DEVELOPMENT OF MODEL OF OSKARSHAMN-2 REACTOR FOR ASSESSMENT OF TRACE/PARCS FOR BOILING WATER REACTOR STABILITY ANALYSIS

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ABSTRACT

Computer simulation of the behavior of nuclear reactors is an important part of their design, regulation, and operation. A phenomenon that is the subject of ongoing study with computer simulation is the stability of boiling water reactors, which can undergo events in which the power level oscillates, including some occasions in which the oscillations can grow, forcing a scram.

TRACE is a thermal-hydraulics code developed by the U.S. Nuclear Regulatory Commission. PARCS is a reactor neutronics code developed at Purdue University. A combination of the two codes is currently being validated for boiling water reactor stability. Earlier work has been done with the Ringhals I benchmark.

Currently, a model is being developed to validate TRACE/PARCS for an instability event that occurred in Sweden’s Oskarshamn II reactor. Several sensitivity analyses were conducted, testing the dependence of the key stability parameters on nodalization, time step size, and other aspects of the model. Several important dependencies are shown, and suggestions are made for future sensitivity studies and improvement of the model.
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1 INTRODUCTION

Stability is an important issue for Boiling Water Reactors (BWRs) that has become of greater interest in the last two decades or so. A number of incidents have brought attention to the issue, including the first widely reported out of phase oscillation at the Caorso plant in 1984 [1]. After additional events at the TVO-1 plant in 1987 and, most famously, LaSalle-2 in 1988, reviews of stability have been required as part of the regulatory process for BWRs [2].

There are three main phenomena [1] that can cause instability in BWRs:

1. Control system instability, in which a control system exhibits oscillatory behavior. It can be mitigated by adjusting gains.

2. Channel density wave oscillations, which are caused when perturbations in the inlet flow oscillate out of phase with the pressure drop. This happens because the density waves in the two-phase mixture, created by variations in the inlet flow, propagate toward the channel outlet at the finite velocity of the fluid. If the pressure drop at the outlet is high compared to the inlet, and the density waves are near 180 degrees out of phase at the inlet and outlet, the pressure drop will oscillate in such a way that it causes increasing variations in the inlet flow.

3. Coupled neutronic – thermal-hydraulic instability, or reactivity instability, which dominates and will be the subject of this thesis. It involves oscillations in the local or global power level, coupled to oscillations in the coolant void fraction through reactivity feedback. A rising power level causes an increase in boiling, which increases the void fraction. This causes a reduction in power through loss of moderation, leading to less boiling and a lower void fraction, increasing the power and leading the cycle to repeat.

This third type is the most important stability phenomenon in BWRs. It can occur both in an in-phase mode, in which the entire core power oscillates together in unison, or it can be out-of-phase, in which the power in different parts of the core oscillate out of phase with each other. Combinations of the two may also occur. The out of phase oscillations are more challenging to detect, because they may not change the core average power.

Stability is not considered a safety issue because it has been demonstrated that oscillations can be detected and suppressed [2]. However, during such incidents were the oscillations increase rather than decrease, a scram may be necessary in order to prevent the thermal safety limits of the fuel from being exceeded. In order to prevent such incidents from beginning, operators try to keep the operating conditions outside an “exclusion zone” in which BWR instabilities have been known to occur. This zone consists of the range of conditions in which the core flow rate is low relative to the power.

Part of the reason that stability has become more of an issue in the last two decades is because of the appearance of new fuel designs. There are two primary ways in which newer fuels can increase the susceptibility of BWRs to instability:
1. They tend to allow larger power peaking factors, permitting more uneven power shapes which are more prone to instability, especially of the local, out-of-phase variety.

2. They contain larger numbers of rods, such as in a nine by nine or ten by ten array, instead of the traditional eight by eight. The rods are smaller, and have thinner cladding. This means that speed at which heat is transferred to the coolant is greater, and thus that the time period for reactivity feedback to occur is shorter.

There is a wide variety of variables that have an influence on the susceptibility of BWRs to instability, including the power and its distribution, the flow rate, inlet subcooling, void distribution, control rod positions, burnup, and flow resistance. Not all of their roles are completely understood, so stability is the subject of continuing study.

According to State of the Art Reporting on Boiling Water Reactor Stability [2], the use of system codes to study BWR stability is recommended, and it is observed that although they have been successful at reproducing instability events, their predictive ability has not yet been fully assessed.

In order to produce data for understanding the phenomenology and for comparison to simulation results, several instability tests have been conducted in plants including Caorso, LaSalle, Forsmark 1 and 2, Oskarshamm 3, and Ringhals 1 [3]. Benchmarks have been established by the OECD’s Nuclear Energy Agency (NEA) for experimental results from Ringhals 1 [4], and for Formark 1 and 2 [3], all located in Sweden.

The Ringhals benchmark, completed in 1996, includes stability tests from 41 operating conditions from four different cycles, and was developed in order to provide a comprehensive set of data that could be used for validating the predictive ability of codes and models for stability analysis. It includes Axial Power Range Monitor (APRM) and Local Power Range Monitor (LPRM) data, coolant flow rates, and values for the two main stability parameters – the decay ratio and natural frequency of the oscillations. The decay ratio can be defined in several ways, but the simplest is that it is the ratio of the amplitude of an oscillation to the amplitude of the previous oscillation. This means that the decay ratio must be less than 1 in order for the oscillations to decrease.

Both time domain codes, such as RELAP5 and RAMONA, and frequency domain codes, such as LAPUR, were used by the participants in the Ringhals benchmark. Frequency domain codes are based on the linearization and Laplace transform of the governing equations [2].

The Forsmark benchmark, completed in 2001, uses only on time domain codes, and aimed at developing noise analysis techniques in order to analyze time series data. It considered such phenomena as variation in the decay ratio and frequency over time, the occurrence of out of phase oscillations, and the simultaneous combination of oscillations with different frequencies. In particular, it discusses the development of algorithms to detect oscillations from the LPRM measurements, so that they can be safely suppressed.

TRACE and PARCS are two codes which have been coupled and applied to stability analysis. TRACE simulates the thermal hydraulics of a plant, while PARCS covers the neutronic
behavior. Both will be described below in chapter 2. Previous work has been done \([5]\) in collaborative efforts between The Pennsylvania State University, Purdue University, and the U.S. Nuclear Regulator Commission (NRC), for the validation of TRACE/PARCS using the Ringhals benchmark. The results showed good agreement between predicted and measured values for the decay ratio and frequency.

The topic of this thesis is the continued work on the validation of TRACE/PARCS using an instability event at the Swedish Oskarshamn 2 reactor, which will be described in chapter 3. The objective of the project is to evaluate the ability of TRACE/PARCS to predict the growing oscillations that occurred under low flow conditions with high inlet subcooling.

A model of Oskarshamn 2 is being developed to simulate this event. In addition to the modelling of the event itself, the model must be validated for two sets of stability tests, which were performed before and after the event. For such stability tests, the reactor power is perturbed, leading to oscillations, which are measured to find the frequency and decay ratio – the ratio of the amplitudes of two successive peaks. The simulation of these tests will be the primary topic discussed in the results and conclusions chapters, (Chapters 6 and 7).
2 OVERVIEW OF CODES

A coupling between the thermal hydraulics system code TRACE and spatial kinetics code PARCS was used to perform the analysis. The following versions were used:

- TRACE Version 5.310
- PARCS Version 3.00

2.1 TRACE

TRACE (TRAC-RELAP Advanced Computational Engine), is a best-estimate code used for analysis of accidents and operational transients in light water reactors (LWR’s), for the purposes of design, licensing, and operation. Formerly known as TRAC-M, it was developed to consolidate the abilities of the Nuclear Regulatory Commission’s four main system codes: TRAC-P, TRAC-B, RELAP5, and RAMONA.

2.1.1 Models

TRACE is capable of modeling one or three-dimensional flow in relatively complex networks. It uses a two fluid, six equation, finite volume model, with mass, momentum, and energy equations for both liquid and gas phases. If more than one type of gas is present, they are treated as a single fluid in thermal and velocity equilibrium.

The rates of transfer of mass, momentum, and energy between phases, the wall friction, and the heat transfer from solid heat structures depends on the specific flow regime. Because of this, the constitutive equations are determined by the flow regime, which is in turn determined from the flow conditions.

Two-dimensional heat transfer in solid components is available with heatstructure (HTSTR) components. Each can be connected to one or two surfaces, and can have power deposited in them, such as in the case of the fuel rods. Power can also be directly deposited into the fluid, such from radiation heating. Additionally, radiation enclosure (RADENC) components may be used to model radiation heat transfer between surfaces.

Other components available for creating TRACE models include PIPEs, PLENUMs, pressurizers (PRIZER), BWR fuel channels (CHAN), PUMPs, jet pumps (JETP), separators (SEPD), TEEs, turbines (TURB), feedwater heaters (HEATR), containment (CONTAN), VALVEs, VESSELs, FILLs, BREAKs, and EXTERIORs. VESSELs can represent any three-dimensional region, in Cartesian or cylindrical coordinates. FILLs represent flow boundary conditions, while BREAKs represent pressure boundary conditions. EXTERIORs are used for developing models that can use parallel execution.

The physical phenomena that are considered include the following:

1) ECC downcomer penetration and bypass, including the effects of countercurrent flow and hot walls;
2) lower-plenum refill with entrainment and phase-separation effects;
3) bottom-reflood and falling-film quench fronts;
4) multidimensional flow patterns in the reactor-core and plenum regions;
5) pool formation and countercurrent flow at the upper-core support plate region;
6) pool formation in the upper plenum;
7) steam binding;
8) water level tracking;
9) average-rod and hot-rod cladding-temperature histories;
10) alternate ECC injection systems, including hot-leg and upper-head injection;
11) direct injection of subcooled ECC water, without artificial mixing zones;
12) critical flow (choking);
13) liquid carryover during reflood;
14) metal-water reaction;
15) water-hammer pack and stretch effects;
16) wall friction losses;
17) horizontally stratified flow, including reflux cooling,
18) gas or liquid separator modeling;
19) noncondensable-gas effects on evaporation and condensation;
20) dissolved-solute tracking in liquid flow;
21) reactivity-feedback effects on reactor-core power kinetics;
22) two-phase bottom, side, and top offtake flow of a tee side channel; and reversible and irreversible form-loss flow effects on the pressure distribution

2.1.2 Solution methods

By default, TRACE advances time using a multistep method called the stability-enhancing two step (SETS) method. The increased stability offered by this method allows the use of larger time steps, exceeding the material Courant limit, for slow transients. A semi-implicit method is also available. The system of non-linear equations is solved by the Newton-Raphson iteration method, resulting in a linear equation system which is solved by direct matrix inversion.

2.1.3 Limitations

Although it is highly versatile, TRACE does not have the ability to resolve thermal stratification in its one-dimensional components, nor does it explicitly model stress/strain effects caused by temperature gradients. Furthermore, it assumes uniform velocities at all junctions, and cannot be used to resolve local momentum effects with any nodalization.

By itself, TRACE cannot be used for core transients with changing asymmetries, such as control rod ejection, because it is only capable of point kinetics. In order to reactivity feedback in which three-dimensional effects are important, it is necessary to couple TRACE with a spatial kinetics code such as PARCS.

2.2 PARCS

PARCS (Purdue Advanced Reactor Core Simulator) is a reactor simulation code which solves the three dimensional (3D) neutron diffusion and low-order transport equations under steady state and transient conditions. It is typically distributed with TRACE, with which it is directly
coupled in order to provide the coolant flow characteristics. It was developed at Purdue University, and the release of the first NRC version occurred in November, 1998. Since then, numerous changes have been made, and it has been converted into FORTRAN 90.

2.2.1 Calculation features

PARCS is capable of making a variety of types of calculations, using several separate modules.

Eigenvalue calculation

For steady-state, or for quasi-steady-state depletion calculations, the following equation, giving the neutron balance for energy group $g$ in node $m$, is solved in order to find the flux distribution and effective multiplication factor $k_{eff}$:

\[
\frac{1}{\psi_g^m} \frac{d\psi_g^m}{dt} = \frac{1}{k_{eff}} \lambda_k \sum_{g=1}^{G} \chi_{pg} \sum_{j=1}^{m} \phi_j^m + \lambda_d \sum_{g=1}^{K} C_k^m \sum_{g, j=1}^{m} \phi_j^m - \sum_{u=x,y,z} h_u^n (J_{gu}^{m+} - J_{gu}^{m-})
\]

(2.1)

in which $G$ is the number of energy groups, $K$ is the number of delayed neutron precursors, $p$ and $d$ represent prompt and delayed neutrons respectively, $\bar{\phi}_g^m$ is the node average flux, $\bar{J}_{gu}^m$ is the surface current in the $u$ direction, and $C_k^m$ is the precursor density, governed by:

\[
\frac{dC_k^m}{dt} = \frac{1}{k_{eff}} \sum_{g=1}^{G} \chi_{dg} \sum_{j=1}^{m} \phi_j^m - \lambda_k C_k^m
\]

(2.2)

The neutron source is given by:

\[
M \phi^{n+1} = s^n \equiv \frac{1}{k_{eff}} F \phi^n
\]

(2.3)

The source is found iteratively, and the convergence is accelerated by using the Wielandt eigenvalue shift method. This was done instead of the common Chebyshev polynomial method because the Krylov solver used for the fixed source problem can only accept minor changes to the eigenvalue calculation.

Transient calculation

During transient calculations, PARCS solved a fixed source problem at each time step to find the cell average fluxes. A Coarse Mesh Finite Difference (CMFD) solver is used, with a nodal
update whenever a significant change in the cross sections occurs. The temporal differencing is based on an exponential transform and the theta method.

**Xenon/Samarium**

The concentrations of Xenon and Samarium vary slowly during a transient. Thus, they are updated based on a quasistatic method which neglects the time dependent variation of delayed neutrons and uses the fluxes from the eigenvalue calculation.

**Decay heat**

The decay heat is modeled by six groups of decay heat precursors, with concentrations calculated for each node. They are handled in a manner similar to delayed neutron precursors.

**Pin Power**

For cases such as Departure from Nucleate Boiling (DNB), the power of each pin within a node can be calculated. This is done with an algorithm that assumes that the pin powers can be determined by multiplying the homogeneous nodal flux distribution by the heterogeneous power form function provided by the lattice physics code. Corner Discontinuity Factors (CDFs) can be used to enhance the accuracy.

**Adjoint calculation**

The adjoint solution is obtained in order to the dynamic reactivity during transient calculations, defined as:

\[
\rho = \frac{\langle \phi_0^*, A\phi \rangle}{\langle \phi_0^*, F\phi \rangle}
\]

(2.4)

where \( \phi_0^* \) is the adjoint flux, \( F \) is the fission source operator, and \( A \) is the net production operator.

**2.2.2 Modeling features**

In the formation of a numerical model that can be solved by a computer, the important issues can be divided into geometry, cross section representation, and thermal hydraulic feedback.

**Geometric representation**

The geometry is represented as a set of homogeneous nodes, typically with the width of a single assembly and a length of 15 to 30 cm. However, it is also possible to use four radial nodes per assembly, or represent the heterogeneous assembly pin-by-pin.
For the boundary conditions, it is possible to use zero current, zero flux, or zero incoming current.

**Cross sections**

The cross section for given conditions within a fuel assembly is formed by interpolation between states stored in the PMAXS (Purdue Macroscopic Cross Section) files which are required by PARCS and produced by the separate code GENPMA XS. They are represented as a linear function of boron concentration, the square root of the fuel temperature, the moderator temperature, and the effective rod fraction. However, they are quadratically related to the moderator density and void fraction. The cross sections are thus given by:

\[
\Sigma(B, T_f, T_m, D_m, \alpha, \xi) = \Sigma_0 + a_1(B - B_0) + a_2\left(\sqrt{T_f} - \sqrt{T_{f0}}\right) + a_3(T_m - T_{m0})
\]

\[
+ a_4(D_m - D_{m0}) + a_5\left(D_m - D_{m0}\right)^2 + a_6\alpha + a_7\alpha^2 + \xi\Delta\Sigma_{CR}
\]

(2.5)

The effective rod fraction for a partially rod driven node is defined as the product of the actual rod fraction and the flux depression factor calculated by the decusping routine.

**Thermal hydraulic feedback**

Thermal hydraulic feedback can be obtained either from TRACE or RELAP5, another NRC system code. The coupling to TRACE is direct, whereas coupling to RELAP5 is accomplished through PVM, an inter-process communication protocol. The two processes are run in parallel, with PARCS sending the power to the thermal hydraulics code, and the thermal hydraulics code sending the fuel temperature, moderator temperature, and moderator density to PARCS.

The correspondence between neutronic assemblies and thermal hydraulic components is given by a special file called “maptab.” Automatic mapping is used for individual nodes, and the nodalization in the thermal hydraulic and neutronic models need not be the same.

Time steps for the thermal hydraulic calculation may at times need to be much smaller than is necessary for the neutronics. At such times, a skip factor may be used so that several thermal hydraulic time steps may occur between updates in the neutronic state.

**1D kinetics**

For axially dominated problems with little variation in the radial distribution, a variety of 1D kinetics options are available. The first is normal 1D kinetics, which is obtained from from radially averaging a given 3D steady state. The second is TRAC-B 1D kinetics, which takes the kinetics parameters from a TRAC-B input deck. The third is quasi-static 1D kinetics, which requires a 3D model as input, and collapses the cross sections into 1D.
Core depletion

The core depletion over time can be obtained from a series of quasi-steady-state calculations, updating the burnup and consequently the cross sections at each time step.

2.2.3 Input/output features

Cardname based input

In order to minimize total input requirements, enable flexibility, and make error detection easier, a card-name based input system was used. It only requires input for a parameter in the case of a non-default value. The input is divided into several blocks, and these blocks can be located in different files for convenience. Cards may be continued onto the next line, and comments or blank lines can be placed anywhere.

Output files

The primary output file echoes the input file as soon as it is read, and gives detailed results of the simulation in easily understandable form. A summary file is also produced which gives the most important output in a compact form.

The following is a list of all of the output files generated by PARCS, with the extensions in parentheses:

- Primary output (out)
- Summary output (sum)
- Pin power output (pin)
- Restart (rst)
- Global parameter plot data (plt)
- Radial power/flux shape (shp)
- Feedback component reactivity (rho)
- XMGR plot window (ace)
- Point kinetics data (pkd)
- 1D collapsed group constants (1dx)
- Debug output (dbg)
- Thermal-hydraulic feedback variables (fbv)

Graphical interface

The NRC’s SNAP application has a plugin which may be used for developing and editing PARCS input files in a graphical environment.

On-line graphics are available through SNAP. Using this feature, it is possible to view plots of variables verses time, or axial or radial distribution plots.
2.2.4 Methods

Nonlinear CMFD method

Spatial discretization is accomplished by a Coarse Mesh Finite Difference (CMFD) method in which the balance of the neutron flux in each node is coupled to its neighbors through leakage. For each node $m$, the currents in the $u$ direction for energy group $g$ are given by:

$$J_{gu}^{m_+} = \mp \tilde{D}_{gu}^{m_\pm} \left( \phi_g^{m_\pm l} - \phi_g^m \right) - \hat{D}_{gu}^{m_\pm} \left( \phi_g^{m_\pm l} - \phi_g^m \right)$$

where \( \tilde{D}_{gu}^{m_\pm} \) is the base nodal coupling coefficient obtained directly from the diffusion coefficients in each node by:

$$\tilde{D}_{gu}^{m_\pm} = \frac{2D_{gu}^{m_\pm l}}{D_{gu}^{m_\pm l} + \Delta u_m + D_g^m \Delta u_{m\pm l}}$$

In the second term on the right side of (2.6), \( \hat{D}_{gu}^{m_\pm} \) is the Corrective Nodal Coupling Coefficient (CNCC), a correction factor obtained from a higher order nodal calculation performed when the flux distribution changes significantly in a fixed source problem, or with a specified frequency in an eigenvalue problem. This will be discussed in the next section.

To solve the CMFD problem, a Krylov subspace method, BiCGSTAB (Bi-Conjugate Gradient Stabilized) is used. This is accompanied by a BILU3D (Blockwise Incomplete Lower/Upper – 3D) preconditioner, which transforms the system of linear equations into a different one which will be more efficiently solved by the BiCGSTAB solver, thus speeding convergence.

Nodal method

Two nodal methods, the Analytic Nodal Method (ANM) and the Nodal Expansion Method (NEM) are available to determine the CNCC \( \hat{D}_{gu}^{m_\pm} \) in (2.6). These solve a two-node problem at each interface, using the node average fluxes from the CMFD calculation to find a higher order approximation of the interface current.

ANM tends to be more accurate and is the preferred method. However, it tends to be unstable when the net leakage of a cell becomes close to zero (the critical node problem), leading to a near-singular matrix. Because of this, the default in PARCS is to use a hybrid method which defaults to ANM, but switches to NEM for near critical nodes.
**Pin power reconstruction**

Pin power reconstruction is accomplished based on the assumption that the pin powers can be given by the product of two separable functions – the local power form function from a lattice physics code, and the homogenized nodal power at the pins location. The first is the ratio of a pin’s power to the average pin power in an assembly. This takes into account variations in the power due to heterogeneity in the assembly, and the non-separable variation of the flux in three dimensions.

The nodal component of the pin power distribution assumes that the radial and axial variation of the power are separable. In the radial direction, eight boundary conditions are applied: the surface average current on each interface, and the flux at each corner. The Corner Discontinuity Factor (CDF), a ratio of the corner flux to average homogenized flux from the lattice physics code, is used in calculating the corner fluxes. From the 8 boundary conditions, the flux is determined analytically using the Method of Successive Smoothing (MSS).

**Control rod cusping correction**

When a control rod is partially inserted into a node, there is a flux depression in the vicinity of the rodded portion. If this is not taken into account, there will be a wavy or “cusp” shape to the variation in $k_{eff}$ as the rod is inserted.

To find the “effective” rodded fraction of the cell, a decusping routine is used which solves a three node problem, involving the partially rodded node and the fully rodded and non rodded nodes below and above. A Fine Mesh Finite Difference (FMFD) method is used to resolve the flux distribution in the vicinity of the control rod, in a manner that is consistent with the average fluxes in the coarse mesh.

**1D nodal kinetics**

The spatial discretization of 1D kinetics is based on ANM, with temporal differencing based on the theta method. A Current Correction Factor (CCF) is used which guarantees the same axial currents as in the fully 3D problem.

The 1D nodal kinetics is capable of using feedback from multiple coolant channels, with weighting factor given for each channel. Additionally, multiple control rod banks can be used.

**Hexagonal geometry**

For hexagonal geometry, such as that found in VVER reactors, the same CMFD formulation is used as for Cartesian geometry. However, the nodal calculation is done using the Triangular Polynomial Expansion Nodal (TPEN) method, which divides the hexagon into six triangles, and expands the flux using a two dimensional third order polynomial.

The same BiCGSTAB solver is used as for Cartesian geometry. However, a simplified diagonal preconditioner is used in place of BILU3D, in order to better handle the many types of symmetries that may occur.
**Fine mesh finite difference**

It is possible to use a Fine Mesh Finite Difference (FMFD) discretization which explicitly represents each fuel pin. This requires pin-by-pin composition maps for each fuel type. FMFD is available with both diffusion and SP3 transport.

**SP3 transport**

In some circumstances, such as when MOX fuel is present, there are strong variations in the angular distribution of flux that are not accounted for by diffusion. Because of this, a Simplified P3 (SP3) transport method was implemented in PARCS. The SP3 equations are obtained from the normal P3 equations by eliminating the odd order angular moments, resulting in a set of diffusion-like equations.

**Temporal differencing**

The theta method is used for temporal differencing, in which the change in flux in group $g$ in node $m$ from steps $n-1$ to $n$ is given by:

$$\frac{\phi_{g}^{m,n} - \phi_{g}^{m,n-1}}{v_{g}^{m} \Delta t_{n}} = \theta R_{g}^{m,n} + (1 - \theta) R_{g}^{m,n-1} \tag{2.8}$$

where $0 < \theta \leq 1$. This can be used with the well known Crank-Nicholsen method with $\theta = 0.5$, which is second order accurate. However, further accuracy can be gained from an exponential transform, in which the flux can be factored as:

$$\phi_{g}^{m} = \exp \left( \alpha_{g}^{m} t \right) \tilde{\phi}_{g}^{m} \tag{2.9}$$

in which the phi-tilde is the slowly varying part of the flux, and the exponential term represents faster variations.

**Control rod scram logic**

It is possible to set a logical condition for the execution of a scram. This entails setting a high flux trip, as well as time delays, rod insertion rates, and stuck rods.

**Restart capability**

Condition data may be written to a restart file with a specified frequency. Any of these states may then be used as the starting point for a future calculation.
Neutronic – thermal-hydraulic mapping

The thermal hydraulic calculation will generally have fewer cells than the neutronic model. However, a neutronic node may occupy the space of more than one thermal hydraulic node, so the feedback parameters are given by:

$$T_i^p = \sum_{k=1}^{N_p} \alpha_{i,j(k)}^p T_{j(k)}^T$$  \hspace{1cm} (2.10)

where the $T$'s are the thermal hydraulic parameters and the $\alpha$'s are the fractions of the neutronic cell overlapping with each thermal hydraulic cell. A similar formula is used for the conversion of PARCS nodal powers into powers deposited in the thermal hydraulic model.

Only the correspondence between thermal hydraulic channels and PARCS assemblies is required as input. The axial mapping is performed automatically. The distributions of each parameter are approximated by linear interpolation, in which the conditions for each cell are assumed to be those of the outlet.

Core depletion

The depletion module works by finding the core flux distribution, incrementing the burnup, and updating the cross sections. The burnup increment is given by:

$$\Delta B_i = \Delta B_c \frac{P G_i}{P_c G}$$  \hspace{1cm} (2.11)

where:
$\Delta B_i$ is the burnup increment at location $i$.
$\Delta B_c$ is the core average burnup increment specified in the input.
$G_i$ is the heavy metal loading in the $i$ reaction.
$G_c$ is the total heavy metal loading of the core.
$P_i$ is the power in region $i$.
$P_c$ is the total core power.
3 PLANT AND EVENT DESCRIPTION

Oskarshamn unit 2 is a boiling water reactor designed by ABB ATOM and located in Oskarshamn, Sweden. It began operation in 1975. Originally rated for a thermal power of 1700 MW, it has since been uprated to 106% of that value, or 1802 MW.

3.1 Event Description

The instability event that is the subject of this project occurred on February 25, 1999, after maintenance had been performed on the electrical switchyard. While the normal electrical supply was being restored, the power supplied to a bus bar was unexpectedly interrupted for 150 milliseconds. This caused a load rejection which led to a turbine trip and the opening of the turbine bypass valves.

However, due to a faulty circuit, the signal did not reach the reactor itself. No automatic control rod insertions or reduction of recirculation pump speed occurred. The feedwater heater ceased to function, causing a rapid decrease in the feedwater temperature (75 °C over 150 seconds).

As the power reached 108% due to the decreasing inlet temperature, a pump rundown was triggered at 45 seconds after the load rejection occurred, decreasing the core flow and thus the power. However, the power began increasing again, and the process was repeated three more times at 70, 100, and 115 seconds. At 125 seconds, operators manually activated a partial scram, inserting 5 pre-selected control rods and reducing the pump flow to its minimum.

Although the power was reduced to 65%, the continually decreasing core inlet temperature caused it to increase once again. The power began to undergo oscillations at about 0.5 Hz with growing amplitude. Finally, a scram was triggered when the power exceeded 132%, successfully ending the oscillation and shutting down the reactor.

3.2 Plant Description

Information about the geometry of Oskarshamn-2 was obtained from drawings provided by the plant, as well as a RAMONA model in [10] and a BISON model in [11]. The reactor vessel has an internal height of 20 m and diameter of 5.2 m. There are no jet pumps, so that all of the core flow passes through the four recirculation loops. Additionally, there are a total of four feedwater pipes and four steam lines.
Figure 3-1: Oskarshamn-2 reactor vessel
Table 3-1: Rated condition data from [11]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal power (MW)</td>
<td>1800</td>
</tr>
<tr>
<td>Operation Pressure (MPa)</td>
<td>7.0</td>
</tr>
<tr>
<td>Steam Temperature (°C)</td>
<td>286</td>
</tr>
<tr>
<td>Steam flow rate (kg/s)</td>
<td>900</td>
</tr>
<tr>
<td>Maximum total recirculation flow (kg/s)</td>
<td>7700</td>
</tr>
</tbody>
</table>

Table 3-2: Reactor pressure vessel data from [11]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal height (m)</td>
<td>20</td>
</tr>
<tr>
<td>Internal diameter (m)</td>
<td>5.2</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>530,000</td>
</tr>
<tr>
<td>Wall thickness (mm)</td>
<td>134</td>
</tr>
</tbody>
</table>

Table 3-3: Reactor core information from [11]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equivalent core diameter (mm)</td>
<td>3672</td>
</tr>
<tr>
<td>Equivalent core height (mm)</td>
<td>3712</td>
</tr>
<tr>
<td>Number of fuel bundles</td>
<td>444</td>
</tr>
<tr>
<td>Burnup (MWd/ton U)</td>
<td>45,000</td>
</tr>
<tr>
<td>Average enrichment (% U-235)</td>
<td>3.4</td>
</tr>
<tr>
<td>Control rod absorber</td>
<td>B4C</td>
</tr>
<tr>
<td>Number of control rods</td>
<td>109</td>
</tr>
<tr>
<td>Means of control rod operation</td>
<td>electro-hydraulic</td>
</tr>
</tbody>
</table>

Table 3-4: Condenser information from [11]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coolant flow (sea water) (m³/s)</td>
<td>26</td>
</tr>
<tr>
<td>Temperature rise (°C)</td>
<td>10.7</td>
</tr>
<tr>
<td>Hotwell contents (m³)</td>
<td>210</td>
</tr>
<tr>
<td>Dumping capacity (%)</td>
<td>110</td>
</tr>
<tr>
<td>Feedwater temperature (°C)</td>
<td>185</td>
</tr>
<tr>
<td>Total number of pre-heating steps</td>
<td>5</td>
</tr>
<tr>
<td>Low pressure pre-heater</td>
<td>3</td>
</tr>
<tr>
<td>High pressure pre-heater</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 3-5: Turbine and generator information from [11]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator rating (MW)</td>
<td>627</td>
</tr>
<tr>
<td>Gross efficiency (%)</td>
<td>35.0</td>
</tr>
<tr>
<td>Generator net rating</td>
<td>602</td>
</tr>
<tr>
<td>Steam flow rate</td>
<td>900</td>
</tr>
<tr>
<td>Primary steam moisture content (%)</td>
<td>0.5</td>
</tr>
<tr>
<td>Steam pressure before high pressure turbine (MPa)</td>
<td>6.75</td>
</tr>
<tr>
<td>Steam temperature before high pressure turbine (°C)</td>
<td>283</td>
</tr>
<tr>
<td>Steam pressure after high pressure turbine (MPa)</td>
<td>0.54</td>
</tr>
<tr>
<td>Steam temperature after high pressure turbine (°C)</td>
<td>158</td>
</tr>
<tr>
<td>Steam pressure in compensator (MPa)</td>
<td>3.1</td>
</tr>
<tr>
<td>Steam temperature in compensator (°C)</td>
<td>30</td>
</tr>
</tbody>
</table>
Table 3-6: Recirculation pump information from [11]

<table>
<thead>
<tr>
<th>Total number of pumps</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal flow per pump at nominal speed (kg/s)</td>
<td>1925</td>
</tr>
<tr>
<td>Pressure rise (MPa)</td>
<td>0.55</td>
</tr>
<tr>
<td>Nominal speed (rpm)</td>
<td>1400</td>
</tr>
<tr>
<td>Pump head (m)</td>
<td>54.5</td>
</tr>
<tr>
<td>Nominal hydraulic torque</td>
<td>6820</td>
</tr>
<tr>
<td>Inertia</td>
<td>26</td>
</tr>
</tbody>
</table>

Table 3-7: Flow areas and hydraulic diameters from [10]

<table>
<thead>
<tr>
<th></th>
<th>Flow Area (m²)</th>
<th>Hydraulic Diameter (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Downcomer</td>
<td>6.960</td>
<td>0.950</td>
</tr>
<tr>
<td>Upper downcomer</td>
<td>1.125</td>
<td>0.600</td>
</tr>
<tr>
<td>Lower plenum 1</td>
<td>8.750</td>
<td>0.300</td>
</tr>
<tr>
<td>Lower plenum 2</td>
<td>9.750</td>
<td>0.300</td>
</tr>
<tr>
<td>Upper plenum</td>
<td>14.950</td>
<td>4.150</td>
</tr>
<tr>
<td>Stand pipes</td>
<td>4.178</td>
<td>0.300</td>
</tr>
<tr>
<td>Steam separators</td>
<td>6.277</td>
<td>0.298</td>
</tr>
<tr>
<td>Steam dome</td>
<td>14.900</td>
<td>0.950</td>
</tr>
<tr>
<td>Bypass</td>
<td>1.7681</td>
<td>0.029</td>
</tr>
</tbody>
</table>
3.3 Fuel

The core has an active height of 3.712 m and contains 444 fuel assemblies, including SVEA 64, KWU 9x9-9, ATRIUM 10, and GE 12 bundle designs. The first contains a full 8x8 array of fuel rods, but the latter three have water rods and the latter two have partial length fuel rods.
Table 3-8: Fuel types present in the core

<table>
<thead>
<tr>
<th></th>
<th>SVEA 64</th>
<th>KWU 9x9-9</th>
<th>ATRIUM 10</th>
<th>GE 12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Array size</td>
<td>8x8</td>
<td>9x9</td>
<td>10x10</td>
<td>10x10</td>
</tr>
<tr>
<td>Full fuel rods</td>
<td>64</td>
<td>72</td>
<td>83</td>
<td>78</td>
</tr>
<tr>
<td>Partial fuel rods</td>
<td>-</td>
<td>-</td>
<td>8</td>
<td>14</td>
</tr>
<tr>
<td>Water rods</td>
<td>-</td>
<td>1 (3x3 rod positions)</td>
<td>1 (3x3 rod positions)</td>
<td>2 (2x2 rod positions)</td>
</tr>
<tr>
<td>Overall assembly width (mm)</td>
<td>137.4</td>
<td>134</td>
<td>134</td>
<td>134.06</td>
</tr>
<tr>
<td>Pin pitch (mm)</td>
<td>15.8</td>
<td>14.45</td>
<td>12.95</td>
<td>12.95</td>
</tr>
<tr>
<td>Rod outside diameter (mm)</td>
<td>12.25</td>
<td>11.0</td>
<td>10.05</td>
<td>10.262</td>
</tr>
<tr>
<td>Pellet outside diameter (mm)</td>
<td>10.44</td>
<td>9.5</td>
<td>8.67</td>
<td>8.814</td>
</tr>
<tr>
<td>Average linear fuel rating (kW/m)</td>
<td>15.8</td>
<td>14.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak linear fuel rating (kW/m)</td>
<td>47.0</td>
<td>47.0</td>
<td>38.7</td>
<td></td>
</tr>
<tr>
<td>Clad thickness (mm)</td>
<td>0.8</td>
<td>0.665</td>
<td>0.605</td>
<td>0.635</td>
</tr>
</tbody>
</table>

3.4 Operating Conditions

A total of eleven reactor conditions were used to validate the model. Along with the steady state on the day of the instability event, there are two sets of five stability measurement points, made on December 12, 1998 (98-12-12) and March 13, 1999 (99-03-13). The first was about two months before the incident, and the second was a few days after.

A set of SIMULATE reference solutions were provided by KTH [12], the Swedish Royal Institute of Technology, giving the boundary conditions for all of these points, as well as much information for tuning and validating the reactor model. A small amount of additional data from POLCA was given in [10].
Table 3-9: Conditions for 98-12-12 stability measurement points

<table>
<thead>
<tr>
<th>Point</th>
<th>Power (%)</th>
<th>Total Flow (%)</th>
<th>Inlet Temp (K)</th>
<th>Bypass Fraction – POLCA SIMULATE (%)</th>
<th>Dome Pressure – POLCA SIMULATE (MPa)</th>
<th>Core Pressure Drop – POLCA SIMULATE (kPa)</th>
<th>Exit Quality – SIMULATE (%)</th>
<th>Keff – POLCA SIMULATE</th>
<th>Decay Ratio – Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>84.5</td>
<td>41.7</td>
<td>538.15</td>
<td>13.00</td>
<td>7.0</td>
<td>51</td>
<td>22.48</td>
<td>1.00290</td>
<td>0.53</td>
</tr>
<tr>
<td>2</td>
<td>81.8</td>
<td>38.9</td>
<td>537.15</td>
<td>11.53</td>
<td>7.02</td>
<td>47</td>
<td>23.22</td>
<td>1.00106</td>
<td>0.45</td>
</tr>
<tr>
<td>3</td>
<td>78.8</td>
<td>39.5</td>
<td>538.15</td>
<td>12.64</td>
<td>7.02</td>
<td>48</td>
<td>22.03</td>
<td>1.00266</td>
<td>0.38</td>
</tr>
<tr>
<td>4</td>
<td>75.6</td>
<td>37.1</td>
<td>538.15</td>
<td>12.59</td>
<td>7.02</td>
<td>47.1965</td>
<td>22.30</td>
<td>1.000301</td>
<td>0.38</td>
</tr>
<tr>
<td>5</td>
<td>72.1</td>
<td>35.6</td>
<td>537.15</td>
<td>12.09</td>
<td>7.02</td>
<td>47.2958</td>
<td>22.15</td>
<td>1.00077</td>
<td>0.43</td>
</tr>
</tbody>
</table>

Table 3-10: Conditions for 99-03-13 stability measurement points

<table>
<thead>
<tr>
<th>Point</th>
<th>Power (%)</th>
<th>Total Flow (%)</th>
<th>Inlet Temp (K)</th>
<th>Bypass Fraction – POLCA SIMULATE (%)</th>
<th>Dome Pressure – POLCA SIMULATE (MPa)</th>
<th>Core Pressure Drop – POLCA SIMULATE (kPa)</th>
<th>Exit Quality – SIMULATE (%)</th>
<th>Keff – POLCA SIMULATE</th>
<th>Decay Ratio – Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>81.7</td>
<td>41.9</td>
<td>539.15</td>
<td>13.01</td>
<td>7.0</td>
<td>51</td>
<td>22.48</td>
<td>1.00290</td>
<td>0.53</td>
</tr>
<tr>
<td>2</td>
<td>78.4</td>
<td>39.2</td>
<td>538.15</td>
<td>11.58</td>
<td>7.02</td>
<td>47</td>
<td>23.22</td>
<td>1.00106</td>
<td>0.45</td>
</tr>
<tr>
<td>3</td>
<td>77.9</td>
<td>39.3</td>
<td>538.15</td>
<td>12.59</td>
<td>7.02</td>
<td>48</td>
<td>22.03</td>
<td>1.00266</td>
<td>0.38</td>
</tr>
<tr>
<td>4</td>
<td>74.9</td>
<td>36.6</td>
<td>538.15</td>
<td>12.57</td>
<td>7.02</td>
<td>47.1965</td>
<td>22.30</td>
<td>1.000301</td>
<td>0.38</td>
</tr>
<tr>
<td>5</td>
<td>72.4</td>
<td>35.3</td>
<td>537.15</td>
<td>12.13</td>
<td>7.02</td>
<td>47.2958</td>
<td>22.15</td>
<td>1.00077</td>
<td>0.43</td>
</tr>
</tbody>
</table>

Table 3-11: Conditions before 99-02-25 instability event

<table>
<thead>
<tr>
<th>Point</th>
<th>Power (%)</th>
<th>Total Flow (kg/s)</th>
<th>Dome Pressure (MPa)</th>
<th>Inlet Temperature (K)</th>
<th>Core Pressure Drop (kPa)</th>
<th>Exit Quality (%)</th>
<th>Keff</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SIMULATE</td>
<td>Measured</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>106</td>
<td>105.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

20
4 PLANT TRACE/PARCS INPUT MODEL

4.1 TRACE Model

The model contains 222 channels, each representing two fuel assemblies in a core with one-half rotational symmetry, and ten other hydraulic components. The plant contains four feedwater pipes, four recirculation loops, and four steam lines, but in each case, all four have been lumped together.

<table>
<thead>
<tr>
<th>Component Number</th>
<th>Type</th>
<th>Description</th>
<th>Nodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1…222</td>
<td>CHAN</td>
<td>Core channels</td>
<td>28 (each)</td>
</tr>
<tr>
<td>919</td>
<td>PIPE</td>
<td>Recirculation suction pipe</td>
<td>4</td>
</tr>
<tr>
<td>920</td>
<td>PUMP</td>
<td>Recirculation pump</td>
<td>2</td>
</tr>
<tr>
<td>921</td>
<td>PIPE</td>
<td>Recirculation discharge pipe</td>
<td>4</td>
</tr>
<tr>
<td>950</td>
<td>SEPD</td>
<td>Steam separators</td>
<td>2</td>
</tr>
<tr>
<td>960</td>
<td>FILL</td>
<td>Feedwater source</td>
<td>1</td>
</tr>
<tr>
<td>961</td>
<td>PIPE</td>
<td>Feedwater pipe</td>
<td>3</td>
</tr>
<tr>
<td>978</td>
<td>PIPE</td>
<td>Steam line</td>
<td>4</td>
</tr>
<tr>
<td>979</td>
<td>VALVE</td>
<td>Turbine control valve</td>
<td>-</td>
</tr>
<tr>
<td>980</td>
<td>BREAK</td>
<td>Turbine inlet</td>
<td>1</td>
</tr>
<tr>
<td>990</td>
<td>VESSEL</td>
<td>Reactor vessel</td>
<td>15 axial x 2 radial</td>
</tr>
</tbody>
</table>

4.1.1 Core model

The core consisted of 222 channels, representing 444 fuel assemblies. The mapping pattern contains one-half rotational symmetry, as can be seen in Figure 4-1. Each channel consists of 28 hydraulic cells, with two inactive cells at the inlet and one at the outlet.
Four separate nodalizations of the core were produced:

1. Equal lengths for all active nodes.
2. Node sizes inversely proportional to the density in the SIMULATE results.
3. Node sizes directly proportional to the average vapor velocity.
4. Node sizes directly proportional to the maximum vapor velocity.

Nodalizations with size proportional to velocity allow the entire core to operate as closely as possible to the Courant limit, reducing numerical diffusion. Additionally, for the fourth nodalization, the top inactive length of the core was altered to make it comparable to the last active cell.

<table>
<thead>
<tr>
<th>Cell</th>
<th>Length (m) Nodalization 1</th>
<th>Length (m) Nodalization 2</th>
<th>Length (m) Nodalization 3</th>
<th>Length (m) Nodalization 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.1155</td>
<td>0.1155</td>
<td>0.1155</td>
<td>0.1155</td>
</tr>
<tr>
<td>2</td>
<td>0.1155</td>
<td>0.1155</td>
<td>0.1155</td>
<td>0.1155</td>
</tr>
<tr>
<td>3</td>
<td>0.14848</td>
<td>0.0863</td>
<td>0.063</td>
<td>0.053</td>
</tr>
<tr>
<td>4</td>
<td>0.14848</td>
<td>0.0866</td>
<td>0.0625</td>
<td>0.053</td>
</tr>
<tr>
<td>5</td>
<td>0.14848</td>
<td>0.0871</td>
<td>0.0643</td>
<td>0.053</td>
</tr>
<tr>
<td>6</td>
<td>0.14848</td>
<td>0.0887</td>
<td>0.0704</td>
<td>0.053</td>
</tr>
<tr>
<td>7</td>
<td>0.14848</td>
<td>0.0899</td>
<td>0.0747</td>
<td>0.0576</td>
</tr>
<tr>
<td>8</td>
<td>0.14848</td>
<td>0.0945</td>
<td>0.076</td>
<td>0.0601</td>
</tr>
<tr>
<td>9</td>
<td>0.14848</td>
<td>0.0974</td>
<td>0.0778</td>
<td>0.0615</td>
</tr>
<tr>
<td>10</td>
<td>0.14848</td>
<td>0.1017</td>
<td>0.0802</td>
<td>0.0631</td>
</tr>
<tr>
<td>11</td>
<td>0.14848</td>
<td>0.1088</td>
<td>0.084</td>
<td>0.0633</td>
</tr>
<tr>
<td>12</td>
<td>0.14848</td>
<td>0.114</td>
<td>0.0896</td>
<td>0.0672</td>
</tr>
<tr>
<td>13</td>
<td>0.14848</td>
<td>0.12</td>
<td>0.0967</td>
<td>0.0755</td>
</tr>
<tr>
<td>14</td>
<td>0.14848</td>
<td>0.1266</td>
<td>0.1051</td>
<td>0.0865</td>
</tr>
<tr>
<td>15</td>
<td>0.14848</td>
<td>0.1337</td>
<td>0.1147</td>
<td>0.0991</td>
</tr>
<tr>
<td>16</td>
<td>0.14848</td>
<td>0.1416</td>
<td>0.1254</td>
<td>0.1129</td>
</tr>
<tr>
<td>17</td>
<td>0.14848</td>
<td>0.1491</td>
<td>0.1372</td>
<td>0.1282</td>
</tr>
<tr>
<td>18</td>
<td>0.14848</td>
<td>0.1572</td>
<td>0.1502</td>
<td>0.1453</td>
</tr>
<tr>
<td>19</td>
<td>0.14848</td>
<td>0.1668</td>
<td>0.1654</td>
<td>0.1643</td>
</tr>
<tr>
<td>20</td>
<td>0.14848</td>
<td>0.1767</td>
<td>0.1827</td>
<td>0.1855</td>
</tr>
<tr>
<td>21</td>
<td>0.14848</td>
<td>0.1871</td>
<td>0.2013</td>
<td>0.209</td>
</tr>
<tr>
<td>22</td>
<td>0.14848</td>
<td>0.1981</td>
<td>0.2215</td>
<td>0.2354</td>
</tr>
<tr>
<td>23</td>
<td>0.14848</td>
<td>0.2122</td>
<td>0.2431</td>
<td>0.2652</td>
</tr>
<tr>
<td>24</td>
<td>0.14848</td>
<td>0.2253</td>
<td>0.2676</td>
<td>0.2986</td>
</tr>
<tr>
<td>25</td>
<td>0.14848</td>
<td>0.2408</td>
<td>0.2944</td>
<td>0.3353</td>
</tr>
<tr>
<td>26</td>
<td>0.14848</td>
<td>0.2551</td>
<td>0.3214</td>
<td>0.374</td>
</tr>
<tr>
<td>27</td>
<td>0.14848</td>
<td>0.2667</td>
<td>0.3428</td>
<td>0.4124</td>
</tr>
<tr>
<td>28</td>
<td>0.362</td>
<td>0.362</td>
<td>0.362</td>
<td>0.417</td>
</tr>
</tbody>
</table>

The pressure loss coefficients for the inlet orifice, tie plates, and spacer grids were taken from the SIMULATE model, and are shown in Table 4-3 and Table 4-4. The orifice loss coefficient is applied to the inlet surface of the channel. The lower and upper tie plate losses are applied to the

---

1 Shaded cells are inactive cells
bottom and top surfaces of the active core, respectively. Each spacer loss coefficient was applied
at whatever surface was closest to the height obtained from the SIMULATE model.

Table 4-3: Inlet orifice and tie plate loss coefficients

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Inlet Orifice Loss Coefficients</th>
<th>Tie Plate Loss Coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Central Semi-Peripheral Peripheral Lower Upper</td>
<td></td>
</tr>
<tr>
<td>SVEA 64</td>
<td>36.9 58.4 86.1 6.0 1.18</td>
<td></td>
</tr>
<tr>
<td>KWU 9x9-9</td>
<td>45.94 - - 2.51 0.35</td>
<td></td>
</tr>
<tr>
<td>ATRIUM 10</td>
<td>45.94 - - 2.87 0.1496</td>
<td></td>
</tr>
<tr>
<td>GE 12</td>
<td>36.3 - - 4.79 0.744</td>
<td></td>
</tr>
</tbody>
</table>

Table 4-4: Spacer grid information

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Number of Spacers and Loss Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>SVEA 64</td>
<td>6 x 0.598</td>
</tr>
<tr>
<td>KWU 9x9-9A</td>
<td>6 x 0.877</td>
</tr>
<tr>
<td>KWU 9x9-9B</td>
<td>6 x 0.812</td>
</tr>
<tr>
<td>ATRIUM 10</td>
<td>4 x 0.834 + 2 x 0.681</td>
</tr>
<tr>
<td>GE 12</td>
<td>6 x 1.1 + 2 x 0.607</td>
</tr>
</tbody>
</table>

All hydraulic information, as well as information on the numbers and dimensions of fuel pins,
was obtained from SIMULATE. Both the ATRIUM 10 and GE 12 fuel types have partial length
rods, and there are zones having different flow areas because of this.

Table 4-5: Channel hydraulic and fuel rod characteristics

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Flow Area (m²)</th>
<th>Hydraulic Diameter (m)</th>
<th>Rod Radius (mm)</th>
<th>Number of Rods</th>
</tr>
</thead>
<tbody>
<tr>
<td>SVEA 64</td>
<td>0.009713</td>
<td>0.011142</td>
<td>6.125</td>
<td>64</td>
</tr>
<tr>
<td>KWU 9x9-9</td>
<td>0.009551</td>
<td>0.012106</td>
<td>5.5</td>
<td>72</td>
</tr>
<tr>
<td>ATRIUM 10 – zone 1</td>
<td>0.009431</td>
<td>0.010697</td>
<td>5.025</td>
<td>91</td>
</tr>
<tr>
<td>zone 2</td>
<td>0.010065</td>
<td>0.012297</td>
<td>5.025</td>
<td>83</td>
</tr>
<tr>
<td>GE 12 – zone 1</td>
<td>0.0099</td>
<td>0.011066</td>
<td>5.131</td>
<td>92</td>
</tr>
<tr>
<td>zone 2</td>
<td>0.009278</td>
<td>0.010199</td>
<td>5.131</td>
<td>92</td>
</tr>
<tr>
<td>zone 3</td>
<td>0.010438</td>
<td>0.013096</td>
<td>5.131</td>
<td>78</td>
</tr>
<tr>
<td>zone 4</td>
<td>0.011059</td>
<td>0.014146</td>
<td>5.131</td>
<td>78</td>
</tr>
</tbody>
</table>

Additionally, three of the fuel types have water rods, which are modeled explicitly using
TRACE’s water rod option for the channel component. All dimensions were obtained from the
SIMULATE model.

Table 4-6: Water rods

<table>
<thead>
<tr>
<th></th>
<th>KWU 9x9-9</th>
<th>ATRIUM 10</th>
<th>GE 12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shape of water rod</td>
<td>square</td>
<td>square</td>
<td>cylinder</td>
</tr>
<tr>
<td>Number of water rods</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Fuel positions per rod</td>
<td>9</td>
<td>9</td>
<td>4</td>
</tr>
</tbody>
</table>
4.1.2 Peripheral hydraulic components

Feedwater source

The four feedwater pipes are lumped together and represented by a fill and a pipe. The temperature and flow rate of the fill are set by controllers described in section 4.1.3.

![Figure 4-2: Feedwater source and pipe](image)

Steam lines

The four steam lines are lumped into one. The turbine inlet is represented by a break, with a pressure set by the pressure controller described in section 4.1.3.

![Figure 4-3: Steam line, turbine control valve, and turbine inlet](image)

Recirculation loop

The four recirculation loops are lumped into one. It has a total length of 20.74 m, and a pipe diameter of 0.6 m. The pump rated values and head/torque curves were taken from a BISON model, and are shown below. The rated flow of 2.0 m$^3$/s has been multiplied by a factor of four to 8.0 m$^3$/s because of the number of pumps represented.

![Figure 4-4: Recirculation loop](image)
Table 4-7: Pump rated values and other options

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump Type</td>
<td>[1] Table Controlled Impeller Rotation</td>
</tr>
<tr>
<td>Reverse Rotation</td>
<td>[0] No</td>
</tr>
<tr>
<td>Degredation Option</td>
<td>[0] Single Phase Curves</td>
</tr>
<tr>
<td>Effective MOI (kg*m$^2$)</td>
<td>26.0</td>
</tr>
<tr>
<td>Pump Curve Options</td>
<td>[0] User Specified Curves</td>
</tr>
<tr>
<td>Rated head (m$^2$/s$^2$)</td>
<td>534.0</td>
</tr>
<tr>
<td>Rated torque (Pa*m$^3$)</td>
<td>6820.0</td>
</tr>
<tr>
<td>Rated volumetric flow (m$^3$/s)</td>
<td>8.0$^2$</td>
</tr>
<tr>
<td>Rated density (kg/m$^3$)</td>
<td>740.0</td>
</tr>
<tr>
<td>Rated speed (rad/s)</td>
<td>146.6</td>
</tr>
</tbody>
</table>

Figure 4-5: Pump head curves

Figure 4-6: Pump torque curves

$^2$ Multiplied by 4 to represent 4 recirculation pumps.
Separator

The separator component represents 90 individual steam separators and consists of two cells, representing the stand pipes and the separators themselves. The ideal separator option was chosen, which means that the carryover and carryunder were set at constant values.

![Separator Diagram](image)

**Figure 4-7: Separator**

Vessel

The reactor vessel has an internal height of 20.0 m and radius of 2.6 m. It is divided into 15 axial layers and two radial rings, as shown in Figure 4-8. The axial positions of the cells are based on drawings, whereas the flow areas were mostly obtained from the RAMONA5 model in [1]. However, some areas are based on estimates from the drawings.

![Vessel Diagram](image)

**Figure 4-8: Vessel nodalization diagram**
### Table 4-8: Vessel radial nodalization

<table>
<thead>
<tr>
<th>Radial Ring</th>
<th>Ring Width (m)</th>
<th>Outer Radius</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.125</td>
<td>2.125</td>
<td>Radius of core shroud.</td>
</tr>
<tr>
<td>2</td>
<td>0.475</td>
<td>2.6</td>
<td>Radius of reactor vessel.</td>
</tr>
</tbody>
</table>

### Table 4-9: Vessel axial nodalization

<table>
<thead>
<tr>
<th>Axial Level</th>
<th>Cell Length (m)</th>
<th>Cumulative Height</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>2.6</td>
<td>20.0</td>
<td>Remainder of height of vessel.</td>
</tr>
<tr>
<td>14</td>
<td>1.3</td>
<td>17.4</td>
<td>Top at top of upper downcomer.</td>
</tr>
<tr>
<td>13</td>
<td>1.3</td>
<td>16.1</td>
<td>Midpoint at elevation steam line.</td>
</tr>
<tr>
<td>12</td>
<td>0.96</td>
<td>14.8</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>2.47</td>
<td>13.84</td>
<td>Top at separator steam outlet.</td>
</tr>
<tr>
<td>10</td>
<td>1.27</td>
<td>11.37</td>
<td>Top at bottom of separator</td>
</tr>
<tr>
<td>9</td>
<td>0.593</td>
<td>10.1</td>
<td>Upper plenum</td>
</tr>
<tr>
<td>8</td>
<td>0.861</td>
<td>9.507</td>
<td>Top at top of core</td>
</tr>
<tr>
<td>7</td>
<td>0.861</td>
<td>8.646</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.861</td>
<td>7.785</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.861</td>
<td>6.924</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.861</td>
<td>6.063</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.885</td>
<td>5.202</td>
<td>Top at bottom of core.</td>
</tr>
<tr>
<td>2</td>
<td>0.885</td>
<td>4.317</td>
<td>Midpoint at recirculation outlet.</td>
</tr>
<tr>
<td>1</td>
<td>3.432</td>
<td>3.432</td>
<td></td>
</tr>
</tbody>
</table>

### Table 4-10: List of connections to vessel

<table>
<thead>
<tr>
<th>Connection to</th>
<th>Level</th>
<th>Ring</th>
<th>Surface</th>
<th>TRACE Elevation (m)</th>
<th>Real Elevation (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam line</td>
<td>13</td>
<td>2</td>
<td>Outward radial</td>
<td>15.45</td>
<td>15.45</td>
</tr>
<tr>
<td>Separator vapor outlet</td>
<td>12</td>
<td>1</td>
<td>Bottom</td>
<td>13.84</td>
<td>-</td>
</tr>
<tr>
<td>Separator liquid outlet</td>
<td>10</td>
<td>1</td>
<td>Top</td>
<td>11.37</td>
<td>-</td>
</tr>
<tr>
<td>Stand pipes inlet</td>
<td>9</td>
<td>1</td>
<td>Top</td>
<td>10.1</td>
<td>10.1</td>
</tr>
<tr>
<td>Feed-water connection</td>
<td>10</td>
<td>2</td>
<td>Outward radial</td>
<td>10.735</td>
<td>10.983</td>
</tr>
<tr>
<td>Recirculation outlet</td>
<td>2</td>
<td>2</td>
<td>Outward radial</td>
<td>3.8745</td>
<td>3.875</td>
</tr>
<tr>
<td>Recirculation discharge</td>
<td>1</td>
<td>2</td>
<td>Outward radial</td>
<td>1.716</td>
<td>-</td>
</tr>
</tbody>
</table>

### 4.1.3 Control system

There are a total of four control systems in the Oskarshamn model:

1. The core flow is controlled by the pump speed
2. The steam dome pressure is controlled by the turbine inlet pressure
3. The water level is controlled by the feed-water flow rate
4. The core inlet temperature is set by the feed-water temperature
Each of these uses a PID controller, where the differential term has been filtered using a special function, “integrate with decay” which removes much of the noise that may otherwise destabilize the controller. The output of this control block is given by:

$$X_0 = G \int_0^t e^{-c_1(t-t')} X_1(t') \, dt'$$ (4-1)

where $X_1$ is the input, $X_0$ is the output, $G$ is the gain, and $c_1$ is a time constant for the filtering. Usually, the gain is set to the same value as the time constant, so that the result will have the same scale as the input.

**Pump speed controller**

The pump controller consists of seven control blocks, shown below. Control block 199 sets the current pump speed.

<table>
<thead>
<tr>
<th>Number</th>
<th>Type</th>
<th>Gain</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>constant</td>
<td>1.0</td>
<td>pump flow setpoint</td>
</tr>
<tr>
<td>101</td>
<td>subtract</td>
<td>0.01</td>
<td>CB100 - (actual pump flow)</td>
</tr>
<tr>
<td>102</td>
<td>integrate</td>
<td>1.0</td>
<td>integrates CB101</td>
</tr>
<tr>
<td>103</td>
<td>differentiate</td>
<td>1.0</td>
<td>differentiates CB101</td>
</tr>
<tr>
<td>104</td>
<td>integrate with decay</td>
<td>1.0</td>
<td>filters CB103 with $c_1 = 1.0$</td>
</tr>
<tr>
<td>190</td>
<td>constant</td>
<td>1.0</td>
<td>initial guess as pump speed</td>
</tr>
<tr>
<td>199</td>
<td>sum</td>
<td>1.0</td>
<td>CB101+CB102+CB104+CB190</td>
</tr>
</tbody>
</table>

**Pressure controller**

The pressure controller consists of six blocks. Control block 299 sets the turbine inlet pressure boundary condition.

<table>
<thead>
<tr>
<th>Number</th>
<th>Type</th>
<th>Gain</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>201</td>
<td>subtract</td>
<td>-0.5</td>
<td>(actual dome pressure) - setpoint</td>
</tr>
<tr>
<td>202</td>
<td>integrate</td>
<td>1.0</td>
<td>integrates CB201</td>
</tr>
<tr>
<td>203</td>
<td>differentiate</td>
<td>1.0</td>
<td>differentiates CB201</td>
</tr>
<tr>
<td>204</td>
<td>integrate with decay</td>
<td>0.2</td>
<td>filters CB203 with $c_1 = 0.2$</td>
</tr>
<tr>
<td>290</td>
<td>constant</td>
<td>1.0</td>
<td>initial guess at pressure</td>
</tr>
<tr>
<td>299</td>
<td>sum</td>
<td>1.0</td>
<td>CB201+CB202+CB204+CB290</td>
</tr>
</tbody>
</table>

**Feed-water flow controller**

The feed-water flow controller consists of six control blocks. Control block 399 sets the feedwater mass flow rate.
### Table 4-13: Feedwater flow controller configuration

<table>
<thead>
<tr>
<th>Number</th>
<th>Type</th>
<th>Gain</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>301</td>
<td>subtract</td>
<td>-500.0</td>
<td>(actual water level) - setpoint</td>
</tr>
<tr>
<td>302</td>
<td>integrate</td>
<td>0.001</td>
<td>integrates CB301</td>
</tr>
<tr>
<td>303</td>
<td>differentiate</td>
<td>0.1</td>
<td>differentiates CB301</td>
</tr>
<tr>
<td>304</td>
<td>integrate with decay</td>
<td>5.0</td>
<td>filters CB303 with $c_1 = 5.0$</td>
</tr>
<tr>
<td>309</td>
<td>constant</td>
<td>1.0</td>
<td>initial guess as feedwater flow</td>
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<tr>
<td>399</td>
<td>sum</td>
<td>1.0</td>
<td>CB301+CB302+CB304+CB309</td>
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</table>

**Feedwater temperature controller**

The feedwater temperature controller consists of six control blocks, as well as using the value of the feedwater mass flow. Control block 499 sets the current feed-water temperature in Kelvin.

### Table 4-14: Feedwater temperature controller configuration

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<th>Description</th>
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<td>401</td>
<td>subtract</td>
<td>-1.0</td>
<td>(actual core inlet temp) - setpoint</td>
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<td>402</td>
<td>integrate</td>
<td>0.1</td>
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<td>403</td>
<td>differentiate</td>
<td>1.0</td>
<td>differentiates CB401</td>
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<td>404</td>
<td>integrate with decay</td>
<td>1.0</td>
<td>filters CB403 with $c_1 = 1.0$</td>
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<td>initial guess as feedwater temperature</td>
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<tr>
<td>499</td>
<td>sum</td>
<td>1.0</td>
<td>CB401+CB402+CB404+CB409+0.11*CB399</td>
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### 4.2 PARCS Model

The PARCS model consists of 444 fuel assemblies, as well as 92 positions around the periphery, representing the reflector. The active core is divided into 25 equal layers, each 14.848 cm thick. There are additional layers representing the reflector at the top and bottom, for a total of 27 layers.

The PMAXXS cross-section files required by PARCS were developed from data generated by CASMO/SIMULATE. Additionally, depletion files were required to give the depletion state for each set of conditions. The data for these was also taken from the SIMULATE output.

There are a total of 19 control rod banks in Oskarshamn. The configuration is given in Figure 4-10.
Figure 4-9: PARCS assembly configuration (0 = dummy region, 1 = reflector, >1 = fuel assembly)

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Figure 4-10: Control rod bank configuration
5 SCRIPTS AND PROCEDURES FOR MODEL GENERATION
AND DATA ANALYSIS

5.1 Running Procedure

The following procedure is used to run each set of conditions as a coupled TRACE/PARCS model:

1. TRACE is run in standalone steady-state mode, with the power distribution from SIMULATE used as a constant boundary condition.
2. TRACE and PARCS are run coupled, in steady state mode. Separate inputs are required for each code. TRACE uses the restart file from step 1 to obtain the initial thermal-hydraulic conditions for this calculation.
3. TRACE and PARCS are run in coupled transient mode. The transient may be a stability measurement test, or the instability event of February 25, 1999. Each code uses its respective restart file from part 2 to obtain the initial conditions.
4. The steady state output is read using the output reading capabilities of the Oskarshamn Perl script system. This creates a file giving the important variables, as well as the axial distributions of power and void fraction. Additional files are created containing the radial distributions of flow and power, which are then in turn used to create plots with MATLAB.
5. For the stability-measurement transients, the distribution of power with respect to time is input into the DRARMAX, a MATLAB script described below, which evaluates the Decay Ration (DR) and Natural Frequency (NF) of the oscillations produced by the simulation.

5.2 Oskarshamn Scripts

A need existed to create TRACE inputs for a variety of boundary conditions, and furthermore, it must be easy to make significant changes to the model. Modifying and creating several versions of the input by hand would be too laborious, as well as prone to human error. Thus, a system of Perl scripts was created to generate input given reference information as well as a set of model options. Furthermore, additions were made to allow reading of output files and automatic organization of the most relevant information.

5.2.1 Input generation capabilities

The Perl script file “InputBuilder.pl” is run in order to generate a thermal hydraulic model, in the form of input file for TRACE standalone. It calls several subroutines located in Perl module files, one subroutine for printing each section of the file. A file named “ModelOptions.txt” is read to obtain the operating conditions, as well as several other options which were varied, such as the core nodalization model. Additionally, output files from SIMULATE are read in order to obtain information for the initial conditions and power distribution.
5.2.2 Output reading capabilities

The output is read by running “OutputReader.pl,” which, like the input builder, calls several separate subroutines located in different files. It reads the key variables, such as pressure, temperature and flow rate at important locations, as well as the core distributions from both TRACE and PARCS. The relevant information is printed to a text file in which everything is clearly labeled.

Additionally, files containing radial distributions are generated, which are then used for plotting. MATLAB is used to generate color-based plots of the radial distributions; with the color of a square representing the magnitude of the quantity in question averaged over one assembly.

5.3 DRARMAX

DRARMAX [8] (Decay Ratio Auto-Regressive Moving Average – eXternal signal) is a package of MATLAB scripts, developed at Purdue University, for the evaluation of decay ratios and frequencies, given a series of values over time – in this case the reactor power. As the name implies it uses a combination of auto-regressive and moving average methods.

5.3.1 Theory

A second-order damped oscillating system can be described by the equation:

\[ x(t) = Ae^{-\alpha t} \cos(\omega t + \varphi) \]  

(5.1)

In such a system, the Decay Ratio (DR) represents the ratio of the amplitude at a given point that from one cycle before. In terms of equation (5.1), this can be given as:

\[ DR = e^{-\frac{2\pi \varphi}{\omega}} \]  

(5.2)

Additionally, a simpler definition is the average between two successive decay ratios measured between individual crests:

\[ DR_p = \frac{1}{2} \left( \frac{B_z}{B_1} + \frac{B_z}{B_2} \right) \]  

(5.3)

Because the data is given at discrete points in time, 4th order Lagrange interpolation is used between points.
The autocorrelation function (ACF) of a function $x(t)$ is defined as:

$$R_{xx}(t) = \int_{0}^{\infty} x(\tau) x(\tau + t) d\tau$$  \hspace{1cm} (5.4)

The ACF is an effective filter for white noise, or a series of uncorrelated values with zero mean, and is used by DRARMAX. A least squares fit for (5.1) is used, both with the raw data and with its ACF.

The response of a system to an impulse $\delta$ can be described as $h(\tau)$, the impulse response function (IRF).

If the input is a function $u(x)$ rather than an impulse, the output is the convolution of the input and the impulse response function.
The impulse response function is responsible for the stability of the system, and can be estimated from $x$ and $u$. In order to do this, it is assumed to be an ARMA (auto-regressive moving average) process:

$$x(i) = \sum_{j=0}^{i-1} h(j)u(n-j) = -\sum_{k=1}^{p} a_k x(i-k) + \sum_{m=0}^{q} b_m u(i-m)$$  \hspace{1cm} (5.6)$$

In (5.6), the first term on the right represents the auto-regressive (AR) part, and the second is the moving average (MA). The $p$ and $q$ are the AR and MA orders, respectively. The system is solved for the $a_k$ and $b_m$, giving an approximation for $h$.

The impulse response function has the advantage that it can be used not only for transients, but also for stationary noise in which no oscillations are clearly visible.

### 5.3.2 Capabilities and Limitations

DRARMAX takes a single input signal, and outputs a series of results for the decay ratio and frequency – those obtained from the raw data, the ACF, and the IRF. For stationary noise, only the IRF is used. The AR and MA orders, $p$ and $q$, can be input, or the code can automatically chose the optimum values. However, the latter is time consuming, and is not generally used.

Sometimes, the code may fail to find a least squares solution. Also, the different values for the decay ratio that result may be very different. Under such circumstances, it is likely that the input signal is too far from a damped sinusoid.

### 5.3.3 Code Structure

The system of scripts is structured as follows:
The descriptions of these functions are given in Figure 5-5.
1) DR arma: driving function of DRarma package.
2) Getdata: this function reads control input from DR.inp, reads signals from DATA file, and generates input signal and sample signal if required.
3) acf: this function estimates auto-correlation function with fft and ifft.
4) DR_two: this function calculates 2 decay ratios and frequencies for given signal.
5) Armaxm: this function generates IRF through armax for DR evaluation and calculates Lyapunov and asymptotic Decay ratios and frequencies.
6) Readstr: this function reads 1 string, and shifts the point after the string.
7) Endposition: this function determines the ending position of useful information in a input card.
8) MakeWhiteNoise: this function generates band white noise for given parameters.
9) linearInterpolation: this function performs linear interpolation.
10) Sampling: this function performs equal-space sampling.
11) find_max: this function finds next local maximum and its location.
12) find_min: this function finds next local minimum and its location.
13) Gauss_Newton: this function solves least square problem with Gauss_Newton method.
14) ExpCos2: this function provides function values and Jacobian of \( x1+x2*\exp(x3*t)*\cos(x4*t+x5)+x6*\exp(x7*t)*\cos(x8*t+x9)-b \) for given vector t and b as parameters. x1 to x9 are independent variables.
15) Armap: this function searches optimal AR order p for given MA order q.
16) Armaq: this function searches optimal MA order q for given AR order p.
17) Armax1: this function invokes penarmax or penarma for signal with/without external signal, it also calls DR_two to evaluate decay ratios and frequencies of IRF.
18) UniRandomize: this function generates uniform random number with mixed congruential method.
19) Cgnr: this function solves the linear system with conjugate gradient method
20) Modeltrust: this function finds small increment of solution when Newton step is too big.
21) pemarmax: this function evaluates AR and MA parameters with input signal by PEM.
22) pemarma: this function evaluates AR and MA parameters without input signal by PEM.
23) polyroots: this function find all roots include complex ones of polynomial equations.
24) pewi: this function evaluates prediction error of ARMAX for given parameters.
25) peni: this function evaluates prediction error and Jacobian matrix of ARMA for given parameters.

Figure 5-5: Function descriptions, from [8]
6 RESULTS

6.1 Steady State Results

The TRACE/PARCS model was tested and tuned for steady-state using the SIMULATE reference solutions. Controllers were used as described in 4.1.3 to enforce the following as boundary conditions:

- Recirculation pump flow rate
- Steam dome pressure
- Reactor water level
- Core inlet temperature

Additionally, the following tuning was done for the loss coefficients:

- The separator loss coefficient was set to tune the core outlet pressure.
- The bypass inlet loss coefficient was set to tune the active core flow fraction.

Table 6-1 shows the steady state results for the first of the five stability tests that occurred before the instability event. The controlled parameters are well converged, and most of the others, such as the steam flow rate are sufficiently close to the values from the SIMULATE reference solution. The pressure drop is slightly higher in TRACE, even though the same frictional coefficients and hydraulic diameters were used as in SIMULATE. This is most likely due to the differences between how the two codes model friction.
Table 6-1: Comparison of steady state parameters to SIMULATE reference solution for 98-12-12 point 1

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<th>Parameter</th>
<th>SIMULATE</th>
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<td>Reactor power (Mw)</td>
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</tr>
<tr>
<td>Enthalpy Balance (MW)</td>
<td></td>
<td>1434.7</td>
<td>1435.0</td>
</tr>
<tr>
<td>Dome Pressure (MPa)</td>
<td>7.00</td>
<td>7.0000</td>
<td>7.0000</td>
</tr>
<tr>
<td>Core Inlet Pressure (MPa)</td>
<td>7.080</td>
<td>7.0819</td>
<td>7.0822</td>
</tr>
<tr>
<td>Core Outlet Pressure (MPa)</td>
<td>7.030</td>
<td>7.0281</td>
<td>7.0282</td>
</tr>
<tr>
<td>Core Pressure Drop (kPa)</td>
<td>50.2074</td>
<td>53.7</td>
<td>54.0</td>
</tr>
<tr>
<td>Channel Pressure drop (kPa)</td>
<td>33.609</td>
<td>36.1</td>
<td>36.4</td>
</tr>
<tr>
<td>Orifice and Lower Plate (kPa)</td>
<td>16.599</td>
<td>17.6</td>
<td>17.6</td>
</tr>
<tr>
<td>Core Average Void</td>
<td></td>
<td>0.4504</td>
<td>0.4587</td>
</tr>
<tr>
<td>Feedwater Temperature (K)</td>
<td></td>
<td>457.93</td>
<td>459.01</td>
</tr>
<tr>
<td>Core Inlet Temperature (K)</td>
<td>538.15</td>
<td>538.16</td>
<td>538.16</td>
</tr>
<tr>
<td>Steam Temperature (K)</td>
<td>558.68</td>
<td>558.68</td>
<td>558.68</td>
</tr>
<tr>
<td>Pump Speed (rad/s)</td>
<td></td>
<td>56.42</td>
<td>56.48</td>
</tr>
<tr>
<td>Total Core Flow (kg/s)</td>
<td>3209.92</td>
<td>3210.1</td>
<td>3210.0</td>
</tr>
<tr>
<td>Core Active Flow (kg/s)</td>
<td>2839.90</td>
<td>2848.3</td>
<td>2850.7</td>
</tr>
<tr>
<td>Bypass Flow (kg/s)</td>
<td>267.27</td>
<td>288.4</td>
<td>286.2</td>
</tr>
<tr>
<td>Water Rod Flow (kg/s)</td>
<td>102.81</td>
<td>73.4</td>
<td>72.9</td>
</tr>
<tr>
<td>Steam Flow Rate (kg/s)</td>
<td>721.47</td>
<td>722.2</td>
<td>723.9</td>
</tr>
<tr>
<td>Downcomer Water Level (m)</td>
<td></td>
<td>8.390</td>
<td>8.396</td>
</tr>
<tr>
<td>k-eff</td>
<td>1.001058</td>
<td></td>
<td>0.999639</td>
</tr>
</tbody>
</table>

The axial distributions of void fraction, relative power, and fuel temperature follow the same trends as in the SIMULATE solution. However, TRACE predicts a higher void fraction as shown in Figure 6-1. This pushes the power slightly toward the bottom of the core, where there is no void, as shown in Figure 6-2. However, this difference is minor and may reflect only a difference in the models of the codes.
The axial fuel temperature also follows the same trend as in SIMULATE. However, as will be shown in the next section, this is very sensitive to at least one parameter, the gap conductivity, which is not known in this case. The similarity to the reference solution may only mean that similar input parameters were used in the two codes and not that the TRACE/PARCS model accurately predicts the temperature.
Figure 6-3: Axial fuel temperature distribution for 98-12-12 point 1

Figure 6-4 shows that radial power distribution in PARCS follows the same pattern as in SIMULATE, while Figure 6-5 shows the differences, mainly that PARCS gives a power that is as much as 10% higher in the peripheral assemblies. However, because the power is very low in these assemblies, a 10% difference is a very small amount of power. The difference may be due to the neutronic boundary conditions which were derived from the Penn State’s Ringhals model, due to the current lack of accurate boundary conditions from Oskarshamn. The Ringhals model, used in the project mentioned in the introduction, was used to obtain various parameters to fill the gaps in the knowledge possessed regarding Oskarshamn.

Figure 6-4: Relative assembly power radial distribution (left = SIMULATE, right = PARCS)
6.2 Sensitivity Analysis

As will be described in detail below, the initial results for the decay ratio were unacceptably low compared to the measured value. For this reason, several sensitivity analyses were conducted in order to determine what corrections might be made to the model.

6.2.1 Fuel rod gap conductivity

The original model used the fourth core nodalization as the default, as well as a value of 4800.0 W/(m²K) for the input parameter hgapo, the conductivity of the gap between the fuel rods and the cladding. This was used because it is the same as that in the above mentioned Ringhals model. The true value is not known, and the conductivity of fuel-clad gaps is, in general, the subject of a great deal of uncertainty [15].

In order to study the sensitivity, runs of TRACE/PARCS were made with the fourth core nodalization, and hgapo values of 2400, 4800, and 1.0E4. Both the control rod and pressure perturbation transients were run, and the frequency and decay ratio were evaluated by DRARMAX.

In all of the tables shown below, the first value in each cell is the one that DRARMAX calculated from the raw data, and the second, shown in parentheses, is that which was obtained from the autocorrelation function. If no value is shown, DRARMAX failed to find a decay ratio and frequency.

<table>
<thead>
<tr>
<th>hgapo (W/(m²K))</th>
<th>DR – CR</th>
<th>FR – CR</th>
<th>DR – PP</th>
<th>FR – PP</th>
<th>DR (measured)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2400</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>4800</td>
<td>-</td>
<td>-</td>
<td>0.337 (0.529)</td>
<td>0.597 (0.502)</td>
<td></td>
</tr>
<tr>
<td>1.0E4</td>
<td>0.330 (0.476)</td>
<td>0.628 (0.549)</td>
<td>0.358 (0.435)</td>
<td>0.575 (0.581)</td>
<td>0.530</td>
</tr>
</tbody>
</table>

As seen in Figure 6-6, only the highest value for hgapo gives reasonable oscillation. Lower values cause the power level to quickly return to a constant, causing DRARMAX to fail when
attempting to calculate the frequency and decay ratio. It is as expected that a higher gap conductivity would lead to decreased stability (i.e. a higher decay ratio), as it speeds the transfer of heat from fuel to coolant, reducing the time delay for the reactivity feedback.

Even for the highest value of hgapo, there is a significant difference between the DRARMAX results for the raw data and for the autocorrelation function. This means that the results for power over time do not sufficiently well resemble pure oscillation (i.e. a function of the form shown in (5.1)).

Figure 6-6: Results for pressure perturbation given different inputs for hgapo for 98-12-12 point 1

Figure 6-7 shows the effect on the temperature distribution. Larger values for gap conductivity reduce the temperature of the fuel. Both the results for hgapo of 4800 and 1.0x10^4 are closer to the SIMULATE results than for 2400, very likely because SIMULATE used a similar value. However, in this case, it is not desirable to perfectly match the SIMULATE reference solution, as it is not necessarily based on a more accurate value for the gap conductivity.
6.2.2 Core nodalization

All four of the core nodalizations described in section 4.1.1 were tested, using an hgapo of $1.0 \times 10^4$. As shown in Table 6-3, nodalizations that are more proportional to the maximum velocity give higher decay ratios than those that are closer to being equally spaced. As previously explained, the spacing proportional to velocity allows TRACE to operate with a higher Courant number, limiting numerical diffusion. It is as expected that numerical diffusion will cause an unphysical dampening of oscillations, reducing the decay ratio.

Table 6-3: DRARMAX results for 98-12-12 point 1 with different core nodalization

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.066 (0.433)</td>
<td>0.527 (0.523)</td>
<td>0.097 (0.581)</td>
<td>0.500 (0.391)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.143 (0.455)</td>
<td>0.611 (0.527)</td>
<td>0.335 (0.569)</td>
<td>0.573 (0.395)</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.272 (0.479)</td>
<td>0.630 (0.544)</td>
<td>0.118 (0.425)</td>
<td>0.574 (0.579)</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.330 (0.476)</td>
<td>0.628 (0.549)</td>
<td>0.358 (0.435)</td>
<td>0.575 (0.581)</td>
<td></td>
</tr>
</tbody>
</table>

Figure 6-7: Axial fuel temperature distribution for 98-12-12 point 1 with different hgapo
Figure 6-8: Results for pressure perturbation given different core nodalizations for 98-12-12 point 1

6.2.3 Core channel surface roughness

Due to the fact that the pressure drop through the core is higher in TRACE than in SIMULATE, a test was made to see if reducing this would effect the stability test results. In order to do this, the surface roughness of the core channels was set to 0.0, instead of the previous default of 1.0E-5.

As can be seen in Table 6-4 and Figure 6-9, the result of setting zero roughness is a very quick dampening of the oscillation. Figure 6-10 and Figure 6-11 show only a small change in the void and power distributions, while Table 6-5 shows no notable changes except for the expected lower core pressure drop.

Table 6-4: DRARMAX results for 98-12-12 point 1 with different core channel surface roughness

<table>
<thead>
<tr>
<th>Roughness (m)</th>
<th>DR – CR</th>
<th>FR – CR</th>
<th>DR – PP</th>
<th>FR – PP</th>
<th>DR (measured)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0E-5</td>
<td>0.330 (0.476)</td>
<td>0.628 (0.549)</td>
<td>0.358 (0.435)</td>
<td>0.575 (0.581)</td>
<td></td>
</tr>
<tr>
<td>0.0</td>
<td>0.069 (0.076)</td>
<td>0.580 (0.412)</td>
<td>0.231 (0.583)</td>
<td>0.593 (0.383)</td>
<td>0.530</td>
</tr>
</tbody>
</table>
Figure 6-9: Results for pressure perturbation given different surface roughness for 98-12-12 point 1

Table 6-5: Comparison of steady state parameters for different surface roughness

<table>
<thead>
<tr>
<th></th>
<th>Roughness = 1.0E-5</th>
<th>Roughness = 0.0</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reactor power (Mw)</strong></td>
<td>1436.50</td>
<td>1436.50</td>
</tr>
<tr>
<td><strong>Enthalpy Balance (MW)</strong></td>
<td>1434.7</td>
<td>1434.6</td>
</tr>
<tr>
<td><strong>Dome Pressure (MPa)</strong></td>
<td>7.00</td>
<td>7.0000</td>
</tr>
<tr>
<td><strong>Core Inlet Pressure (MPa)</strong></td>
<td>7.080</td>
<td>7.0822</td>
</tr>
<tr>
<td><strong>Core Outlet Pressure (MPa)</strong></td>
<td>7.030</td>
<td>7.0282</td>
</tr>
<tr>
<td><strong>Core Pressure Drop (kPa)</strong></td>
<td>50.2074</td>
<td>54.0</td>
</tr>
<tr>
<td><strong>Channel Pressure drop (kPa)</strong></td>
<td>33.609</td>
<td>36.4</td>
</tr>
<tr>
<td><strong>Orifice and Lower Plate (kPa)</strong></td>
<td>16.599</td>
<td>16.7</td>
</tr>
<tr>
<td><strong>Core Average Void</strong></td>
<td>0.4504</td>
<td>0.4573</td>
</tr>
<tr>
<td><strong>Feedwater Temperature (K)</strong></td>
<td>457.93</td>
<td>457.92</td>
</tr>
<tr>
<td><strong>Core Inlet Temperature (K)</strong></td>
<td>538.15</td>
<td>538.16</td>
</tr>
<tr>
<td><strong>Steam Temperature (K)</strong></td>
<td>558.68</td>
<td>558.68</td>
</tr>
<tr>
<td><strong>Pump Speed (rad/s)</strong></td>
<td>56.42</td>
<td>56.56</td>
</tr>
<tr>
<td><strong>Total Core Flow (kg/s)</strong></td>
<td>3209.92</td>
<td>3210.0</td>
</tr>
<tr>
<td><strong>Core Active Flow (kg/s)</strong></td>
<td>2839.90</td>
<td>2858.0</td>
</tr>
<tr>
<td><strong>Bypass Flow (kg/s)</strong></td>
<td>267.27</td>
<td>294.5</td>
</tr>
<tr>
<td><strong>Water Rod Flow (kg/s)</strong></td>
<td>102.81</td>
<td>57.5</td>
</tr>
<tr>
<td><strong>Steam Flow Rate (kg/s)</strong></td>
<td>721.47</td>
<td>722.0</td>
</tr>
<tr>
<td><strong>Downcomer Water Level (m)</strong></td>
<td>8.390</td>
<td>8.396</td>
</tr>
<tr>
<td><strong>k-eff</strong></td>
<td>1.001058</td>
<td>1.000120</td>
</tr>
</tbody>
</table>
6.2.4 Time step size

The Courant number, defined as $v\Delta t/\Delta x$, is an important factor in the numerical diffusion. Each cell has its own Courant number, because the $v$'s $\Delta x$'s are unique. In order to study the sensitivity, the maximum time step size was set at 0.02 and 0.01 seconds. When the limit is set at the usual 0.1 seconds, the step size is approximately 0.04 seconds, set so that the maximum Courant number is less than or equal to 1.
As expected, lower time step sizes cause the numerical diffusion to dampen the oscillations, resulting in a much lower decay ratio.

Table 6-6: DRARMAX results for 98-12-12 point 1 with different time step limits

<table>
<thead>
<tr>
<th>$\Delta t_{\text{max}}$ (s)</th>
<th>DR – CR</th>
<th>FR – CR</th>
<th>DR – PP</th>
<th>FR – PP</th>
<th>DR (measured)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.330 (0.476)</td>
<td>0.628 (0.549)</td>
<td>0.358 (0.435)</td>
<td>0.575 (0.581)</td>
<td></td>
</tr>
<tr>
<td>0.02</td>
<td>0.101 (0.442)</td>
<td>0.598 (0.526)</td>
<td>0.098 (0.555)</td>
<td>0.539 (0.394)</td>
<td>0.530</td>
</tr>
<tr>
<td>0.01</td>
<td>0.092 (0.427)</td>
<td>0.569 (0.520)</td>
<td>0.204 (0.553)</td>
<td>0.535 (0.390)</td>
<td></td>
</tr>
</tbody>
</table>

Figure 6-12: Results for pressure perturbation transient given different maximum time step sizes

6.3 Additional Measurement Point

In order to ensure that the under-prediction of the decay ratio was not unique to the stability measurement point above, two simulations were run of a point from the second set of stability tests, with two different values for hgapo. The result was a similarly under-predicted decay ratio, and a similar difference between the predictions made from the raw data and from the autocorrelation function.

Table 6-7: DRARMAX results for 99-03-13 point 3

<table>
<thead>
<tr>
<th>hgapo (W/(m$^2$K))</th>
<th>DR – CR</th>
<th>FR – CR</th>
<th>DR – PP</th>
<th>FR – PP</th>
<th>DR (measured)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4800</td>
<td>0.099 (0.594)</td>
<td>0.671 (0.606)</td>
<td>0.321 (0.424)</td>
<td>0.606 (0.565)</td>
<td></td>
</tr>
<tr>
<td>1.0E4</td>
<td>0.400 (0.484)</td>
<td>0.614 (0.581)</td>
<td>0.406 (0.498)</td>
<td>0.585 (0.582)</td>
<td>0.650</td>
</tr>
</tbody>
</table>
7 CONCLUSIONS

A coupled TRACE/PARCS model of the Oskarshamn-2 reactor has been developed to simulate an instability event in order to validate the two codes for boiling water reactor stability analysis. The model was based on an earlier model in SIMULATE, the solution of which is used as a reference for tuning and validating the TRACE/PARCS model.

Several sensitivity analyses were conducted for the stability test transients. An analysis of the sensitivity to the fuel-cladding gap thermal conductivity showed that higher values resulted in higher, more accurate, results for the decay ratio. A nodalization study showed that cell sizes that are proportional to the maximum vapor velocity at each axial level have less dampening due to numerical diffusion, and thus better prediction of the decay ratio. Additionally, a study in the reduction of the time step, lowering the Courant number, further showed how numerical diffusion damps the oscillations.

The stability behavior showed remarkable sensitivity to the removal of the surface roughness from the core. It is not known if this effects the results differently than reducing the friction through other means, such as changing the hydraulic diameters. Further study is warranted, including of the effects of increasing the roughness. Furthermore, it should be determined if reducing the friction through changing spacer loss coefficients or hydraulic diameters has a similar effect.

The predicted decay ratio even for the best cases shown here is too low, showing that the model is not yet ready to be expected to reasonably represent the stability of the reactor for the instability event that it the topic of this project. However, the sensitivity to several parameters, the true values of which are not known, has been shown, and these can be used to tune the model once a more detailed understanding has been developed.
REFERENCES

12. KTH (Royal Institute of Technology), CASMO/SIMULATE output.
APPENDIX A: SAMPLE TRACE INPUT

The following is a sample input model for TRACE. However, for the purpose of brevity, only one channel out of 222 is shown. Additionally, long lists of all channels or channel connections are omitted where noted below.

free format
* * Input deck for Oskarshamn-2
* Stability Measurements 98-12-12 Point 1
* Created by Jeff Magedanz at Penn State.
*
* main data
*
* numtcr ieos inopt nmat id2o
* 1 0 1 0 0
*
* name list data
*
* sinopts
 link
  dtstrt=1.0E-4,
  graphlevel="minimal",
  HomMultAWD=true,
  iambwr=.TRUE.,
  icflow=2,
  igeom=3,
  ipowr=1,
  nfrc=1,
  noair=0,
  nolt=0,
  nosets=0,
  tracbout=1,
  usesjc=3,
  npower=1,
  fluids='H2O',
  itdmr=0
  numgentbl=0,
  nhtstr=0,
  iunlab=0
end
*
* Model Flags
*
* dstep timet
0 0.0
* stdyst transi ncomp njun ipak
  1 0 233 456 1
* epsc eps
t 1.0E-4 1.0E-4
* oitmax sitmax isolut ncontr nccfl
  10 10 0 0 0
* ntsv ntcb ntcf ntrp ntcp
  26 41 40 1 0
*
* Component-Number Data
*
* Component input order (IORDER)

** type ** num ************ name ************ +  jun1  jun2  jun3
* PIPE 919 s Pump Suction + 919 920
* PUMP     * 920 s * Recirculation Pump + 920 921 
* PIPE     * 921 s * Pump Outlet + 921 922 
* SEPD     * 950 s * Steam Separators + 950 951 952 
* FILL     * 960 s * Feedwater Supply + 960 
* PIPE     * 961 s * Feedwater Pipe + 960 961 
* PIPE     * 978 s * Steam Line + 978 979 
* VALVE    * 979 s * Turbine Control Valve + 979 980 
* BREAK    * 980 s * Turbine Break + 980 
* VESSEL   * 990 s * Reactor Vessel + 
* CHAN     * 1 s * KWU 9x9-9A Central + 1001 2001 

[Long list of channels] 

* POWER     * 999 e * power com + 

* Signal Variables

* n: Pump flow rate
  * idsv isvn ilcn icn1 icn2
  1 70 920 2 0
  * n: Steam dome pressure
  * idsv isvn ilcn icn1 icn2
  2 21 990 1015 0
  * n: DC water level
  * idsv isvn ilcn icn1 icn2
  3 106 990 1 0
  * n: Inlet temperature
  * idsv isvn ilcn icn1 icn2
  4 23 990 1003 0
  * n: Problem time
  * idsv isvn ilcn icn1 icn2
  5 0 0 0 0
  * n: Steam line mass flow
  * idsv isvn ilcn icn1 icn2
  6 69 978 1 0
  * n: Feedwater flow rate
  * idsv isvn ilcn icn1 icn2
  7 69 961 1 0
  * n: Steam line enthalpy
  * idsv isvn ilcn icn1 icn2
  8 105 978 1 0
  * n: Feedwater enthalpy
  * idsv isvn ilcn icn1 icn2
  9 105 961 1 0
  * n: Lower plenum pressure
  * idsv isvn ilcn icn1 icn2
  10 21 990 1003 0
  * n: Upper plenum pressure
  * idsv isvn ilcn icn1 icn2
  11 21 990 1009 0
  * n: Bypass out-flow
  * idsv isvn ilcn icn1 icn2
  12 69 990 1008 0
  * n: Bypass in-flow
  * idsv isvn ilcn icn1 icn2
  13 69 990 1003 0
  * n: Separator steam flow
  * idsv isvn ilcn icn1 icn2
  14 29 950 4 0
  * n: Liquid flow from separator top
  * idsv isvn ilcn icn1 icn2
  15 32 950 4 0
  * n: Vapor flow from side-tube
  * idsv isvn ilcn icn1 icn2
  16 29 950 5 0
  * n: Liquid flow from side tube
  * idsv isvn ilcn icn1 icn2

51
*n: Lower Plenum Density
  * idsv isvn ilcn icn1 icn2
  17  32    950    5    0

*n: Upper Plenum Density
  * idsv isvn ilcn icn1 icn2
  18    76    990  1003    0

*n: Bulk Fluid Region Pressure (ring 2, level 10)
  * idsv isvn ilcn icn1 icn2
  19    76    990  1009    0

*n: Bulk Fluid Region Density (ring 2, level 10)
  * idsv isvn ilcn icn1 icn2
  20    76    990  2010    0

*n: Recirculation Outlet Pressure
  * idsv isvn ilcn icn1 icn2
  21    21    990  2002    0

*n: Recirculation Discharge Pressure
  * idsv isvn ilcn icn1 icn2
  22    21    990  2001    0

*n: Separator Pressure
  * idsv isvn ilcn icn1 icn2
  23    21    990    1    0

*n: Separator Density
  * idsv isvn ilcn icn1 icn2
  24    76    950    1    0

*n: Steam line temperature
  * idsv isvn ilcn icn1 icn2
  25    22    978    1    0

**********************************************************************
** Control Blocks                                                **
**********************************************************************

**** Pump Flow Rate Controller Section *******************************

*n: Pump flow setpoint
  * idcb icbn icb1 icb2 icb3
  -100    9    0    0    0
  * cbgain cbxmin cbmax cbcon1 cbcon2
    1.0  -1.0E20  1.0E20  3210.0    0.0

*n: Difference between pump flow rate (CV1) and setpoint
  * idcb icbn icb1 icb2 icb3
  -101    54   -100    1    0
  * cbgain cbxmin cbmax cbcon1 cbcon2
    0.001  -1.0E20  1.0E20    0.0    0.0

*n: Integral term
  * idcb icbn icb1 icb2 icb3
  -102    23   -101    0    0
  * cbgain cbxmin cbmax cbcon1 cbcon2
    1.0  -500.0  500.0    0.0    0.0

*n: Differential term
  * idcb icbn icb1 icb2 icb3
  -103    12   -101    0    0
  * cbgain cbxmin cbmax cbcon1 cbcon2
    1.0  -100.0  100.0    0.0    0.0

*n: Differential term integrated with decay
  * idcb icbn icb1 icb2 icb3
  -104    78   -103    1    0
  * cbgain cbxmin cbmax cbcon1 cbcon2
    1.0  -100.0  100.0    1.0    0.0

*n: Initial guess at pump speed

52
***** Pressure Controller Section ************************************************

*n: Difference between steam dome pressure (CV2) and setpoint (-cbcon1)

*  idcb     icbn     icb1     icb2     icb3
-199  56     58     0     0
*  cbgain   cbxmin   cbmax   cbcon1   cbcon2
-0.5 -1.0E20  1.0E20  -7.0E6   0.0

*n: Integral term

*  idcb     icbn     icb1     icb2     icb3
-201  23     0     0
*  cbgain   cbxmin   cbmax   cbcon1   cbcon2
 0.2 -1.0E20  1.0E20   0.0   0.0

*n: Differential term

*  idcb     icbn     icb1     icb2     icb3
-203  12     0     0
*  cbgain   cbxmin   cbmax   cbcon1   cbcon2
 0.2 -1.0E20  1.0E20   0.0   0.0

*n: Differential term integrated with decay

*  idcb     icbn     icb1     icb2     icb3
-204  78     1     1
*  cbgain   cbxmin   cbmax   cbcon1   cbcon2
 1.0 -1.0E20  1.0E20   0.2   0.0

*n: Initial guess at turbine inlet pressure

*  idcb     icbn     icb1     icb2     icb3
-290  9     0     0
*  cbgain   cbxmin   cbmax   cbcon1   cbcon2
 1.0 -1.0E20  1.0E20  6.15E6   0.0

*n: Pressure controller

*  idcb     icbn     icb1     icb2     icb3
-299 103     1     1
*  cbgain   cbxmin   cbmax   cbcon1   cbcon2
 1.0  5.0E6  8.0E6   0.0   0.0
* weights*  1.0  1.0  1.0  1.0e
* ids   * -201 -202 -204 -290e

***** Water Level Controller Section *******************************************

*n: Difference between water level (CV3) and setpoint (-cbcon1)

*  idcb     icbn     icb1     icb2     icb3
-301  56     0     0
*  cbgain   cbxmin   cbmax   cbcon1   cbcon2
-500.0 -1.0E5  1.0E5   -8.4   0.0

*n: Integral term
* idcb  icbn  icb1  icb2  icb3
   -302  23  -301  0  0
* cbgain  cbxmin  cbmax  cbcon1  cbcon2
   0.01  -100.0  100.0  0.0  0.0
* n: Differential term
* idcb  icbn  icb1  icb2  icb3
   -303  12  -301  0  0
* cbgain  cbxmin  cbmax  cbcon1  cbcon2
   0.1  -10.0  10.0  0.0  0.0
* n: Differential term integrated with decay
* idcb  icbn  icb1  icb2  icb3
   -304  78  -303  1  1
* cbgain  cbxmin  cbmax  cbcon1  cbcon2
   1.0  -10.0  10.0  5.0  0.0
* n: Initial guess for feedwater flow rate
* idcb  icbn  icb1  icb2  icb3
   -309  9  0  0  0
* cbgain  cbxmin  cbmax  cbcon1  cbcon2
   1.0  -1.0E20  1.0E20  722.1  0.0
* weights*  1.0  1.0  1.0  1.0e
* ids*  -302  -304  -301  -309e
* ***** Subcooling Control Section *************************************
* n: Difference between core inlet temperature (CV4) and setpoint (-cbcon1)
* idcb  icbn  icb1  icb2  icb3
   -401  56  4  0  0
* cbgain  cbxmin  cbmax  cbcon1  cbcon2
   -1.0  -1.0E5  1.0E5  -538.15  0.0
* n: Integral term
* idcb  icbn  icb1  icb2  icb3
   -402  23  -401  0  0
* cbgain  cbxmin  cbmax  cbcon1  cbcon2
   0.1  -100.0  100.0  0.0  0.0
* n: Differential term
* idcb  icbn  icb1  icb2  icb3
   -403  12  -401  0  0
* cbgain  cbxmin  cbmax  cbcon1  cbcon2
   1.0  -1.0E20  1.0E20  0.0  0.0
* n: Differential term integrated with decay
* idcb  icbn  icb1  icb2  icb3
   -404  78  -403  1  1
* cbgain  cbxmin  cbmax  cbcon1  cbcon2
   1.0  -1.0E20  10.0  1.0  0.0
* n: Initial guess at feedwater temperature
* idcb  icbn  icb1  icb2  icb3
   -490  9  0  0  0
* cbgain  cbxmin  cbmax  cbcon1  cbcon2
*n: Subcooling controller
*  
*  
*  
*  
*  

1.0  -1.0E20  1.0E20  377.78  0.0

*weights*  1.0  1.0  1.0  1.0s
*weights*  0.11e
*ids*  -401  -402  -404  -490s
*ids*  -399e

***** Pressure Distribution Calculation *******************************

*n: Pressure at bottom of bulk fluid region
*c: Approximated by P + 1/2 h g rho
*  
*  
*  
*  
*  

1.0  -1.0E20  1.0E20  377.78  0.0

*weights*  1.0  1.0  1.0  1.0s
*weights*  0.11e
*ids*  -401  -402  -404  -490s
*ids*  -399e

*n: Core inlet pressure
*c: Approximated by P_LP - 1/2 h_LP g rho_LP
*  
*  
*  
*  
*  

1.0  -1.0E20  1.0E20  377.78  0.0

*weights*  1.0  1.0  1.0  1.0s
*weights*  0.11e
*ids*  -401  -402  -404  -490s
*ids*  -399e

*n: Core outlet pressure
*c: Approximated by P_UP + 1/2 h_UP g rho_UP
*  
*  
*  
*  
*  

1.0  -1.0E20  1.0E20  377.78  0.0

*weights*  1.0  1.0  1.0  1.0s
*weights*  0.11e
*ids*  -401  -402  -404  -490s
*ids*  -399e

*n: Pressure at top of upper plenum
*c: Approximated by P_UP - 1/2 h_UP g rho_UP
*  
*  
*  
*  
*  

1.0  -1.0E20  1.0E20  377.78  0.0

*weights*  1.0  1.0  1.0  1.0s
*weights*  0.11e
*ids*  -401  -402  -404  -490s
*ids*  -399e

*n: Pressure at bottom of separator
*c: Approximated by P_UP - 1/2 h_UP g rho_UP
*  
*  
*  
*  
*  

1.0  -1.0E20  1.0E20  377.78  0.0

*weights*  1.0  1.0  1.0  1.0s
*weights*  0.11e
*ids*  -401  -402  -404  -490s
*ids*  -399e

*n: Bulk fluid region pressure change
*  
*  
*  
*  
*  

1.0  -1.0E20  1.0E20  377.78  0.0

*weights*  1.0  1.0  1.0  1.0s
*weights*  0.11e
*ids*  -401  -402  -404  -490s
*ids*  -399e
### Downcomer pressure change

- **idcb**: 511, **icbn**: 54, **icb1**: 22, **icb2**: -500, **icb3**: 0
- **cbgain**: 1.0, **cbxmin**: -1.0E20, **cbmax**: 1.0E20, **cbcon1**: 0, **cbcon2**: 0

### Recirculation loop pressure change

- **idcb**: 512, **icbn**: 54, **icb1**: 23, **icb2**: 22, **icb3**: 0
- **cbgain**: 1.0, **cbxmin**: -1.0E20, **cbmax**: 1.0E20, **cbcon1**: 0, **cbcon2**: 0

### Lower plenum pressure change

- **idcb**: 513, **icbn**: 54, **icb1**: 22, **icb2**: -501, **icb3**: 0
- **cbgain**: 1.0, **cbxmin**: -1.0E20, **cbmax**: 1.0E20, **cbcon1**: 0, **cbcon2**: 0

### Core pressure drop

- **idcb**: 514, **icbn**: 54, **icb1**: 22, **icb2**: -502, **icb3**: 0
- **cbgain**: 1.0, **cbxmin**: -1.0E20, **cbmax**: 1.0E20, **cbcon1**: 0, **cbcon2**: 0

### Upper plenum pressure drop

- **idcb**: 515, **icbn**: 54, **icb1**: 22, **icb2**: -503, **icb3**: 0
- **cbgain**: 1.0, **cbxmin**: -1.0E20, **cbmax**: 1.0E20, **cbcon1**: 0, **cbcon2**: 0

### Stand pipe pressure drop

- **idcb**: 516, **icbn**: 54, **icb1**: 22, **icb2**: -504, **icb3**: 0
- **cbgain**: 1.0, **cbxmin**: -1.0E20, **cbmax**: 1.0E20, **cbcon1**: 0, **cbcon2**: 0

### Separator pressure drop

- **idcb**: 517, **icbn**: 54, **icb1**: 22, **icb2**: -505, **icb3**: 0
- **cbgain**: 1.0, **cbxmin**: -1.0E20, **cbmax**: 1.0E20, **cbcon1**: 0, **cbcon2**: 0

### Net Enthalpy Outflow Calculation

- **idcb**: 601, **icbn**: 39, **icb1**: 6, **icb2**: 8, **icb3**: 0
- **cbgain**: 1.0, **cbxmin**: -1.0E20, **cbmax**: 1.0E20, **cbcon1**: 0, **cbcon2**: 0

### Enthalpy inflow

- **idcb**: 602, **icbn**: 39, **icb1**: 7, **icb2**: 9, **icb3**: 0
- **cbgain**: 1.0, **cbxmin**: -1.0E20, **cbmax**: 1.0E20, **cbcon1**: 0, **cbcon2**: 0

### Net enthalpy outflow

- **idcb**: 603, **icbn**: 54, **icb1**: -601, **icb2**: -602, **icb3**: 0
- **cbgain**: 1.0, **cbxmin**: -1.0E20, **cbmax**: 1.0E20, **cbcon1**: 0, **cbcon2**: 0
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**Recirculation loop components**

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* tv  f  559.15 e
* p   f  7.09E6  7.32E6 e
* pa  f  0.0 e
* pmptb  r  0.0  1000.0  1000.0 e

******* type  num  userid  component name
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  ncells  nodes  jun1  jun2  epsw
  4  0  921  922  1.0E-5
  nsides
  0
  ichf  iconc  pipetype  ipow  npipes
  1  0  0  4
  radin  th  hout1  houtv  tout1
  0.0  0.0  0.0  0.0  0.0
  toutv  pwin  pwoff  rpwxm  pwscl
  0.0  0.0  0.0  0.0  0.0
  dx  2.232  2.1171667  r  1.9666667 e
  vol  0.63108313  0.59861478  r  0.55606191 e
  fa  0.28274334 e
  kfac  f  0.0 e
  grav  0.0  r  1.0  r  0.0 e
  hd  f  0.6 e
  icflg  f  0 e
  nff  r  1
  alp  f  0.0 e
  vl  3.6446 e
  vv  3.6446 e
  tl  538.15 e
  tv  559.15 e
  p  7.32E6  7.30E6  r  7.28E6 e
  pa  f  0.0 e

Steam separator

* type  num  id  ctitle
sepd  950  0  Separator
  jcell  nodes  ichf  cost  epsw
  2  0  1  1.0  1.0E-5
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  90  0  0  0.00  0.0000
  alpsmn  alpsmx
  0.01  0.99
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  toutv  pwin  pwoff  rpwxm  pwscl
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  0  0  952  0
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  toutv2  pwin2  pwoff2  rpwxm2  pwscl2
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  dx1  1.27  1.6 e
  vol1  0.05895622  0.111591 e
  fa1  0.04642222  0.04642222  0.0697444 e
  kfac1  0.1  14.6  1.0 e
  grav1  f  1.0 e
  hd1  0.300  0.300  0.298 e
  icflg1  f  0 e
  nff1  f  -1  1  -1 e
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### Feedwater Components

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### Pipe

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### Steam Line and Turbine Break

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Steam Line

* ncells nodes jun1 jun2 epsw
  1 0 978 979 1.0e-5

* nsides
  0

* ichf icnc pipetype ipow npipes
  1 0 0 0 4

* radin th houtl houtv toutl
  0 0 0.0 0.0 0.0

* toutv pwin pwoff rpwxm pwscl
  0 0.0 0.0 0.0 0.0

* dx 12.2 e

* vol 1.95761 e

* fa f 0.160460 e

* kfac f 0.0 0.5 e

* grav f 0.0 e

* hd f 0.452 0.452 e

* icfig f 0 e

* nff -1 1 e

* alp 1.0 e

* vl f 30.798 e

* vv f 30.798 e

* tl * 559.15 e

* tv * 559.15 e

* p * 6.15E6 e

* pa * 0.0 e

******* type num userid component name
valve 979 1 Turbine Control Valve

* ncells nodes jun1 jun2 epsw
  0 0 979 980 1.0e-5

* ichf icnc ivty ivps nvtb2
  1 0 3 0 0

* ivtr ivsv nvtb1 nsvv nvrf
  -1 5 2 0 0

* ivtrov ivtrv
  0 0

* rvmx rvov fminov fmaxov
  10.0 0.0 0.0 0.0

* radin th houtl houtv toutl
  0.0 0.0 0.0 0.0 0.0

* toutv avlve hvlve favlve xpos
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* dx f 0.0 e

* vol f 0.0 e

* fa f 0.64184 e

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* icfig f 0 e

* nff f -1 e

* alp f 0.0 e

* vl f 0.0 e

* vv f 0.0 e

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* tv f 0.0 e

* p f 0.0 e

* pa f 0.0 e

* vtbl 
  0.0 1.0 s

* vtbl 1.0E6 1.0 e

******* type num userid component name
break 980 1 Turbine Break

* jun1 ibty isat ioff adjpress
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* ibtr ibsv nbtb nbsv nbvf
  0 0 0 0 0

* dxin volin alpin tin pin
  1.0 0.856 1.0 559.15 6.15E6
* pain concin rhmx poff belv
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* ibpsv ibtlsv ibtvsy ibasv ibpasp
-299 0 0 0 0
* ibcnsv
  0
*
**********************************************************************
*
Reactor Vessel
**********************************************************************
*
****** type num userid component name
vessel 990 1 Reactor Vessel
*
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  15 2 1 451 0
*  idcu idcl idcr icru icrl
  9 1 1 8 3
*  icrr ilcsp lucsp iuhp iconc
  1 3 8 9 0
*  igeom nvent nvvtb nsgrid vesstype
  0 0 0 0 0
*  shelv epsw nolt
  0.0 1.0e-5 0
* z * 3.432 4.317 5.202 6.074 6.074 s
* z * 6.946 7.818 8.69 9.562 9.562 s
* z * 10.1 11.37 12.97 14.8 14.8 s
* z * 16.1 17.4 20.0 20.0 e
* r * 2.125 2.6 e
* t * 360.0 e
*  lisrl lisrc lisrf ljuns zfrac
  2 2 3 919 * Pump suction connection.
  1 2 3 922 * Pump discharge connection.
  9 1 2 950 * Stand pipes inlet.
  12 1 2 951 * Separator steam outlet.
  10 1 2 952 * Separator liquid outlet.
  10 2 3 961 * Feedwater connection.
  13 2 3 978 * Steam line connection.
  3 1 2 1001
  9 1 -2 2001

[Long list of channel connections]
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* cfzvz * 0.0 0.0 e
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* frvol * 0.654422 0.400000 e
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* vtnxr * -0.225 0.000 e
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* tln * 538.15 538.15 e
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level 2

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frfayt * 0.000000 0.000000 e
frfaz * 0.687285 0.987106 e
frfaxr * 0.000000 0.000000 e
hdyt * 0.00 0.00 e
hdz * 0.30 0.95 e
hdxr * 0.00 0.00 e
alpn * 0.00 0.00 e
vvnz * 0.00 0.00 e
vvnxr * 0.00 0.00 e
vnyt * 0.0 0.0 e
vinn * 0.423 -0.592 e
vlnxr * 0.00 0.00 e
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tln * 538.15 538.15 e
pn * 7.26e6 7.06e6 e
p * 0.0 0.0 e
ilev * 0 1 e

level 3

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cfzvz * 1716.0 0.0 e
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frfaz * 0.144866 0.987106 e
frfaxr * 0.000000 0.000000 e
hdyt * 0.00 0.00 e
hdz * 0.02 0.95 e
hdxr * 0.00 0.00 e
alpn * 0.00 0.00 e
vvnz * 0.0 0.0 e
vvnxr * 0.00 0.00 e
vnyt * 0.0 0.0 e
vinn * 0.261 -0.592 e
vlnxr * 0.00 0.00 e
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tln * 538.15 538.15 e
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p * 0.0 0.0 e
ilev * 0 1 e

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* Core channels

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</table>

[Inputs for channels 2 to 222 follow.]
<table>
<thead>
<tr>
<th>type</th>
<th>num</th>
<th>userid</th>
<th>component name</th>
</tr>
</thead>
<tbody>
<tr>
<td>power</td>
<td>999</td>
<td>1</td>
<td>power com</td>
</tr>
</tbody>
</table>

* numpwr chanpow
  222 1
* htnum *
  1 2 3 4 5 s
  6 7 8 9 10 s
  11 12 13 14 15 s
  16 17 18 19 20 s
  21 22 23 24 25 s
  26 27 28 29 30 s
  31 32 33 34 35 s
  36 37 38 39 40 s
  41 42 43 44 45 s
  46 47 48 49 50 s
  51 52 53 54 55 s
  56 57 58 59 60 s
  61 62 63 64 65 s
  66 67 68 69 70 s
  71 72 73 74 75 s
  76 77 78 79 80 s
  81 82 83 84 85 s
  86 87 88 89 90 s
  91 92 93 94 95 s
  96 97 98 99 100 s
  101 102 103 104 105 s
  106 107 108 109 110 s
  111 112 113 114 115 s
  116 117 118 119 120 s
  121 122 123 124 125 s
  126 127 128 129 130 s
  131 132 133 134 135 s
  136 137 138 139 140 s
  141 142 143 144 145 s
  146 147 148 149 150 s
  151 152 153 154 155 s
  156 157 158 159 160 s
  161 162 163 164 165 s
  166 167 168 169 170 s
  171 172 173 174 175 s
  176 177 178 179 180 s
  181 182 183 184 185 s
  186 187 188 189 190 s
  191 192 193 194 195 s
  196 197 198 199 200 s
  201 202 203 204 205 s
  206 207 208 209 210 s
  211 212 213 214 215 s
  216 217 218 219 220 s
  221 222 e

* irpwt * ndgx ndhx nrts nhist
  0 0 0 0
* izpwt * izpwsv nzpwtb nzpwsv nzpwr
  0 5 1 0
* ipwr * ipdep promheat decaheat wtbypass
  0 0.04 0.04 0.5
* nzpw * nzpwzi nfbpwt nrpwr nrpwzi
  26 -1 0 1 0
* react tneut rpowoff rrpwmx rpwsci
  0.0 4.5065E-4 0.0 1.0E20 1.0
* rpowzi * rpowzi * rpowzi
  1.436589 0.0 0.0 1.0E20
* extsou * pldr pdrat fucrac
  0.0 0.0 1.2898 0.0
* zpwzi * 0.0 0.14848 0.29696 0.44544 0.59392 s
* zpwzi * 0.7424 0.89088 1.03936 1.18784 1.33632 s
* zpwzi * 1.4848 1.63328 1.78176 1.93024 2.07872 s
* zpwzi * 2.2272 2.37568 2.52416 2.67264 2.82112 s
* zpwzi * 2.9696 3.11808 3.26656 3.41504 3.56352 s
* zpwzi * 3.712 e
* zpwtb 0.0 0.0
* zpwtb1* 0.294 0.940 1.157 1.212 1.211 s
* zpwtb1* 1.177 1.138 1.095 1.080 1.065 s
* zpwtb1* 1.055 1.045 1.060 1.074 1.083 s
* zpwtb1* 1.085 1.099 1.102 1.096 1.080 s
* zpwtb1* 1.045 0.972 0.845 0.675 0.316 s
* zpwtb1* 0.316 s
* zpwtb2* 1.0E6 s
* zpwtb2* 0.294 0.940 1.157 1.212 1.211 s
* zpwtb2* 1.177 1.138 1.095 1.080 1.065 s
* zpwtb2* 1.055 1.045 1.060 1.074 1.083 s
* zpwtb2* 1.085 1.099 1.102 1.096 1.080 s
* zpwtb2* 1.045 0.972 0.845 0.675 0.316 s
* zpwtb2* 0.316 e
*
* end
*
**********************************************************************
* Timestep Data
**********************************************************************
*                                                                 *
* dtmin           dtmax           tend           rtwfp
* 1.0E-6           0.1           500.0           1.0
* edint           gfint           dmpint           sedint
* 500.0           10.0           100.0           100.0
*                                                                 *
* endflag
* -1.0
**********************************************************************
* End of Input File
**********************************************************************
APPENDIX B: SAMPLE PARCS INPUT

The following is the steady-state input for PARCS for 98-12-12 point 1. However, values for the other operating conditions are available, and can be adjusted by altering which lines are commented with a “!”.

```
!________________________________________________________________________
! INPUT FOR OSKARSHAMN UNIT 2                                           |
! INPUT PREPARED AT NUCLEAR POWER SAFETY, ROYAL INSTITUTE OF TECHNOLOGY.|
! SEP 2008                                                               |
! PLEASE REPORT THE CHANGES OR MODIFICATIONS TO NPS                     |
! sean@safety.sci.kth.se                                                 |
!________________________________________________________________________|
CASEID parcs_co                                                        |
! Coupled steady state (CO) PARCS input                                 |
!________________________________________________________________________|

!________________________________________________________________________|
!                        CONTROL CARD                                          |
CNTL ! control card
CORE_TYPE    BWR          ! core type, PWR or BWR
! Boundary condition option 1: core power
! CORE_POWER   106.0       ! 990225 Pre-transient event conditions
CORE_POWER    84.5         ! 981212 p1
! CORE_POWER    81.8        ! 981212 p2
! CORE_POWER    78.8        ! 981212 p3
! CORE_POWER    75.6        ! 981212 p4
! CORE_POWER    72.1        ! 981212 p5
! CORE_POWER    81.7        ! 990313 p1
! CORE_POWER    78.4        ! 990313 p2
! CORE_POWER    77.9        ! 990313 p3
! CORE_POWER    74.9        ! 990313 p4
! CORE_POWER    72.4        ! 990313 p5
! Boundary condition option 2: control rod positions
! 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20
! BANK_POS     100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 23. 98. 1990225
BANK_POS     100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 22. 42. 981212 p1 & p2
BANK_POS     100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 8. 21. 41. 981212 p3
BANK_POS     100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 8. 22. 42. 981212 p4
BANK_POS     100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 8. 23. 43. 981212 p5
BANK_POS     100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 51. 100. 990313 p1 - p3
BANK_POS     100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 48. 100. 990313 p4
BANK_POS     100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 100. 45. 100. 990313 p5
! 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 100 T T F F F T F T F F T F !txk set a=F to get symmetric results
! a,x,e,p,d,v,i,y,e,g,h,l,h
!warning: ADFs are temporarily off to obtain symmetric solution without ADF rotation
ROT_ADF      T
XE_SM        l 1       ! Xe, Sm options 0=no Xe/Sm, 1=Eq, 2=tr
TH_FDBK      T ! True or False
! EXT_TH      T ./other/maptab_o2_003ch TRAC 100 l 1.0e+4 ! T or F, if T must specify
! EXT_TH      T ./other/maptab_o2_111ch TRAC 100 l 1.0e+4 ! T or F, if T must specify
TRANSIENT    F
restart      F     ./parcs_co.rst 402
! PRINT OPTIONS
!                   input iteration planar     adj
! edit    table    power    pin    reac
print_opt      T F T F
! fdbk     flux    planar
```

74
rhoprecurs flux Xe T/H

print_opt F F F F F F

! print_opt F F F F F F

oneD PKRE Radial P Radial Flux assy

! const Data Shape Shape const

print_opt F F F F F F

XS_EXTRAP 1.0 1.0 1.0 1.0

! END of CONTROL CARD

! PARAM CARD

PARAM

! Basic Iteration Control Parameters

n_iters 2 1500 ! min, max

! Convergence Criteria

conv_ss 1.0e-6 1.0e-5 5.0e-4 0.001 ! keff, fobfis, 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 ! nonlinear update: nupdcy, nitout, nthpnod

eps_anm 0.005 ! ann stabilization criteria

eps_erf 0.005 ! cv for inners exit

! Decusping

decusp 1 ! rod: 0=no, 1=flux, 2=ax discont

init_guess 0 ! 0=cos, 1=flat

! END of PARAM CARD

! GEOM CARD

! Boundary condition option 3: geometry file to use

GEOM

! file ./other/geom_o2_v7 ! Default geometry file

file ./other/geom_o2_v7_981212 ! Special geometry file for 981212

! END of GEOM CARD

! TH CARD

! OBS OBS OBS NEEDS TO BE UPDATED WITH NEW INFO FROM OKG

TH

UNIF_TH 0.721 626.85 302.85 !uniform TH state Dm,Tf,Tm, used when no fdbk

n_pingt 208 17 !npin,ngt

FA_POWPIT 3.8288 15.275 !assembly power(Mw) and pitch(cm)

pin_dim 4.6955 5.4640 0.673 6.731 !pin radii, rs,rw,tw, and rgt in mm

flow_cond 289.84 90.7448 !tin,cmfrfa(Kg/sec)

cdc_ded 3 2 !txk: WR addition

gamma_frac 0.00 0.00 !txk: WR addition, direc heating fraction

hgap 11356. !hgap(w/M^2-C)

n_ring 6 !number of meshes in pellet

thmesh_x 24*1 ! Number of T/H Nodes per FA in X-dir

thmesh_y 24*1 ! Number of T/H Nodes per FA in Y-dir

thmesh_z 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 !junction locations

! END of TH CARD

! TRAN

! time_step 20.00 0.00001 1.0 10.0 ! tend,delt0,tswitch,texpand

! scram T 116.6 0.0 1.3

! move_bank 1 0.0 100.0 1.1 100.0 245.0 0.0 !scram by screw drive

! move_bank 2 0.0 100.0 1.1 100.0 245.0 0.0

! move_bank 3 0.0 100.0 1.1 100.0 245.0 0.0
move_bank 4 0.0 100.0 1.1 100.0 245.0 0.0
move_bank 5 0.0 95.0 1.1 95.0 232.75 0.0
move_bank 6 0.0 100.0 1.1 100.0 245.0 0.0
move_bank 7 0.0 100.0 1.1 100.0 245.0 0.0
move_bank 8 0.0 100.0 1.1 100.0 245.0 0.0
move_bank 9 0.0 100.0 1.1 100.0 245.0 0.0
move_bank 10 0.0 100.0 1.1 100.0 245.0 0.0
move_bank 11 0.0 100.0 1.1 100.0 245.0 0.0
move_bank 12 0.0 100.0 1.1 100.0 245.0 0.0

theta 1.0 1.0 1.0

DEPL CARD

Boundary condition option 4: core history
DEPL
INP_HST './other/osk990225.dep' 1 1 1990225
INP_HST './other/osk981212p1.dep' 1 1 981212 p1
INP_HST './other/osk981212p2.dep' 1 1 981212 p2
INP_HST './other/osk981212p3.dep' 1 1 981212 p3
INP_HST './other/osk981212p4.dep' 1 1 981212 p4
INP_HST './other/osk990313p1.dep' 1 1 990313 p1
INP_HST './other/osk990313p2.dep' 1 1 990313 p2
INP_HST './other/osk990313p3.dep' 1 1 990313 p3
INP_HST './other/osk990313p4.dep' 1 1 990313 p4
INP_HST './other/osk990313p5.dep' 1 1 990313 p5
INP_HST './other/exposure_ideal.dep' 1 1 !History for restart, format, restart point
HST_OPT 'T T F F' !HCR, HMD, HSB, HTM 'txk use "T T F F" to read CR, MD, TF history
INP_OPT 'F F T T' !PPM, CRP, THS, XESM 'txk use "F F T T" to read TH and XESM
OUT_OPT 'T T T T' !POW, HST, THS, XESM, XS

BANK_NR 10 10 10 10 10 10 10 8 8 8 8 7

PMAXS_F 1 './PMAXS/botref_c.pmax' 1 txk: replace with correct xsec
PMAXS_F 2 './PMAXS/radref_c.pmax' 2 txk: replace with correct xsec
PMAXS_F 3 './PMAXS/topref_c.pmax' 28 txk: replace with correct xsec
PMAXS_F 4 './PMAXS/REFLB.PMAX' 1 txk: replace with correct xsec
PMAXS_F 5 './PMAXS/REFLR.PMAX' 2 txk: replace with correct xsec
PMAXS_F 6 './PMAXS/REFLT.PMAX' 28 txk: replace with correct xsec
PMAXS_F 7 './PMAXS/dummy.PMAX' 30 comment
PMAXS_F 8 './PMAXS/dummy.PMAX' 31 comment
PMAXS_F 9 './PMAXS/dummy.PMAX' 29 comment
PMAXS_F 10 './PMAXS/dummy.PMAX' 29 comment
PMAXS_F 11 './PMAXS/dummy.PMAX' 29 comment
PMAXS_F 12 './PMAXS/dummy.PMAX' 29 comment
PMAXS_F 13 './PMAXS/dummy.PMAX' 29 comment
PMAXS_F 14 './PMAXS/dummy.PMAX' 29 comment
PMAXS_F 15 './PMAXS/dummy.PMAX' 29 comment
PMAXS_F 16 './PMAXS/dummy.PMAX' 29 comment
PMAXS_F 17 './PMAXS/dummy.PMAX' 29 comment
PMAXS_F 18 './PMAXS/dummy.PMAX' 29 comment
PMAXS_F 19 './PMAXS/dummy.PMAX' 29 comment
PMAXS_F 20 './PMAXS/dummy.PMAX' 29 comment
PMAXS_F 21 './PMAXS/dummy.PMAX' 29 comment
PMAXS_F 22 './PMAXS/dummy.PMAX' 29 comment
PMAXS_F 23 './PMAXS/dummy.PMAX' 29 comment
PMAXS_F 24 './PMAXS/dummy.PMAX' 29 comment
PMAXS_F 25 './PMAXS/dummy.PMAX' 29 comment
PMAXS_F 26 './PMAXS/dummy.PMAX' 29 comment
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