

SANDIA REPORT

SAND2018- 9593

Unlimited Release

Printed August 2018

Response Technical Tools User Guide

Nathan Andrews, Chun Fu and Alex Kaberlin

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.



Sandia National Laboratories

Issued by Sandia National Laboratories, operated for the United States Department of Energy by National Technology and Engineering Solutions of Sandia, LLC.

NOTICE: This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government, nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, make any warranty, express or implied, or assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represent that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government, any agency thereof, or any of their contractors or subcontractors. The views and opinions expressed herein do not necessarily state or reflect those of the United States Government, any agency thereof, or any of their contractors.

Printed in the United States of America. This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831

Telephone: (865) 576-8401
Facsimile: (865) 576-5728
E-Mail: reports@osti.gov
Online ordering: <http://www.osti.gov/scitech>

Available to the public from
U.S. Department of Commerce
National Technical Information Service
5301 Shawnee Rd
Alexandria, VA 22312

Telephone: (800) 553-6847
Facsimile: (703) 605-6900
E-Mail: orders@ntis.gov
Online order: <https://classic.ntis.gov/help/order-methods/>



SAND2018-9593
Printed Month Year
Unlimited Release

Response Technical Tools User Manual

Nathan Andrews, Chun Fu and Alex Kaberlin
Nuclear Energy Safety Technologies
Sandia National Laboratories
P. O. Box 5800
Albuquerque, New Mexico 87185-MS0748

Abstract

Developed by the U.S. Nuclear Regulatory Commission for assessment of reactor accidents, Response Technical Manual (RTM) is a paper-based report which contains simple methods for estimating possible accident scenarios and relevant consequences for different kinds of radiological events. Based on RTM, a software called Response Technical Tools (RTT) was developed by Sandia National Laboratories to convert the paper manual into an automated and easy-to-use code.

In particular, the RTT focuses on the nuclear power plant severe accidents and is informed by state-of-the-art analyses and software programs, such as MELCOR and MAAP. RTT evaluations can be used to track and predict, at a very coarse level, the progression of a severe accident in nuclear power plant. The RTT allows a user to track the progress of an accident in a nuclear power plant from the point of initiation through the point of containment breach and release to the environment.

ACKNOWLEDGMENTS

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

This report and the corresponding software program was developed by Sandia National Laboratories for the United States Nuclear Regulatory Commission, under the purview of Rick Hasselberg and Michael Salay.

The software development team is thanked for their hard work in creating this program.

- John Fulton, Business Development
- Dustin Whitener, Lead Developer
- Wes Folz, Developer
- Linda Gallagher, Developer
- Alejandro Gonzales, Developer
- Natalia Harms, Developer
- Josh Herman, Developer

For technical support, please contact:

- Nathan Andrews, nandrew@sandia.gov, 505-845-8321

TABLE OF CONTENTS

1	RTT Overview	7
1.1	Purpose and Objective	7
1.2	General Features.....	7
1.3	Scope	7
2	Access and Installation	8
2.1	USNRC Mandated Non-Disclosure Agreement.....	8
2.2	Accessing and Downloading the Software	8
2.3	Installing the Software	9
3	Overview of a Reactor Core Damage Assessment	10
3.1	Step 1: Assess Critical Safety Systems	10
3.2	Step 2: Core Uncovery Determination	10
3.2.1	For PWR Assessments.....	10
3.2.2	For BWR Assessments.....	11
3.3	Step 3: Estimate Timing of Core Damage.....	11
3.4	Step 4: Assess Core Damage State	11
3.5	Step 5: Deflagration	12
3.6	Step 6: Continued Assessments and Monitoring.....	12
4	Reactor Incident Setup and Key Features.....	13
4.1	Setting up an Incident.....	13
4.1.1	Choose Plant and Incident Type	13
4.1.2	Reactor Incident Initial Conditions.....	14
4.1.3	Setting Shutdown Time.....	15
4.2	Key Features	15
4.2.1	Reactor Incident Menu Options.....	15
4.2.2	Reactor Core Damage Assessment Tabs	16
4.2.3	Plant State	17
4.2.4	Plant Information Tab.....	18
4.2.5	Tools Tab.....	18
4.2.6	Help Tab.....	19
4.2.7	Warnings	21
5	Reactor Incident Walkthrough.....	22
5.1	Step 1: Assess Critical Safety Systems	22
5.1.1	Plant Shutdown and Core Uncovery State.....	23
5.1.2	Water Injection in Primary and Secondary Systems.....	24
5.1.3	Decay Heat Removal.....	26
5.2	Step 2: Core Uncovery Determination	27
5.2.1	Sub-Cooling Margin and Hot/Cold Leg Delta T	27

5.2.2	User-Defined Core Uncovery	29
5.2.3	Reactor Vessel Water Levels	29
5.2.4	Steam Generator Water Levels	30
5.2.5	System Pressure	31
5.2.6	Source Range Monitors	32
5.3	Step 3: Estimate Timing of Core Damage	34
5.3.1	RTM Assumptions	34
5.3.2	Core Damage Estimation	36
5.4	Step 4: Assess Core Damage State	39
5.4.1	Containment Radiation	40
5.4.2	Containment Release	40
5.4.3	Coolant Concentration	41
5.4.4	Hydrogen Concentration	42
5.5	Step 5: Deflagration	43
5.6	Show All Steps	43
6	Spent Fuel Incident	44
6.1	Boil-Off Estimation	44
	References	46

1 RTT Overview

1.1 Purpose and Objective

Developed by the U.S. Nuclear Regulatory Commission for assessment of reactor accidents, Response Technical Manual (RTM) is a paper-based report which contains simple methods for estimating possible accident scenarios and relevant consequences for different kinds of radiological events. Based on RTM, a software called Response Technical Tools (RTT) was developed by Sandia National Laboratories to convert the paper manual into an automated and easy-to-use code. In particular, the RTT focuses on the nuclear power plant severe accidents and is informed by state-of-the-art analyses and software programs, such as MELCOR and MAAP. RTT evaluations can be used to track and predict, at a very coarse level, the progression of a severe accident in nuclear power plant. [1]

As RTT is undergoing further development, the current primary effort is to update old methods to incorporate modern research and add new predictive features. The latest released revision of RTT is version 1.3, released on 01/30/2017. This manual covers features that will be incorporated in RTT version 1.4, which is currently in its beta release.

1.2 General Features

The RTT allows a user to track the progress of an accident in a nuclear power plant from the point of initiation through the point of containment breach and release to the environment. It is to be used by reactor safety experts in order to provide an accurate and relevant assessment of the status of a nuclear power plant a consequence analysis team. The consequence analysis team, using a tool such as the Radiological Assessment System for Consequence Analysis (RASCAL).

Currently, the program has all operating reactors within the United States pre-programmed based on relevant design data. It is planned to eventually expand the library of reactors to other reactors around the world and distribute the program to international partners of the USNRC.

1.3 Scope

This document is intended to inform a user on the capabilities of the RTT software program, so that they may use it to perform an assessment of an accident at a nuclear power plant. This manual walks the user through each of the panels found within the RTT, and informs them of communications between panels and assessment steps.

This manual does not cover, in-depth, the physics behind the modeling decisions and assumptions presented. It is recommended that the user refer to the RTM for a discussion of the relevant physics. [1]

2 Access and Installation

2.1 USNRC Mandated Non-Disclosure Agreement

In order to obtain and use the RTT, a user must first obtain and sign a non-disclose agreement (NDA) with the USNRC. This NDA can be obtained from the USNRC Office of Research, Fuel and Source Term Code Development Branch.

Additionally, a user who requests the software from Sandia National Laboratories (SNL) may be asked to sign additional agreements specific to the Nuclear Incident Response Program (NIRP) website. [2]

Distribution of the RTT software to anyone who has not signed the required NDA(s) is prohibited.

2.2 Accessing and Downloading the Software

The RTT software program can be downloaded from SNL's NIRP website. This is the same website that is used to distribute Turbo FRMAC, SHARC, SAFIRE and several other response programs. In order to download the software, a user account must first be created. Upon creation a user is able to request to download the RTT software program.

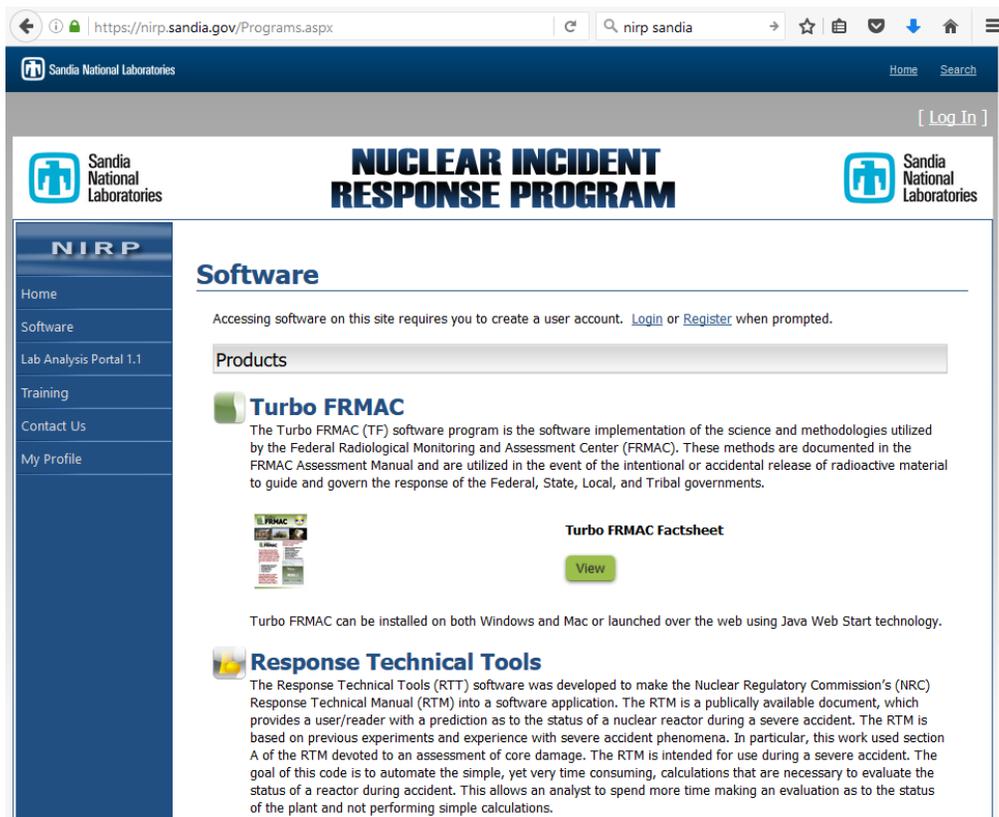


Figure 2-1 NIRP Website [2]

Upon approval to access the software, the user is able to download the program and install. This approval is required in order to access any Sandia-run website. Currently the RTT is able to run only on Windows-based computers. Depending on customer requirements, this is something that may change in the future.

NIRP Website: <https://nirp.sandia.gov/Default.aspx> (See Figure 2-1.) [2]

2.3 Installing the Software

Upon downloading the software installer, the user can open it and install the RTT. See Figure 2-2. When installing, the user must specify the installation directory and agree to a license agreement. The default installation location is within the “Program Files” folder. The installation pop-up for the RTT v1.4 can be seen in Figure 2-2.

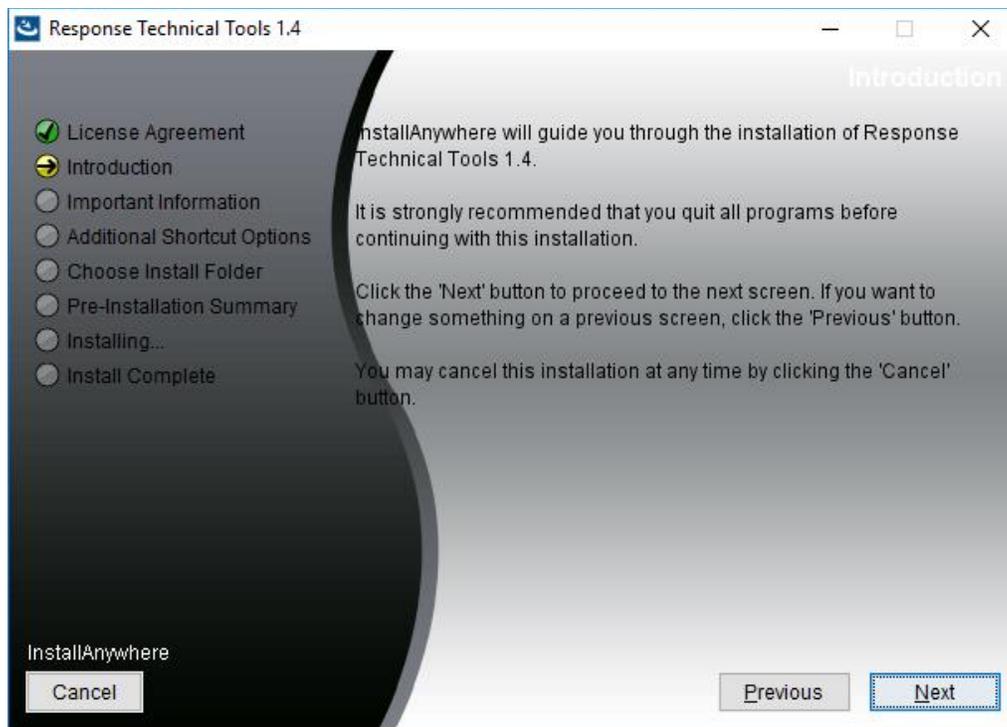


Figure 2-2 Choose Plant

3 Overview of a Reactor Core Damage Assessment

This chapter of the manual is heavily taken from the NRC's Response Technical Manual Section A, which cover a reactor core damage assessment. It is provided for the purpose of completeness and to introduce a user of the software to the assessment methodology used. The technical basis for this assessment methodology is found within NUREG-1228. The Response Technical Manual is the basis for this RTT software program. [1]

In assessing core conditions, do not lose sight of the big picture! Never use just one instrument as the basis for your assessment.

Core damage assessment is a continual process. The steps in this process are listed below in the approximate order that the needed information might be available. After completing any method in this section, the assessor must continue to monitor the core status for changes and must update core damage assessments for others performing related assessments.

3.1 Step 1: Assess Critical Safety Systems

Assess the current status of the critical safety functions by answering the following questions. These questions are key indicators for the long-term coolability of the reactor core. A negative response indicates that there is a higher likelihood for a core damage event and release is higher.

- Is the plant subcritical (shutdown)? How is this confirmed?
- Is the core covered now and will it be in the long term? How is this confirmed?
- Is the amount of water being injected into the primary or secondary system sufficient to remove the decay heat?
- Is decay heat being removed to the environment? How is this confirmed?

3.2 Step 2: Core Uncovery Determination

Monitor the following indications, which differ for BWRs and PWRs, for detecting imminent uncovering of the reactor core. Consider the reliability of the indications or instrument readings during accident conditions as discussed below.

If there are indications of imminent uncovering of the core, go to Step 3. If not, provide an assessment of critical safety functions and core status. Continue to monitor plant indicators.

3.2.1 For PWR Assessments

Core exit thermocouple (CET) readings and primary cooling system pressure can be used to evaluate whether the core will be uncovered. A loss of sub-cooling margin indicates that sufficient water injection is not being provided to keep the core covered. If the core is uncovered, the CET readings will continue to rise but will be considerably lower than the actual average and maximum core temperatures. CET readings are not accurate after core damage.

In-vessel water level indication system can also be used as an indicator of potential uncovering of the core. Decreasing water levels can confirm that there is insufficient water injection to keep the core covered. Water level indications should be used only to detect trends because of the considerable (up to 30%) uncertainties in the measurements during accident conditions. This system is not reliable after core damage.

3.2.2 For BWR Assessments

Water level can be used under some accident conditions to confirm that insufficient water is being injected to protect the core and to estimate the time at which the core will be uncovered. Consider the following limitations:

- The lower limit of the water measurement system is at or above the level at which core heat-up begins (20% uncovered).
- High drywell temperature (e.g., LOCA) can cause the BWR reactor water level to read erroneously high.
- During low pressure accidents, the BWR water level can read erroneously high.
- Mechanical Yarway instruments may indicate a false on-scale water level at about 1 ft above the top of core if the actual water level fell below the lower end of the instrument range.

3.3 Step 3: Estimate Timing of Core Damage

If core is projected to be uncovered or there are indications that this is imminent, use relevant methods to determine projected times for the following core damage states: (1) time to gap release from fuel, and (2) time to in-vessel core melt.

If actual or projected core damage is detected, the accident should be classified as a General Emergency and protective actions should be considered. Do not wait for core damage to be confirmed.

3.4 Step 4: Assess Core Damage State

Monitor the radiation levels to attempt initial confirmation of core damage. Detection of very large increases (orders of magnitude) in radiation levels by radiation monitors (e.g., containment) can confirm actual core damage. If the release is into the containment, assess the level of damage. Compare with core damage estimate from Step 3. The following possibilities should be considered:

- The release may bypass the monitor.
- Monitors may be influenced by a source not intended to be monitored.
- Areas monitored may not be representative of the entire containment.
- Calibration assumptions may not match accident conditions.
- Shielding or other design factors may have been incorrectly considered.
- Monitor may show high, low, or center range if it fails.
- Monitor may be read incorrectly.

If actual or projected core damage is detected, the accident should be classified as a General Emergency and protective actions should be considered.

3.5 Step 5: Deflagration

As part of any reactor assessment, it is often necessary to determine the flammability of the primary containment, secondary containment or reactor buildings. This stand-alone assessment is performed as required in order to support an analyst as they move through the previous four steps of the assessment.

3.6 Step 6: Continued Assessments and Monitoring

After the core is uncovered, continue to evaluate the amount of core damage using the available information. The following methods may be used:

- Evaluate core once uncovered
- Evaluate containment radiation
- Evaluate coolant concentrations
- Evaluate containment hydrogen

If actual or projected core damage is detected, the accident should be classified as a General Emergency and protective actions should be considered. Note that these methods for estimating core damage can be time-consuming and may be unreliable. Do not delay protective actions by waiting for confirmation of core damage.

4 Reactor Incident Setup and Key Features

Presented in this chapter is a description of how a user would setup a reactor incident in the RTT software. Subsequent to this chapter, a walkthrough of performing an assessment is provided. Key features of the RTT are then presented and described to the user.

4.1 Setting up an Incident

After installing the RTT, the user is taken to the initial screen where they are able to setup the program for the analysis of the accident currently being monitored.

4.1.1 Choose Plant and Incident Type

Upon entering the RTT application to start an incident, the analyst first chooses a plant from the pick list of the inventory of operating reactors in the US fleet shown in Figure 4-1.

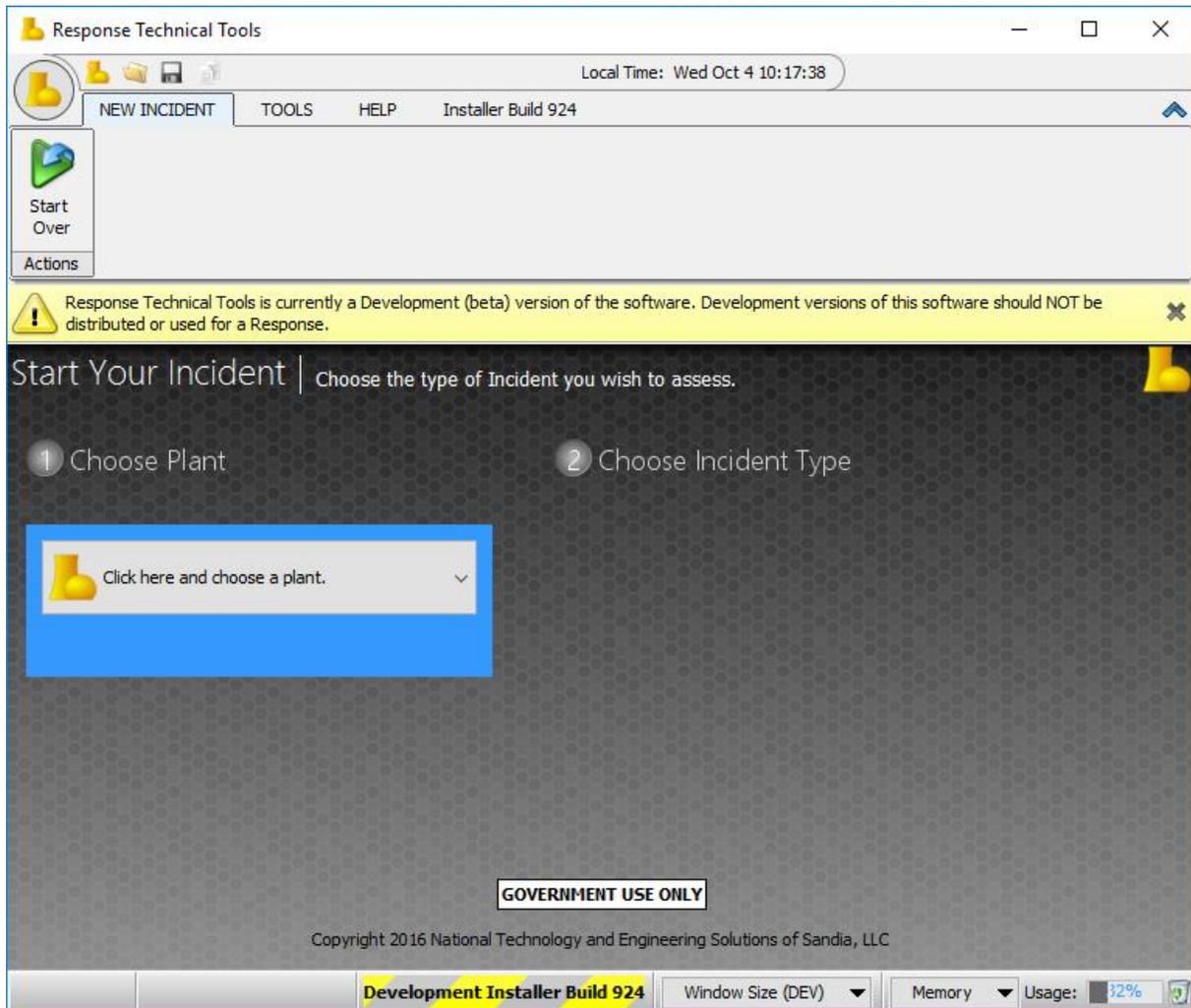


Figure 4-1 Choose Plant

After identifying the plant, the analyst will choose either a reactor incident or a spent fuel incident, as shown in Figure 4-2. This chapter and the next will further cover how to setup a reactor accident, while Chapter 6 will cover a spent fuel pool incident.

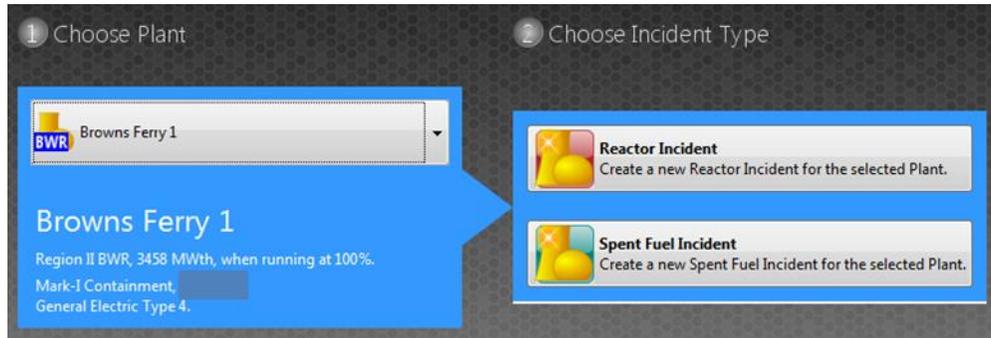


Figure 4-2 Incident Type

4.1.2 Reactor Incident Initial Conditions

After selecting Reactor Incident, an initial conditions form will appear prompting the analyst to input specific knowledge regarding the incident as shown in Figure 4-3. The analyst enters known information, which may be very little at this stage of the incident, and then clicks Start Reactor Assessment. The default initial conditions are available and the analyst may select Start Reactor Assessment at any time.

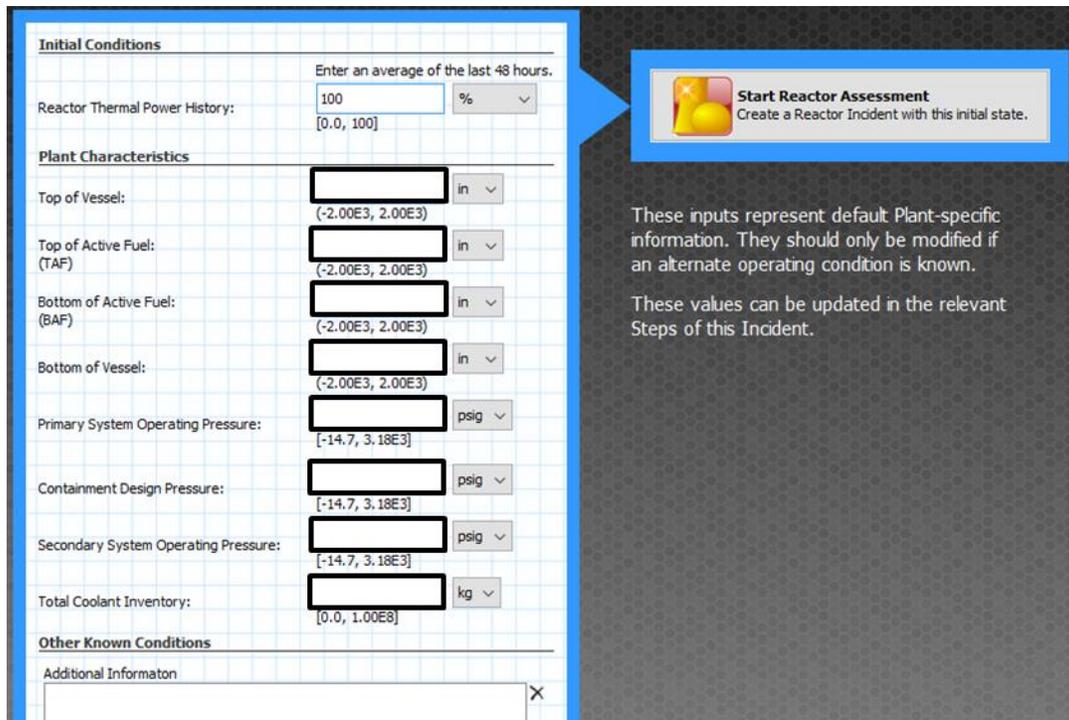


Figure 4-3 Default Parameters Screen

4.1.3 Setting Shutdown Time

As a first step in any incident, the analyst must input a shutdown time for the reactor incident. This is done by clicking on the Set Shutdown Time tab. A small window will pop up, as shown in Figure 4-4 allowing the analyst to enter the date and time of the plant shutdown. The analyst can also change the time zones if desired. When the plant shutdown time is saved, time since shutdown is calculated by the code, instead of being a user input. Also the “Refresh” button for calculating plant state since shutdown is enabled (shown below many panels), for example, in “Water Injection” calculation.

Note: It is important that analysts in the Operations Centers use the same plant shutdown time.

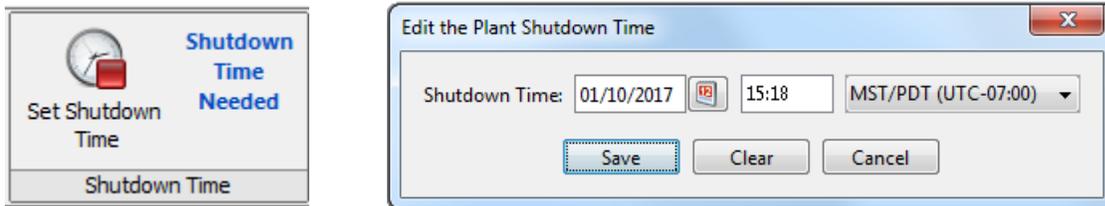


Figure 4-4 Shutdown Time Tab and Edit the Plant Shutdown Time Pop-up

4.2 Key Features

This section covers several of the key features of the RTT software. Of particular note are the “Tools Tab,” the “Help Tab” and the ability to submit a bug to the development team at SNL and the USNRC.

4.2.1 Reactor Incident Menu Options

Upon selecting “Start Reactor Assessment” the analyst enters the analysis portion of the tool. The RTT main ribbon as shown in Figure 4-5 is along the top of the screen (under the “Home Tab”) and functions like a toolbar. Data from the “Initial Knowledge State” screen will populate within the tool, and can be changed at any time as updated information is received.



Figure 4-5 Menu Options Ribbon

A few administrative features may be found under the gold reactor icon in the top left-hand side of the screen as shown in Figure 4-6.

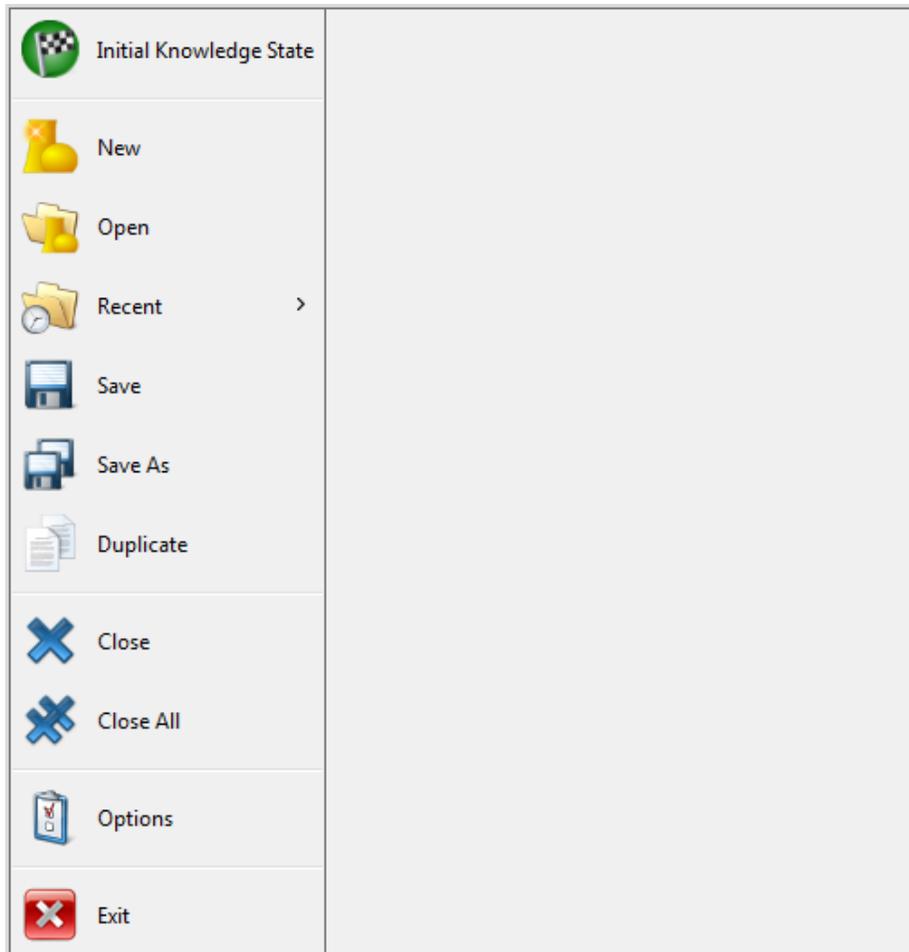


Figure 3-6 RTT Menu

Under this icon, the analyst may open a new incident, review the “Initial Knowledge State” information, open a previous project or save a current project, or close the incident, which saves the RTT file (*.rttx) to a designated location. There are also some icons on the quick access toolbar at the top left-hand side of the screen. Multiple cases can be created for different plants and different incidents. Use Switch Incidents in the menu options shown in Figure 4-5 to switch to a different currently open incident. Under the RTT menu, the user has the ability to fully duplicate the current incident. This allows the user to perform “what if” analysis of the current scenario.

4.2.2 Reactor Core Damage Assessment Tabs

RTT uses the reactor core damage assessment to evaluate the condition of a light water core reactor for use in classifying an accident, projecting possible consequences, and informing the Protective Measures Team (PMT). The assessment tabs as shown in Figure 4-7 are the major navigation options. Steps 1 through 5 are available to the analyst in any order. In other words, the analyst does not have to start assessment from step 1, although information from an earlier step is often needed for a subsequent step. An option exists for the analyst to show all of the steps, allowing the analyst to scroll and access all the steps in the program.

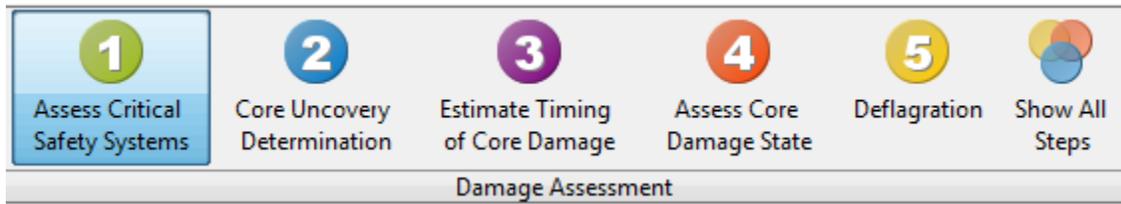


Figure 4-7 Reactor Core Damage Assessment Tabs

4.2.3 Plant State

On the bottom left corner of the screen there is a scroll down menu that shows the plant state since shutdown as shown in Figure 4-8. It covers main items for the reactor incident, providing the analyst with a different option of navigation. The analyst can click on the item and the program will take the analyst there. The icon to the left of the category will also show the warning in the assessment. The plant state will be different between a BWR and PWR. A PWR contains an extra step which is the core boiling as shown in Figure 4-8.

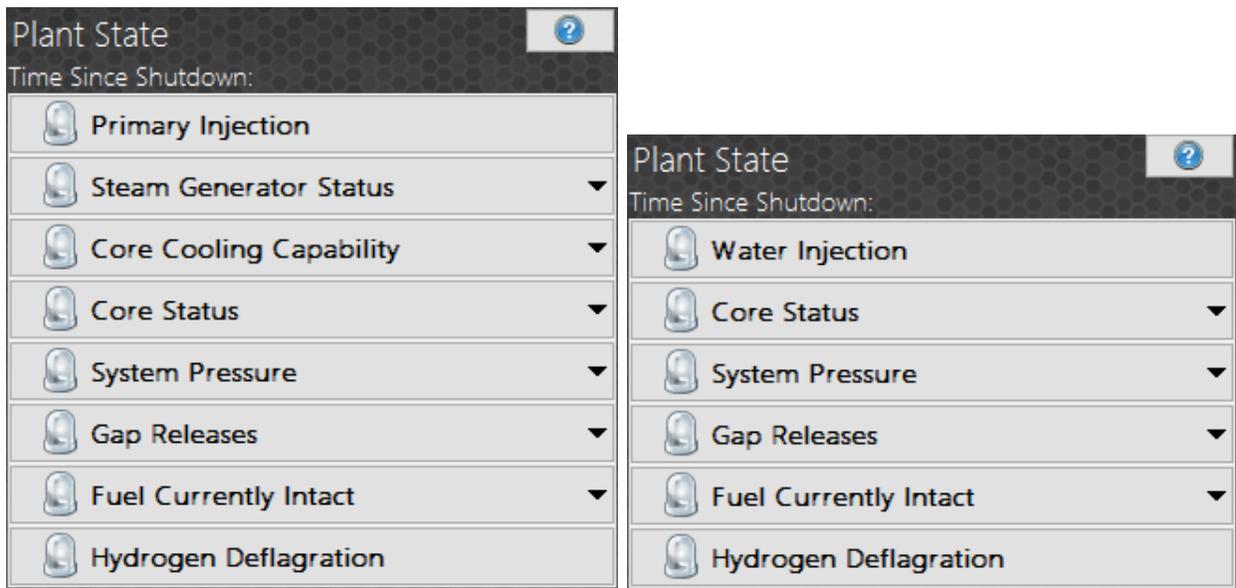


Figure 4-8 Plant State Menu for a PWR (Left) and a PWR (Right)

If the icon is red then it means that the item needs to be fixed. If the icon is yellow then it means that there might be an error in the data in that particular area. If the icon is green then it means that the program has accepted the data. The reactor icons for each of the plant state items are grey prior to the analysis. These warning indications are described in Figure 4-9, along with a blown-up BWR PWR plant state menu.

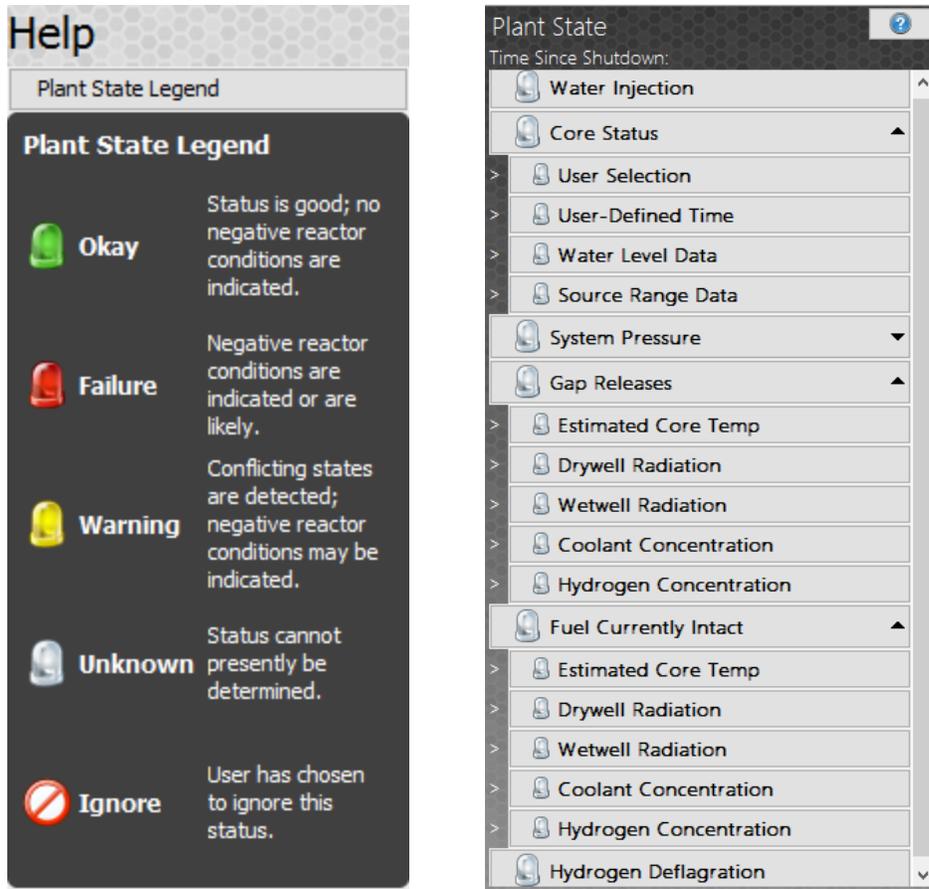


Figure 4-9 Plant State Legend (Left) and Expanded Plant State for a BWR (Right)

4.2.4 Plant Information Tab

The Plant Information Tab on the main ribbon provides basic information on the selected plant as shown in Figure 4-10. Included is the thermal power, containment type, plant type and containment volume.

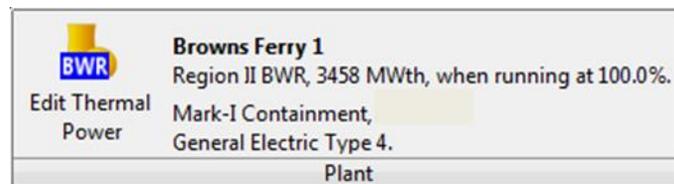


Figure 4-10 Plant Information

4.2.5 Tools Tab

A unit converter and screen capture capability are provided in the tools tab, as shown in Figure 4-11. The analyst can also view settings from this location. Here the analyst can perform backups for their program, change their database settings, display settings, and warning settings.



Figure 4-11 TOOLS Tab

Administrative options are available for the analyst to perform backups, change their database settings, message view, and the refresh rate as shown in Figure 4-12.

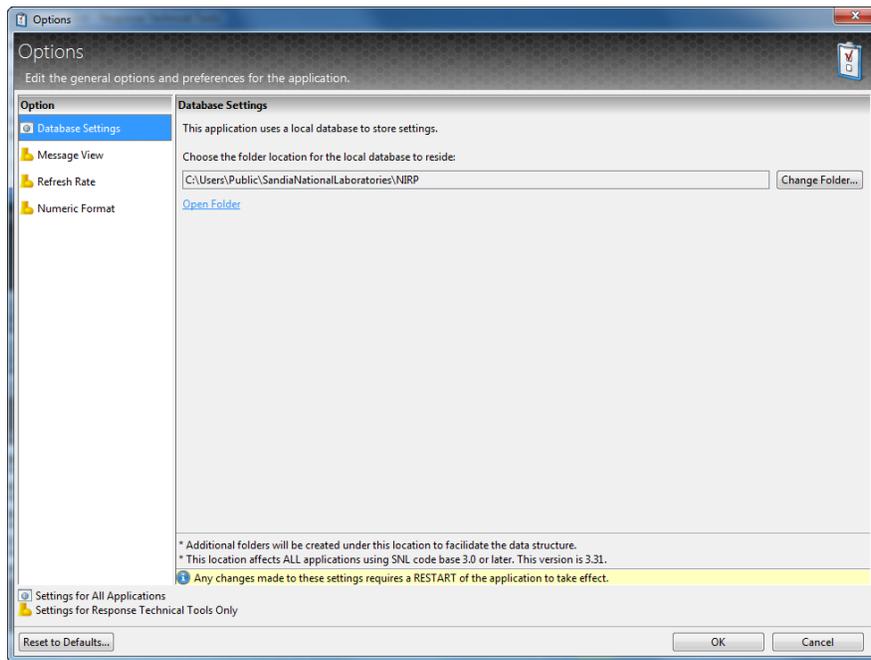


Figure 4-12 Administrative Options

4.2.6 Help Tab

Under the help tab, the analyst may see the “about” page of the software, review the response technical manual, and contact software developers for feedback as shown in Figure 4-13.

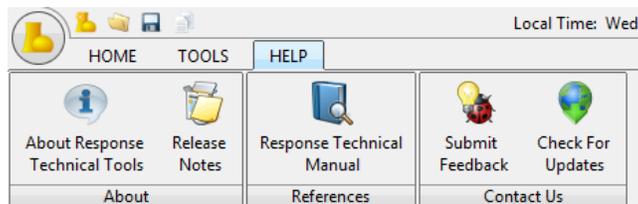


Figure 4-13 HELP Tab

In addition to the “Help Tab,” the analyst may click on the “Help” button located at the top right corner of each analysis method and information appears explaining the step as shown in Figure 4-14.

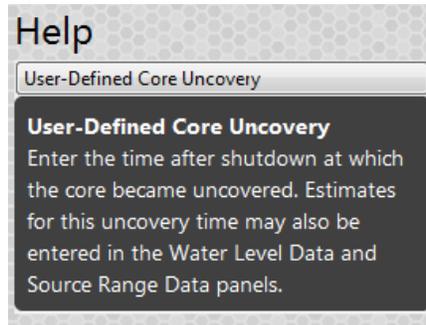


Figure 4-14 Individual Help Option

The “Submit Feedback,” in Figure 5-15, button allows the user to submit feedback to the developers at SNL. The user is able to send it via email with a screen shot included.

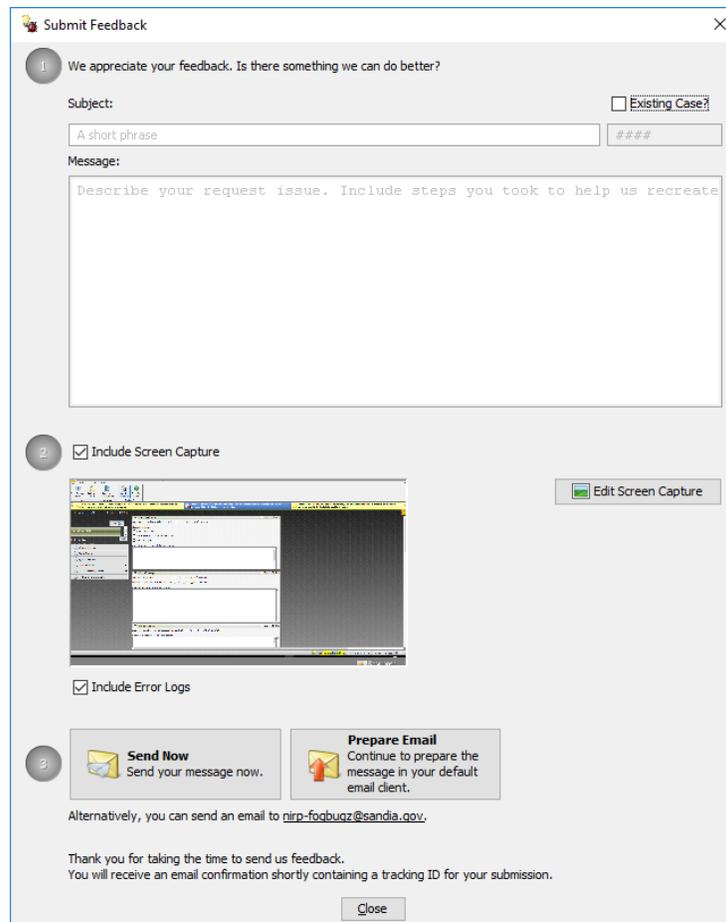
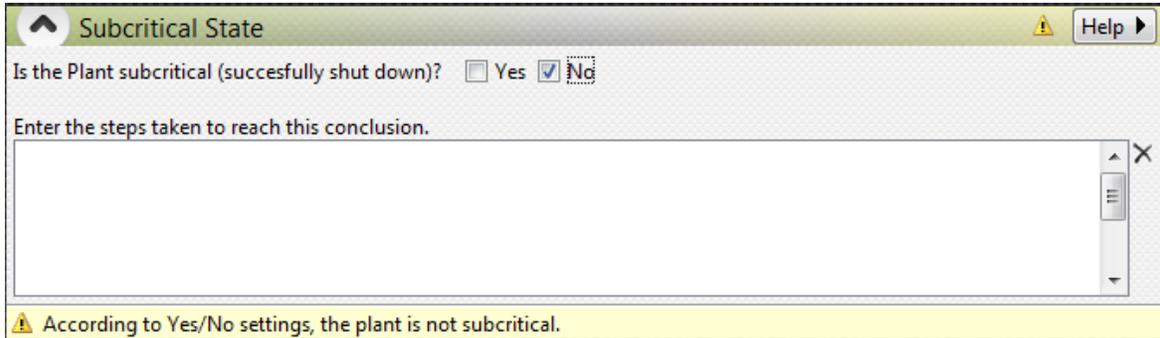


Figure 4-15 Individual Help Option

4.2.7 Warnings

Warnings are located throughout RTT to alert the analyst of important anomalies. The warnings appear at the bottom of the assessment form as shown in Figure 4-16 and on the method steps on the left hand side of the screen as shown in Figure 4-17.



The screenshot shows a form titled "Subcritical State" with a "Help" button in the top right corner. The main question is "Is the Plant subcritical (successfully shut down)?" with radio buttons for "Yes" and "No". The "No" button is selected. Below the question is a text area labeled "Enter the steps taken to reach this conclusion." At the bottom of the form, a yellow banner displays a warning icon and the text: "According to Yes/No settings, the plant is not subcritical."

Figure 4-16 Warning in the Assessment Form



Figure 4-17 Warnings on the Scroll Down Menu

Warnings may be viewed at the top of the reactor incident as shown in Figure 4-18. This is where the analyst can see how many warnings there are in the assessment and if there are any errors. The analyst clicks on "view warnings" to see specific warning messages and the associated steps in which those warnings appear.



Figure 4-18 View Warnings Banner

5 Reactor Incident Walkthrough

Presented in this chapter is a walkthrough of how a user would proceed through the RTT to make an actual assessment during an accident scenario. This walkthrough is not to be seen as a substitute for training by severe accident and operations experts on how to use the information within the code to make an assessment.

5.1 Step 1: Assess Critical Safety Systems

Step 1 includes four parts shown in Figure 5-1 used for the analyst to input data related to critical safety systems. The analyst may select the desired part on the left side of the screen, or may scroll down the screen where the parts are available in sequential order. As the analyst inputs data throughout the RTT assessment, a continuous Plant State is provided.

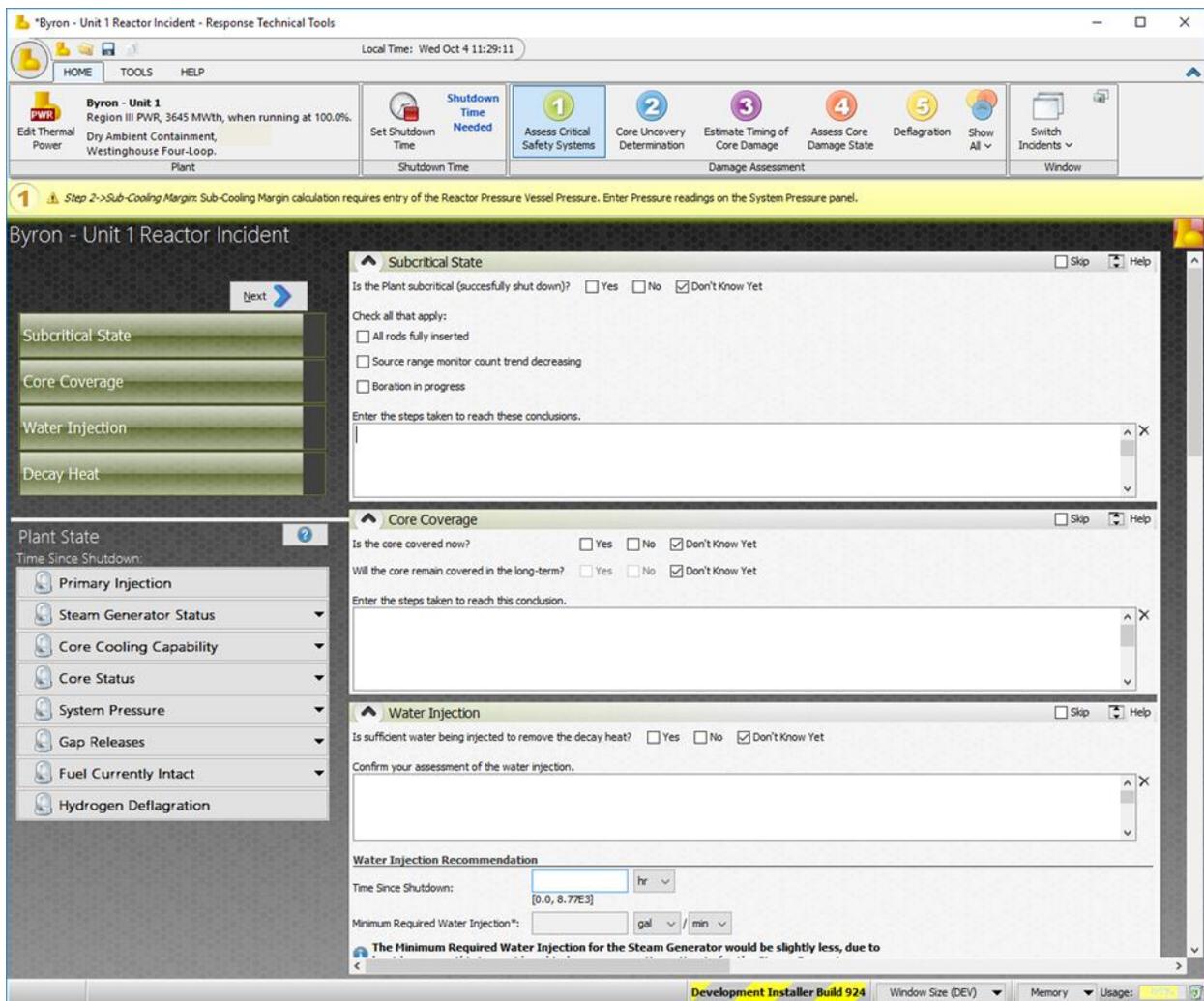


Figure 5-1 Step One Elements and Plant State

In Step 1, the analyst assesses the current status of the critical safety functions by answering designated questions identified in the forms in this step. If any of the critical safety functions are not being met or are degraded, the core may not be coolable. If this is the case, the analyst then moves on to Steps 2 and 3. Even if the assessments in Step 1 indicate that the core may be adequately cooled through injection, an analyst should still perform the analyses in Step 2 in order to verify conclusions reached in Step 1.

5.1.1 Plant Shutdown and Core Uncovery State

The analyst identifies the status of plant shutdown and describes the steps taken to justify this decision. Similarly, the analyst identifies the state of core coverage and describes the steps taken to justify this decision. The analyst may add justification as shown in Figures 5-2 and 5-3.

Subcritical State Skip Help

Is the Plant subcritical (succesfully shut down)? Yes No Don't Know Yet

Check all that apply:

- All rods fully inserted
- Source range monitor count trend decreasing
- Boration in progress

Enter the steps taken to reach these conclusions.

Figure 5-2 Subcritical State Panel

Core Coverage Skip Help

Is the core covered now? Yes No Don't Know Yet

Will the core remain covered in the long-term? Yes No Don't Know Yet

Enter the steps taken to reach this conclusion.

Figure 5-3 Core Coverage Panel

5.1.2 Water Injection in Primary and Secondary Systems

Next, the analyst determines if the amount of water being injected into the primary and secondary systems is sufficient to remove decay heat. The analyst identifies if sufficient water is being injected and describes the steps taken to justify this decision as shown in Figure 5-4. The analyst then inputs data for the required water injection. The analyst will enter the time since shutdown. When a time is entered, RTT will calculate the minimum required water injection. The calculation is based on the equation:

$$inject_{plant} = inject_{3000} \times \frac{MW(t)_{plant}}{3000} \quad (1)$$

Where:

$inject_{3000}$ = amount of injected water for 3000 MWth plant

$MW(t)_{plant}$ = plant specific power from RTT database in MW(t) [$MW(t) \approx 3 \times MW(e)$]

$inject_{plant}$ = amount of injected water needed for this plant

The analyst then enters the actual water injection and any leakage. Following this, the RTT will determine if enough water is being injected to remove all decay heat.

Water Injection Skip Help

Is sufficient water being injected to remove the decay heat? Yes No Don't Know Yet

Confirm your assessment of the water injection.

Water Injection Recommendation

Time Since Shutdown: hr [0.0, 8.77E3]

Minimum Required Water Injection*: gal / min

i The Minimum Required Water Injection for the Steam Generator would be slightly less, due to heat losses; so this is considered to be a conservative estimate for the Steam Generator.

Primary Injection (Vessel)

Actual Water Injection: gal / min [0.0, 1.00E6]

Known Leak Rate: gal / min [0.0, 1.00E6]

Effective Water Injection: gal / min (Actual Injection - Known Leak Rate)

Secondary Injection (Steam Generator)

Actual Water Injection: gal / min [0.0, 1.00E6]

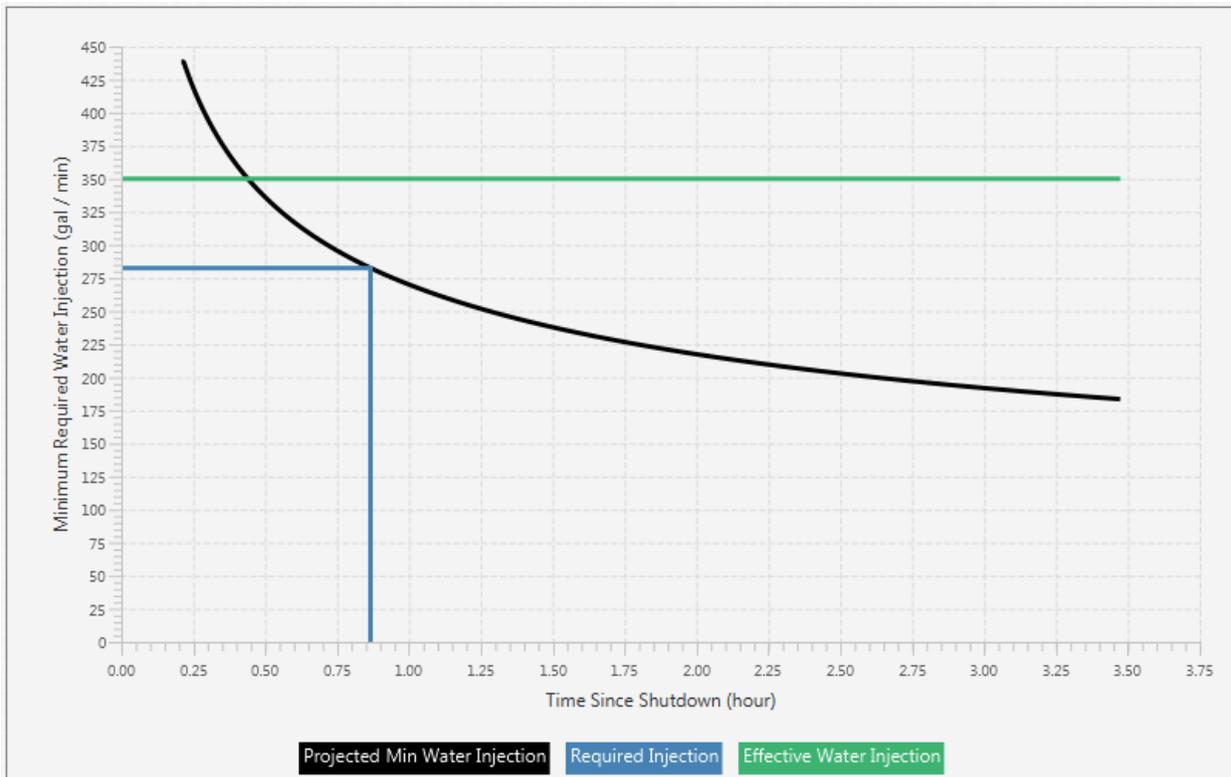
Known Leak Rate: gal / min [0.0, 1.00E6]

Effective Water Injection: gal / min (Actual Injection - Known Leak Rate)

Figure 5-4 Water Injection Panel, Input Data

The actual water injection is plotted as shown in Figure 5-5. The black curve shows the projected minimum water injection and the blue lines represent the minimum required water injection at the current time since shutdown. If the actual exceeds the minimum, a green line representing the actual injection will be plotted above the Projected Minimum Water Injection line. If the actual is less than the minimum, the line will appear in red, indicating that insufficient water is being injected.

If plant shutdown time has been input by the user, then the time since shutdown is calculated by the code. Use Refresh button to update the water injection graph for results at the current time since shutdown.



*Recommendation is based on this 3458 MWth plant, recently running at 100.0%.
 If the core has been uncovered for 15-30 minutes or longer,
 increase the Minimum Required Water by a factor of 2 to 3.



Figure 5-5 Water Injection Panel, Results Graph

5.1.3 Decay Heat Removal

Next, the analyst identifies whether decay heat is being removed to the environment and describes the steps taken to justify how this has been confirmed (see Figure 5-6).

Decay Heat Skip Help

Is the decay heat being removed to the environment? Yes No Don't Know Yet

Check all ways that decay heat is being removed:

Pressurizer relief valve / safety valve

Steam Generator relief valve / safety valve

Condenser

Enter the steps taken to reach these conclusions.

Figure 5-6 Decay Heat Panel

5.2 Step 2: Core Uncovery Determination

In Step 2, the analyst monitors indications for detecting imminent uncovering of the reactor core. This section provides a description of the core uncovery assessments that are performed within the RTT framework. These assessments are addressed more in-depth in the relevant sub-sections. Many of these assessments require the user to interpret reading from instruments. A screen shot of the appearance of Step 2 to the user can be seen in Figure 5-7.

Note: The analyst should consider the reliability of the indications or instrument readings during accident conditions.

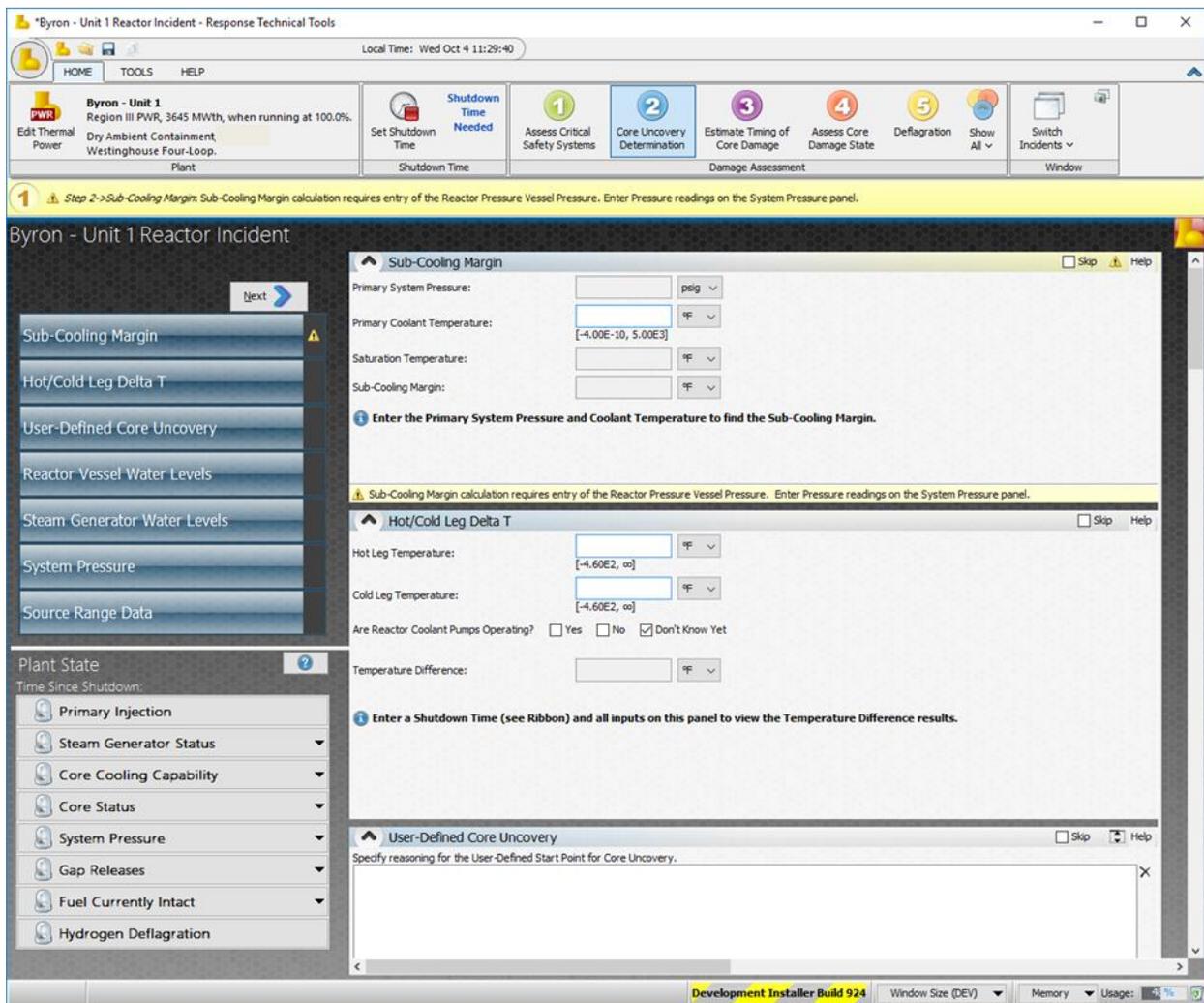


Figure 5-7 Step Two Elements and Plant State

5.2.1 Sub-Cooling Margin and Hot/Cold Leg Delta T

For a PWR, complete the required fields for the sub-cooling margin (see Figure 5-8). Enter the primary system pressure and saturation coolant temperature, and RTT will calculate the saturation temperature and sub-cooling margin. These field will not populate for a BWR since

the instrumentation is different. Core exit thermocouple (CET) readings, inlet temperature readings and primary cooling system pressure can be used to evaluate whether the core will be uncovered. Two separate assessments can be performed with this information, the first is to evaluate the sub-cooling margin and the second is to predict uncovering based on the change in water temperature from core inlet to outlet.

Note: CET readings are not accurate after core damage.

A loss of sub-cooling margin indicates that sufficient water injection is not being provided to keep the core covered. If the core is uncovered, the CET readings will continue to rise but will be considerably lower than the actual average and maximum core temperatures.

This calculation is based on the equation:

$$\text{sub cooling margin} = \text{temp}_{\text{sat}} - \text{temp}_{\text{PWR}} \quad (2)$$

The hot and cold leg temperature difference is an indicator to the user the effectiveness of coolant flowing through the core in removing decay heat. It provides the user warning if the total amount of heat removed from the core is too high (indicating insufficient cooling and injection rate) or if the injection rate is too low (indicating an error in the system). Options are provided to the user as to whether or not circulation pumps in the primary system are operating.

Note: It is important to remember that a negative sub-cooling margin in a PWR indicates that water is boiling in the reactor vessel and that the core may be uncovered.

The image shows two software panels. The top panel, titled "Sub-Cooling Margin", has a "Skip" button and a "Help" link. It contains four input fields: "Primary System Pressure" (range [0.0, 1.00E4], unit "psia"), "Primary Coolant Temperature" (range [-4.00E-10, 5.00E3], unit "°F"), "Saturation Temperature" (unit "°F"), and "Sub-Cooling Margin" (unit "°F"). Below the fields is an information icon and the text: "Enter the Primary System Pressure and Coolant Temperature to find the Sub-Cooling Margin." The bottom panel, titled "Hot/Cold Leg Delta T", also has a "Skip" button and a "Help" link. It contains four input fields: "Hot Leg Temperature" (range [-4.60E2, ∞], unit "°F"), "Cold Leg Temperature" (range [-4.60E2, ∞], unit "°F"), "Are Reactor Coolant Pumps Operating?" (radio buttons for "Yes", "No", and "Don't Know Yet", with "Don't Know Yet" selected), and "Temperature Difference" (unit "°F"). Below the fields is an information icon and the text: "Enter a Shutdown Time (see Ribbon) and all inputs on this panel to view the Temperature Difference results."

Figure 5-8 Sub-cooling Margin and Hot/Cold Leg Delta T Panels

5.2.2 User-Defined Core Uncovery

If sufficient information has been provided to the user, then it may be possible for the analyst to estimate the time since shutdown of projected core uncovery. Upon doing this, sufficient justification is required (see Figure 5-9).

User-Defined Core Uncovery Skip Help

Specify reasoning for the User-Defined Start Point for Core Uncovery.

User-Defined Start Point for Core Uncovery: hr Since Shutdown
[0.0, 8.77E3]

User-Defined Start Point for Core Recovery: hr Since Shutdown
[0.0, 8.77E3]

Figure 5-9 User-defined Core Uncovery Panel

5.2.3 Reactor Vessel Water Levels

Next, evaluate the water level starting with the input of the bottom of active fuel (BAF) and the top of active fuel (TAF).

Note: The in-vessel water level indication system is not reliable after core damage.

The in-vessel water level indication system can also be used as an indicator of the potential uncovery of the core. Decreasing water levels can confirm that there is insufficient water injection to keep the core covered. Water level indications should be used only to detect trends because of the considerable (up to 30%) uncertainty in the measurements during accident conditions.

The analyst inputs time since shutdown and water level readings to track the progression of water level (see Figure 5-10). The number of entries is unlimited and the plot adjusts the scale accordingly. The red lines in the graph represent BAF and TAF levels input by the analyst. All water level readings recorded in the table should be relative to the bottom of the RPV. The panel provides both a plot of the water level and a graphic of the current water level relative to BAF and TAF.

Determine, based on water level readings, whether there are indications that core uncovery is imminent and describe the reasoning for this assessment. Lastly, input the estimated time of core uncovery and the estimated time of core recovery, if applicable. An estimation of uncovery timing can be provided by the RTT if two or more data points are inputted into the tool.

NOTE: A severely damaged core may not be in a coolable state, even if it is re-covered with water. Core temperature (core exit thermocouple) and primary system water temperature (delta T) indications cannot confirm a coolable core.

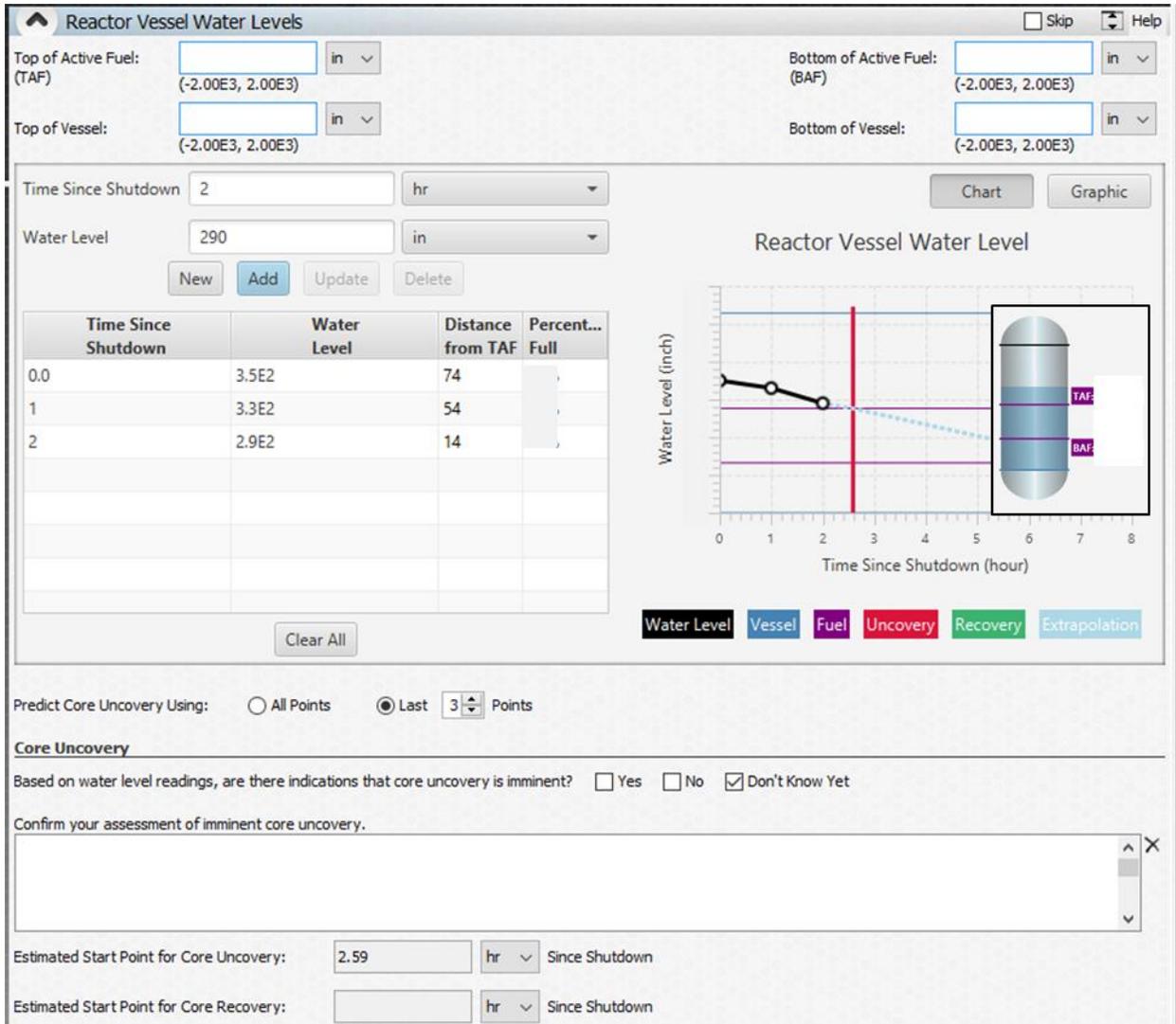


Figure 5-10 Reactor Vessel Water Levels Panel

5.2.4 Steam Generator Water Levels

A user is also prompted to enter the water level of the steam generators for PWRs. Separate tables are provided for each of the steam generators in the plant. These are listed in the top left of the water level table. Similar to the reactor pressure vessel water level tool, an estimation of the time at which the steam generator will dry out is provided based on a linear interpolation (see Figure 5-11).

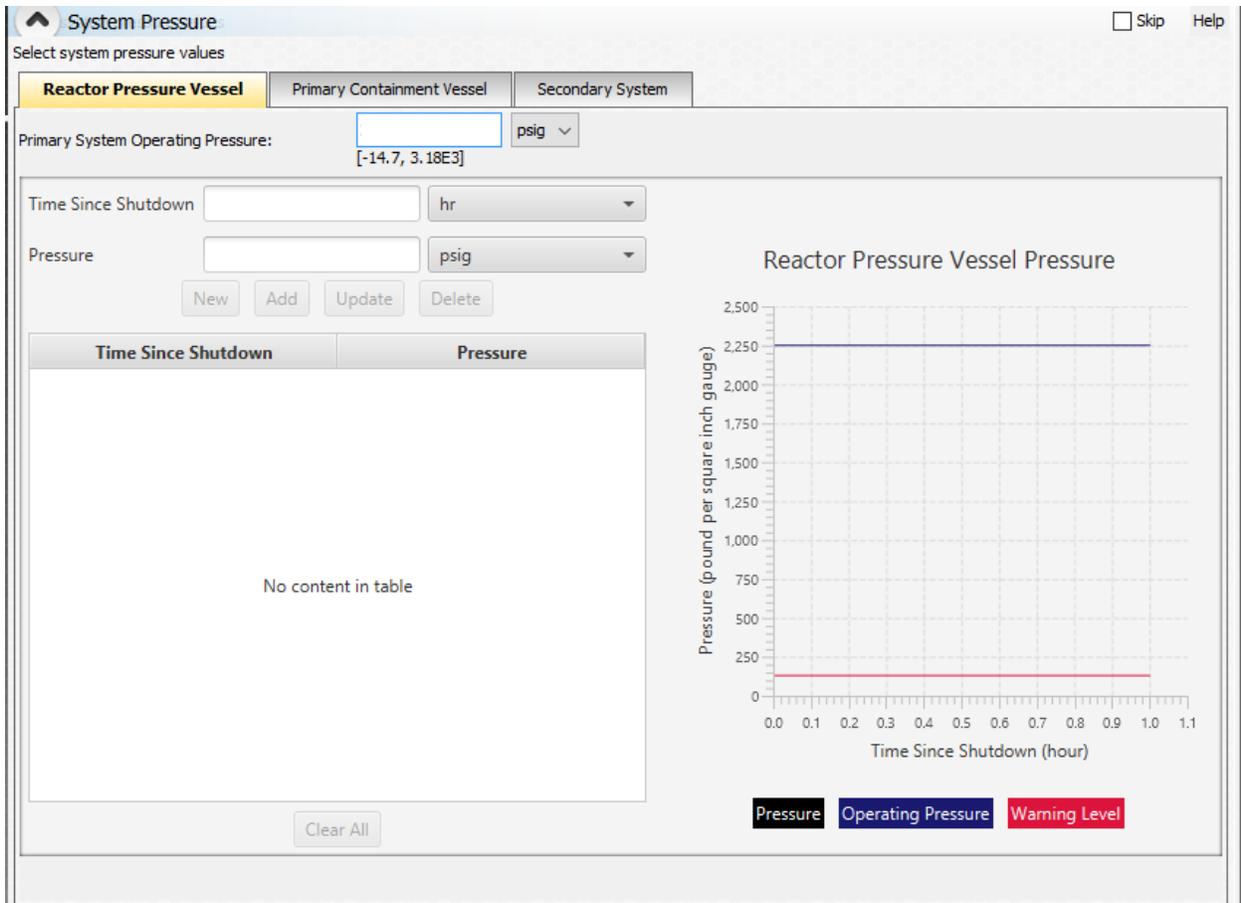


Figure 5-12 System Pressure Panel

5.2.6 Source Range Monitors

RTT uses the evaluation of source range counts to determine if and when the core has been uncovered. Source range instruments provide a measurement of the neutron flux in and around the reactor core when the reactor is shut down. The analyst inputs time since shutdown and counts per second (see Figure 5-13).

Note: BWR source range monitors are located within the core region and will detect *fewer* neutrons when voiding occurs. A fully voided core may indicate as much as two orders of magnitude *less* than would otherwise be expected.

Note: PWR source range monitors are located outside the core region and will detect *more* neutrons when voiding occurs. A fully voided core may indicate as much as two orders of magnitude *higher* than would otherwise be expected.

The graph shows the data input as a black line. The green line represents the BWR/PWR 100% voided. The light blue line represents Homogeneous voiding and the dark blue line represents the normal trend. The analyst may turn the voiding comparison lines off by clicking on the appropriate button. Having reviewed and interpreted the Source Range Data plot, input the

estimated time of core uncovering and core recovery, if applicable. The trends for 100% voided and homogeneous voiding differ for BWRs and PWRs as shown in Figure 5-14.

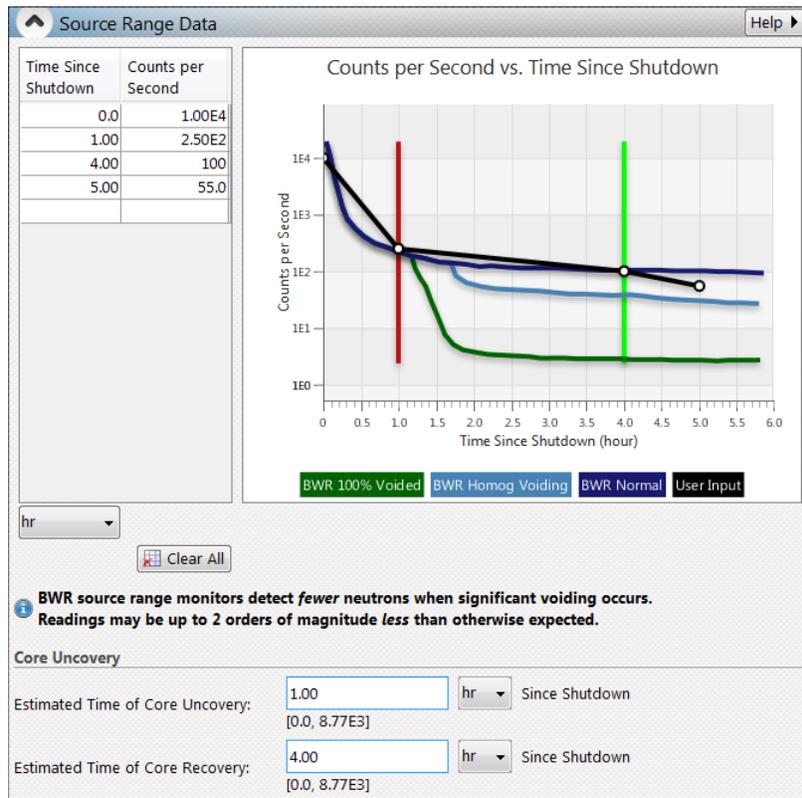


Figure 5-13 Source Range Data

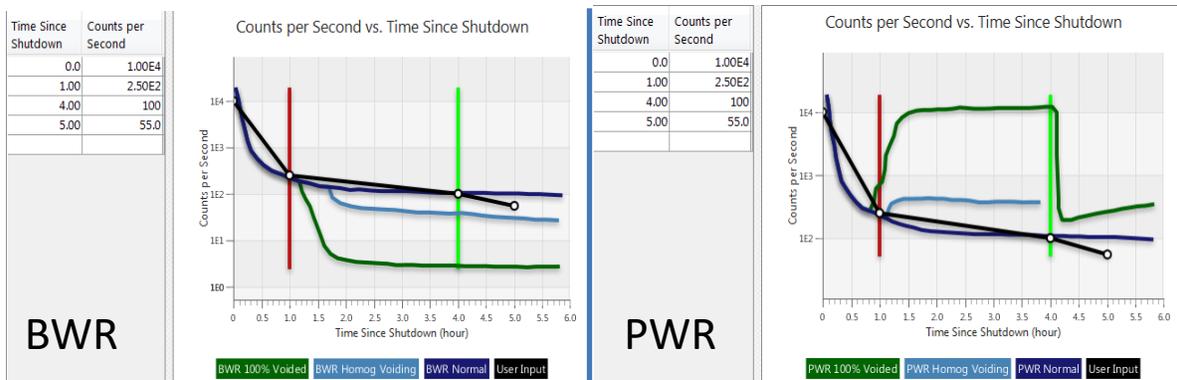


Figure 5-14 Source Range Data Graph Comparison

At this point, if there are indications of imminent uncovering of the core, the analyst should proceed to Step 3. If not, provide an assessment of critical safety functions and core status to those assessing the emergency classification, assessing early phase protective actions, or projecting consequences. Continue to monitor plant indicators in Steps 1 and 2.

5.3 Step 3: Estimate Timing of Core Damage

Step three allows the analyst to estimate core temperature and damage progression once the core is uncovered. The initial “Step 3” screen, before anything is inputted, can be seen in Figure 5-14. Core damage estimations are based on three separate assumptions for uncover and recovery timings. The first is a “user-defined” value. The second is based on water level entries. The third is based on source range estimations. The scientific assumptions in the RTT are covered briefly here and are primarily based on the RTM.

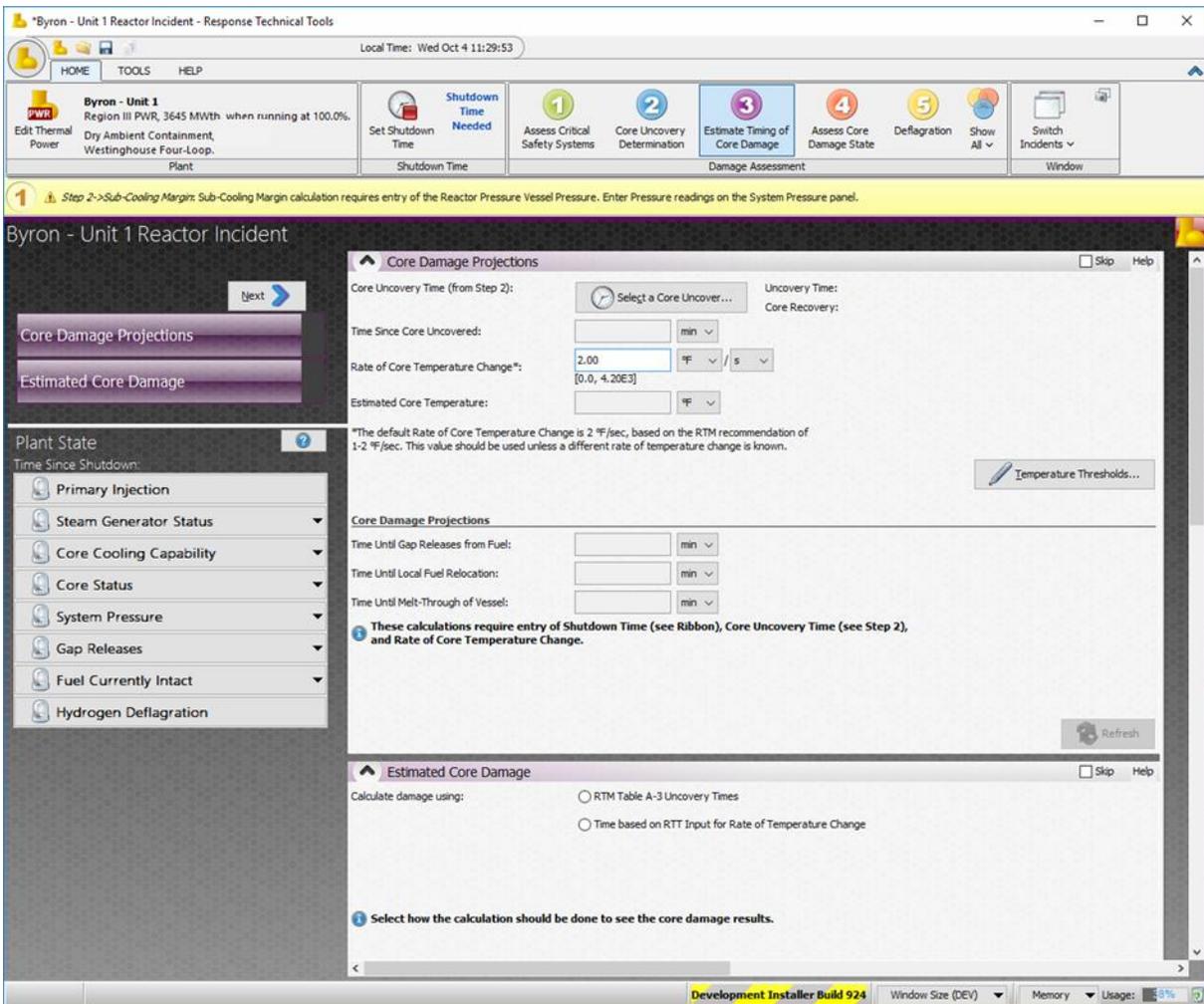


Figure 5-14 Step Three Elements and Plant State

5.3.1 RTM Assumptions

The RTT takes its main assumptions from the RTM. The core damage thresholds used in the RTM are shown in Figure 5-15. The RTT assumes that the lowest number in the core damage range is the point at which fuel relocation begins to occur. It also assumes that fuel damage has fully ended by the time the core temperature reaches maximum in the range. So core damage linearly increases as the core temperature increases from 2400 to 4200 F. The RTM recommends assuming that fuel temperature increases from 1 to 2 F. [1] The lower end of this

range corresponds to a boil-off in which there is water in the core during the fuel damage event. The higher end corresponds to less, almost no water. Fuel heatup in PWR is assumed to occur when the TAF is reached. Fuel damage in a BWR is assumed to begin after water level has reached 80% of TAF; this is a conservative assumption, and MELCOR analysis performed in the SOARCA analysis indicate that this occurs closer to 66% TAF. Core damage thresholds can be changed by the analyst in the “Core Damage Temperature Thresholds” pop-up.

Time PWR or 20% of BWR active core is uncovered (h)	Core temperature		Possible core damage
	(°F)	(°C)	
0	>600	>315	<ul style="list-style-type: none"> None
0.5 to 0.75	1800–2400	980–1300	<ul style="list-style-type: none"> Local fuel melting Burning of cladding with steam production (exothermic Zr-H₂O reaction with rapid H₂ generation) Rapid fuel cladding failure (gap release from the core^a)
0.5 to 1.5	2400–4200	1300–2300	<ul style="list-style-type: none"> Rapid release of volatile fission products (in-vessel severe core damage release from core^a) Possible relocation (slump) of molten core Possible uncoolable core
1 to 3+	>4200	>2300	<ul style="list-style-type: none"> Melt-through of vessel with possible containment failure and release of additional less-volatile fission products

Figure 5-15 Core Damage Thresholds, Taken from Table A-3 of the RTM [1]

Core Damage Temperature Thresholds

Core Damage Temperature Thresholds

Set the temperature threshold values to be used for Core Damage Projections.

Reset to Defaults

Initial Core Temperature: 6.00E2 °F [-4.60E2, 8.31E3]

Gap Release Threshold: 1.80E3 °F [-4.60E2, 8.31E3]

Fuel Relocation Threshold: 2.40E3 °F [-4.60E2, 8.31E3]

Melt-Through Threshold: 4.20E3 °F [-4.60E2, 8.31E3]

Thresholds are listed in order of increasing severity. Values must also increase, from a low of Initial Core Temperature to a high of Melt-Through Threshold.

Figure 5-16 Default Core Damage Thresholds within the RTT

5.3.2 Core Damage Estimation

The first action a user must take in the third step is to select a core uncover timing (see Figure 5-17 and Figure 5-18) There are three separate options a user can select. These three options are from the analyses performed in Step 2.

- User-Defined Input
- Water Level Estimate
- Source Range Estimate

RTT then automatically populates the data from the selected option and begins projecting the current amount of core damage. This damage amount is based on time since shutdown. The temperature thresholds for damage and the rate of core temperature change can both be edited on this first panel.

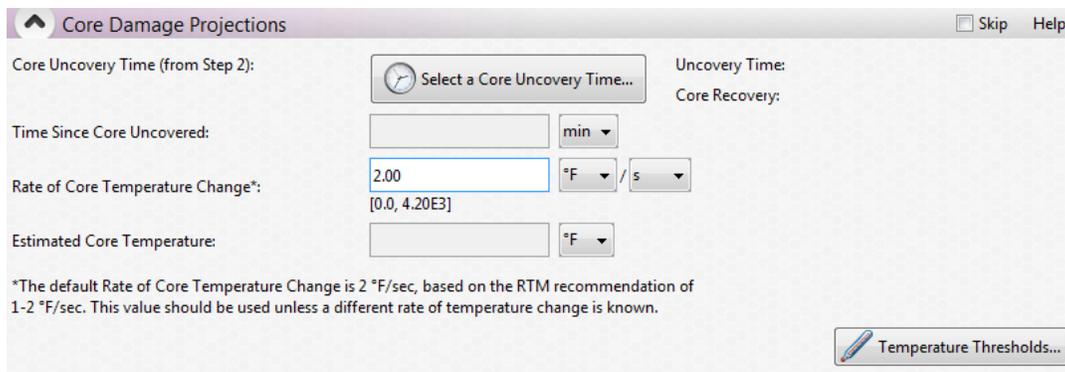


Figure 5-17 Core Damage Projections Panel, Input Portion

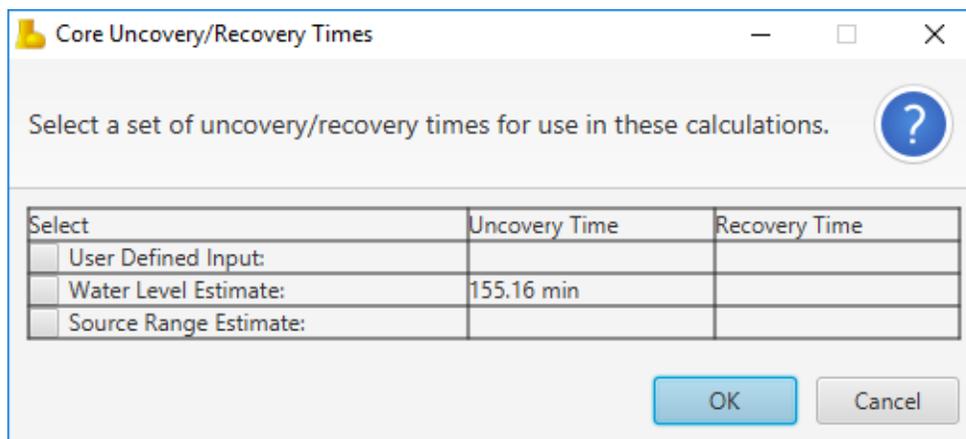


Figure 5-18 Core Uncovery/Recovery Times Pop-up Panel

RTT then populates the timing of gap release, fuel relocation, and melt through of vessel, as shown in Figure 5-19.

Core Damage Projections

Time Until Gap Releases from Fuel: min ▾

Time Until Local Fuel Relocation: min ▾

Time Until Melt-Through of Vessel: min ▾

i These calculations require entry of Shutdown Time (see Ribbon), Core Uncovery Time (see Step 2), and Rate of Core Temperature Change.

Figure 5-19 Core Damage Projections Panel, Time until Fuel Damage Events

A plot of core temperature rise is then provided to the user, as seen in Figure 5-20. The timings of all key events can be seen on this plot. The plot also takes into account the halt in core damage progression that occurs that after the core has been reflooded/recovered.



Figure 5-20 Core Damage Projections Part 3

The tool also provides an estimation of the percentage of gap release and fuel damage that have occurred. These damage projections can be based on the RTM uncovery timings or the input in the RTT. This can be seen in Figure 5-21. [1]

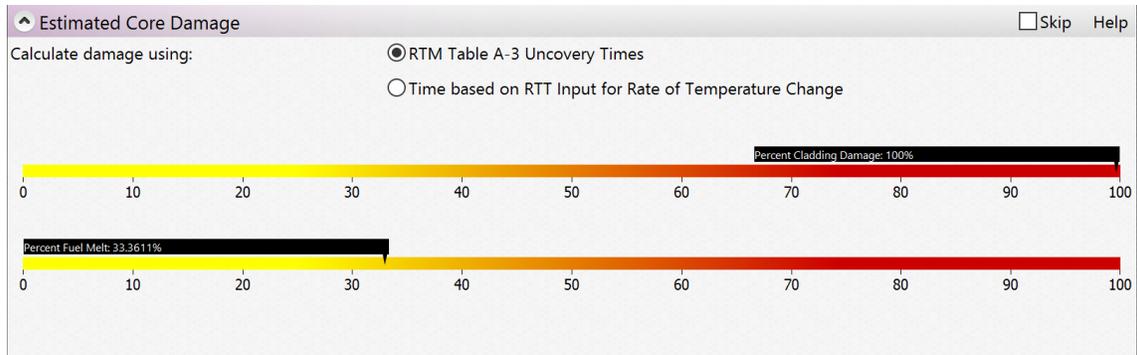


Figure 5-21 Estimated Core Damage

5.4 Step 4: Assess Core Damage State

In this step, the user analyzes the core damage state based on:

- Containment Radiation
- Containment Release
- Coolant Concentration
- Hydrogen Concentration

A screenshot of this fourth step can be seen in Figure 5-22. All four of these core damage assessments provide the analyst with a confirmation as to the total amount of core damage that has occurred thus far during an incident. Each of these four assessments provide feedback to the relevant Plant State warning on the lower left hand side of the screen. If two of these independent assessments indicate that core damage occurred, then this is likely the case.

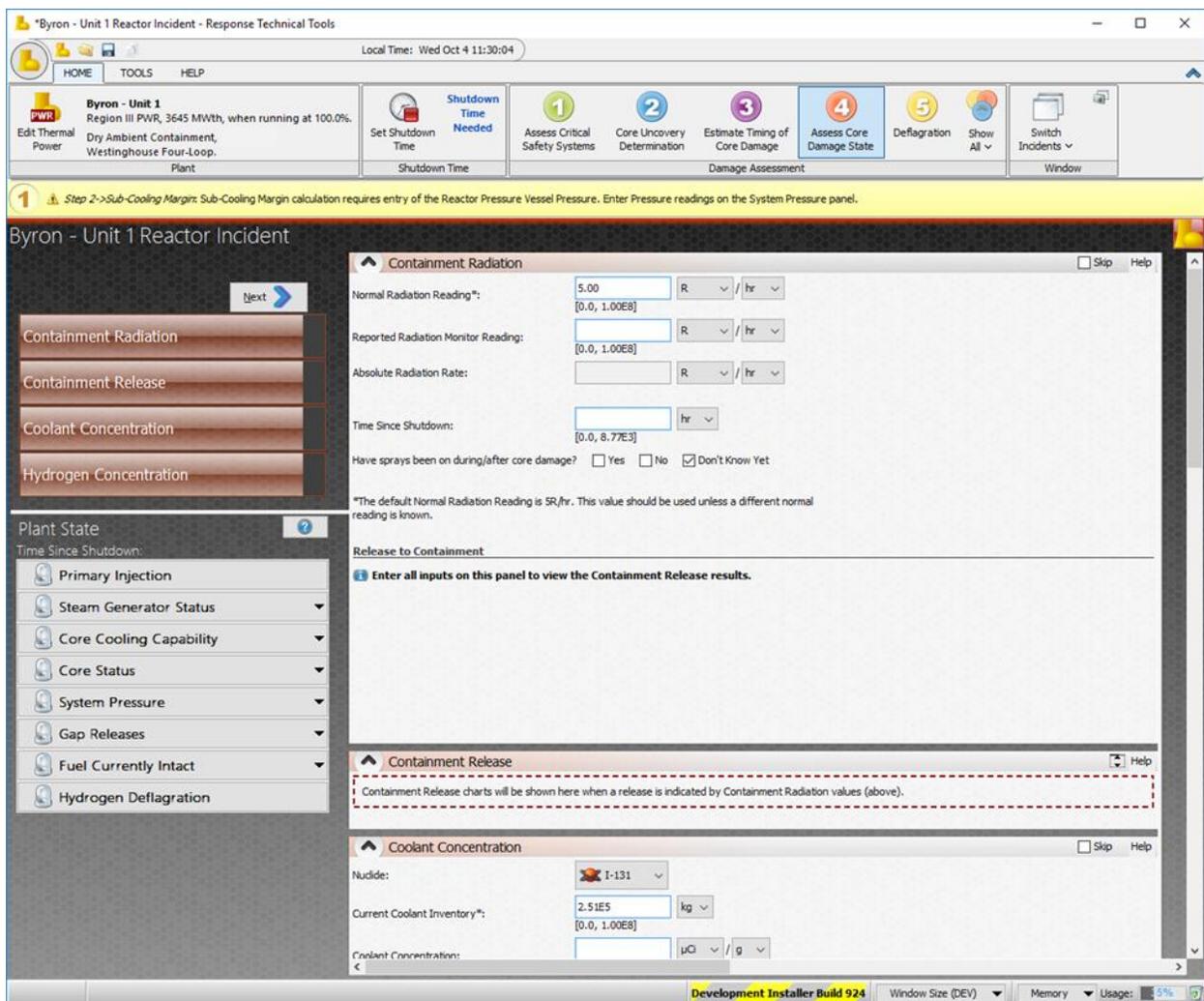


Figure 5-22 Step Three Elements and Plant State

5.4.1 Containment Radiation

For a BWR, select either drywell or wetwell values. This wetwell option does not exist for the PWR. The user then inputs the normal radiation reading (see Figure 5-23) and then the reported radiation monitor reading

The absolute radiation rate is then shown. The calculations in this question are based the equation:

$$absolute\ radiation\ rate = reported\ monitor\ reading - normal\ radiation\ monitor\ reading$$

Next, input the time of reading relative to shutdown time.

Finally, for a PWR or the drywell of a BWR, identify whether the sprays have been on during or after core damage.

RTT then provides release percents for in-vessel core melt, the gap activity, and the normal coolant activity.

Figure 5-23 Drywell Containment Release

5.4.2 Containment Release

Based on the inputs shown in Figure 5-23, containment release plots are generated as shown in Figure 5-24.

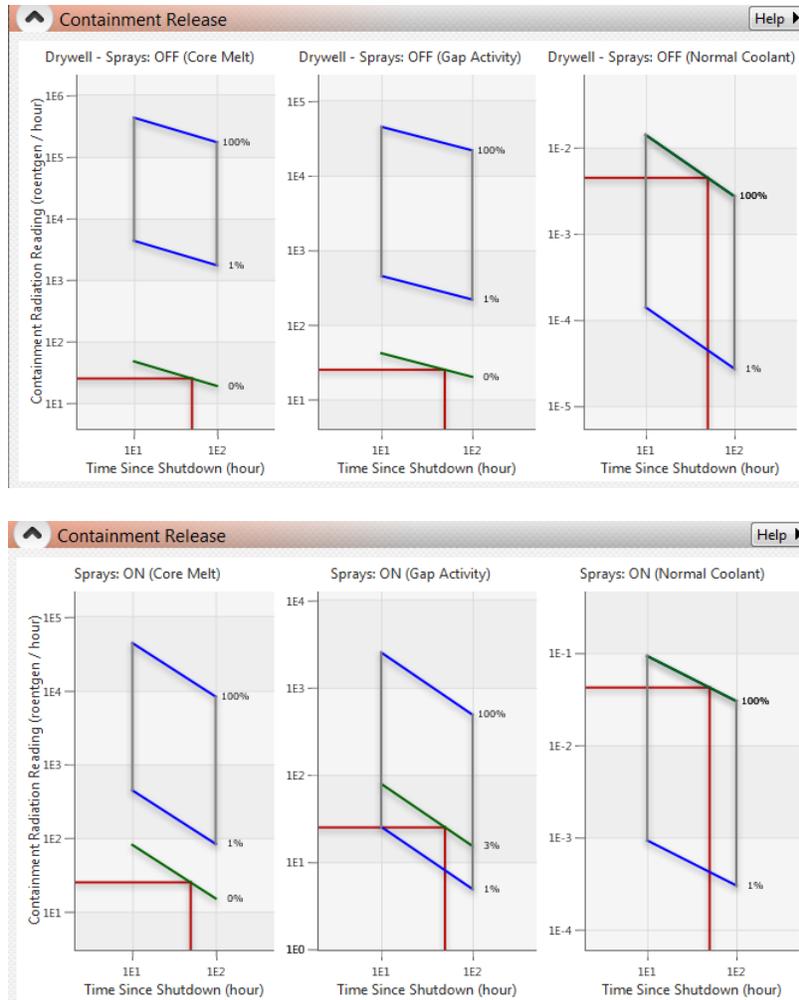


Figure 5-24 Containment Release Graphs, with Sprays Off (Top) and Sprays On (Bottom)

5.4.3 Coolant Concentration

This tool allows the user to estimate core damage progression through the concentration of key radionuclides in the coolant. The user selects the nuclide of interest in the drop-down list and then inputs the reactor coolant inventory (a default value is pre-populated and based on reactor power). The user then inputs the coolant concentration. This value is adjusted to the time of reactor shutdown, so that the correct comparison is performed.

RTT plots the normal coolant concentration, the after transient spike release, the after 100% gap release, and the after 100% in-vessel melt against the current coolant concentration normalized to the shutdown time. This is shown in Figure 5-25.

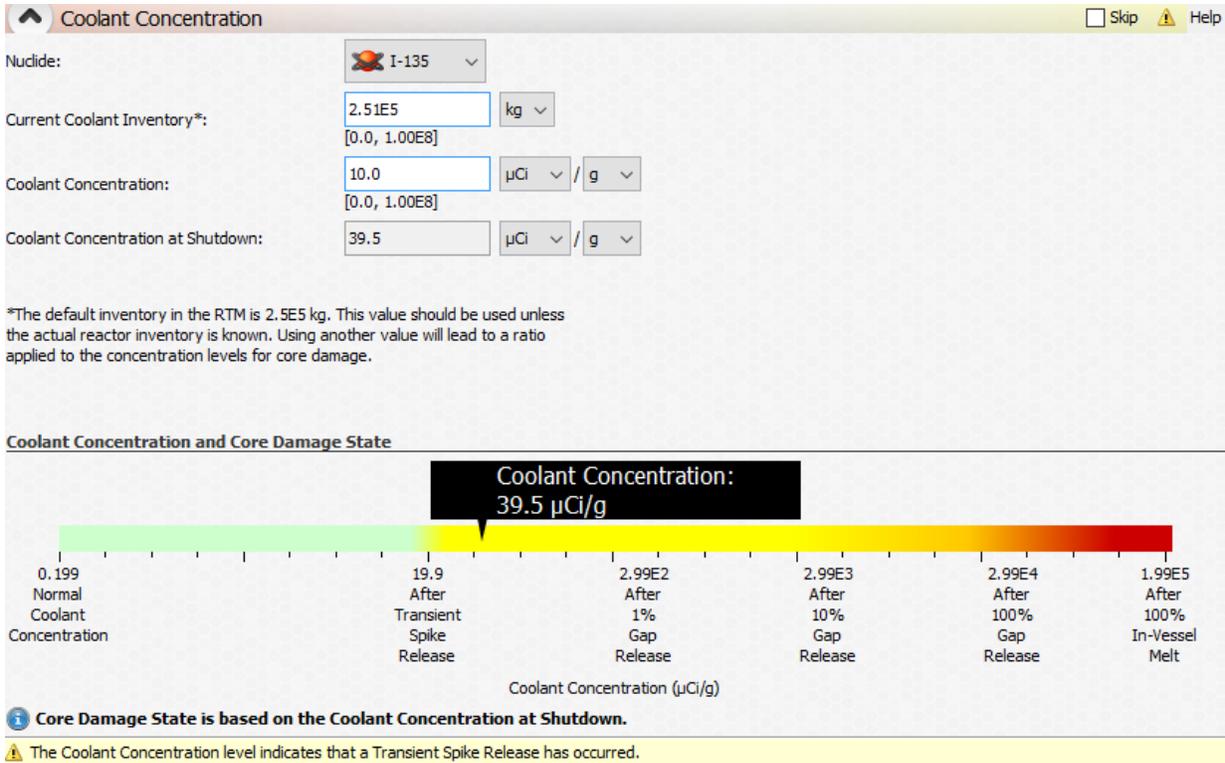


Figure 5-25 Coolant Concentration Analysis Tool

5.4.4 Hydrogen Concentration

In this tool, the user inputs the hydrogen concentration and the RTT plots the metal-water reaction and core damage state as shown in Figure 5-26.

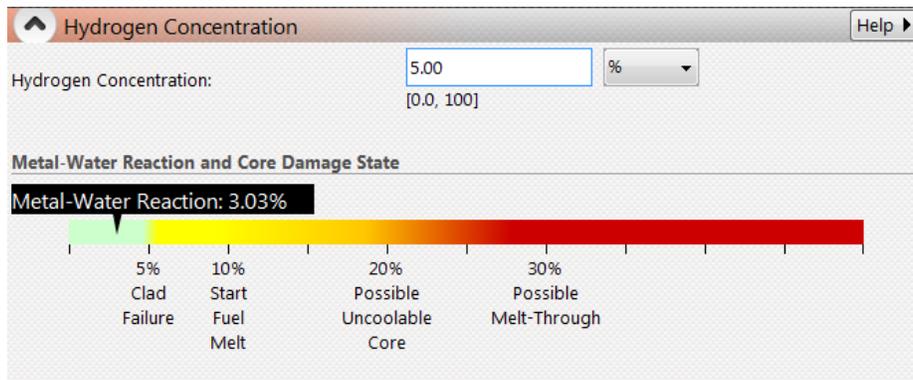


Figure 5-26 Hydrogen Concentration and Metal-water Reaction Analysis Tool

5.5 Step 5: Deflagration

In Step 5 potential for deflagration is assessed. Default values for the flammability region on a Shapiro diagram are provided to the analyst. These values may be altered with appropriate justification. The user then inputs the current hydrogen concentration and is provided with a line indicating the flammability of the mixture. Figure 5-27 shows the full Step 5 analysis.

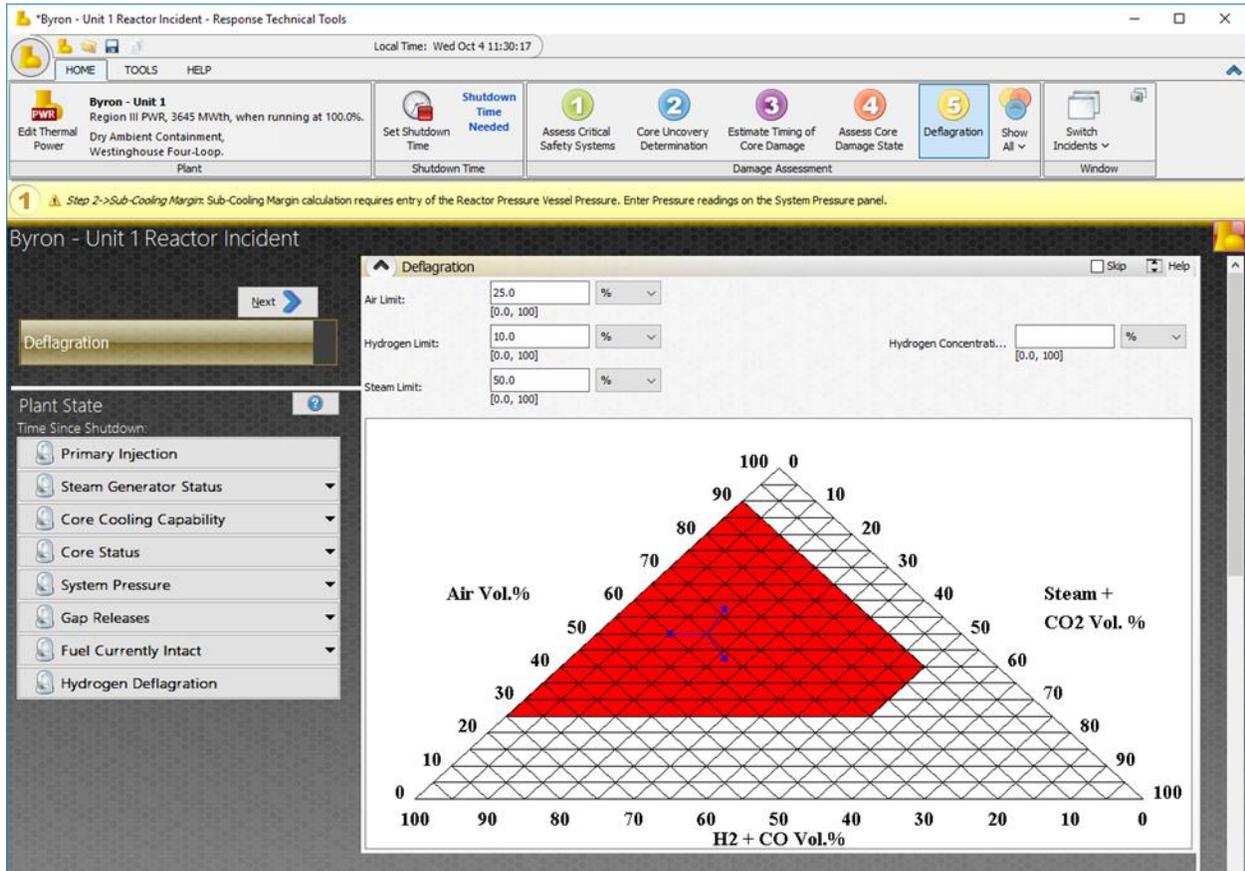


Figure 5-27 Step Three Elements and Plant State

5.6 Show All Steps

This tab is located at the top of the screen along with all five steps to the damage assessment. This tab will allow the analyst to view and edit all the data for all five steps. So if the analyst needs to navigate through certain parts in certain steps then they can do that quickly and easily. When the analyst clicks on the tab, RTT will then have a scroll down menu on the left hand side of the screen appear. This menu will show all the parts to every step so that the analyst can quickly navigate through the steps that need edited or revision. The analyst will also be able to scroll down on the main screen to navigate through the steps. This scroll down menu will be different depending on what reactor type the analyst chose.

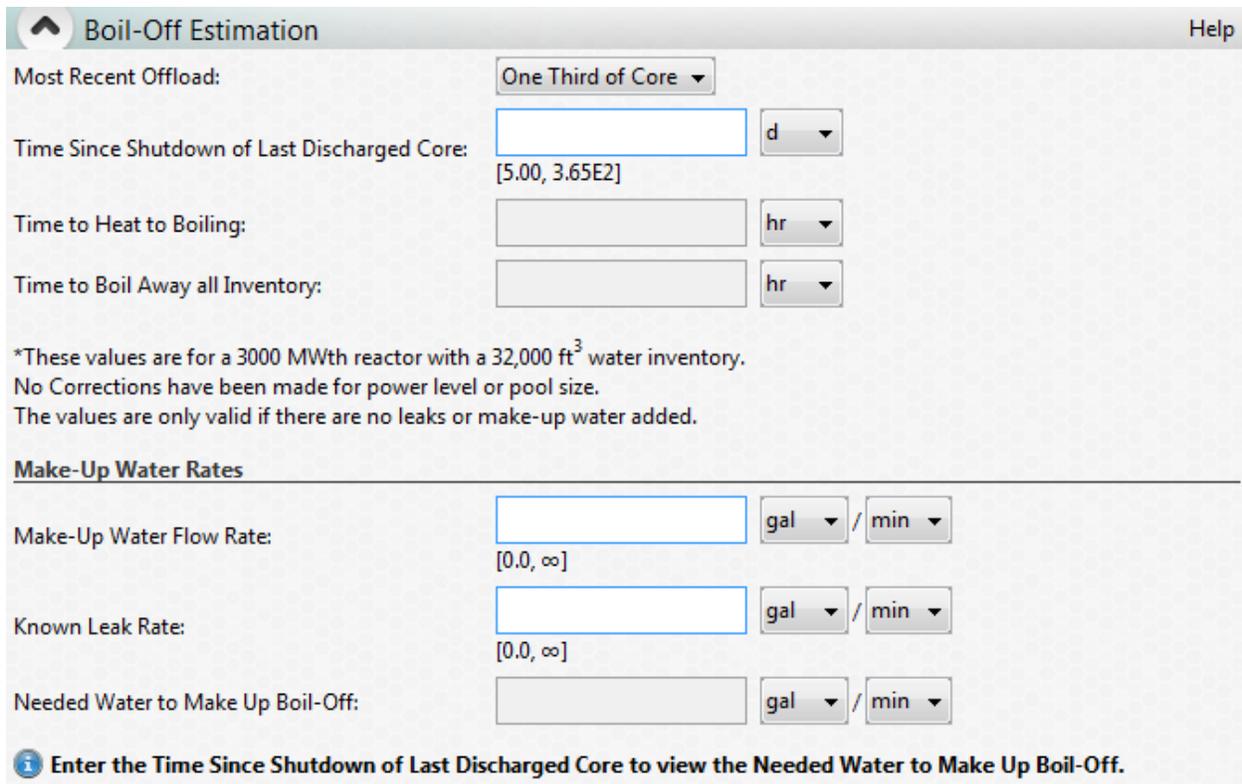
6 Spent Fuel Incident

6.1 Boil-Off Estimation

Develop a boil-off estimate of the spent fuel pool by first selecting one third core or a full core as shown in Figure 6-1. The user input the time since shutdown of last discharged core.

RTT then estimates the time to heat to boiling and time to boil away all inventory. The analyst may then input the make-up water flow rate and the estimated or known leak rate. If these values are known or can be estimated.

RTT provides the flow rate of water needed to make up boil off. If the make-up water flow rate is not greater than the needed water, RTT will give a warning that boil-off and loss of pool inventory may be occurring.



Boil-Off Estimation Help

Most Recent Offload: One Third of Core ▾

Time Since Shutdown of Last Discharged Core: d ▾
[5.00, 3.65E2]

Time to Heat to Boiling: hr ▾

Time to Boil Away all Inventory: hr ▾

*These values are for a 3000 MWth reactor with a 32,000 ft³ water inventory.
No Corrections have been made for power level or pool size.
The values are only valid if there are no leaks or make-up water added.

Make-Up Water Rates

Make-Up Water Flow Rate: gal ▾ / min ▾
[0.0, ∞]

Known Leak Rate: gal ▾ / min ▾
[0.0, ∞]

Needed Water to Make Up Boil-Off: gal ▾ / min ▾

i Enter the Time Since Shutdown of Last Discharged Core to view the Needed Water to Make Up Boil-Off.

Figure 6-1 Boil-off Estimation Panel

REFERENCES

1. McKenna, T., Trefethen, J., Gant, K. Jolicoeur, J., Kuzo, G. and Athey, G., *Response Technical Manual 96 (TRM-96) (NUREG/BR-0150, Volume 1, Revision 4)*, NUREG/BR-0150 Vol. 1 Rev. 4, U.S. Nuclear Regulatory Commission, Washington, DC, March 1996.
2. Sandia National Laboratories, Nuclear Incident Response Program: Software, <https://nirp.sandia.gov/Programs.aspx>, Accessed June 29, 2018.

DISTRIBUTION

1	MS0748	Nathan Andrews	8852 (electronic copy)
1	MS0899	Technical Library	9536 (electronic copy)

