) of the vector must both be less than 10^{-5} [14]. If all three of these criteria are satisfied, the solution is said to have converged.

NEM can simulate using Cartesian, cylindrical, and hexagonal-Z coordinate systems. This project, like most U.S. commercial fuel and core loading designs [2], uses Cartesian coordinates. Cylindrical coordinate systems are useful for high temperature pebble-bed reactor modeling. Finally, methodology for hexagonal-Z coordinates is still being improved for use with fast breeder, VVER, and other European reactors.

Lastly, as mentioned above, NEM needs cross section data for its calculations. Typically, users can simply enter this data directly into NEM's input deck (NEMIN). However, there is a second method that makes more sense for more complete cross section data, which was used for this project. This is the method mentioned briefly above: using NEMTAB. In this way, each material has a complete set of cross section tables with transport, absorption, fission (multiplied by the average neutron production per fission), kappa-fission, and scattering cross sections between energy groups. Additional information such as delayed neutron fraction, discontinuity factors, and precursor decay constants can be added, as well. For completeness, the data will be tabulated for the full range of thermal hydraulic conditions required. A short example of the cross section library can be seen below in Figure 3.

```
***************       Assembly Disc. Factor Table
*
 0.6611400D+00 0.7118700D+00 0.7520600D+00 0.0000000D+00 0.1000000D+04
 0.2000000D+04 0.5600000D+03 0.9000000D+03 0.1320000D+04 0.9367900D+00
 0.9363800D+00 0.9359600D+00 0.9412500D+00 0.9411500D+00 0.9416200D+00
 0.9449000D+00 0.9455200D+00 0.9462000D+00 0.9363800D+00 0.9358300D+00
 0.9356700D+00 0.9408300D+00 0.9409700D+00 0.9411800D+00 0.9444800D+00
 0.9451000D+00 0.9457800D+00 0.9359200D+00 0.9354400D+00 0.9352300D+00
 0.9403500D+00 0.9404900D+00 0.9405900D+00 0.9440000D+00 0.9446100D+00
 0.9452700D+00
*
***************            Fission Spectrum
*
* GROUP 1             2
* 0.1000000D+01 0.0000000D+00
*
***************            Inv. Neutron Velocities
*
* GROUP 1             2
 0.5501520D-07 0.2472120D-05
*
***************  Delay Neutron Decay Constant (Lambda)
*
* GROUP 1           2             3             4             5             *6
* 0.1336930D-01 0.3169750D-01 0.1192630D+00 0.3059730D+00 0.8693510D+00 *0.2909520D+01
*
*
***************            Delay Neutron Fraction (Beta)
*
* GROUP 1             2             3             4             5             *6
* 0.1442910D-03 0.9057430D-03 0.8084930D-03 0.1861820D-02 0.9306930D-03 *0.3604620D-03
*
*
*       Mod Dens      Boron ppm     T Fuel        T Mod.
              3             3             3             0
*******           X-Section set #        2
   2
*
*      Group No.  1
*
***************            Transport X-section Table
*
 0.6611400D+00 0.7118700D+00 0.7520600D+00 0.0000000D+00 0.1000000D+04
 0.2000000D+04 0.5600000D+03 0.9000000D+03 0.1320000D+04 0.2290480D+00
 0.2374990D+00 0.2441700D+00 0.2279160D+00 0.2361430D+00 0.2426280D+00
 0.2268540D+00 0.2348800D+00 0.2411860D+00 0.2289140D+00 0.2373540D+00
 0.2440170D+00 0.2277710D+00 0.2359830D+00 0.2424630D+00 0.2266940D+00
 0.2347090D+00 0.2410060D+00 0.2287840D+00 0.2372220D+00 0.2438750D+00
```

Figure 3. Example NEMTAB Table

As mentioned above, NEM is controlled by its input deck NEMIN. Through NEMIN the user is able to make a number of changes to how the code functions. The input deck is divided into numbered Cards and Card Sets. Cards input scalar values while Card Sets are read into arrays in NEM [12]. Cards 1 through 8 establish the general definition of the problem. This is where the user controls the geometry type, the number of neutron groups, the number of delayed neutron groups, the number of nodes in each direction, iteration limits and adjusts convergence criteria. Meanwhile, Card Sets 10 through 12 provide information about the energy group yields and delayed neutrons. Normally, the cross section sets are input through Card Sets 13 to 21, but

as discussed above NEMTAB is used for this feature. Node geometries and boundary conditions are then set with Card Sets 22 through 31. Card Set 32 and 33 set Material Specifications, while assembly info is provided in Card Sets 34 through 36. Lastly, Card Sets 37 to 40 input mesh sizes in each direction as well as number of reflector nodes and initial feedback parameters for the core such as moderator temperature, moderator density, and fuel temperature.

For this project, the version of NEM used includes additional Card Sets to allow for the ejection of a control rod. These sets define the number of control rod banks, their cross sections in NEMTABR (a NEMTAB for the rods), initial positions, and parameters to describe movement. An example of these Card Sets can be seen in Figure 4 below.

```
*-------------------------------------------------------------------------*
!          Card Set 51 CONTROL ROD CONDITIONS                             !
!-------------------------------------------------------------------------!
!   Flag for CR                 # of RB          # of rodded XS sets!
!   0 - no CR present                            in NEMTABR          !
!   1 - CR present (PWR)                                             !
!-------------------------------------------------------------------------!
        1                           9                 8
!-------------------------------------------------------------!
!           PLANAR VIEW OF CONTROL ROD LOCATIONS              !
!    0 - No CR at location                                    !
!    # - CR from Rod Bank # at location                       !
!-------------------------------------------------------------!
                  0  0  0  0  0  0  0
               0  0  0  0  0  0  0  0  0  0  0
            0  0  5  0  2  0  3  0  2  0  5  0  0
         0  0  0  0  7  0  6  0  6  0  7  0  0  0  0
         0  5  0  4  0  0  0  8  0  0  0  4  0  5  0
      0  0  0  7  0  0  0  0  0  0  0  0  0  7  0  0  0
      0  0  2  0  0  0  3  0  1  0  3  0  0  0  2  0  0
      0  0  0  6  0  0  0  0  0  0  0  0  0  6  0  0  0
      0  0  3  0  8  0  1  0  4  0  1  0  8  0  3  0  0
      0  0  0  6  0  0  0  0  0  0  0  0  0  6  0  0  0
      0  0  2  0  0  0  3  0  1  0  3  0  0  0  2  0  0
      0  0  0  7  0  0  0  0  0  0  0  0  0  7  0  0  0
         0  5  0  4  0  0  0  8  0  0  0  9  0  5  0
         0  0  0  0  7  0  6  0  6  0  7  0  0  0  0
            0  0  5  0  2  0  3  0  2  0  5  0  0
               0  0  0  0  0  0  0  0  0  0  0
                  0  0  0  0  0  0  0  0
!
!-------------------------------------------------------------------------------------------------------------!
!   Initial Position into Core (cm)                                                                           !
!-------------------------------------------------------------------------------------------------------------!
   387.136    387.136   387.136   387.136   21.42   21.42   21.42   21.42   387.136
!-------------------------------------------------------------------------------------------------------------!
!  # RB Moving  RB1   NM1
!-------------------------------------------------------------------------------------------------------------!
      1        9     1
!-------------------------------------------------------------------------------------------------------------!
!     Bank         Move Start Time (s)      Velocity into Core (cm/s)   Final Depth into Core (cm)     !
!-------------------------------------------------------------------------------------------------------------!
       9                0.0                                -3657.16                 21.42
!-------------------------------------------------------------------------------------------------------------!
!                         END OF INPUT DECK                                                                   !
!-------------------------------------------------------------------------------------------------------------!
```

Figure 4. Control Rod Card Sets

The inclusion of these sets was necessary for this project in order to model transient conditions involving a rod ejection through a control rod movement. The control rod movement is performed using the control rod model implemented in NEM.

As NEM runs, results are output in a file called NEMOUT. NEMOUT contains a variety of parameters. First it returns the parameters defining the basic problem, such as, geometric information, nodalization, delayed neutron fractions and assembly material maps, etc. Then comes the data most important to this project for the purpose of benchmarking. Problem k_{eff}, axial normalized powers (by node), and a 2-D map of assembly average powers are given for the core. At steady state this data is given for the converged core. During a transient run, this data is output after each time-step as determined by CTF. For this project's transient analysis, power results are to be printed every .01 seconds.

NEM and CTF Coupling

Alone, neither CTF nor NEM offer a very complete picture of a nuclear reactor. A core's neutronic behavior is very strongly dependent upon thermal hydraulic conditions. Similarly, the thermal hydraulic conditions will be heavily dependent upon the power distribution within the core which is a direct result of neutronic behavior. For these reasons, a complete model must incorporate results from neutronic analysis (NEM) and thermal hydraulics (CTF). In coupling CTF and NEM, the goal is to utilize power distributions to calculate thermal hydraulic conditions and then use thermal hydraulic conditions to determine neutronic behavior which, in turn, will return a power distribution and so on. On startup, CTF will use an initial guess of the core power distribution and calculate the thermal hydraulic feedback parameters to send to NEM. Then

NEM will use those values to determine a new power distribution. Eventually, these parameters and distributions will converge to steady state values. From there, transient modeling can begin by iterating the couple over each time step.

Coupled codes is a very broad term. For CTF/NEM, there are several characteristics that distinguish this couple from others. CTF and NEM are coupled explicitly, online, with a master-slave relationship [3]. Coupling implicitly would not truly be coupling these two codes at all. An implicit couple requires solutions to be solved simultaneously as one system. For this reason, an "implicit coupled" code would have meant almost completely rewriting both codes into one uniform code. On the other hand, in an explicit coupling scheme the two codes remain more or less independent. In CTF/NEM, CTF will execute and send only the required thermal hydraulic feedback parameters to NEM. Then NEM will execute and send a power distribution back. In this way, the two codes are running independently but coupled together. A brief illustration of this type of couple can be seen in the Figure 5 below.

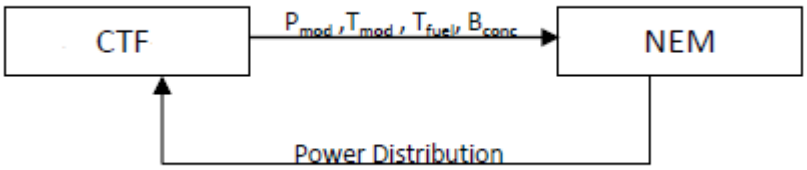

Figure 5. Online Explicit Coupling Scheme for CTF/NEM [3]

This couple is an online couple because the coupled code will run as one. Conversely, an offline couple would require the user to run an iteration of one code, then run the other code using the results from the first manually. The passing of parameters is accomplished internally through coding the online couple. Online coupling is easier to use and saves a ton of time especially when many coupled iterations are needed, as is the case for this project.

Since the program has to begin somewhere, a master-slave relationship is developed between the codes. In CTF/NEM, CTF is the master which utilizes NEM to accomplish its goals. In this way, CTF calls upon NEM only when needed, treating it as part of its own repertoire of callable subroutines. This makes implementation of the couple a lot easier. Only two new subroutines needed to be introduced to the coupled code environment for CTF/NEM [3]. These subroutines exists to assist in the passing of data between the codes. As the master, the input DECK.inp for CTF contains additional options pertaining to the coupled code. First, the user inputs whether to run either NEM or CTF as standalone codes or the coupled code. Assuming a coupled run is chosen the user then selects the mode to run in. Options are as follows: coupled steady convergence, coupled steady convergence with boron transient, coupled k-search, or a control rod transient. As seen in the Figure 6 below, additional parameters are input to aid in the couple. Output from the coupled codes functions the same as the standalone codes described above.

```
*******************************************************************************
* PURDUE Core, FA-by-FA:193 Subchannels Model                                  *
* Code version: CTF/NEM                                                       *
*******************************************************************************
* VERSION                                COUPLED_MODE
*  = 0 CTF/NEM coupled version            = 0 Coupled Steady Convergence
*  = 1 CTF stand alone version            = 1 Coupled Steady Convergence + Boron Transient
*  = 2 NEM stand alone version            = 2 Coupled Boron kEFF Search
*                                         = 3 Control Rod Transient
*
* VERSION  COUPLED_MODE (Version=0)  ERROR_R_MOD    ERROR_T_MOD    ERROR_T_FUEL
     0          0                       0.0001         0.0001          0.0001
* K-Search (Specify only if using k-search coupled mode = 2)
  1.0000000
*       ICOBRA
            1
*      INITIAL          DUMPF
            1              1
*         EPSO         OITMAX         IITMAX
        0.001             50            200
```

Figure 6. Coupled Input Options

PARCS Benchmark Code

Purdue Advanced Reactor Core Simulator (PARCS) is, as its name implies, a code similar to NEM for modeling neutronics within reactor cores. The data used for this project comes from a two energy group simulation completed with PARCS for the MOX Benchmark Core described in an earlier section. Modularized and written with FORTRAN, PARCS is useful for predicting transient behavior of light water reactors. PARCS utilizes the two-group, time-dependent form of the neutron diffusion equation for standard Cartesian coordinates to calculate the neutron flux distribution [9]. Heat transfer calculations allow PARCS to include thermal-hydraulic feedback effects which in turn allow for the calculation of eigenvalues at steady-state and transient conditions. PARCS can be used to perform rod ejections, rod withdrawals, rod drops, and boron insertion. One key difference between NEM and PARCS is the method used to solve multinode problems. Both the nodal expansion method and the analytical nodal method can be used to obtain two-node solutions [9]. While the analytical method is the primary solver in PARCS, it is aided by a hybrid ANM/NEM scheme for near critical problems [9].

PARCS is typically coupled with RELAP5 which is a best-estimate transient simulation of light water reactor coolant systems [7]. RELAP5 can be used for the simulation of a variety of hydraulic and thermal transients in nuclear systems. It's based on non-homogeneous and non-equilibrium model for two-phase systems [7]. This allows it to model systems of mixtures of steam, water, non-condensable and solute quickly using a partially implicit numerical scheme.

For these reasons, data from PARCS is widely accepted to be accurate estimations for reactor scenarios. The Purdue MOX Core is not in use in any physical reactors today. For this reason, experimental data is not obtainable for code benchmarking purposes. Therefore,

CTF/NEM must be verified against other codes such as PARCS. PARCS was chosen as the benchmark for this project for those reasons.

Chapter 3

Verification

Three main test cases are examined for this project. First, the reactor core will be tested at Hot Zero Power (HZP) steady-state, then Hot Full Power (HFP) steady-state, and finally transient conditions during a rod ejection. The conditions of each run followed those specified in the Purdue MOX Benchmark Core description. Each of these cases will be explained in full in the sections below.

Hot Zero Power

During HZP steady-state, the core maintains a power of 10^{-4}% of full power. All shutdown banks are fully withdrawn, while all control rod banks are fully inserted. As listed in Table 1, core average moderator temperature is initially set to 560 K. Hot Zero Power conditions represents a scenario after a rapid shutdown or SCRAM of the reactor. The steam loop and coolant surrounding the core are still hot but the reactor itself is no longer producing a large quantity of power.

Figure 7 displays a comparison of the normalized axial power distribution from NEM to that of PARCS. As can be seen in the graph, the results from NEM match those from PARCS almost perfectly. The difference in axial distribution is imperceptible.

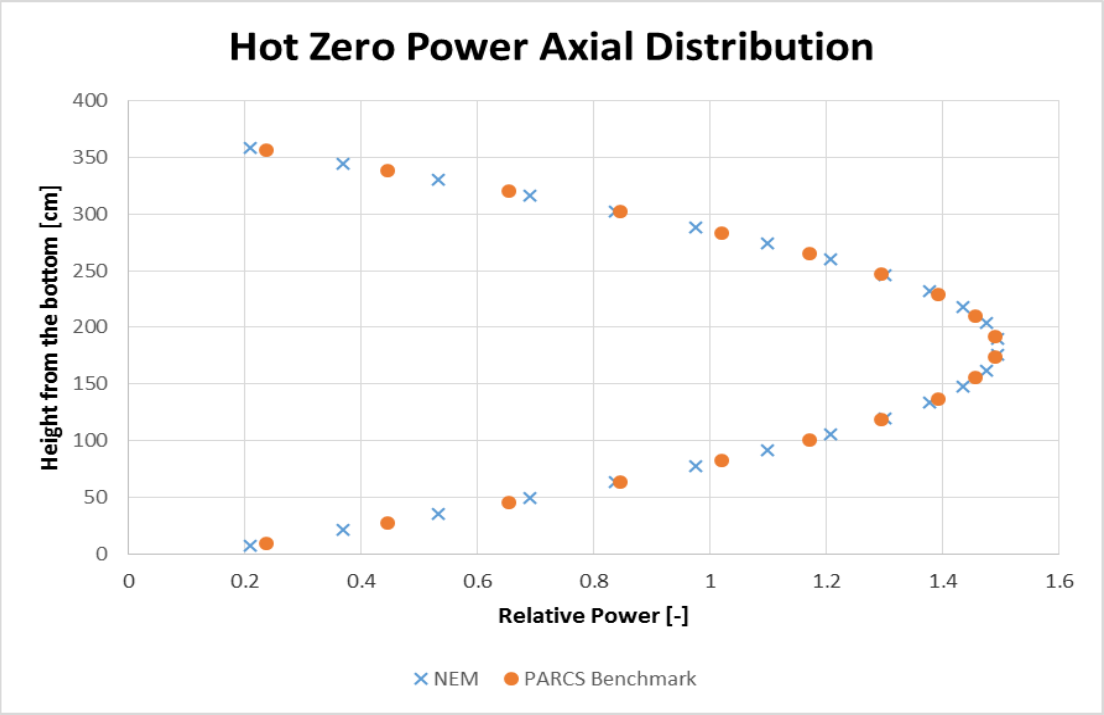

Figure 7. PARCS and NEM HZP Axial Distributions

Table 2 shows the critical boron concentration in ppm along with the Power Weighted Error (PWE), Error Weighted Error (EWE), and the k_{eff} to verify criticality. Both of these error values are calculated using assembly average powers summed over the whole core. The formulas used to calculate %PWE and %EWE can be found in Appendix C along with a brief discussion of their meaning and worth. Additionally, an example of the core assembly averaged power map is in Appendix B in the sample NEM output with an example map for the reference at the end of Appendix C.

Table 2. HZP Boron Concentration, Assembly Errors, and k_{eff}

	Boron Conc. [ppm]	%PWE	%EWE	k_{eff}
CTF/NEM	1345.16	0.61140	0.95183	0.999999211
PARCS	1340.71	REF	REF	CRITICAL

Hot Full Power

At HFP steady-state, all shutdown and control rods are fully withdrawn or All Rods Out (ARO) state. Additionally, the core maintains 100% power. Initial moderator temperature is set to 580 K and fuel temperature is set to 900 K, as listed in Table 1. Hot Full Power conditions represent a typical scenario of reactor operation for generation of electricity. If a MOX core such as the one modeled were to be used in industry its performance at HFP is important.

Figure 8 contains normalized axial power distribution comparison between PARCS and NEM. A blue x marks each NEM data point while an orange circle denotes each PARCS data point. As you can see, the shape of the distribution from NEM closely matches that of the PARCS benchmark. However, there is a small shift in the distribution and the maximum is slightly higher than the PARCS distribution. The maximum in NEM is only .375% higher than that of PARCS using a relative error calculation like the one shown at the end of Appendix C.

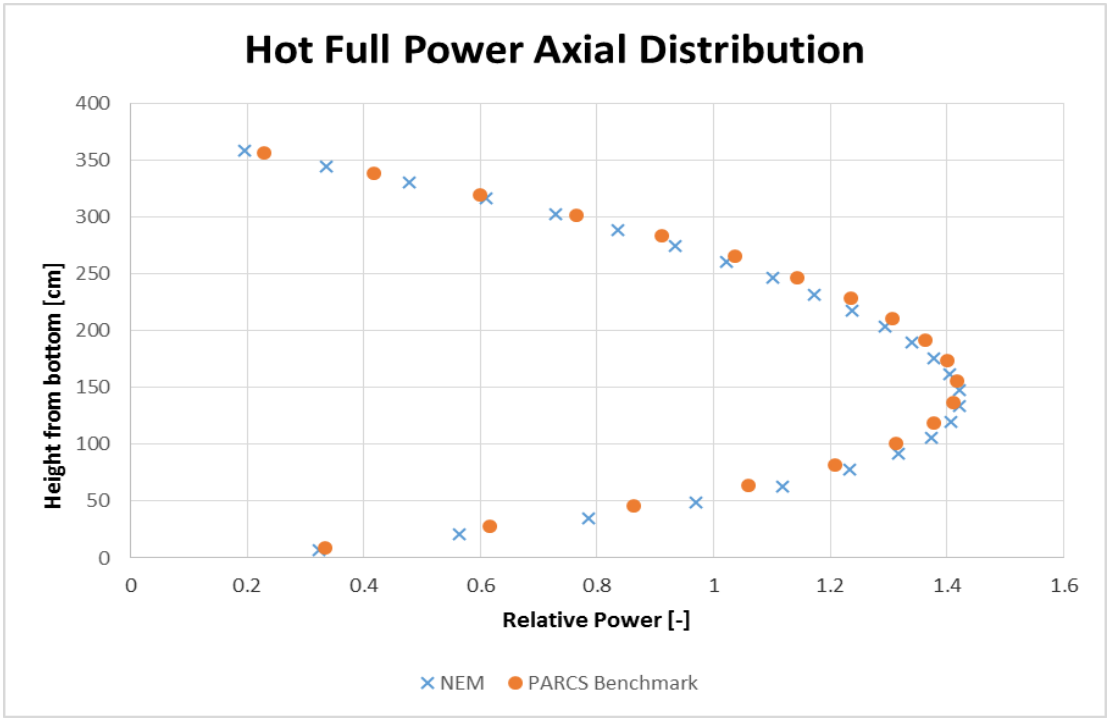

Figure 8. PARCS and NEM HFP Axial Distributions

Table 3 shows critical boron concentration in ppm for comparison between PARCS and NEM, as well as, %PWE and %EWE as discussed above, and K_{eff} to verify criticality. The differences between values for this case are very small. Again, the formulas for %PWE and %EWE can be found in Appendix C along with explanation of their meaning.

Table 3. HFP Boron Concentration, Assembly Errors, and K_{eff}

	Boron Conc. [ppm]	%PWE	%EWE	K_{eff}
CTF/NEM	1669.01	0.60414	0.82493	0.999800631
PARCS	1679.3	REF	REF	CRITICAL

The larger deviations observed at HFP as compared to HZP are coming from the differences in thermal-hydraulic feedback models and axial nodalization in NEM/CTF and PARCS. PARCS uses its own simplified PWR thermal-hydraulic model, which is difference than the CTF model. At HFP, the thermal-hydraulic feedback modeling plays an important role while at HZP the deviations are coming mostly from neutronics models and nodalizations.

Rod Ejection Accident

In a PWR, a rupture of the drive mechanism casing located on the reactor pressure vessel can cause the need for a rapid ejection of a control rod. In MOX cores, rod ejections are particularly important because the delayed neutron fraction is significantly lower than that of cores fueled primarily with UO_2. In nuclear reactors today, the presence of delayed neutrons allows the reactor to remain critical without being prompt critical. Prompt criticality is dangerous because of how quickly the number of neutrons throughout the core is increasing. The presence of delayed neutrons counteracts this because they can push the reactor to criticality in a time

scale in which the operators can react. In this way, a lower delayed neutron fraction contributes to the overall instability of a reactor and makes it harder to control.

The rod ejection problem is an important one for assessing the computational abilities of a neutronic code. Such transient conditions result in significant, localized perturbations of neutronic and thermal-hydraulic parameters [15]. Particularly in a heterogeneous MOX core, such as the one being modeled, these perturbations make it difficult for codes to accurately model real world effects. For these reasons, analyzing a rod ejection scenario with CTF/NEM is desirable.

As can be seen in Figure 9 on the next page, Control Rod Bank D, or CR-D, is located in the middle of the lower right quadrant of the core. Bank D controls only one rod in the entire core. It is the 9^{th} rod bank devised for the purpose of a single rod ejection from the core. CR-D is also pictured in the quarter-core configuration map presented in Figure 1. This single-rod for a full core model is a specification provided by the benchmark. Additionally, this rod should be fully ejected after .1 second with no reactor scram afterwards [15]. Prior to ejection, the core should have critical boron concentration at steady state HZP with all control rod banks fully inserted and all shutdown banks fully withdrawn. Performing this transient, therefore, requires a steady state solution be reached before implementation of the rod ejection. Then, boron concentration and other rod locations are assumed to be constant during the single rod ejection which will occur over the course of 1.0 second. The required changes to the input decks of CTF and NEM are shown in Table 4 and Table 5.

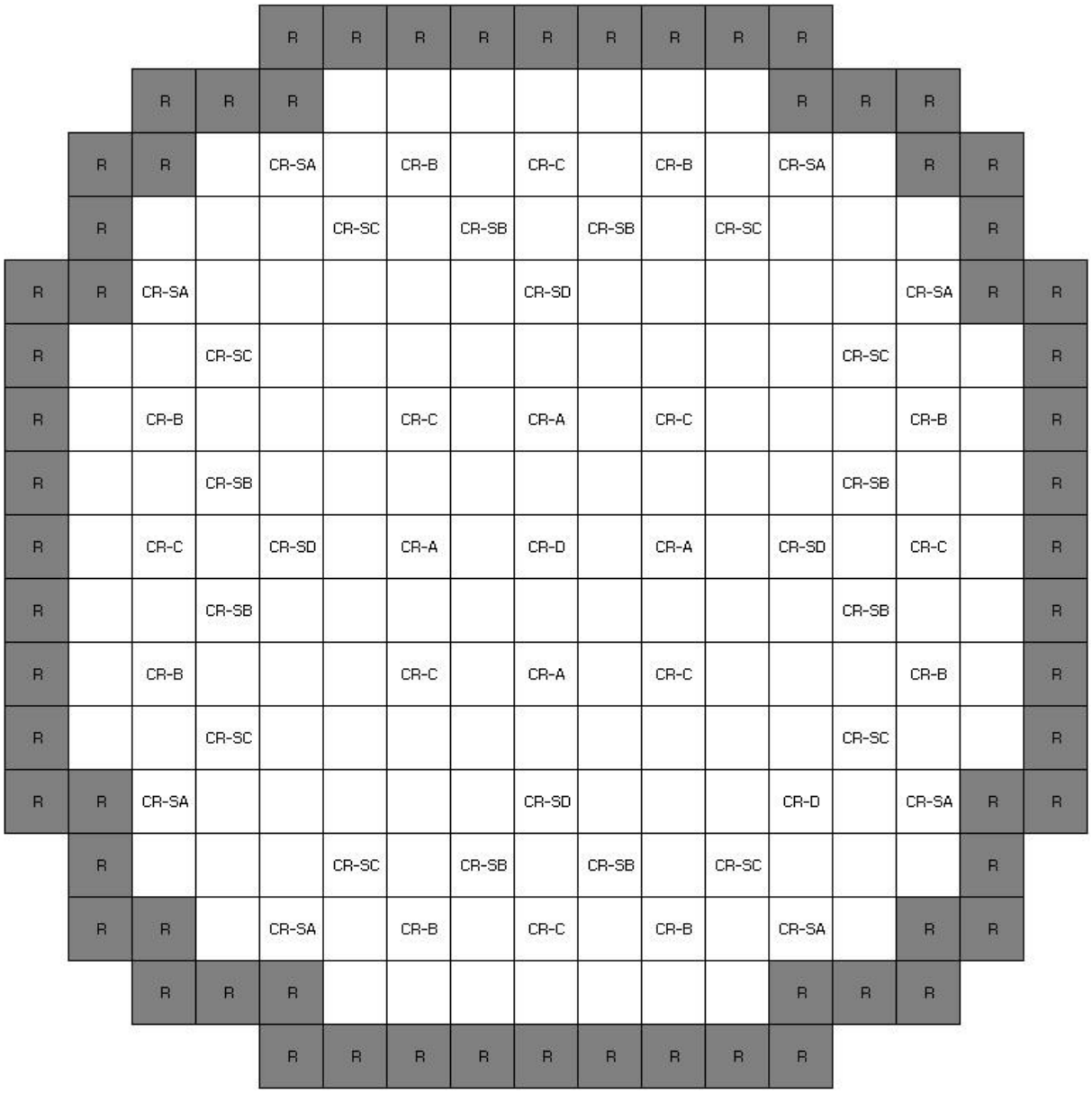

Figure 9. Control Rod Map [3]

Table 4. NEM Input Parameters for Rod Ejection [15]

Parameter	Variable	Input Deck	Input Value
Initial moderator temperature (K)	T_mod_initial	NEM Card 50	560.0
Initial moderator density (g/cm^3)	R_mod_initial	NEM Card 50	0.752
Initial fuel temperature (K)	T_fuel_initial	NEM Card 50	560.0
Initial boron concentration (ppm)	Conc	NEM Card 50	1345.16
Flag for control rod model	NEMFLAG	NEM Card 51	1
Number of control rod banks	NUMRB	NEM Card 51	9
Number of rodded cross-sections sets	NUMXSEC	NEM Card 51	8
Radial control rod bank radial position	CR_NODE	NEM Card 52	(pictured below)

```
                    0   0   0   0   0   0   0
            0   0   0   0   0   0   0   0   0   0   0
        0   0   5   0   2   0   3   0   2   0   5   0   0
    0   0   0   0   7   0   6   0   6   0   7   0   0   0   0
    0   5   0   4   0   0   0   8   0   0   0   4   0   5   0
0   0   0   7   0   0   0   0   0   0   0   0   0   7   0   0   0
0   0   2   0   0   0   3   0   1   0   3   0   0   0   2   0   0
0   0   0   6   0   0   0   0   0   0   0   0   0   6   0   0   0
0   0   3   0   8   0   1   0   4   0   1   0   8   0   3   0   0
0   0   0   6   0   0   0   0   0   0   0   0   0   6   0   0   0
0   0   2   0   0   0   3   0   1   0   3   0   0   0   2   0   0
0   0   0   7   0   0   0   0   0   0   0   0   0   7   0   0   0
    0   5   0   4   0   0   0   8   0   0   0   9   0   5   0
    0   0   0   0   7   0   6   0   6   0   7   0   0   0   0
        0   0   5   0   2   0   3   0   2   0   5   0   0
            0   0   0   0   0   0   0   0   0   0   0
                    0   0   0   0   0   0   0
```

Parameter	Variable	Input Deck	Input Value
Initial axial control rod bank position (cm)	INITCR	NEM Card 53	(pictured below)

```
387.136   387.136   387.136   387.136   21.42   21.42   21.42   21.42   387.136
```

Parameter	Variable	Input Deck	Input Value
Number of banks moving during transient	RBMOVE	NEM Card 54	1
Number of rod bank that is moving	RB	NEM Card 54	9
Number of movements of the bank	NM	NEM Card 54	1
Number of bank for first movement	BANK	NEM Card 55	9
Start time of rod ejected per movement (s)	MOVESTART	NEM Card 55	0.0
Velocity of rod ejected (cm/s) (into the core)	VEL	NEM Card 55	-3657.16
Final axial position rod ejected (cm)	FINALPOS	NEM Card 55	21.42

Table 5. CTF Input Parameters for Rod Ejection [15]

Parameter	Variable	Input Deck	Input Value
Code version (Coupled code: CTF/NEM)	VERSION	CTF Card 0	0
Simulation mode (Transient)	COUPLED_MODE	CTF Card 0	3
Time Step for Output (in seconds)	EDINT	CTF Card 15	.01

As can be seen in the tables, activating control rod movement requires in depth definition of the movement desired. Adjusting the input deck as shown tells the code to prepare the 9th bank for one movement at a speed of 3657.16cm/s (negative to signify ejection) with a final position

of 21.42 and a starting position of 387.136cm. Additionally, for this study, data was to be collected every .01s, which is specified in CTF's input deck.

The important parameters determining rod ejection transient evolution are the ejected rod worth, delayed neutron fraction and Doppler (fuel temperature) reactivity feedback effect. Before running the transient the ejected rod and core averaged delayed neutron fraction (β_{eff}) have been evaluated. NEM predicted ejected rod worth is 653.33 pcm (PARCS = 648 pcm) and NEM β_{eff} = 579.39 pcm (PARCS = 579.39 pcm). Please note that 1 pcm = $1x10^{-5}$ dk/k. These results indicate that both NEM/CTF and PARCS will be simulating super-prompt critical rod ejection transients but the inserted reactivity by CTF/NEM (1.127$) is larger than the reactivity inserted by PARCS (1.120$), which will lead to larger power excursion with CTF/NEM.

Figure 10 shows the change in percent power over time. Data from PARCS is listed in orange while blue is data from NEM. The general trend of the two data sets match quite well. The ejection takes place over the first .1 seconds of the transient. As can be seen, the resulting jump in power doesn't occur until shortly after .2 seconds. The maximum power is reached at .33 seconds for NEM and .34 seconds for PARCS. There is a difference in the maximums reached. NEM's value for the power spike is 190.49% while PARCS provides a maximum of 145.84%. After this time, feedback effects begin to dominate and the power level starts its fall to its final value of around 20%. NEM outputs a final power of 22.79% while PARCS gives a final power of 19.11%.

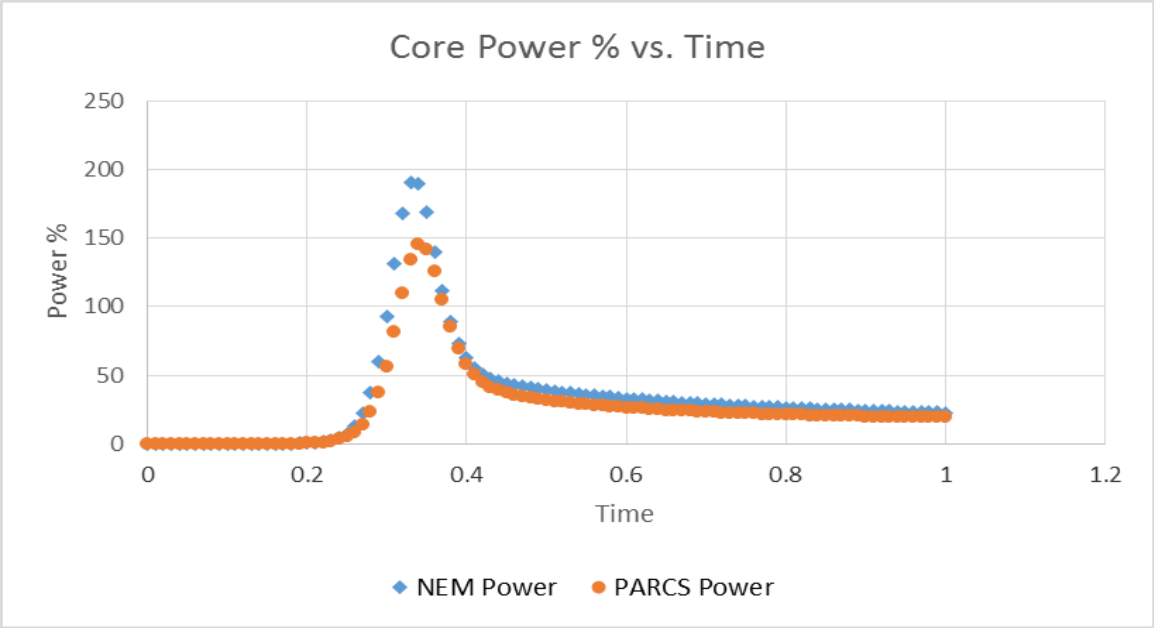

Figure 10. Percent Core Power Over Time During Rod Ejection

Chapter 4

Conclusion

Analysis of Data

The data from the steady state HZP and HFP cases matched the benchmarks rather well. The shape of the axial distribution for both cases closely follows the distributions from PARCS. Additionally, the errors, which are also outlined in Chapter 3 are small. The power level results from the Rod Ejection Accident (REA), matched the trend of the benchmark well, but, the values were slightly higher.

The results at steady state HZP were excellent. First, the axial normalized power distributions were a perfect match. Since the core is producing very little power, the results here must match exactly to make sense. If there was a discrepancy at what is essentially zero power in the distribution that would be a sign of a big problem in how power is calculated in NEM. The concentration of boron required for criticality at steady state HZP in NEM was very close to that used for the PARCS benchmark. The difference was only .333%. Additionally, measures of assembly error were very small. As listed in Table 2, percent PWE was .61140 and percent EWE was .82493. Such small error in the axial distribution and assembly relative to the benchmark implies accuracy of CTF/NEM at steady state HZP conditions.

Overall, the results at steady state HFP were very good. In the axial distribution, the trends match. There is, however, a small shift toward the bottom of the core. The shift is very small though. This small shift caused NEM's axial maximum normalized power to occur about 5cm lower than the maximum in PARCS. Despite this, NEM's raw, maximum normalized power

was only .375% off that of PARCS. Such small error is a very good sign. The boron concentration required for criticality differed by .613%, which is also very low. Finally, the measures of assembly error were very low, as well. Both the percent PWE (.60414) and the percent EWE (.82493) were below 1, as listed in Table 3. Such agreement on an assembly scale, when considered in the scope of the agreement of the axial distributions is very encouraging. These results suggest the CTF/NEM coupled codes are accurate for analysis at steady state HFP.

Finally, the power level results during the transient rod ejection accident conditions were also close to that of the PARCS benchmark. For the rod ejection problem, the most important features for comparison are the time of the power spike and the final power level after ejection. In these two areas, the data from NEM matches the PARCS benchmark data well. Just looking at the graph in Figure 10, the spike occurs right at the same time and the power level drops down to about 20% which is what the PARCS data predicts. The error in final power level after 1 second is 16.15%, which is high. However, when taken in the scope of the full distribution, an absolute difference of about 4% is rather small. For these reasons, CTF/NEM is reliable for performing this kind of rod ejection analysis with some accuracy.

In conclusion, coupled CTF/NEM produces accurate data for steady state HZP, steady state HFP, and for REA. In light of the motivations and objectives for this project, the code seems to be more than qualified for use in a classroom setting, however, the high error for the REA case should be noted if the coupled codes are to be used for reactor analysis where real world application and safety could be involved. This is because for the rod ejection the trend fits perfectly which is very useful for teaching, but, if specific power levels are required, the error is sufficiently large as to not be trusted implicitly when safety is of the utmost importance.

Suggestions for future work

During the course of the project, problems arose and were dealt with. That being said, there still exists area for further research. One important area to delve further into is why the predicted power spike for NEM is higher than that of PARCS for the REA. Additionally, other methods of comparison between the two codes for REA should be considered. For instance, pin peaking, assembly peaking, and point pin peaking factors could be gathered in NEM and compared at each time step. In order to perform this analysis more simply, some minor modification to NEM's code could be implemented to create a new output file containing only the peaking factors for each time step.

Other cases could be explored, as well. With some modification to the input decks, a different rod ejection or withdrawn scenarios could be simulated. This would provide a wealth of new data for analysis and comparison. Data for a rod drop experiment could be obtained from PARCS. Accurate results from a rod withdrawn would also increase confidence in the coupled codes for other analyses.

Lastly, results from CTF/NEM should be compared to other reactor simulating codes. PARCS is an acceptable code for simple comparison but further comparison to other codes would give a better idea of the true accuracy of CTF/NEM coupled codes. More verification and validation of the codes would only further enhance the confidence in and ability to use CTF/NEM for important reactor analyses.

Appendix A

Purdue MOX Core Benchmark

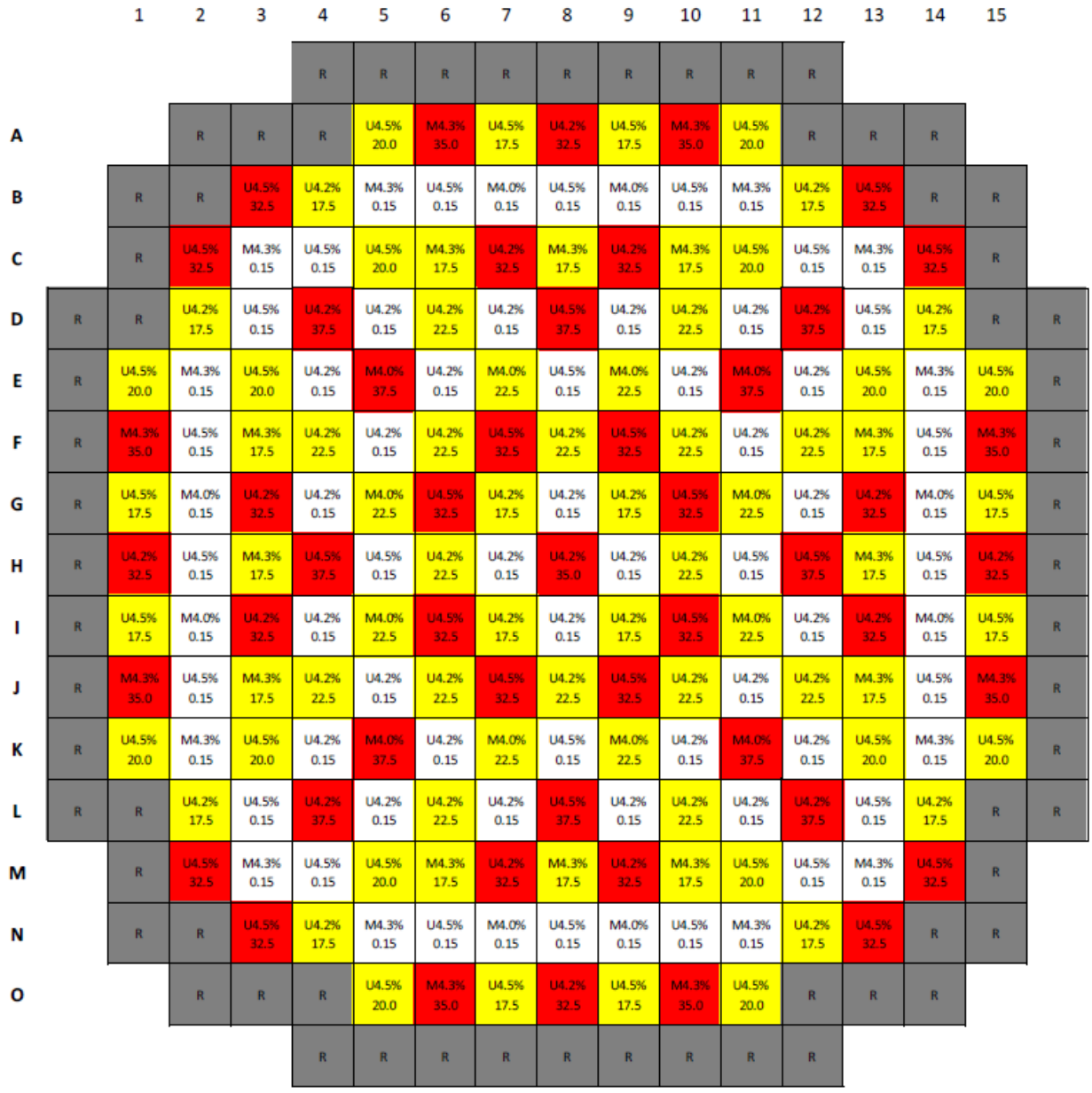

Figure 11. Benchmark Assembly Loading Map [3]

Table 6. Core Refueling Strategy [8]

Assembly type	Fresh fuel 0 GWd/tHM	Once-burned 20.0 GWd/tHM	Twice-burned 35.0 GWd/tHM
UO_2 4.2%	28	28	17
UO_2 4.5%	24	24	20
MOX 4.0%	8	8	4
MOX 4.3%	12	12	8
Total	72	72	49

Table 7. Heavy Metal Composition in Fuel [8]

Assembly type	Density [g/cm^3]	HM material	
UO_2 4.2%	10.24	^{235}U: 4.2 wt.%, ^{238}U: 95.8 wt.%	
UO_2 4.5%	10.24	^{235}U: 4.5 wt.%, ^{238}U: 95.5 wt.%	
MOX 4.0%	10.41	Corner zone: 2.5 wt.% Pu-fissile	Uranium vector: 234/235/236/238 = 0.002/0.2/0.001/99.797 wt.% Plutonium vector: 239/240/241/242 = 93.6/5.9/0.4/0.1 wt.%
		Peripheral zone: 3.0 wt.% Pu-fissile	
		Central zone: 4.5 wt.% Pu-fissile	
MOX 4.3%	10.41	Corner zone: 2.5 wt.% Pu-fissile	
		Peripheral zone: 3.0 wt.% Pu-fissile	
		Central zone: 5.0 wt.% Pu-fissile	

Table 8. Other Burnable Materials [8]

Absorber material	Density [g/cm^3]	Material
Control rod	1.84	B_4C
IFBA	1.69	ZrB_2
WABA	3.5635	Al_2O_3-B_4C, 10.0 wt.% B_4C

Table 9. Other Non-Burnable Materials [8]

Other material	Density [g/cm^3]	Material
Clad	6.504	Zircaloy-2: Zr/Sn/Fe/Cr/N = 98.23/1.50/0.12/0.10/0.05 at.%
Gap	0.001	^{16}O
Baffle	7.82	SS-304: Fe/Cr/Ni/Mn = 70.351/19.152/8.483/2.014 at.%
Coolant	0.75206	Water at 560 K and 15.5 MPa
Coolant	0.71187	Water at 580 K and 15.5 MPa
Coolant	0.66114	Water at 600 K and 15.5 MPa

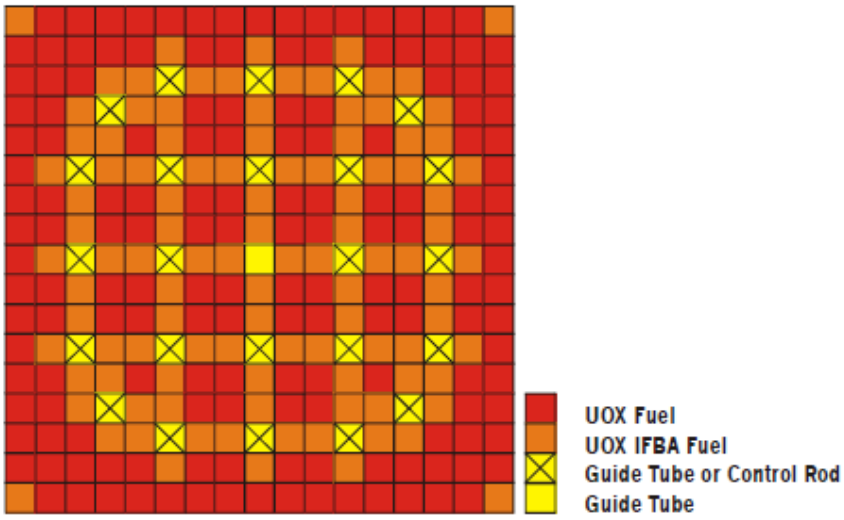

Figure 12. UO_2 Fuel Assembly with 104 IFBA Pins [8]

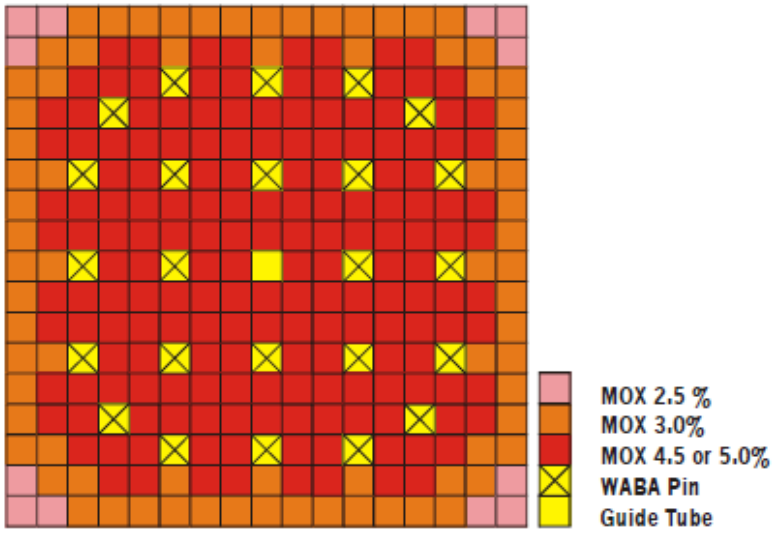

Figure 13. MOX Fuel Assembly with 24 WABA Pins

Appendix B

Sample Decks for CTF and NEM

NEM Sample Input Deck

```
*-----------------------------------------------------------------------*
* NEM INPUT DECKFOR MOX Benchmark (Purdue Univ) nemin 2d unrod 3 base*
*-----------------------------------------------------------------------*
*-----------------------------------------------------------------------*
* CARD 1: Read general problem definition                               *
*-----------------------------------------------------------------------*
*     NDGR     IGEOM        NG    ITRANS    IADF  ITRS IKAPPA
         6         0         2         0       0     2      1
*-----------------------------------------------------------------------*
* CARD 4: Read first set of model input specifications if IGEOM = 0  *
*         or IGEOM = 1 (Cartesian and Cylindical geometries)          *
*-----------------------------------------------------------------------*
*    NXNDS     NYNDS     NZNDS    NXSETS     NASMX     NASMY     NASMZ
        17        17        28        26        17        17         28
*-----------------------------------------------------------------------*
* CARD 5: Read second set of model input specifications if IGEOM = 0 *
*         or IGEOM = 1 (Cartesian and Cylindical geometries)          *
*-----------------------------------------------------------------------*
*    NXCDS     NYCDS     NZCDS    NXSCDS    NINNER      ILNG       IIN
        17        17        28        26         5         0          0
*-----------------------------------------------------------------------*
* CARD 6: Read third set of model input specifications for all        *
*         geometry types                                              *
*-----------------------------------------------------------------------*
*   MOUTER      IREB      IAEX       IQL    APTCVG   AAVCVG      AKCVG
     2000         0         1         1     1.e-5     1.e-5     1.e-7
*-----------------------------------------------------------------------*
* CARD 7: Read fourth set of model input specifications for all       *
*         geometry types                                              *
*-----------------------------------------------------------------------*
*   IUSCAT    MXCMIT     CMEMD     IWEIL    OMEGOR
         0       100       0.0         0       1.2   0
*-----------------------------------------------------------------------*
* CARD 8: If IUSCAT = 1 read the highest upscattering group and the  *
*         number of upscattering iterations per one outer iteration  *
*         Otherwise read group inverse velocities                     *
*-----------------------------------------------------------------------*
*   ITUGRP   ITERSUM
*   0.5e-7    0.24e-5
*-----------------------------------------------------------------------*
* CARD 10: Read delayed neutron fractions and decay constants         *
*-----------------------------------------------------------------------*
* Delayed neutron group 1
*     BETA    LAMBDA
  1.70885E-04    1.34289E-02
* Delayed neutron group 2
*     BETA    LAMBDA
```

```
 1.00785E-03    3.20089E-02
* Delayed neutron group 3
*     BETA    LAMBDA
  9.26333E-04     1.19840E-01
* Delayed neutron group 4
*     BETA    LAMBDA
 2.12242E-03     3.07049E-01
* Delayed neutron group 5
*     BETA    LAMBDA
  1.02261E-03      8.72507E-01
* Delayed neutron group 6
*     BETA    LAMBDA
  4.03532E-04      2.91524E+00
*------------------------------------------------------------------------*
* CARD 11: Read delayed neutron emission spectra  fractions              *
*------------------------------------------------------------------------*
*   CHID(1)    CHID(2)
      1.0        0.0
*------------------------------------------------------------------------*
* CARD 12: Read prompt fission neutron emission spectra fractions        *
*          for Cartesian and cylindrical geometries                      *
*------------------------------------------------------------------------*
*   CHIP(1)    CHIP(2)
  1.0000D+00  0.0000D+00
  1.0000D+00  0.0000D+00
  1.0000D+00  0.0000D+00
  1.0000D+00  0.0000D+00
  1.0000D+00  0.0000D+00
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  1.0000D+00  0.0000D+00
  1.0000D+00  0.0000D+00
  1.0000D+00  0.0000D+00
  1.0000D+00  0.0000D+00
  1.0000D+00  0.0000D+00
  1.0000D+00  0.0000D+00
  1.0000D+00  0.0000D+00
  1.0000D+00  0.0000D+00
  1.0000D+00  0.0000D+00
*-----------------------------------------------------------------------
* CARD 22: Node dimensions in X-direction                                *
*------------------------------------------------------------------------*
* DELXT(1) DELXT(2)
21.42
21.42
21.42
21.42
21.42
21.42
21.42
21.42
```

```
21.42
21.42
21.42
21.42
21.42
21.42
21.42
21.42
21.42
*-------------------------------------------------------------------------*
* CARD 23: Node dimensions in Y-direction                                 *
*-------------------------------------------------------------------------*
* DELYT(1)
21.42
21.42
21.42
21.42
21.42
21.42
21.42
21.42
21.42
21.42
21.42
21.42
21.42
21.42
21.42
21.42
21.42
21.42
*-------------------------------------------------------------------------*
* CARD 24: Node dimensions in Z-direction                                 *
*-------------------------------------------------------------------------*
* DELZ(1)
21.42
14.066
14.066
14.066
14.066
14.066
14.066
14.066
14.066
14.066
14.066
14.066
14.066
14.066
14.066
14.066
14.066
14.066
14.066
14.066
14.066
14.066
14.066
14.066
14.066
14.066
14.066
14.066
14.066
14.066
```

```
21.42
*------------------------------------------------------------------------*
* CARD 25: Number of the first node in X-direction for each row Y       *
*------------------------------------------------------------------------*
*  NLNDS(1)  NLNDS(2)
   6 4 3 2 2 1 1 1 1 1 1 1  2 2 3 4 6
*------------------------------------------------------------------------*
* CARD 26: Number of the last node in X-direction for each row Y        *
*------------------------------------------------------------------------*
* NXYNDS(1) NXYNDS(2)
  12 14 15 16 16 17 17 17 17 17 17 17 16 16 15 14 12
*------------------------------------------------------------------------*
* CARD 27: Number of the first coarse node in X-direction for each row *
*------------------------------------------------------------------------*
*  NLCDS(1)  NLCDS(2)
 6 4 3 2 2 1 1 1 1 1 1 1  2 2 3 4 6
*------------------------------------------------------------------------*
* CARD 28: Number of the last coarse node in X-direction for each row *
*-------------------------------------------------------------------------
* NXYCDS(1) NXYCDS(2)
 12 14 15 16 16 17 17 17 17 17 17 17 16 16 15 14 12
*------------------------------------------------------------------------*
* CARD 29: Number of the first assembly in X-direction for each row Y  *
*------------------------------------------------------------------------*
*  NLADS(1)  NLADS(2)
6 4 3 2 2 1 1 1 1 1 1 1  2 2 3 4 6
*------------------------------------------------------------------------*
* CARD 30: Number of the last assembly in X-direction for each row Y*
*------------------------------------------------------------------------*
*  NXYADS(1)  NXYADS(2)
  12 14 15 16 16 17 17 17 17 17 17 17 16 16 15 14 12
*------------------------------------------------------------------------*
* CARD 31: Read outer boundary conditions for Cartesian and             *
*          cylindrical geometries                                       *
*------------------------------------------------------------------------*
*     IOBR      IOBL      IOBT      IOBB      IOBU      IOBD
         3         3         3         3         3         3
*------------------------------------------------------------------------*
* CARD 32: Read planar map of assembly types                            *
*------------------------------------------------------------------------*
* IDEN(1)   IDEN(2)   IDEN(3)   IDEN(4)
                  18 18 18 18 18 18 18
              18 18 15 13 12  7 12 13 15 18 18
           18  9  8 16  4 11  4 11  4 16  8  9 18
        18  9 16  4 15  6  7  6  7  6 15  4 16  9 18
        18  8  4 17  2  3  2  5  2  3  2 17  4  8 18
     18 15 16 15  2 14  2 10  4 10  2 14  2 15 16 15 18
     18 13  4  6  3  2  3  9  3  9  3  2  3  6  4 13 18
     18 12 11  7  2 10  9  8  2  8  9 10  2  7 11 12 18
     18  7  4  6  5  4  3  2  1  2  3  4  5  6  4  7 18
     18 12 11  7  2 10  9  8  2  8  9 10  2  7 11 12 18
     18 13  4  6  3  2  3  9  3  9  3  2  3  6  4 13 18
     18 15 16 15  2 14  2 10  4 10  2 14  2 15 16 15 18
        18  8  4 17  2  3  2  5  2  3  2 17  4  8 18
        18  9 16  4 15  6  7  6  7  6 15  4 16  9 18
           18  9  8 16  4 11  4 11  4 16  8  9 18
              18 18 15 13 12  7 12 13 15 18 18
                    18 18 18 18 18 18 18
*------------------------------------------------------------------------*
* CARD 33: Read axial composition for each assembly type                *
*------------------------------------------------------------------------*
```

```
*  IAR(1)  IAR(2)  IAR(3)
18 18 18  18 18 18 18 18 18 18 18 18 18 18 18 18 18 18 18 18 18 18 18 18 18 18
1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26
1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26
1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26
1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26
1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26
1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26
1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26
1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26
1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26
1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26
1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26
1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26
1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26
1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26
1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26
1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26
1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26
1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26
1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26
1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26
1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26
1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26
1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26
1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26
1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26
1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26
18 18 18  18 18 18 18 18 18 18 18 18 18 18 18 18 18 18 18 18 18 18 18 18 18 18
*-----------------------------------------------------------------------*
* CARD 34: Read X assembly numbers                                      *
*-----------------------------------------------------------------------*
*  IASMX(1) IASMX(2)
 1  2  3  4  5  6  7  8  9  10  11  12  13  14  15 16 17
*-----------------------------------------------------------------------*
* CARD 35: Read Y assembly numbers                                      *
*-----------------------------------------------------------------------*
*  IASMY(1) IASMY(2)
 1  2  3  4  5  6  7  8  9  10  11  12  13  14  15 16 17
*-----------------------------------------------------------------------*
* CARD 36: Read Z assembly numbers                                      *
*-----------------------------------------------------------------------*
*  IASMZ(1)
 1  2  3  4  5  6  7  8  9  10  11  12  13  14  15 16 17 18 19 20 21 22 23 24 25 26 27
28
*-----------------------------------------------------------------------*
* CARD 37: Read X coarse mesh numbers                                   *
*-----------------------------------------------------------------------*
*  ICMX(1)  ICMX(2)
 1  2  3  4  5  6  7  8  9  10  11  12  13  14  15 16 17
*-----------------------------------------------------------------------*
* CARD 38: Read Y coarse mesh numbers                                   *
*-----------------------------------------------------------------------*
*  ICMY(1)  ICMY(2)
 1  2  3  4  5  6  7  8  9  10  11  12  13  14  15 16 17
*-----------------------------------------------------------------------*
* CARD 39: Read Z coarse mesh numbers                                   *
*-----------------------------------------------------------------------*
*  ICMZ(1)
 1  2  3  4  5  6  7  8  9  10  11  12  13  14  15 16 17 18 19 20 21 22 23 24 25 26 27
28
```

```
*--------------------------------------------------------------------*
*nref_nodes_ax nref_nodes_rad T_mod_initial R_mod_initial *T_fuel_initial   Conc
(Boron)
*--------------------------------------------------------------------*
      2           48           560.0      0.752         560.0             1345.16
*--------------------------------------------------------------------*
!          Card Set 51 CONTROL ROD CONDITIONS                        !
!--------------------------------------------------------------------!
!   Flag for CR           # of RB             # of rodded XS sets    !
!   0 - no CR present                           in NEMTABR           !
!   1 - CR present (PWR)                                             !
!--------------------------------------------------------------------!
         1                          9                 8
!-------------------------------------------------------!
!           PLANAR VIEW OF CONTROL ROD LOCATIONS        !
!    0 - No CR at location                              !
!    # - CR from Rod Bank # at location                 !
!-------------------------------------------------------!
                     0  0  0  0  0  0  0
                  0  0  0  0  0  0  0  0  0  0  0
               0  0  5  0  2  0  3  0  2  0  5  0  0
            0  0  0  0  7  0  6  0  6  0  7  0  0  0  0
            0  5  0  4  0  0  0  8  0  0  0  4  0  5  0
         0  0  0  7  0  0  0  0  0  0  0  0  0  7  0  0  0
         0  0  2  0  0  0  3  0  1  0  3  0  0  0  2  0  0
         0  0  0  6  0  0  0  0  0  0  0  0  0  6  0  0  0
         0  0  3  0  8  0  1  0  4  0  1  0  8  0  3  0  0
         0  0  0  6  0  0  0  0  0  0  0  0  0  6  0  0  0
         0  0  2  0  0  0  3  0  1  0  3  0  0  0  2  0  0
         0  0  0  7  0  0  0  0  0  0  0  0  0  7  0  0  0
            0  5  0  4  0  0  0  8  0  0  0  9  0  5  0
            0  0  0  0  7  0  6  0  6  0  7  0  0  0  0
               0  0  5  0  2  0  3  0  2  0  5  0  0
                  0  0  0  0  0  0  0  0  0  0  0
                     0  0  0  0  0  0  0

!-------------------------------------------------------------------------------------!
!   Initial Position into Core (cm)!
!-------------------------------------------------------------------------------------!
    387.136    387.136   387.136   387.136   21.42   21.42   21.42   21.42   387.136
!-------------------------------------------------------------------------------------!
!  # RB Moving      RB1   NM1
!-------------------------------------------------------------------------------------!
       1        9      1
!-------------------------------------------------------------------------------------!
!  Bank         Move Start Time       Velocity into Core        Final Depth in Core!
!-------------------------------------------------------------------------------------!
    9                 0.0                                  -3657.16              21.42
!-------------------------------------------------------------------------------------!
!                         END OF INPUT DECK
!
!-------------------------------------------------------------------------------------!
```

NEM Sample Output

```
abstot =   9.98140792911419883E-01 fissot =    9.99999693238406762E-01 k_total =   1.00186236284519015E+00
abstot all groups =   0.997422314596772
fissot/abstot_all_groups =    1.00258403948249

   number of ss outer iterations =     6
   problem keff =    9.99210592937376241E-01


    1-D  core axial powers
 0.00000000000000E+000  0.210332871310045       0.369902930442376
 0.533871039478040      0.690531531968904       0.838096982815235
 0.974604634661487       1.09825100193849        1.20741120751300
  1.30064568424249       1.37673072355666        1.43466743249254
  1.47369647041076       1.49331427669251        1.49326092097096
  1.47353980627399       1.43441003318196        1.37638560366766
  1.30023560307692       1.20695977232881        1.09778145870229
 0.974137378116974      0.837657246782674       0.690142587751805
 0.533553572989543      0.369675145340548       0.210204083290036
 0.00000000000000E+000


    2-D  assembly average powers

17                                  0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000

16                       0.0000 0.0000 0.4081 0.3530 0.3988 0.3035 0.3988 0.3530 0.4081 0.0000 0.0000

15                 0.0000 0.4791 0.8924 1.0956 0.5426 0.8245 0.4738 0.8245 0.5426 1.0956 0.8924 0.4791 0.0000

14           0.0000 0.4791 1.1599 1.4185 1.4559 1.3495 1.0502 1.1573 1.0502 1.3495 1.4559 1.4185 1.1599 0.4791 0.0000

13           0.0000 0.8924 1.4185 0.6225 1.6294 1.6167 1.7463 1.2789 1.7463 1.6167 1.6294 0.6225 1.4185 0.8924 0.0000

12 0.0000 0.4081 1.0956 1.4559 1.6294 1.2960 1.5475 1.3383 1.4737 1.3383 1.5475 1.2960 1.6294 1.4559 1.0956 0.4081 0.0000

11 0.0000 0.3530 0.5426 1.3495 1.6167 1.5475 0.5872 0.7571 0.4908 0.7571 0.5872 1.5475 1.6167 1.3495 0.5426 0.3530 0.0000

10 0.0000 0.3988 0.8245 1.0502 1.7463 1.3383 0.7571 0.7667 0.7506 0.7667 0.7571 1.3383 1.7463 1.0502 0.8245 0.3988 0.0000

 9 0.0000 0.3035 0.4738 1.1573 1.2789 1.4737 0.4908 0.7506 0.3283 0.7506 0.4908 1.4737 1.2789 1.1573 0.4738 0.3035 0.0000

 8 0.0000 0.3988 0.8245 1.0502 1.7463 1.3383 0.7571 0.7667 0.7506 0.7667 0.7571 1.3383 1.7463 1.0502 0.8245 0.3988 0.0000

 7 0.0000 0.3530 0.5426 1.3495 1.6167 1.5475 0.5872 0.7571 0.4908 0.7571 0.5872 1.5475 1.6167 1.3495 0.5426 0.3530 0.0000

 6 0.0000 0.4081 1.0956 1.4559 1.6294 1.2960 1.5475 1.3383 1.4737 1.3383 1.5475 1.2960 1.6294 1.4559 1.0956 0.4081 0.0000

 5           0.0000 0.8924 1.4185 0.6225 1.6294 1.6167 1.7463 1.2789 1.7463 1.6167 1.6294 0.6225 1.4185 0.8924 0.0000

 4           0.0000 0.4791 1.1599 1.4185 1.4559 1.3495 1.0502 1.1573 1.0502 1.3495 1.4559 1.4185 1.1599 0.4791 0.0000

 3                 0.0000 0.4791 0.8924 1.0956 0.5426 0.8245 0.4738 0.8245 0.5426 1.0956 0.8924 0.4791 0.0000

 2                       0.0000 0.0000 0.4081 0.3530 0.3988 0.3035 0.3988 0.3530 0.4081 0.0000 0.0000

 1                                  0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000

      1      2      3      4      5      6      7      8      9     10     11     12     13     14     15     16     17
```

Figure 14. Steady State NEM Output

Appendix C

Calculating Error

Two important measurements of error over a distribution used in this project are PWE and EWE, expressed as percentages above. These are weighted averages of the error at each corresponding point of comparison. Using PWE allows the focus to be placed on areas of high power within the core [8]. Error from areas with lower power are weighted less heavily. EWE provides a more balanced view. The biggest percent error receive the most weight similar to RMS error [8]. Examining both allows for a complete picture of the agreement between two data sets.

Equation 1. Power Weighted Error (PWE)

$$PWE = \frac{\sum_i |e_i| ref_i}{\sum_i ref_i}$$

Equation 2. Error Weighted Error (EWE)

$$EWE = \frac{\sum_i |e_i| |e_i|}{\sum_i |e_i|}$$

For Equation 1 and Equation 2 e_i is defined in the following way.

$$e_i = \frac{calc_i - ref_i}{ref_i} \times 100$$

Equation 3. Relative Error

$$\frac{measured - reference}{reference} x\ 100\%$$

	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8
H					0.40	0.48	0.58	0.49	0.58	0.48	0.40				
G			0.32	0.64	1.01	1.11	1.11	1.12	1.11	1.11	1.01	0.64	0.32		
F		0.32	0.84	1.12	1.18	1.19	0.97	1.12	0.97	1.19	1.18	1.12	0.84	0.32	
E		0.64	1.12	0.93	1.29	1.21	1.30	1.01	1.30	1.21	1.29	0.93	1.12	0.64	
D	0.40	1.01	1.18	1.29	1.07	1.33	1.20	1.37	1.20	1.33	1.07	1.29	1.18	1.01	0.40
C	0.48	1.11	1.19	1.21	1.33	1.17	1.07	1.19	1.07	1.17	1.33	1.21	1.19	1.11	0.48
B	0.58	1.11	0.97	1.30	1.20	1.07	1.25	1.37	1.25	1.07	1.20	1.30	0.97	1.11	0.58
A	0.49	1.12	1.12	1.01	1.37	1.19	1.37	1.09	1.37	1.19	1.37	1.01	1.12	1.12	0.49
B	0.58	1.11	0.97	1.30	1.20	1.07	1.25	1.37	1.25	1.07	1.20	1.30	0.97	1.11	0.58
C	0.48	1.11	1.19	1.21	1.33	1.17	1.07	1.19	1.07	1.17	1.33	1.21	1.19	1.11	0.48
D	0.40	1.01	1.18	1.29	1.07	1.33	1.20	1.37	1.20	1.33	1.07	1.29	1.18	1.01	0.40
E		0.64	1.12	0.93	1.29	1.21	1.30	1.01	1.30	1.21	1.29	0.93	1.12	0.64	
F		0.32	0.84	1.12	1.18	1.19	0.97	1.12	0.97	1.19	1.18	1.12	0.84	0.32	
G			0.32	0.64	1.01	1.11	1.11	1.12	1.11	1.11	1.01	0.64	0.32		
H					0.40	0.48	0.58	0.49	0.58	0.48	0.40				

Figure 15. Example Reference Assembly Average Power Map

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Radiation Detection and Measurement
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