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Technical Evaluation Study

Evaluation of ATR cycle 145B Physics Analysis Inaccuracy

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1. INTRODUCTION

Before the start of each Advanced Test Reactor (ATR) operating cycle, a physics analysis is performed and documented. The primary purpose of this analysis is to ensure that the fuel element safety basis limits are not exceeded during a specific operating cycle. The results of this analysis are included in the Core Safety Assurance Package (CSAP) for the cycle. The CSAP is used by the reactor operators during the cycle.

1.1 Description of the Issue

Routine surveillance of the operation of Cycle 145B, including the startup critical shim prediction and a comparison of the actual excess reactivity to the calculated excess reactivity, raised questions with the ATR nuclear engineering staff that the reactor performance was not consistent with historical behavior. Investigation indicated that the cross-sections used in the physics analysis for the test in the center lobe of ATR were inaccurate. The reactor was shut down while the physics analysis was redone with revised cross-sections for the center lobe test. The CSAP was revised and reissued for use by the ATR operators.

1.2 Problem Statement

There are several questions that need to be answered. First, were inaccurate neutron cross-sections generated and used in the physics analysis? Second, how significant were the differences between the first and second physics calculations? Third, if this sort of thing happens again, is it necessary to shut down the reactor while awaiting revised physics analysis results?

2. BACKGROUND

2.1 Preparation of Cross-Sections to be Used in the Physics Analysis

Figure 1 shows a cross-section of the ATR reactor core. The fuel elements (numbered 1 through 40) are laid out in a serpentine design which surrounds, or partially surrounds, 9 flux traps. A variety of tests are irradiated in the 9 flux traps and in other locations in and around the ATR core.

When a new test is proposed for inclusion in ATR, the analyst evaluates the best way to model the geometry of the test within the 2-dimensional PDQ physics model. Next, the analyst uses appropriate software to develop the cross-sections necessary to represent the test in the physics model.

The specific software used to develop the cross-sections depends on the materials and geometry of the new test. The code, S_n Code for the Analysis of Multigroup Problems (SCAMP), is often used for this purpose. SCAMP is a 1-dimensional transport code capable of modeling rectangular, cylindrical, or spherical

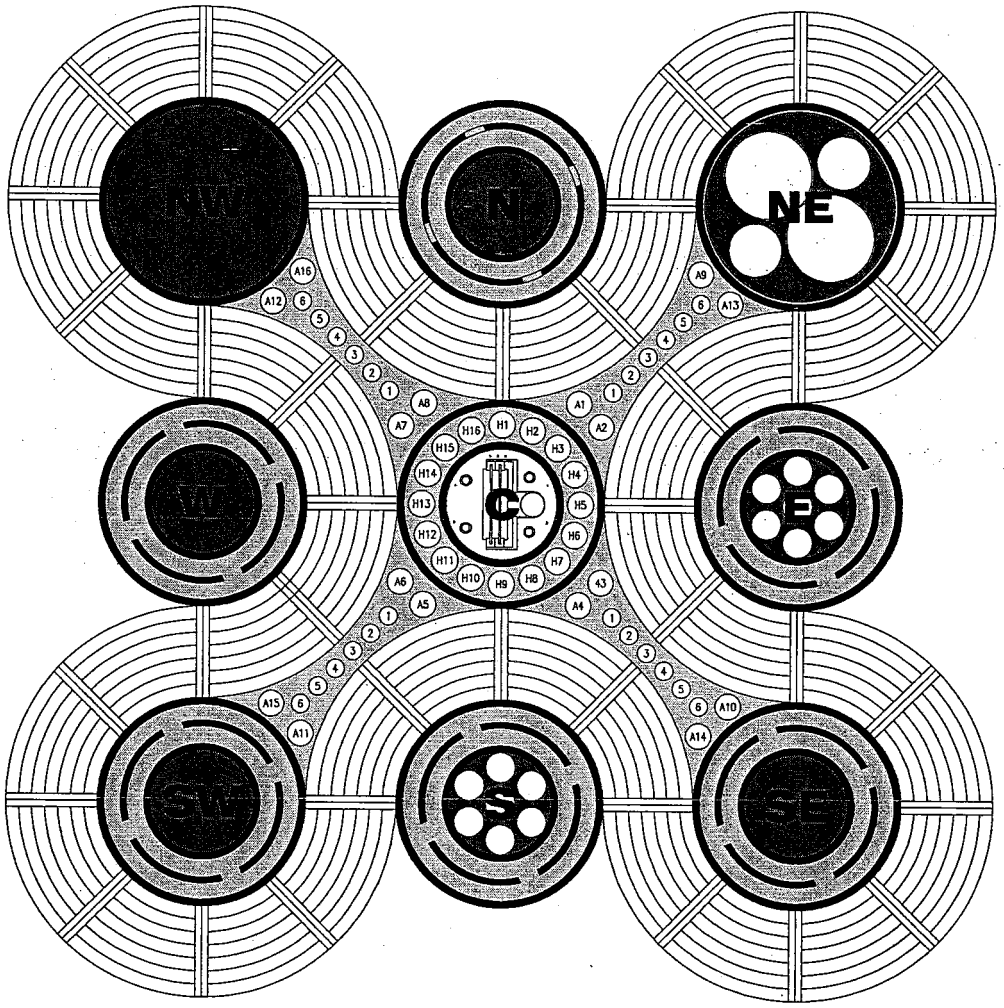

Figure 1. ATR core layout with experiment positions

geometries. The cylindrical geometry is normally used when deriving neutron cross-sections for use by PDQ. The cylindrical models used by SCAMP must be built using regions delineated by concentric circles centered at the center of the flux trap. These concentric circles become larger and larger and ultimately reach the fuel elements where, for most of the flux traps, the concentric circles match with the curvature of the fuel plates. However, for the center flux trap, the concentric circles do not match the curvature of the surrounding fuel plates. This mismatch of geometry could explain why, over the years, it has been observed that SCAMP models of tests in the center flux trap often provide cross-sections that are less accurate than the other lobes. Analysts, using engineering judgment,

have concluded that center lobe test cross-sections may not be as accurate as those produced for other lobes, but that the cross-sections provide sufficient accuracy to ensure the safety of the core.

2.2 The AFIP Test

In 2006 the ATR Full-Size Plate In Center Flux Trap Position (AFIP) experiment was proposed to be inserted into ATR. The AFIP test was initially designed to hold four plates. Each plate was about half the length of the ATR core. The design allowed 2 flat plates to be stacked one on top of the other in each of two vertical columns. When all four plates contained fuel, the test was called a 4-plate test. When the two plates in one column contained fuel and the two plates in the other column were unfueled, the test was called a 2-plate test. The reactivity of these two configurations was analytically determined to be significantly different from each other.[1] Thus, a backup test was developed for each configuration. One backup test consisted of an aluminum rod having a 1-inch diameter hole in the center (BU-1), while the other backup test consisted of an aluminum rod with a ½-inch diameter hole in the center (BU-2). The reactivity of BU-1 matched fairly well with the reactivity of the 2-plate test and the reactivity of BU-2 matched fairly well with the reactivity of the 4-plate test.

In late 2007, cross-section sets were developed using SCAMP to represent the 2-plate test, the 4-plate test, BU-1, and BU-2. In February of 2008, the first AFIP test was inserted in ATR. It was a 2-plate test inserted in Cycle 141A. A variety of different AFIP configurations[2,3,4,5,6,7,8] involving either one column or two columns of fueled plates were inserted in ATR from February 2008 through October 2009. The first time an AFIP backup test[9] was used in ATR was in November 2009 at the start of Cycle 145B, the cycle that is the focus of this technical evaluation.

2.3 Historical Tracking of Excess Reactivity

In late 1994 the physics analysis software (notably PDQ) was modified to run on a UNIX workstation instead of a mainframe computer.[10] Since then, the physics analysis software has remained essentially the same and has been used to perform the physics analysis of nearly 100 ATR cycles. The analysis results have been compared to actual reactor performance. Figure 2 shows the typical comparison of calculated and observed excess reactivity during ATR Cycle 145A. No significant deviation from this behavior would be expected and an observed deviation from this behavior would be noteworthy.

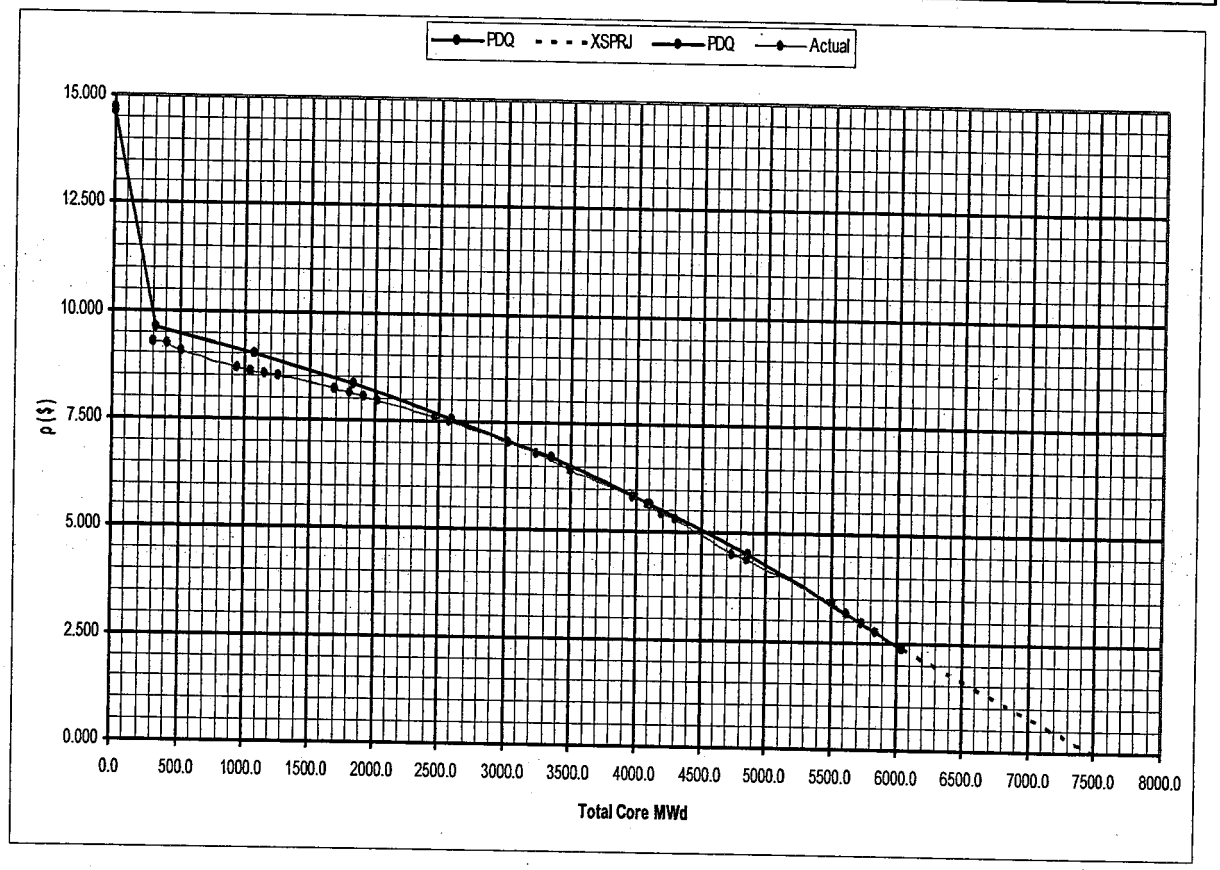

Figure 2. Typical plot of excess reactivity (cycle 145A).

3. Description of Cycle 145B Calculation Inaccuracy

3.1 Timeline with Comments

- January – March, 2007 - Drawings of the various AFIP experiment configurations began to be available. (For example, see reference 11.)

- June, 2007 - The initial MCNP physics analysis of the AFIP experiment was documented.[12]

- September – December, 2007 - The AFIP experiment was measured in ATRC.[13,14] The ATRC measurements of the reactivity of the test and the backups agreed with the reactivity predicted by the MCNP calculations to within 0.05$.

- October – December, 2007 - SCAMP was used to generate cross-sections for two AFIP test configurations and two AFIP backup configurations.

These analyses were not formally documented which is consistent with normal practice. The analyses of the two fueled test configurations were checked but the analyses of the backup configurations were not formally checked. Normal practice at the time would have been to formally check all four of the analyses soon after they were completed.

- December 2007 through December 2008 - The computer files associated with the cross-section generation process were preserved on the workstation where the analysis was performed (brimstone).

- December 2008 through January 2009 – The computer files associated with the cross-section generation process were transferred to another workstation (castalia) and the original workstation (brimstone) was retired. Nothing crucial was lost in the transfer. The only information lost was the exact date that some of the files were created.

- September 2, 2009 – The letter describing the CFT Experiment Loading for Cycle 145B-1 is issued. It states that the backup test is to be used at the discretion of Nuclear Safety.[9]

- September 21, 2009 - Preliminary Experiment Requirements Letter[15] stated that an AFIP backup would be inserted in the center lobe, but did not specify which backup was to be used. Revisions 1, 2, and 3[16] of this letter were also non-specific about which backup, BU-1 or BU-2, would be inserted. Revision 3 of the letter was dated October 15, 2009.

- October 20, 2009 – PDQ calculations were completed for cycle 145B-1. The calculations were performed using the cross-sections generated by SCAMP in late 2007 for the AFIP BU-2 backup configuration. The entire suite of physics calculations was completed before November 2, 2009.

- October 2009 - Review of ECAR-807, Results of Reactor Physics Safety Analysis for Advanced Test Reactor Cycle 145B,[17] was initiated and the reviewer noted that Revision 3 of the Preliminary Experiment Requirements Letter[16] did not state a specific AFIP backup but that the PDQ calculations assumed the use of AFIP backup BU-2. Reviewer initiated discussion to correct the Preliminary Experiment Requirements Letter.

- November 2, 2009 - Preliminary Experiment Requirements Letter, Revision 4[18] stated that the AFIP backup BU-2 would be inserted in the center lobe.

- November 3, 2009 – ECAR-807,[17] was issued and stated that AFIP BU-2 would be in the center lobe

- November 10, 2009 - Preliminary Experiment Requirements Letter, Revision 5[19] stated that the AFIP backup BU-2 would be inserted in the center lobe.

- November 10, 2009 – CSAP submitted to SORC for review.

- November 22, 2009 – Reactor attained criticality. The predicted shim position for criticality based on the PDQ calculation was 53.2°, corresponding to a worth of 4.441$. The empirical method, which estimates critical shim position based on previous cycle loading and performance, predicted a position of 42.8°, corresponding to a worth of 3.146$. Thus, there was a difference of 1.30$ between the two predictions.

  This difference was somewhat larger than normal, but is not indicative of an error in either the PDQ or empirical shim prediction calculation. As an example, the difference between the PDQ and empirical shim predication for Cycle 145A was 1.26$. For Cycle 145A, the difference between the actual critical shim position and the PDQ prediction (-0.38$) was less than the difference between the actual critical shim position and the empirical prediction (0.89$). For Cycle 145B, the nominal average predicted shim position was 48.1° with an upper limit of 54.0°, and a lower limit of 39.7° which corresponds to +0.75$ and -1.0$. The reactor actually went critical at a shim position of 42.8° which was much earlier than the nominal predicted value. However, since it was within limits it was judged to be acceptable.

- November 30, 2009 – The first core monitoring data point was taken.

- Morning of December 1, 2009 – The second core monitoring data point was taken. The two core monitoring data points raised suspicions (compare Figure 3 to Figure 2) about the validity of the physics calculation even though they were within normally accepted limits. An investigation into the cause of the discrepancy began.

- Morning of December 1, 2009 – Determined that the AFIP BU-2 test cross-sections, used in the original PDQ calculation, resulted in a calculated reactivity change that deviated by about 0.80$ from that measured in ATRC. Nuclear Engineering staff began to evaluate the SCAMP model that had been used to develop the cross-sections for BU-2.

- Morning of December 1, 2009 – Work began to repeat the physics calculation using cross-sections for the AFIP 4-plate test instead of AFIP BU-2. This was an appropriate alternative because the reactivity of each, when measured in ATRC, differed by only about 0.08$.[14,20]

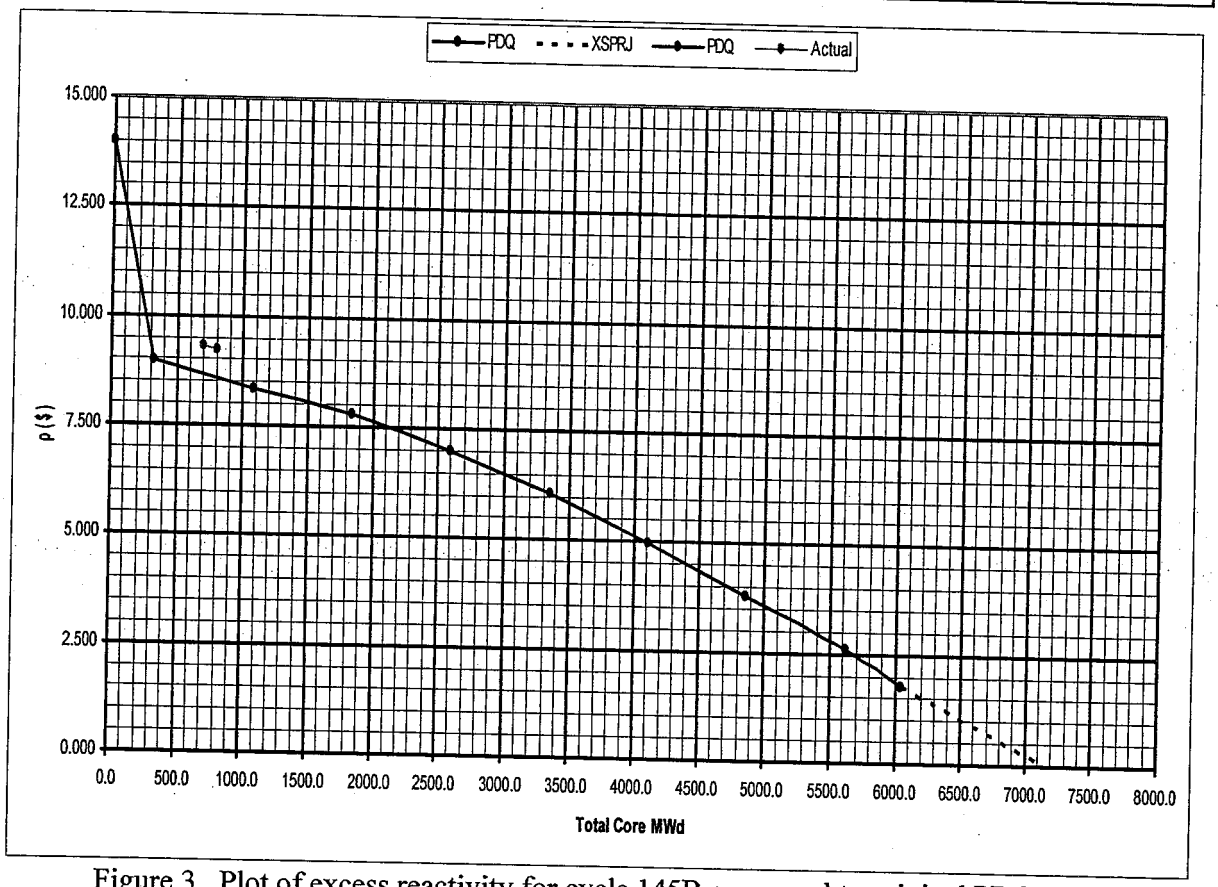

Figure 3. Plot of excess reactivity for cycle 145B compared to original PDQ calculation.

- Late morning of December 1, 2009 – Nuclear Engineering staff met with operations staff to discuss the situation. Operations staff, referring to TSR-186, 3.6.1, SR 4.6.1.1, concluded that the reactor should be shut down. Nuclear Engineering staff, knowing that the inaccuracy would not risk a violation of the Effective Plate Power limits, advised that the reactor did not need to be shut down. The decision was made to err on the side of conservatism and shut the reactor down.

- Approximately Noon, December 1, 2009 – The reactor was shut down.

- December 2, 2009 – Nuclear Engineering determined that the AFIP BU-2 SCAMP model had used the wrong diameter hole in the center of the rod. Nuclear Engineering found that the SCAMP model had not been checked previously for accuracy.

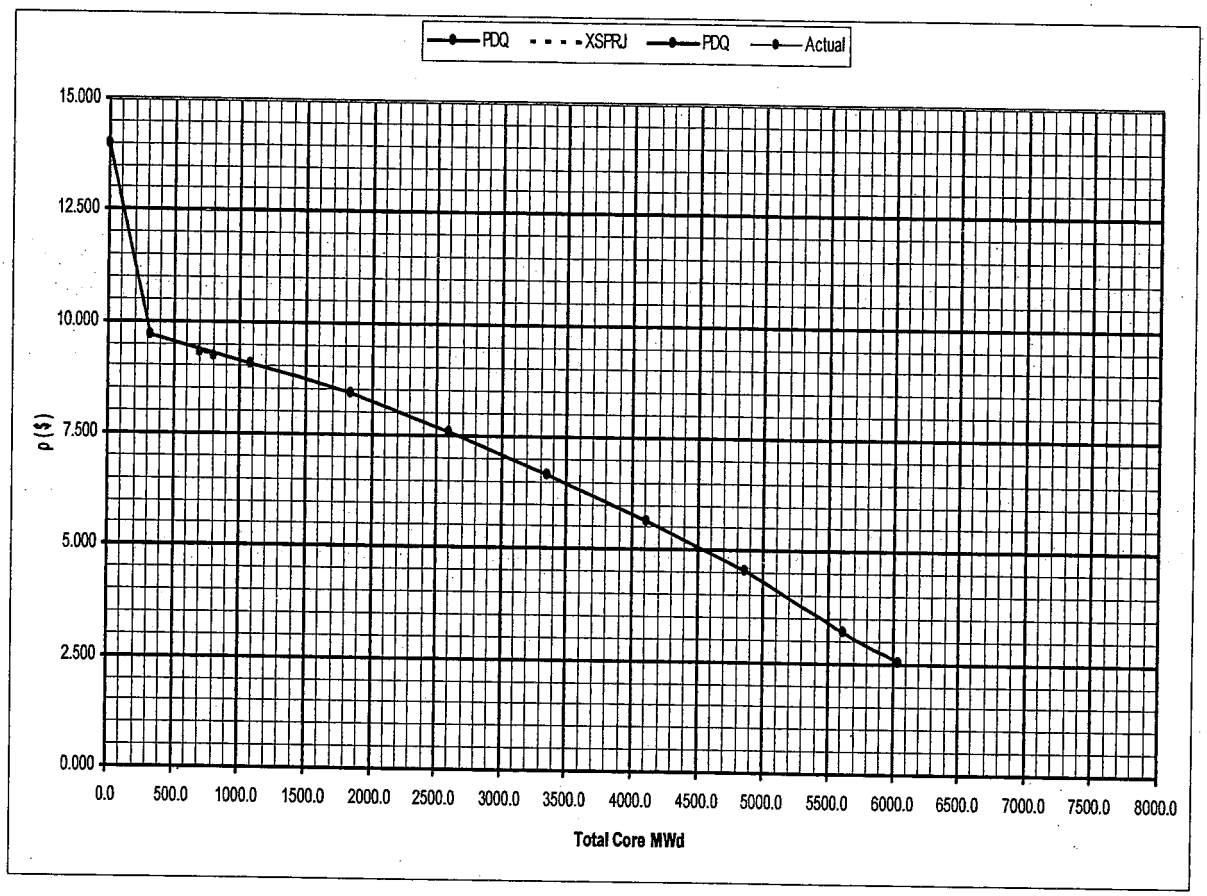

Figure 4. Plot of excess reactivity for Cycle 145B compared to revised PDQ calculation.

- December 2, 2009 - Revised physics calculations completed. A comparison of the surveillance excess reactivity data to the new calculated excess reactivity showed good agreement – see Figure 4.
- December 3, 2009 - Revised physics ECAR (ECAR-807, rev.1) completed.
- Approximately 5 pm, December 3, 2009 - Revised CSAP completed.
- Early December 4, 2009 - Reactor restart.

3.2 Logic for Reactor Shut Down

- SR 4.6.1.1 requires that we "Verify reactor performance calculation" prior to REACTOR OPERATION after CORE CHANGES and "prior to planned changes not within the existing reactor performance calculation."
- Action Statement 3.6.1 E.1 states "Reactor performance calculation not verified" verify reactor scram immediately.
- TSR Bases notes that the surveillance ensures that the core operates within the safety analysis assumptions.
- The TSR does not allow time to analyze the consequence of an analysis deviation prior to reactor shut down. Nor does it allow that the reactor may not need to be shut down at all if the consequence is determined to be acceptable.

3.3 Consequence of Inaccuracy

A few specific values from the physics analysis are incorporated into the CSAP. A review of the original and the revised CSAP has been performed to evaluate the consequences of the use of inaccurate cross-sections in the initial physics calculation.

On page 2 of the CSAP, reactivity values for control surfaces (i.e. safety rods and regulating rods) were compared to the applicable SAR or TSR limits. The largest adjustment resulted in a less than 4% change in reactivity. All reactivity values are at least 1.00$ from the applicable limit. Thus, neither the original nor the revised values are significantly close to exceeding the applicable limits.

On page 4 of the CSAP, the maximum center lobe power was increased due to the direct effect of a change in the modeling of the center lobe experiment backup. The modeling change created an increase in center lobe reactivity of significant magnitude to cause the maximum lobe power to increase by 1 MW.

On page 6 of the CSAP, there are two Tables which reference Effective Plate Power values that are calculated by the physics analysis. All of the values are limited by safety considerations and must be less than 362. The maximum calculated value in the original CSAP is 262 and in the revised CSAP is 274. Neither the original nor the revised values are significantly close to exceeding the limit.

On page 7 of the CSAP, the maximum fuel element power and the highest point-to-average power density were changed. The maximum element power affects the fuel element cooling time (discussed below). The highest point-to-average

power density affects the element to be inspected after the cycle completes. Although the value changed, the element with the highest power density did not. Thus, the particular elements named remained the same.

On page 13 of the CSAP, reactivity insertions due to voiding increased by a maximum of 1.7%. Neither the original nor the revised values are significantly close to exceeding the applicable limits.

On page 15 of the CSAP, Table IV lists the Reference Lobe Power for Quadrant ΔT Setpoints. Lower values are more limiting than higher values. All of the values in the table changed except the value for the NW lobe. The value which lowered by the largest percentage was for the SE lobe. It went down from 59.9 MW to 59.4 MW which corresponds to a 0.83% change. The PDQ calculations[17] show that the SE lobe power would not exceed 36.56 MW even if the ΔT setpoint for the SE lobe were incorrectly set at 59.9 MW rather than 59.4 MW.

On page 20 of the CSAP, fuel elements that are expected to no longer have recycle potential are listed. An additional element was added to this list. The list is only used for planning purposes. Actual element recycle potential is evaluated once a cycle is completed.

On page 21 of the CSAP, there is a table listing the Effective Point Powers calculated by the physics analysis. All of the values are limited by safety considerations and must be less than 428. The largest table value changed from 312 in the original calculation to 325 in the revised calculation. Neither the original nor the revised values are significantly close to exceeding the limit.

On page 22 of the CSAP, the fuel element cooling time is presented. Although the original calculation presented a maximum element power of 4.34 MW and the revised calculation presented a value of 4.44 MW, the resulting cooling time for both cases was 4.1 hours.

On page 28 of the CSAP, a table lists the lobe MWd exposure at the fission density limit for each of the 5 lobes of the reactor. It also lists the corresponding effective full power days (EFPD) which can be operated, assuming lobe maximum power, before reaching the lobe MWd limit. The maximum power for the center lobe is typically set high to allow for an expedited cycle startup, but for most of the cycle, the center lobe power will be much lower. Consequently, for most ATR cycles, the center lobe EFPD limit shown in this table is shorter than the cycle length. Typically this issue is addressed in the CSAP by saying, "...exceeding the fission density limit is considered improbable. Nuclear Engineering will track actual C Lobe MWds, to ensure fissions density limits in the C Lobe are not exceeded during the cycle."

The original calculation found a center lobe limit of 1630 MWd of exposure which equated to 54.3 EFPDs. The revised calculation found a center lobe limit

of 1578 MWd of exposure which equated to 50.9 EFPDs. Both of the EFPD values are shorter than the planned cycle length of 56 EFPDs. In each case the CSAP addressed that issue with the statement shown in the previous paragraph so the difference between the two calculations made no difference in the execution of the cycle. The power history letter, issued after the completion of cycle 145B,[21] indicated that the center lobe power, averaged over the full cycle length of 57.3 EFPDs, was 23 MW. Thus the center lobe operated for 1321.4 MWd, which was below the limit allowed in either of the calculations.

On Page 35 of the CSAP, maximum relative source powers were listed. The largest change in source power was 2.3%. On Page 36 of the CSAP, the power limits are listed. The largest change in absolute power limits was 3.3%. The largest change in relative power limits was 4.1%. These limits for both the original and the revised calculation are greater than the powers planned during cycle operation.

4. Evaluation

4.1 The Physics Analysis Process

The physics analysis for each ATR cycle is performed by following a guidance document which is saved on the ATR nuclear engineering file server. Typically, the experiments included in a new cycle are mostly the same as those loaded in a previous cycle. Thus for most cycles the PDQ input deck includes very few new cross-section sets. As each set of cross-sections is developed for the first time it is labeled with descriptive text to indicate what is represented by those cross-sections. As a part of the physics analysis process, an independent "data verifier" completes a checklist[22] to help assure that the physics calculation has been performed correctly. The checklist includes a section in which the text descriptions are compared to the Preliminary Experiment Requirements letter (see for example reference 19.) During the check of the original physics calculation, the verifier found that the text describing the center lobe test said it was the AFIP ½" backup test. The data verifier compared this description to Revision 3 of the Preliminary Experiment Requirements letter.[16] Although that revision of the letter was not specific about which AFIP backup test was being used, the verifier accepted it. The next revision of the letter[18] did indicate that the center lobe test was AFIP BU-2, the ½" backup test. Thus, the calculation appeared to be using the correct cross-sections for the center lobe test.

Although there were a series of Preliminary Experiment Requirements letters that did not clearly define which AFIP backup test was planned to be inserted in Cycle 145B, the cross-sections used in the PDQ analysis were the ones that had been developed for the test that was included. Therefore, the uncertainty in the Preliminary Experiment Requirements letter did not contribute to the inaccuracy of the calculation.

The cross-sections for the AFIP BU-2 test were developed during late 2007. The files related to that development process have been examined and informally checked since the problem occurred. The files associated with the development of the cross-sections for the 2-plate test, the 4-plate test, and the 1-inch backup test (BU-1) all appear to be correct. The SCAMP input deck for the ½" backup test (BU-2) erroneously used a diameter of the innermost region (the water-filled central hole) of 0.875 inches instead of 0.5 inches. It is not known how this erroneous value came to be used, but if the model had been formally checked, this error would have been found. In 2007, and still today, there is no formal process in place to check the development of cross-sections for new tests planned for ATR. A formal process to check the development of cross-sections needs to be implemented.

4.2 The Decision to Shut Down the Reactor

ATR staff referred to Technical Safety Requirements for the Advanced Test Reactor, TSR-186-A-3/4.6, section 3.6.1, Bases SR 4.6.1.1. Specifically, the last sentence in that section states that the 24 hour grace period provision of SR 4.0.3 does not apply because "REACTOR OPERATION without an analysis or outside the analysis is not allowed". Thus, the TSR provides no allowance to evaluate the significance of the CSAP inaccuracy while the reactor remains at power, so the reactor was shut down. If it had been possible to allow the reactor to run while the significance was evaluated, it would have been evident that the reactor could have remained at power without any more risk than is accepted during normal operation.

5. FILE LOCATION

The files associated with this evaluation are located on workstation castalia. The files associated with the original SCAMP calculations are located in directory /disk4/prod/afip. The files associated with the original PDQ analysis are located in directory /disk3/prod/atr/cy145b_error. The files associated with the revised PDQ analysis are located in directory /disk3/prod/atr/cy145b_csap.

6. RECOMMENDATION

A formal process to check the development of cross-sections needs to be implemented. TSR-186 does not currently allow the reactor to remain at power during the time that the consequences of an inaccuracy in the physics analysis are being evaluated. Adding a provision in TSR-186 to allow short-term continuation of operation could avoid a reactor shut down.

7. CONCLUSIONS

An appropriate questioning attitude successfully identified an inaccuracy in the physics analysis for ATR Cycle 145B. Even though the discrepancy was minor and the consequences were insignificant, the proper course of action was followed. The reactor was shut down quickly, the situation was corrected, and the reactor was restarted without any significant delay. A lesson has been learned that a formal process must be implemented to check the development of cross-sections to be used in PDQ input models. It may be advisable to revise TSR-186 to allow continued reactor operation while the consequences of a physics analysis inaccuracy are being evaluated.

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