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RAZORBACK – A Research Reactor Transient Analysis Code, Version 1.0

Volume 1: User's Manual

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Abstract

Razorback is a research reactor transient analysis computer code designed to simulate the operation of a research reactor (such as Sandia National Laboratories' Annular Core Research Reactor (ACRR)). The code provides a coupled numerical solution of the point reactor kinetics equations, the energy conservation equation for fuel element heat transfer, the equation of motion for fuel element thermal expansion, and the mass, momentum, and energy conservation equations for the water cooling of the fuel elements. This input manual describes how an input file is composed, and facilitates an understanding of the various code input parameters. The makeup of the various code output files is also described. This manual also provides instructions for the installation and setup of the code, and how to report bugs and/or errors.

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ACRONYMS

ACRR	Annular Core Research Reactor
BeO-UO ₂	Beryllium Oxide-Uranium Dioxide
CR	Control Rod
DOE	Department of Energy
DSA	Documented Safety Analysis
RHU	Rod Holdup
SR	Safety Rod
SNL	Sandia National Laboratories
TR	Transient Rod
TRW	Transient Rod Withdrawal
V&V	Verification and Validation

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1. INTRODUCTION

1.1. Code Overview

1.1.1. Background

Razorback is a research reactor transient analysis computer code designed to determine the response of a pool-type natural circulation research reactor such as Sandia National Laboratories' (SNL) Annular Core Research Reactor (ACRR) to reactivity additions. Razorback was designed with the ACRR in mind, but is expected to be useful in application to other research reactors. As such, a brief description of the ACRR is expected to be helpful in understanding the functions of the code and the construction of the input file.

The ACRR core, shown in Fig. 1, is located in a 3 m diameter 10 m deep pool water tank. The circulation of the coolant water is driven by means of natural circulation as the reactor heats the water within the core. The core consists of 236 fuel elements (of which 2 are fuel followed neutron absorbing safety rods and 6 are fuel followed neutron absorbing control rods). The elements of the core are arranged in a 4.2 cm pitch hexagonal grid.

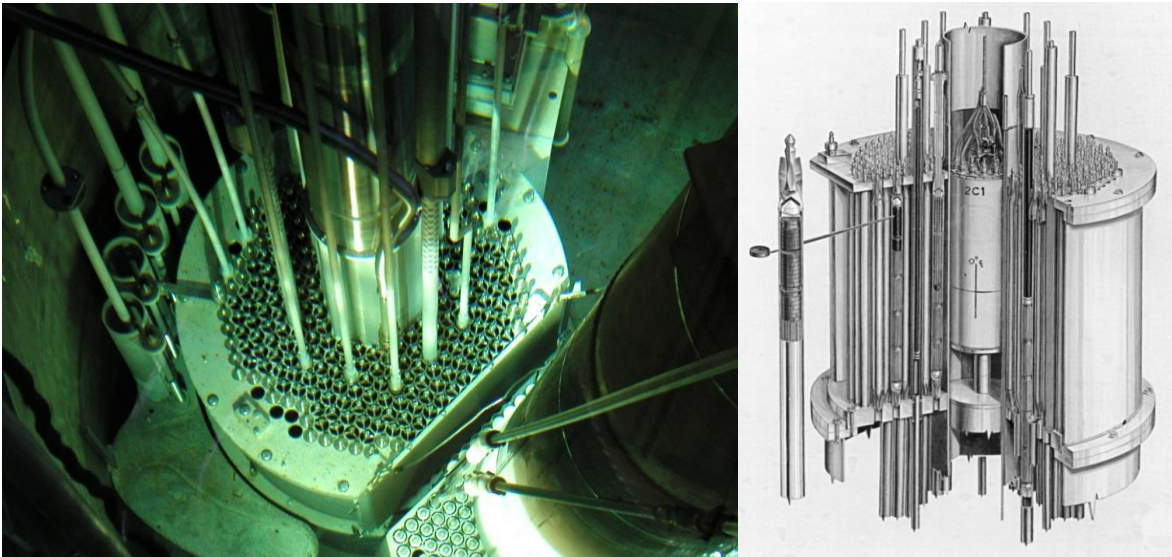


Figure 1. Photograph of the ACRR in its reactor pool water tank and a cutaway depiction.

The fuel itself, shown in Fig. 2, consists of a dispersion of uranium oxide within a beryllium oxide matrix (BeO-UO_2) cold-pressed and sintered into dual concentric annuli. The inner and outer annuli are cut into 180° arcs. These fuel pellets are stacked within niobium cans to a total fuel height of ~ 0.5 m. The fueled cans are sealed within stainless steel tubes 3.7 cm in outer diameter. The fuel element is sealed and backfilled with ~ 2 atm of helium, which occupies the various gap spaces between fuel annuli, the niobium can, and the stainless steel cladding.

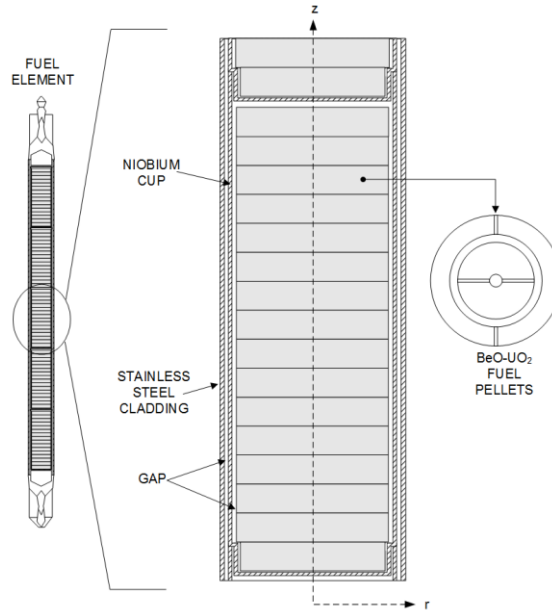


Figure 2. Schematic drawing of the ACRR fuel pellets within a fuel element.

The ACRR has three independent reactivity control mechanisms: a safety rod bank, a control rod bank, and a transient rod bank. The ACRR can be operated in a “steady-state” mode in which relatively slow changes in reactor power level up to ~2.5 MW are made via operator movement of the control rod bank out of or into the core. Rapid ejection of the transient rod bank allows the ACRR to be operated in a “pulse” mode in which Gaussian shaped reactor power pulses result with peak powers of up to ~30,000 MW with pulse widths of ~7 ms.

1.1.2. Nature of Problem Solved

Razorback determines the response of a natural circulation water cooled reactor system to additions of reactivity. The computations are based upon user-provided data related to fuel element geometry and materials, nuclear reactor kinetics parameters and reactivity feedback coefficients, coolant channel geometry, and reactor pool parameters. The nuclear reactor kinetic parameters are utilized to determine the change in reactor power due to the reactivity addition. Reactor power changes drive energy deposition within the fuel element model, which is then transferred within the fuel element components and into the adjacent coolant. Temperature changes within the fuel element induce thermal expansion displacements. Changes in the rate of heat transfer into the coolant result in coolant temperature and flowrate changes. These changes induce reactivity feedback to be coupled with the subsequent reactivity element movements. The overall result is a time history of reactor power, fuel element component temperatures and displacements, coolant channel temperatures and flowrate, etc., in response to the reactivity addition induced reactor transient. Razorback Version 1.0 has been verified and validated with respect to prediction of ACRR operations (Ref. 1).

Razorback performs a coupled numerical solution of the point reactor kinetics equations, the energy conservation equation for fuel element heat transfer, the equation of motion for fuel element material thermal expansion, and the mass, momentum, and energy conservation equations for the

water cooling of the fuel elements. The solution is currently formulated in cylindrical coordinates and focused on a single fuel element/coolant channel with a specified peaking factor.

The code evaluates the response of a reactor core consisting of multiple fuel elements (e.g., 236 with the ACRR) to reactivity additions such as from the movement of neutron absorbing control rods, by modeling a single reactor fuel element. Since only a single fuel element is modeled, the code uses a scheme to weight the contributions to total reactivity feedback within the fuel element and coolant channel model to determine the total reactivity feedback of the reactor.

Razorback may also be used to simulate the response of a natural circulation coolant channel to a user-specified time-dependent heat input (i.e., without simulating a reactor or fuel element), or for solving the point reactor kinetics equations to determine the response to a specified reactivity input with no reactivity feedback, or with a simple energy-release dependent reactivity feedback.

1.1.3. Use Cases for Razorback

The following are examples of problems or simulation scenarios to which Razorback may be applied:

- Determine the temperature distribution within a fuel element and its associated coolant channel for a fuel element operating at a specified steady power level.
- Determine the reactor power, fuel element temperature, and coolant channel temperature and flow histories in response to a specified reactivity addition or multiple reactivity additions over time.
- Determine the temperature distribution within a fuel element and its associated coolant channel for a fuel element in response to a specified transient power history.

1.1.4. Code Features

The following are examples of features of the Razorback code:

- Multiple radial fuel element material regions within a fuel element (to address fuel element types such as the ACRR's BeO-UO₂ fuel pellets, niobium fuel cans, stainless steel cladding, and helium-filled gaps)
- "Quasi-2D" heat transfer from fuel to coolant (1D radial heat transfer from a "stack" of axial fuel element segments)
- 1D natural circulation coolant flow
- Models to simulate a control rod bank, a safety rod bank, and a transient rod bank (including simulating pneumatic ejection)
- Multiple reactivity feedback mechanisms (fuel temperature, fuel expansion, cladding expansion, coolant density and temperature)
- Multiple scram system monitored variables (e.g., reactor power, reactor period, fuel temperature, pool water level) with setpoints

1.1.5. Code Limitations

The following describe the limitations of the Razorback code:

- The code presumes that fuel element materials remain in a solid state at all times, and has no mechanism for material relocation or movement due to melting or slumping. Execution will not cease if the temperature of a material exceeds its melting point. The user must recognize cases for which this occurs and treat the results appropriately.
- The code presumes that fuel element materials remain in a linear elastic stress-strain state (Hooke's law) at all times, and has no mechanism for material plastic behavior beyond a yield stress. Execution will not cease if the stress state in a material exceeds its elastic yield point. The user must recognize cases for which this occurs and treat the results appropriately.
- The Groeneveld Lookup Table (Ref. 6) used for critical heat flux prediction is known to be based upon limited data for low-pressure and low-flow regimes.
- Experimental data appropriate for the validation of two-phase flow computations in an ACRR-like configuration (low pressure, natural circulation, small channel flow area) has not yet been identified. Thus, the user must exercise caution and apply conservative judgment for problems in which the code results move into a two-phase flow boiling situation.

1.2. Organization of This Manual

The remainder of this manual is organized as follows:

Section 2 Installation and Use	Describes the process for installing and using the Razorback code. Also describes the installation testing utility, and how to report code bugs and errors.
Section 3 Input File Requirements	Describes the details of an <i>rsim.in</i> input file, including the various options and capabilities which may be employed.
Section 4 Output File Descriptions	Describes the various output files created by the code when executing a run.

2. INSTALLATION AND USE

The Razorback code is distributed as a compiled executable (*Razorback-V1.0.exe*), with a sample input file (*rsim.in*) which defines a simulation for an ACRR pulse operation. Also included is a zip file directory (*Test_Suite*) which contains all the files and scripts necessary to test the installation and proper execution of the Razorback code.

2.1. Computer Hardware/Software Requirements

The *Razorback-V1.0.exe* file has been run successfully under Windows 7, 8, and 10 operating systems.¹ The executable and sample input files require ~7 MB. The regression test suite for installation testing requires ~300 MB. Depending upon print frequency specifications in an input file, a Razorback run can generate 200-300 MB in output data files.

2.2. Installation

1. Copy the *Razorback-V1.0.exe* file to a directory of the user's choice.
2. Copy the sample *rsim.in* file to a directory of the user's choice. (See Section 2.4 for an important note regarding code execution and the *rsim.in* file.)
3. Copy the *Test_Suite* directory zip file to a directory of the user's choice.
4. Should the user desire, the PATH variable may be modified to add the directory in which the *Razorback-V1.0.exe* file will be located.

2.3. Testing

The installed version of Razorback may be tested by running the regression test script provided in the *Test_Suite* directory zip file. Successful installation is demonstrated with a regression test script log file indicating that no file differences were found. No differences are expected. If significant differences in numerical results are found, a re-installation is recommended. If the re-installation does not solve the problem, then please report this in the manner described in Section 2.5 below.

2.4. Execution

- A valid *rsim.in* file must be in the directory in which the Razorback execution command is given. The code does not have the ability to accept a different input file location. Copy the sample *rsim.in* file, or construct an *rsim.in* file using the instructions in Section 3 of this report in the same directory in which the Razorback execution command is to be given.
- Razorback may be run by double-clicking the *Razorback-V1.0.exe* file, or entering the command *Razorback-V1.0* at a DOS Command Prompt window associated with the

¹ Current plans are to make available executable files for Apple OSX and Linux/Unix systems in the near future.

executable directory. **NOTE:** The *rsim.in* file must be present in the directory from which the execution command is given.

- Input and output files that the user wishes to retain from a Razorback run must be moved/copied to an alternate location before executing Razorback again in the same location because output files resulting from Razorback execution will be overwritten by any subsequent execution of the code. Alternatively, the user must move to a new directory with its own *rsim.in* file to perform a subsequent Razorback run. Of course, script files may be created by the user to accommodate these execution realities.
- The code conducts a very limited amount of checking of the inputs for consistency. When such problems are found, the code will in many cases execute a FORTRAN *stop* statement with a brief message describing the issue.² If code execution fails quickly after it begins, the likely cause is an error in the input file (e.g., missing input card or a missing value on an input card).
- Error traps for some issues (e.g., requested coolant properties exceeding the pressure for which data is available in the code) which may arise during execution are included in the code, and are logged to an *error.log* file. Unfortunately, not all errors such as these have error traps that will cause an entry in the *error.log* file before code execution fails.

2.5. Error and Bug Reporting

For users who discover apparent issues with Razorback, it is recommended that a fellow user with similar or more experience be consulted. The Razorback software point-of-contact (POC) may also be contacted for consultation. This will aide in distinguishing code errors/bugs from user errors.

The Razorback POC will ensure that errors or bugs in Razorback are appropriately entered into a problem reporting and corrective action process as laid out in the Razorback Software Quality Assurance Plan (SSQAP) and TA-V administrative procedures.

Razorback POC: Darren Talley
 (505) 284-9611
 dgtalle@sandia.gov

All users are encouraged to send suggested improvements to the same e-mail address.

² FORTRAN *stop* messages are displayed in the DOS window execution environment. If the code was started with a DOS command line, the user will see the message. If the code was started by double-clicking the executable, the execution window will close too fast for the user to see the message.

3. INPUT REQUIREMENTS

This section presents a description of the input requirements for the execution of the RAZORBACK code.

Note that unless specifically stated otherwise below, **all** input parameters are **required**. An entry value may be arbitrary, depending upon option selections, but in general an entry must still be made.

RAZORBACK input files, as distributed with the code, have many comment lines which serve as a guide to specifying the various input parameters. A comment line is any line which begins with the asterisk character (*) in the first space of the line. The user may include as many comment lines as desired. In addition, the user may retain input parameter lines for ease of recall in future runs by simply placing an asterisk in the first space of that line, and creating a new input parameter line in its place.

As a means of facilitating the listing and description of input parameters, the subsections below will include the input-guiding comment lines from the RAZORBACK input file followed by the parameters (variable names) which must be included for that input line. Variable names in all lowercase letters are single value variables. Variable names in all uppercase letters are arrays which can have multiple values.

The maximum single line length for input values is 80 characters. At least one space is required between each input value.

After all of the required input values are entered on a line, the user is free to add text to annotate the input file. This is allowed because once all required input values on a line have been read in by the code, the remainder of the line is ignored.

In general, variable names beginning with letters a-g or o-z are real type variables, while names beginning with i-n are integer type variables. Integer type entries have no decimal. Real type entries may be in any of the following forms: 100., 1000.0, 1.00e2, 1.00e+2, 1.00e+02, 1.00d+2, 1.00d+02, 100.0e0, 100.0 d0, 100.e0, 0.025, .025, 0.025e0, etc. The code is written in Fortran, so the exponential format values with a “d” indicate that the code will read that value as a double-precision value.

A sample input file is provided in Appendix A.

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3.1. Calculation and Printing Controls

The input file begins with a Calculation and Printing Controls sections which control, among other things, the calculation type, time step control, and output file print frequency.

3.1.1. High Level Calculation Control and Title Cards

```

*****
*                               CALCULATION AND PRINTING CONTROLS
*****
*-----|-----|-----|-----|
* Calculation Type | Rx Kinetics (0) | Total | Number of |
* (1=steady-state, | or Power History | Transient | Title Cards |
* 0=transient)    | Data File (1)   | Time (s) | (up to 20)  |
*-----|-----|-----|-----|
*          issflg          |          irx_off          |          tmax          |          n_title_cards
*-----|-----|-----|-----|
*                               Title Cards
*-----|-----|-----|-----|
*          TITLE_CARD
*-----|-----|-----|-----|

```

Table 1. Calculation type parameters and title cards.

Item	Input Parameter Description
<i>issflg</i>	This parameter controls the type of calculation which will be executed. 0 → specifies a transient calculation. 1 → specifies a steady-state calculation.
<i>irx_off</i>	This parameter controls the means by which the power in the fuel is determined. 0 → specifies that the power will be determined by a reactor kinetics calculation. 1 → specifies that a text file (<i>pwrhis.dat</i>) with power history data points will be used. The first line of the text file is assumed to have title and/or column heading information. Subsequent lines are assumed to be time(s)-power(W) data pairs ³ , formatted as two real numbers separated by at least one space. The code will scan the data pairs to ensure that the final time entry is greater than or equal to <i>tmax</i> (see below). If not, then the code will stop execution with an error message.
<i>tmax</i>	This parameter sets the termination time of a transient calculation. When the time variable in the code reaches or exceeds this specified time, the calculation will cease, final outputs will be written, and code execution will end.
<i>n_title_cards</i>	This parameter specifies the number of title cards that the input processor is to expect beginning with the next non-comment line. Up to 20 title cards are allowed.
<i>TITLE_CARD(n)</i>	The title cards read in here will be printed at the beginning of the main code output file <i>rsim.out</i> to provide user-desired description of the code run. Each title card will be read in as an 80 character text string. Any number of initial spaces on the title cards is acceptable (within the total 80 character limit). NOTE: The first character cannot be an asterisk (*).

³ The routine which interpolates reactor power between time points in the user-supplied *pwrhis.dat* file has some difficulty when time points are closely spaced (e.g., on the order of milliseconds). The result is that code execution fails.

3.1.2. Initial Condition Stabilization Option

A Razorback transient analysis must begin from a system at a stable steady-state initial condition. The code will compute this steady-state initial condition prior to starting the transient calculation. An option here allows the user to run a “pre-transient” for a specified amount of time in order to assure that the initial conditions have indeed stabilized. The user specifies a time duration and a constant time step. The code will then begin from its computed steady-state condition and march forward in time. No reactivity addition is allowed, no reactivity feedback is computed, and reactor power remains constant. If the initial condition were not truly at a steady-state, then the code will move toward a new stable steady-state condition. Note that the user must specify the duration and time step such that the achievement of a stable steady-state solution occurs. At the end of the specified time, the code takes the current conditions, and treats those as the new steady-state initial condition. Time is reset to zero, and the transient calculation begins.

```

*-----|
* Number of Time Step Ranges | Initial Condition Stabilization |
* (up to 20) | Duration (s) | Time Step (s) |
*-----|-----|-----|
* ntsteps4 | t_ss_stabilize | dt_ss_stabilize |
*-----|

```

Table 2. Initial condition stabilization option parameters.

Item	Input Parameter Description
<p><i>ts_ss_stabilize</i></p> <p><i>dt_ss_stabilize</i></p>	<p>These parameters control whether the code will perform an initial condition stabilization run prior to executing the transient run.</p> <p>If <i>ts_ss_stabilize</i> > 0, then a stabilization run will be executed for <i>ts_ss_stabilize</i> seconds (analysis time, not clock time) using a constant time step of <i>dt_ss_stabilize</i> seconds.</p> <p>During a stabilization run, reactivity feedback is disabled, and power will remain constant. The purpose of this option is to allow time to ensure that the initial conditions have reached a stable equilibrium.</p> <p>The need for and use of this option is at the user’s discretion and judgment.</p>

⁴ See the following section (Sect. 3.1.3) for a discussion of this input parameter.

3.1.3. Time Step Specifications

Based upon the user-specified reactivity addition commands (addressed in later sections), the user may desire to specify time step restrictions (e.g., and upper and lower limit) for various time spans of the calculation. Here, the code allows for the user to specify up to 20 time ranges to set different maximum and minimum time step specifications. In addition, the user may activate an automatic time step controller within these time ranges. The time step controller methodology is described in Ref. 2.

Within a given time step time range, a constant time step (equal to the maximum time step entry) will be used, unless the time step controller is active in that time range. If the time step controller is active, then the time step will increase or decrease (within the minimum and maximum time step bounds set here by the user) based upon the time step controller algorithm.

Finally, we note that the code allows the user to specify a “thermal-hydraulic” time step for each time range. This thermal-hydraulic time step option was included for cases in which the solution of the reactor kinetics equation requires very small time steps, but the solution for the coolant channel flow thermal-hydraulics could advance with larger time steps. An example is during the reactor power rise due to a rapid reactivity addition, when the reactor kinetics time step may be microseconds or less, the thermal-hydraulic time step may only need to be on the order of milliseconds or perhaps greater. With this option active the code will compute the reactor kinetics and fuel thermomechanical solutions over many small time steps, but skip the coolant channel thermal-hydraulics solution until the sum of the time steps reaches the user-specified thermal-hydraulic time step.

```

*-----|-----|-----|
* Number of Time Step Ranges | Initial Condition Stabilization |
* (up to 20) | Duration (s) | Time Step (s) |
*-----|-----|-----|
*          ntsteps          |          t_ss_stabilize          |          dt_ss_stabilize          |
*-----|-----|-----|
*          |          |          Time Step Control (TSC)          |
*          |          |          (If TSC is off, then          |
*          |          |          dt = max time step of range)          |
* Time Range | Time Step | T/H | TSC | TSC |
* Begin(s)/End(s) | max(s) / min(s) | dt(s) | "Error" | (1=y/0=n) |
*-----|-----|-----|
* TSR_LOW TSR_HIGH | TS_MAX TS_MIN | DT_TH | DP_OVER_P | ITSC |
*-----|-----|-----|

```

Table 3. Time step specifications and automatic time step control options.

Item	Input Parameter Description
<i>ntsteps</i>	This parameter specifies the number of time step range cards that the input processor is to expect beginning with the next non-comment line. Up to 20 time step range cards are allowed.
<i>TSR_LOW(n)</i> <i>TSR_HIGH(n)</i>	These parameters specify the calculation time range over which the subsequent parameter controls on this card are applied. <i>TSR_LOW</i> is the beginning time (s) of time range <i>n</i> . <i>TSR_HIGH</i> is the ending time (s) of the range. NOTE: The final <i>TSR_HIGH</i> value must be greater than the total calculation time (<i>tmax</i>).
<i>TS_MAX(n)</i> <i>TS_MIN(n)</i>	These parameters specify the maximum and minimum time steps for time step range <i>n</i> . <i>TS_MAX</i> is the maximum time step (s) of time range <i>n</i> . <i>TS_MIN</i> is the minimum time step (s) of time range <i>n</i> . NOTE: If the time step controller is not used for time range <i>n</i> (i.e., if <i>ITSC</i> =0), then the time step used for all of time range <i>n</i> will be <i>TS_MAX</i> . NOTE: Code execution will begin by using the maximum time step specified for the first time range. The user should ensure that an appropriate time step is selected if the initial reactivity addition is rapid.
<i>DT_TH(n)</i>	This parameter specifies the maximum allowed thermal-hydraulic time step for time step range <i>n</i> (if <i>ITSC</i> =1, see below). NOTE: <i>TS_MAX</i> for time range <i>n</i> . is not allowed to be larger than <i>DT_TH</i> for the same time range. If this rule is violated, then code execution will stop during the reading of the input file.
<i>DP_OVER_P(n)</i>	This parameter specifies a relative error for time step range <i>n</i> to be used by the time step controller (if <i>ITSC</i> =1, see below).
<i>ITSC(n)</i>	This parameter specifies whether the time step controller routine. 0 → Time step controller is off. 1 → Time step controller is on. NOTE: It is currently recommended that the time step controller be used for all cases. A known bug causes a divide-by-zero error if <i>ITSC</i> =0. This user may effectively turn the time step controller off by setting <i>ITSC</i> =1, but also setting <i>TS_MAX</i> and <i>TS_MIN</i> to have the same value. The time step controller routine will still be executed, but the routine will not be able to change the time step from <i>TS_MAX</i> = <i>TS_MIN</i> .

3.1.4. Screen and File Print Frequency Specifications

Razorback prints information to the console screen (see Sect. 3.1.5), to several output data files (see Sects. 4.2-4.5), and a primary output file (see Sect. 4.1.1). The user may set the print frequency of these printing actions, and the user may specify different print frequencies for different time ranges of the calculation. This section describes the parameters used to implement this function.

```

*-----|-----|
* Number of Print Increment Ranges | |
*      (up to 20)                   | |
*-----|-----|
*          n_incr_ranges
*-----|-----|
*          screen | plot | file |
* Print Time Range | print | print | print |
* Begin(s)/End(s) | incr.(s) | incr.(s) | incr.(s) |
*-----|-----|
*          TPR_LOW  TPR_HIGH          P_INCR_S  P_INCR_P  P_INCR_F
*-----|-----|

```

Table 4. Output file print frequency parameters.

Item	Input Parameter Description
<i>n_incr_ranges</i>	This parameter specifies the number of time ranges for which print frequencies will be provided.
<i>TPR_LOW</i> (<i>n</i>) <i>TPR_HIGH</i> (<i>n</i>)	This parameter specifies the lower and upper time values for the <i>n_incr_ranges</i> print frequency time ranges.
<i>P_INCR_S</i> (<i>n</i>)	This parameter specifies the time (s) between instances when the code prints output to the computer screen. Screen output is printed every <i>P_INCR_S</i> seconds of analysis time (not CPU or real time).
<i>P_INCR_P</i> (<i>n</i>)	This parameter specifies the time (s) between instances when the code prints output to the main data plot file <i>rsim.dat</i> . Plot data output is printed every <i>P_INCR_P</i> seconds of analysis time (not CPU or real time). This print frequency also applies to all output data files described in Sections 4.3, 4.4, and 4.5 of this manual.
<i>P_INCR_F</i> (<i>n</i>)	This parameter specifies the time (s) between instances when the code prints output to the main output file <i>rsim.out</i> . Output file data is printed every <i>P_INCR_F</i> seconds of analysis time (not CPU or real time).

3.1.5. Pulse Characteristic File Print and Fuel Element/Channel View Print

Razorback can print a summary of pulse parameters when the main calculation is complete (see Fig. 3). In addition, the user may suppress the full fuel element and coolant conditions display (see Fig. 4) in favor of a shortened display data set. This section describes the parameters used to implement this function.

```

*-----|-----|
* pulse parameter file print | fuel rod screen/file print |
*   (1=yes, 0=no)           |   (1=yes, 0=no)           |
*-----|-----|
*           i_pulse_print           |           i_fuel_print           |
*-----|-----|

```

Item	Input Parameter Description
<i>i_pulse_print</i>	<p>This parameter controls whether the code will review the output data at the end of the calculation in order to determine various pulse parameters (e.g., peak power, energy yield, pulse width, etc.). A depiction of this pulse parameter summary data printout is shown in Fig. 3.</p> <p>0 → No pulse parameter summary printout. 1 → Include a pulse parameter summary printout at the end of the <i>rsim.out</i> file.</p>
<i>i_fuel_print</i>	<p>This parameter controls whether the code will printout (on screen and in <i>rsim.out</i>) of the fuel element and coolant channel conditions display. A depiction of the screen display is shown in Fig. 4.</p> <p>0 → No fuel element/coolant channel conditions printout. Only the portion of Fig. 4 from the “Time” to the “Peak Values” will be printed on the screen and in <i>rsim.out</i>. 1 → Print the fuel element/coolant channel conditions display on screen and in the <i>rsim.out</i> file.</p> <p>The screen display will be updated at the <i>P_INCR_S</i> frequency. The output file version will be printed at the <i>P_INCR_F</i> frequency in <i>rsim.out</i>.</p>

Pulse Parameters

The TR reactivity addition was	1.911 \$	
The pulse peak occurred at	368.17E-03 s	
The peak system reactivity was	1.911 \$ at	318.08E-03 s
The rod holdup time was	0.400 s	
The peak power was	5.612E+09 W	
The FWHM was	14.792E-03 s	
The LEHM was	7.082E-03 s	
The TEHM was	7.710E-03 s	
The minimum period was	3.622E-03 s at	341.04E-03 s
The pulse yield at the peak was	44.4E+06 J	
The pulse yield at peak+3*FWHM was	95.2E+06 J	
The total pulse yield was	112.2E+06 J at	20.001 s
The peak measured fuel temperature was	422.7 C at	14.0E+00 s

Figure 3. Example of a pulse parameter printout.

```

Time = 0.0000 s Current time step = 1.00E-03 s 0
Rod Position CR SR TR 0.0000
Reactivity Addition 0.000$ 0.000$ 0.000$

Reactor Power : 23.90E+00 W 1.00E-03 %
System Reactivity : 0.00E+00 $
RCS Added Reactivity : 0.00E+00 $
Total Reactivity Feedback : 0.00E+00 $
fuel tmp feedback : 0.00E+00 $
fuel exp feedback : 0.00E+00 $
clad exp feedback : 0.00E+00 $
coolant feedback : 0.00E+00 $
Reactor Period : 10.00E+09 s or 0.00E+00 dpm SUR
Minimum Reactor Period : 100.00E+19 s at t = 0.00E+00 s
Reactor Yield : 0.0E+00 J

Max./Meas. Fuel Temperature : 20.14 C / 20.11 C
Inner / Outer Clad Temperature : 20.13 C / 20.10 C
Coolant Channel Mass Flow : 0.30 g/s
Outlet Quality / Boiling Length : -16.97 % / 0.00 cm
Inlet / Outlet Temperature : 20.00 C / 20.13 C
Inlet / Outlet Enthalpy : 83.94 J/g / 84.44 J/g
Fuel Power : 149.94E+03 W
Heat Transfer Power : 149.94E+03 W
Neutron/Gamma Heating Power : 1.97E-03 W
Total Power to Coolant : 151.91E+03 W
Coolant Convection Power : 151.91E+03 W

MCHFPR is 910.41E+03 at fuel height of 21.77 cm
Peak Values : 0.00E+00 W and 0.00E+00 J at 0.00E+00 s

j I1 I2 I3 I4 I5 I6 I7 I8 I9 I10 h x % vf % mdot P dens gmfi gmfo hxc Re q'' M/cm2 CHF-GLUT
51 ----- 20.1 84.44 -16.97 0.00 0.30 21.011 0.9981 0.0736 0.0736 0.000 1.01E+01 0.000E+00 -----
52 ----- 20.1 84.44 -16.97 0.00 0.30 21.026 0.9981 0.0736 0.0736 0.000 1.01E+01 0.000E+00 -----
50 ----- 20.1 84.44 -16.98 0.00 0.30 21.040 0.9981 0.0736 0.0736 0.000 1.01E+01 0.000E+00 -----
49 ----- 20.1 84.44 -16.98 0.00 0.30 21.054 0.9981 0.0736 0.0736 0.000 1.01E+01 0.000E+00 -----
48 ----- 20.1 84.44 -16.99 0.00 0.30 21.069 0.9981 0.0736 0.0736 0.000 1.01E+01 0.000E+00 -----
47 ----- 20.1 84.44 -16.99 0.00 0.30 21.083 0.9981 0.0736 0.0736 0.000 1.01E+01 0.000E+00 -----
46 ----- 20.1 84.44 -17.00 0.00 0.30 21.097 0.9981 0.0736 0.0736 0.000 1.01E+01 0.000E+00 -----
45 ----- 20.1 84.44 -17.00 0.00 0.30 21.112 0.9981 0.0736 0.0736 0.000 1.01E+01 0.000E+00 -----
44 ----- 20.1 84.44 -17.01 0.00 0.30 21.126 0.9981 0.0736 0.0736 0.000 1.01E+01 0.000E+00 -----
43 ----- 20.1 84.45 -17.01 0.00 0.30 21.146 0.9981 0.0736 0.0736 0.000 1.01E+01 0.000E+00 -----
42 20 20 20 20 20 20 20 20 20.1 84.44 -17.02 0.00 0.30 21.171 0.9981 0.0736 0.0736 0.020 1.01E+01 1.310E-04 2.09E+06
41 20 20 20 20 20 20 20 20 20.1 84.43 -17.03 0.00 0.30 21.195 0.9981 0.0736 0.0736 0.020 1.01E+01 1.363E-04 1.98E+06
40 20 20 20 20 20 20 20 20 20.1 84.42 -17.03 0.00 0.30 21.220 0.9981 0.0736 0.0736 0.020 1.01E+01 1.497E-04 1.83E+06
39 20 20 20 20 20 20 20 20 20.1 84.41 -17.04 0.00 0.30 21.245 0.9981 0.0736 0.0736 0.020 1.01E+01 1.636E-04 1.68E+06
38 20 20 20 20 20 20 20 20 20.1 84.39 -17.05 0.00 0.30 21.270 0.9981 0.0736 0.0736 0.020 1.01E+01 1.786E-04 1.54E+06
37 20 20 20 20 20 20 20 20 20.1 84.38 -17.06 0.00 0.30 21.295 0.9981 0.0736 0.0736 0.020 1.01E+01 1.941E-04 1.42E+06
36 20 20 20 20 20 20 20 20 20.1 84.36 -17.07 0.00 0.30 21.320 0.9981 0.0736 0.0736 0.020 1.01E+01 2.093E-04 1.32E+06
35 20 20 20 20 20 20 20 20 20.1 84.35 -17.07 0.00 0.30 21.345 0.9981 0.0736 0.0736 0.020 1.01E+01 2.240E-04 1.24E+06
34 20 20 20 20 20 20 20 20 20.1 84.33 -17.08 0.00 0.30 21.370 0.9981 0.0736 0.0736 0.020 1.01E+01 2.379E-04 1.17E+06
33 20 20 20 20 20 20 20 20 20.1 84.32 -17.09 0.00 0.30 21.395 0.9981 0.0736 0.0736 0.020 1.01E+01 2.510E-04 1.11E+06
32 20 20 20 20 20 20 20 20 20.1 84.30 -17.10 0.00 0.30 21.420 0.9981 0.0736 0.0736 0.020 1.01E+01 2.630E-04 1.06E+06
31 20 20 20 20 20 20 20 20 20.1 84.28 -17.11 0.00 0.30 21.444 0.9981 0.0736 0.0736 0.020 1.01E+01 2.741E-04 1.02E+06
30 20 20 20 20 20 20 20 20 20.1 84.26 -17.11 0.00 0.30 21.469 0.9981 0.0736 0.0736 0.020 1.01E+01 2.841E-04 985.16E+03
29 20 20 20 20 20 20 20 20 20.1 84.24 -17.12 0.00 0.30 21.494 0.9981 0.0736 0.0736 0.020 1.01E+01 2.929E-04 958.23E+03
28 20 20 20 20 20 20 20 20 20.1 84.22 -17.13 0.00 0.30 21.519 0.9981 0.0736 0.0736 0.020 1.01E+01 3.005E-04 937.21E+03
27 20 20 20 20 20 20 20 20 20.1 84.20 -17.14 0.00 0.30 21.544 0.9981 0.0736 0.0736 0.020 1.01E+01 3.066E-04 922.04E+03
26 20 20 20 20 20 20 20 20 20.1 84.17 -17.15 0.00 0.30 21.569 0.9981 0.0736 0.0736 0.020 1.01E+01 3.110E-04 912.94E+03
25 20 20 20 20 20 20 20 20 20.1 84.15 -17.16 0.00 0.30 21.594 0.9981 0.0736 0.0736 0.020 1.01E+01 3.134E-04 910.41E+03
24 20 20 20 20 20 20 20 20 20.1 84.13 -17.16 0.00 0.30 21.619 0.9981 0.0736 0.0736 0.020 1.01E+01 3.135E-04 915.26E+03
23 20 20 20 20 20 20 20 20 20.0 84.11 -17.17 0.00 0.30 21.644 0.9981 0.0736 0.0736 0.020 1.01E+01 3.111E-04 928.64E+03
22 20 20 20 20 20 20 20 20 20.0 84.09 -17.18 0.00 0.30 21.668 0.9981 0.0736 0.0736 0.020 1.01E+01 3.059E-04 952.15E+03
21 20 20 20 20 20 20 20 20 20.0 84.07 -17.19 0.00 0.30 21.693 0.9981 0.0736 0.0736 0.020 1.01E+01 2.978E-04 987.96E+03
20 20 20 20 20 20 20 20 20 20.0 84.05 -17.20 0.00 0.30 21.718 0.9981 0.0736 0.0736 0.020 1.01E+01 2.867E-04 1.04E+06
19 20 20 20 20 20 20 20 20 20.0 84.03 -17.21 0.00 0.30 21.743 0.9981 0.0736 0.0736 0.020 1.01E+01 2.729E-04 1.11E+06
18 20 20 20 20 20 20 20 20 20.0 84.01 -17.21 0.00 0.30 21.768 0.9981 0.0736 0.0736 0.020 1.01E+01 2.569E-04 1.21E+06
17 20 20 20 20 20 20 20 20 20.0 84.00 -17.22 0.00 0.30 21.793 0.9981 0.0736 0.0736 0.020 1.01E+01 2.393E-04 1.34E+06
16 20 20 20 20 20 20 20 20 20.0 83.98 -17.23 0.00 0.30 21.818 0.9981 0.0736 0.0736 0.020 1.01E+01 2.215E-04 1.48E+06
15 20 20 20 20 20 20 20 20 20.0 83.97 -17.24 0.00 0.30 21.843 0.9981 0.0736 0.0736 0.020 1.01E+01 2.052E-04 1.60E+06
14 20 20 20 20 20 20 20 20 20.0 83.95 -17.25 0.00 0.30 21.868 0.9981 0.0736 0.0736 0.020 1.01E+01 1.928E-04 1.70E+06
13 20 20 20 20 20 20 20 20 20.0 83.94 -17.25 0.00 0.30 21.892 0.9981 0.0736 0.0736 0.020 1.01E+01 1.875E-04 1.75E+06
12 ----- 20.0 83.94 -17.26 0.00 0.30 21.912 0.9981 0.0736 0.0736 0.000 1.01E+01 0.000E+00 -----
11 ----- 20.0 83.94 -17.26 0.00 0.30 21.926 0.9981 0.0736 0.0736 0.000 1.01E+01 0.000E+00 -----
10 ----- 20.0 83.94 -17.27 0.00 0.30 21.941 0.9981 0.0736 0.0736 0.000 1.01E+01 0.000E+00 -----
9 ----- 20.0 83.94 -17.27 0.00 0.30 21.955 0.9981 0.0736 0.0736 0.000 1.01E+01 0.000E+00 -----
8 ----- 20.0 83.94 -17.28 0.00 0.30 21.970 0.9981 0.0736 0.0736 0.000 1.01E+01 0.000E+00 -----
7 ----- 20.0 83.94 -17.28 0.00 0.30 21.984 0.9981 0.0736 0.0736 0.000 1.01E+01 0.000E+00 -----
6 ----- 20.0 83.94 -17.28 0.00 0.30 21.998 0.9981 0.0736 0.0736 0.000 1.01E+01 0.000E+00 -----
5 ----- 20.0 83.94 -17.29 0.00 0.30 22.013 0.9981 0.0736 0.0736 0.000 1.01E+01 0.000E+00 -----
4 ----- 20.0 83.94 -17.29 0.00 0.30 22.027 0.9981 0.0736 0.0736 0.000 1.01E+01 0.000E+00 -----
3 ----- 20.0 83.94 -17.30 0.00 0.30 22.041 0.9981 0.0736 0.0736 0.000 1.01E+01 0.000E+00 -----
2 ----- 20.0 83.94 -17.30 0.00 0.30 22.056 0.9981 0.0736 0.0736 0.000 1.01E+01 0.000E+00 -----
1 ----- 20.0 83.94 -17.31 0.00 0.30 22.070 0.9981 0.0736 0.0736 0.000 1.01E+01 0.000E+00 -----
0 ----- 20.0 83.94 -17.31 0.00 0.30 22.084 0.9981 0.0736 0.0736 0.000 0.00E+00 0.000E+00 -----

```

Figure 4. Example of the fuel element printout screen display.

3.2. Reactor Power Initial Conditions

This section specifies the initial reactor power level. If a steady-state run is being executed, then the initial power input here is the steady-state reactor power. Razorback performs its analyses based on simulating the response of a single fuel element/coolant channel. The power in that element is determined by the dividing the reactor power by the user-supplied number of fuel elements in the reactor core and multiplying by the user-supplied element peaking factor.

```

*****
*
* REACTOR POWER INITIAL CONDITIONS
*
*-----|-----|-----|-----|
* Initial Reactor | 100% Reactor | Number of | Element |
* Power (%)      | Power (W)    | Fuel Elements | Peak-to-Average |
*-----|-----|-----|-----|
*          pct_pwr          power_100          nrods          fr_peak
*-----|

```

Item	Input Parameter Description
<i>pct_pwr</i>	This parameter specifies the initial reactor power level (%) in terms of percent of full power.
<i>power_100</i>	This parameter specifies the value of 100% full power (W) in the reactor.
<i>nrods</i>	This parameter specifies the number of fuel elements (or fuel rods) in the reactor core.
<i>fr_peak</i>	This parameter specifies the fuel element peaking factor that will be used to determine the element power. The fuel element power is given by <div style="text-align: center;"> $P_{element} = \frac{\frac{pct_pwr}{100} power_100}{nrods} fr_peak$ </div>

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3.3. Reactivity Addition System Controls

Reactor transients in a research reactor are typically initiated by controlled movements of neutron absorbing rods generically referred to as control rods. Razorback has three separate and independent neutron absorbing rod “bank” functions which are used to add reactivity to initiate a reactor transient: (1) the control rod bank, (2) the safety rod bank, and (3) the transient rod bank. The movement of these banks is accomplished by specifying rod bank commands which prescribe bank speeds or reactivity ramp rates for specified time durations. The control rod bank and safety rod bank function in essentially the same way (i.e., the type of input parameters are the same), but can be operated independently (with different input parameter values). The transient rod bank functions similarly to the control and safety rod banks, but has some different features. Lastly, we note that in addition to these three rod bank functions, there is one additional independent reactivity addition capability by which the user may specify a prescribed reactivity addition as a function of time.

3.3.1. Control Rod Bank

The control rod function may be turned off, set to add reactivity with constant reactivity rate (\$/s) commands, or set to add reactivity in constant rod bank speed (cm/s) commands. Up to 20 commands may be entered, but all commands must either be for prescribed reactivity rate additions, or prescribed rod bank speed additions (i.e., a mixture of reactivity rate commands and speed commands is not allowed). The user must supply the initial control rod bank position, and the position values for which the rod bank is considered fully down and fully up. Lastly, the user must supply a total control rod bank worth, and a differential reactivity worth curve. When a constant reactivity rate addition option is chosen, the amount of reactivity added in a given time step is the product of the time step and the reactivity rate value which is valid at a given time. When the rod bank speed option is chosen, the amount of reactivity added in a given time step is the product of the time step, the rod bank worth, the differential reactivity worth curve function value for the current rod bank position, and the rod bank speed which is valid at a given time.

The control rod bank worth and a differential reactivity worth curve for a reactor may be constructed using a neutron transport code such as MCNP (Ref. 3). The total bank reactivity worth must be entered in units of dollars (which is accomplished by dividing a reactivity change by the delayed neutron fraction for the reactor system). The differential reactivity worth curve to be supplied as an input is presumed to fit a general sine-squared curve

$$\left(\frac{d\rho}{dz}\right)_{cr} = A \cdot \sin^2(B \cdot z + C)$$

The user must use neutron transport calculation results to determine the parameters A, B, and C for the curve. Because the code will multiply this differential worth curve by the total rod bank worth, the “A” parameter must be entered as the “A” determined from a fit of the neutron transport data divided by the total rod bank worth. Otherwise, the control rod bank worth input value should be set as \$1.0. In other words, for either choice, the integral of the differential reactivity worth curve must be normalized to the total rod bank worth.

```

*****
*
*           REACTIVITY ADDITION SYSTEM CONTROLS
*
*****
*-----|-----|
*   Control Rod Bank Control      |   Number of CR Bank Commands   |
*   (1=on w/curve, 0=off, 2=ramp) |   (up to 20)                   |
*-----|-----|
*           idir_cr                |           n_cr_cmds            |
*-----|-----|
*   CR Start                      |   CR End                      |   CR Speed (cm/s) |
*   Time (s)                      |   Time (s)                    |   or Ramp ($/s)   |
*-----|-----|
*           TS_CR                  |           TE_CR                |           CR_RATE       |
*-----|-----|
*   CR Start                      |   CR down                    |   CR Up           |
*   Position (cm)                 |   Position (cm)              |   Position (cm)   |
*-----|-----|
*           crp                    |           cr_down              |           cr_up         |
*-----|-----|
*   CR Bank                      |   CR Bank Differential Reactivity Curve |
*   Total                        |    $\text{drho/dz} = A \sin^2[ B(z) + C ]$  |
*   Worth ($)                    |   A                          |   B              |   C              |
*-----|-----|
*           cr_worth              |           a_cr                  |           b_cr          |           c_cr          |
*-----|-----|

```

Table 5. Control rod bank movement and reactivity addition control parameters.

Item	Input Parameter Description
<i>idir_cr</i>	This parameter tells the program if the Control Rod bank will be moving during the analysis, and if so, specifies the type of reactivity addition which will occur. 0 → No Control Rod bank movement. 1 → Control Rod bank movement at a specified bank speed (cm/s). 2 → Control Rod bank movement at a specified reactivity addition rate (\$/s).
<i>n_cr_cmds</i>	This parameter specifies number of Control Rod bank command lines to follow.
<i>TS_CR(n)</i> <i>TE_CR(n)</i> <i>CR_RATE(n)</i>	These parameters specify the starting time (<i>TS_CR</i>), ending time (<i>TE_CR</i>) for a Control Rod bank command line. <i>CR_RATE</i> specifies the Control Rod bank speed (if <i>idir_cr</i> =1), or Control Rod bank reactivity addition rate (if <i>idir_cr</i> =2) to be applied during the time interval between <i>TS_CR</i> and <i>TE_CR</i> . A total of <i>n_cr_cmds</i> command lines containing each of these three parameters is expected.
<i>crp</i>	This parameter specifies the initial position of the Control Rod bank.
<i>cr_dn</i>	This parameter specifies the full down position of the Control Rod bank.
<i>cr_up</i>	This parameter specifies the full up position of the Control Rod bank.
<i>cr_worth</i> <i>a_cr</i> <i>b_cr</i> <i>c_cr</i>	These parameters specify coefficients of the Control Rod bank differential reactivity worth curve. The differential reactivity worth (\$/cm) curve is given by $\left(\frac{d\rho}{dz}\right)_{cr} = cr_worth \cdot a_cr \cdot \sin^2(b_cr \cdot z + c_cr)$ Note that <i>a_cr</i> must be normalized so that <i>cr_worth</i> is total Control Rod bank worth (\$). Also note that <i>a_cr</i> , <i>b_cr</i> , and <i>c_cr</i> must be specified such that <i>z</i> is in cm.

3.3.2. Safety Rod Bank

The safety rod bank functions in the same manner as the control rod bank. Thus, the collection of input parameters is similar, but independent of the control rod bank.

*----- -----		
* Safety Rod Bank Control	Number of SR Bank Commands	
* (1=on w/curve, 0=off, 2=ramp)	(up to 20)	
*----- -----		
<i>idir_sr</i>	<i>n_sr_cmds</i>	
*----- -----		
* SR Start	SR End	SR Speed (cm/s)
* Time (s)	Time (s)	or Ramp (\$/s)
*----- -----		
<i>TS_SR</i>	<i>TE_SR</i>	<i>SR_RATE</i>
*----- -----		
* SR Start	SR down	SR Up
* Position (cm)	Position (cm)	Position (cm)
*----- -----		
<i>srp</i>	<i>sr_down</i>	<i>sr_up</i>
*----- -----		
* SR Bank	SR Bank Differential Reactivity Curve	
* Total	drho/dz = A sin2[B(z) + C]	
* Worth (\$)	A	B C
*----- -----		
<i>sr_worth</i>	<i>a_sr</i>	<i>b_sr</i> <i>c_sr</i>
*----- -----		

Table 6. Safety rod bank movement and reactivity addition control parameters.

Item	Input Parameter Description
<i>idir_sr</i>	This parameter tells the program if the Safety Rod bank will be moving during the analysis, and if so, specifies the type of reactivity addition which will occur. 0 → No Safety Rod bank movement. 1 → Safety Rod bank movement at a specified bank speed (cm/s). 2 → Safety Rod bank movement at a specified reactivity addition rate (\$/s).
<i>n_sr_cmds</i>	This parameter specifies number of Safety Rod bank command lines to follow.
<i>TS_SR(n)</i> <i>TE_SR(n)</i> <i>SR_RATE(n)</i>	These parameters specify the starting time (<i>TS_SR</i>), ending time (<i>TE_SR</i>) for a Safety Rod bank command line. <i>SR_RATE</i> specifies the Safety Rod bank speed (if <i>idir_sr</i> =1), or Safety Rod bank reactivity addition rate (if <i>idir_sr</i> =2) to be applied during the time interval between <i>TS_SR</i> and <i>TE_SR</i> . A total of <i>n_sr_cmds</i> command lines containing each of these three parameters is expected.
<i>srp</i>	This parameter specifies the initial position of the Safety Rod bank.
<i>sr_dn</i>	This parameter specifies the full down position of the Safety Rod bank.
<i>sr_up</i>	This parameter specifies the full up position of the Safety Rod bank.
<i>sr_worth</i> <i>a_sr</i> <i>b_sr</i> <i>c_sr</i>	These parameters specify coefficients of the Safety Rod bank differential reactivity worth curve. The differential reactivity worth (\$/cm) curve is given by $\left(\frac{d\rho}{dz}\right)_{sr} = sr_worth \cdot a_sr \cdot \sin^2(b_sr \cdot z + c_sr)$ Note that <i>a_sr</i> must be normalized so that <i>sr_worth</i> is total Safety Rod bank worth (\$). Also note that <i>a_sr</i> , <i>b_sr</i> , and <i>c_sr</i> must be specified such that <i>z</i> is in cm.

3.3.3. Transient Rod Bank

The transient rod bank functions in the same manner as the control and safety rod banks when operated in the constant bank speed or constant reactivity addition rate mode. The primary difference is that the differential reactivity curve has an additional offset parameter z_0

$$\left(\frac{d\rho}{dz}\right)_{tr} = A \cdot \sin^2[B \cdot (z - z_0) + C]$$

The z_0 offset parameter allows for modeling situations for which the active reactivity worth region of the bank does not range from fully down to fully up. Rather, the active reactivity worth region begins at a bank position higher than 0 cm, and ends at a position before the full travel distance of the bank, with the positions below and above having essentially no reactivity worth. The ACRR transient rod bank active reactivity worth region begins at ~23 cm and ends at ~78 cm, while the full bank travels from position 0 cm to position 90 cm. Additional input parameters are provided for the transient rod bank so that the user may specify a lower and upper position, below and above which the differential worth is set at zero.

In addition, the transient rod bank function also has a pneumatic pulse operation mode, and this is discussed in the next section.

```

*-----|-----|
*   Transient Rod Bank Control           |   Number of TR Bank Commands   |
*   (0=off, 1=on w/curve)                |   (up to 20)                   |
*   (2=pulse, 3=ramp)                    |                                 |
*-----|-----|
*           idir_tr                       |           n_tr_cmds           |
*-----|-----|
*   TR Start                             |   TR End                       |   TR Speed (cm/s)   |
*   Time (s)                             |   Time (s)                     |   or Ramp ($/s)    |
*-----|-----|
*   Pulse Operation (1 TR Bank Command;  |   only TR Start Time is needed) |
*           TS_TR                         |           TE_TR                 |           TR_RATE         |
*-----|-----|
*   TR Start                             |   TR down                      |   TR Up             |
*   Position (cm)                       |   Position (cm)                |   Position (cm)     |
*-----|-----|
*           trp                           |           tr_down                |           tr_up           |
*-----|-----|
*   TR Bank                             |   TR Bank Differential Reactivity Curve |
*   Total                               |   drho/dz = A sin2[ B(z - z0) + C] |
*   Worth($)                            |   A           |   B           |   C           |   z0          |
*-----|-----|
*           tr_worth                       |           a_tr                   |           b_tr                   |           c_tr                   |           z0_tr           |
*-----|-----|
*   Range of Validity for TR Bank Differential Reactivity Curve |
*   lower end (cm)                       |   upper end (cm)                |
*-----|-----|
*           tr_lb                           |           tr_rb                   |
*-----|-----|

```

Table 7. Transient rod bank movement and reactivity addition control parameters.

Item	Input Parameter Description
<i>idir_tr</i>	<p>This parameter tells the program if the Transient Rod bank will be moving during the analysis, and if so, specifies the type of reactivity addition which will occur.</p> <p>0 → No Transient Rod bank movement. 1 → Transient Rod bank movement at a specified bank speed (cm/s). 2 → Transient Rod bank pulse. 3 → Transient Rod bank movement at a specified reactivity addition rate (\$/s).</p>
<i>n_tr_cmds</i>	<p>This parameter specifies number of Transient Rod bank command lines to follow. NOTE: For a pulse operation (<i>idir_tr</i>=2), only one command line is needed.</p>
<i>TS_TR(n)</i> <i>TE_TR(n)</i> <i>TR_RATE(n)</i>	<p>These parameters specify the starting time (<i>TS_TR</i>), ending time (<i>TE_TR</i>) for a Transient Rod bank command line. <i>TR_RATE</i> specifies the Transient Rod bank speed (if <i>idir_tr</i>=1), or Transient Rod bank reactivity addition rate (if <i>idir_tr</i>=3) to be applied during the time interval between <i>TS_TR</i> and <i>TE_TR</i>. A total of <i>n_tr_cmds</i> command lines containing each of these three parameters is expected.</p> <p>As noted above, for a pulse operation (<i>idir_tr</i>=2), only one command line is needed. This line will specify the time <i>TS_TR</i> at which the transient rod operation begins. Arbitrary values for <i>TE_TR</i> and <i>TR_RATE</i> must be provided, but are not used for a pulse.</p>
<i>trp</i>	<p>This parameter specifies the initial position of the Transient Rod bank.</p>
<i>tr_dn</i>	<p>This parameter specifies the full down position of the Transient Rod bank.</p>
<i>tr_up</i>	<p>This parameter specifies the full up position of the Transient Rod bank.</p>
<i>tr_worth</i> <i>a_tr</i> <i>b_tr</i> <i>c_tr</i> <i>z0_tr</i>	<p>These parameters specify coefficients of the Transient Rod bank differential reactivity worth curve. The differential reactivity worth (\$/cm) curve is given by</p> $\left(\frac{d\rho}{dz}\right)_{tr} = tr_worth \cdot a_tr \cdot \sin^2[b_tr(z - z0_tr) + c_tr]$ <p>Note that <i>a_tr</i> must be normalized so that <i>tr_worth</i> is total Transient Rod bank worth (\$). Also note that <i>a_tr</i>, <i>b_tr</i>, <i>c_tr</i>, and <i>z0_tr</i> must be specified such that <i>z</i> is in cm.</p>
<i>tr_lb</i> <i>tr_rb</i>	<p>These parameters specify the Transient Rod bank position bounds over which the differential reactivity worth curve is applicable. The lower bound is <i>tr_lb</i> (cm), and the upper bound is <i>tr_rb</i> (cm). For Transient Rod bank positions <i>z</i> < <i>tr_lb</i> and <i>z</i> > <i>tr_rb</i>, the differential worth is zero.</p>

3.3.4. Transient Rod Bank Pneumatic System

As noted above, the transient rod bank function has an additional operation option which is designed to simulate pressurized nitrogen gas being utilized to enter a piston cylinder and rapidly force the transient rod bank upward. The rapid “ejection” of the transient rod bank to its fully withdrawn position produces a prompt critical power excursion which is terminated by fuel temperature reactivity feedback. This type of operation is referred to as a pulse operation.

When using the transient rod pulse function, a single transient rod bank command is entered (see Section 3.3.3). The purpose of this single command line is to provide the transient rod bank movement start time (TR_TS). The other values on the command line must have an entry, but they are not used. The TR_TS value may of course be 0.0 s, but can be a value greater than 0.0 s if a pulse delay time is desired. A nitrogen gas valve opening delay time (dt_valve) may also be entered by the user. The transient rod bank will begin to move after time is greater than $TR_TS + dt_valve$. Figure 5 illustrates the pulse pneumatic ejection system timing.

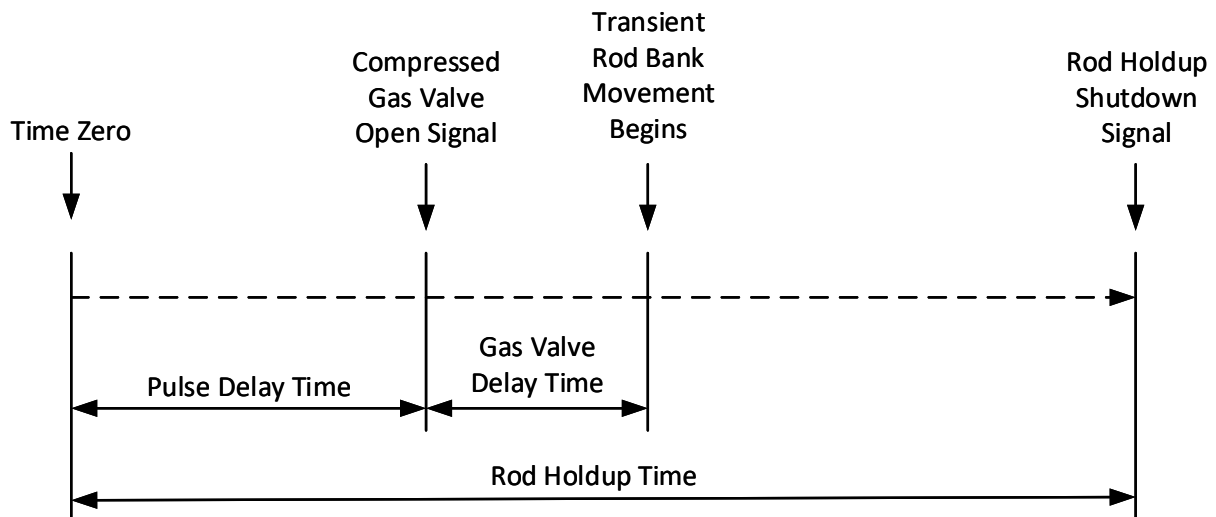


Figure 5. Transient rod bank pulse ejection and rod holdup timing.

Also shown on Fig. 5 is a Rod Holdup time. The transient rod bank function includes a capability to begin shutting down the reactor at a user-specified time, referred to as the Rod Holdup time (t_{RHU}).

The transient rod bank moves based upon a constant acceleration value. The acceleration (a_{TR}) value is determined from the user-supplied nitrogen gas pressure (P_{N2}), effective piston area (A_{eff}), and transient rod mass (m_{TR}) as

$$a_{TR} = \frac{P_{N2} \cdot A_{eff}}{m_{TR}}$$

A final option determines how a Rod Holdup time shutdown will be achieved. For the “pulse” submode option, the transient rod bank and the safety rod bank will be “dropped” to shutdown the reactor when a Rod Holdup time shutdown is initiated. For the “pulse reduced tail” submode option, the transient rod bank, the safety rod bank, and the control rod bank will be “dropped” to shutdown the reactor when a Rod Holdup time shutdown is initiated. By dropping all three rod banks, the decay power level of the pulse “tail” is reduced.

```

*-----|
*           Transient Rod Pulse Pneumatic System |
* N2 Valve | N2      | N2 Accum. | Piston      | TR          |
* opening  | Pressure | Volume    | Effective   | Mass (kg)  |
* time (s) | (psig)  | (cm3)     | Area (cm2) |            |
*-----|-----|-----|-----|-----|
* dt_valve  p_n2      vol_n2      tr_piston_area  tr_mass
*-----|-----|-----|-----|-----|
*           Transient Rod Pulse | Pulse Submode |
*           Rod Holdup Time (s) | (Pulse=0 or PRT=1) |
*-----|-----|-----|-----|-----|
*           t_rhu | i_pulse_mode
*-----|

```

Table 8. Pulse pneumatic ejection system and rod holdup shutdown parameters.

Item	Input Parameter Description
<i>dt_valve</i>	This parameter specifies the delay time (s) for a three-way control valve to allow pressurized N ₂ to begin flowing to each Transient Rod bank piston in order to eject the Transient Rod bank.
<i>p_n2</i>	This parameter specifies the pressure (psig) that will be applied to each Transient Rod piston.
<i>vol_n2</i>	This parameter specifies the volume (cm ³) of the pressurized N ₂ accumulator associated with each Transient Rod. NOTE: This parameter is not currently used by the code, so the entry value is arbitrary.
<i>tr_piston_area</i>	This parameter specifies the effective area of the piston of each Transient Rod to which pressure is applied to eject the Transient Rod bank.
<i>tr_mass</i>	This parameter specifies the mass of each Transient Rod in the Transient Rod bank.
<i>t_rhu</i>	This parameter specifies the time measured from t=0 after which the Transient Rod bank will be signaled to begin falling back to their down position. NOTE: This is not a “scram,” per se, but the scram delay time (see Section 3.5) is applied so that Transient Rod bank downward motion begins at t= <i>t_rhu</i> + <i>t_delay</i> or t= <i>t_rhu</i> + <i>spec_scram_delay</i> .
<i>i_pulse_mode</i>	This parameter specifies which rod banks will be dropped after the <i>t_rhu</i> time is reached. 0 → The Transient Rod bank and Safety Rod bank will be dropped. 1 → The Transient Rod bank, Safety Rod bank, and Control Rod bank will be dropped.

3.3.5. Functional Reactivity Addition

The final reactivity addition method option is a functional reactivity addition. This option allows for further flexibility if reactivity addition system rates and differential reactivity worth data are not available to the user, or if it is simply more desirable to add reactivity as some function of time.

```

*-----|-----|-----|
* Functional Reactivity Addition | Number of | Time to Turn |
* (0=off, 1=polynomial, 2=sine) | Terms (</=5) | Addition Off (s) |
*-----|-----|-----|
*           irhoadd           nraterms           tendradd
*-----|-----|-----|
* If irhoadd = 0 enter no terms
* If irhoadd = 1 enter up to 5 polynomial coefficients
* If irhoadd = 2 enter magnitude, freq, and phase shift of sine func
*-----|-----|-----|
*           RPC
*-----|-----|-----|

```

Table 9. Functional reactivity addition option parameters.

Item	Input Parameter Description
irhoadd	This parameter sets an option to allow for a functional reactivity addition. This addition, if chosen, will be superimposed upon any Control, Safety, or Transient rod bank additions. 0 → No functional reactivity addition. 1 → Reactivity addition (\$) defined by a polynomial $\rho(t)$. 2 → Sinusoidal reactivity addition (\$).
nraterms	This parameter specifies the number of polynomial coefficients to be used for the functional reactivity addition. If irhoadd = 0, no functional addition is used, but an arbitrary value for nraterms must still be included on this card.
tendradd	This parameter specifies the time after which the functional reactivity addition will be set to zero. If irhoadd = 0, no functional addition is used, but an arbitrary value for tendradd must still be included on this card.
RPC(n)	These parameters specify the coefficients of the functional reactivity addition curve $\rho(t)$ where ρ is in dollars (\$). The reactivity addition is assumed to begin at $t = 0$. The reactivity addition will end at $t > \mathbf{tendradd}$. For irhoadd = 1, the reactivity addition is given by $\rho(t) = \sum_{n=1}^5 RPC_n \cdot t^{n-1}$ For irhoadd = 2, the reactivity addition is given by $\rho(t) = RPC_1 \cdot \sin(RPC_2 \cdot t + RPC_3)$ NOTE: If irhoadd = 0, then the RPC(n) entry line must be deleted, or the line must be commented out.

3.4. Reactor Kinetics Parameters

3.4.1. Neutron Generation Time and Delayed Neutron Parameters

This portion of the input file provides the basic reactor system parameters necessary for a point reactor kinetics model: neutron generation time, effective delayed neutron fraction, the number of delayed neutron precursor groups to be used, and the decay constants and group fractions for each of these precursor groups.

```

*****
*
* REACTOR KINETICS PARAMETERS
*
*-----|-----|-----|
* Neutron Generation | Effective Delayed | No. of Delayed |
* Time (s) | Neutron Fraction | Neutron Groups |
*-----|-----|-----|
* gen_time | beta_eff | ndg |
*-----|-----|-----|
* Delayed Neutron |
* Group Decay Constants (1/s) - lambda i's |
* (up to 18 groups allowed -- up to 6 lambdas per line) |
*-----|-----|-----|
* ALAM |
*-----|-----|-----|
* Delayed Neutron |
* Group Fractions - beta i's |
* (up to 18 groups allowed -- up to 6 betas per line) |
*-----|-----|-----|
* BETA |
*-----|-----|-----|

```

Table 10. Neutron generation time and delayed neutron parameters.

Item	Input Parameter Description
gen_time	This parameter specifies the neutron generation time (s).
beta_eff	This parameter specifies the total effective delayed neutron fraction.
ndg	This parameter specifies the total number of delayed neutron precursor groups to be considered in the calculation.
ALAM(n)	These parameters specify the effective delayed neutron precursor group decay constant (s ⁻¹) for each delayed neutron group. A total of ndg entries is required for this card set. Up to 18 delayed neutron groups are allowed. For ndg > 6, only six entries per card are allowed.
BETA(n)	These parameters specify the effective delayed neutron fraction for each delayed neutron group. A total of ndg entries is required for this card set. Up to 18 delayed neutron groups are allowed. For ndg > 6, only six entries per card are allowed. NOTE: The parameters are the individual β_n values, not the β_n/β_{eff} values.

3.4.2. Reactivity Feedback Coefficient Parameters

The kinetic behavior of the reactor depends not only upon the reactivity added by means of a control system, but also upon the reactivity added by the reactor itself via changes in fuel, cladding, and coolant temperatures, or dimensional changes. The reactivity added by the reactor itself is referred to as reactivity feedback, and it often characterized by a reactivity feedback coefficient. Razorback utilizes several reactivity feedback coefficients to convert temperature and dimensional changes to positive or negative reactivity feedback additions. These coefficients may be obtained using a neutron transport code such as MCNP (Ref. 3).

```

*-----|-----|
*      Fuel Temperature Feedback          |      Coolant Reactivity          |
*      drho/dT = c1 + c2/(T**0.5)        |      Feedback Coefficients      |
*      c1                                |      Density                    |      Spectral                    |
*      ($/K)                             |      ($/%void)                 |      ($/K)                      |
*-----|-----|-----|-----|
*      c1_fuel                          |      c2_fuel                  |      c1_cool_dens              |      c1_cool_spec              |
*-----|-----|-----|-----|
*      Fuel Expansion Reactivity Feedback Coefficients
*      Outer Radius                       |      Inner Radius               |      Density                      |
*      ($/cm)                             |      ($/cm)                    |      [$/ (g/cm3)]              |
*-----|-----|-----|-----|
*      c_ro_f                           |      c_ri_f                   |      c_d_f                      |
*-----|-----|-----|-----|

```

Table 11. Fuel reactivity feedback coefficient parameters.

Item	Input Parameter Description
<i>c1_fuel</i> <i>c2_fuel</i>	These are the parameters for the fuel Doppler feedback coefficient (\$/K) given by $\frac{\partial \rho}{\partial T} = c1_fuel + \frac{c2_fuel}{\sqrt{T}}$ where T is the absolute temperature of the fuel.
<i>c1_cool_dens</i>	This parameter is the coolant density feedback coefficient (\$/%-void).
<i>c1_cool_spec</i>	This parameter is the coolant spectral feedback coefficient (\$/K).
<i>c_ro_f</i>	This parameter is for the fuel expansion feedback coefficient (\$/cm) based on the change of the outer fuel radius.
<i>c_ri_f</i>	This parameter is for the fuel expansion feedback coefficient (\$/cm) based on the change of the inner fuel radius.
<i>c_d_f</i>	This parameter is the fuel density feedback coefficient [\$/ (g/cm ³)].

Cladding Expansion Reactivity Feedback Coefficients		
Outer Radius	Inner Radius	Density
(\$/cm)	(\$/cm)	[\$/(g/cm)]
<i>c_ro_c</i>	<i>c_ri_c</i>	<i>c_d_c</i>

Table 12. Cladding expansion reactivity feedback coefficient parameters.

Item	Input Parameter Description
<i>c_ro_c</i>	This parameter is for the cladding expansion feedback coefficient (\$/cm) based on the change of the cladding outer radius.
<i>c_ri_c</i>	This parameter is for the cladding expansion feedback coefficient (\$/cm) based on the change of the cladding inner radius.
<i>c_d_c</i>	This parameter is the cladding density feedback coefficient [\$(g/cm ³)].

The user is provided with two means to scale the magnitude of the reactivity feedback computed by the code. The first means is comprised of four scaling factors (*fb_ft_scl*, *fb_fe_scl*, *fb_cld_scl*, *fb_c_scl*) that may be applied, individually, to fuel temperature feedback (Doppler feedback), to fuel expansion feedback, to cladding expansion feedback, and to coolant feedback. Through these scaling factors, the user may explore sensitivities related to the various potential reactivity feedback mechanisms.

The second means of scaling reactivity feedback is more essential to the accurate simulation of the response of a reactor to changing conditions in reactor fuel elements and coolant channels. Razorback currently utilizes a single fuel element/coolant channel system to determine the reactivity feedback due to the entire reactor. Temperature changes (and thermal expansion changes) of the fuel element materials and the coolant are computed for many radial and axial segment volumes in the element/coolant channel system. These changes are individually transformed into local reactivity feedback effects which are then volume weighted and summed for an aggregate element/coolant system reactivity feedback. In addition to the volume weighting, a weighting function ($[F_r(r)F_z(z)]^{adj-exp}$) which is dependent upon the axial and radial location of the segment volumes within the fuel element is applied. For the coolant channel, the weighting function is $[F_z(z)]^{adj-exp}$. Lastly, a weighting factor (*fr_adj*) dependent upon the location of the individual element/coolant channel section within the overall reactor system must also be applied. This allows the code to related the reactivity feedback determined for the element which is being modeled to the total feedback of all of the elements in the core.

Reactivity Feedback Scaling and Adjustment Factors					
Scaling					
Fuel T	Fuel Exp	Clad	Coolant	PLA	Exp
<i>fb_ft_scl</i>	<i>fb_fe_scl</i>	<i>fb_cld_scl</i>	<i>fb_c_scl</i>	<i>fr_adj</i>	<i>adj_exp</i>

Table 13. Reactivity feedback scaling and core location adjustment parameters.

Item	Input Parameter Description
<i>fb_ft_scl</i>	This parameter allows the user to apply a scaling factor to the fuel temperature (Doppler) feedback.
<i>fb_fe_scl</i>	This parameter allows the user to apply a scaling factor to the fuel expansion feedback.
<i>fb_cld_scl</i>	This parameter allows the user to apply a scaling factor to the cladding expansion and density feedback.
<i>fb_cool_scl</i>	This parameter allows the user to apply a scaling factor to the coolant density and spectral feedback.
<i>fr_adj</i>	This parameter allows the user to apply a scaling factor to the total reactivity feedback at each time step to adjust for the core location peaking factor being used in the analysis (<i>fr_peak</i>). This parameter would be expected to be related to the adjoint flux at that core location, and will thus be reactor dependent. For the ACRR, a value determined by the following relation appears to work well (assuming <i>adj_exp</i> = 2.0) $fr_adj = \frac{1.35}{fr_peak}$
<i>adj_exp</i>	This parameter is the exponent used for total reactivity feedback weighting to account for the location within the fuel element. This parameter is used in the following relation $local\ feedback\ weighting\ factor = [F_r(r)F_z(z)]^{adj_exp}$ where r and z refer to the location within the fuel element under consideration. The feedback in the coolant is weighted in a similar matter with the same <i>adj_exp</i> value, but only as a function of the z (axial) location. For the ACRR, a value of 2.0 appears to work well.

3.5. Reactor Protection System Settings

Razorback includes a reactor protection system (RPS) capability, allowing the user to simulate the action of a scram system and determine its effectiveness in protecting the reactor. The RPS monitors the evolution of various important reactor, reactor fuel, and coolant parameters during a transient simulation. If one of these parameters exceeds a user-supplied setpoint, the code will switch to a scram mode in which all further reactivity control system commands are overridden, and a gravity-driven drop of the control, safety, and transient rod banks is initiated.⁵

3.5.1. Reactor Protection System Setpoints

The RPS capability allows the user to have the RPS monitor up to eight reactor system parameters and compare those parameters to user-supplied scram setpoints. A setpoint value must be supplied in the input file. However, an extremely high/large value may be entered if the user does not wish that particular parameter to be able to initiate a scram.

An additional RPS non-scram capability known as “Rod Block” is also included as an option. The Rod Block⁶ function monitors the startup rate (i.e., period) of the reactor power. If the startup rate exceeds the user-supplied setpoint, the code will override any programmed motion of the control rod bank for as long as the setpoint is exceeded. Once the startup rate falls back below the setpoint, any programmed motion of the control rod bank is now allowed again.

```

*****
*
* REACTOR PROTECTION SYSTEM SETTINGS
*
*-----|-----|-----|
* Percent | Reactor | Element |
* Power (%) | Power (W) | Power (W) |
*-----|-----|-----|
* rx_pp_scram | rx_p_scram | rx_pep_scram |
*-----|-----|-----|
* Reactor | Rod Block | Rod Block |
* Period (s) | (1=on,0=off) | Rate (dpm) |
*-----|-----|-----|
* rx_pd_scram | irod_block_flag | rod_block_dpm |
*-----|-----|-----|
* Reactor Yield (J) | Fuel Temperature (C) |
*-----|-----|-----|
* rx_y_scram | tf_scram |
*-----|-----|-----|
* Pool Level Scram | Inlet Temperature |
* (cm below tank top) | Scram (C) |
*-----|-----|-----|
* pool_lvl_scram | t_in_scram |
*-----|-----|-----|

```

⁵ This description of the scram mode is somewhat simplified here. Other factors such as scram delay times and “specified” scrams (vs. control, safety, and transient rod drops) are described later in this section.

⁶ This is a feature of the ACRR reactivity control system.

Table 14. Reactor protection system scram setpoints.

Item	Input Parameter Description
<i>rx_pp_scram</i>	This parameter specifies the setpoint (%) for a reactor percent-power scram.
<i>rx_p_scram</i>	This parameter specifies the setpoint (W) for a reactor power scram.
<i>rx_pep_scram</i>	This parameter specifies the setpoint (W) for an element power scram.
<i>rx_pd_scram</i>	This parameter specifies the setpoint (s) for a reactor period scram.
<i>irod_block_flag</i>	This parameter determines if a rod block feature will be applied to the movement of the control rod bank. This feature disables control rod bank movement whenever the reactor power change rate exceeds a setpoint (<i>rod_block_dpm</i>). Movement is automatically re-enabled when the reactor power change rate falls below the setpoint. The feature is active when <i>irod_block_flag</i> = 1, and inactive when <i>irod_block_flag</i> = 0.
<i>rod_block_dpm</i>	This parameter specifies the setpoint (decades per minute) for reactor power change rate rod block feature. Only active when <i>irod_block_flag</i> = 1.
<i>rx_y_scram</i>	This parameter specifies the setpoint (J) for an integrated reactor power scram.
<i>tf_scram</i>	This parameter specifies the setpoint (°C) for a fuel temperature scram. The parameter monitored by this scram function is the fuel “measured” temperature. The “measured” fuel temperature location is set by the <i>I_TC(1)</i> and <i>I_TC(2)</i> parameters in the fuel element model input (Section 3.8). NOTE: It is up to the user to ensure that the element peaking factor (<i>fr_peak</i>) is properly chosen when utilizing this scram function.
<i>pool_lvl_scram</i>	This parameter specifies the setpoint (cm) for a reactor pool water level scram. The pool level value is defined as the distance (cm) from the top of the pool tank to the pool water level.
<i>t_in_scram</i>	This parameter specifies the setpoint (°C) for a reactor coolant channel inlet temperature scram.

3.5.2. Reactor Protection System Scram Parameters

There are two options for simulating a reactor scram in the event that an RPS scram is actuated: (1) a specified scram, and (2) a normal scram. The specified scram allows for the user to specify the magnitude of the negative scram reactivity to be added and the time period over which this reactivity is added. Thus, the specified scram is essentially a negative ramp reactivity addition. Further, the user may also specify a scram delay time. The specified scram will initiate after the delay time has expired.

```

*-----|
* Scram Mode | Specified Scram Parameters |
* 0=normal | Scram | Scram | Scram |
* 1=specified | Reactivity ($) | Delay Time (s) | Addition Time (s) |
*-----|-----|-----|-----|
* i_scram_opt | spec_scram_rho | spec_scram_delay | spec_scram_time |
*-----|-----|-----|-----|

```

Table 15. Reactor scram parameters.

Item	Input Parameter Description
<i>i_scram_opt</i>	This parameter specifies the type of scram action that will be modeled. 0 → Normal scram in which Control, Safety, and Transient rod banks will fall from their position at the time of the scram (after a specified delay time). The negative reactivity addition of this type of scram is the integrated reactivity worth of the rod banks using their differential reactivity worth curves. 1 → “Specified” scram in which a specified negative reactivity addition will occur over a specified time beginning at the time of the scram after a specified delay time.
<i>spec_scram_rho</i>	This parameter is the negative reactivity addition to be used for a “Specified” scram (<i>i_scram_opt</i> =1). NOTE: The value entered must be positive . The code will employ it as a negative reactivity addition.
<i>spec_scram_delay</i>	This parameter is the scram delay time to be used for a “Specified” scram (<i>i_scram_opt</i> =1).
<i>spec_scram_time</i>	This parameter is the length of time over which negative reactivity addition of a “Specified” scram (<i>i_scram_opt</i> =1) will be accomplished. As such, the “Specified” scram is essentially a negative reactivity addition ramp of magnitude <i>spec_scram_rho</i> over time <i>spec_scram_time</i> .

The other scram option is a normal scram. For a normal scram, the control, safety, and transient rod banks are allowed to fall by “gravity” from the position they are at when the scram begins. The user specifies a rod bank fall time for each bank. This fall time is considered to be the time required for a given bank to fall from its full up position to its full down position. The code computes a constant downward acceleration to be applied⁷ to each rod bank based upon this specified fall time. The user may also specify a scram delay time. The scram will initiate after the delay time has expired.

In addition to the rod fall times for each bank, the user may also specify a “stuck rod” factor. The purpose of this feature is to allow the user to simulate a scram in which one (or more) rods in a given bank is “stuck,” while the other rods in the bank fall. The factor (ranging from 0 to 1) multiplies the rod bank worth within the code. For example, if a single rod in a bank is worth ~20% of the bank worth, then a stuck rod factor of 0.80 would simulate having a single rod stuck in place during the scram.

```
*-----|-----|-----|
*   Scram      | Rod Fall Times (s) |      Stuck Rod Factors |
* Delay Time (s) | CRs | SRs | TRs | CRs | SRs | TRs |
*-----|-----|-----|
*   t_delay    t_rod_fall_cr t_rod_fall_sr t_rod_fall_tr ...
*               stuck_rod_fctr_cr stuck_rod_fctr_sr stuck_rod_fctr_tr
*-----|-----|-----|
```

NOTE: The yellow highlighted entries above must be placed on a single line in an input file. They are shown on two lines here only because the variable names do not fit on one line.

⁷ By applying a constant acceleration value, shorter effective fall times can be realized depending upon the initial position of the rod banks at the time the scram begins.

Table 16. Scram rod bank delay time, fall time, and “stuck rod” factor.

Item	Input Parameter Description
<i>t_delay</i>	This parameter is the scram delay time to be used for a “Normal” scram (<i>i_scram_opt</i> =0).
<i>t_rod_fall_cr</i>	This parameter is the time that it takes for the Control Rod bank to fall from fully withdrawn to fully inserted. This will be used to set an effective gravitational acceleration for a “Normal” scram (<i>i_scram_opt</i> =0).
<i>t_rod_fall_sr</i>	This parameter is the time that it takes for the Safety Rod bank to fall from fully withdrawn to fully inserted. This will be used to set an effective gravitational acceleration for a “Normal” scram (<i>i_scram_opt</i> =0).
<i>t_rod_fall_tr</i>	This parameter is the time that it takes for the Transient Rod bank to fall from fully withdrawn to fully inserted. This will be used to set an effective gravitational acceleration for a “Normal” scram (<i>i_scram_opt</i> =0).
<i>stuck_rod_fctr_cr</i>	This parameter is a Control Rod bank worth scaling factor that can be used to simulate the occurrence of one or more rods in the bank being stuck in its position prior to the “Normal” scram (<i>i_scram_opt</i> =0). Once a scram is actuated, the input variable <i>cr_worth</i> (see Sect. 3.3.1) becomes <i>stuck_rod_fctr*cr_worth</i> . Thus, if a single control rod is worth ~20% of the bank worth, then a stuck rod factor of 0.80 would simulate a condition in which one control rod is stuck in place while the others participate in the scram (i.e., fall freely).
<i>stuck_rod_fctr_sr</i>	This parameter is a Safety Rod bank worth scaling factor that can be used to simulate the occurrence of one or more rods in the bank being stuck in its position prior to the “Normal” scram (<i>i_scram_opt</i> =0). Once a scram is actuated, the input variable <i>sr_worth</i> (see Sect. 3.3.2) becomes <i>stuck_rod_fctr*sr_worth</i> .
<i>stuck_rod_fctr_tr</i>	This parameter is a Transient Rod bank worth scaling factor that can be used to simulate the occurrence of one or more rods in the bank being stuck in its position prior to the “Normal” scram (<i>i_scram_opt</i> =0). Once a scram is actuated, the input variable <i>tr_worth</i> (see Sect. 3.3.3) becomes <i>stuck_rod_fctr*tr_worth</i> .

Lastly, the user may simulate an event for which a scram signal occurs and the RPS fails to initiate the scram, but an operator recognizes the situation and initiates a scram “manually.” This feature is activated by setting a scram failure flag, and providing a “manual” scram delay time.

```

*-----|-----|
*      Scram Failure      |      Manual Scram      |
*      (1 = yes, 0 = no)  |      Delay Time (s)    |
*-----|-----|
*           i_fail           |           t_op_delay   |
*-----|-----|

```

Table 17. Scram failure simulation parameters.

Item	Input Parameter Description
<i>i_fail</i>	This parameter allows for the simulation of an automatic scram system “failure” for either a “Specified” or “Normal” scram. Scram action then occurs after a time delay (<i>t_op_delay</i>) required for an operator to actuate a “manual” scram.
<i>t_op_delay</i>	This parameter is the time delay for an operator to recognize that an expected scram action did not occur, and to actuate a “manual” scram.

3.6. Pool Tank, Water, and Cooling System Parameters

3.6.1. Reactor Pool/Tank Parameters

Razorback, in general, assumes that the reactor operates inside a water-filled tank. The water is referred to as the reactor pool. It is expected that other structures, besides the reactor itself, are in the pool, and will displace pool water volume. In addition, since the reactor pool water is the immediate heat sink for the reactor, Razorback also includes a simple model for a pool cooling system to serve as the ultimate heat sink. The reactor pool system is shown schematically in Fig. 6.

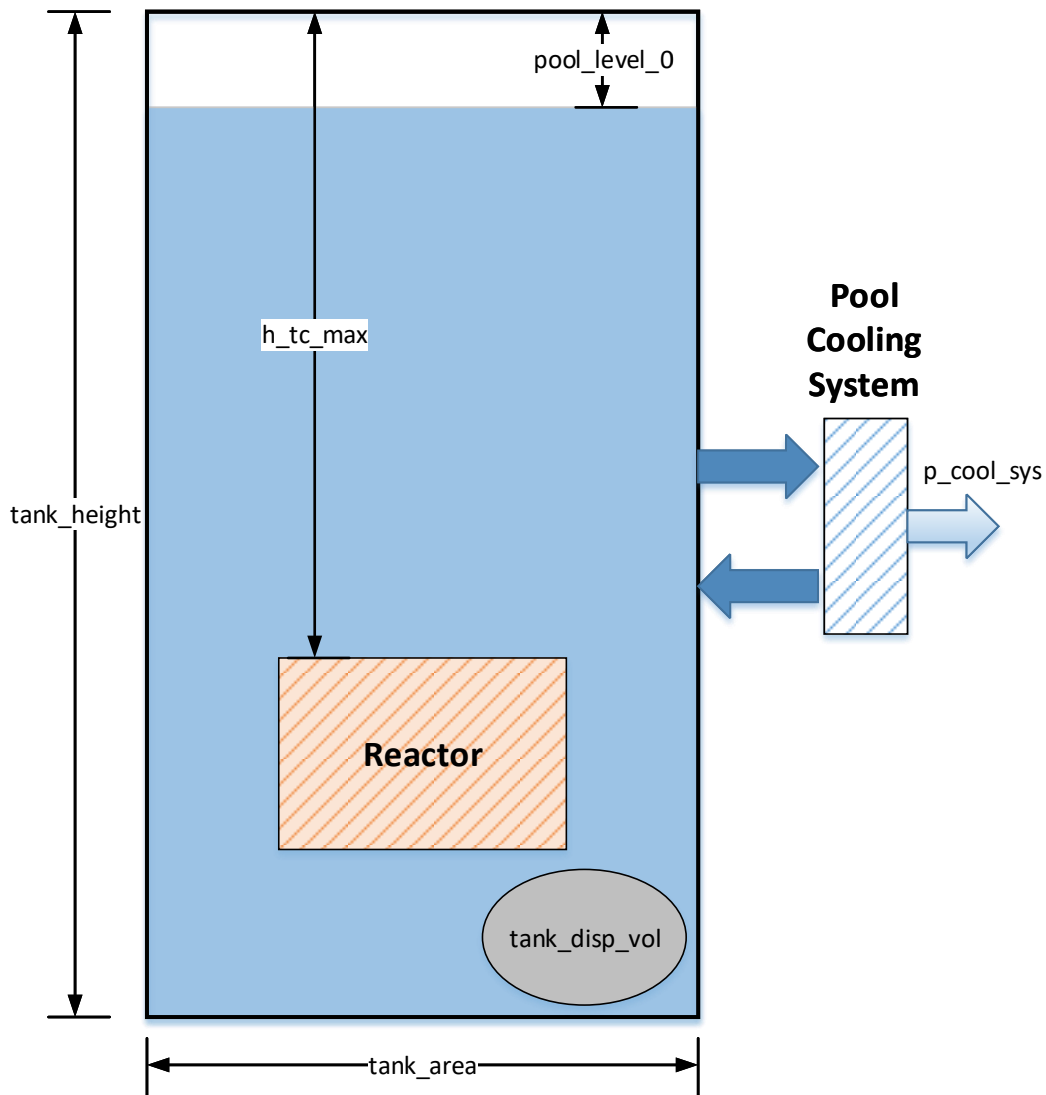


Figure 6. Schematic of reactor pool water system parameters

Below are the input parameters for the reactor pool water system, and these correspond to the parameters shown in Fig. 6.

```

*****
*                POOL TANK/WATER AND POOL WATER COOLING SYSTEM
*                INITIAL CONDITIONS AND TRANSIENT(S)
*****
*-----|
*                | Pool Tank |
* Pool Tank | Pool Tank | Displaced | Maximum Water Height |
* Height (cm) | Area (cm2) | Volume (cm3) | Above Reactor Core (cm) |
*-----|-----|-----|-----|
* tank_height | tank_area | tank_disp_vol | h_tc_max
*-----|
*                | Cooling System |
* Initial Pool Water | Initial Pool Water Level (cm) | Heat Removal |
* Temperature (C) | (Distance Below Tank Lip) | (% of Rx Power) |
*-----|-----|-----|
* t_pool | pool_level_0 | p_cool_sys
*-----|

```

Table 18. Reactor tank, pool water, and pool water cooling system parameters.

Item	Input Parameter Description
<i>tank_height</i>	This parameter specifies the height (cm) from the bottom of the reactor pool tank to the lip of the tank.
<i>tank_area</i>	This parameter specifies the cross-sectional area (cm ²) of the reactor pool tank.
<i>tank_disp_vol</i>	This parameter specifies the volume (cm ³) within the reactor pool water which is displaced by various structures or components.
<i>h_tc_max</i>	This parameter specifies the height (cm) from the top of the reactor coolant channel (i.e., just above the top of the upper grid plate) to the lip of the tank.
<i>t_pool</i>	This parameter specifies the initial reactor pool water temperature (°C).
<i>pool_level_0</i>	This parameter specifies the initial reactor pool water level (cm) as measured from the lip of the tank to the water surface.
<i>p_cool_sys</i>	This parameter specifies the rate at which heat is being removed from the reactor pool water by a pool cooling system. The input here is in units of percent of full reactor power.

3.6.2. Reactor Pool Heatup Parameters

During operation, the power generated by the reactor is dissipated into the reactor pool water facilitated by the natural circulation flow of the reactor pool water through the reactor core. In general, the inlet temperature of the coolant to the reactor is equal to the average pool water temperature. Razorback provide several options for a time dependent reactor pool water/inlet temperature

- Pool water temperature is held constant during the run execution.
- Pool water temperature increases as the energy carried away by the coolant is instantaneously and uniformly mixed with the reactor pool water.
- Power water temperature increases or decreases at a user-specified rate over a user-specified start and end time.
- Power water temperature remains constant, but the channel inlet temperature increases or decreases at a user-specified rate over a user-specified start and end time.

```

*-----|
*                               |
*                               | Pool Heatup |
* Flag = 0 -> no pool heatup (constant Tpool = Tinlet) |
* Flag = 1 -> pool heatup by reactor/cooling system (Tpool = Tinlet) |
* Flag = 2 -> pool temperature ramp (Tpool = Tinlet) |
* Flag = 3 -> inlet temperature ramp (constant Tpool <> Tinlet) |
*                               |
*                               |
* Flag          | Ramp (degC/s) | Start Time (s) | End Time (s) |
*-----|-----|-----|-----|
*          i_pool_hu          |          t_in_rate          |          t_in_start          |          t_in_end          |
*-----|-----|-----|-----|

```

Table 19. Reactor pool water heatup parameters.

Item	Input Parameter Description
<i>i_pool_hu</i>	This parameter specifies the manner in which the reactor pool water temperature will be calculated to increase or decrease. 0 → The reactor pool water temperature will remain constant at its initial value. 1 → The reactor pool water temperature will increase/decrease based on the heat added by the reactor power and removed by the pool cooling system. 2 → The reactor pool water temperature will be increased/decreased by a specified ramp rate over a specified start and stop time. 3 → The inlet temperature of the fuel element coolant channel will be increased/decreased by a specified ramp rate over a specified start and stop time. NOTE: For options 0, 1, and 2, the inlet temperature of the fuel element coolant channel is equal to the reactor pool water temperature. For option 3, the reactor pool water temperature remains constant while the fuel element coolant channel inlet temperature increases/decreases.
<i>t_in_rate</i>	When <i>i_pool_hu</i> equals 2 or 3, this parameter specifies the rate (°C/s) at which pool water temperature (or channel inlet temperature) increases or decreases.
<i>t_in_start</i>	When <i>i_pool_hu</i> equals 2 or 3, this parameter specifies the start time at which a pool water temperature (or channel inlet temperature) increase or decrease begins.
<i>t_in_end</i>	When <i>i_pool_hu</i> equals 2 or 3, this parameter specifies the end time of a pool water temperature (or channel inlet temperature) increase or decrease.

3.6.3. Loss of Coolant Accident Parameters

These input specifications may be utilized to simulate at loss of coolant accident (or more precisely, a leaking reactor pool accident). The primary effect of using this option is that the pressure at the core inlet and outlet will be reduced as the level of the pool water decreases. Note, this option should not be used for formal safety analysis calculations until it has been subjected to verification and validation testing.

The reactor pool loss of coolant simulation is currently designed specifically for a large pipe break leak at the ACRR Facility. The leak occurs at the capped off end of a large diameter pipe which draws from the bottom of the reactor pool (see Fig. 7).

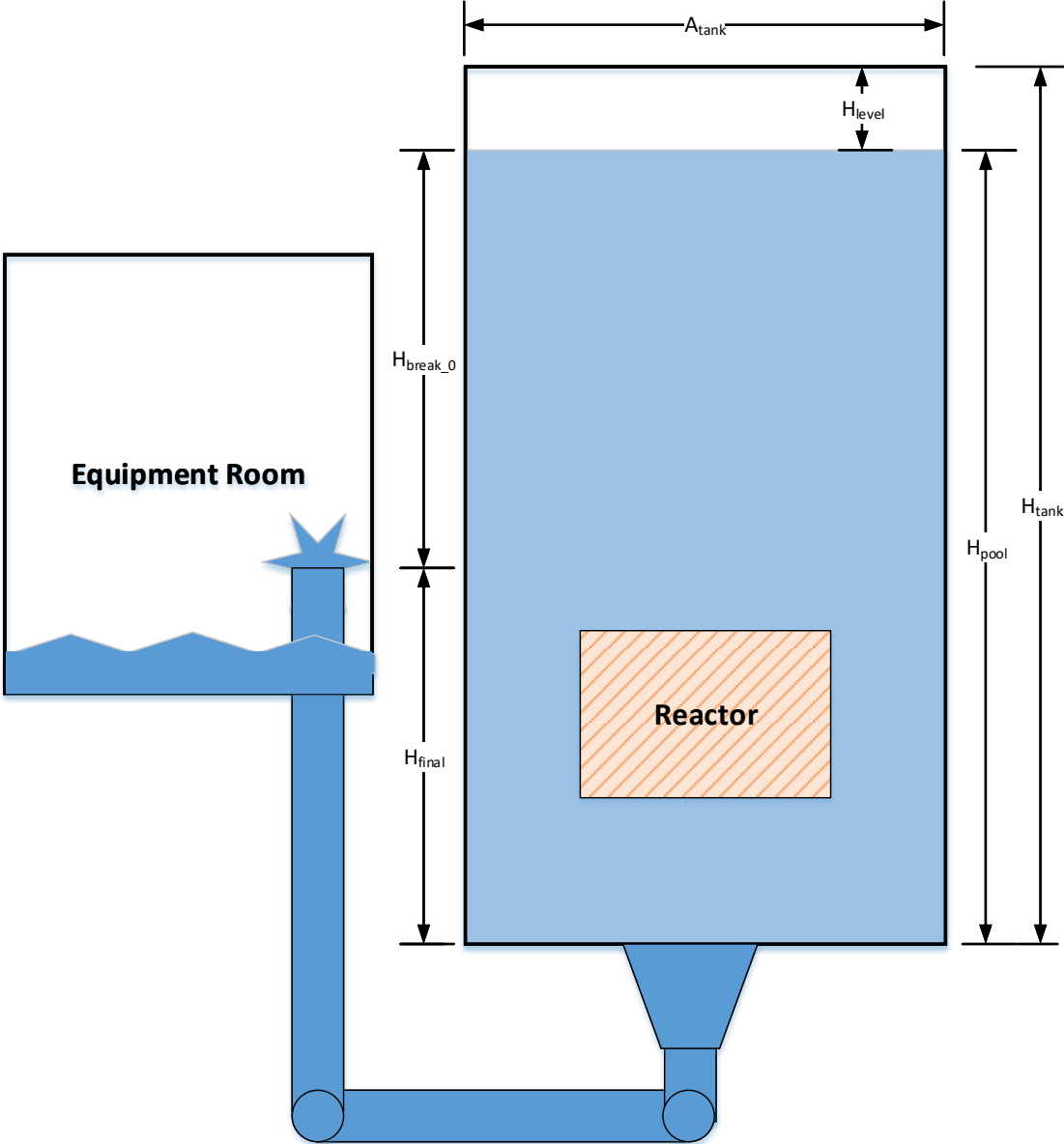


Figure 7. Schematic of reactor pool loss of coolant scenario.

```

*-----|
*      Loss of Coolant Accident      |
*      Flag      |      Start      |      Break      |      Effective Reactor      |
* (1=on, 0=off) |      Time (s)   |      Size (cm2) |      Power (W)             |
*-----|-----|-----|-----|
*      i_loca      |      t_break      |      break_area      |      rx_heat_scl      |
*-----|-----|-----|-----|

```

Table 20. Loss of coolant accident simulation parameters.

Item	Input Parameter Description
<i>i_loca</i>	This parameter activates a Loss of Coolant Accident (LOCA) simulation. 0 → No LOCA. 1 → LOCA activated.
<i>t_break</i>	This parameter specifies the time (s) at which the LOCA break occurs.
<i>break_area</i>	This parameter specifies the area (cm ²) of the LOCA break from which water will flow out of the reactor pool.
<i>rx_heat_scl</i>	This parameter not currently used by the code, but an arbitrary entry value is required.

3.6.4. Loss of Heat Sink Accident Parameters

These input specifications may be utilized to simulate a loss of heat sink accident (or more precisely, a linear decrease of pool water heat removal to zero). The primary effect of using this option is that the pool water temperature will begin to increase with less or no heat removal. Note, this option should not be used for formal safety analysis calculations until it has been subjected to verification and validation testing.

```

*-----|
*           Loss of Heat Sink Accident           |
*           Flag           |           Start Time           |           Flowrate Cooldown           |
*           (1=on, 0=off)  |           (s)                   |           Time (s)                   |
*-----|-----|-----|
*           i_lohs           |           t_lohs                   |           t_coast                   |
*-----|

```

Table 21. Loss of heat sink accident simulation parameters.

Item	Input Parameter Description
<i>i_lohs</i>	This parameter activates a Loss of Heat Sink (LOHS) accident simulation. 0 → No LOHS. 1 → LOHS activated.
<i>t_lohs</i>	This parameter specifies the time (s) at which the LOHS event begins.
<i>t_coast</i>	This parameter specifies the time span (s) over which the reactor pool water cooling system will coast down from its initial heat removal rate operating point (see <i>p_cool_sys</i> in Sect. 3.6.1 above) to a state of no heat removal.

3.6.5. Reactor Fuel Decay Heat Power Option

These input specifications may be utilized to simulate decay heat power from the built-up fission product inventory in the reactor fuel. If this option is turned on, then the fission product inventory will be assumed as that resulting from operating from $t=-\infty$ to $t=0$ at the initial reactor power level (Sect. 3.2). Once the reactor kinetics equation power level falls below the decay heat curve from ANS 5.1, then the ANS 5.1 decay heat power will be the fuel element power. Note, this option should not be used for formal safety analysis calculations until it has been subjected to verification and validation testing.

```

*-----|
*-----|
*   Decay Heat Option (1=on,0=off)   |
*-----|
*           i_dkp_opt                 |
*-----|

```

Table 22. ANS 5.1 decay heat power option switch.

Item	Input Parameter Description
<i>i_dkp_opt</i>	This parameter allows the activation of a routine which sets reactor power to the decay heat power level determined using ANS 5.1 once the reactor kinetics routine calculated power falls below the ANS 5.1 curve. 0 → ANS 5.1 Decay Heat power option is off. 1 → ANS 5.1 Decay Heat power option is on.

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3.7. Numerical Solution Settings

In early code development, the coolant channel mass, momentum, and energy numerical solution equations were formulated with factors that specified the degree of implicitness in advanced time terms. The three factors could be input as value from 0 (fully explicit) to 1 (fully implicit). The code's numerical solution equations are currently defined as fully implicit, so that these inputs are no longer used.

```

*****
*
*                      NUMERICAL SOLUTION SETTINGS
*
*-----|
*  Implicit Formulation Factors |
*-----|
*  Theta   |   Phi   |   Psi   |
*-----|
*  theta   |   phi   |   psi   |
*-----|

```

Table 23. Numerical solution implicit formulation factors.

Item	Input Parameter Description
<i>theta</i>	This parameter is no longer used by the code, but a value must be entered.
<i>phi</i>	This parameter is no longer used by the code, but a value must be entered.
<i>psi</i>	This parameter is no longer used by the code, but a value must be entered.

The code allows the user to specify three relative error values which are used for convergence criteria for the steady-state fuel element temperature distribution and coolant channel flow rate solution, and for steady-state and transient heat transfer coefficient computations under subcooled boiling conditions.

```

*-----|
*                      Iteration Error Limits |
*                      Steady-State          |          Transient |
*-----|-----|-----|
*  Temperature   |          Flow          |          Temperature |
*-----|-----|-----|
*  eps_temp_ss   |          eps_flow_ss   |          eps_temp   |
*-----|

```

Table 24. Numerical solution iteration error limit settings.

Item	Input Parameter Description
<i>eps_temp_ss</i>	This parameter specifies the minimum relative error that must be achieved by the code when iterating to a steady-state fuel element temperature distribution solution.
<i>eps_flow_ss</i>	This parameter specifies the minimum relative error that must be achieved by the code when iterating to a steady-state coolant channel flowrate solution.
<i>eps_temp</i>	This parameter specifies the minimum relative error that must be achieved by the code when iterating to find subcooled boiling heat transfer coefficient/cladding surface temperature solutions during steady-state and transient calculations.

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3.8. Fuel Element Model

The fuel element model defines the materials and geometric layout of the different materials of the reactor fuel element (or fuel rod). The fuel element model is laid out in an r-z cylindrical coordinate system⁸ by defining the radii which bound the various material regions. The radial layout is presumed to be the same over the entire vertical axis of the fuel element. Nuclear reactor fuel elements typically consist of a stack of fuel pellet surrounded by a metal cladding, with a gas-filled gap between the fuel and the cladding. To model such a case, the fuel, gap, and cladding would constitute three material regions which are called zones within Razorback. The ACRR fuel element (see Fig. 8) consists of concentric slotted annular fuel pellets, a niobium fuel cup, a stainless steel cladding, and gaps between each material. Thus, eight material zones are required to construct an ACRR fuel element model for Razorback.

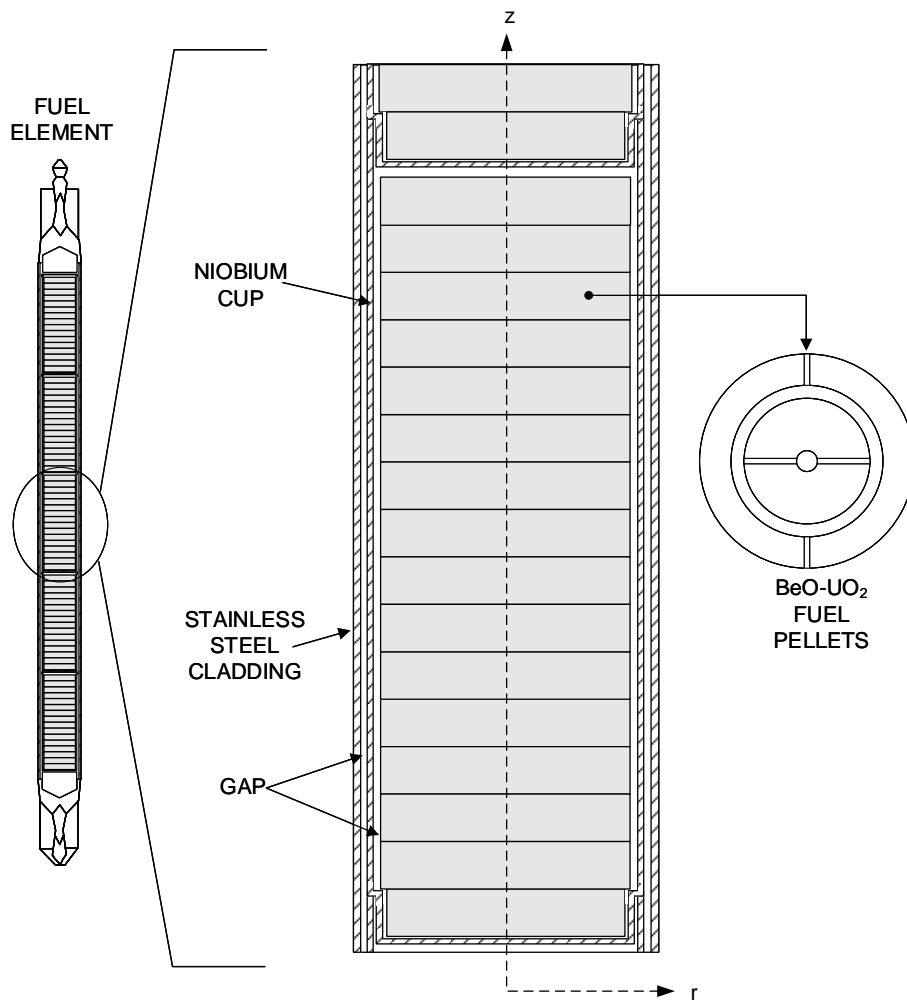


Figure 8. ACRR fuel element diagram showing various materials and gaps.

⁸ Many of the equations within the heat transfer and thermal expansion routines within Razorback were set up to handle x-z rectangular coordinates, but this capability has not yet been verified to be fully functional.

Using the ACRR fuel element as an example, the fuel element model would be constructed of eight zones:

1. Gas-filled inner void region (He gas).
2. Inner annular fuel pellet (BeO-UO₂). Note that the slots are ignored for the model.
3. Gas-filled gap between the inner and outer annular fuel pellets (He gas).
4. Outer annular fuel pellet (BeO-UO₂). Note that the slots are ignored for the model.
5. Gas-filled gap between the outer annular fuel pellet and the fuel cup (He gas).
6. Refractory metal fuel cup (niobium).
7. Gas-filled gap between the fuel cup and the cladding (He gas).
8. Metal cladding (stainless steel).

Before continuing, it is noted that the first region could have been left out in favor of specifying a non-zero inner radius for the inner fuel pellet. The assumption would then be that the temperature of the inner void zone gas is always equal to the inner surface temperature of the inner fuel pellet (i.e., The gas heats up instantaneously as the inner fuel surface heats up.).

For the purpose of computing a numerical solution for the heat transfer and thermal expansion within the fuel element, each of the zones must be divided into multiple “small” nodes. In general, the smaller the nodes (or the more nodes specified for each zone), the more accurate the numerical solution will be. Also, in general, thicker radial zones and zones which have low thermal conductivities will require more nodes for a better solution. The total number of nodes (i.e., the sum of all nodes for all zones) is limited within the code to 200.

Razorback can model radiation heat transfer across the gas-filled gap between two material zones. Thus, the fuel element model input specifies whether a given zone is a gas-filled gap or not.

Figure 9 presents a depiction of the zone/node model layout approach used by Razorback. In the figure, one can see a total of N zones, which have each been divided into a number of nodes. Conductive heat transfer will be modeled across/through all zones. Radiation heat transfer will be modeled only across the zones depicted as gaseous.

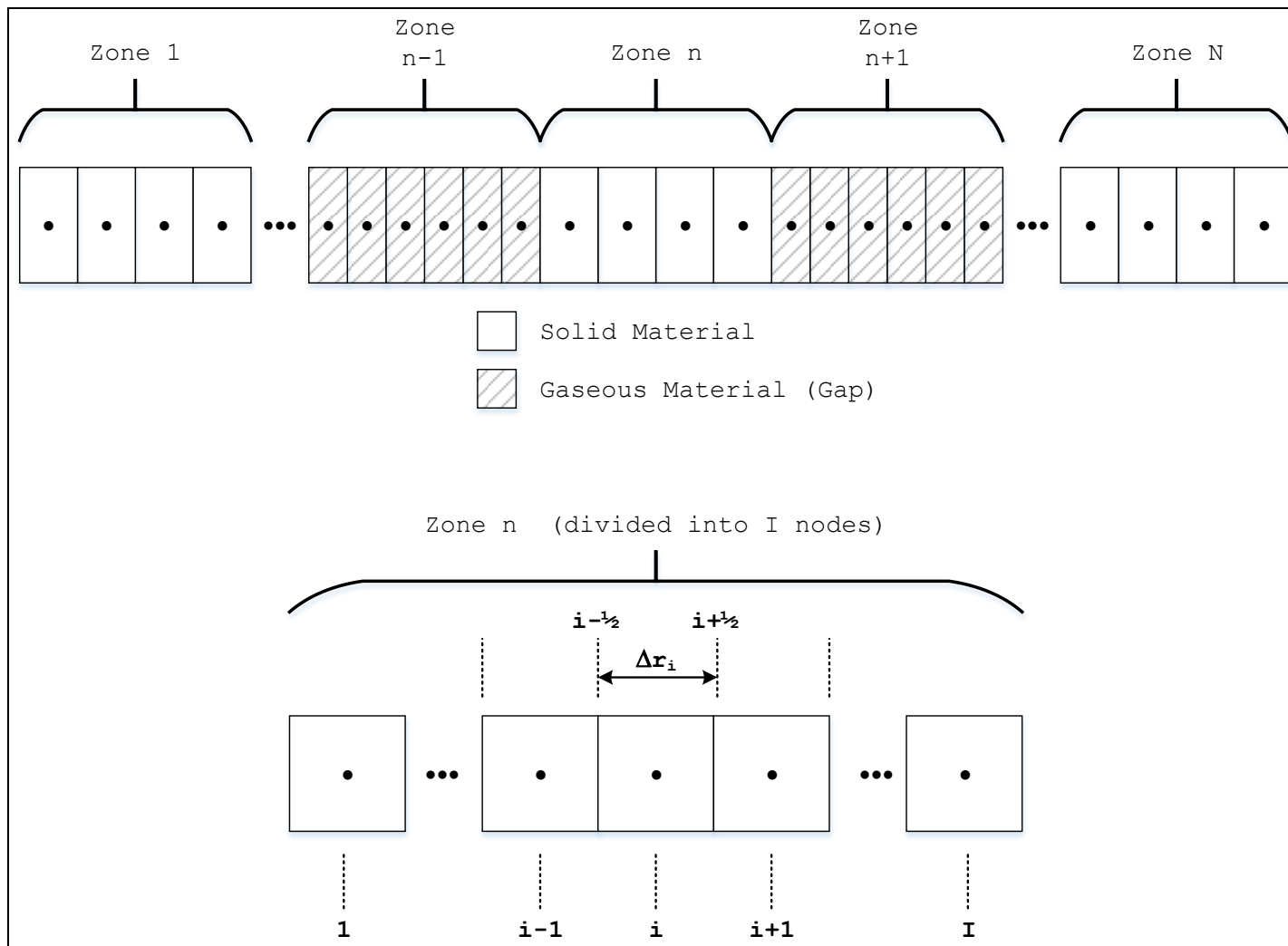


Figure 9. Depiction of the zones and nodes of a fuel element model.

3.8.1. Fuel Element Zoning

Here, the user specifies the number of radial zones into which the fuel element will be divided (see Fig. 9), the outer radial dimensions of these zones, and the fuel element model coordinate system geometry (**NOTE**: only cylindrical geometry has been verified). In addition, the user will specify the number of nodes to be used for each zone, the material type to be assigned to each zone, and whether or not the zone is a gap.

The user will also specify the fraction of the fission energy release which is deposited in each zone. Such information may be obtained via neutron and photon transport calculations using MCNP which determine the total neutron and gamma heating in the material zones. The fraction of the energy release which is deposited directly in the coolant channel is equal to 1.0 minus the sum of the deposition fractions for the element zones.

VERY IMPORTANT NOTE: In its current configuration, the code may not be able to correctly model fuel elements with more than one fuel zone, other than the ACRR. Only one radial fission energy deposition profile ($F_r(r)$, i.e., the fuel element internal material radial peaking factor) is entered and used in the code (see Sect. 3.8.5). The fuel material was presumed to be a single zone, or two contiguous zones separated by negligibly small gaps like the two fuel pellets of the ACRR. The energy deposition factors for the fuel zones, likewise apply to the whole of the fuel material. In the ACRR, 97.846% of the energy deposition occurs in the two fuel pellets taken as a whole. Therefore, the fission energy deposition factor for both fuel zones is entered as 0.97846. The user is cautioned that attempts to model other types of fuel with multiple fuel zones, may not be successful unless a similar approach to defining the fuel zone energy deposition factors is feasible.

One final option allows the user to specify the material stress/strain condition for each zone. The intent was to allow two options: (1) plane stress, and (2) plane strain. However, only the plane stress option has been verified.

```

*****
*
*                               FUEL ELEMENT MODEL
*
*****
*-----|-----|-----|-----|-----|-----|
* Number |         | Fuel Element Coordinate System Geometry |
* of     | R_inner |         0 = plate geometry                |
* Zones |   (cm) |         1 = cylindrical geometry          |
* (10 max) |       |                                           |
*-----|-----|-----|-----|-----|
*
*           nzones   r_inner           icse
*-----|-----|-----|-----|-----|
* Zone Outer | Number | Material | Gap? | Fiss. Energy | Th. Exp. |
* Radius (cm) | of nodes | Type | (0=n/1=y) | Dep. Frac. | Option |
*-----|-----|-----|-----|-----|
*
*           R_OUTER   NNODES   MAT_TYPE   IR_TRANS   FEDF   I_EXP_OPT
*-----|-----|-----|-----|-----|

```

Table 25. Fuel element zone definition parameters.

Item	Input Parameter Description
<i>nzones</i>	<p>This parameter specifies the number of radial material zones within the fuel element. There must be a new zone for every radial material change, even if more than one zone has the same material type assignment.</p> <p>NOTE: If thermal expansion will be computed, then solid material zones must be separated by gas-filled zones. Also, if the gas-filled zone is extremely small, and there is a thermal expansion mismatch between the separated solid materials, then it is likely that code crashes will occur when the gas-filled gap size becomes negative.</p>
<i>r_inner</i>	<p>This parameter specifies the inner radius (cm) of the first material zone. This will be non-zero only when the user decides not to specify a gas-filled central zone. In such a case, the inner radius is modeled as an adiabatic boundary.</p>
<i>icse</i>	<p>This parameter specifies the fuel element geometry type. 1 → cylindrical geometry</p> <p>NOTE: The code was designed with the intent to allow for plate geometry (<i>icse</i>=0). However, this feature has not yet been verified by testing.</p>
<i>R_OUTER(n)</i>	<p>This parameter specifies the outer radii (cm) of material zone <i>n</i>.</p>
<i>NNODES(n)</i>	<p>This parameter specifies the number of radial nodes into which material zone <i>n</i> will be divided.</p>
<i>MAT_TYPE(n)</i>	<p>This parameter specifies the material type number to be assigned to material zone <i>n</i>.</p>
<i>IR_TRANS(n)</i>	<p>This parameter specifies the whether the material type in material zone <i>n</i> is a gas-filled gap (<i>IR_TRANS</i>=1) or a solid (<i>IR_TRANS</i>=0).</p>
<i>FEDF(n)</i>	<p>This parameter specifies the fraction of fuel element power which will be deposited in material zone <i>n</i>. This allows for modeling neutron/gamma heating in fuel element materials as a fraction of the total fuel element power.</p> <p>NOTE: The fraction of fuel element power deposited directly into the coolant will be equal to 1.0 minus the sum of the <i>FEDF</i> values.</p>
<i>I_EXP_OPT(n)</i>	<p>This parameter specifies the thermal expansion conditions to be assumed in material zone <i>n</i>. 1 → plane stress.</p> <p>NOTE: An option for plane strain (<i>I_EXP_OPT</i>=2) has been included in the code, but has not yet been verified by testing.</p>

3.8.2. Fuel Height and Grid Geometry

With the radial fuel dimensions and material zones and types specified, the user now describes the axial length and arrangement of the fuel elements. Razorback presumes that the fuel elements are arranged, with their axial length vertical, between top and bottom grid plates which set the arrangement geometry and pitch. The two fuel element arrangement geometries are square and hexagonal (also called triangular) and are shown in Fig. 10.

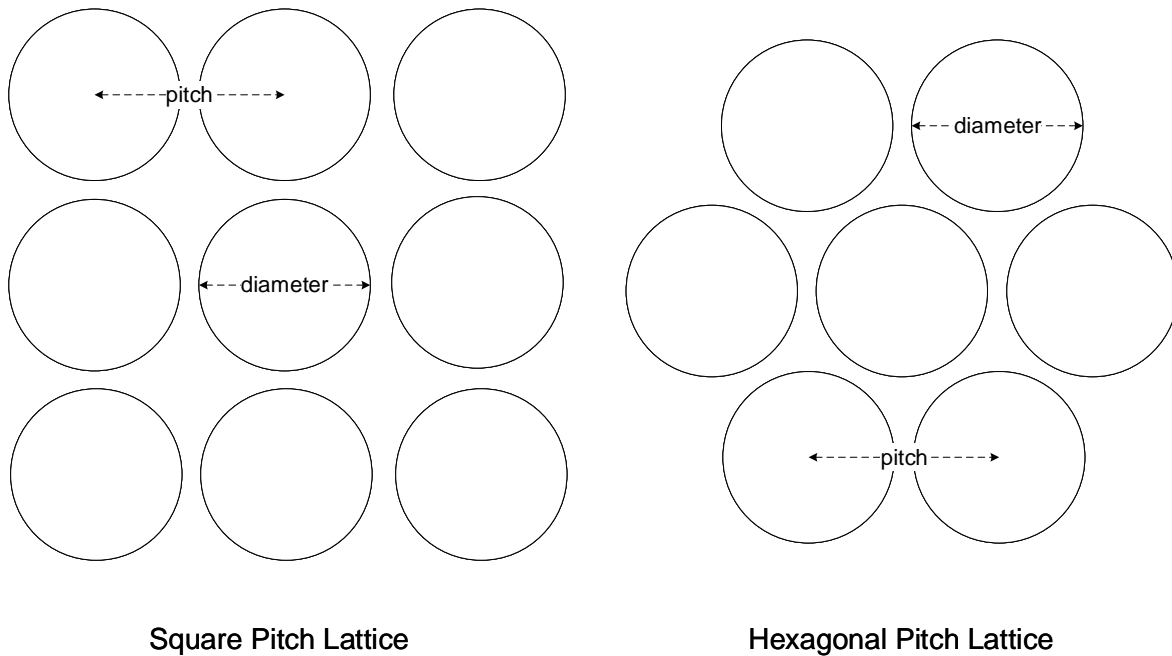


Figure 10. Fuel element core geometry arrangements.

```

*-----|
*           Fuel Element Geometry           |
*-----|
*           |           |           |           |
*   Fuel    |   Number  |   Pitch or  |   Pitch/Flow Geometry   |
*   Length (cm) | of Nodes | Channel O.D. | (1=square pitch,2=hex pitch |
*               |          | (cm)         | 3=annulus, 4=tube)         |
*-----|-----|-----|-----|
*   h_fuel   | nf_nodes | pitch      | igetyp                   |
*-----|-----|-----|-----|

```

Table 26. Fuel height and number input parameters.

Item	Input Parameter Description
<i>h_fuel</i>	This parameter specifies the height (cm) of the fuel stack within a fuel element.
<i>nf_nodes</i>	This parameter specifies the number of axial fuel element nodes. As such, it also specifies the axial node height (Δz_f) as $\Delta z_f = \frac{h_{fuel}}{nf_nodes}$
<i>pitch</i>	For <i>igetyp</i> = 1 or 2, this parameter specifies the pitch, or center-to-center distance (cm) of the geometrical arrangement of fuel elements. For <i>igetyp</i> = 3, this parameter specifies the outer diameter of the annulus. For <i>igetyp</i> =4, this parameter specifies the diameter of the tube.
<i>igetyp</i>	This parameter specifies the geometrical arrangement of the fuel elements. 1 → square pitch. 2 → hexagonal (triangular) pitch. 3 → annulus (heat from inner annulus surface; adiabatic outer annulus surface). 4 → tube (heat from outer surface). Figures 11 and 12 show these types of flow channel geometries.

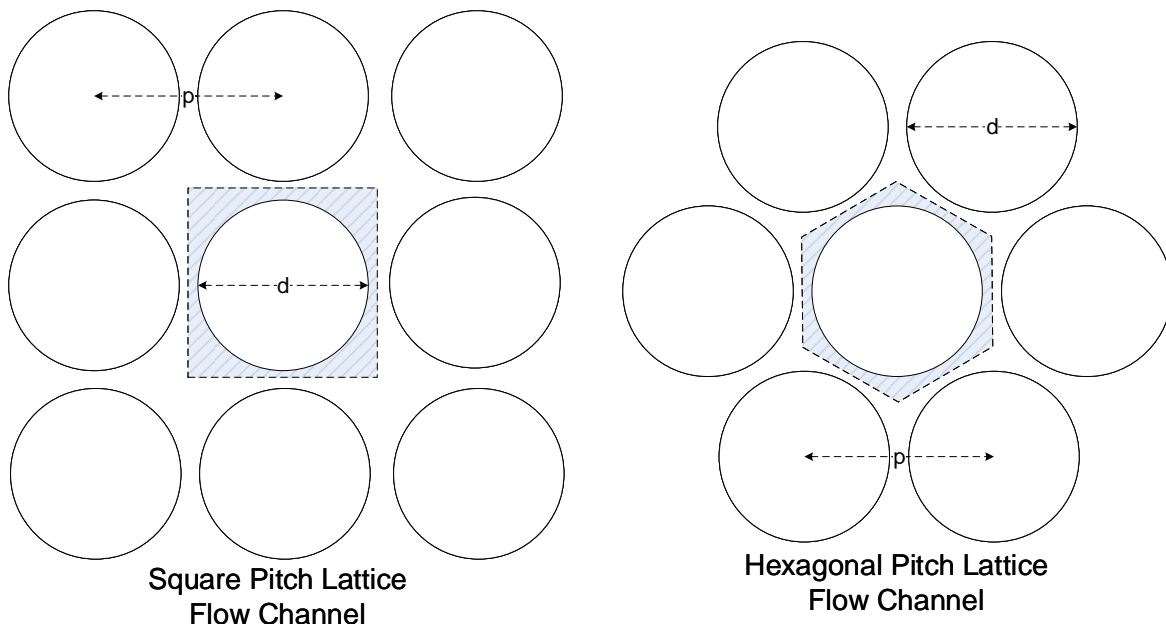


Figure 11. Flow channel depiction for square and hexagonal pitch element geometries.

In addition to the fuel element arrangements discussed above, Razorback has two other flow channel types: annulus and tube. These will only be used when performing an analysis using the flow channel only (i.e., no fuel element) option (see Section 3.9.1). For the annulus, the outer diameter of the fuel element model (Section 3.8.1)⁹ is used for the inner diameter, and the pitch is used for the outer diameter. The heat is presumed to flow into the channel from the inner diameter surface, and the outer diameter is assumed to be insulated. For a tube, the *pitch* input is used to specify the diameter of the tube. Figure 12 shows the annulus and tube geometries.

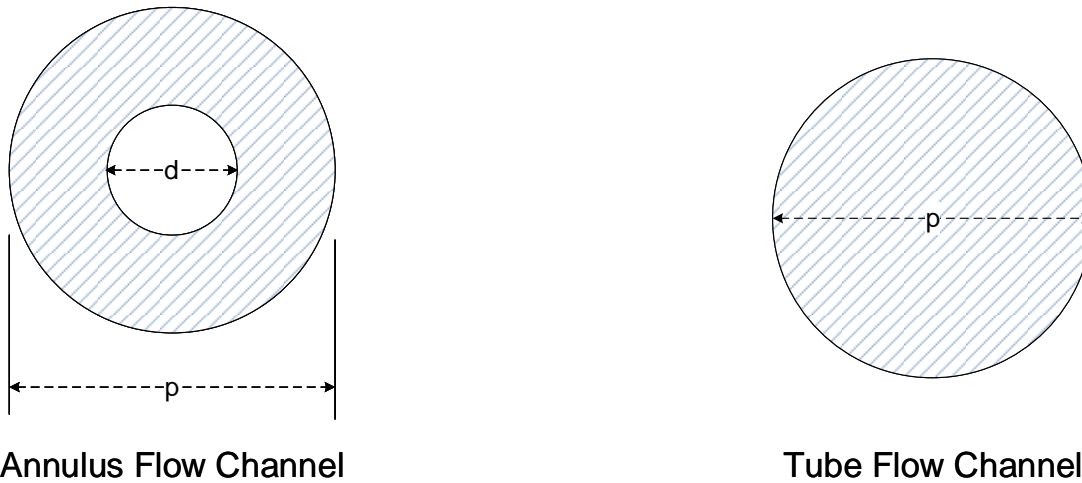


Figure 12. Depictions of annulus and tube flow channel geometry types.

The pitch (center-to-center distance, p), element outer diameter (d), and arrangement geometry type are used to define the flow channel area (A_f), the hydraulic diameter (d_{hyd}), and the wetted perimeter (P_w). Table 27 shows the formulae used to compute these important flow parameters.

Table 27. Flow area, hydraulic diameter, and wetted perimeter formulae.

Flow Channel	Flow Area	Hydraulic Diameter	Wetted Perimeter
Square Pitch	$A_f = p^2 - \frac{\pi}{4} d^2$	$d_{hyd} = d \left[\frac{4}{\pi} \left(\frac{p}{d} \right)^2 - 1 \right]$	$P_w = \pi d$
Hexagonal Pitch	$A_f = \frac{\sqrt{3}}{2} p^2 - \frac{\pi}{4} d^2$	$d_{hyd} = d \left[\frac{2\sqrt{3}}{\pi} \left(\frac{p}{d} \right)^2 - 1 \right]$	$P_w = \pi d$
Annulus	$A_f = \frac{\pi}{4} (p^2 - d^2)$	$d_{hyd} = p - d.$	$P_w = \pi(p + d)$
Tube	$A_f = \frac{\pi}{4} p^2$	$d_{hyd} = p$	$P_w = \pi p$

⁹ As with most of the input file parameters, even though one would specify the channel-only option for the annulus or tube flow geometries, a fuel element model must be specified. Ultimately, only the outer radius is used in the channel-only option.

3.8.3. Fuel Element Fissile Material Type, Pressure, and Calculation Options

Here the user will specify several options, and two fuel element pressure initial condition values. The material number in which fission will occur is specified. The user will also specify whether thermal expansion will be allowed, and whether radiation heat transfer across the fuel element gaps will be allowed.

The user may also specify the initial internal pressure of the fill gas within the element. This will allow the code to compute the changing internal pressure based upon the internal gap volume which may change with thermal expansion. The user may utilize the sign of the entry to instruct the code on whether or not to apply the internal pressure in the computation of component stress states.

Likewise, the user specifies the external pressure on the surface of the fuel element cladding. This external pressure is presumed to apply uniformly over the height of the fuel element, and does not vary with time.

```
*-----|
* Fissile   | Internal   | External   | Allow      | Allow Gap |
* Mat. #    | Element    | Element    | Thermal Exp. | Rad HX    |
* (only one) | Press (psia) | Press (psia) | (0=no,1=yes) | (0=no,1=yes) |
*-----|-----|-----|-----|-----|
n_fuel_mat_type press_ele0   press_ext0           iexpand           irad
*-----|
```

Table 28. Fuel element fissile material type, pressure, and calculation option parameters.

Item	Input Parameter Description
<i>n_fuel_mat_type</i>	This parameter specifies the fuel material number which corresponds to the material which is heated by nuclear fission.
<i>press_ele0</i>	This parameter specifies the initial internal pressure (psia) of the fill gas within the fuel element. The code will compute changes to this pressure with both internal temperatures and gas space volume changes due to thermal expansion. NOTE: If <i>press_ele0</i> is entered as a negative value, then the changing internal pressure will still be calculated, but only the initial value of $ press_ele0 $ will be applied in computing the stress on fuel element components.
<i>press_ext0</i>	This parameter specifies the external pressure (psia) on the fuel element cladding. It is currently treated in the code as constant both axially, and with time.
<i>iexpand</i>	This parameter controls whether the code will compute thermal expansion and stress. 0 → No thermal expansion or stress. 1 → Compute thermal expansion and stress.
<i>irad</i>	This parameter controls whether the code will compute thermal radiation heat transfer across gas-filled gaps in the fuel element. 0 → No thermal radiation heat transfer. 1 → Compute thermal radiation heat transfer.

3.8.4. Fuel Element Measured Temperature Location

A research reactor may contain fuel elements which are instrumented with thermocouples. Razorback includes a feature which allows the user to select a particular radial location within the fuel element fuel material to define a “measured” temperature. This location is assumed within the code to occur at/near the axial midplane of the fuel. Thus, the axial node used for the measured temperature is $j = nf_nodes/2$. As this axial index j is an integer value, if nf_nodes is an odd number, the result of dividing by two will be truncated to an integer.

With the radial location (node) is defined for the measured temperature, a second input allows the user to specify that the measured temperature is a volume-weighted average temperature of the specified radial node, and an equal number of radial nodes on either side of the selected node.

```

*-----|
* Center radial node of fuel "TC" | # of radial nodes to average |
* (at half fuel height) | on each side of the center node |
*-----|-----|
* I_TC(1) | I_TC(2) |
*-----|

```

Table 29. Parameters for defining a location for a “Measured” temperature.

Item	Input Parameter Description
<i>I_TC(1)</i>	This parameter specifies the radial node at the axial midplane ($j=nf_nodes/2$) in the fuel element which will be used as the basis for a “measured” fuel temperature.
<i>I_TC(2)</i>	This parameter specifies the number of radial nodes in the fuel element, on each side of the <i>I_TC(1)</i> node, which will be used to compute a “measured” fuel temperature. The measured fuel temperature is given by a volume weighted average $T_{measured} = \frac{1}{V_{meas}} \sum_{i=I_TC(1)-I_TC(2)}^{I_TC(1)+I_TC(2)} T_{i,nf_nodes/2} \cdot V_{i,nf_nodes/2}$ where V_{meas} is the sum of the individual radial node volumes ($V_{i,nf_nodes/2}$).

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3.9. Coolant Channel Model

The coolant channel model, as depicted in Fig. 13, consists of three distinct regions: (1) a lower unheated length, (2) a length heated by the fuel, and (3) an upper unheated length. The input information for the portion of the coolant channel that is heated by the fuel was defined in Section 3.8.2, by specifying the height of the fuel (h_{fuel}), the number of axial fuel element nodes (nf_nodes), the outer radius of the cladding ($R_OUTER(nzones)$), the pitch ($pitch$), and the flow geometry type ($igetyp$). The parameters allow the code to compute the number of heated coolant nodes and their height, the flow channel area, and the flow channel hydraulic diameter.

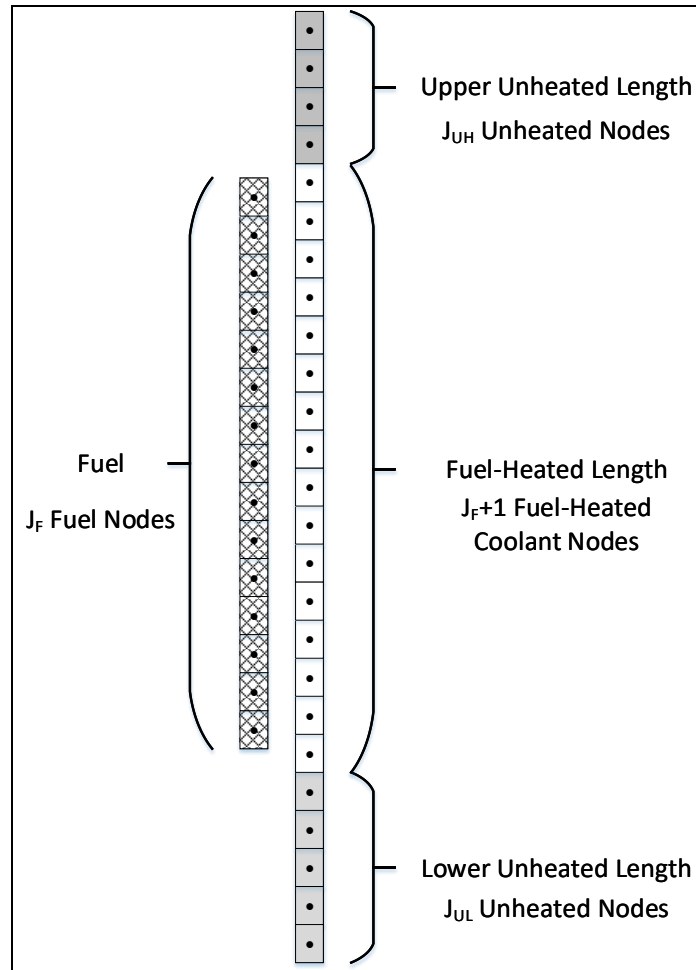


Figure 13. Coolant channel model layout.

The length of the coolant channel which is heated by the fuel is constructed such that it is offset from the fuel axial nodes (see Fig. 13). As a result, the fuel-heated coolant nodes are the same axial height as the fuel axial nodes (see Sect. 3.8.2), and the number of fuel-heated coolant nodes is one greater than the number of fuel axial nodes.

The upper and lower unheated lengths, obviously, are not heated by fuel segments, and the code currently does not include and direct neutron/gamma heating of these nodes. The user is free to set the number of upper and lower unheated length nodes to zero.

3.9.1. Coolant Channel Modeling Options

Razorback is generally intended to model a reactor with fuel elements that are cooled by a coolant flowing parallel to the fuel element. The heat transferred to the coolant is determined by computing the heat transfer of energy deposited in the fuel and conducted to the fuel element cladding surface. An alternative option, **not currently available**, allows the user to specify a time-dependent element power, which is translated directly to a cladding surface heat flux (i.e., the energy deposition/heat transfer calculation within the “fuel” is bypassed). This option allows the user to model a situation such as a critical heat flux experiment where an electrically heated rod provides a heat flux to a flow channel. The time dependent element power is input as a power history file using the *irx_off* option (see Sect. 3.1.1).

Two other input options are specified here: (1) the coolant material type, and (2) the coolant channel flow mechanism. Currently, Razorback has only one coolant material type – water, and allows only one flow mechanism – natural convection.

```

*****
*                               COOLANT CHANNEL MODEL
*****
*-----|-----|-----|
*  Coolant Channel Option      | Coolant Type |      Flow Type      |
* (0 = fuel coupled to coolant) | (1 = water)  | (1=Natural Conv.)  |
* (1 = channel only)          |              | (0=Forced Conv.)   |
*-----|-----|-----|
*           i_ch_only           |           icmat_no           |           i_nat_conv           |
*-----|-----|-----|

```

Table 31. Coolant channel modeling options.

Item	Input Parameter Description
<i>i_ch_only</i>	This parameter determines if the code will function in a mode in which the channel is heated by a fuel element model, or simply by a specified heat flux (i.e., no fuel element). 0 → Normal code operation (i.e., fuel element coupled to the coolant channel). 1 → Channel only mode in which fuel element computations are not performed. NOTE: If <i>i_ch_only</i> =1, then the coolant channel is heated by a heat flux determined from the current reactor power (via a <i>pwrhis.dat</i> file), fuel element outer diameter (<i>R_OUTER(nzones)</i>) and fuel length (<i>h_fuel</i> and <i>nf_nodes</i>), fuel element geometry (<i>pitch</i> and <i>igetyp</i>), axial fission density profile (Sect. 3.8.5). Thus, although no computations are made to determine fuel element temperature distributions and expansion, a fuel element model must still be specified in the input. NOTE: Channel only option (<i>i_ch_only</i> =1) is not currently available.
<i>icmat_no</i>	This parameter specifies the coolant material type. NOTE: Water is the only option available (<i>icmat_no</i> =1).
<i>i_nat_conv</i>	This parameter specifies whether coolant flow is driven by natural or forced circulation. NOTE: Natural circulation is the only option available (<i>i_nat_conv</i> =1).

3.9.2. Coolant Channel Flow Model Parameters

This input card contains information for the implementation of the drift flux model for two-phase flow. A nominal value for the drift velocity (u_{gj}) is input here. The code will internally apply a scale function to the drift velocity which depends upon the local void fraction (α). The drift velocity is the velocity of the vapor phase (u_g) relative to the superficial flow velocity (j). Lahey (Ref. 4) recommends using the terminal rise velocity of a bubble for u_{gj} (see Table 13 below). Note that bubble distribution/flow regime effects can be accounted for to define an effective drift velocity (u'_{gj}) as

$$u'_{gj} = (C_o - 1)\langle j \rangle + u_{gj}$$

where $\langle j \rangle$ is the void fraction weighted superficial flow velocity, and C_o is a parameter which characterizes the bubble/flow regime. However, Razorback currently treats C_o as equal to 1. Therefore, $u'_{gj} = u_{gj}$.

Regarding the boiling expansion factor input (**boil_exp_fctr**), it is important to note that the use of this value is a heuristic technique to avoid unbounded instabilities in the computation of the saturated flow boiling conditions. The parameter (we shall call ξ here) modifies the void fraction-static quality (α, χ_s) relationship.

$$\alpha = \frac{\frac{1}{\xi} \frac{\rho_f}{\rho_g} \chi_s}{1 + \chi_s \left(\frac{1}{\xi} \frac{\rho_f}{\rho_g} - 1 \right)}$$

It has the effect of reducing the void fraction resulting from a given static quality, thus restricting the expansion of the vapor phase. This parameter should be used with caution and judgment. At a minimum, the user should seek the smallest value of ξ for which unbounded instabilities are suppressed.

The input parameters related to the forced convection flow option here (**dum1** and **dum2**) are not used by the code, since only natural circulation is allowed. And, the “artificial viscosity” input parameter (**dum3**) is not used. However, three arbitrary input values must be entered on this input card line.

* Two-Phase Flow	Boiling	(Forced Conv.-Not Active)		Artificial
* Drift Velocity	Expansion	Inlet	Inlet	Viscosity
* Nominal Value	Suppression	Pressure	Mass Flow	Constant
* (cm/s)	Factor	(psia)	(g/sec)	
<i>ugj_nom</i>	<i>boil_exp_fctr</i>	<i>dum1</i>	<i>dum2</i>	<i>dum3</i>

Table 32. Coolant channel flow model parameters.

Item	Input Parameter Description
<i>ugj_nom</i>	<p>This parameter specifies the drift velocity (u_{gj}) in cm/s for the drift flux model used in situations of two-phase flow. A value may be obtained from a relation presented in Ref. 4</p> $u_{gj} = 2.9 \left[\frac{(\rho_f - \rho_g)\sigma g}{\rho_f^2} \right]^{\frac{1}{4}}$ <p>Where ρ_f and ρ_g are the saturated liquid and vapor densities, σ is the surface tension, and g is gravitational acceleration.</p>
<i>boil_exp_fctr</i>	<p>This parameter specifies a “boiling expansion factor,” similar to a slip ratio, which helps to minimize coolant flow fluctuations in saturated boiling regions. NOTE: This is a strictly heuristic technique to allow the code to continue through saturated boiling situations to obtain assessments of the progression of events which induce significant saturated boiling.</p>
<i>dum1</i> <i>dum2</i> <i>dum3</i>	<p>These parameters are not used by the code, but values must be entered on the card. Values of 1.0 for each is suggested, but the input values are truly arbitrary.</p>

3.9.3. Reactor Pool Water Surface Ambient Pressure

The magnitude of the pressure at the bottom of the fuel element coolant channel is controlled by the pressure at the surface of the reactor pool, the distance from the pool surface to the bottom of the channel, and the average temperature of the pool water. The pressure at the pool surface would be local atmospheric pressure of an open pool. The pressure input here could, of course, be set at a value above or below local atmospheric. However, the coolant properties built into the code currently only cover a pressure range up to 50 psia, and the nominal coolant pressure for the code validation cases was ~20 psia.

```

*-----|
*           Atmospheric Pressure           |
*           Above Pool Water (psia)       |
*-----|
*                               p_atm    |
*-----|
  
```

Table 33. Ambient pressure at the reactor pool water surface.

Item	Input Parameter Description
<i>p_atm</i>	This parameter specifies the ambient pressure (psia) at the top surface of the reactor pool water.

3.9.4. Coolant Channel Inlet Node

This portion of the input allows the user to specify the geometry and form loss coefficient for the channel inlet node. The channel inlet node is where the pressure boundary condition for the lower end of the channel is applied. Provision is made for cases in which the inlet area of the inlet node is different from the exit area of the inlet node. A form loss coefficient (a.k.a., a minor loss coefficient) may be specified for the inlet node.

```

*-----|
*           Channel Inlet Node Definition |
* Node Inlet   | Node Exit   |           |
* Flow Area (cm2) | Flow Area (cm2) | Minor Loss Coefficient |
*-----|
*           a_inlet           a_outlet           formk_ent |
*-----|
  
```

NOTE: Currently, the inlet and exit flow areas (*a_inlet* and *a_outlet*) must be set to the same value as the fuel region channel flow area.

Table 34. Coolant channel inlet node definition.

Item	Input Parameter Description
<i>a_inlet</i>	This parameter specifies the inlet area (cm ²) of the first node of the coolant channel.
<i>a_outlet</i>	This parameter specifies the outlet area (cm ²) of the first node of the coolant channel.
<i>formk_ent</i>	This parameter specifies the minor loss coefficient for the channel inlet, <u>including</u> that due to any inlet/outlet area transition for this first node.

3.9.5. Coolant Channel Unheated Inlet and Outlet Length Nodes

This portion of the input allows the user to specify the number of unheated nodes for the inlet (below the fuel) and outlet (above the fuel).

```

*-----|
*           Unheated Channel Length (Lower and Upper) |
*-----|
*   Number of Lower Nodes | Number of Upper Nodes |
*-----|
*           n_uhi_nodes | n_uho_nodes |
*-----|
  
```

Table 35. Number of unheated length nodes at the channel inlet and outlet.

Item	Input Parameter Description
<i>n_uhi_nodes</i>	This parameter specifies number of nodes into which the lower unheated length of the coolant channel will be divided. NOTE: It is recommended that this number be specified so that the node length in the lower unheated section is close to the same length (within a factor of 2) of the fuel region coolant channel nodes.
<i>n_uho_nodes</i>	This parameter specifies number of nodes into which the upper unheated length of the coolant channel will be divided. NOTE: It is recommended that this number be specified so that the node length in the upper unheated section is close to the same length (within a factor of 2) of the fuel region coolant channel nodes.

3.9.6. Coolant Channel Lower Unheated Length Description

NOTE: If *n_uhi_nodes* is 0, then this card is *not* required.

Here, an entry is made for each lower unheated length coolant channel node to specify the node height, exit flow area, wetted perimeter, and form loss coefficient. The inlet flow area is set to the exit flow area of the previous node (for the first node, this would be the channel inlet node of Sect. 3.9.4). The node heights do not have to be equal, but it is recommended that they be similar in size to a fuel-heated length node height.

```

*-----|
*           Lower Unheated Length Description |
*-----|
* Node Height | Exit Flow | Wetted Perimeter | Exit |
*   (cm)      | Area (cm2) | (cm)              | Loss |
*-----| |-----| |-----| |-----|
*           DZC | AF_C | PW_C | FORMK |
*-----|
  
```

NOTE: Currently, the exit flow area (*AF_C*) must be set to the same value as the fuel region channel flow area.

Table 36. Lower unheated length parameters.

Item	Input Parameter Description
<i>DZC(j)</i>	This parameter specifies the axial length (cm) of coolant channel lower unheated length node <i>j</i> .
<i>AF_C(j)</i>	This parameter specifies the cross-sectional area (cm ²) of coolant channel lower unheated length node <i>j</i> .
<i>PW_C(j)</i>	This parameter specifies the wetted perimeter (cm) of coolant channel lower unheated length node <i>j</i> .
<i>FORMK(j)</i>	This parameter specifies the minor loss coefficient of coolant channel lower unheated length node <i>j</i> .

3.9.7. Coolant Channel Upper Unheated Length Description

NOTE: If *n_uho_nodes* is 0, then this card is *not* required.

Here, an entry is made for each upper unheated length coolant channel node to specify the node height, exit flow area, wetted perimeter, and form loss coefficient. The inlet flow area is set to the exit flow area of the previous node (for the first node, this would be the flow area of the fuel-heated channel nodes of Sect. 3.8.2). The node heights do not have to be equal, but it is recommended that they be similar in size to a fuel-heated length node height.

```

*-----|
*           Upper Unheated Length Description           |
*-----|
* Node Height | Exit Flow | Wetted Perimeter |      Exit |
*   (cm)      | Area (cm2)|      (cm)        | Loss Coefficient |
*-----|-----|-----|-----|
*           DZC       AF_C       PW_C       FORMK
*-----|

```

NOTE: Currently, the exit flow area (*AF_C*) must be set to the same value as the fuel region channel flow area.

Table 37. Upper unheated length parameters.

Item	Input Parameter Description
<i>DZC(j)</i>	This parameter specifies the axial length (cm) of coolant channel upper unheated length node <i>j</i> .
<i>AF_C(j)</i>	This parameter specifies the cross-sectional area (cm ²) of coolant channel upper unheated length node <i>j</i> .
<i>PW_C(j)</i>	This parameter specifies the wetted perimeter (cm) of coolant channel upper unheated length node <i>j</i> .
<i>FORMK(j)</i>	This parameter specifies the minor loss coefficient of coolant channel upper unheated length node <i>j</i> .

3.9.8. Coolant Channel Outlet Node

Here, the user may specify the channel exit flow area and form loss coefficient. The inlet flow area is set to the exit flow area of the previous node.

```

*-----|
*           Channel Outlet Node Definition |
*   Node Exit Flow Area (cm2) | Minor Loss Coefficient |
*-----|-----|
*           a_outlet | formk_exit |
*-----|

```

NOTE: Currently, the exit flow area (*a_outlet*) must be set to the same value as the fuel region channel flow area.

Table 38. Coolant channel outlet node definition.

Item	Input Parameter Description
<i>a_outlet</i>	This parameter specifies the exit area (cm ²) of the coolant channel. The inlet area of this final node will be either the last <i>AF_C</i> value for the upper unheated length, or the flow area of the fuel region channel.
<i>formk_exit</i>	This parameter specifies the minor loss coefficient for the channel exit, <u>including</u> that due to any inlet/outlet area transition for this final node.

3.10. Code Test Options

3.10.1. Fuel Heat Transfer Test Options

This portion of the input file is a remnant of early development testing options for the heat transfer module. Setting the variable *i_test_mode* to 0 allows normal code execution, and is recommended as the only option to the user.

```

*****
*   Test Options
*****
*-----|
*                Test Mode                |
*-----|
*   0 = Normal (no test; next card not required, so comment out) |
*   1 = Specify BCs and/or Conductivities (next card required)   |
*-----|
*                                i_test_mode
* Fuel Element Surface BC  1=convection / 2=constant T --> BC Temp
*          ibc_r                                ts_input
*-----|

```

NOTE: If *i_test_mode* is 0, then the *ibc_r/ts_input* card must be commented out or not entered.

Table 39. Fuel heat transfer test options.

Item	Input Parameter Description
<i>i_test_mode</i>	This parameter determines if the code will function in a test mode. 0 → Normal code operation (i.e., not in test mode). 1 → Test mode operation.
<i>ibc_r</i>	If <i>i_test_mode</i> =1, then this parameter specifies whether the code will apply a convection (<i>ibc_r</i> =1) or constant surface temperature (<i>ibc_r</i> =2) boundary condition to the outer fuel element surface.
<i>ts_input</i>	If <i>i_test_mode</i> =1 and <i>ibc_r</i> =2, then this parameter specifies the constant surface temperature used for the outer fuel element surface boundary condition.

3.10.2. Reactor Kinetics Only Option

An option is available for the user to execute problems involving only the solution of the point reactor kinetics equations. No fuel element heat transfer or expansion, or coolant channel thermal-hydraulics calculations will be performed. A simple feedback option for the reactor kinetics only option is available. The feedback will be proportional to the energy release of the reactor (i.e., the time-integrated reactor power).

```

*-----|
*           Reactor Only Test Option           |
*-----|
*   Reactor Only (1=y/0=no)   |   Energy Yield Feedback ($/J-Rx)   |
*-----|-----|
*           irx_only           |           c_rho_nf           |
*-----|

```

Table 40. Reactor kinetics solution only option.

Item	Input Parameter Description
<i>irx_only</i>	If <i>i_test_mode</i> =1 then this parameter determines if the code will only execute the reactor kinetics routines, and not perform computations related to the fuel element or the coolant channel. 0 → Normal code operation. 1 → Reactor Only operation mode.
<i>c_rho_nf</i>	This parameter specifies an energy-based reactivity feedback (\$/J) coefficient to be used if <i>irx_only</i> =1.

3.11. Fuel Element Material Properties

This portion of the input file specifies the correlations to be used for the material properties of the materials used in the fuel element model. For the evaluation of transient heat transfer and thermal expansion within the fuel element, the following material properties are required:

- Density (g/cm^3),
- Thermal conductivity ($\text{W}/\text{cm}\cdot\text{K}$),
- Specific heat capacity ($\text{J}/\text{g}\cdot\text{K}$),
- Thermal radiation surface emissivity,
- Thermal radiation transmissivity,
- Linear thermal expansion coefficient (K^{-1}),
- Young's modulus (Pa), and
- Poisson's ratio.

The code currently allows for the properties of up to 10 different materials to be defined. The thermal conductivity, specific heat capacity, linear thermal expansion coefficient, and Young's modulus may be defined using correlations (as a function of absolute temperature) of up to sixth order. The density is entered as a constant representing the room temperature density. Temperature-dependent changes in density are based on the state of thermal expansion of the material with respect to room temperature dimensions.¹⁰ The entries for the other properties (surface emissivity, transmissivity, and Poisson's ratio) are constants, and thus assumed to be independent of material temperature.

Razorback allows for up to 5 different correlations to be entered for the thermal conductivity and the specific heat capacity. The purpose of this capability is to allow the user to better define the temperature dependence of a material property for instances in which a single correlation does not provide a good fit of the property data over the entire temperature range of interest. In such instances, the user may define up to 5 temperature ranges, with five corresponding correlations to define the property over those temperature ranges.

Razorback also allows for a temperature shift factor (T_{shift}) and a scaling factor (f_{scale}) to be defined for all correlation entries. A non-zero temperature shift factor causes the associated correlation to be a function of $T - T_{\text{shift}}$. If $T_{\text{shift}} = 273.15 \text{ K}$, then the correlation becomes a function of Celsius temperature. This feature is also helpful for correlations for temperature ranges where the value of the temperature is high (e.g., $>1000 \text{ K}$, $>2000 \text{ K}$, etc.). A temperature shift factor can be used to reduce the temperature value when correlating the data, making the correlation results less sensitive to the number of significant digits in the correlation coefficients. The scaling factor provides a simple means for the user to examine sensitivity/uncertainty cases in which a particular property is increased or decreased by a simple ratio value.

Again, it is noted that the temperature correlations are to be functions of $T - T_{\text{shift}}$ in units of degrees K, and must result in values with the dimensions specified in the listing above.

¹⁰ This approach, therefore, treats the density as independent of temperature for code executions in which the thermal expansion option is turned off.

The first entry in the material property definition section of the input file specifies how many different material types will be defined.

```
*****
*   Begin Material Property Entries
*****
nmats # of materials
*
*-----
```

Table 41. Entry for number of materials to be defined in the input file.

Item	Input Parameter Description
<i>nmats</i>	This parameter specifies the number of materials for which property data will be provided. Up to 10 materials are allowed.

3.11.1. *Density and Material Name*

Here, the density is specified, along with a name for the material.

```
*-----
* A_DENS      M_NAME
*-----
```

Table 42. Density and material name entries.

Item	Input Parameter Description
<i>A_DENS(m)</i>	This parameter specifies reference density (g/cm^3) of material m at 20°C .
<i>M_NAME(m)</i>	This parameter specifies a name for material m (a text string of ≤ 20 characters).

3.11.2. Thermal Conductivity

The material thermal conductivity is defined for up to 5 temperature ranges. First, the number of temperature ranges is entered, followed by the temperature range limits and correlations for each range.

```

*-----
N_TEMP_CON # of temperature ranges for k (</= 5)
ATR_CON_LO ATR_CON_HI
n_order AK_CON ASCL_CON
A_CON
*-----

```

Table 43. Thermal conductivity material property definition entries.

Item	Input Parameter Description
<i>N_TEMP_CON(m)</i>	This parameter specifies the number of temperature ranges for which a thermal conductivity correlation will be provided for material <i>m</i> . Up to three temperature ranges are allowed.
<i>ATR_CON_LO(m,r)</i> <i>ATR_CON_HI(m,r)</i>	These parameters the lower and upper temperatures (K) limits for range <i>r</i> of material <i>m</i> .
<i>n_order</i> <i>AK_CON(m,r)</i> <i>ASCL_CON(m,r)</i>	The parameters specify the order (<i>n_order</i>) of the correlation polynomial for range <i>r</i> of material <i>m</i> . <i>AK_CON(m,r)</i> specifies a constant (in units of K) to be subtracted from the temperature (K) for range <i>r</i> of material <i>m</i> . <i>ASCL_CON(m,r)</i> specifies a scaling factor which will multiply the <i>n_order</i> correlation polynomial for range <i>r</i> of material <i>m</i> .
<i>A_CON(n,m,r)</i>	These parameters specify the 1 to <i>n_order</i> +1 coefficients of the up to ninth order polynomial which represents the thermal conductivity (W/cm-K) for temperature range <i>r</i> of material <i>m</i> . The polynomial is given by $k_{m,r}(T) = ASCL_CON_{m,r} \sum_{n=0}^{n_order} A_CON_{n,m,r} (T - AK_CON_{m,r})^n$ This correlation will be applied to determine the thermal conductivity for material <i>m</i> over the temperature range $ATR_CON_LO_{m,r} \leq T \leq ATR_CON_HI_{m,r}$.

3.11.3. Specific Heat Capacity

The material specific heat capacity is defined for up to 5 temperature ranges. First, the number of temperature ranges is entered, followed by the temperature range limits and correlations for each range.

*-----
N_TEMP_CP # of temperature ranges for cp (</= 5)
ATR_CP_LO ***ATR_CP_HI***
n_order ***AK_CP*** ***ASCL_CP***
A_CP
 *
 *-----

Table 44. Specific heat capacity material property definition entries.

Item	Input Parameter Description
<i>N_TEMP_CP(m)</i>	This parameter specifies the number of temperature ranges for which a specific heat capacity correlation will be provided for material <i>m</i> . Up to three temperature ranges are allowed.
<i>ATR_CP_LO(m,r)</i> <i>ATR_CP_HI(m,r)</i>	These parameters the lower and upper temperatures (K) limits for range <i>r</i> of material <i>m</i> .
<i>n_order</i> <i>AK_CP(m,r)</i> <i>ASCL_CP(m,r)</i>	The parameters specify the order (<i>n_order</i>) of the correlation polynomial for range <i>r</i> of material <i>m</i> . <i>AK_CP(m,r)</i> specifies a constant (in units of K) to be subtracted from the temperature (K) for range <i>r</i> of material <i>m</i> . <i>ASCL_CP(m,r)</i> specifies a scaling factor which will multiply the <i>n_order</i> correlation polynomial for range <i>r</i> of material <i>m</i> .
<i>A_CP(n,m,r)</i>	These parameters specify the 1 to <i>n_order</i> +1 coefficients of the up to ninth order polynomial which represents the specific heat capacity (J/g-K) for temperature range <i>r</i> of material <i>m</i> . The polynomial is given by $cp_{m,r}(T) = ASCL_CP_{m,r} \sum_{n=0}^{n_order} A_CP_{n,m,r} (T - AK_CP_{m,r})^n$ This correlation will be applied to determine the thermal conductivity for material <i>m</i> over the temperature range $ATR_CP_LO_{m,r} \leq T \leq ATR_CP_HI_{m,r}$.

3.11.4. Thermal Radiation Properties

The material thermal radiation surface emissivity and transmissivity are defined here. While the emissivity may be any value between 0 and 1, the transmissivity must be either 0 for a solid material, or 1 for a gaseous material.

*-----
A_EPS **A_TAU**
 *-----

Table 45. Radiation heat transfer material property parameters.

Item	Input Parameter Description
<i>A_EPS(m)</i>	This parameter specifies the thermal blackbody radiation surface emissivity for material <i>m</i> .
<i>A_TAU(m)</i>	This parameter specifies the thermal radiation transmissivity for material <i>m</i> . NOTE: A value of 0.0 is specified for solid materials, and a value of 1.0 for gaseous materials.

3.11.5. Thermal Expansion Properties

The material linear thermal expansion coefficient is defined by entering correlation coefficients. Next, Young's modulus is defined in a similar manner. Finally, a constant value for Poisson's ratio is entered.

```

*-----
n_order AK_ALE ASCL_ALE
A_ALE
*
n_order AK_YM ASCL_YM
A_YM
*
A_NU
*-----

```

Table 46. Thermal expansion material property parameters.

Item	Input Parameter Description
<i>n_order</i> <i>AK_ALE(m)</i> <i>ASCL_ALE(m)</i>	The parameters specify the order (<i>n_order</i>) of the linear thermal expansion coefficient correlation polynomial for material <i>m</i> . <i>AK_ALE(m)</i> specifies a constant (in units of K) to be subtracted from the temperature (K) for material <i>m</i> . <i>ASCL_ALE(m)</i> specifies a scaling factor which will multiply the <i>n_order</i> correlation polynomial for material <i>m</i> .
<i>A_ALE(n,m)</i>	These parameters specify the 1 to <i>n_order</i> +1 coefficients of the up to ninth order polynomial which represents the linear thermal expansion coefficient (K ⁻¹) for material <i>m</i> . The polynomial is given by $\alpha_m(T) = ASCL_ALE_m \sum_{n=0}^{n_order} A_ALE_{n,m}(T - AK_ALE_m)^n$
<i>n_order</i> <i>AK_YM(m)</i> <i>ASCL_YM(m)</i>	The parameters specify the order (<i>n_order</i>) of the Young's modulus correlation polynomial for material <i>m</i> . <i>AK_YM(m)</i> specifies a constant (in units of K) to be subtracted from the temperature (K) for material <i>m</i> . <i>ASCL_YM(m)</i> specifies a scaling factor which will multiply the <i>n_order</i> correlation polynomial for material <i>m</i> .
<i>A_YM(n,m)</i>	These parameters specify the 1 to <i>n_order</i> +1 coefficients of the up to ninth order polynomial which represents the Young's modulus (Pa) for material <i>m</i> . The polynomial is given by $E_m(T) = ASCL_YM_m \sum_{n=0}^{n_order} A_YM_{n,m}(T - AK_YM_m)^n$
<i>A_NU(m)</i>	This parameter specifies the Poisson's ratio for material <i>m</i> .

3.11.6. Example Material Property Inputs

In this section, we provide an example of material property inputs to illustrate the process of defining material properties. Three materials will be defined: a ceramic, a metal, and a gas. Note that the example entries for the correlations coefficients are arbitrary and for illustrative purposes only (i.e., the correlations coefficients entered in this example are not expected to result in meaningful correlation values.).

```
*****
* Begin Material Property Entries
*****
3 # of materials
```

The first material is a ceramic with density of 2.80 g/cm³, and it is given the name “Ceramic”.

```
*-----Material 1-----
2.800000d+00 Ceramic
```

The thermal conductivity for the ceramic is defined over two temperature ranges ($273.15\text{K} \leq T \leq 2423.15\text{K}$ and $2423.15\text{K} < T \leq 3273.15\text{K}$). The first correlation is a sixth order polynomial, with a $T_{\text{shift}} = 0$ K, and a scaling factor of 1.0. The correlation coefficients are listed in the order $a_0, a_1, a_2, a_3, a_4, a_5,$ and a_6 , where a_0 is the constant (zeroth order term) and a_6 is the coefficient for the $(T-T_{\text{shift}})^6$ term. A maximum of 5 coefficients are allowed on a single input line, so $a_0 - a_4$ are listed on one line, followed by a_5 and a_6 on the next line. The second correlation is a zeroth order polynomial, with a $T_{\text{shift}} = 0$ K, and a scaling factor of 1.0. Thus, the thermal conductivity will be a constant value of 1.0 W/cm-K for the second temperature range.

```
2 # of temperature ranges for k (</= 5)
273.15d0 2423.15d0
6 0.00d0 1.000000d+00
1.000000d+00 -1.000000d-01 1.000000d-02 -1.000000d-03 1.000000d-04
-1.000000d-05 1.000000d-06
2423.15d0 3273.15d0
0 0.00d0 1.000000d+00
1.000000d+00 assume constant after 2423.15 K
*
```

The specific heat capacity of the ceramic is defined over two temperature ranges ($273.15\text{K} \leq T \leq 1800.15\text{K}$ and $1800.15\text{K} < T \leq 3273.15\text{K}$). The first correlation is a sixth order polynomial, with a $T_{\text{shift}} = 0$ K, and a scaling factor of 1.0. The correlation coefficients are listed in the order $a_0, a_1, a_2, a_3, a_4, a_5,$ and a_6 , where a_0 is the constant (zeroth order term) and a_6 is the coefficient for the $(T-T_{\text{shift}})^6$ term. A maximum of 5 coefficients are allowed on a single input line, so $a_0 - a_4$ are listed on one line, followed by a_5 and a_6 on the next line. The second correlation is a zeroth order polynomial, with a $T_{\text{shift}} = 0$ K, and a scaling factor of 1.0. Thus, the specific heat capacity will be a constant value of 1.0 J/g-K for the second temperature range.

```
2 # of temperature ranges for cp (</= 5)
273.15d0 1800.15d0
6 0.00d0 1.000000d+00
```

```

1.000000d+00 -1.000000d-01 1.000000d-02 -1.000000d-03 1.000000d-04
-1.000000d-05 1.000000d-06
1800.15d0 3273.15d0
0 0.00d0 1.000000d+00
1.000000d+00 assume constant after 1800.15 K

```

The thermal radiation surface emissivity of the ceramic is defined as 0.8. The thermal radiation surface transmissivity of the ceramic is defined as 0.0 (i.e., the ceramic is an opaque solid).

```

*
0.8d0 0.0d0

```

The linear thermal expansion coefficient of the ceramic is defined as a second order polynomial, with a $T_{\text{shift}} = 0$ K, and a scaling factor of 1.0. The Young's modulus is 100 GPa, and is entered as a zeroth order polynomial, with a $T_{\text{shift}} = 0$ K, and a scaling factor of 1.0. Poisson's ratio is 0.22.

```

*
2 0.00d0 1.000000d+00
1.000000d-06 -1.000000d-08 1.000000d-12
*
0 0.00d0 1.000000d+00
100.0000d+09
*
0.22d0
*-----

```

The first material is a metal with density of 8.00 g/cm³, and it is given the name "Metall".

```

*-----Material 2-----
8.000000d+00 Metall

```

The thermal conductivity for the metal is defined over one temperature ranges ($273.15\text{K} \leq T \leq 3273.15\text{K}$). The correlation is a second order polynomial, with a $T_{\text{shift}} = 0$ K, and a scaling factor of 1.0.

```

1 # of temperature ranges for k (</= 5)
273.15d0 3273.15d0
2 0.00d0 1.000000d+00
0.500000d+00 1.000000d-04 -6.000000d-09
*

```

The specific heat capacity for the metal is defined over one temperature ranges ($273.15\text{K} \leq T \leq 3273.15\text{K}$). The correlation is a fifth order polynomial, with a $T_{\text{shift}} = 273.15$ K, and a scaling factor of 1.0.

```

1 # of temperature ranges for cp (</= 5)
273.15d0 3273.15d0
5 273.15d0 1.000000d+00
2.000000d-01 2.000000d-04 -3.000000d-07 2.000000d-10 -8.000000d-14
1.000000d-17

```

The thermal radiation surface emissivity of the metal is defined as 0.9. The thermal radiation transmissivity of the ceramic is defined as 0.0 (i.e., the metal is an opaque solid).

```
*
0.9d0  0.0d0
*
```

The linear thermal expansion coefficient of the ceramic is defined as a second order polynomial, with a $T_{\text{shift}} = 0$ K, and a scaling factor of 1.05. The Young's modulus is 105 GPa, and is entered as a zeroth order polynomial, with a $T_{\text{shift}} = 0$ K, and a scaling factor of 1.0. Poisson's ratio is 0.4.

```
2  0.00d0  1.050000d+00
1.000000d-06  2.000000d-09  -3.000000d-13
*
0  0.00d0  1.000000d+00
105.0000d+09
*
0.4d0
*-----
```

The third (and final) material is a gas with density of 3.328×10^{-4} g/cm³, and it is given the name "Gas".

```
*-----Material 3-----
3.328d-04  Gas
```

The thermal conductivity for the gas is defined over one temperature ranges ($273.15\text{K} \leq T \leq 3273.15\text{K}$). The correlation is a second order polynomial, with a $T_{\text{shift}} = 0$ K, and a scaling factor of 1.0.

```
1  # of temperature ranges for k (</= 5)
  273.15d0  3273.15d0
2  0.00d0  1.000000d+00
5.000000d-04  3.000000d-06  -2.000000d-10
*
```

The specific heat capacity for the gas is defined over one temperature ranges ($273.15\text{K} \leq T \leq 3273.15\text{K}$). The correlation is a zeroth order polynomial, with a $T_{\text{shift}} = 0$ K, and a scaling factor of 1.0.

```
1  # of temperature ranges for cp (</= 5)
  273.15d0  3273.15d0
0  0.00d0  1.000000d+00
5.100000d+00
```

The thermal radiation surface emissivity of the metal is defined as 1.0. Note that this value is arbitrary (the material is a gas), but a value must be entered. In cases like this, a value of 1.0 is recommended. The thermal radiation transmissivity of the gas is defined as 1.0 (i.e., the gas is transparent).

```
*
1.0d0  1.0d0
*
```

The linear thermal expansion coefficient of the gas is defined as a zeroth order polynomial, with a $T_{\text{shift}} = 0$ K, and a scaling factor of 1.00. The value of the linear thermal expansion coefficient is set at 0.0 K^{-1} . This value is arbitrary because the code does not “expand” a gas material. Rather, the size of the gas gap will vary with the expansion/contraction of the two adjacent solids). The Young’s modulus is 1.0×10^{-20} Pa, and is entered as a zeroth order polynomial, with a $T_{\text{shift}} = 0$ K, and a scaling factor of 1.0. This value is not entirely arbitrary, as the code uses the Young’s modulus of adjacent materials in its expansion/stress calculations. A very small numerical value for the Young’s modulus of a gas so that essential no resistance is offered to the expansion of adjacent solid materials. Poisson’s ratio is 0.3. This value too is somewhat arbitrary. However, the code’s expansion/stress algorithms include the Poisson’s ratio of gas-filled gaps, and an entry of 0.0 would likely cause divide-by-zero errors. A value of 0.3 is recommended.

```
0  0.00d0  1.000000d+00
0.000000d-00
*
0  0.00d0  1.000000d+00
1.000000d-20
*
0.3d0
*-----
```

3.12. Heat Transfer Correlation Parameters

This portion of the input file specifies the correlations to be used for the local heat transfer coefficient of the coolant. The following flow/heat transfer regimes are covered:

- Natural Convection: The coolant channel flow rate is very low (near quiescent). Heat transfer occurs due to flow currents parallel to and very near the cladding surface. The heat transfer coefficient is determined from a correlation where the Nusselt number is a function of the Rayleigh number.
- Laminar/Turbulent Flow Convection: The coolant channel flow rate axial flow is presumed to be non-zero across the radial extent of the flow channel. The flow regime may be either laminar or turbulent based on the Reynolds number and a user-specified laminar-turbulent transition Reynolds number. The heat transfer coefficient is determined from a correlation where the Nusselt number is a function of the Reynolds number, the Prandtl number, and the ratio of absolute viscosities at the bulk coolant and cladding surface temperatures.
- Subcooled Boiling Flow Convection: The local cladding surface temperature exceeds the local saturation temperature of the coolant, and the local heat flux exceeds the heat flux for incipient boiling. Bubbles form at the cladding surface, but rapidly collapse into the bulk flow, because the bulk coolant temperature is less than the local saturation temperature. Subcooled boiling is a very effective heat transfer mechanism, and the heat transfer coefficient can be quite large. The heat transfer coefficient is determined from a correlation where the local heat flux is a function of the local pressure and the difference between the local cladding surface temperature and the local saturation temperature.
- Saturated Boiling Flow Convection: The local bulk coolant temperature exceeds the local saturation temperature of the coolant. Bubbles form at the cladding surface, but do not collapse into the bulk flow, because the bulk coolant temperature equals or exceeds the local saturation temperature. The heat transfer is assumed to occur at the cladding surface and continue similar to a subcooled boiling mechanism. Thus, the heat transfer coefficient is determined from the correlation used for subcooled boiling.

3.12.1. Natural Convection

These inputs define the Nusselt number correlation for the natural convection (i.e., free convection) heat transfer regime.

```
*****
* Begin Heat Transfer Coefficient Correlation Entries
*****
*
*-----Natural Convection-----
*      C          Ra exp
*  c_nconv      ra_exp
*
*-----
```

Table 47. Natural convection heat transfer correlation parameters.

Item	Input Parameter Description
<i>c_nconv</i> <i>ra_exp</i>	These parameters are for the Nusselt number (Nu) correlation when the heat transfer mode is natural convection. The correlation has the form $Nu = c_{nconv} \cdot Ra^{ra_exp}$ where Ra is the Rayleigh number.

3.12.2. Laminar and Turbulent Flow Convection

These inputs define the Nusselt number correlation for the laminar and turbulent flow convection heat transfer regime.

```
*-----Laminar Forced Convection-----
* C          Re exp          Pr exp          visc ratio exp          Re Transition
* c_fc_l      re_exp_l      pr_exp_l      vr_exp_l      re_trans_lt
*-----Turbulent Forced Convection-----
* C          Re exp          Pr exp          visc ratio exp
*  c_fc_t      re_exp_t      pr_exp_t      vr_exp_t
*
*-----
```

Table 48. Laminar/Turbulent flow convection heat transfer correlation parameters.

Item	Input Parameter Description
<p><i>c_cf_l</i> <i>re_exp_l</i> <i>pr_exp_l</i> <i>vr_exp_l</i></p>	<p>These parameters are for the Nusselt number (Nu) correlation when the heat transfer mode is laminar flow forced convection. The correlation has the form</p> $Nu = c_cf_l \cdot Re^{re_exp_l} Pr^{pr_exp_l} \left(\frac{\mu_b}{\mu_s} \right)^{vr_exp_l}$ <p>where Re is the Reynolds number, Pr is the Prandtl number, μ_s and μ_b are the absolute viscosity at the surface temperature and bulk coolant temperature, respectively.</p>
<p><i>re_trans_lt</i></p>	<p>This parameter specifies the Reynolds number for which flow transition from laminar to turbulent.</p> <p>NOTE: It has been observed that the value of this parameter can affect the convergence of the steady state solution at the beginning of the calculation. The user may need to adjust this value up or down to enable steady state solution convergence.</p>
<p><i>c_cf_t</i> <i>re_exp_t</i> <i>pr_exp_t</i> <i>vr_exp_t</i></p>	<p>These parameters are for the Nusselt number (Nu) correlation when the heat transfer mode is turbulent flow forced convection. The correlation has the form</p> $Nu = c_cf_t \cdot Re^{re_exp_t} Pr^{pr_exp_t} \left(\frac{\mu_b}{\mu_s} \right)^{vr_exp_t}$ <p>where Re is the Reynolds number, Pr is the Prandtl number, μ_s and μ_b are the absolute viscosity at the surface temperature and bulk coolant temperature, respectively.</p>

3.12.3. Subcooled and Saturated Boiling Flow Convection

This input defines the heat transfer correlation for subcooled and saturated boiling flow convection heat transfer regime. Currently only the Jens-Lottes correlation (Ref. 5) is available as an option.

```
*-----Boiling Heat Transfer Coefficient Option-----
*           i_bht           |
*      (1 = Jens-Lottes)   |
*           i_bht         |
*-----
```

Table 49. Subcooled/Saturated flow boiling heat transfer correlation parameters.

Item	Input Parameter Description
<i>i_bht</i>	<p>This parameter sets the correlation used for subcooled boiling (when the surface temperature exceeds the local coolant saturation temperature). Currently, the only available option is the Jens-Lottes correlation (<i>i_bht</i>=1) for which the surface heat flux (q''_{JL}) is given by</p> $\frac{q''_{JL}}{10^6} = \frac{\exp(\frac{4p}{62})}{25^4} (T_w - T_{sat})^4$ <p>where q''_{JL} = heat flux (W/m²), p = coolant pressure (bar), T_w = cladding surface temperature (°C), and T_{sat} = local coolant saturation temperature (°C).</p>

3.12.5. Post-Critical Heat Flux Options

These inputs allow the user to set up a post-CHF heat transfer coefficient for instances in which the local CHF ratio falls below a user-specified value. If this option is not activated, then the code will continue to utilize the heat transfer coefficients defined above.

```
*-----Post-CHF Heat Transfer Coefficient Option-----
*           MCHFR Limit           |           Post-CHF HT Coefficient (W/cm2/K)
*           CHF_min_limit       |           hx_coef_post_chf
*-----
```

Table 50. Post dryout critical heat flux heat transfer options.

Item	Input Parameter Description
CHF_min_limit	<p>This parameter specifies a critical heat flux (CHF) ratio value below which the surface is assumed to have reached dryout CHF conditions.</p> <p>If this value is negative, then no action is taken by the code if the CHF ratio falls below the CHF_min_limit.</p> <p>If this value is positive, then the code will set the heat transfer coefficient at that location to a specified value (hx_coef_post_chf below) when the CHF ratio falls below the CHF_min_limit. If a sufficiently low heat transfer coefficient value is applied, then this option can simulate CHF dryout conditions, and allow the code to compute the rate at which the local surface temperature rises.</p>
hx_coef_post_chf	<p>This parameter specifies the value of the post-CHF heat transfer coefficient (W/cm²-K) to be applied when the CHF_min_limit is reached (if CHF_min_limit entry is negative). This value remains in effect for all time after the CHF_min_limit has been reached.</p>

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4. CODE OUTPUT FILES

This section presents a description of the various output files produced by the code during its execution.

4.1. Main Code Output Files

4.1.1. Main Output File (*rsim.out*)

The main output file *rsim.out* provides the history of the code calculation. The file begins with a date/time stamp, followed by the title cards, and a summary of many of the input parameters. From this point, an initial condition printout of the fuel element and coolant channel parameters is provided. The fuel element and coolant channel parameter printout is arranged so that the data listing shows the axial and radial zone temperatures of the fuel element from top-to-bottom, along with the axial node coolant channel parameters. This printout is then repeated at the specified frequency(ies) until the end of the calculation. At the end of the calculation, a summary of “pulse” data is presented, followed by a listing of the scram setpoints. The file ends with a date/time stamp. Appendix B presents a sample main output file.

4.1.2. Initial Fuel Element Conditions File (*steady_ic.dat*)

The output file *steady_ic.dat* provides a detailed listing of the initial steady-state conditions within the fuel element. It includes both the nominal radii (cm) of each radial node, as well as the thermal expansion displacement (cm) and the displaced radii (cm). It also includes the temperature (°C) at each radial node, the principal axes stresses (MPa), and the von Mises stress (MPa). This data set is printed out for each axial node in the fuel element model. Appendix C presents a sample *steady_ic.dat* output file.

4.1.3. Final Fuel Element Conditions File (*final_state.dat*)

The output file *final_state.dat* provides a detailed listing of the final conditions within the fuel element. It includes the same type of data as in the *steady_ic.dat* file for the conditions at the end of the calculation. Note that when the calculation type is a steady-state run, the *steady_ic.dat* file is the final state, and no *final_state.dat* output file will be produced.

4.2. Output Data Files

The primary code data output file is *rsim.dat*. This output data file was designed for easy import into a spreadsheet-type program with data plotting capabilities. Appendix D provides a listing of the data columns included in this file.

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4.3. Fuel Element Data Output Files

4.3.1. Element Component Temperature Output Files

4.3.1.1. Maximum Element Temperature Data (*max_temps.dat*)

The output data file *max_temps.dat* logs the time (s) and the maximum temperature of each fuel element zone. The maximum temperature values are obtained by scanning all axial locations of a given zone.

4.3.1.2. Cladding Surface Temperature Data (*cstemp.dat*)

The output data file *cstemp.dat* logs the cladding surface temperature (°C) as a function of coolant channel axial position (cm). The file includes an initial “title line” with a short description of the file’s data. The second line is a listing of the axial locations (cm) to which the cladding surface temperature data corresponds.

4.3.1.3. Axial Melting Data (*melt.dat*)

The output data file *melt.dat* is a work-in-progress. The data should not be used.

4.3.2. Element Component Thermal Expansion/Stress Output Files

4.3.2.1. Thermal Expansion Data (*expand.dat*)

The output data file *expand.dat* logs the time (s), the element internal gas pressure (psia), the outer radius (cm) of each fuel element zone, and the gap size (cm) of each fuel element gap. The radii and gap sizes are taken from the zones at the axial midpoint of the element.

4.3.2.2. Compressive Stress Data (*cs_stress.dat*)

The output data file *cs_stress.dat* logs the time (s) and the maximum compressive stress (MPa) of each fuel element zone. The maximum compressive stress values are obtained by scanning all axial locations of a given zone.

4.3.2.3. Tensile Stress Data (*ts_stress.dat*)

The output data file *ts_stress.dat* logs the time (s) and the maximum tensile stress (MPa) of each fuel element zone. The maximum tensile stress values are obtained by scanning all axial locations of a given zone.

4.3.2.4. Von Mises Stress Data (*vm_stress.dat*)

The output data file *vm_stress.dat* logs the time (s) and the maximum von Mises stress (MPa) of each fuel element zone. The maximum tensile stress values are obtained by scanning all axial locations of a given zone.

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4.4. Coolant Channel Data Output Files

The code provides several output data files which log coolant channel data during the analysis. These are listed in Table 51. Each file includes an initial “title line” with a short description of the file’s data. The second line is a listing of the axial locations (cm) to which the subsequent data corresponds. All subsequent lines contain a time (s) and the value of the particular parameter at each of the axial locations listed at the beginning.

Table 51. Coolant channel data output files.

Data File Name	Description
<i>gchan.dat</i>	Data file logging the coolant mass flux (g/s/cm^2) for each coolant channel axial position (cm) as a function of time (s).
<i>hchan.dat</i>	Data file logging the coolant enthalpy (J/g) for each coolant channel axial position (cm) as a function of time (s).
<i>pchan.dat</i>	Data file logging the coolant pressure (psia) for each coolant channel axial position (cm) as a function of time (s).
<i>vfchan.dat</i>	Data file logging the coolant void fraction for each coolant channel axial position (cm) as a function of time (s).
<i>xschan.dat</i>	Data file logging the coolant quality for each coolant channel axial position (cm) as a function of time (s).

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4.5. Reactivity/Reactivity Control System Data Output Files

The code produces an output data file called *reactivity.dat*. This file contains data related to the reactivity control system (i.e., control, safety, and transient rods) and the system reactivity and feedback. Table 52 shows the data included in the *reactivity.dat* file. The first line is a column header line, and subsequent lines log the Table 52 data at the user-specified print frequency. Except for the bank speeds, the data is the same as that in the *rsim.dat* file, and descriptions of the data can be found in Appendix D.

Table 52. Reactivity/Reactivity Control System output data.

Quantity	Units
Time	s
Control Rod Bank Position	units
Control Rod Bank Speed	cm/s
Control Rod Bank Reactivity Addition Rate	\$/s
Control Rod Bank Total Reactivity Addition	\$
Safety Rod Bank Position	units
Safety Rod Bank Speed	cm/s
Safety Rod Bank Reactivity Addition Rate	\$/s
Safety Rod Bank Total Reactivity Addition	\$
Transient Rod Bank Position	units
Transient Rod Bank Speed	cm/s
Transient Rod Bank Reactivity Addition Rate	\$/s
Transient Rod Bank Total Reactivity Addition	\$
System Reactivity	\$
Total Reactivity Feedback	\$
Fuel Reactivity Feedback	\$
Fuel Temperature Reactivity Feedback	\$
Fuel Expansion Reactivity Feedback	\$
Cladding Reactivity Feedback	\$
Coolant Reactivity Feedback	\$

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4.6. Error/Warning Message Log File

The code produces an output file called *error.log*. This file contains text statements indicating instances for which the code encountered the following:

- A request to use a coolant property correlation (as a function of pressure) based on a pressure that is outside the data range. Code execution will terminate.
- A request to use the Groeneveld Lookup Table for critical heat flux based on a coolant quality outside the data range. Code execution will terminate.
- A request to use the Groeneveld Lookup Table for critical heat flux based on a pressure or a mass flux outside the data range. Code execution will continue using the upper or lower limit of the parameter range, but a note will be logged in the *error.log* file.
- A gas-filled gap within the fuel element has “closed” due to thermal expansion. Code execution will terminate.
- The code cannot reach convergence on a local cladding temperature during the steady-state initialization. Code execution will terminate.
- The code computes an inconsistency in the application of the Jens-Lottes subcooled/saturated flow boiling correlation such that the local heat flux is less than that required for incipient boiling, but the local cladding surface temperature is greater than saturation.
- The final time point entry in the power history data file (if this option is used) is less than the total transient calculation time entered in the *rsim.in* file. Code execution will terminate.

Note: While some error recognitions and warnings are programmed into the code, the extent of such error checking is not exhaustive. The user must always review code data results with a critical eye.

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5. REFERENCES

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4. Lahey, R. T., and F. J. Moody, The Thermal-Hydraulics of a Boiling Water Nuclear Reactor, American Nuclear Society, 3rd printing, 1984.
5. Jens, W. H., and P. A. Lottes, “Analysis of Heat Transfer, Burnout, Pressure Drop and Density Data for High-Pressure Water,” ANL-4627, Argonne National Laboratory, Chicago, IL, May 1, 1951.
6. Groeneveld, D. C., et. al., “The 2006 CHF look-up table,” *Nuclear Engineering and Design*, 237 (2007), 1909-1922.

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APPENDIX A: SAMPLE *RSIM.IN* INPUT FILE

This appendix contains a sample *rsim.in* input data file which will simulate a continuous control rod bank withdrawal from an initial bank position of 15.0 cm for the ACRR. Page breaks have been added to this file listing for ease of reading.

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```

*****
*
*           RAZORBACK Input File
* Note: an "*" in the first column denotes a comment statement
*****
*
*           CALCULATION AND PRINTING CONTROLS
*****
*-----|-----|-----|-----|
* Calculation Type | Rx Kinetics (0) | Total | Number of |
* (1=steady-state, | or Power History | Transient | Title Cards |
* 0=transient) | Data File (1) | Time (s) | (up to 20) |
*-----|-----|-----|-----|
*           0           0           300.0           5
*-----|-----|-----|-----|
*
*           Title Cards
*-----|-----|-----|-----|
Uncontrolled Rod Withdrawal
- Withdraw to 55 cm (full up) from 15 cm
- Power 23.9 W, 236 elements, 1.50 Core Radial Peaking Factor
- ACRR Fuel Element Model
- Plane Stress Conditions Assumed
*
*-----|-----|-----|-----|
* Number of Time Step Ranges | Initial Condition Stabilization |
* (up to 20) | Duration (s) | Time Step (s) |
*-----|-----|-----|-----|
*           3           0.0           0.05
*-----|-----|-----|-----|
*
*           Time Step Control (TSC)
*           (If TSC is off, then
*           dt = max time step of range)
* Time Range | Time Step | T/H | TSC | TSC |
* Begin(s)/End(s) | max(s) / min(s) | dt(s) | "Error" | (1=y/0=n) |
*-----|-----|-----|-----|
*           0.00  0.10 | 1.0d-4 1.0d-9 | 1.0d-3 | 1.0d-3 | 1 |
*           0.10  60.00 | 1.0d-3 1.0d-9 | 1.0d-3 | 1.0d-3 | 1 |
*           60.0 10000.00 | 1.0d-3 1.0d-9 | 1.0d-3 | 1.0d-3 | 1 |
*
*-----|-----|-----|-----|
* Number of Print Increment Ranges |
* (up to 20) |
*-----|-----|-----|-----|
*           1
*-----|-----|-----|-----|
*
* Print Time Range | screen | plot | file |
* Begin(s)/End(s) | print | print | print |
* | incr.(s) | incr.(s) | incr.(s) |
*-----|-----|-----|-----|
*           0.0 10000.0 | 100.0e-3 | 100.0e-3 | 5.0e-0
*-----|-----|-----|-----|
* pulse parameter file print | fuel rod screen/file print |
* (1=yes, 0=no) | (1=yes, 0=no) |
*-----|-----|-----|-----|
*           1           1
*****

```

```

*****
*
* REACTOR POWER AND INITIAL CONDITIONS
*
*****
*-----|-----|-----|-----|
* Initial Reactor | 100% Reactor | Number of | Element |
* Power (%) | Power (W) | Fuel Elements | Peak-to-Average |
*-----|-----|-----|-----|
* 1.0d-03 | 2.39d+06 | 236 | 1.50 |
*-----|-----|-----|-----|
*
*****
* REACTIVITY ADDITION SYSTEM CONTROLS
*
*****
*-----|-----|-----|-----|
* Control Rod Bank Control | Number of CR Bank Commands |
* (1=on w/curve, 0=off, 2=ramp) | (up to 20) |
*-----|-----|-----|-----|
* 1 | 2 |
*
*-----|-----|-----|-----|
* CR Start | CR End | CR Speed (cm/s) |
* Time (s) | Time (s) | or Ramp ($/s) |
*-----|-----|-----|-----|
* 0.0 | 40.0 | 1.00 |
* 40.0 | 10000.0 | 0.00 |
*-----|-----|-----|-----|
*
* Note: 0.1 cm/s CR Speed = slow speed; 2.0 cm/s CR Speed = fast speed
*
*-----|-----|-----|-----|
* CR Start | CR down | CR Up |
* Position (cm) | Position (cm) | Position (cm) |
*-----|-----|-----|-----|
* 15.00 | 0.0 | 55.00 |
*-----|-----|-----|-----|
*
*-----|-----|-----|-----|
* CR Bank | CR Bank Differential Reactivity Curve |
* Total | drho/dz = A sin2[ B(z) + C] |
* Worth ($) | A | B | C |
*-----|-----|-----|-----|
* 12.00 | 0.03003581 | 0.0463939 | 0.425066 |
*-----|-----|-----|-----|
*
*-----|-----|-----|-----|
* Safety Rod Bank Control | Number of SR Bank Commands |
* (1=on w/curve, 0=off, 2=ramp) | (up to 20) |
*-----|-----|-----|-----|
* 0 | 2 |
*
*-----|-----|-----|-----|
* SR Start | SR End | SR Speed (cm/s) |
* Time (s) | Time (s) | or Ramp ($/s) |
*-----|-----|-----|-----|
* 0.0 | 1.0 | 0.0 |
* 1.0 | 10000.0 | 0.0 |
*-----|-----|-----|-----|

```

```

*-----|
*
* Note: 0.24 cm/s CR Speed = slow speed, 7.26 cm/s = fast speed
*
*-----|-----|-----|
*   SR Start      |   SR down      |   SR Up      |
*   Position (cm) |   Position (cm) |   Position (cm) |
*-----|-----|-----|
*           55.00 |           0.0  |           55.00 |
*-----|-----|-----|
*
*-----|-----|-----|
*   SR Bank      |   SR Bank Differential Reactivity Curve |
*   Total        |   drho/dz = A sin2[ B(z) + C] |
*   Worth ($)    |   A          |   B          |   C          |
*-----|-----|-----|
*           2.00  |   0.03003581 |   0.0463939 |   0.425066  |
*
*-----|-----|-----|
*   Transient Rod Bank Control |   Number of TR Bank Commands |
*   (0=off, 1=on w/curve)    |   (up to 20) |
*   (2=pulse, 3=ramp) |
*-----|-----|-----|
*           0          |           1 |
*
*-----|-----|-----|
*   TR Start      |   TR End      |   TR Speed (cm/s) |
*   Time (s)      |   Time (s)    |   or Ramp ($/s)  |
*-----|-----|-----|
*           0.135    |           1.000 |           0.000  |
*-----|-----|-----|
*
*-----|-----|-----|
*   TR Start      |   TR down     |   TR Up      |
*   Position (cm) |   Position (cm) |   Position (cm) |
*-----|-----|-----|
*           90.00   |           43.70 |           90.00 |
*-----|-----|-----|
*
* Note: TR full down = 22.00 cm   TR pedestal down = 43.70 cm
*-----|-----|-----|
*   TR Bank      |   TR Bank Differential Reactivity Curve |
*   Total        |   drho/dz = A sin2[ B(z - z0) + C] |
*   Worth($)     |   A          |   B          |   C          |   z0 |
*-----|-----|-----|-----|
*           4.258  |   0.030489   |   0.046212   |   0.569848   |   25.0 |
*
*-----|-----|-----|
*   Range of Validity for TR Bank Differential Reactivity Curve |
*   lower end (cm) |   upper end (cm) |
*-----|-----|-----|
*           25.0   |           85.0   |
*-----|-----|-----|
*
*-----|-----|-----|
*   Transient Rod Pulse Pneumatic System |
*   N2 Valve | N2 | N2 Accum. | Piston | TR |
*   opening | Pressure | Volume | Effective | Mass (kg) |
*   time (s) | (psig) | (cm3) | Area (cm2) |
*-----|-----|-----|-----|
*           76.0e-3 | 65.0 | 2.00d+5 | 28.96 | 13.75 |
*-----|-----|-----|

```

```

*-----|
* Pulse Rod Holdup (= time after pulse when rods drop back into core)
* Time begins from t=0
* PRT submode all rods drop
* Pulse submode TRs and SRs drop (CRs do not)
*-----|
*          Transient Rod Pulse          |          Pulse Submode          |
*          Rod Holdup Time (s)          |          (Pulse=0 or PRT=1)    |
*-----|-----|
*          0.4e0                        |          1                        |
*-----|-----|
* Functional Reactivity Addition | Number of | Time to Turn |
* (0=off, 1=polynomial, 2=sine) | Terms(</=5) | Addition Off (s) |
*-----|-----|
*          0                            |          1                            |          1e10
*****
* REACTOR KINETICS PARAMETERS
*****
*-----|-----|-----|
* Neutron Generation | Effective Delayed | No. of Delayed |
* Time (s)           | Neutron Fraction  | Neutron Groups  |
*-----|-----|-----|
*          24.0e-06   |          0.0073   |          8       |
*-----|-----|-----|
*          Delayed Neutron
*          Group Decay Constants (1/s) - lambda i's
*          (up to 18 groups allowed -- up to 6 lambdas per line)
*-----|-----|-----|-----|-----|-----|
*          1.25e-02   2.83e-02   4.25e-02   1.33e-01   2.92e-01   6.66e-01
*          1.63e-00   3.55e-00
* (Campbell and Spriggs 8 groups)
*-----|-----|-----|-----|-----|-----|
*          Delayed Neutron
*          Group Fractions - beta i's
*          (up to 18 groups allowed -- up to 6 betas per line)
*-----|-----|-----|-----|-----|-----|
*          2.409e-04  1.1242e-03  6.643e-04  1.4381e-03  2.4163e-03  6.570e-04
*          5.913e-04  1.679e-04
* (Campbell and Spriggs 8 groups)
*-----|-----|-----|-----|-----|-----|
*          Fuel Temperature Feedback          |          Coolant Reactivity
*          drho/dT = c1 + c2/(T**0.5)        |          Feedback Coefficients
*          c1 | c2 | Density | Spectral
*          ($/K) | ($/K^1/2) | ($/%void) | ($/K)
*-----|-----|-----|-----|-----|-----|
*          -0.000988   -0.079422   -0.382   -0.00116
*-----|-----|-----|-----|-----|-----|
*          Fuel Expansion Reactivity Feedback Coefficients
*          Outer Radius | Inner Radius | Density
*          ($/cm) | ($/cm) | [$/ (g/cm)]
*-----|-----|-----|-----|-----|-----|
*          47.50   -6.31   11.26
*-----|-----|-----|-----|-----|-----|
*          Cladding Expansion Reactivity Feedback Coefficients
*          Outer Radius | Inner Radius | Density
*          ($/cm) | ($/cm) | [$/ (g/cm)]
*-----|-----|-----|-----|-----|-----|
*          -122.51   104.46   -0.71
*-----|-----|-----|-----|-----|-----|

```

```

*-----|
*           Reactivity Feedback Scaling and Adjustment Factors           |
*           Scaling -----|-----|
*   Fuel T | Fuel Exp | Clad | Coolant |   PLA   |   Exp   |
*-----|-----|-----|-----|-----|
*         1.00   1.00   1.00   1.00         0.900  2.0
*
*****
*           REACTOR PROTECTION SYSTEM SETTINGS
*****
*-----|-----|-----|
*   Percent      |   Reactor      |   Element      |
*   Power (%)    |   Power (W)    |   Power (W)    |
*-----|-----|-----|
* 115.0e+40     | 20.0e+49      | 25.00e+43     |
*-----|-----|-----|
*   Reactor      |   Rod Block    |   Rod Block    |
*   Period (s)   |   (1=on,0=off) |   Rate (dpm)   |
*-----|-----|-----|
* 8.50e-20      | 0              | 4.0e10         |
*-----|-----|-----|
*   Reactor Yield (J) |   Fuel Temperature (C) |
*-----|-----|-----|
* 300.0e46      | 1250.0e20     |
*-----|-----|-----|
*   Pool Level Scram |   Inlet Temperature |
*   (cm below tank top) |   Scram (C) |
*-----|-----|-----|
* 100.0e20      | 40.0e20       |
*-----|-----|-----|
*   Scram Mode |   Specified Scram Parameters |
*   0=normal   |   Scram | Scram | Scram |
*   1=specified | Reactivity ($) | Delay Time (s) | Addition Time (s) |
*-----|-----|-----|-----|
* 0           | -6.25   | 0.500 | 2.000 |
*-----|-----|-----|-----|
*   Scram      |   Rod Fall Times (s) |   Stuck Rod Factors |
* Delay Time (s) | CRs | SRs | TRs | CRs | SRs | TRs |
*-----|-----|-----|-----|
* 0.500       | 2.0   2.0   4.0   | 1.0   1.0   1.0   |
*-----|-----|-----|-----|
*   Scram Failure |   Manual Scram |
*   (1 = yes, 0 = no) |   Delay Time (s) |
*-----|-----|-----|
* 0           | 10.0 |
*****
*           POOL TANK/WATER AND POOL WATER COOLING SYSTEM
*           INITIAL CONDITIONS AND TRANSIENT(S)
*****
*-----|-----|-----|
*   Pool Tank | Pool Tank | Pool Tank |
*   Height (cm) | Area (cm2) | Displaced | Maximum Water Height |
*   Volume (cm3) | Above Reactor Core (cm) |
*-----|-----|-----|
* 857.25      | 72965.88 | 0.0d+00   | 700.0 |
*-----|-----|-----|
*   Initial Pool Water |   Initial Pool Water Level (cm) |   Cooling System |
*   Temperature (C) | (Distance Below Tank Lip) | Heat Removal |
*   (% of Rx Power) |
*-----|-----|-----|
* 20.0d0      | 100.0 | 0.0 |
*-----|

```

```

*-----|
*                               Pool Heatup                               |
*   Flag = 0 -> no pool heatup (constant Tpool = Tinlet)                 |
*   Flag = 1 -> pool heatup by reactor/cooling system (Tpool = Tinlet)   |
*   Flag = 2 -> pool temperature ramp (Tpool = Tinlet)                   |
*   Flag = 3 -> inlet temperature ramp (constant Tpool <> Tinlet)       |
*                                                                           |
*   Flag          | Ramp (degC/s) | Start Time (s) | End Time (s) |
*-----|-----|-----|-----|
*           0          |         0.0         |         0.0         |         0.0         |
*-----|-----|-----|-----|
*                               Loss of Coolant Accident                   |
*   Flag          | Start      | Break      | Effective Reactor |
* (1=on, 0=off) | Time (s)   | Size (cm2) | Power (W)         |
*-----|-----|-----|-----|
*           0          |      0.1      |      40.64      |      2.0e6         |
*-----|-----|-----|-----|
*                               Loss of Heat Sink Accident                 |
*   Flag          | Start Time | Flowrate Cooldown |
* (1=on, 0=off) | (s)        | Time (s)          |
*-----|-----|-----|
*           0          |      5.0      |      1.00        |
*-----|-----|-----|
*   Decay Heat Option (1=on,0=off) |
*-----|
*                               0
*-----|
*****
*                               NUMERICAL SOLUTION SETTINGS              *
*****
*-----|
*   Implicit Formulation Factors                                         |
*-----|
*   Theta   | Phi   | Psi   |
*-----|-----|-----|
*   1.00    | 1.00  | 1.00  |
*-----|-----|-----|
*-----|-----|-----|
*                               Iteration Error Limits                    |
*   Steady-State | Transient |
*-----|-----|-----|
*   Temperature  | Flow      | Temperature  |
*-----|-----|-----|
*   1.0e-4       | 1.0e-3   | 1.0e-3      |
*-----|-----|-----|
*****

```

```

*****
*
*                               FUEL ELEMENT MODEL
*
*****
*
*                               Standard ACRR Thermal-Hydraulics Model
*-----|-----|-----|-----|-----|-----|
* Number | Fuel | Fuel Coordinate System Geometry |
* of Fuel | R_inner | 0 = plate geometry |
* Zones | (cm) | 1 = cylindrical geometry |
* (10 max) | | |
*-----|-----|-----|-----|-----|
*           8      0.00000              1
*-----|-----|-----|-----|-----|
* Zone Outer | Number | Material | Gap? | Fiss. Energy | Th. Exp. |
* Radius (cm) | of nodes | Type | (0=n/1=y) | Dep. Frac. | Option |
*-----|-----|-----|-----|-----|
* 0.24130 | 10 | 3 | 1 | 0.0 | 1 |
* 1.09982 | 30 | 1 | 0 | 0.97846 | 1 |
* 1.11760 | 10 | 3 | 1 | 0.0 | 1 |
* 1.68402 | 10 | 1 | 0 | 0.97846 | 1 |
* 1.73228 | 10 | 3 | 1 | 0.0 | 1 |
* 1.77038 | 10 | 2 | 0 | 0.00400 | 1 |
* 1.82245 | 10 | 3 | 1 | 0.0 | 1 |
* 1.87325 | 10 | 4 | 0 | 0.00456 | 1 |
*-----|-----|-----|-----|-----|
*                               Fuel Element Geometry
*-----|-----|-----|-----|-----|
* Fuel | Number | Pitch or | Pitch/Flow Geometry |
* Length (cm) | of Nodes | Channel O.D. | (1=square pitch,2=hex pitch |
* | | (cm) | 3=annulus, 4=tube) |
*-----|-----|-----|-----|-----|
*           52.25      104      4.171              2
*-----|-----|-----|-----|-----|
* Fissile | Internal | External | Allow | Allow Gap |
* Mat. # | Element | Element | Thermal Exp. | Rad HX |
* (only one) | Press (psia) | Press (psia) | (0=no,1=yes) | (0=no,1=yes) |
*-----|-----|-----|-----|-----|
*           1           0.0           0.0           1           1
*-----|-----|-----|-----|-----|
* Center radial node of fuel "TC" | # of radial nodes to average |
* (at half fuel height) | on each side of the center node |
*-----|-----|-----|-----|-----|
*           25              6
*-----|-----|-----|-----|-----|
*                               Fuel Pellet Radial Fission Density Peaking Distribution
*                               f(r) = A*exp(B*r) + C
*-----|-----|-----|-----|-----|
*           A | B | C |
*-----|-----|-----|-----|-----|
*           0.0157 | 1.9370 | 0.8211
*-----|-----|-----|-----|-----|
* # of Axial |
* Peaking | Control Rod Positions (cm) for each Distribution |
* Distributions | (at least one entry is required, but arbitrary, |
* (max of 5) | if only one distribution) |
*-----|-----|-----|-----|-----|
*           1 | 0.00 13.75 27.50 41.25 55.00
*-----|-----|-----|-----|-----|

```

```

*-----|
*           Fuel Element Axial Fission Peaking Distribution |
*           f(z) = SUM{a(i)*(z/H)^(i)} for i = 0 to 6 |
*-----|-----|-----|-----|-----|-----|
*           0.7721  -0.6252   24.0903  -89.6026  141.5383  -108.8048  33.1631
*****
*           COOLANT CHANNEL MODEL
*****
*
*-----|-----|-----|-----|-----|
* Coolant Channel Option | Coolant Type | Flow Type |
* (0 = fuel coupled to coolant) | (1 = water) | (1=Natural Conv.) |
* (1 = channel only) | | (0=Forced Conv.) |
*-----|-----|-----|-----|-----|
*           0           1           1
*-----|-----|-----|-----|-----|
* Two-Phase Flow | Boiling | (Forced Conv.-Not Active) | Artificial |
* Drift Velocity | Expansion | Inlet | Inlet | Viscosity |
* Nominal Value | Suppression | Pressure | Mass Flow | Constant |
* (cm/s) | Factor | (psia) | (g/sec) | |
*-----|-----|-----|-----|-----|
*           50.0           160.0           22.0           100.0           0.0
*-----|-----|-----|-----|-----|
*           Atmospheric Pressure
*           Above Pool Water (psia)
*-----|-----|-----|-----|-----|
*           12.5
*-----|-----|-----|-----|-----|
*           Channel Inlet Node Definition
* Node Inlet | Node Exit | |
* Flow Area (cm2) | Flow Area (cm2) | Minor Loss Coefficient
*-----|-----|-----|-----|-----|
*           4.042398           4.042398           1.50
*-----|-----|-----|-----|-----|
*           Unheated Channel Length (Lower and Upper)
*-----|-----|-----|-----|-----|
*           Number of Lower Nodes | Number of Upper Nodes
*-----|-----|-----|-----|-----|
*           12           9
*-----|-----|-----|-----|-----|
*           Lower Unheated Length Description
*-----|-----|-----|-----|-----|
* Node Height | Exit Flow | Wetted Perimeter | Exit
* (cm) | Area (cm2) | (cm) | Loss Coefficient
*-----|-----|-----|-----|-----|
* 1.0048076923 | 4.042398 | 11.76998 | 0.0
* 1.0048076923 | 4.042398 | 11.76998 | 0.0
* 1.0048076923 | 4.042398 | 11.76998 | 0.0
* 1.0048076923 | 4.042398 | 11.76998 | 0.0
* 1.0048076923 | 4.042398 | 11.76998 | 0.0
* 1.0048076923 | 4.042398 | 11.76998 | 0.0
* 1.0048076923 | 4.042398 | 11.76998 | 0.0
* 1.0048076923 | 4.042398 | 11.76998 | 0.0
* 1.0048076923 | 4.042398 | 11.76998 | 0.0
* 1.0048076923 | 4.042398 | 11.76998 | 0.0
* 1.0048076923 | 4.042398 | 11.76998 | 0.0
*-----|-----|-----|-----|-----|

```

```

*-----|
*           Upper Unheated Length Description           |
*-----|
* Node Height | Exit Flow | Wetted Perimeter |      Exit
*   (cm)      | Area (cm2) |      (cm)         | Loss Coefficient
*-----|-----|-----|-----|
1.0048076923 | 4.042398 | 11.76998         | 0.0
1.0048076923 | 4.042398 | 11.76998         | 0.0
1.0048076923 | 4.042398 | 11.76998         | 0.0
1.0048076923 | 4.042398 | 11.76998         | 0.0
1.0048076923 | 4.042398 | 11.76998         | 0.0
1.0048076923 | 4.042398 | 11.76998         | 0.0
1.0048076923 | 4.042398 | 11.76998         | 0.0
1.0048076923 | 4.042398 | 11.76998         | 0.0
1.0048076923 | 4.042398 | 11.76998         | 0.0
*-----|-----|-----|-----|
*           Channel Outlet Node Definition           |
* Node Exit Flow Area (cm2) |      Minor Loss Coefficient
*-----|-----|-----|
                4.042398                1.50
*****
* Test Options (only the "Reactor Only" option is currently available)
*****
*-----|
*           Test Mode                               |
*-----|
* 0 = Normal (no test; next 3 cards not required, so comment out)
* 1 = Specify BCs and/or Conductivities (next 2 cards required)
*-----|
                0
*
* Fuel Element Surface BC 1=convection / 2=constant T --> BC Temp
*           2                120.0
*
*-----|
*           Reactor Only Test Option               |
*-----|
* Reactor Only (1=y/0=no) |      Energy Yield Feedback ($/J-Rx)
*-----|-----|
                0                -3.87597e-4
*****

```

```

*****
*   Begin Material Property Entries
*****
4 # of materials
*-----BeO-UO2-----
3.500000d+00 BeO-UO2
2 # of temperature ranges for k (<= 3)
273.15d0 2423.15d0
6 0.00d0 1.000000d+00
7.388187d+00 -2.472780-02 3.932623d-05 -3.484550d-08 1.742192d-11
-4.576267d-15 4.902442d-19
2423.15d0 3273.15d0
0 0.00d0 1.000000d+00
0.178994d+00 assume constant after eutectic melt
*
3 # of temperature ranges for k (<= 3)
273.15d0 2423.15d0
6 0.00d0 1.000000d+00
-6.988880d-01 8.637336d-03 -1.476482d-05 1.390025d-08 -7.220731d-12
1.947498d-15 -2.126275d-19
2423.15d0 2623.15d0
6 -2400.00d0 1.000000d+00
2.684542d+00 -6.808448d-03 3.586942d-04 -5.392987d-06 4.553262d-08
-1.882605d-10 3.243747d-13
2623.15d0 3273.15d0
6 -2600.00d0 1.000000d+00
2.154782d+02 -2.532661d+01 1.239674d+00 -3.122766d-02 4.305744d-04
-3.087149d-06 9.072820d-09
*
0.8d0 0.0d0
*
*0 0.00d0 1.000000d+00
*8.500000d-06
2 0.00d0 1.000000d+00
4.380929d-06 6.667636d-09 -8.749789d-13
*
0 0.00d0 1.000000d+00
345.0000d+09
*
0.26d0
*-----Niobium-----
8.570000d+00 Niobium
1 # of temperature ranges for k (<= 3)
273.15d0 3273.15d0
2 0.00d0 1.000000d+00
0.48705456d+00 1.6410260d-04 -6.1258996d-09
*
1 # of temperature ranges for k (<= 3)
273.15d0 3273.15d0
5 0.00d0 1.000000d+00
2.145847d-01 2.429998d-04 -3.253767d-07 2.386227d-10 -8.133768d-14
1.102552d-17
*
0.8d0 0.0d0
*
2 0.00d0 1.000000d+00
6.696000d-06 2.191880d-09 -3.141264d-13
*
0 0.00d0 1.000000d+00
105.0000d+09
*
0.4d0
*-----

```

```

*-----Helium-----
3.328d-04 Helium
1 # of temperature ranges for k (<= 3)
 273.15d0 3273.15d0
2 0.00d0 1.000000d+00
5.259485d-04 3.333698d-06 -2.484752d-10
*
1 # of temperature ranges for cp (<= 3)
 273.15d0 3273.15d0
0 0.00d0 1.000000d+00
5.193122d+00
*
1.0d0 1.0d0
*
0 0.00d0 1.000000d+00
0.00000d-00
*
0 0.00d0 1.000000d+00
1.00000d-20
*1.00000d+06
*
0.3d0
*-----Stainless Steel-----
7.950000d+00 Stainless_Steel
1 # of temperature ranges for k (<= 3)
 273.15d0 3273.15d0
1 0.00d0 1.000000d+00
0.08116d+00 0.0001618d+00
*
1 # of temperature ranges for cp (<= 3)
 273.15d0 3273.15d0
1 0.00d0 1.000000d+00
0.46287d+00 1.3289d-04
*
0.3d0 0.0d0
*
0 0.00d0 1.000000d+00
1.730000d-05
*
0 0.00d0 1.000000d+00
190.0000d+09
*
0.3d0
*-----

```

```

*****
*   Begin Heat Transfer Coefficient Correlation Entries
*****
*
*-----Natural Convection-----
*
*      C          Ra exp
* 0.2720d+00    0.250d-00
*
*-----Laminar Forced Convection-----
*
*      C          Re exp      Pr exp      visc ratio exp      Re Transition
* 1.061d+00    0.3400d-00    0.3333d-00      0.0d-00      4137.47d-00
* 1.061d+00    0.3400d-00    0.3333d-00      0.0d-00      3000.0d-00
*
*-----Turbulent Forced Convection-----
*
*      C          Re exp      Pr exp      visc ratio exp
* 0.0230d+00    0.800d-00    0.4000d-00      0.0d-00
*
*-----Boiling Heat Transfer Coefficient Option-----
*
*          i_bht          |
* (1 = Jens-Lottes)      |
*          1
*
*-----Post-CHF Heat Transfer Coefficient Option-----
*
*      MCHFR Limit          |      Post-CHF HT Coefficient (W/cm2/K)
*          -2.0              |              0.001
*
*****

```

APPENDIX B: EXCERPTS OF SAMPLE *RSIM.OUT* OUTPUT FILE

This appendix contains an abbreviated excerpt from the *rsim.out* output data file which is described in Section 4.1.1 of the main report.

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RAZORBACK Output File
09/22/2016
09:56:46.11

Uncontrolled Rod Withdrawal

- Withdraw to 55 cm (full up) from 15 cm
- Power 23.9 W, 236 elements, 1.50 Core Radial Peaking Factor
- ACRR Fuel Element Model
- Plane Stress Conditions Assumed

Input File Summary

Reactor Data

Initial Power = 1.00E-03 % of 2.39E+06 W Full Power

Number of Fuel Elements = 236

Fuel Element Peaking Factor = 1.50

Neutron Generation Time = 24.00E-06 s

Delayed Neutron Fraction = 0.0073

Number of Delayed Neutron Groups = 8

Delayed Neutron Group Fractions

0.241E-03 0.112E-02 0.664E-03 0.144E-02 0.242E-02 0.657E-03
0.591E-03 0.168E-03

Delayed Neutron Group Decay Constants - 1/s

0.125E-01 0.283E-01 0.425E-01 0.133E+00 0.292E+00 0.666E+00
0.163E+01 0.355E+01

Fuel Temperature Feedback \$/K

$d_{\rho}/dT = c1 + c2/T^{0.5}$

$c1 = -0.98800E-03$ $c2 = -0.79422E-01$

Coolant Density Feedback \$/%void = -0.3820

Coolant Spectral Feedback \$/degC = -0.0012

Fuel Spectral Feedback Scale Factor = 1.00

Fuel Expansion Feedback Scale Factor = 1.00

Coolant Total Feedback Scale Factor = 1.00

Feedback Rod Location Adjustment Factor = 0.90

Reactivity Control System Data

Control Rod Bank Initial Position = 1500 units

Control Rod Bank Worth = 12.00 \$

Control Rods programmed to move outward
from 0.000 s
to 40.000 s
at a Bank Speed of 1.00 cm/s

Control Rods programmed to pause
from 40.000 s
to ***** s

The ending time (10000 s) for the
Control Rod program time range
exceeded the print format space
allocation.

Fuel Element Model Data

Zone	R_inner(cm)	R_outer(cm)	# of Nodes	Material
1	0.00000	0.24130	10	Helium
2	0.24130	1.09982	30	UO2-BeO
3	1.09982	1.11760	10	Helium
4	1.11760	1.68402	10	UO2-BeO
5	1.68402	1.73228	10	Helium
6	1.73228	1.77038	10	Niobium
7	1.77038	1.82245	10	Helium
8	1.82245	1.87325	10	SS-304

Radiation heat transfer across gas-filled gaps will be modeled.

Thermal expansion of materials will be modeled.

Fission heat generation will occur in the UO2-BeO .

Radial fission heating profile within the fuel rod

$A_{exp}(Br) + C$

A = 0.15668E-01 B = 0.19370E+01 C = 0.81941E+00

Normalization = 1.0000

Axial fission heating profile within the fuel rod

6th order polynomial fit

a1 = 0.77210E+00

a2 = -0.62520E+00

a3 = 0.24090E+02

a4 = -0.89603E+02

a5 = 0.14154E+03

a6 = -0.10880E+03

a7 = 0.33163E+02

Normalization = 0.9999

This is the end of the restatement
of input file parameters.
Calculation output begins next.

Time = 0.0000 s Current time step = 1.00E-04 s

	CR	SR	TR
Rod Position	1500	5500	9000
Reactivity Addition	0.00\$	0.00\$	0.00\$

Reactor Power : 23.90E+00 W 1.00E-03 %
System Reactivity : 0.00E+00 \$
RCS Added Reactivity : 0.00E+00 \$
Total Reactivity Feedback : 0.00E+00 \$
fuel tmp feedback : 0.00E+00 \$
fuel exp feedback : 0.00E+00 \$
clad exp feedback : 0.00E+00 \$
coolant feedback : 0.00E+00 \$
Reactor Period : 10.00E+09 s or 0.00E+00 dpm SUR
Minimum Reactor Period : 100.00E+18 s at t = 0.00E+00 s
Reactor Yield : 0.0E+00 J

Max./Meas. Fuel Temperature : 20.14 C / 20.11 C
Inner / Outer Clad Temperature : 20.13 C / 20.13 C
Coolant Channel Mass Flow : 0.30 g/s
Outlet Quality / Boiling Length : -16.97 % / 0.00 cm
Inlet / Outlet Temperature : 20.00 C / 20.13 C
Inlet / Outlet Enthalpy : 83.94 J/g / 84.44 J/g

Fuel Power : 149.94E-03 W
Heat Transfer Power : 149.94E-03 W
Neutron/Gamma Heating Power : 2.06E-03 W
Total Power to Coolant : 152.00E-03 W
Coolant Convection Power : 151.91E-03 W

Fuel element/coolant channel energy balance data.

MCHFR is 910.24E+03 at fuel height of 21.85 cm

Peak Values : 0.00E+00 W and 0.00E+00 J at 0.00E+00 s

j	T1	T2	T3	T4	T5	T6	T7	T8	Ts	Tw	h	x %	vf %	mdot	P	dens	...
126	----	----	----	----	----	----	----	----	----	20.1	84.44	-16.97	0.00	0.30	21.011	0.9981	...
:																	
117	----	----	----	----	----	----	----	----	----	20.1	84.44	-17.01	0.00	0.30	21.137	0.9981	...
116	20	20	20	20	20	20	20	20	20	20.1	84.44	-17.01	0.00	0.30	21.144	0.9981	...
115	20	20	20	20	20	20	20	20	20	20.1	84.44	-17.01	0.00	0.30	21.151	0.9981	...
:																	
14	20	20	20	20	20	20	20	20	20	20.0	83.94	-17.25	0.00	0.30	21.877	0.9981	...
13	20	20	20	20	20	20	20	20	20	20.0	83.94	-17.25	0.00	0.30	21.884	0.9981	...
12	----	----	----	----	----	----	----	----	----	20.0	83.94	-17.25	0.00	0.30	21.894	0.9981	...
:																	
1	----	----	----	----	----	----	----	----	----	20.0	83.94	-17.30	0.00	0.30	22.052	0.9981	...
0	----	----	----	----	----	----	----	----	----	20.0	83.94	-17.30	0.00	0.30	22.067	0.9981	...

...	gmfi	gmfo	hxc	Re	q" W/cm2	CHFR-GLUT
...	0.0736	0.0736	0.000	1.01E+01	0.000E+00	---
:						
...	0.0736	0.0736	0.000	1.01E+01	0.000E+00	---
...	0.0736	0.0736	0.020	1.01E+01	1.297E-04	2.11E+06
...	0.0736	0.0736	0.020	1.01E+01	1.307E-04	2.10E+06
:						
...	0.0736	0.0736	0.020	1.01E+01	1.872E-04	1.75E+06
...	0.0736	0.0736	0.020	1.01E+01	1.876E-04	1.75E+06
...	0.0736	0.0736	0.000	1.01E+01	0.000E+00	---
:						
...	0.0736	0.0736	0.000	1.01E+01	0.000E+00	---
...	0.0736	0.0736	0.000	0.00E+00	0.000E+00	----

The "----" entries correspond to unheated inlet and outlet lengths of the flow channel to indicate that the code does not associate a fuel element node with the unheated lengths.

This data (from "j" to "CHFR-GLUT") is on a single line in the rsim.out file. Also, a line for each axial node ("j") is included in the rsim.out file. The actual layout has been changed here due to margin limitations.

Pulse Parameters

The TR reactivity addition was	0.000	\$	
The pulse peak occurred at	3.63E+00	s	
The peak system reactivity was	1.095	\$ at	3.53E+00 s
The rod holdup time was	0.400	s	
The peak power was	106.695E+06	W	
The FWHM was	119.804E-03	s	
The LEHM was	66.270E-03	s	
The TEHM was	53.533E-03	s	
The minimum period was	30.742E-03	s at	3.53E+00 s
The pulse yield at the peak was	6.0E+06	J	
The pulse yield at peak+3*FWHM was	20.6E+06	J	
The total pulse yield was	3.7E+09	J at	300.000 s
The peak measured fuel temperature was	2339.1	C at	48.4E+00 s

At no time during the run, was a
scram trip signal initiated.

The percent power scram setting was 1.15E+42 %

The peak element power scram setting was 2.00E+50 W

The fuel temperature scram setting was 1.25E+23 C

The reactor period scram setting was 8.50E-20 s

The reactor yield scram setting was 3.00E+48 J

```
-----  
RAZORBACK Run Complete  
09/22/2016  
16:44:13.51  
-----
```

APPENDIX C: EXCERPT OF SAMPLE *STEADY_IC.DAT* OUTPUT FILE

This appendix contains an excerpt from the *steady_ic.dat* output data file which is described in Section 4.1.2 of the main report. The excerpt shown is for the first (lowest) axial segment of the fuel. A full *steady_ic.dat* file will contain the same type of data for all axial segments.

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Steady-State Stress Results

NOTE: Assumes Plane Stress Conditions

Fuel element temperature, displacement, and stress at the element vertical segment 1, fuel elevation 0.2512 cm

r0 (cm)	r (cm)	T(C)	u (cm)	sig_x1(MPa)	sig_x2(MPa)	sig_x3(MPa)	sig_vm(MPa)	
12.06500E-03	12.06500E-03	20.03191E+00	10.24029E-09	7.46162E-33	10.72608E-33	0.00000E+00	9.52317E-33	---GAP---
36.19500E-03	36.19501E-03	20.03191E+00	10.24029E-09	1.74083E-33	3.35145E-33	0.00000E+00	2.90317E-33	---GAP---
60.32500E-03	60.32501E-03	20.03191E+00	13.78931E-09	2.52482E-33	3.04328E-33	0.00000E+00	2.82003E-33	---GAP---
84.45500E-03	84.45502E-03	20.03191E+00	18.01901E-09	2.68393E-33	2.93874E-33	0.00000E+00	2.81998E-33	---GAP---
108.58500E-03	108.58502E-03	20.03191E+00	22.48723E-09	2.74262E-33	2.89372E-33	0.00000E+00	2.82121E-33	---GAP---
132.71500E-03	132.71503E-03	20.03191E+00	27.06538E-09	2.77077E-33	2.87059E-33	0.00000E+00	2.82201E-33	---GAP---
156.84500E-03	156.84503E-03	20.03191E+00	31.70294E-09	2.78646E-33	2.85723E-33	0.00000E+00	2.82251E-33	---GAP---
180.97500E-03	180.97504E-03	20.03191E+00	36.37613E-09	2.79610E-33	2.84884E-33	0.00000E+00	2.82284E-33	---GAP---
205.10500E-03	205.10504E-03	20.03191E+00	41.07235E-09	2.80244E-33	2.84324E-33	0.00000E+00	2.82306E-33	---GAP---
229.23500E-03	229.23505E-03	20.03191E+00	45.78428E-09	2.80684E-33	2.83932E-33	0.00000E+00	2.82322E-33	---GAP---
241.30000E-03	241.30005E-03	20.03191E+00	48.14584E-09	-11.77199E-12	-78.80070E-06	0.00000E+00	78.80070E-06	
255.60867E-03	255.60872E-03	20.03191E+00	51.00492E-09	275.11056E-09	-73.17110E-06	0.00000E+00	73.30904E-06	
284.22600E-03	284.22606E-03	20.03191E+00	56.72288E-09	390.72030E-09	-63.81254E-06	0.00000E+00	64.00880E-06	
312.84333E-03	312.84340E-03	20.03191E+00	62.44064E-09	72.71436E-09	-56.36097E-06	0.00000E+00	56.39736E-06	
341.46067E-03	341.46073E-03	20.03191E+00	68.15819E-09	-431.36128E-09	-50.27709E-06	0.00000E+00	50.06280E-06	
370.07800E-03	370.07807E-03	20.03191E+00	73.87554E-09	-995.55821E-09	-45.19593E-06	0.00000E+00	44.70647E-06	
398.69533E-03	398.69541E-03	20.03191E+00	79.59270E-09	-1.55496E-06	-40.86314E-06	0.00000E+00	40.10827E-06	
427.31267E-03	427.31275E-03	20.03191E+00	85.30968E-09	-2.07643E-06	-37.09689E-06	0.00000E+00	36.10349E-06	
455.93000E-03	455.93009E-03	20.03191E+00	91.02648E-09	-2.54383E-06	-33.76435E-06	0.00000E+00	32.56703E-06	
484.54733E-03	484.54743E-03	20.03191E+00	96.74312E-09	-2.95022E-06	-30.76652E-06	0.00000E+00	29.40263E-06	
513.16467E-03	513.16477E-03	20.03190E+00	102.45958E-09	-3.29367E-06	-28.02837E-06	0.00000E+00	26.53529E-06	
541.78200E-03	541.78211E-03	20.03190E+00	108.17589E-09	-3.57492E-06	-25.49215E-06	0.00000E+00	23.90601E-06	
570.39933E-03	570.39945E-03	20.03190E+00	113.89203E-09	-3.79608E-06	-23.11275E-06	0.00000E+00	21.46792E-06	
599.01667E-03	599.01679E-03	20.03190E+00	119.60801E-09	-3.95990E-06	-20.85454E-06	0.00000E+00	19.18360E-06	
627.63400E-03	627.63413E-03	20.03190E+00	125.32383E-09	-4.06936E-06	-18.68901E-06	0.00000E+00	17.02311E-06	
656.25133E-03	656.25146E-03	20.03190E+00	131.03949E-09	-4.12740E-06	-16.59310E-06	0.00000E+00	14.96262E-06	
684.86867E-03	684.86880E-03	20.03190E+00	136.75499E-09	-4.13685E-06	-14.54801E-06	0.00000E+00	12.98365E-06	
713.48600E-03	713.48614E-03	20.03190E+00	142.47032E-09	-4.10035E-06	-12.53822E-06	0.00000E+00	11.07288E-06	
742.10333E-03	742.10348E-03	20.03190E+00	148.18548E-09	-4.02030E-06	-10.55082E-06	0.00000E+00	9.22308E-06	
770.72067E-03	770.72082E-03	20.03190E+00	153.90048E-09	-3.89889E-06	-8.57500E-06	0.00000E+00	7.43633E-06	
799.33800E-03	799.33816E-03	20.03190E+00	159.61530E-09	-3.73808E-06	-6.60160E-06	0.00000E+00	5.73386E-06	
827.95533E-03	827.95550E-03	20.03190E+00	165.32994E-09	-3.53966E-06	-4.62282E-06	0.00000E+00	4.18766E-06	
856.57267E-03	856.57284E-03	20.03190E+00	171.04441E-09	-3.30521E-06	-2.63195E-06	0.00000E+00	3.02530E-06	
885.19000E-03	885.19018E-03	20.03190E+00	176.75869E-09	-3.03613E-06	-623.17505E-09	0.00000E+00	2.77748E-06	
913.80733E-03	913.80752E-03	20.03189E+00	182.47278E-09	-2.73370E-06	1.40859E-06	0.00000E+00	3.64800E-06	
942.42467E-03	942.42485E-03	20.03189E+00	188.18667E-09	-2.39903E-06	3.46781E-06	0.00000E+00	5.10886E-06	
971.04200E-03	971.04219E-03	20.03189E+00	193.90037E-09	-2.03312E-06	5.55847E-06	0.00000E+00	6.80670E-06	
999.65933E-03	999.65953E-03	20.03189E+00	199.61386E-09	-1.63685E-06	7.68413E-06	0.00000E+00	8.61991E-06	
1.02828E+00	1.02828E+00	20.03189E+00	205.32715E-09	-1.21101E-06	9.84799E-06	0.00000E+00	10.50597E-06	
1.05689E+00	1.05689E+00	20.03189E+00	211.04022E-09	-756.29305E-09	12.05300E-06	0.00000E+00	12.44839E-06	
1.08551E+00	1.08551E+00	20.03189E+00	216.75307E-09	-273.33679E-09	14.30184E-06	0.00000E+00	14.44045E-06	
1.09982E+00	1.09982E+00	20.03189E+00	219.60938E-09	2.53232E-12	15.45078E-06	0.00000E+00	15.45078E-06	
1.10071E+00	1.10071E+00	20.03182E+00	219.27868E-09	-3.42604E-33	964.34617E-36	0.00000E+00	3.99645E-33	---GAP---

1.10249E+00	1.10249E+00	20.03167E+00	218.61891E-09	-3.41896E-33	957.27145E-36	0.00000E+00	3.98479E-33	---GAP---
1.10426E+00	1.10427E+00	20.03153E+00	217.96077E-09	-3.41192E-33	950.23088E-36	0.00000E+00	3.97320E-33	---GAP---
1.10604E+00	1.10604E+00	20.03139E+00	217.30426E-09	-3.40492E-33	943.22424E-36	0.00000E+00	3.96166E-33	---GAP---
1.10782E+00	1.10782E+00	20.03125E+00	216.64936E-09	-3.39794E-33	936.25130E-36	0.00000E+00	3.95018E-33	---GAP---
1.10960E+00	1.10960E+00	20.03111E+00	215.99607E-09	-3.39101E-33	929.31186E-36	0.00000E+00	3.93876E-33	---GAP---
1.11138E+00	1.11138E+00	20.03097E+00	215.34438E-09	-3.38410E-33	922.40570E-36	0.00000E+00	3.92740E-33	---GAP---
1.11315E+00	1.11316E+00	20.03083E+00	214.69428E-09	-3.37723E-33	915.53260E-36	0.00000E+00	3.91610E-33	---GAP---
1.11493E+00	1.11493E+00	20.03069E+00	214.04577E-09	-3.37039E-33	908.69236E-36	0.00000E+00	3.90485E-33	---GAP---
1.11671E+00	1.11671E+00	20.03055E+00	213.39884E-09	-3.36358E-33	901.88476E-36	0.00000E+00	3.89366E-33	---GAP---
1.11760E+00	1.11760E+00	20.03048E+00	213.07615E-09	-13.59729E-12	-47.76582E-06	0.00000E+00	47.76581E-06	
1.14592E+00	1.14592E+00	20.03047E+00	218.48064E-09	-787.68608E-09	-43.88386E-06	0.00000E+00	43.49537E-06	
1.20256E+00	1.20256E+00	20.03047E+00	229.28816E-09	-2.00273E-06	-36.30029E-06	0.00000E+00	35.34151E-06	
1.25920E+00	1.25921E+00	20.03047E+00	240.09426E-09	-2.82540E-06	-28.85985E-06	0.00000E+00	27.55600E-06	
1.31585E+00	1.31585E+00	20.03047E+00	250.89894E-09	-3.30438E-06	-21.48828E-06	0.00000E+00	20.04144E-06	
1.37249E+00	1.37249E+00	20.03046E+00	261.70220E-09	-3.47851E-06	-14.12328E-06	0.00000E+00	12.74516E-06	
1.42913E+00	1.42913E+00	20.03046E+00	272.50401E-09	-3.37898E-06	-6.71150E-06	0.00000E+00	5.81238E-06	
1.48577E+00	1.48577E+00	20.03046E+00	283.30435E-09	-3.03099E-06	793.87049E-09	0.00000E+00	3.49619E-06	
1.54242E+00	1.54242E+00	20.03045E+00	294.10320E-09	-2.45488E-06	8.43487E-06	0.00000E+00	9.89343E-06	
1.59906E+00	1.59906E+00	20.03045E+00	304.90051E-09	-1.66710E-06	16.25022E-06	0.00000E+00	17.14467E-06	
1.65570E+00	1.65570E+00	20.03044E+00	315.69624E-09	-680.99769E-09	24.27645E-06	0.00000E+00	24.62401E-06	
1.68402E+00	1.68402E+00	20.03044E+00	321.09328E-09	4.94202E-12	28.42687E-06	0.00000E+00	28.42687E-06	
1.68643E+00	1.68643E+00	20.03011E+00	320.13746E-09	-3.71787E-33	782.95104E-36	0.00000E+00	4.16491E-33	---GAP---
1.69126E+00	1.69126E+00	20.02945E+00	318.23391E-09	-3.70504E-33	770.12644E-36	0.00000E+00	4.14413E-33	---GAP---
1.69609E+00	1.69609E+00	20.02878E+00	316.33836E-09	-3.69233E-33	757.41115E-36	0.00000E+00	4.12338E-33	---GAP---
1.70091E+00	1.70091E+00	20.02812E+00	314.45076E-09	-3.67972E-33	744.80393E-36	0.00000E+00	4.10314E-33	---GAP---
1.70574E+00	1.70574E+00	20.02747E+00	312.57103E-09	-3.66722E-33	732.30357E-36	0.00000E+00	4.08292E-33	---GAP---
1.71056E+00	1.71056E+00	20.02681E+00	310.69912E-09	-3.65482E-33	719.90887E-36	0.00000E+00	4.06290E-33	---GAP---
1.71539E+00	1.71539E+00	20.02616E+00	308.83495E-09	-3.64253E-33	707.61863E-36	0.00000E+00	4.04305E-33	---GAP---
1.72022E+00	1.72022E+00	20.02550E+00	306.97845E-09	-3.63034E-33	695.43168E-36	0.00000E+00	4.02339E-33	---GAP---
1.72504E+00	1.72504E+00	20.02485E+00	305.12957E-09	-3.61826E-33	683.34687E-36	0.00000E+00	4.00391E-33	---GAP---
1.72987E+00	1.72987E+00	20.02420E+00	303.28824E-09	-3.60628E-33	671.36306E-36	0.00000E+00	3.98460E-33	---GAP---
1.73228E+00	1.73228E+00	20.02388E+00	302.37132E-09	-3.41960E-12	-5.50385E-06	0.00000E+00	5.50385E-06	
1.73419E+00	1.73419E+00	20.02388E+00	302.70397E-09	-4.18809E-09	-4.94685E-06	0.00000E+00	4.94475E-06	
1.73800E+00	1.73800E+00	20.02388E+00	303.36924E-09	-13.78810E-09	-3.83875E-06	0.00000E+00	3.83187E-06	
1.74181E+00	1.74181E+00	20.02388E+00	304.03444E-09	-20.92413E-09	-2.73507E-06	0.00000E+00	2.72467E-06	
1.74562E+00	1.74562E+00	20.02388E+00	304.69959E-09	-25.62491E-09	-1.63578E-06	0.00000E+00	1.62312E-06	
1.74943E+00	1.74943E+00	20.02387E+00	305.36469E-09	-27.91590E-09	-540.84322E-09	0.00000E+00	527.43963E-09	
1.75324E+00	1.75324E+00	20.02387E+00	306.02973E-09	-27.82220E-09	549.77775E-09	0.00000E+00	564.20357E-09	
1.75705E+00	1.75705E+00	20.02387E+00	306.69471E-09	-25.36867E-09	1.63612E-06	0.00000E+00	1.64895E-06	
1.76086E+00	1.76086E+00	20.02387E+00	307.35964E-09	-20.57984E-09	2.71820E-06	0.00000E+00	2.72855E-06	
1.76467E+00	1.76467E+00	20.02387E+00	308.02452E-09	-13.47998E-09	3.79608E-06	0.00000E+00	3.80284E-06	
1.76848E+00	1.76848E+00	20.02387E+00	308.68934E-09	-4.09603E-09	4.86977E-06	0.00000E+00	4.87182E-06	
1.77038E+00	1.77038E+00	20.02387E+00	309.02172E-09	-248.42550E-15	5.40383E-06	0.00000E+00	5.40383E-06	
1.77298E+00	1.77298E+00	20.02352E+00	320.56471E-09	49.24866E-33	16.52865E-33	0.00000E+00	43.40209E-33	---GAP---
1.77819E+00	1.77819E+00	20.02283E+00	343.58574E-09	49.15314E-33	16.67816E-33	0.00000E+00	43.29444E-33	---GAP---
1.78340E+00	1.78340E+00	20.02215E+00	366.54240E-09	49.05846E-33	16.77284E-33	0.00000E+00	43.18809E-33	---GAP---
1.78860E+00	1.78860E+00	20.02146E+00	389.43525E-09	48.96461E-33	16.86670E-33	0.00000E+00	43.08303E-33	---GAP---
1.79381E+00	1.79381E+00	20.02078E+00	412.26485E-09	48.87157E-33	16.95973E-33	0.00000E+00	42.97923E-33	---GAP---
1.79902E+00	1.79902E+00	20.02010E+00	435.03175E-09	48.77934E-33	17.05196E-33	0.00000E+00	42.87668E-33	---GAP---
1.80423E+00	1.80423E+00	20.01942E+00	457.73648E-09	48.68791E-33	17.14340E-33	0.00000E+00	42.77537E-33	---GAP---
1.80943E+00	1.80943E+00	20.01874E+00	480.37959E-09	48.59726E-33	17.23404E-33	0.00000E+00	42.67527E-33	---GAP---

1.81464E+00	1.81464E+00	20.01807E+00	502.96161E-09	48.50739E-33	17.32391E-33	0.00000E+00	42.57637E-33	---GAP---
1.81985E+00	1.81985E+00	20.01740E+00	525.48305E-09	48.41830E-33	17.41300E-33	0.00000E+00	42.47866E-33	---GAP---
1.82245E+00	1.82245E+00	20.01706E+00	536.71375E-09	-63.74736E-12	-124.30114E-06	0.00000E+00	124.30111E-06	
1.82499E+00	1.82499E+00	20.01706E+00	537.46394E-09	-126.92234E-09	-111.65070E-06	0.00000E+00	111.58729E-06	
1.83007E+00	1.83007E+00	20.01705E+00	538.96345E-09	-401.71244E-09	-86.50687E-06	0.00000E+00	86.30671E-06	
1.83515E+00	1.83515E+00	20.01704E+00	540.46209E-09	-605.55534E-09	-61.49153E-06	0.00000E+00	61.19100E-06	
1.84023E+00	1.84023E+00	20.01703E+00	541.95986E-09	-739.39153E-09	-36.60338E-06	0.00000E+00	36.23934E-06	
1.84531E+00	1.84531E+00	20.01703E+00	543.45677E-09	-804.14760E-09	-11.84115E-06	0.00000E+00	11.46026E-06	
1.85039E+00	1.85039E+00	20.01702E+00	544.95282E-09	-800.73651E-09	12.79641E-06	0.00000E+00	13.21498E-06	
1.85547E+00	1.85547E+00	20.01701E+00	546.44802E-09	-730.05780E-09	37.31054E-06	0.00000E+00	37.68087E-06	
1.86055E+00	1.86055E+00	20.01700E+00	547.94236E-09	-592.99778E-09	61.70247E-06	0.00000E+00	62.00110E-06	
1.86563E+00	1.86563E+00	20.01700E+00	549.43586E-09	-390.42985E-09	85.97341E-06	0.00000E+00	86.16929E-06	
1.87071E+00	1.87071E+00	20.01699E+00	550.92852E-09	-123.21463E-09	110.12456E-06	0.00000E+00	110.18622E-06	
1.87325E+00	1.87325E+00	20.01699E+00	551.67443E-09	39.98584E-12	122.12785E-06	0.00000E+00	122.12783E-06	

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APPENDIX D: LISTING/DESCRIPTION OF *RSIM.DAT* FILE

This appendix contains a table which lists the parameter values printed by the code to a columnar data file called *rsim.dat*. The data are printed to this file at a frequency specified by the user (see Section 3.1.2 of the main report).

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Quantity	Units	Description
Time	s	Time (analysis time) at which the subsequent quantities are printed.
Reactor Power	W	The overall reactor power level.
Reactor Power	%FP	The overall reactor power level expressed as a percent of the full power value input by the user.
Reactor Energy Yield	J	Integral of the reactor power up to time t .
System Reactivity	\$	The overall reactivity of the system. This is the sum of all added reactivity and all feedback reactivity.
Total Reactivity Feedback	\$	Sum of all feedback reactivity.
Fuel Reactivity Feedback	\$	Sum of fuel temperature and expansion feedback reactivity.
Fuel Temperature (Doppler) Reactivity Feedback	\$	Fuel temperature Doppler effect reactivity feedback.
Fuel Expansion Reactivity Feedback	\$	Fuel thermal expansion reactivity feedback.
Cladding Reactivity Feedback	\$	Cladding thermal expansion reactivity feedback.
Coolant Reactivity Feedback	\$	Coolant density and temperature (spectral) reactivity feedback.
Reactor Period	s	Instantaneous reactor period (τ) given by $\tau = \left(\frac{1}{\rho} \frac{d\rho}{dt}\right)^{-1}$
Reactor Startup Rate	decades per minute	Instantaneous reactor startup rate (SUR) given by $SUR = \frac{26.06}{\tau}$, where τ is the reactor period in seconds.
Fuel Element Power	W	Fission and n/γ heating energy deposition rate in the fuel and fuel element components.
Maximum Fuel Temperature	°C	Maximum temperature in the fuel material determined by scanning the full radial and axial extent of the fuel.
“Measured” Fuel Temperature	°C	Temperature corresponding to the temperature measured by a thermocouple at the fuel axial midplane. See Sect. 3.8 for a description of the “measured” temperature.
Maximum Inner Cladding Surface Temperature	°C	Maximum inner cladding surface temperature determined by scanning all axial inner cladding surface nodes.
Maximum Outer Cladding Surface Temperature	°C	Maximum outer cladding surface temperature determined by scanning all axial outer cladding surface nodes.

Quantity	Units	Description
Coolant Channel Power	W	Calculation of the instantaneous rate at which energy is being carried away by the flow of coolant.
Coolant Channel Outlet Temperature	°C	Coolant temperature at the outlet node of the coolant channel.
Coolant Channel Outlet Enthalpy	J/g	Coolant enthalpy at the outlet node of the coolant channel.
Coolant Channel Outlet Quality	%	Coolant thermodynamic quality at the outlet node of the coolant channel given by $x = \frac{h-h_f}{h_{fg}}$.
Coolant Channel Outlet Void Fraction	%	Coolant void fraction at the outlet node of the coolant channel.
Lower Coordinate of Boiling Region	cm	Lower axial extent of the region of coolant experiencing saturated boiling. Note that the value is zero if no saturated boiling is occurring in the channel.
Upper Coordinate of Boiling Region	cm	Upper axial extent of the region of coolant experiencing saturated boiling. Note that the value is zero if no saturated boiling is occurring in the channel.
Boiling Length	cm	Axial length of the region of coolant experiencing saturated boiling. Note that the value is zero if no saturated boiling is occurring in the channel.
Coolant Channel Outlet Mass Flowrate	g/s	Coolant mass flowrate at the outlet node of the coolant channel.
Coolant Channel Outlet Mass Flux	g/s/m ²	Coolant mass flux at the outlet node of the coolant channel.
Maximum Cladding Surface Heat Flux	W/m ²	Maximum cladding surface heat flux determined by scanning all axial outer cladding surface nodes.
Control Rod Bank Position	units	Current position of the Control Rod bank in rod units. 1 rod unit = 0.01 cm
Control Rod Bank Reactivity Addition Rate	\$/s	Instantaneous Control Rod bank reactivity addition rate.
Control Rod Bank Total Reactivity Addition	\$	Total reactivity added by Control Rod bank motion up to time t .
Safety Rod Bank Position	units	Current position of the Safety Rod bank in rod units. 1 rod unit = 0.01 cm
Safety Rod Bank Reactivity Addition Rate	\$/s	Instantaneous Safety Rod bank reactivity addition rate.
Safety Rod Bank Total Reactivity Addition	\$	Total reactivity added by Safety Rod bank motion up to time t .
Transient Rod Bank Position	units	Current position of the Transient Rod bank in rod units. 1 rod unit = 0.01 cm
Transient Rod Bank Reactivity Addition Rate	\$/s	Instantaneous Transient Rod bank reactivity addition rate.
Transient Rod Bank Total Reactivity Addition	\$	Total reactivity added by Transient Rod bank motion up to time t .

Quantity	Units	Description
Reactor Pool Water Level	m	Distance from the top lip of the reactor pool water tank to the reactor pool water level.
Reactor Pool Water Height	m	Distance from the bottom of the reactor pool water tank to the surface of the reactor pool water.
Coolant Channel Inlet Temperature	°C	Coolant temperature at the inlet node of the coolant channel.
Coolant Channel Inlet Enthalpy	J/g	Coolant enthalpy at the inlet node of the coolant channel.
Coolant Channel Inlet Mass Flowrate	g/s	Coolant mass flowrate at the inlet node of the coolant channel.
Coolant Channel Outlet Saturation Temperature	°C	Coolant saturation temperature at the outlet node of the coolant channel.
Element Heat Transfer Rate	W	Total heat transfer rate from the element to the coolant.
Outer Radius of Zone n	cm	Outer radii of the n fuel element zones.
Element Internal Gas Pressure	psia	Internal gas pressure of the fuel element.
Minimum Critical Heat Flux Ratio (MCHFR)		Minimum value of the CHF ratio along the axial length of the coolant channel.
Axial Location of MCHFR	cm	Axial coolant channel location at which the minimum CHF ratio exists.
Time Step	s	Current calculation time step.

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