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BOILING WATER REACTOR TRANSIENT INSTABILITY STUDIES OF RINGHALS 1 REACTOR USING TRACE COUPLED WITH PARCS

A Thesis in

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by

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ABSTRACT

Reactor plant design often incorporates data and insight ascertained from computer code simulations of plant dynamics and reactor core behavior. Increasing utilization of data gathered from simulations aids operators and designers in planning for overall plant operation and most importantly, safety.

The United States (US) Nuclear Regulatory Commission (NRC) in researching reactor plant safety utilizes several computer codes, or models. The two codes used for work on this thesis are TRACE and PARCS. TRACE (TRAC RELAP5 Advanced Computational Engine) is a thermal-hydraulic code that models the coolant system under numerous variables in operating conditions. Coolant flow is especially important and the ability to model two-phase flow is essential in modeling boiling water reactors. Two-phase flow modeling is integral as it models the vast differences in flow from the bottom of the core to the top at the steam separators. TRACE has the ability to reproduce these essential parameters. PARCS (Purdue Advanced Reactor Core Simulator) is a multi-dimensional reactor kinetics code. TRACE coupled with PARCS has the computing power to provide accurate coupled power and flow distributions under various reactor transients or casualties. TRACE/PARCS was previously validated for use with Pressurized Water Reactor (PWR) transient analysis using the OECD/NEA Main Steam Line Break Benchmark.

This thesis focuses on the evaluation of Boiling Water Reactor (BWR) transient analysis, mainly the NEA Ringhals 1 Stability Benchmark from 1996. This benchmark performed a series of tests on the Ringhals 1 reactor during the beginning of cycles 14, 15, 16, and 17. Three techniques for initiating instabilities (pressure perturbation, control rod perturbation, and simulated noise) were performed on each test point during each cycle. The steady state data as well as the transient results predicted by TRACE/PARCS reasonably agree with the measured data from the NEA Ringhals 1 Stability Benchmark.

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Chapter 1

Introduction

The use of computer codes to simulate reactor core behavior has been used for several years and is becoming more and more prevalent in the design of reactor plants. The use of these codes to simulate reactor core and plant dynamics as well as the interaction between the two will aid designers and operators to increase overall plant safety and help minimize costs of the power plant.

Computer models or codes are used to study various reactor plant phenomena in regards to reactor safety. The computer code TRACE (TRAC RELAP5 Advanced Computational Engine) is used to study thermal-hydraulic effects of the reactor coolant system under a wide range of operating flow conditions. TRACE is also able to model multi-phase thermal-hydraulics which is crucial in the study of boiling water reactors due to the change of states from liquid to vapor while coolant is operating inside of the reactor. Accurate thermal-hydraulic simulations are only one half of the problem though. Core neutronics is also very important and the code PARCS (Purdue Advanced Reactor Core Simulator) is used to provide multidimensional time dependent power distributions to TRACE via coupling. With the power of TRACE and PARCS coupled together a core designer has the ability to model a new core and run various reactor accident scenarios to see how stable the design performs. Also, the US NRC has established new guidelines and regulations on boiling water reactors with regard to their instabilities and TRACE/PARCS can analyze these issues. TRACE/PARCS was previously validated for use with Pressurized Water Reactor (PWR) transient analysis using the OECD/NEA Main Steam Line Break Benchmark.

The objectives of this thesis are focused on the assessment of Boiling Water Reactor (BWR) transient analysis using the OECD/NEA Ringhals 1 Stability Benchmark of 1996. In this benchmark a series of tests were performed on the Ringhals 1 reactor during the beginning of cycles 14, 15, 16, 17, as well as the middle of cycle 16. It should be noted that no simulations in this thesis were performed on the three test points from the middle of cycle 16 since the core burnup data was unable to be obtained. These simulations included a pressure perturbation, control rod perturbation, and simulated noise. This thesis should give the reader a basic understanding of how the modeling was performed, how the programs were run, how the stability analysis was performed using a separate program, and an understanding of the results obtained and conclusions drawn. The following programs were used in preparing the work done on this thesis: TRACE, PARCS, AptPlot, and Matlab. The goal of running all of these tests using TRACE/PARCS is to assess the accuracy of TRACE/PARCS for BWR stability analysis.

Chapter 2 of this thesis discusses the Ringhals 1 reactor and the OECD/NEA Benchmark.

Chapter 3 describes the codes TRACE and PARCS and how they are coupled together.

Chapter 4 discusses the modeling of the Ringhals 1 reactor in TRACE and PARCS.

Chapter 5 describes the procedures for running TRACE coupled with PARCS.

Chapter 6 describes the mechanics of how to perform stability analysis.

Chapter 7 provides the results from all simulated test points.

Chapter 8 provides a summary and conclusions drawn on from the work done for this thesis.

Chapter 2

Boiling Water Reactors and the Ringhals I Benchmark

Boiling water reactors (BWRs) are a subset of a major group of reactors called light water reactors. Light water reactors use demineralized water as a coolant and neutron moderator. The other subset of light water reactors are pressurized water reactors. Pressurized water reactors (PWR) keep the main coolant pressurized to very high pressures to avoid boiling. This pressurized hot water travels through steam generators to heat up a secondary system to steam which drives turbines to produce electricity. In a boiling water reactor there is no secondary system. The coolant boils while inside the core, goes through several moisture separators and transforms to steam to turn turbines and produce electricity. One key difference between BWRs and PWRs is their size. Boiling water reactors tend to be much larger than PWRs. For this reason, there are no BWRs reactors for nuclear propulsion.

There are several advantages and some disadvantages to boiling water reactors, such as Ringhals 1. Some key advantages are that the reactor vessel is subjected to a much lower pressure from one in a PWR, the vessel gets significantly less irradiation and therefore is less subject to neutron embrittlement, which can decrease core life. Also, boiling water reactors do not use soluble boron (in the form of boric acid) for reactor control and therefore have a smaller likelihood of corrosion within the reactor vessel and associated piping. There are disadvantages to boiling water reactors such as complex calculations due to two phase flow in the core (which is mitigated by codes such as

TRACE), a much larger pressure vessel than a pressurized water reactor, and control rods are inserted from below which must use a source of power to insert if there is a loss of power, or control of the reactor instead of allowing gravity to insert control rods as in a pressurized water reactor. One critical disadvantage which is part of the subject of this thesis is that boiling water reactors are subject to inadvertent power oscillations under certain operating conditions. These power oscillations are discussed in further detail in section 2.2.

2.1 Ringhals 1 General Data

The Ringhals nuclear power plant is located in Varberg, Sweden and is operated by Vattenfall. This nuclear power plant was been operational since 1976. It includes four reactors; three pressurized reactors and one boiling water reactor. The total power rating for the power plant is 3560 MWe. Ringhals 1 is the boiling water reactor associated with the Ringhals nuclear power plant. Ringhals 1 has a nominal power of 2270 MWth, 157 control rods, and 648 fuel assemblies. There are 3 different types of fuel assemblies in Ringhals 1: 8x8 with 63 rods and SVEA assemblies with 63 or 64 rods. There were 6 recirculation pumps running during all of the test points.

2.2 Overview of Ringhals 1 Benchmark

There have been several documented inadvertent power oscillations in boiling water reactors. Their exact cause is unknown but certain events may occur that can cause them. Some of these events are loss of flow due to recirculation pumps tripping resulting in a sudden onset of natural circulation and a loss of feedwater heaters. These power oscillations may be in phase (core wide) or out of phase (asymmetric). Also, these oscillations lead to high localized neutron flux levels that may not be detected, and therefore no automatic protective actions such as a scrams would occur which could ultimately result in fuel damage. The Ringhals 1 Benchmark was developed to allow code developers to research and test new codes to validate their predictive capability and ultimately be used in core design for stability analysis. The data included in the benchmark comes from test points at the beginning of cycles 14, 15, 16, 17, as well as the middle of cycle for cycle 16. The work on this thesis is to analyze all test points that had an observed decay ratio of at least 0.40 for all of the beginning of cycle test points for cycles 14, 15, 16, and 17.

The benchmark was made up of eight participant organizations in eight countries. These countries include Spain, The United States of America, Japan, Switzerland, Sweden, Germany, and Italy. The work of these organizations tested different codes in both the frequency and time domain. The data from four cycles included plant conditions and the measured oscillations. This allowed for the organizations to test the predictive ability of their codes using the data from these cycles. The benchmark includes a total of 41 test points with one of these test points (cycle 14, test point 9) having observed regional oscillations which allowed participants to test codes that operate in the time domain.

Another goal of the benchmark was to develop models and algorithms to validate data from noise measurements and for on-line monitoring of stability [1]. This was not a major goal of the benchmark but was proposed as a follow up study. The work from this thesis shall use the data in attempting to predict oscillations from noise transients.

The data included in the benchmark for the four cycles is APRM and LPRM responses, coolant flows, feedwater flows, operating history, and cycle specific data such as control rod patterns and three dimensional power profiles [2]. Also included are digital recordings of about 90 channels for approximately 11 minutes with a sample frequency of 80ms. Most importantly, data includes evaluated decay ratios and oscillation frequencies for all test points in these cycles.

To model the Ringhals 1 reactor, several data was given in the benchmark specifications to include: general reactor data, geometry, fuel description, cross sections, kinetic parameters, thermal-hydraulic data, fuel rod data, steam line data and recirculation loop data [3]. All of the data from the benchmark specifications were used in building the TRACE and PARCS models for the Ringhals 1 reactor for this thesis. The discussion of the development of the core model is in chapter 4.

2.3 Benchmark Results

The benchmark includes tables showing the power and flow conditions for each test point and the evaluated decay ratios and frequencies for each case, or test point. A sample table for cycle 14 data is shown in Table 2-1. A complete set of results is given in Appendix A.

Table 2-1: Ringhals 1 BOC Cycle 14 Stability Test Results

Case	Power %	Core Flow kg/s	Global DR	 f (Hz)	Regional DR	 f (Hz)
1	65	4105	0.30	0.43	-	-
3	65	3666	0.69	0.43	0.57	0.43
4	70	3657	0.79	0.55	0.75	0.52
5	70	3868	0.67	0.51	0.60	0.50
6	70.2	4126	0.64	0.52	0.59	0.50
8	75.1	3884	0.78	0.52	0.79	0.50
9	72.6	3694	0.80	0.56	0.99	0.54
10	77.7	4104	0.71	0.50	0.63	0.49

The evaluated decay ratios have a fairly large degree of uncertainty, especially at decay ratios lower than 0.40. Since decay ratios lower than 0.40 are so uncertain, the work in this thesis was not performed on these test cases. The benchmark uncertainty results are shown in Table 2-2.

Table 2-2: Uncertainty in Estimating the Decay Ratio

Decay Ratio	Uncertainty + or -
0.2	0.15
0.4	0.09
0.6	0.07
0.8	0.05

Chapter 3

TRACE/PARCS Code Description

The simulation and calculation analyses used in this thesis involve the implementation of computer programming codes. These tools are used to model the thermal-hydraulics and neutronics within the reactor core and surrounding systems. The thermal-hydraulic code TRACE and the three-dimensional neutron kinetics code PARCS are used and coupled together to produce a simulation of the Ringhals 1 reactor under various operating conditions. This chapter will describe each of these codes as well as the assumptions and approximations made during the analysis and justification for these as well. The description starts out with a detailed description of TRACE, then PARCS, then a discussion of how they are coupled. As a side note, an additional post processing code called DRARMAX is used to extract decay ratio (DR) and natural frequency (FR) from the transient results. DRARMAX will be described more in detail in Chapter 6.

3.1 Thermal-Hydraulics Code TRACE

TRACE (TRAC RELAP5 Advanced Computational Engine) is a reactor analysis code used by the United State Nuclear Regulatory Commission [2]. It has been designed to perform best-estimate analysis of reactor system parameters under various operating conditions. These operating conditions include, but are not limited to operational transients, loss of coolant accidents, and other reactor accidents in Boiling Water

Reactors (BWRs) and Pressurized Water Reactors (PWRs). The extreme temperature and flow conditions and phenomena such as multidimensional two-phase flow, non-equilibrium thermodynamics, level tracking, and point reactor kinetics experienced during these transients and casualties are also able to be modeled by TRACE. Additionally TRACE has the ability to reach steady-state automatically and restart from a previous run's dump file.

3.1.1 TRACE Field Equations

TRACE uses two-fluid, two phase field equation set. The modeled after a single phase Navier-Stokes equation for each separate phase, and conditions between the phases. This field equation set consists of energy, momentum, and mass conservations for liquids and gases using six partial differential equations. Non-condensable gases in the steam mixture are assumed to move at the same velocity and temperature. This allows for single momentum and energy equations to simulate the gas mixture. The concentrations of non-condensable gases and steam are simulated using separate equations. This allows for TRACE to treat different elements in air separately if desired by using two separate components of the gas field. The set of field equations can be expanded to include the boron concentration in the core as well. The combinations of equations undergo time and volume averaging to calculate a set of two-fluid, two phase conservation equations. This is done in both one and three dimensions.

TRACE uses a quasi-steady approach for calculating heat transfer between the wall and fluid. This technique requires detailed knowledge of the local fluid parameters and ignores the time dependencies so that the rate of change in the closure relationships becomes zero and time constants become infinite. This is very beneficial since it can be applied to a wide array of problems and is relatively simple since it does not require any previous knowledge of a transient. More detailed discussion of the quasi-steady approach may be found in [2].

The partial differential equations are solved using the finite volume method. The heat transfer equations are calculated using a semi-implicit time-differencing technique. The fluid dynamics equations for both the spatial one-dimension and the three-dimensional components use a multi-step time-differencing procedure which allows the Courant-limit to be exceeded. The hydrodynamic phenomena modeled by finite difference equations create a system of coupled, nonlinear equations solved by the Newton-Raphson iteration method.

TRACE breaks up the reactor system into several components. Each piece of equipment can be represented by a component, and each component can be further broken up into a fixed number of cells (or physical volume) where fluid, conduction, and kinetics equations are averaged. The number of components and cells has no physical limit but is instead limited based on the available computer memory. The following reactor hydraulics components TRACE may include are: CHANs (fuel channels in BWRs), CONTANs (containments), HEATRs (feedwater heaters), HTSTR (heat structures), JETPs (jet pumps, which are not used in Ringhals I), PIPEs, PLENUMs, PRIZERs (pressurizers), SEPDs (seperators), TEEs, TURBs (turbines), VALVEs, and VESSELs. Also, a component called a REPEAT-HTSTR is used to model fuel elements or heated walls in the reactor system. All of these components are used to compute two-dimensional conduction and surface convection heat transfer in Cartesian or Cylindrical geometries. POWER components are used to deliver energy to the fluid using the HTSTR component. FLPOWER (fluid power) components are used to deliver energy directly to the fluid which could occur during flow oscillations and reversals. RADENC (radiation enclosure) components are used to simulate radiation heat transfer between different surfaces. Fill and break components are used to apply the required flow and pressure conditions to achieve steady state and transient analysis. Lastly, EXTERIOR components are available to allow for the development of input models designed to utilize TRACE's parallel processing features.

3.2 Neutron Kinetics Code PARCS

PARCS is a three-dimensional reactor core simulator that can solve steady-state and time-dependent, multigroup neutron diffusion and transport equations in orthogonal and non-orthogonal geometries. PARCS may be coupled with the thermal-hydraulic code TRACE to allow for temperature, pressure, and flow information to be passed into PARCS via the group cross sections. Another code called GENPMAXS is used to convert cross sections developed by lattice physics codes into the PMAX format so that PARCS can read the data.

PARCS has been updated several times since its initial release of version 1.01 in November 1998. There have been numerous function improvements and feature add-ons since the initial release up to the current release of version 2.8 as well. The major calculations featured in PARCS are: eigenvalue calculations, kinetics calculations, Xenon transient calculations, decay heat calculations, pin power calculations, and adjoint calculations for light water reactors (LWR). PARCS has the ability to use a three-dimensional model to realistically model the reactor. It also has the ability to only model the reactor in one dimension for faster runtimes and for a transient in which the main change in flux occurs in the axial direction, such as boiling water reactor transients.

PARCS uses a card name input system to allow for minimizing input data while maximizing the default settings for certain types of cards. Similarly to TRACE, PARCS has a restart feature to continue a transient calculation from the point where a restart file was written, usually upon reaching steady-state. PARCS has the ability to show various results of the calculations and has the ability to graphically display some of the results.

PARCS uses several complicated spatial kinetics calculations to calculate various parameters with high efficiency and accuracy. One method used is the Coarse Mesh Finite Difference (CMFD) method which allows a fast transient calculation by not using time consuming nodal calculations at times during the transient when there is not a high rate of change in the spatial neutron flux. A transient problem is solved by creating and analyzing a fixed transient source at each time step during the transient. For spatial discretization of the transient problems, two main methods are used, Analytical Nodal Method (ANM) and Nodal Expansion Method (NEM).

In order to minimize the computational runtime, advanced numerical solution methods are used in PARCS. The CMFD linear system described above is solved using a Krylov subspace method which utilizes a BILU3d preconditioner. To calculate the eigenvalue for steady-state the Wielandt eigenvalue shift method is used. A pin power reconstruction method is used for the two group nodal methods in which predefined heterogeneous powers from functions are combined with a homogeneous intranodal distribution.

One of the add-on features of PARCS in later versions is core depletion analysis. Burnup dependent macroscopic cross sections are read from the PMAX files and the node-wise power is used to calculate the region burnup increment for time advancing the macroscopic cross sections. More detailed descriptions of the PMAX files and the GENPMAXS code are provided in the GENPMAXS manual.

PARCS was written in FORTRAN 90 and therefore is able to be ported to several platforms and operating systems. It has been tested on SUN Solaris UNIX, DEC ALPHA UNIX, HP UNIX, LINUX, as well as several Windows Operating systems. For the bulk of the work involved in this thesis PARCS was run on Windows XP and Windows Vista. Since PARCS has several different calculation features, it can be run in several execution modes. The following section provides a brief overview of the most important PARCS calculation features.

3.2.1 PARCS Calculation Features

PARCS is capable of calculating various modules needed to predict the global and regional response of the reactor in steady-state as well as transient conditions. The various features of PARCS are described in this section along with the corresponding modules.

Eigenvalue Calculation

The most essential calculation for steady-state problems is the eigenvalue calculation. PARCS performs the eigenvalue calculation using the Wielandt eigenvalue shift method. The eigenvalue obtained is used to adjust the nu (ν) values of the following transient calculation in order to make the reactor critical. The eigenvalue is the value for k-effective. In addition to this calculation, the critical boron concentration (CBC) search function is also available and may be utilized using the SEARCH card of the control block input

Transient Calculations

Calculating the transient or neutron kinetics equations for prompt and delayed neutrons is the primary function of PARCS. This solves the time-dependent neutron diffusion equation. The transient option is toggled on and off by the TRANSIENT card in the CNTL block. The temporal differencing based on the theta method and the exponential transform gives a transient fixed source at each time step. As discussed earlier, the Coarse Method Finite Difference (CFMD) method is used to update a conditional nodal scheme. The temporal discretization schemes are specified by the THETA and EXPO_OPT cards in the TRAN input block. By turning on an option in the EXPO_OPT card, the exponential extrapolation method can be used to obtain an initial flux “guess” at each new time step. If higher order nodal updates are needed such as when a substantial change in cross sections is observed, the conditional nodal update scheme is activated. This is controlled by the EPS_XSEC card in the TRAN block.

Decay Heat Calculation

PARCS employs a rather simple six group model of decay heat precursor groups to model decay heat. This six group equation is solved the same way as the delayed neutron precursor equation. Therefore the solution is node wise and calculated at each time step then added to the fission power to determine the total power produced in the node. Default values are used for uranium oxide fueled cores. However, the user has the ability to modify these default values for the precursor fractions and decay constants. The decay heat option is covered under the DECAY_HEAT card in the CNTL block and the input parameters are specified in the DHP_BETA and DHP_LAMBDA cards in the XSEC block.

Xenon Transient Calculation

Xenon transients are only significant in slow reactor transients since they are a function of decay time and power. In PARCS, this transient is not solved using the transient fixed source but instead solved by the quasi-static eigenvalue problem solver. The number densities of Xenon and Samarium are updated by balancing the fluxes resulting from the eigenvalue calculation. The Xenon option is controlled in the XE_SM card in the CNTL block and has three options: 1 – No Xenon, 2 – Equlibrium Xenon, or 3 – Transient Xenon.

Pin Power Calculations

Node average fluxes and interface currents are the primary dependent variables in PARCS. In order to obtain local pin power distributions, pin powers are rebuilt from various points. PARCS performs this by multiplying the heterogeneous power form functions with the homogeneous intra-nodal flux distribution. The homogeneous intranodal flux is calculated by performing an analytical solution of a two dimensional fixed source problem in which the surface average currents are specified at the four boundaries. The surface average currents are acquired from the converged node average flux distribution. Pin power rebuilding is performed for steady-state and transients. The pin power calculation is activated by the PIN_POWER card in the CNTL block and the heterogeneous power form functions are in the PFF block. To improve the accuracy, corner discontinuity factors can be specified in the CDF card in the XSEC block. The transient pin power calculation does not need to be calculated at every time step since the pin-to-box factor does not change significantly unless the core configuration is changed dramatically. This allows for faster runtime. The transient pin power calculation frequency is turned on by the PIN_FREQ card in the TRAN block.

3.3 Core Modeling in PARCS

The goal of any neutronics reactor simulator is the ability to represent the physical system with an accurate numerical model. The key modeling issues in reactor kinetics calculations are geometric representation, cross section representation, and thermal-hydraulic feedback. PARCS can represent a core in three dimensions (3D) that can be reduced to 2D, 1D, or 0D by choosing appropriate boundary conditions. There is an ability within PARCS to make the one dimensional geometric model more accurate and more versatile using a special 1D kinetics capability. Geometric modeling will be described in the first subsection below. PARCS functionalizes the macroscopic cross sections with linear or quadratic dependence on the thermal-hydraulic state variables.

Cross section details in PARCS will be discussed in the second subsection below. Thermal-Hydraulic (T-H) calculations are usually done external to PARCS, but PARCS does have the ability to do basic T-H calculations using an internal solver mainly used for code testing. Thermal-Hydraulics shall be discussed in the third subsection below.

3.3.1 Geometric Modeling

In PARCS, the reactor core is modeled by a group of homogeneous computational nodes. This computational node can either be rectangular or hexagonal radially. The size of the node is based on the fuel assembly pitch. Axially, the size is approximately 10 to 30cm. If the rectangular option is chosen, the core geometry is specified in the GEOM block. If the core is being modeled hexagonally, the block is named GEOMH. The RAD_CONF card in the GEOM block is used to specify the radial configuration of a fuel assembly. The radial node size is then specified by the number of subdivisions of the assembly node by the NEUTMESH_X and NEUTMESH_Y cards. Therefore the number of nodes per assembly is simply the number of x nodes times the number of y modes. For basic calculations, one or four nodes per assembly are used. It is possible to perform a fine mesh calculation using the geometry input structure. Also, if you take the assembly-wise configuration as the pin-wise configuration, a pin-by-pin heterogeneous core representation is possible. This refined geometry model is limited to a rectangular modeling of the core only. In the case of the hexagonal modeling, a hexagon is always represented with one node although it is divided into six triangular nodes (similarly to a pie slice) within the TPEN kernel.

3.3.2 Cross Section Modeling

PARCS uses macroscopic cross sections which can be input in either the two group or multi-group form using the same input cards. These cross sections are functionalized in terms of boron concentration, square root of fuel temperature, moderator density and temperature, void fraction, and the effective rodded fractions. The linear dependence of cross sections is considered on these state variables except for the moderator density and void fraction which quadratic variation is provided.

The effective rodded fraction is defined as the product of the volumetric rodded fraction and the flux depression factor that is calculated by a de-cusping routine for the partially rodded node. The same is performed for Xenon and Samarium cross sections when performing Xenon calculations.

3.3.3 Thermal-Hydraulic Feedback

As discussed earlier, PARCS has the ability to couple with an external code for the thermal-hydraulic parameters to provide feedback back to neutronics portion. PARCS is coupled with TRACE using the EXT_TH card in the CNTL block. Coupling is achieved by the inter-process protocol, PVM. The two processes are loaded in parallel and the PARCS process transfers nodal power to TRACE. TRACE then sends PARCS data for the temperature (fuel and the coolant) and density. This is all done internally and automatically without the user having to translate any of the data.

The neutronics spatial mesh/node structure differs from the thermal-hydraulic spatial mesh/node structure. This difference is overcome by a proper mapping scheme which is in a file called MAPTAB. In order to this to be more user friendly, an automatic mapping scheme was developed taking both the PARCS and TRACE input files to create a file to map all information correctly.

As a way to increase efficiency and decrease runtimes, not every thermal-hydraulic time-step's data is used in a neutronics calculation. This is because a time step used in the thermal hydraulic code is very small due to a stability consideration. This time step can be so small that no appreciable changes occur in the core thermal-hydraulic condition and performing a neutronics calculation would be wasteful since no data has changed. Therefore, a skip factor may be added in the PARCS data can be specified for transient and steady-state conditions. Skip factors are added in the EXT_TH card.

Chapter 4

Modeling of Ringhals I

As discussed in chapter 2, the Ringhals 1 Benchmark Specifications included several key data points for modeling Ringhals 1. The modeling of Ringhals 1 in TRACE was a joint effort between the US Nuclear Regulatory Commission, students at Purdue University, and students at The Pennsylvania State University. The TRACE model was based off of cycle 14, test Point 10 data. Figure 4-1 shows the power history for cycle 14. [3]

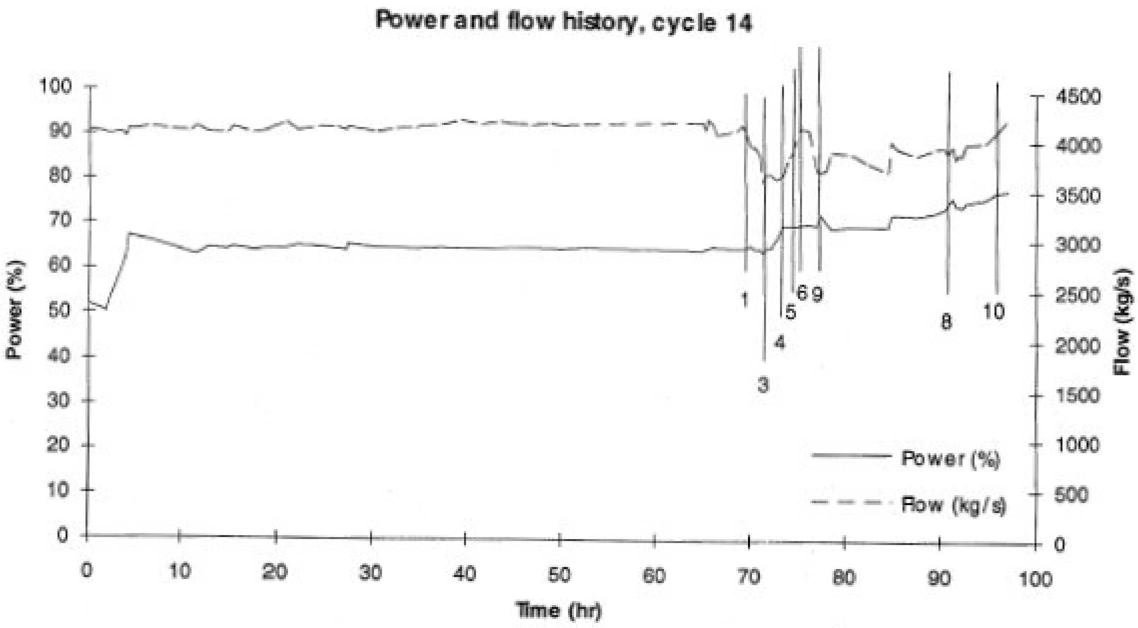


Figure 4-1: Ringhals 1 Cycle 14 Power History

In addition to the power history, the operating conditions from test point 10 were also used. However, not all of the data points needed to model the core were included in the specification for the benchmark. Some data points had to be assumed by the analyst due to not being included in the benchmark specifications, or from inconsistencies within the specifications. During these events where assumed data was used, data from other similar boiling water reactors such as Peach Bottom were used, as well as mathematical calculations to form a "best guess" data point. To improve upon these assumptions, sensitivity studies were done to validate them, as well as discussion with personnel at Ringhals and personnel at the U.S. NRC. Some of the discrepancies noted were several handwritten notes over documented measurements. One example was the reactor vessel height did not correlate between multiple graphs in the benchmark or between various technical documents.

To get an overall basic understanding of the Ringhals 1 geometry, Figure 4-2 shows an excerpt from the benchmark specifications. The boundaries for the TRACE model are the main steam line and feed water piping. It should be noted that the overall core volume given in the figure on the next page is hand-written and did not agree with other data within the benchmark specifications.

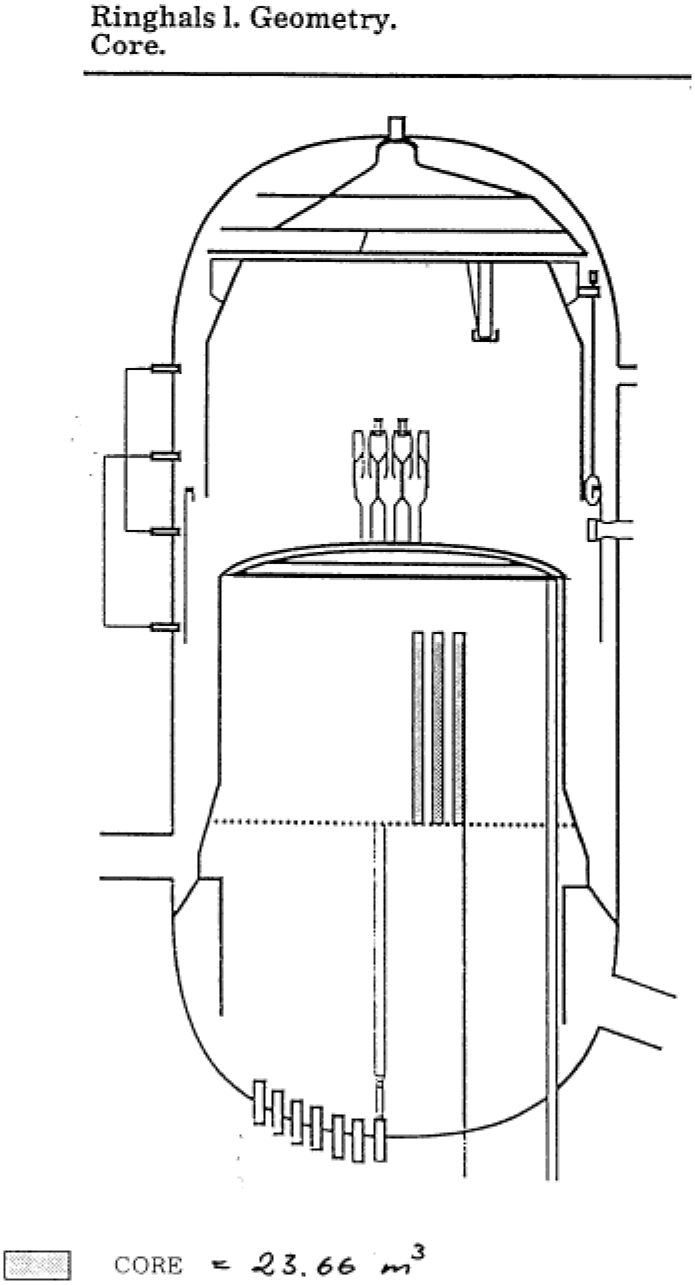


Figure 4-2: Ringhals 1 Geometry from Benchmark

The TRACE model includes the reactor pressure vessel and recirculation loops with the boundaries discussed earlier. The TRACE nodalization of the core is shown in

Figure 4-3. The graphical representation of the model was created using a program under development and testing called SNAP, which allows the operator to graphically create a model in TRACE.

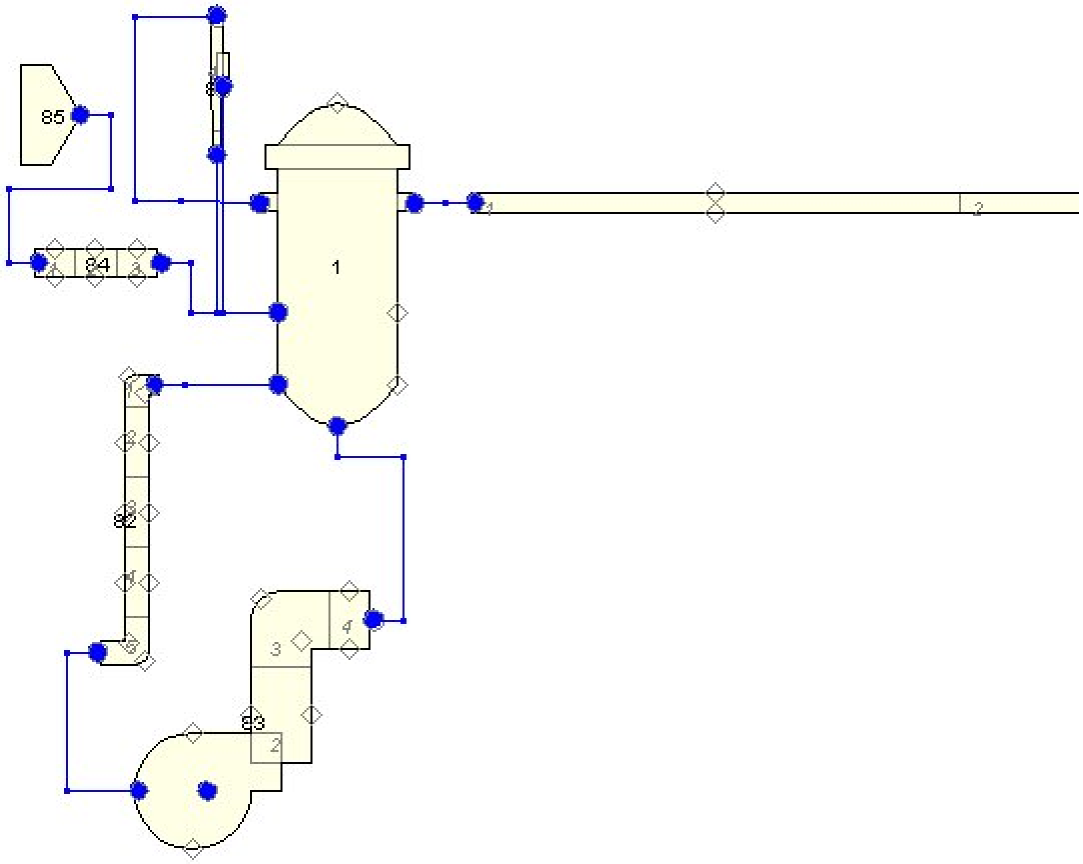


Figure 4-3: TRACE Nodalization of Ringhals 1

Half-core symmetry for the 648 core channels was used in order to decrease the computational power required and overall runtime of the simulation. The TRACE channel mapping is shown in Figure 4-4.

```
                                              342 329 315 215 229 242
                                            353 341 328 314 214 228 241 253
                                377 370 362 352 340 327 313 213 227 240 252 262 270 277
                            382 376 369 361 351 339 326 312 212 226 239 251 261 269 276 282
                        385 381 375 368 360 350 338 325 311 211 225 238 250 260 268 275 281 285
                    086 384 380 374 367 359 349 337 324 310 210 224 237 249 259 267 274 280 284 186
                085 084 083 379 373 366 358 348 336 323 309 209 223 236 248 258 266 273 279 183 184 185
            082 081 080 079 078 372 365 357 347 335 322 308 208 222 235 247 257 265 272 178 179 180 181 182
        077 076 075 074 073 072 071 364 356 346 334 321 307 207 221 234 246 256 264 171 172 173 174 175 176 177
        070 069 068 067 066 065 064 063 355 345 333 320 306 206 220 233 245 255 163 164 165 166 167 168 169 170
        062 061 060 059 058 057 056 055 054 344 332 319 305 205 219 232 244 154 155 156 157 158 159 160 161 162
    053 052 051 050 049 048 047 046 045 044 043 331 318 304 204 218 231 143 144 145 146 147 148 149 150 151 152 153
042 041 040 039 038 037 036 035 034 033 032 031 030 317 303 203 217 130 131 132 133 134 135 136 137 138 139 140 141 142
029 028 027 026 025 024 023 022 021 020 019 018 017 016 302 202 116 117 118 119 120 121 122 123 124 125 126 127 128 129
015 014 013 012 011 010 009 008 007 006 005 004 003 002 001 101 102 103 104 105 106 107 108 109 110 111 112 113 114 115
115 114 113 112 111 110 109 108 107 106 105 104 103 102 101 001 002 003 004 005 006 007 008 009 010 011 012 013 014 015
129 128 127 126 125 124 123 122 121 120 119 118 117 116 202 302 016 017 018 019 020 021 022 023 024 025 026 027 028 029
142 141 140 139 138 137 136 135 134 133 132 131 130 217 203 303 317 030 031 032 033 034 035 036 037 038 039 040 041 042
    153 152 151 150 149 148 147 146 145 144 143 231 218 204 304 318 331 043 044 045 046 047 048 049 050 051 052 053
        162 161 160 159 158 157 156 155 154 244 232 219 205 305 319 332 344 054 055 056 057 058 059 060 061 062
        170 169 168 167 166 165 164 163 255 245 233 220 206 306 320 333 345 355 063 064 065 066 067 068 069 070
        177 176 175 174 173 172 171 264 256 246 234 221 207 307 321 334 346 356 364 071 072 073 074 075 076 077
            182 181 180 179 178 272 265 257 247 235 222 208 308 322 335 347 357 365 372 078 079 080 081 082
                185 184 183 279 273 266 258 248 236 223 209 309 323 336 348 358 366 373 379 083 084 085
                    186 284 280 274 267 259 249 237 224 210 310 324 337 349 359 367 374 380 384 086
                        285 281 275 268 260 250 238 225 211 311 325 338 350 360 368 375 381 385
                            282 276 269 261 251 239 226 212 312 326 339 351 361 369 376 382
                                277 270 662 252 240 227 213 313 327 340 352 362 370 377
                                            253 241 228 214 314 328 341 353
                                                242 229 215 315 329 342
```

Figure 4-4: 325 Channel Half-Core Symmetry TRACE Model Used

While modeling the Ringhals 1 reactor, several updates to the TRACE version were developed and tested as a result of this model. These updates are bug fixes that are not yet implemented in version RC3, two phase multipliers for local losses, TRAC-B wall drag and Martinelli-Nelson-Jones fixes for the two phase wall drag multiplier, and a feature that will set the time step size to a constant if it is less than the courant limit which prevents TRACE from having a mathematical instability at high time step sizes. A PID (proportional-integral-derivative) controller was used on several controllers to decrease overshooting and settling time. PID controllers were used for core flow, steam dome pressure, down comer water level, and core inlet temperature. Controllers used specific logic to come up with the most stable and reliable data. For example, the logic for recirculation pumps is shown in Figure 4-5.

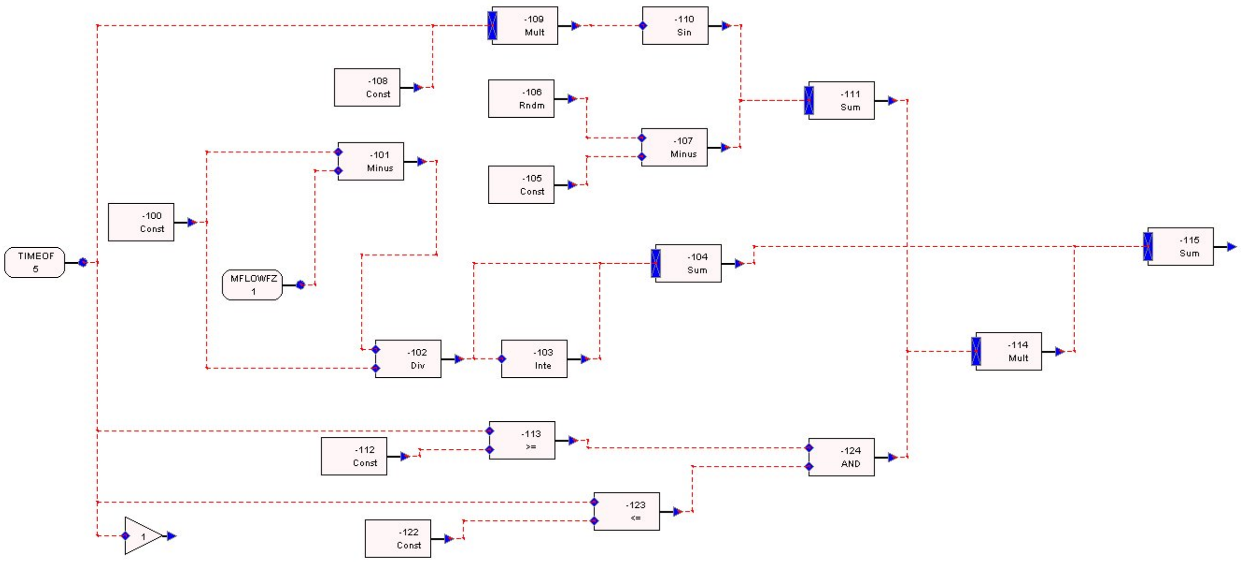


Figure 4-5: Recirculation Pump Logic

Chapter 5

Detailed Procedures for running TRACE/PARCS

During the course of the two years of work on this research the procedures performed were tweaked and eventually simplified to include scripts to generate input decks. Before these scripts were introduced all input deck modifications between test points as well as changes between transients were done manually. There are usually five steps to perform consistent Ringhals stability analysis. These steps are:

1) Generate TRACE input deck (tracin)
2) Run TRACE standalone in steady state
3) Run TRACE/PARCS coupled in steady state
4) Run TRACE/PARCS coupled transient cases
5) Perform stability analysis

It is important to have steady state standalone thermal-hydraulic conditions (step 2) before the initiation of the coupled calculations since the effect of thermal-hydraulic variations on the cross-sections and neutronics calculations may fail the coupled calculations. After a steady thermal-hydraulic state is achieved by standalone (TRACE only) run (step 2), the coupled steady-state calculations (step 3) should be performed in order to initialize neutronics and thermal-hydraulic conditions together. Coupled transient calculations (step 4) must be started after steady-state coupled conditions are reached. Before the initiation of a real transient, a period of null transient is recommended to avoid the effect of numerical oscillations on the transient calculations. These oscillations may happen in the beginning of coupled transient calculations even though coupled steady-steady state conditions may seem perfect and the calculation is very well converged. While running a null transient, the code simply runs in transient mode constantly providing thermal-hydraulic and neutronic feedback to the reactor based on current operating conditions and then modifying these conditions and repeating. A null transient allows the code to continue doing this instead of perturbing (pressure, control rod, or noise perturbations) the reactor core and therefore verifying the system is, as expected at steady state.

It should be noted that PARCS code was coupled with previous TRACE code versions through **P**arallel **V**irtual **M**achine (PVM). Recently, PARCS was integrated into TRACE version 5.0. Therefore, a separate PARCS run is not required for coupled calculations for TRACE5.0. In other words, TRACE/PARCS expressions at step 3 and step 4 refer to a single TRACE run. The detailed run procedures for those steps are meticulously explained in the following sub-sections. It should be noted that the following procedures are valid for the Windows operating systems. The procedures in the other operating systems may be slightly different than the following ones.

5.1 Generation of the TRACE Input Deck

TRACE Ringhals full model standalone input deck has the following main sections as shown in Figure 5-1.

1) Main Data, Namelist Data, Problem Options, Component Order Data
2) Control System, Signal Variables, Control Blocks, Trips

3) Reactor Power
4) Recirculation Loop
5) Steam Lines
6) Separator
7) Feedwater
8) Core Channels
9) Reactor Pressure Vessel (RPV)
10) Problem Time Options

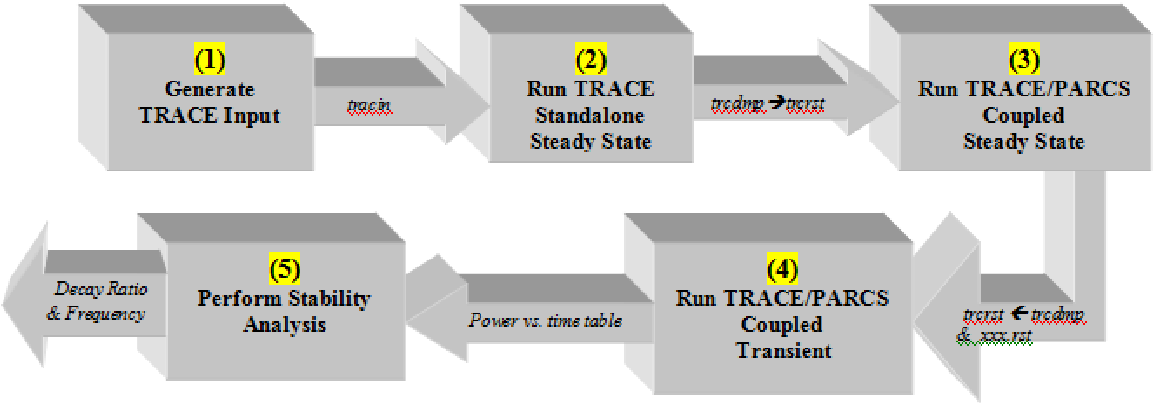


Figure 5-1: Schematic Representation of TRACE Ringhals 1 Stability Analysis Calculation Procedure

The sections listed above need a vast amount of input information along with detailed calculations for those input parameters. For this reason, MATLAB scripts were developed to create TRACE standalone input decks. These MATLAB scripts were initially designed to create input decks for test points 9 and 10 (Ringhals 1 Cycle 14). It is possible to generate whole system model or plenum to plenum model. The main advantage of these scripts is lumping core channels to the desired corresponding number of channels. The original plant has 648 core channels during the stability tests. MATLAB scripts allow user to lump those channels. For the duration of these tests, 324 channel models and 325 channel models were used, this allowed for a 2 to 1 mapping of the core

(648 channels total). Cycle 14 used 325 channels due to the fact that it included asymmetric fuel assemblies.

Descriptions of the some of the important MATLAB files are:

- **chflowPXX.m:** Reference Test Point channel flow rates for each of the 648 channels.
- **NodeWisePowerXX_Spec.m:** Reference Test Point 3D power for each node in the core.
- **printringhalsmodel.m:** This is the main option module that generates standalone TRACE input deck and PARCS mapping file (maptab) for coupled calculations. Users can specify the required information for the following parameters.
    - Number of lumped channel information (i.e. C1=1; C26=2; Cgroup=3; C2T1=4; C1T1=5; MixModels=C1)
    - Whole system or plenum to plenum model choice. (PP=0 is for whole system while PP=1 for only plenum to plenum model)
    - Core axial meshing: (uniformmesh=0 for non-uniform axial mesh and uniformmesh=1 for uniform axial mesh nodalization)
    - Scripts take the initial values (i.e. pressures, temperatures, velocities etc.) from corresponding TRACE output file (trcout) and put into the input when readtrcout=1. This option not only helps to input meaningful initial guesses for the temperatures, pressures, etc. but also helps with convergence. A detailed void profile from trcout is extracted in the case when a new input is created with trcout=1 option.
    - Channel initial values can be input when readchan is 1.

- Channel leakpath model is designed for the core by-pass flow when chanleak=1.
- Point=9 refers to Ringhals test point 9 while point=10 stands for test point 10, etc.
- APS=1 is for control block adjusted pump speed while APS=0 for constant pump speed.
- It is possible to add vessel levels when addlevel=1. Otherwise legacy 11-level vessel model is used.

Users should run *printringhalsmodel.m* under the MATLAB directory to generate TRACE inputs. Two files will be created shortly after *printringhalsmodel.m* is executed (when trcout=0). These files will look like the following:

- **R1C14_325P09Vn:** Standalone TRACE input deck.
- **maptab_325:** PARCS external thermal-hydraulic mapping file specified at EXT_TH line of the PARCS input.

Where the abbreviations mean the following:

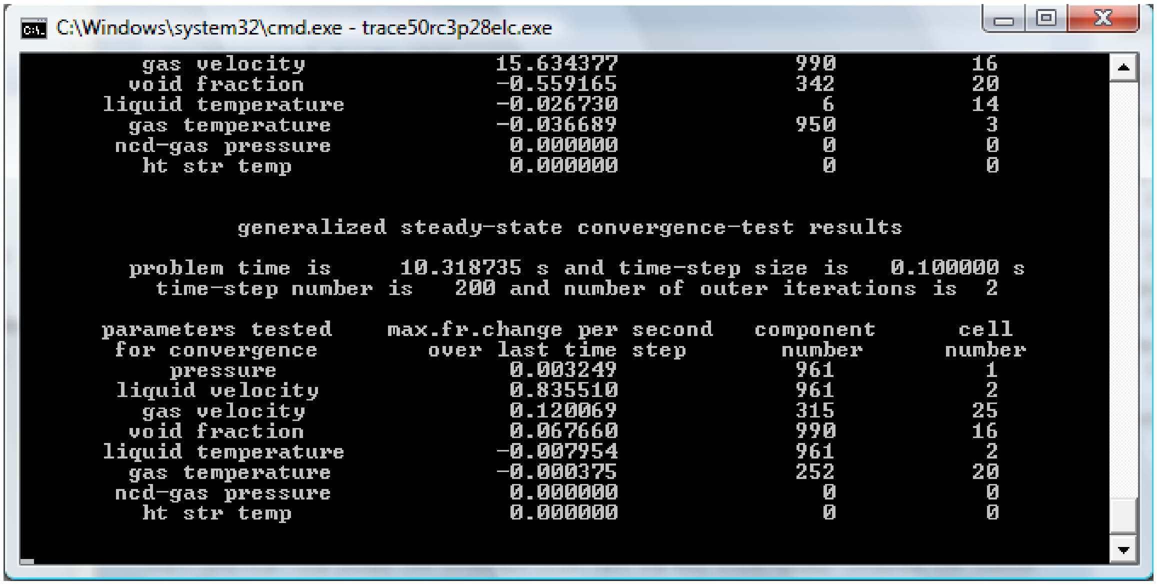
R1C14:	Ringhals Nuclear Power Plant Unit 1 Cycle14
_325:	Number of core channels (in this case it is 325)
P09:	Test point 9 (for the case of point 10 it is **P10**)
V:	Whole system model (for plenum model it is **P**)
n:	Non-uniform meshing (for uniform meshing it is **u**)

In the case of trcout=1 and readchannels=1 in *printringhalsmodel.m* module, channels void fractions and flow rates from trcout are extracted and printed out in the file void_ (i.e. void_325). These are used to calculate void fraction.

Eventually, all of this manual manipulation of the input decks is resolved by newer versions of the MATLAB scripts ultimately culminating in a user defined model.inp file read by printringhalsmodel.m which generates the trace input files without having to manually open the input decks. These higher level scripts and batch files are explained in section 5.5.

5.2 Running TRACE in standalone steady-state

The following files are needed to run TRACE in standalone steady-state: the input deck (i.e. R1C14_325P09Vn) and the executable. In the namelist data section of the input deck it should be noted that itdmr be set to zero (for standalone mode) and that graphLevel be set to minimal (to keep runtime down to a minimum). All important data will still be available for viewing as graphs in AptPlot since they are labeled in the input deck as signal variables. It is best to run TRACE on a computer with no other programs running in the background as runtimes can be quite long. The two main factors for run time are the problem runtime which was set to 200 seconds and the time step increment between calculations which was set at 0.1 seconds for standalone steady state. TRACE will continue to run until either the problem runtime is reached or convergence is reached. While running, TRACE will display the following data as shown in Figure 5-2.



```
         gas velocity            15.634377          990          16
        void fraction            -0.559165          342          20
      liquid temperature         -0.026730            6          14
        gas temperature          -0.036689          950           3
       ncd-gas pressure           0.000000            0           0
         ht str temp              0.000000            0           0


                generalized steady-state convergence-test results

        problem time is     10.318735 s and time-step size is   0.100000 s
          time-step number is   200 and number of outer iterations is  2

      parameters tested    max.fr.change per second   component      cell
       for convergence        over last time step       number       number
           pressure               0.003249          961           1
       liquid velocity            0.835510          961           2
         gas velocity             0.120069          315          25
        void fraction             0.067660          990          16
      liquid temperature         -0.007954          961           2
        gas temperature          -0.000375          252          20
       ncd-gas pressure           0.000000            0           0
         ht str temp              0.000000            0           0
```

Figure 5-2: Screenshot of TRACE running

5.3 Running TRACE/PARCS coupled steady state

Once TRACE has completed running in steady state standalone mode it is quite easy to continue into coupled steady state mode. The TRACE input deck is slightly different from the standalone deck and much simpler. ITDMR must be set to 1, which informs TRACE to run coupled with PARCS. Under the Problem Options header dstep should be set to -1 which will allow TRACE to read all of the data from the tracerst (Trace Restart file) to use as the starting point for this run. It must be noted that the tracedmp (Dump file) from the standalone run must be renamed to tracerst for this to work properly.

The PARCS input file contains reactor data such as the core type, power, rod positions and burnup data. All burnup data and rod bank heights come from CASMO-3 simulator outputs. Core power comes from the benchmark. PARCS also requires several support files in which their locations must be defined in the input deck. These files include the sim file and geometry file which are derived from manipulating CASMO-3 output files, the MAPTAB file (Made during the Matlab input deck scripts), and several PMAX files which describe the fuel assemblies.

The actual running of TRACE/PARCS coupled in steady state is identical to TRACE running in standalone. The problem runtime is much longer, on the average of 8 hours depending on convergence criteria and run time. The outputs from running TRACE/PARCS coupled are much different however. The TRACE outputs are the same (trcout, trcdmp, etc) but there are several PARCS files created. The PARCS files of significance include C14P09V325n_co.out, C14P09V325n_co.rst and C14P09V325n_co.sum where the filename is the CASEID given in the PARCS input file. The use of all of the significant outputs from TRACE and PARCS will be explained in detail in Chapter 6.

5.4 Running Transients with TRACE/PARCS

Once the coupled steady state problem has finished it is imperative that a backup copy of the trcrst file (once renamed from trcdmp) and the parcs.rst file be made due to the fact that the three transient runs (Pressure, Control Rod, and Noise perturbation) will all be using the same starting point for their runs, which is the end of the coupled steady state run. As discussed earlier, there are three transients (representative of the three types of perturbations initiating instabilities) to be run on each test point. The order of these transients does not matter but it is recommended to run the noise transient last due to it's much larger runtime. Running the transient input decks is very simple and only requires minimal changes to the input decks. Control rod and pressure transients have very short runtimes since the problem only runs for twenty seconds. Noise transients have a runtime of three hundred seconds. The reason for this difference is that the perturbation of pressure and control rod heights has an instantaneous effect on reactor power and flow (as well as several other parameters) but the noise perturbation has to take time to fully affect the system.

Pressure perturbations simulate a turbine trip casualty. They are designed for the pressure to suddenly jump to a value much higher than the value set for the test point and then after 1 millisecond, the pressure returns to the previous value. This is done through the TRACE input deck control blocks since this transient deals with thermal/hydraulic parameters.

The control rod transients and noise perturbations are created in the PARCS input decks since these parameters are defined in that input deck. For control rod transients, one whole bank of control rods is moved slightly higher then moved back 1 millisecond later. The noise perturbation is done by adding a white noise to the LPRM (Linear Power Range Monitors) while the problem is in an otherwise steady state scenario.

Null transients may be run periodically at the operator's discretion to ensure that the coupled steady state solution is in fact steady state. To run a null transient simply run a transient input deck without adjusting any conditions in the input deck. A runtime of twenty seconds is more than sufficient to verify that the problem was in fact at steady state at the end of that run and that any oscillations seen during the actual transient simulations are indeed from that perturbation.

5.5 User Generated Scripts and Batch Files

As discussed in the beginning of this chapter, Matlab scripts were developed to generate input decks for TRACE. Batch files have also been developed to more easily run a test point from TRACE standalone to coupled transients all with a single command. These improvements greatly increase productivity and allow for a test point to be fully run allowing for all of the analysis of the point to be completed at one time. There are some things that cannot be changed using the scripts. The PARCS files have to be manually changed between points but this is a fairly streamlined process. Parameters that are changed between test points are power and rod bank heights as previously discussed. To make this process easier, when developing a PARCS input file, all of these parameters are entered and then commented out so they are not used. So, the operator simply has to select the newest point and comment out the one previously used.

Another advantage of the scripts is that they will automatically make the maptab files used in PARCS based on the data in the CASMO-3 and core simulator outputs. The reason a script is needed for this is because the output from CASMO-3 has 2-dimensional data for all 648 channels but TRACE and PARCS are not modeling all 648 channels one to one and TRACE runs in three dimensions. Therefore, the script will automatically model the data down to the appropriate level.

To run the scripts, simply open Matlab and run the printringhalsmodel.m script once all of your test point's data has been entered into the model.inp file. The scripts require source files which are all text files from CASMO-3 and include *.geom, *.crdgrp, *.sim, and DIST-(testpoint).txt (which has the two dimensional parameter mappings).

A batch file was created to allow one test point to completely run and the operator performs all of the analysis at the end. It may take upwards of twelve hours to run a complete simulation from steady state standalone to coupled transient problems and it is very computer processing intensive. The batch file is critical in optimizing time the operator may work at the computer since it is basically not usable while running a test point in TRACE/PARCS. Usually the computer is allowed to run overnight and then the operator may perform all of the analysis or troubleshooting during the workday instead of waiting for the program to finish. An example of the batch file is shown in Figure 5-3 on the next page.

```
:C16R324P04_324Vn_co
echo on
mkdir output
mkdir run
cd run
set trace=..\..\trace5044p28ecls.exe

:SA
copy /y ..\trace\R1C16P04_V324n tracin
%trace%

move trcout ..\output\R324P04Vn_sa.out
move trcxtv ..\output\R324P04Vn_sa.xtv
move trcdmp ..\output\R324P04Vn_sa.dmp
move trcmsg ..\output\R324P04Vn_sa.msg
copy ..\output\R324P04Vn_sa.dmp trcrst

CO
copy /y ..\trace\R1C16_324V_CO tracin
copy /y ..\parcs\C16P04co.inp parcs.inp
%trace%
move C16P04_324Vn_co.out ..\output\.
copy C16P04_324Vn_co.rst ..\output\.
move trcxtv ..\output\C16P04_324Vn_co.xtv
move trcout ..\output\C16P04_324Vn_co.trcout
move trcdmp ..\output\C16P04_324Vn_co.dmp
move trcmsg ..\output\C16P04_324Vn_co.msg
move parcs.out ..\output\C16P04_324Vn_co.parcsout
copy /y ..\output\C16P04_324Vn_co.dmp trcrst

:NT
:copy /y ..\trace\R1C16_324V_NT tracin
:copy /y ..\parcs\P04nt.inp parcs.inp
:%trace%
:move P04_324Vn_nt.plt ..\output\.

:NT_TXE
:copy /y ..\trace\R1C16_324V_NT tracin
:copy /y ..\parcs\P04nt_txe.inp parcs.inp
:%trace%
:move P04_324Vn_nt_txe.plt ..\output\.

:PP
copy /y ..\trace\R1C16_324V_PP tracin
copy /y ..\parcs\C16P04pp.inp parcs.inp
%trace%
move C16P04_V324n_pp.plt ..\output\.

:CR
copy /y ..\trace\R1C16_324V_CR tracin
copy /y ..\parcs\C16P04cr.inp parcs.inp
%trace%
move C16P04_V324n_cr.plt ..\output\.

:NS
copy /y ..\trace\R1C16P04_V324n.ns tracin
copy /y ..\parcs\C16P04ns.inp parcs.inp
%trace%
move C16P04_V324n_ns.plt ..\output\.

:END
cd ..
```

Figure 5-3: Example BATCH file

This batch file is for Cycle 16 Test Point 04 as shown in the very first line of code. Since some of the files used throughout the process are the same, the batch file makes directories for the outputs (so they are not overwritten by the next run) and the files being used currently (run directory). It must be noted that particular care is given to the CASEID function in PARCS since it gives the PARCS output files their filename. If the file name does not match exactly with what is in the batch file, data will be lost or mislabeled.

Chapter 6

Performing Stability Analysis

Once a test point has been completely run using the batch files the first thing the operator should do is go to the output folder under that test point's folder and verify that there are outputs for each portion of the run from standalone steady state to coupled transients. If there is a missing portion or some files have different file names but are the exact same size on the disk there may have been an error with the filenames or paths selected in the batch file or CASEID in PARCS. If everything is correct the operator may go on to start analyzing the data.

Several parameters are compared to the data given by the NEA benchmark and are: Reactor power, Steam dome pressure, Core flow rate, Core channel flow rate, Core inlet temperature, Lower plenum pressure, Upper plenum pressure, Collapsed (DC) water level, and K-effective. It should be noted however, that some of the data from the benchmark is the reactor plant specifications and some of the data comes from the measured data provided in the benchmark. In addition to these, void fraction, and reactor power are analyzed using a graphical two dimensional representation comparing their perspective values over core height.

6.1 Performing Steady State Problem Analysis

To analyze a standalone steady state run, almost all data is analyzed using AptPlot. Java based AptPlot (Plotting Tools) from Applied Programming Technology, Inc can be utilized to plot TRACE outputs from trcxtv files. This tool is the updated version of AcGrace (or previously known as XMGR).

Note that only information of signal variables, control blocks, general and trip data are available in the trcxtv file when graphLevel is set to 'minimal' in the namelist card of the tracin file. GraphLevel "minimal" option can be chosen in the case of a small trcxtv file is desired and to minimize computer runtime. The following is a short description of the important parameters and how to find them using AptPlot.

a. Total core flow rate:

From trcxtv by using AptPlot, read parameter:

vessel-990 mmflz-990A03R01T01 or signal sv-1.

b. Core channel flow rate:

For multi-channel calculations, see the information below item m.

c. Core total by-pass flow rate:

Subtract the value of core channel flow rate from value of total core flow rate.

d. Dome pressure:

From trcxtv by using AptPlot, read parameter:

vessel-990 pn-990A11R01T01 or signal sv-2.

e. Upper plenum pressure:

From trcxtv by using AptPlot, read parameter:

vessel-990 pn-990A06R01T01 or signal sv-11.

f. Lower plenum pressure:

From trcxtv by using AptPlot, read parameter:

vessel-990 pn-990A03R01T01 or signal sv-10.

g. Core inlet temperature:

From trcxtv by using AptPlot, read parameter:

vessel-990 tln-990A03R01T01 or signal sv-4.

h. Feedwater flow rate:

From trcxtv by using AptPlot, read parameter:

fill-960 fxmass-960 or signal sv-7.

i. Steamline flow rate:

From trcxtv by using AptPlot, read parameter:

pipe-978 rmvm-978A01 or signal sv-6.

j. DC water level:

From trcxtv by using AptPlot, read parameter:

signal sv-3.

k. Feedwater temperature:

From trcxtv by using AptPlot, read parameter:

pipe-961 tln-961A01.

l. Power:

rpower (reactor power) in trcxtv is only for the power from heat structures. In order to get the total power, the trcout file needs to be analyzed. Total power is given at the end of the trcout file. (keyword: *"Total Power is "*)

m. Core average axial void profile:

For the multi-channel model, the procedure in section 6.1.1 through MATLAB needs to be applied properly. Not only void fraction information but also channel flow rate information (for above item b.) can be extracted after the following procedure.

6.1.1 Void Fraction and Channel Flow Rate Extraction Procedure

- Open MATLAB.
- Edit printringhalsmodel.m (or model.inp)

  - Set both trcout=1 and readchans=1

  - Set path for the trcout:

  (i.e. trcout='C:\\ringhals\p10\output\R325P10Vn_co.out';)

  - Check options (cycle, point, number of channels, PP, APS, etc.) in the printringhalsmodel.m. These options must be consistent with the options utilized to create the input deck of the trcout file.

- trcout also needs to be modified as follows:

  - keep the very first line in the output. (i.e. TRACE Version 5.0RC3)

  - search the keyword “trac large edit” and find the last trac large edit.

  - Delete the lines between the very first line of the trcout and the line starting “trac large edit” for the last time step. Note that problem time in the trcout is generally states 0.00 s. For this reason check the *time-step number* to be sure that this is the last trac large edit.

- Save the trcout file and finally run printringhalsmodel.m in the MATLAB application. This will generate the files including void fraction and channel flow rate information. (i.e. void_325)

For the void fraction, the data is compared to a simplification of three-dimensional data down to one-dimensional data from SIMULATE and the POLCA-T core simulator and compared graphically as shown in Figure 6-1.

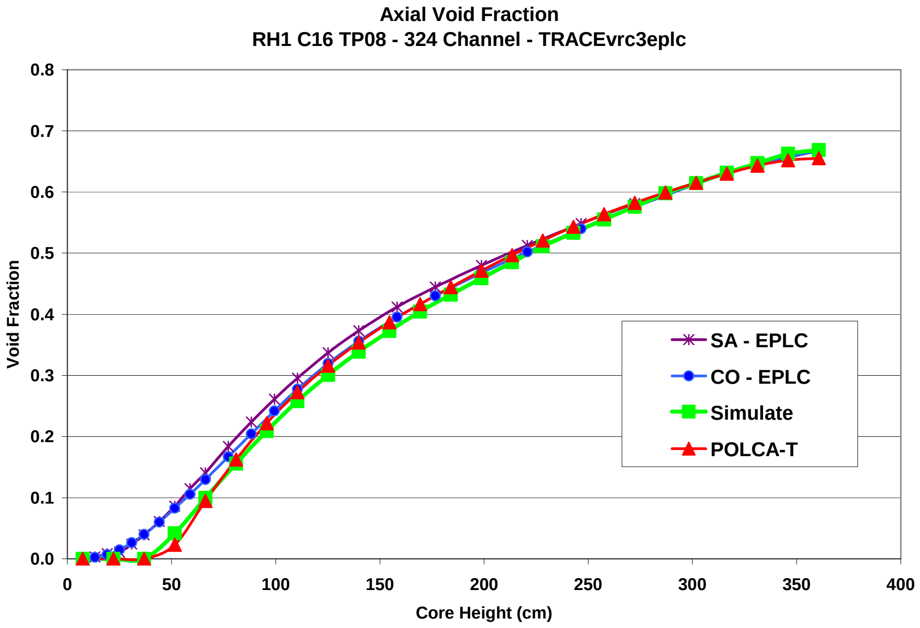


Figure 6-1: Sample Void Fraction Comparison

As discussed earlier, when running printringhalsmodel.m for this extraction procedure it allows the user to also extract the channel flow information. It displays the flow information in axial and radial form as shown in Figure 6-2.

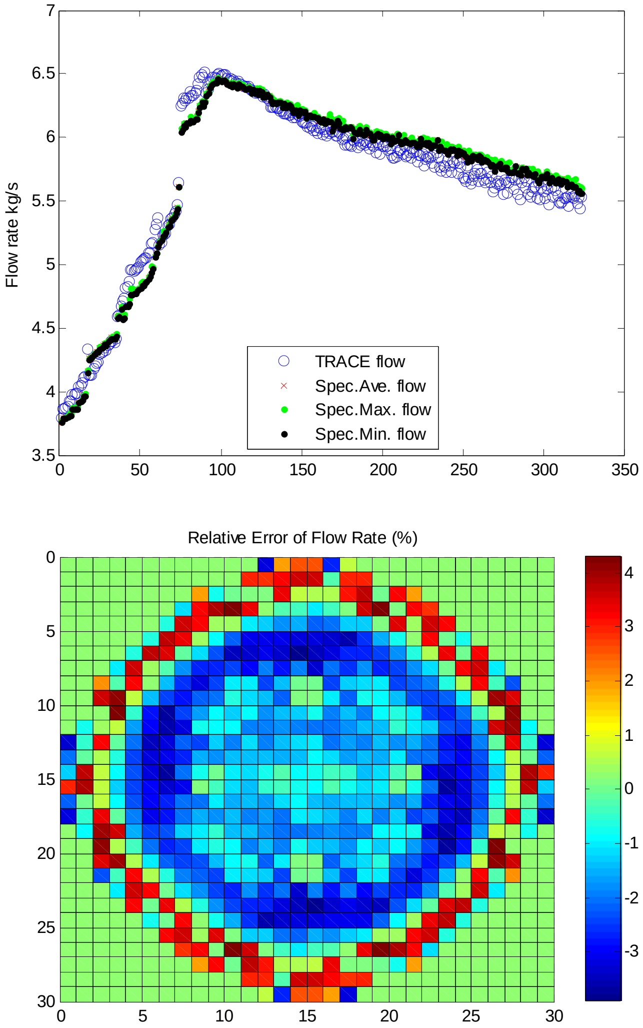


Figure 6-2: Axial flow Rate and Relative Radial Flow Rate Percent error

AptPlot only shows a graphical representation of the data as shown in Figure 6-3 below. In order to get the actual numerical data, the operator must display the data as a list of variables and use the last timestep's data.

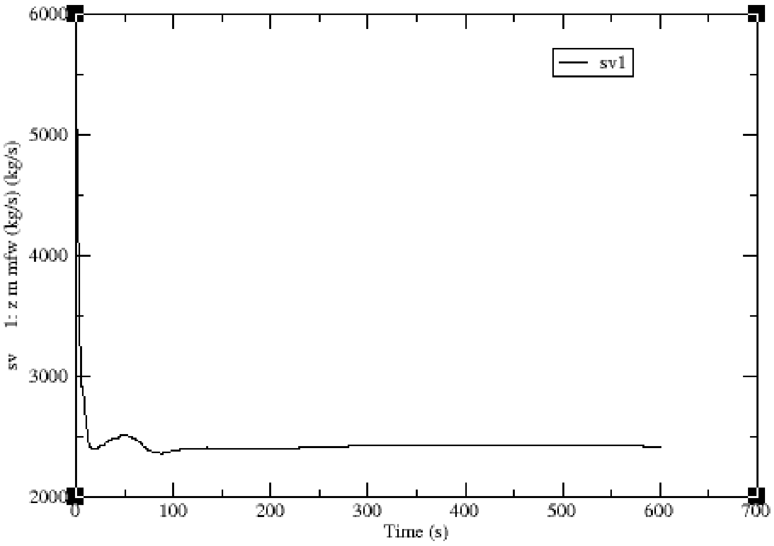


Figure 6-3: AptPlot Sample Data for Total Core Flow Rate

Once all of the numerical data has been retrieved from AptPlot, the data is compiled in a table as shown in Table 6-1.

Table 6-1: Steady State Data Table

TRACE C16PT08 - 324 Channels			**EPLC Version**	
	Specifications	**Measured**	**SA**	**CO**
Reactor power (Mw)	1700.23	N/A	1700.2	1700.2
Steam dome pressure (Mpa)	7.03	N/A	7.03	7.03
Core flow rate (kg/s)	3907	N/A	3907	3907
Core channel flow rate (kg/s)	N/A	3539.9	3517	3517.7
Steam flow rate (kg/s)	N/A	N/A	813.29	813.39
Core inlet temperature (K)	535.45	N/A	535.45	535.45
Lower plenum pressure (Mpa)	N/A	N/A	7.104	7.104
Upper plenum pressure (Mpa)	N/A	N/A	7.051	7.051
Collapsed (DC) water level (m)	N/A	N/A	8.32	8.29
K-effective	1.000000	N/A	N/A	0.994723

6.1.2 Coupled Steady State Analysis

Coupled steady state problem analysis is done identically to standalone steady state analysis for all of the outputs from TRACE. For PARCS outputs, the operator must extract two additional pieces of data, K-effective and axial power.

To extract the eigenvalue simply search the PARCS output file (parcs.out for example) for “K-Effective:” and the value is displayed towards the end of the document. Ideally, the eigenvalue should be equal to 1.000000 but is usually slightly less than this value due to the fact that the problem may have ended before the problem fully converged or due to not having a one to one mapping of the system. A value within three significant digits to one is assumed to be critical and at steady state.

To extract normalized axial power search the PARCS summary file (parcs.sum) for “Summary of Axial Power Density” which is at the end of the file also. This data is also compared graphically to power data from SIMULATE and POLCA-T and is shown in Figure 6-4.

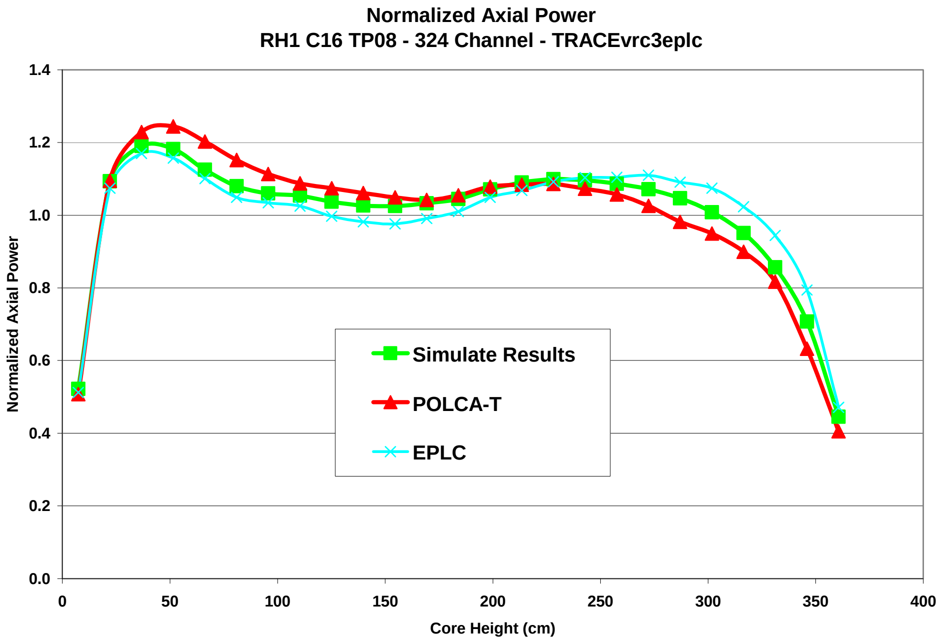


Figure 6-4: Normalized Axial Power

Reactor power is also compared radially using a MATLAB script similar to the same way void fraction is extracted. This MATLAB script is called "compare_power.m" and has an input file that will read from the parcs.out file and automatically create four graphs. These graphs are the radial power from PARCS, radial power from SIMULATE, and the RMS (Root Mean Squared) error between PARCS and POLCA-T and SIMULATE and POLCA-T. POLCA-T was a reactor core simulator used in the DIST files given in the benchmark. An example of one of these graphs is shown in Figure 6-5.

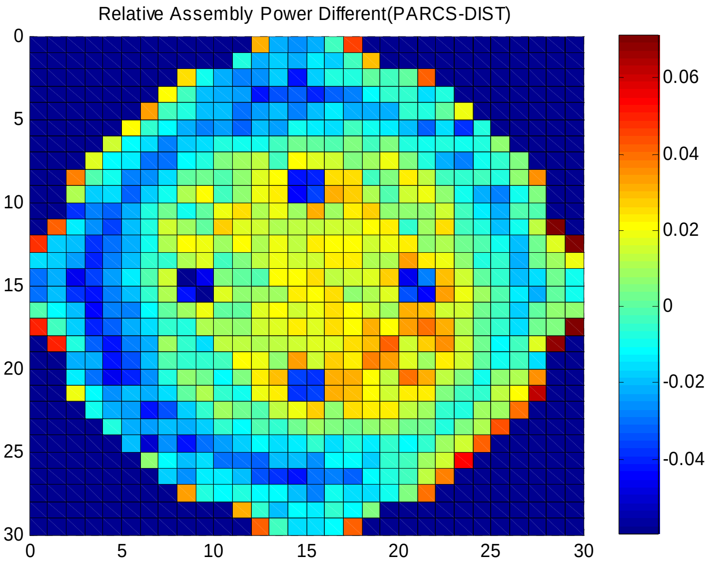


Figure 6-5: Relative Radial Power RMS between PARCS and POLCA-T (DIST)

6.2 Performing Transient Analysis

All of the work up to this point has been to verify that the test point is indeed modeled correctly and at a steady state point. The overall function of these tests has been to observe how TRACE/PARCS can model the instabilities caused by the earlier discussed perturbations. To extract the decay ratios and natural frequencies from the output files, a program called DRARMAX was used.

6.2.1 DRARMAX

DRARMAX was developed at Purdue University by Dr. Yunlin Xu. It is a program run through MATLAB that is used to analyze decay ratios and natural frequencies from output files. DRARMAX is able to extract this data from short perturbations such as control rod and pressure perturbations as well as long running transients such as noise transients. The program must know what type of signal (short or long term perturbation) it is attempting to analyze in order to correctly extract the decay ratio (DR) and natural frequency (NF). DRARMAX uses three types of functions: the output signal from TRACE/PARCS (RAW data), the output signal's autocorrelation function (ACF), and the impulse response function (IRF) to calculate the DR and NF. All three of these different functions are fitted with a damped sinusoidal function:

$$x(t) = c_0 + ce^{-\alpha t}\cos(\omega t + \varphi) \tag{6-1}$$

One thing that must be noted is that this function must ignore the portion of the output file before the perturbation occurs. This is one of the inputs into DRARMAX. Once the rest of the output file's data is fitted with the damped sinusoid it attempts to model the data using a least square fit. The least square fitting is used for transients with short perturbations, such as control rod and pressure perturbations. If this fit is within tolerances the DR and NF are calculated using:

$$DR_f = e^{-2\pi\alpha/\omega} \tag{6-2}$$

$$Fr_f = \omega/(2\pi) \tag{6-3}$$

For longer perturbations, such as measured or simulated noise signals, DRARMAX uses the impulse response function. The IRF is extracted by an autoregressive and moving average (ARMA) method [8].

$$x(i) = -\sum_{k=1}^{p} a_k x(i-k) + \sum_{m=0}^{q} b_m u(i-m) \tag{6-4}$$

Where *u* and *x* are the input and output signals, *p* and *q* are the orders of the ARMA method, and the a_k and b_m coefficients are obtained using the prediction-error identification method (PEM). Since there are user defined inputs into this process, an index known as final prediction error (FPE) is used to estimate the quality of the ARMA method:

$$FPE = \frac{N+q+1}{N-2p-q-1} \| x - \hat{x} \| \tag{6-5}$$

Where N is the number of sampled data points and $\hat{x}$ is an approximation of the output signal by the ARMA method.

Therefore, instead of using the least squared fitting method and extracting the DR and NF as discussed earlier, a slightly different method must be used for noise signals. The Lyapunov DR and NR are used:

$$DR_L = e^{-2\pi \operatorname{Re}(\gamma)/\operatorname{Im}(\gamma)} \tag{6-6}$$

$$Fr_L = \operatorname{Im}(\gamma)/(2\pi\Delta t) \tag{6-7}$$

Where Δt is the time interval of input and output time series, and $\gamma = \ln(\beta_m)$ and β_m is the dominant root of $1 + \sum_{k=1}^{p} a_k \beta^k$ [8].

6.2.2 Mechanics of Performing Transient Analysis

Once TRACE/PARCS has completed running the transients the operator may perform stability analysis on them. The only output file used for this analysis is not the tracout file but instead the trac.plt (plot) file. Similarly to the operator slightly changing the paths and support files to the PARCS inputs, the operator has to change a few things in the input files for DRARMAX. A sample DRARMAX input file for a control rod perturbation is shown in Figure 6-6.

```
DATA_FILE    ..\run\C16P09_V324n_pp.plt   0  0.0      !file name,skip lines at
                                                      !beginning, time interval
 COLUMNS     T   O
SAMPLING     0.0 1.0 20           !sampling interval, start time, end time
TAB_TIME     0.0 1.0 1.1   1.2 20.0
TAB_INPT     0.0 0.0 1.0  0.0 0.0
DR_EVAL       2    2    2         ! Decay ratio evaluation option for 3 function
EVAL_TIME    1    20          !
ARMA_ORDER   20 0         ! Pairs of AR and MA order
```

Figure 6-6: Sample DRARMAX input file

Where the DATA FILE is the path to the *.plt file and SAMPLING is from 1 to 20 seconds. The output of DRARMAX is shown in an output file and shown graphically in MATLAB. A sample output file and graph are shown in Figure 6-7.

```
Read 2 series with length 516 from file ..\run\ C16P09_V324n_pp.plt
   1 time point serial
   0 input signal
   1 output signal
Sampled 488 points with interval 0.039s from     1.020s to    19.944s

            Dr-P   Fr-P   Dr-LS  Fr-LS  Dr-Ly  Fr-Ly  Dr-As  Fr-As
   RAW     0.946  0.429  0.949  0.429
   ACF     0.826  0.426  0.760  0.426
```

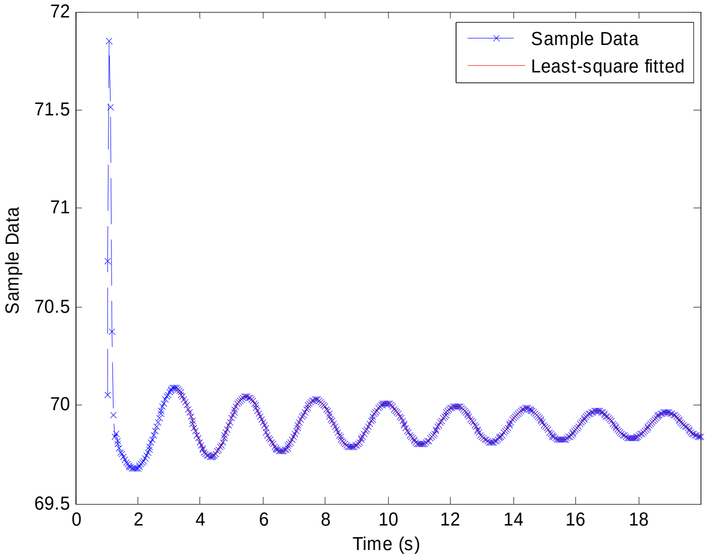


Figure 6-7: Sample DRARMAX output file and graph

The calculation for DR and NF for noise transients is identical except a slightly different input deck is used since the IRF is used to determine DR and NF for those types of transients. In the above output file the calculated decay ratio is 0.95 and natural frequency is 0.43. It should be noted that DRARMAX outputs data under two columns, RAW and ACF (autocorrelation function). Originally, both of these outputs were used in simulating the decay ratio and natural frequencies but it was discovered that the autocorrelation function did not always overlay properly on the sample data. (Figure 6-7 shows it matching the sample data) It was then observed that many times that this occurred the results for calculated decay ratios were much worse, therefore the ACF data was not used or shown in the results of this thesis.

Chapter 7

Simulation Results

Steady state and transient results for all beginning of cycle (BOC) test points from cycles 14, 15, 16, and 17 with a reference decay ratio of at least 0.40 are included in detail in this chapter. The main purpose of this thesis is in the transient results, which are compared to the benchmark results. The transient results are shown and discussed next.

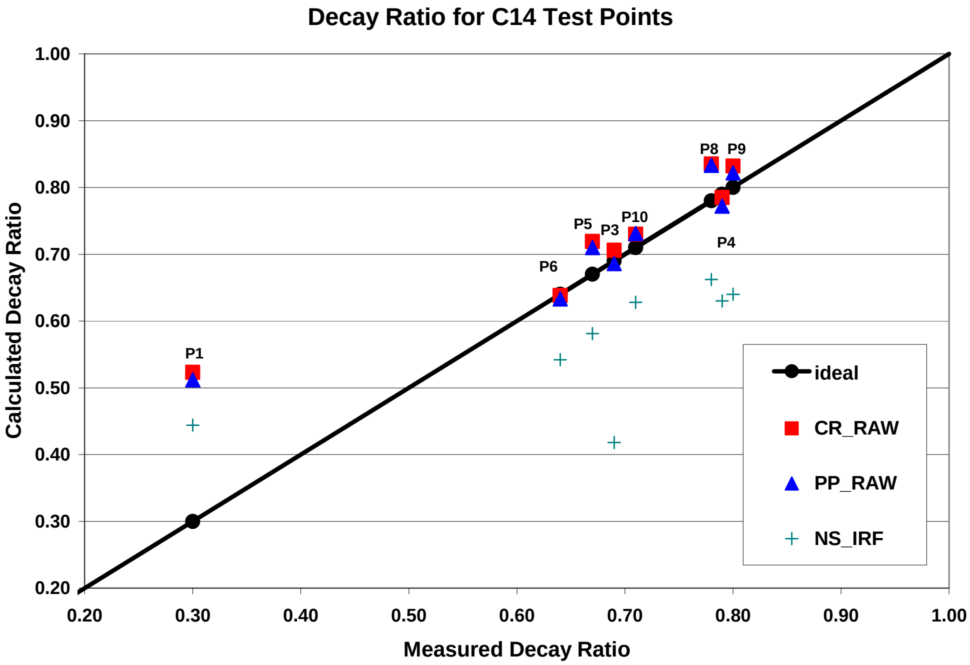
7.1 Cycle 14 Transient Results

Cycle 14 data is the basis for the Ringhals 1 model and was tested in TRACE so it should be expected that the results should be the best on the test points in this cycle. It should be noted that this cycle also has the most out of phase oscillations. Table 7-1 and Figure 7-1 display the calculated values with the benchmark results in tabular and graphical form respectively.

Table 7-1: Cycle 14 Decay Ratio and Frequency Results

Cycle 14 (BOC) Comparisons with RAW Method				
	Reference	Calculated DR (Global)		
TP	**DR (Global)**	**CR**	**PP**	**NS**
1	0.30	0.52	0.51	0.44
3	0.69	0.71	0.69	0.42
4	0.79	0.79	0.77	0.63
5	0.67	0.72	0.71	0.58
6	0.64	0.64	0.63	0.54
8	0.78	0.84	0.83	0.66
9	0.80	0.83	0.82	0.64
10	0.71	0.73	0.73	0.63

Cycle 14 (BOC) Comparisons with RAW Method				
	Reference	Calculated Fr (Global)		
TP	**FR (Global)**	**CR**	**PP**	**NS**
1	0.43	0.41	0.41	0.40
3	0.43	0.41	0.41	0.45
4	0.55	0.50	0.50	0.50
5	0.51	0.49	0.49	0.49
6	0.52	0.48	0.48	0.48
8	0.52	0.48	0.48	0.47
9	0.56	0.51	0.51	0.52
10	0.50	0.48	0.48	0.47



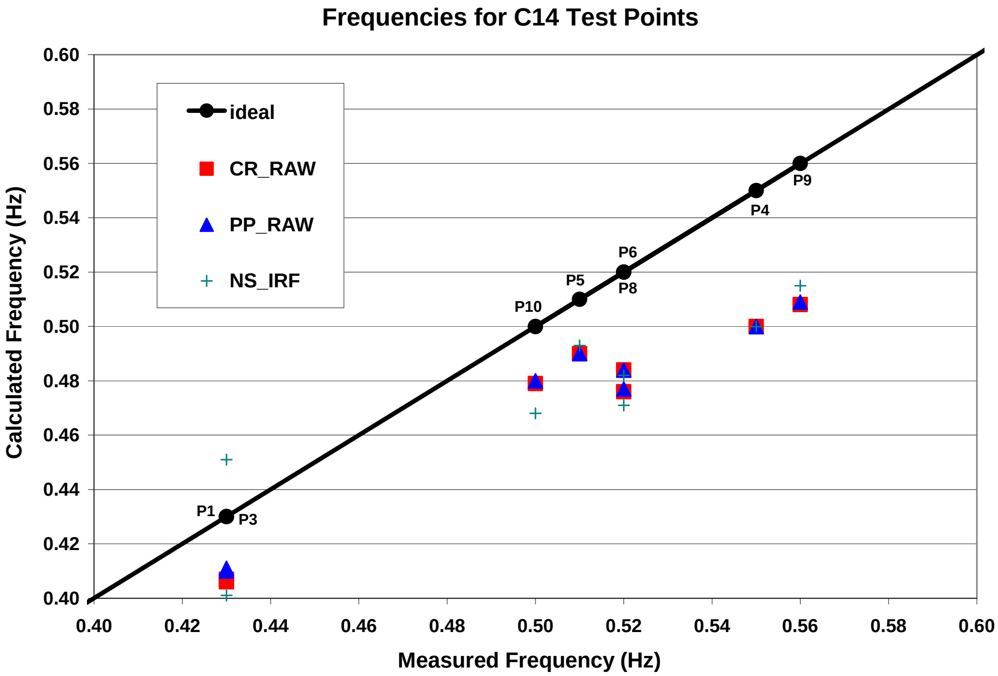
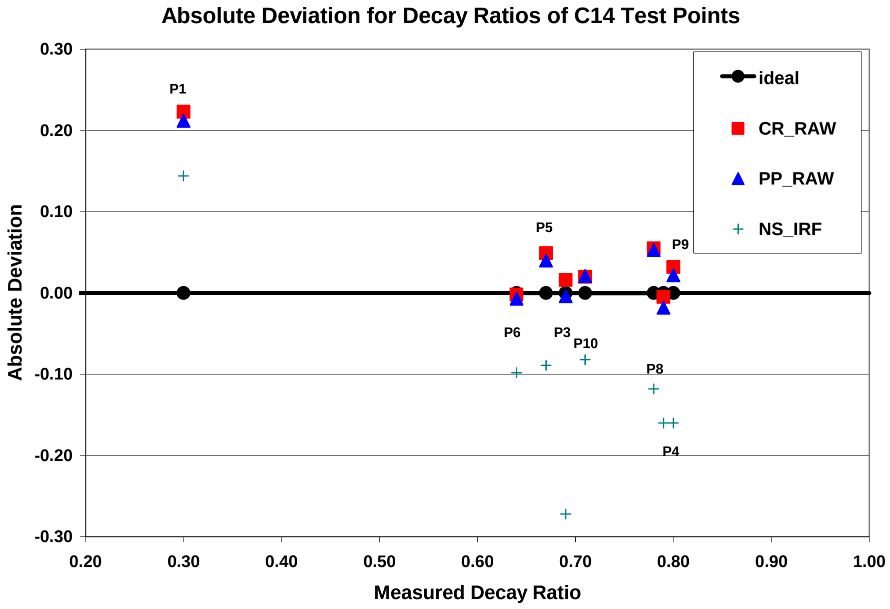


Figure 7-1: Graphical Representation of Cycle 14 Results

The average difference between simulated results and benchmark decay ratios was 0.06 for cycle 14 with a standard deviation of 0.09 for control rod and pressure perturbations and 0.16 for noise transients, with an overall average (all three transients combined) of 7.5% deviation from the benchmark results. For frequencies, the overall difference was 0.03, while standard deviations were 0.04 for all three types of transients, with an overall percent deviation of 7.4%. Each test point's deviation is shown in Figure 7-2.



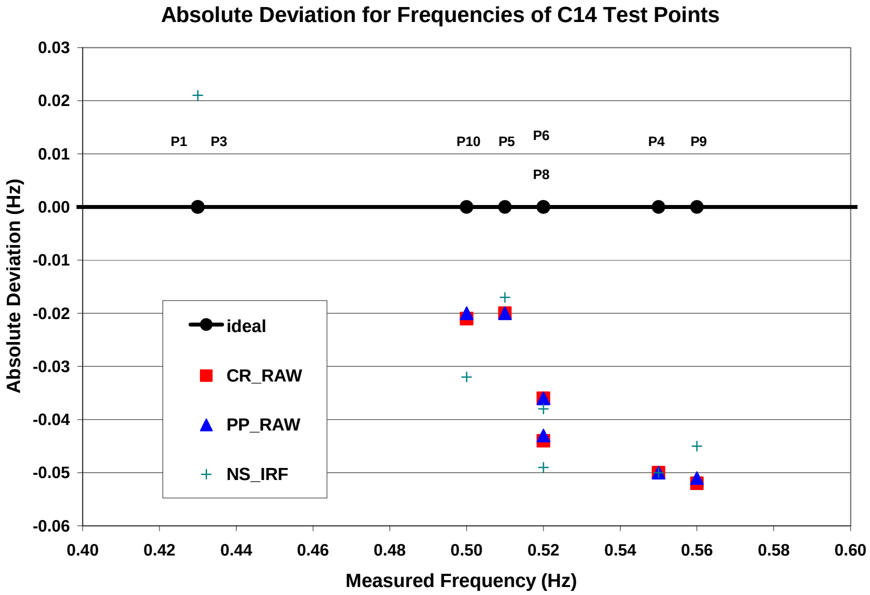


Figure 7-2: Cycle 14 Absolute Deviations

7.2 Cycle 15 Transient Results

Cycle 15 featured ten test points. Of these test points, simulations were only ran on points five through ten due to the very low decay ratios observed in test points one through four. One major difference between cycles 14 and 15 was the number of channels simulated. The Cycle 14 model had 325 channels in the core where cycle 15 had 324. The reason for this difference is due to the fact that the types of assemblies in cycle 14 were different than those in cycle 15. Cycle 14 includes some of the asymmetric assemblies (SVEA 63 Channel fuel assemblies) where cycle 15 uses symmetrical SVEA 64 channel fuel assemblies. Table 7-2 displays the calculated decay ratios and frequencies compared to the benchmark results. Figure 7-3 displays the same data in a graphical form where the solid black line is the reference (benchmark) value.

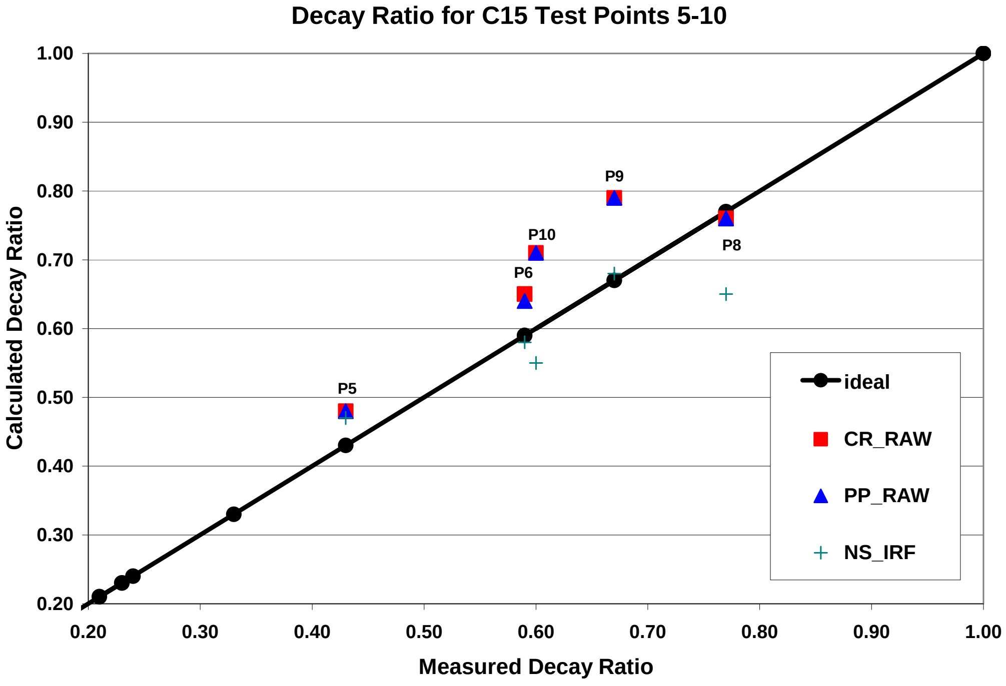
Table 7-2: Cycle 15 Decay Ratio and Frequency Results

Cycle 15 (BOC) Comparisons with RAW Method

	Reference	**Calculated DR (Global)**		
TP	**DR (Global)**	**CR**	**PP**	**NS**
1	0.23	-	-	-
2	0.24	-	-	-
3	0.21	-	-	-
4	0.33	-	-	-
5	0.43	0.48	0.48	0.47
6	0.59	0.65	0.64	0.58
8	0.77	0.76	0.76	0.65
9	0.67	0.79	0.79	0.68
10	0.6	0.71	0.71	0.55

Cycle 15 (BOC) Comparisons with RAW Method

	Reference	**Calculated Fr (Global)**		
TP	**FR (Global)**	**CR**	**PP**	**NS**
1	0.44	-	-	-
2	0.42	-	-	-
3	0.43	-	-	-
4	0.44	-	-	-
5	0.44	0.43	0.43	0.43
6	0.47	0.44	0.45	0.44
8	0.55	0.50	0.50	0.50
9	0.53	0.50	0.50	0.52
10	0.54	0.51	0.51	0.50



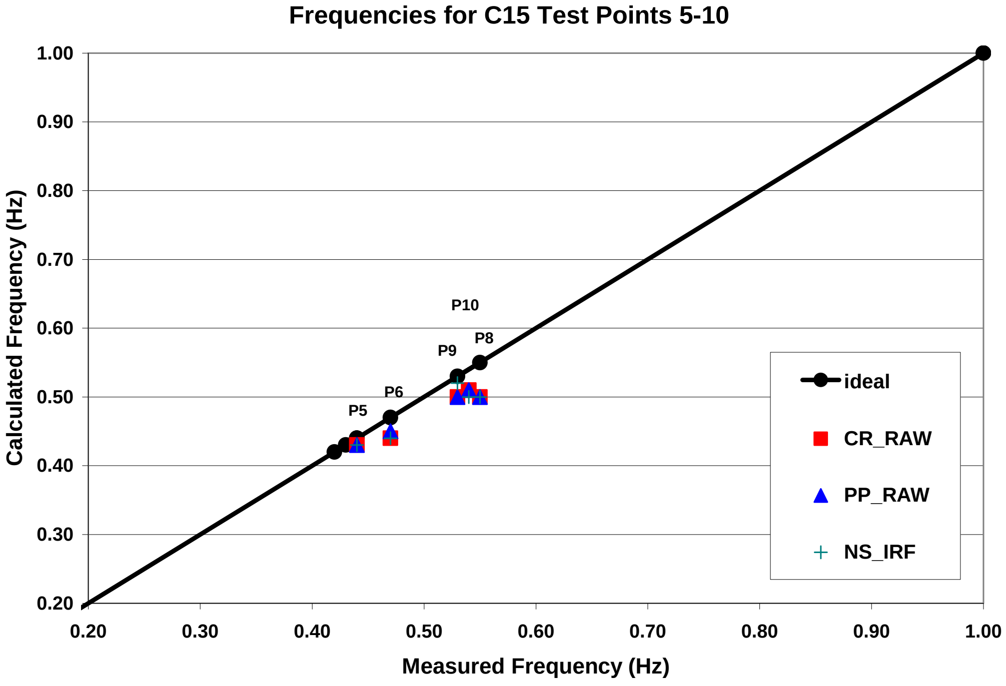


Figure 7-3: Graphical Representation of Cycle 15 Results

For cycle 15, the overall difference between calculated decay ratios and simulated decay ratios was 0.05. The standard deviation for cycle 15 decay ratios was 0.07 for control rod and pressure perturbations and 0.05 for noise transients, with an overall average of 6.4% deviation from the benchmark results. For frequencies, the overall difference was 0.03, standard deviations were 0.03 for all three types of transients, with an overall percent deviation of 6.1%. Each test point's deviation is shown in Figure 7-4.

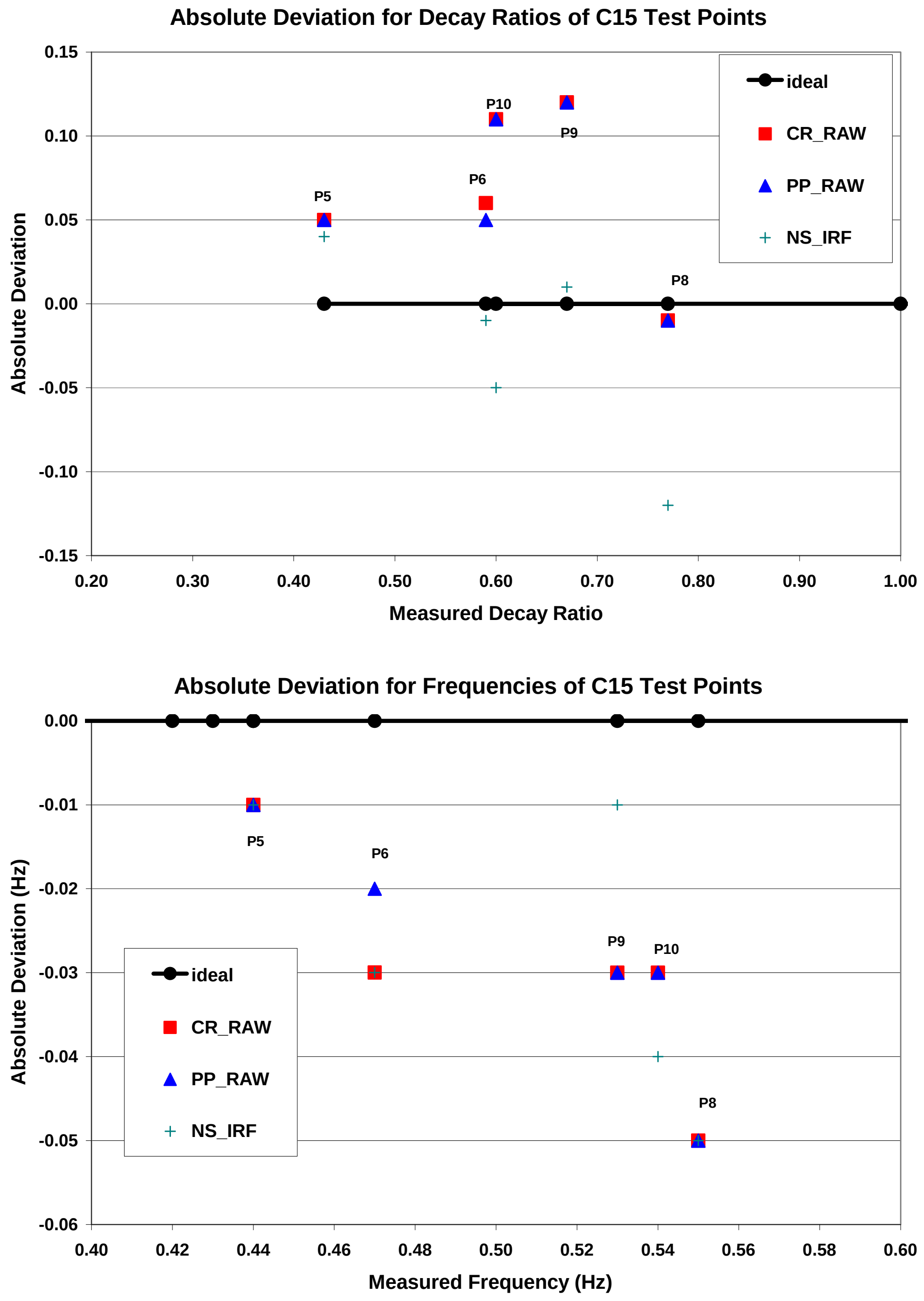


Figure 7-4: Cycle 15 Absolute Deviations

7.3 Cycle 16 Transient Results

Cycle 16 features eleven test points with a minimum decay ratio of 0.54. During the course of the analysis of cycle 16 it was discovered that the loss coefficients being used for the SVEA fuel assemblies were incorrect. This resulted in calculated decay ratios being slightly larger than the benchmark results with a constant bias in this regard. The reason this was not discovered earlier is due to the fact that SVEA assemblies were not as predominant in cycles 14 and 15 but over the core life and after refueling they were the primary fuel assembly being used in cycle 16. Once this was discovered and fixed cycles 14 and 15 were recomputed with even better results. These new results were the ones shown in sections 7.1 and 7.3. Table 7-3 displays the calculated decay ratios and frequencies compared to the benchmark results. Figure 7-5 displays the same data in a graphical form where the solid black line is the reference (benchmark) value.

Table 7-3: Cycle 16 Decay Ratio and Frequency Results

Cycle 16 (BOC) Comparisons with RAW Method				
	Reference	**Calculated DR (Global)**		
TP	**DR (Global)**	**CR**	**PP**	**NS**
1	0.54	0.60	0.60	0.69
2	0.54	0.66	0.66	0.68
3	0.69	0.75	0.74	0.75
4	0.71	0.65	0.63	0.62
5	0.67	0.74	0.72	0.69
6	0.79	0.84	0.83	0.80
7	0.72	0.74	0.74	0.71
8	0.82	0.80	0.79	0.78
9	0.87	**0.90**	**0.88**	**0.90**
10	0.65	0.71	0.67	0.71
11	0.66	0.76	0.77	0.70

Cycle 16 (BOC) Comparisons with RAW Method				
	Reference	**Calculated Fr (Global)**		
TP	**FR (Global)**	**CR**	**PP**	**NS**
1	0.48	0.44	0.43	0.42
2	0.48	0.43	0.43	0.41
3	0.47	0.43	0.43	0.41
4	0.52	0.45	0.45	0.43
5	0.49	0.44	0.44	0.43
6	0.49	0.43	0.43	0.42
7	0.50	0.45	0.45	0.43
8	0.49	0.44	0.44	0.43
9	0.48	0.43	0.43	0.42
10	0.50	0.45	0.44	0.43
11	0.48	0.46	0.45	0.46

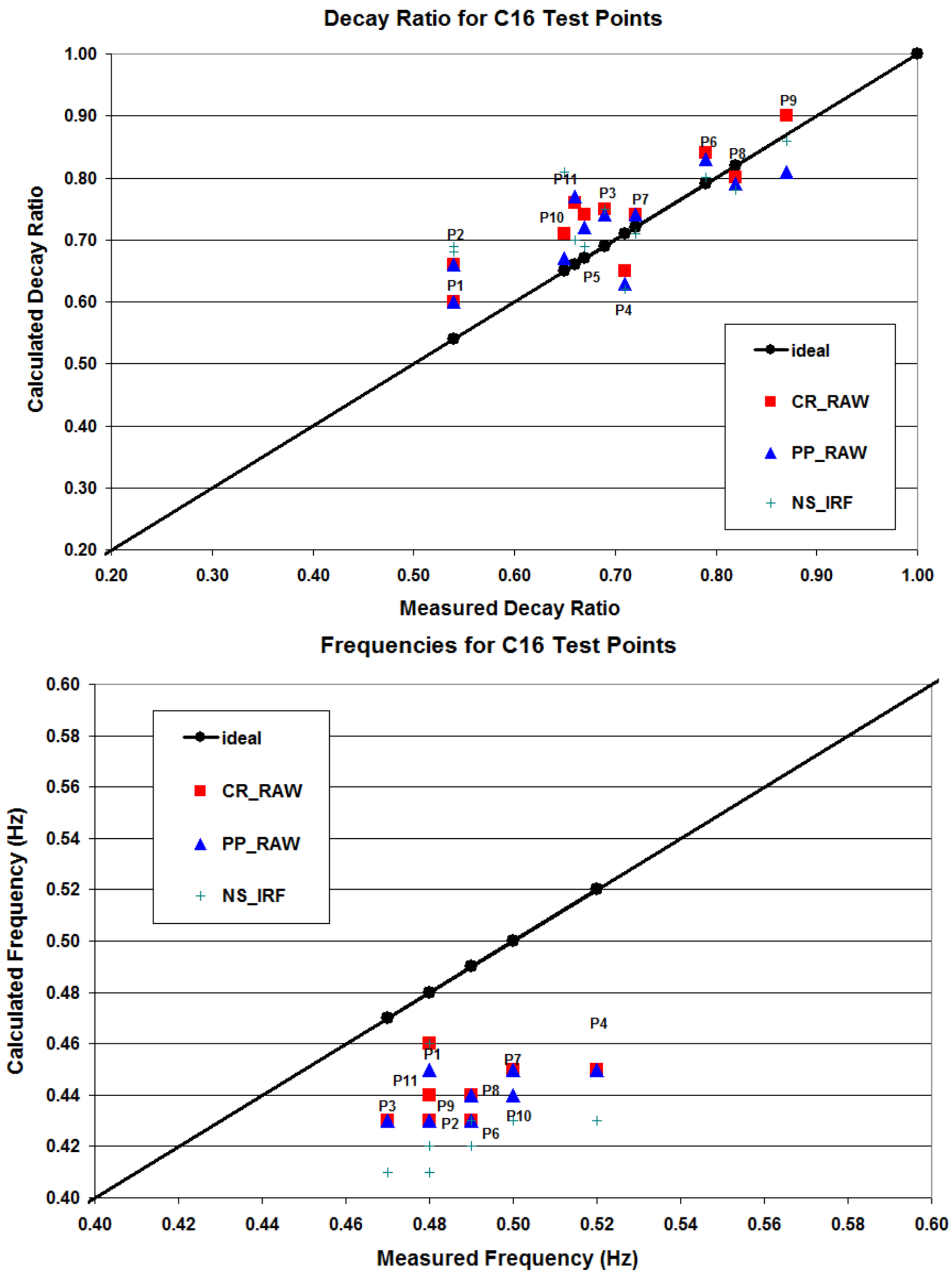


Figure 7-5: Graphical Representation of Cycle 16 Results

For cycle 16 the average difference in decay ratios was 0.04. The standard deviation for cycle 16 decay ratios was 0.06 for control rod 0.07 for pressure perturbations and noise transients, with an overall average of 4.2% deviation from the benchmark results. For frequencies, the average difference was 0.05, while standard deviations were 0.05 for control rod and pressure perturbations and 0.07 for noise transients, with an overall percent deviation of 10.5%. Each test point's deviation is shown in Figure 7-6.

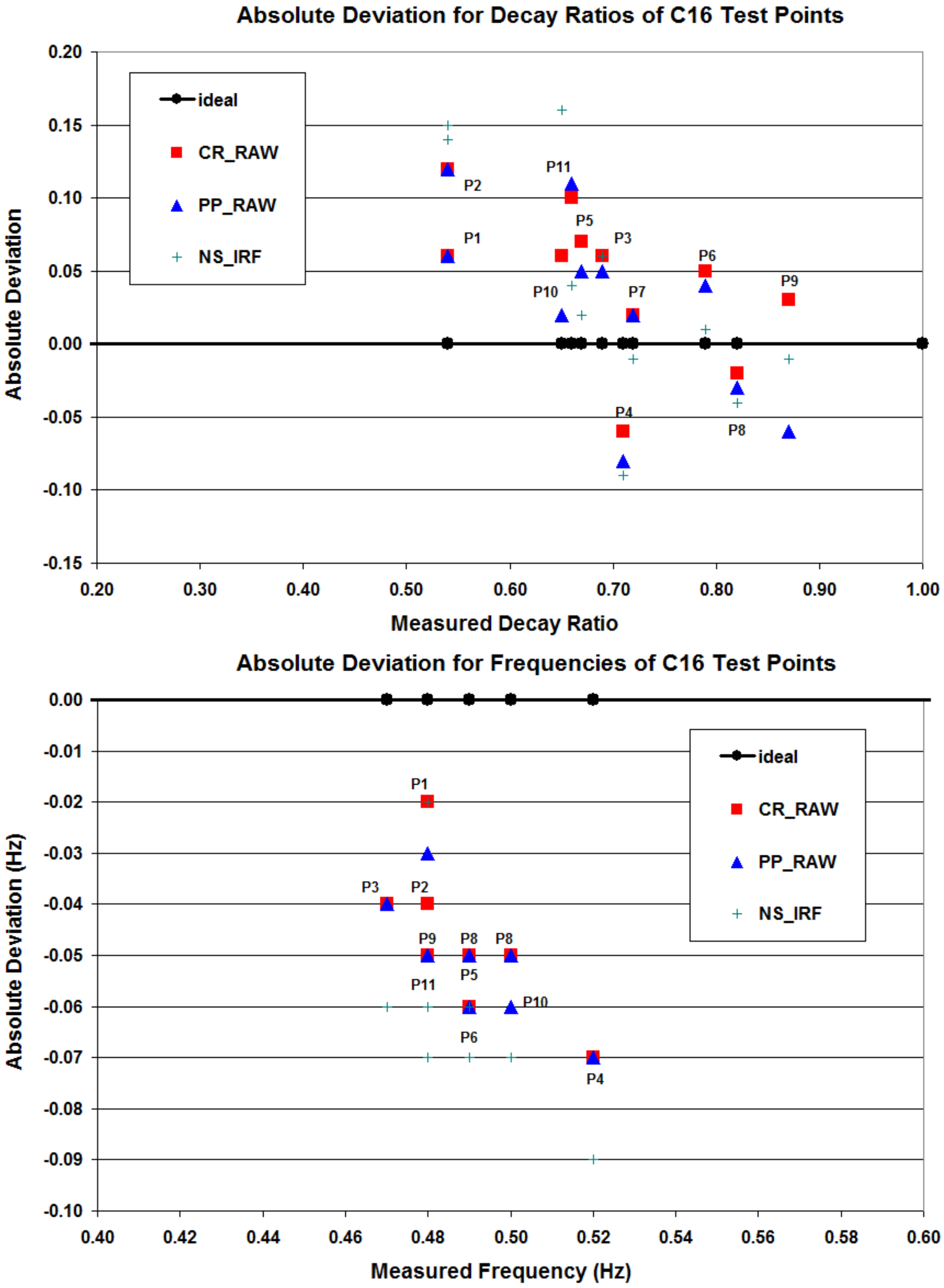


Figure 7-6: Cycle 16 Absolute Deviations

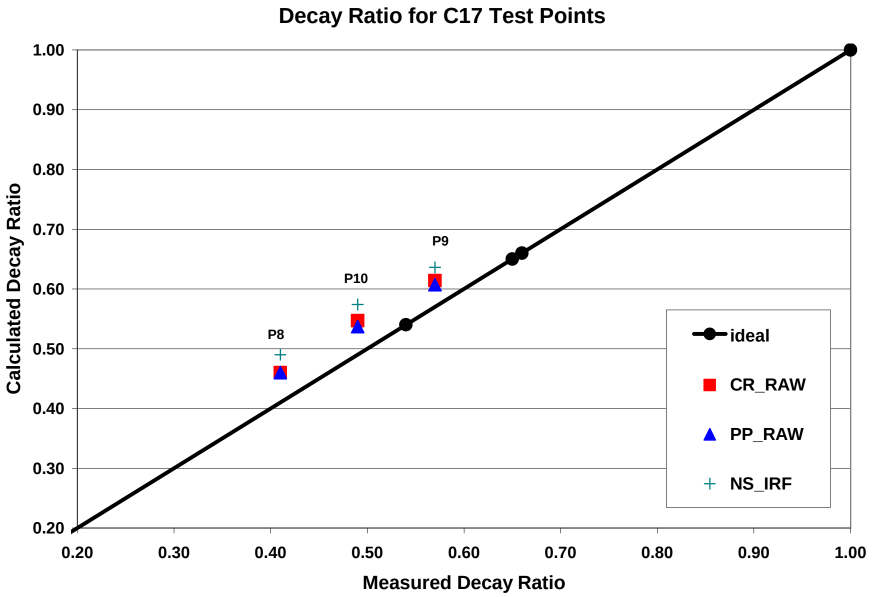
7.4 Cycle 17 Transient Results

Cycle 17 featured nine test points. Of these test points, simulations were only ran on points eight through ten due to the very low decay ratios observed in test points two through seven (there was no test point 1 in this cycle). Cycle 17 results are very similar to cycle 16 due to that the types of fuel assemblies are the same between the two cycles for the most part. Table 7-4 displays the calculated decay ratios and frequencies compared to the benchmark results. Figure 7-7 displays the same data in a graphical form where the solid black line is the reference (benchmark) value.

Table 7-4: Cycle 17 Decay Ratio and Frequency Results

Cycle 17 (BOC) Comparisons with RAW Method				
	Reference	Calculated DR (Global)		
TP	DR (Global)	CR	PP	NS
8	0.41	0.46	0.46	0.49
9	0.57	0.61	0.61	0.64
10	0.49	0.55	0.54	0.57

Cycle 17 (BOC) Comparisons with RAW Method				
	Reference	Calculated Fr (Global)		
TP	FR (Global)	CR	PP	NS
8	0.48	0.43	0.43	0.42
9	0.47	0.42	0.42	0.40
10	0.49	0.43	0.43	0.42



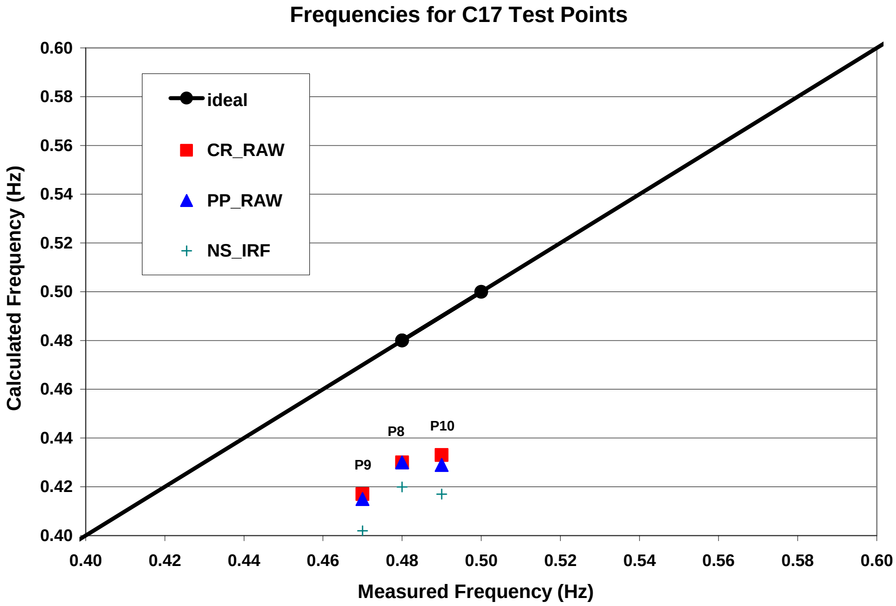


Figure 7-7: Graphical Representation of Cycle 17 Results

Cycle 17 had an average difference in decay ratios of 0.06. The standard deviation for cycle 17 decay ratios was 0.03 for control rod and pressure perturbations and 0.05 for noise transients, with an overall average of 12.0% deviation from the benchmark results. For frequencies, average difference was also 0.06, while the standard deviations were 0.03 for control rod and 0.04 for pressure perturbations and noise transients, with an overall percent deviation of 12.2%. Each test point's deviation is shown in Figure 7-8.

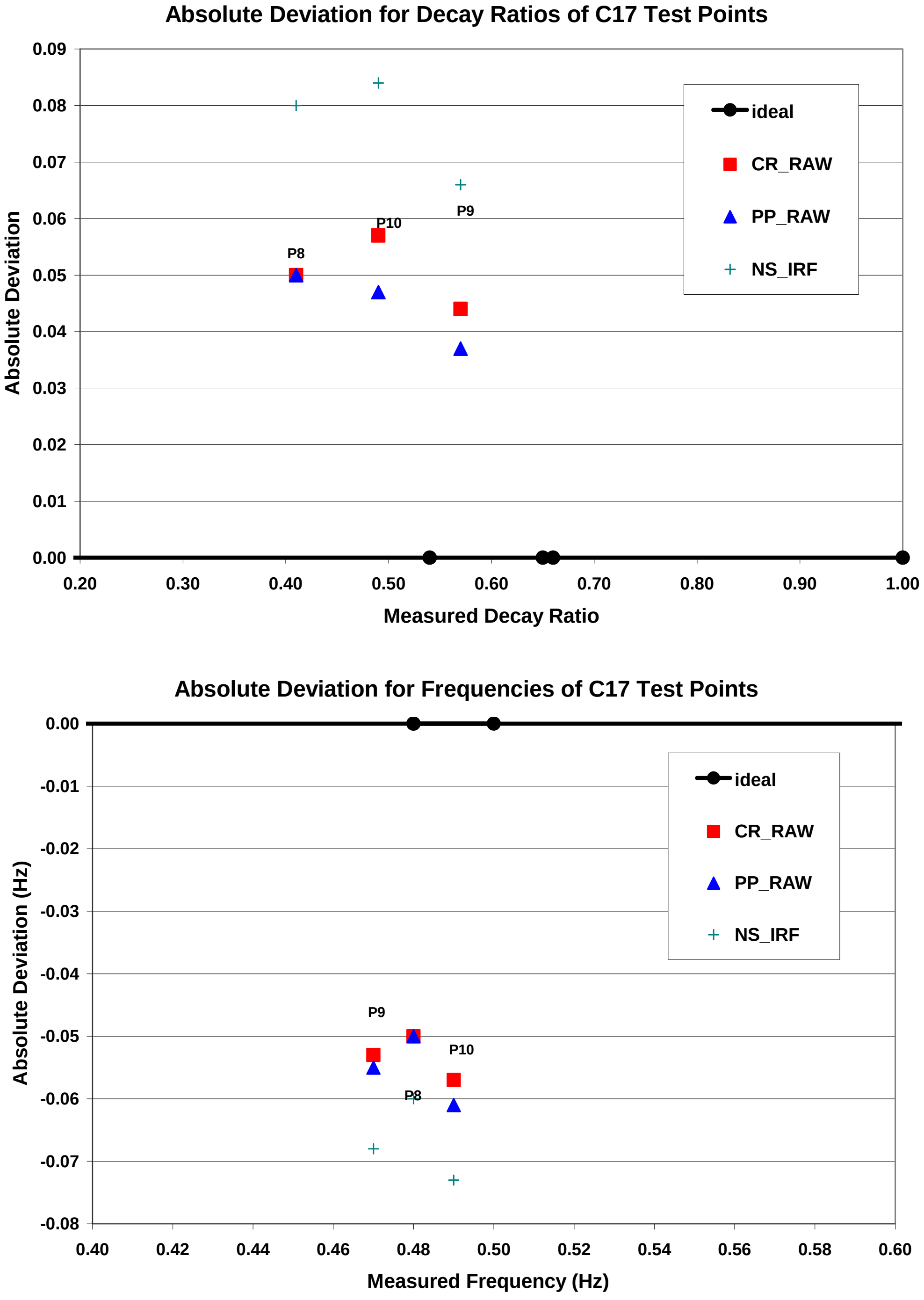


Figure 7-8: Cycle 17 Absolute Deviations

7.5 Steady State Results

For each test point, steady state reactor parameters are shown in tables. Flow, void fraction, and axial power are shown graphically in figures. There were a total of 27 test points simulated over the course of the work of this thesis. All transient results are given, as shown in the above sections. Since the steady state results are only a quality assurance check, only one test point will be discussed to provide a basic understanding of how the data was analyzed in this thesis. The sample test point shown is cycle 16 test point 7.

Table 7-5 shows the key reactor plant parameters analyzed during steady state standalone (SA) and coupled (CO) runs of TRACE/PARCS.

Table 7-5: Cycle 16 Test Point 7 Steady State Results

TRACE C16PT07 - 324 Channels			**EPLC Version**	
	Specifications	**Measured**	**SA**	**CO**
Reactor power (Mw)	1688.88	N/A	1688.9	1688.9
Steam dome pressure (Mpa)	7.03	N/A	7.03	7.03
Core flow rate (kg/s)	4081	N/A	4081	4081
Core channel flow rate (kg/s)	N/A	3690.5	3664	3664
Steam flow rate (kg/s)	N/A	N/A	804.15	806.42
Core inlet temperature (K)	536.55	N/A	536.41	536.55
Lower plenum pressure (Mpa)	N/A	N/A	7.107	7.107
Upper plenum pressure (Mpa)	N/A	N/A	7.050	7.050
Collapsed (DC) water level (m)	N/A	N/A	8.34	8.30
K-effective	1.000000	N/A	N/A	0.995268

As shown in the above table, the overall values agree quite well with the specifications laid out in the benchmark and with the measured data also supplied in the digital recordings of the benchmark. Not all parameters have reference values, and were used as a “common sense” check to ensure there were not any issues in the model for the test point.

The void fraction is shown in Figure 7-9. Void fraction is crucial to the operation of boiling water reactors since it provides a majority of the reactor’s inherent stability. Over every test point, the void fraction in the TRACE/PARCS simulation matches very well with the results from SIMULATE-3 and the benchmark data, with the exception of the values below a core height of 100cm. The mass flow rate, pressure, and temperature in the sub cooled region low in the core are over predicted by TRACE systematically. This is due to problems in the code relating to models in the interfacial heat transfer.

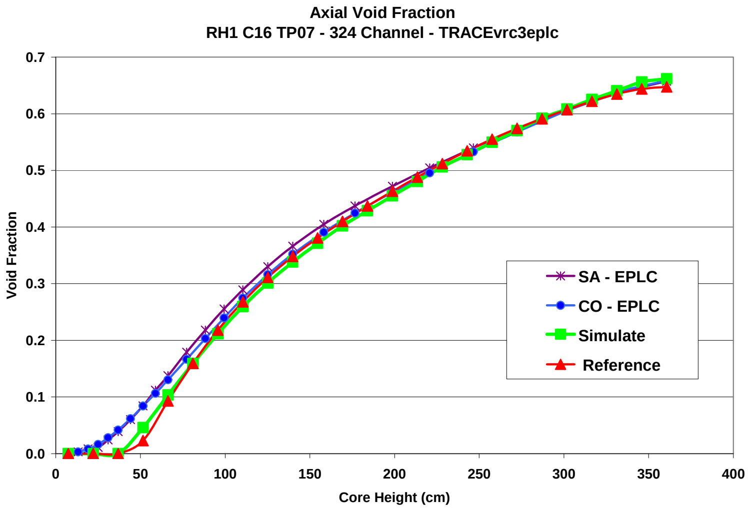


Figure 7-9: Cycle 16 Test Point 7 Void Fraction

Normalized axial power for this test point is shown in Figure 7-10. TRACE/PARCS (shown as EPLC in the figure) simulate the power distribution very accurately. The reactor power is slightly higher in the bottom of the core due to the void fraction issue discussed earlier.

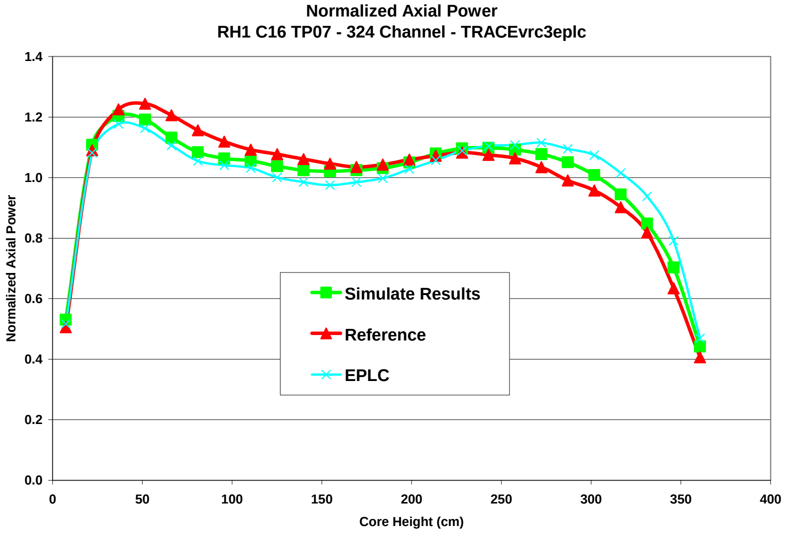


Figure 7-10: Normalized Axial Power.

Reactor power was analyzed both axially and radially. Figure 7-11 shows the radial power of PARCS and the benchmark specifications.

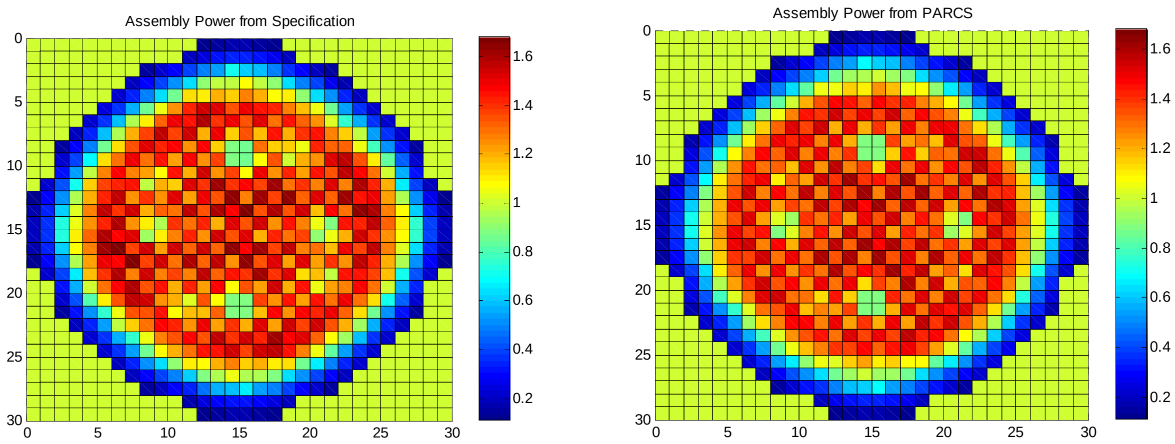


Figure 7-11: Radial Power

The absolute deviation of the radial power is shown graphically in Figure 7-12 where it clearly shows a very good agreement.

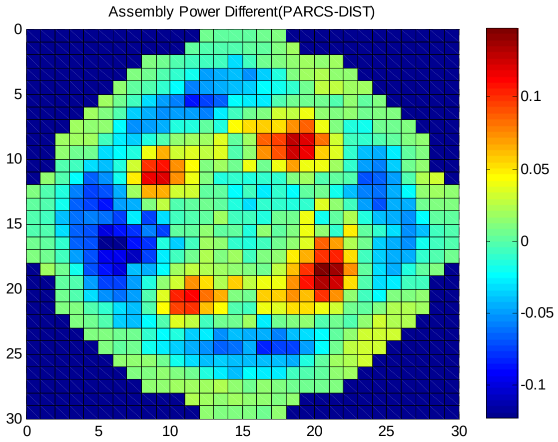


Figure 7-12: Absolute deviation between PARCS and the benchmark results (DIST).

Core flow was also analyzed both axially and radially. Figure 7-13 shows the results of the simulation.

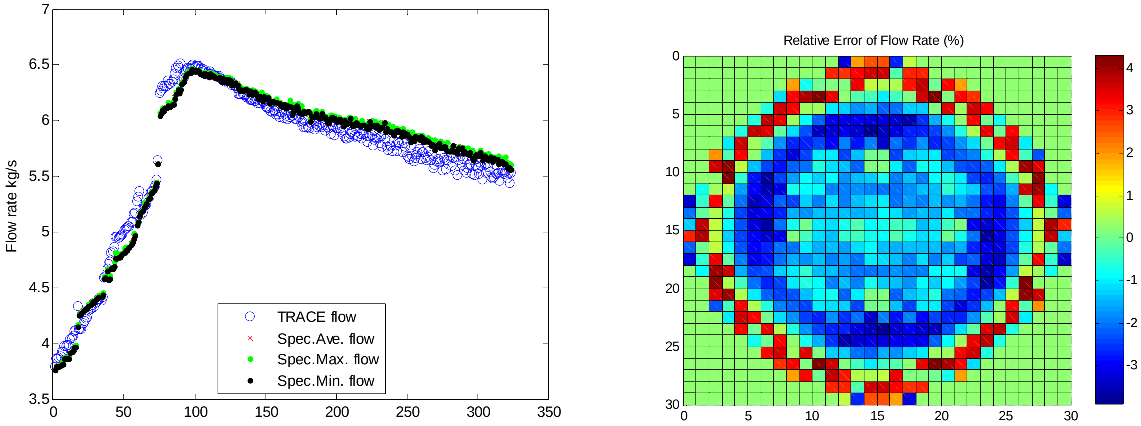


Figure 7-13: Flow rate (kg/s) and Relative Error of Flow (%)

Overall, the steady state results agreed quite well with the limited data given in the benchmark. It was agreed upon through all three parties (US NRC, Penn State, and Michigan) that all simulation results accurately modeled the test points and reached steady-state fully converged.

7.6 Sensitivity Studies

Sensitivity studies were performed on the test points to further validate the TRACE/PARCS model of Ringhals 1 and to verify the results from the benchmark. As previously discussed, the loss coefficients of the spacer grids in the SVEA fuel assembly were changed during the course of this work. The frequency was not affected by the slight changes in the loss coefficients but the flow and decay ratios were changed slightly. The new loss coefficients increased the flow by about 1-2% and decreased the decay ratios by 0.1 to 0.2 making both the flow and decay ratio predictions more accurate.

It was noted that over the course of the work that decay ratio calculations for noise transients were significantly lower than the calculations predicted by pressure pulses and control rod transients. This was due to the selection of time step size in TRACE during the simulation of noise transients. It was discovered that as time-step size increased the results also got closer and closer to the benchmark results. However, if the time-step size was increased too large, TRACE would fail due to a numerical instability. Setting the time-steps as close as possible to the Courant limit helps avoid some of the implicit errors during the semi implicit (SI) calculations performed by TRACE. Performing this study showed that the noise transient calculations performed best when setting the time-step near the Courant limit. Figure 7-14 displays the results of this sensitivity study for Cycle 14 Test Point 10.

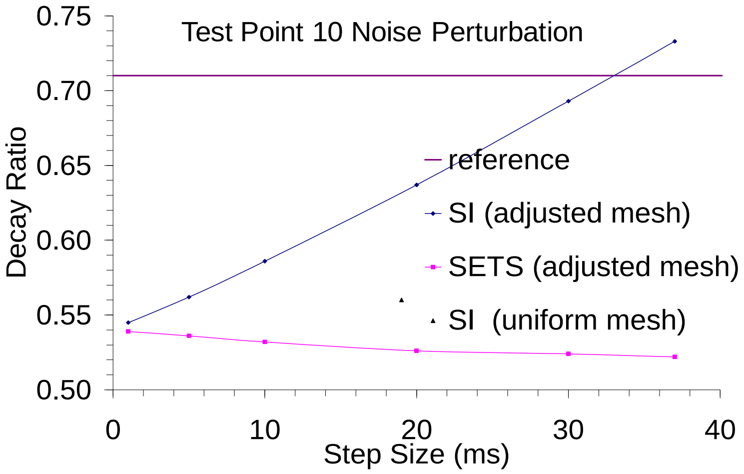


Figure 7-14: Time-step size vs. Decay Ratios for Noise Calculations

Chapter 8

Summary and Conclusions Drawn

A previous model of the Ringhals 1 nuclear reactor was used and modified to perform stability analysis. The types of transients were control rod perturbations, pressure pulses, and noise transients. The TRACE model was then coupled with PARCS in order to perform analyses with a three-dimensional neutron kinetics code.

The three various transients demonstrated that the coupled TRACE/PARCS model of Ringhals 1 is able to predict steady state and transient conditions and agrees quite well with the observed and predicted data in the OECD/NEA Ringhals 1 Stability Benchmark. Decay ratios were, on average, within 7% of the benchmark results and frequencies were within 9% on average. The sensitivity studies showed that the transient response is very sensitive to fuel assembly separator modeling (loss coefficients). This was due to the fact that the separator modeling effects the initial location of the bulk boiling in the core channels.

In observing steady state test points, one of the most important aspects is the prediction of void fraction. This is affected by the modeling of core channels, dryers/separators, recirculation loops, and the abilities of the thermal-hydraulics code TRACE (heat transfer models and sub-cooled boiling models). At low core heights, a small discrepancy was noted in the core axial void distribution and this was attributed to the application of the heat transfer model used in the TRACE code version.

Once the steady state data had been validated, and had converged, three transients were run on the test point. Overall, the pressure pulse transient had the best correlation with the benchmark results for decay ratio and natural frequency. This can be explained by noting that control rod transients result in areas of highly localized power spikes around the rods that were moved. The noise transients performed the worst, and this is believed to be a mathematical limit of TRACE while running in the semi implicit modes at high time steps. When calculating decay ratios and frequencies, the first few peaks of power need to be skipped because they are highly localized and could give skewed results of the overall plant response.

In conclusion, it can be stated with a high degree of confidence that TRACE coupled with PARCS is able to model boiling water reactor steady state conditions and power oscillation transients. This will aid reactor core designers in the future by being able to test their designs against core oscillations and newer, more stringent guidelines set by the U.S. Nuclear Regulatory Commission.

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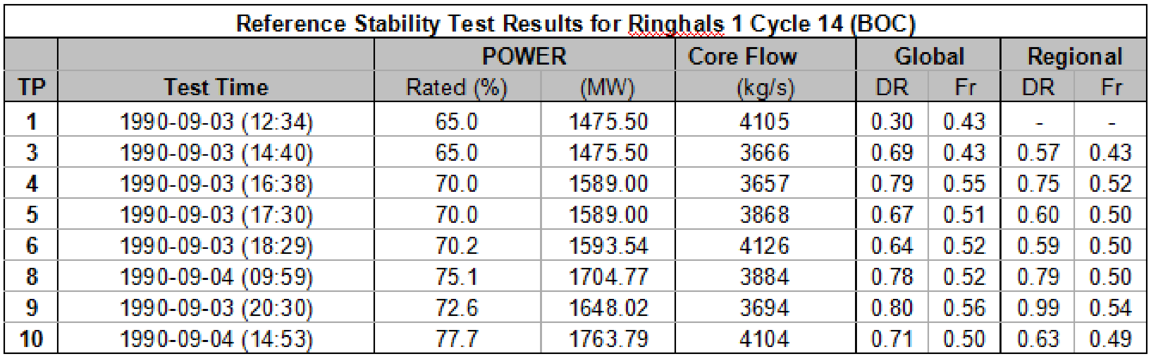
Appendix A

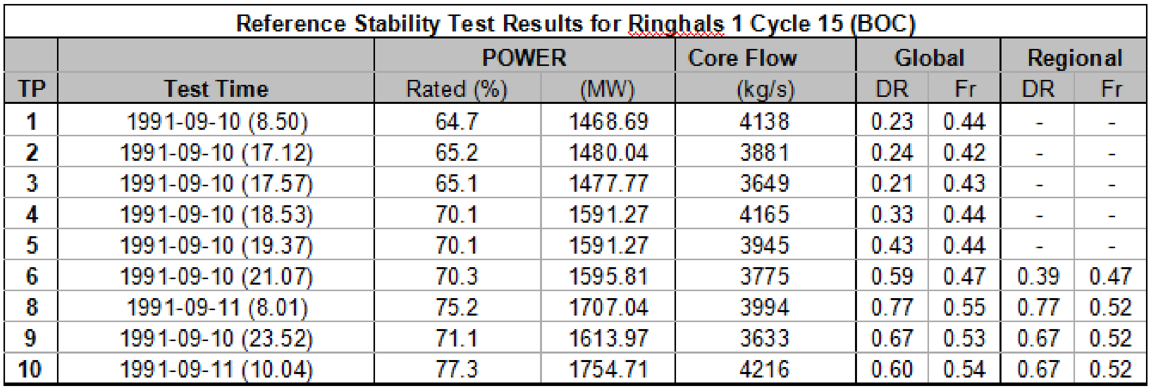
Summary of Benchmark Results

This appendix serves as a quick reference guide of all of the pertinent data and results from the OECD/NEA Benchmark.



Reference Stability Test Results for Ringhals 1 Cycle 14 (BOC)

		POWER		Core Flow	Global		Regional	
TP	**Test Time**	Rated (%)	(MW)	(kg/s)	DR	Fr	DR	Fr
1	1990-09-03 (12:34)	65.0	1475.50	4105	0.30	0.43	-	-
3	1990-09-03 (14:40)	65.0	1475.50	3666	0.69	0.43	0.57	0.43
4	1990-09-03 (16:38)	70.0	1589.00	3657	0.79	0.55	0.75	0.52
5	1990-09-03 (17:30)	70.0	1589.00	3868	0.67	0.51	0.60	0.50
6	1990-09-03 (18:29)	70.2	1593.54	4126	0.64	0.52	0.59	0.50
8	1990-09-04 (09:59)	75.1	1704.77	3884	0.78	0.52	0.79	0.50
9	1990-09-03 (20:30)	72.6	1648.02	3694	0.80	0.56	0.99	0.54
10	1990-09-04 (14:53)	77.7	1763.79	4104	0.71	0.50	0.63	0.49



Reference Stability Test Results for Ringhals 1 Cycle 15 (BOC)

		POWER		Core Flow	Global		Regional	
TP	**Test Time**	Rated (%)	(MW)	(kg/s)	DR	Fr	DR	Fr
1	1991-09-10 (8.50)	64.7	1468.69	4138	0.23	0.44	-	-
2	1991-09-10 (17.12)	65.2	1480.04	3881	0.24	0.42	-	-
3	1991-09-10 (17.57)	65.1	1477.77	3649	0.21	0.43	-	-
4	1991-09-10 (18.53)	70.1	1591.27	4165	0.33	0.44	-	-
5	1991-09-10 (19.37)	70.1	1591.27	3945	0.43	0.44	-	-
6	1991-09-10 (21.07)	70.3	1595.81	3775	0.59	0.47	0.39	0.47
8	1991-09-11 (8.01)	75.2	1707.04	3994	0.77	0.55	0.77	0.52
9	1991-09-10 (23.52)	71.1	1613.97	3633	0.67	0.53	0.67	0.52
10	1991-09-11 (10.04)	77.3	1754.71	4216	0.60	0.54	0.67	0.52

Reference Stability Test Results for Ringhals 1 Cycle 16 (BOC)

		POWER		Core Flow	Global		Regional	
TP	**Test Time**	Rated (%)	(MW)	(kg/s)	DR	Fr	DR	Fr
1	1993-02-11 (16.36)	64.3	1459.61	4112	0.54	0.48	-	-
2	1993-02-11 (17.06)	64.6	1466.42	3925	0.54	0.48	-	-
3	1993-02-11 (17.51)	64.6	1466.42	3698	0.69	0.47	0.55	0.45
4	1993-02-11 (18.25)	70.2	1593.54	4165	0.71	0.52	-	-
5	1993-02-11 (21.33)	69.9	1586.73	3932	0.67	0.49	0.51	0.49
6	1993-02-11 (22.39)	69.5	1577.65	3673	0.79	0.49	0.74	0.48
7	1993-02-12 (0.04)	74.4	1688.88	4081	0.72	0.50	0.50	0.49
8	1993-02-12 (3.20)	74.9	1700.23	3907	0.82	0.49	0.66	0.49
9	1993-02-12 (5.03)	74.6	1693.42	3678	0.87	0.48	0.82	0.47
10	1993-02-12 (6.01)	76.0	1725.20	4217	0.65	0.50	0.64	0.51
11	1993-02-27 (4.56)	66.1	1500.47	3653	0.66	0.48	0.55	0.45

Reference Stability Test Results for Ringhals 1 Cycle 17 (BOC)

		POWER		Core Flow	Global		Regional	
TP	**Test Time**	Rated (%)	(MW)	(kg/s)	DR	Fr	DR	Fr
2	1993-11-17 07.56	65.6	1489.12	3954	0.24	0.46	-	-
3	1993-11-17 08.37	65.6	1489.12	3680	0.22	0.44	-	-
4	1993-11-17 09.36	69.5	1577.65	4166	0.32	0.46	-	-
5	1993-11-17 10.30	69.9	1586.73	4015	0.28	0.42	-	-
6	1993-11-17 11.08	69.7	1582.19	3758	0.34	0.46	-	-
7	1993-11-17 13.15	74.9	1700.23	4140	0.33	0.46	-	-
8	1993-11-17 13.41	75.1	1704.77	4020	0.41	0.48	-	-
9	1993-11-17 14.31	75.4	1711.58	3739	0.57	0.47	0.43	0.49
10	1993-11-17 15.14	78.1	1772.87	4058	0.49	0.49	-	-

Appendix B

Sample PARCS Input File

The following is a sample PARCS input file for a steady state simulation on test point 09 of cycle 14. Items prefaced with a “!” are commented (not part of the code).

```
!______________________________________________________________________________
!
!                        Input deck for Ringhals 1 C14                         |
!
CASEID  C14P09_325Vn_co
!                                                                              |
!______________________________________________________________________________


!______________________________________________________________________________
!                                                                              |
!                        CONTROL CARD                                          |
CNTL                                    ! control card
      CORE_TYPE    BWR                  ! core type, PWR or BWR
      CORE_POWER    72.6                ! initial relative power, % point  9
      BANK_POS     0. 4. 11. 19. 50. 86. 88. 94. 94. 100. 100. 100. 100. 50.0
!     bank positions, 100 fully withdrawn, 0 fully in (caveat: in entree: 100 =
!                                                      fully in)
      PPM          0.0                  ! boron ppm
      DEPLETION    T  1.0e-2
      TREE_XS      T  28 T T F F F F T F T F F T T F
!                        a,x,j,e,p,d,v,t,y,c,g,b,l,h
      XS_EXTRAP   10.0 0.5  1.0
      ROT_ADF      T
      XE_SM        3   0              ! Xe, Sm options 0=no Xe/Sm, 1=Eq, 2=tr
      TH_FDBK      T                  ! True or False
      EXT_TH       T '../parcs/maptab_325' TRAC 1 1 -1.0e+4 ! T or F
      RESTART      F C14P09_325Vn_co.rst 0
      TRANSIENT    F
!     PRINT OPTIONS
!                    input  iteration     planar                   adj
!                     edit      table      power        pin       reac
      print_opt          F          T          T          F          F
!                     fdbk       flux     planar
!                      rho    precurs       flux         Xe        T/H
      print_opt          F          F          F          F          T
!                     oneD       PKRE     Radial P   Radial Flx   harmonic
!                    const       Data     Shape       Shape       flux
      print_opt          F          F          F          F          F
!
!                        END of CONTROL CARD                                   |
!______________________________________________________________________________
!______________________________________________________________________________
!                                                                              |
!                        PARAM CARD                                            |
PARAM
! Basic Iteration Control Parameters
      n_iters    2      1500                  ! min, max
! Convergence Criteria
```

```
      conv_ss    1.0e-6  1.e-5  5.e-4  0.001 ! keff, globfis, locfis, tfuel
! Wielandt Shift Control
     wielandt   0.04   0.2    1.0    ! shift, intishit, keff goal
! Nonlinear Update Control
!   nodal_kern FDM                   ! kernel method FDM, HYBRID, ANM
   nodal_kern hybrid                 ! kernel method FDM, HYBRID, ANM
      nlupd_ss   2 2 1               ! nonlin updte: nupdcy, ninitout, nthpnod
      eps_anm    0.005                       ! anm stabilization criteria
      eps_erf    0.005                       ! cv for inners exit
! Decusping
      decusp     0                          ! rod: 0=no, 1=flux, 2=ax discont
      init_guess 0                          ! 0=cos, 1=flat
!
!                        END of PARAM CARD                                     |
!______________________________________________________________________________|
!______________________________________________________________________________
!                                                                              |
!                        GEOM CARD                                             |
GEOM
       file       '../parcs/ring_dep.geom'
!                                                                              |
!                        END of GEOM CARD                                      |
!______________________________________________________________________________|
!______________________________________________________________________________
!                                                                              |
!                        TH CARD                                               |
!
TH
!    UNIF_TH 0.786 261.85 261.85  !uniform TH state Dm,Tf,Tm, used when no fdbk
     FA_POWPIT  3.503  15.275     !assembly power(Mw) and pitch(cm)
     CDC_DED    0 1
     gamma_frac 0.02  0.02                !direct heating fraction
!                        END of TH CARD                                        |
!______________________________________________________________________________
!                                                                              |
!                        DEPL CARD                                             |
DEPL
  INP_HST '../parcs/PT09.sim' 2  1  !input history file name and type     !point 9
  HST_OPT   T  T  F  F  F     !HCR HMD HSB HTF HTM
  INP_OPT   F  F  F  T        !PPM,CRP,THS,XESM
  OUT_OPT   T  T  T  T  F     !POW,HST,THS,XESM, XS
!           1  2   3   4   1   6   7   8   9   10  11   12 13  14
  BANK_NR   2  2   2   2   2   4   4   4   4    4   4  116  7   1
!        Index     PMAXS File Name      Branch_structure
 PMAXS_F  1  '../../Ringhals-PMAXS/SEG01.PMAX'  1  !/ SVEA 9X9 63pin
 PMAXS_F  2  '../../Ringhals-PMAXS/SEG02.PMAX'  1  !/ SVEA 9X9 63pin
 PMAXS_F  3  '../../Ringhals-PMAXS/SEG03.PMAX'  1  !/ SVEA 9X9 63pin
 PMAXS_F  4  '../../Ringhals-PMAXS/SEG04.PMAX'  1  !/ 8X8      63pin
 PMAXS_F  5  '../../Ringhals-PMAXS/SEG05.PMAX'  1  !/ 8X8      63pin
 PMAXS_F  6  '../../Ringhals-PMAXS/SEG06.PMAX'  1  !/ 8X8      63pin
 PMAXS_F  7  '../../Ringhals-PMAXS/SEG07.PMAX'  1  !/ SVEA 9X9 63pin
 PMAXS_F  8  '../../Ringhals-PMAXS/SEG08.PMAX'  1  !/ SVEA 9X9 63pin
 PMAXS_F  9  '../../Ringhals-PMAXS/SEG09.PMAX'  2  !/ SVEA 9X9 64pin
 PMAXS_F 10  '../../Ringhals-PMAXS/SEG10.PMAX'  2  !/ SVEA 9X9 64pin
 PMAXS_F 11  '../../Ringhals-PMAXS/SEG11.PMAX'  2  !/ SVEA 9X9 64pin
 PMAXS_F 12  '../../Ringhals-PMAXS/SEG12.PMAX'  2  !/ SVEA 9X9 64pin
 PMAXS_F 13  '../../Ringhals-PMAXS/SEG13.PMAX'  2  !/ SVEA 9X9 64pin
 PMAXS_F 14  '../../Ringhals-PMAXS/SEG14.PMAX'  2  !/ SVEA 9X9 64pin
 PMAXS_F 15  '../../Ringhals-PMAXS/SEG15.PMAX'  2  !/ SVEA 9X9 64pin
 PMAXS_F 16  '../../Ringhals-PMAXS/SEG16.PMAX'  2  !/ SVEA 9X9 64pin
 PMAXS_F 17  '../../Ringhals-PMAXS/SEG17.PMAX'  2  !/ SVEA 9X9 64pin
 PMAXS_F 18  '../../Ringhals-PMAXS/SEG18.PMAX'  2  !/ SVEA 9X9 64pin
 PMAXS_F 19  '../../Ringhals-PMAXS/SEG19.PMAX'  2  !/ SVEA 9X9 64pin
 PMAXS_F 20  '../../Ringhals-PMAXS/SEG20.PMAX'  2  !/ SVEA 9X9 64pin
 PMAXS_F 21  '../../Ringhals-PMAXS/SEG21.PMAX'  2  !/ SVEA 9X9 64pin
 PMAXS_F 22  '../../Ringhals-PMAXS/SEG22.PMAX'  2  !/ SVEA 9X9 64pin
 PMAXS_F 23  '../../Ringhals-PMAXS/SEG23.PMAX'  3  !/ 8X8      63pin
 PMAXS_F 24  '../../Ringhals-PMAXS/SEG24.PMAX'  3  !/ 8X8      63pin
 PMAXS_F 25  '../../Ringhals-PMAXS/SEG25.PMAX'  3  !/ 8X8      63pin
```

```
 PMAXS_F 26  '../../Ringhals-PMAXS/REFLR.PMAX'  4  ! / Radial Reflector
 PMAXS_F 27  '../../Ringhals-PMAXS/REFLB.PMAX'  4  !/ Axial  Bottom Reflector
 PMAXS_F 28  '../../Ringhals-PMAXS/REFLT.PMAX'  4  !/ Axial  Top Reflector
!                                                                              |
!                        END of DEPL CARD                                      |
!______________________________________________________________________________
```