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A RELOAD AND STARTUP PLAN FOR CONVERSION OF THE NIST RESEARCH REACTOR

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ABSTRACT

The National Institute of Standards and Technology operates a 20 MW research reactor for neutron-based research. The heavy-water moderated and cooled reactor is fueled with high-enriched uranium (HEU) but a program to convert the reactor to low-enriched uranium (LEU) fuel is underway. Among other requirements, a reload and startup test plan must be submitted to the U.S. Nuclear Regulatory Commission (NRC) for their approval. The NRC provides guidance for what should be in the plan to ensure that the licensee has sufficient information to operate the reactor safely. Hence, a plan has been generated consisting of two parts.

The reload portion of the plan specifies the fuel management whereby initially only two LEU fuel elements are in the core for eight fuel cycles. This is repeated until a point when the optimum approach is to place four fresh LEU elements into the reactor each cycle. This final transition is repeated and after eight cycles the reactor is completely fueled with LEU. By only adding two LEU fuel elements initially, the plan allows for the consumption of HEU fuel elements that are expected to be in storage at the time of conversion and provides additional qualification of production LEU fuel under actual operating conditions.

Because the reload is to take place over many fuel cycles, startup tests will be done at different stages of the conversion. The tests, to be compared with calculations to show that the reactor will operate as planned, are the measurement of critical shim arm position and shim arm and regulating rod reactivity worths. An acceptance criterion for each test is specified based on technical specifications that relate to safe operation. Additional tests are being considered that have less safety significance but may be of interest to bolster the validation of analysis tools.

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1. INTRODUCTION

1.1 Objectives of the Reload and Startup Plan

The NIST (National Institute of Standards and Technology) research reactor (aka NBSR) is a heavy water moderated and cooled reactor operating at 20 MW. It provides users with thermal and cold neutron beams to carry out diverse world-class research. It is fueled with high-enriched uranium (HEU) fuel elements but a program is underway to convert the reactor to low-enriched uranium (LEU) fuel. To accomplish this, the fuel meat within each fuel plate will change from U_3O_8 (with fully enriched uranium) in an aluminum powder dispersion to U10Mo metal foil (with 19.75% enriched U). The Al cladding and fuel plate external geometry will remain the same.

The U.S. Nuclear Regulatory Commission (NRC) has to approve the conversion proposal and provides guidance as to what should be in the proposal. In particular, Chapter 18 of NUREG-1537 (NRC, 1996) provides the format and content for the conversion Safety Analysis Report (SAR) (in Part 1) and the standard review plan and acceptance criteria for the conversion SAR (in Part 2). Section 12.6 of the conversion SAR is to discuss the "Reactor Reload and Startup Plan" which is "to ensure that the licensee has sufficient information to operate the reactor safely."

According to the NRC guidance, the reload and startup plan (RSUP) "should provide for testing any newly installed equipment; a proposed fuel loading procedure and schedule; radiation surveys; a systematic set of subcritical measurements in the approach to critical with the new fuel; experiments and measurements that compare predicted and calculated reactor parameters; and verification of compliance with license conditions, including technical specifications, of the LEU-fueled reactor." How the NRC guidance is utilized for the NBSR RSUP is explained in this report. The RSUP is a supplement to the fuel qualification that will have preceded loading of the first LEU fuel element. This includes the irradiations of prototypic fuel plates that are planned at the Advanced Test Reactor at the Idaho National Laboratory [e.g., see (Wolstenhulme, 2012)] and the hydraulic tests planned at Oregon State University (Marcum, 2013).

Although an otherwise complete preliminary SAR (Diamond, 2014) has been submitted to the NRC, it was premature at the time of submittal to discuss both the way in which the reactor would be loaded with LEU fuel and what tests would be done to ensure that the reactor would operate as planned.

The NRC-suggested components of the conversion startup plan form the basic objectives of the NBSR plan discussed herein. The NRC guidance is blended with the operational needs and experience at the NBSR. This approach is also consistent with the guidelines set forth by the International Atomic Energy Agency in Appendix L of IAEA-TECDOC-643 (IAEA, 1992), which benefitted from the earlier work that had been done for NUREG-1537.

1.2 Outline of Report

The most probable approach to reloading the reactor with LEU fuel elements is discussed in Section 2. The proposed plan is for a reload that will not take place at one time but will involve loading different amounts of LEU fuel elements at different times. The recommendation for tests then must be a function of the particular reloading taking place. The tests that would constitute the startup plan are provided in Section 3. The objective of these tests is to assure that the LEU fueled core matches the core that was expected (i.e., previously calculated) and for which the safety analysis was carried out. This requires each test to have an acceptance criterion. Section 4 contains references.

2. RELOAD PLAN

It is not possible to simply replace a core containing HEU fuel in an equilibrium burnup state with a core consisting of fresh LEU fuel elements (FEs). This leads to a core having an excess reactivity and a shutdown margin that violate the reactor's Technical Specifications (NIST, 2010).

One viable option is to reload with LEU fuel (Hanson, 2011) while retaining the current fuel management scheme wherein four fuel elements are removed every 38.5-day cycle, the remaining fuel reshuffled, and four fresh elements added. With four LEU fuel elements loaded each cycle none of the eight fuel cycles needed to switch out all 30 HEU fuel elements will have enough excess reactivity to operate for a normal 38.5-day period. This will be a penalty on the experimental program that is unacceptable. A solution is to have the first transition cycle with a reduced length (22 days will work) leaving enough excess reactivity so that the remaining cycles can be the standard 38.5-day length. This approach would result in a transition that would not be in violation of Technical Specifications on excess reactivity and shutdown margin. It would take eight cycles to completely replace all 30 HEU fuel elements, although a true equilibrium core would not be achieved until after several additional cycles with 100% LEU fuel elements.

Although the above option is feasible, another plan (Hanson, 2012) to reload in a more "cautious" manner is the preferred approach. This plan uses "lead acceptance elements" (LAEs) and it is motivated by the fact that even though the irradiations as part of the fuel qualification program will be useful, none of the proposed tests use an actual NBSR fuel element. The LAE scheme is to conservatively prepare for uncertainties in supply and performance of the new fuel. In the unlikely event that there is a problem which necessitates the removal of the LEU fuel, it would not be too difficult to get the reactor operational again with only HEU fuel. Furthermore, since the NBSR is expected to have several years of HEU fuel in storage at the time that LEU fuel becomes available for use, the LAE scheme allows for continued use of the remaining inventory of HEU fuel while formally achieving "conversion[a]."

[a] Conversion is formally considered achieved when LEU is first introduced into the core.

At present, each fuel cycle starts with two fresh HEU fuel elements that will remain in the core for eight cycles and two fresh HEU fuel elements that will remain for seven cycles. In the LAE scheme, two LEU fuel elements are inserted in the core in the first transition cycle in lieu of the two fresh HEU elements that would normally remain for eight cycles. Two HEU fuel elements are also loaded that will remain for seven cycles. At the end of this cycle four HEU fuel elements are removed and for the next seven cycles four fresh HEU elements are loaded to replace four burned HEU fuel elements as is presently done. After eight cycles have been completed, the two depleted LEU fuel elements are removed (along with two HEU fuel elements). Two additional LEU fuel elements are then inserted into the core for another eight cycles.

Figure 1 shows a flow diagram for the reload program. It shows the LAE approach being repeated for an indefinite period of time. However, this process is expected to be repeated for a limited number of cycles, the exact time being dependent on LEU fuel performance and the actual HEU inventory at the start of the LAE program. After the LAE program is completed, the conversion would proceed by having four fresh LEU fuel elements loaded in every cycle.

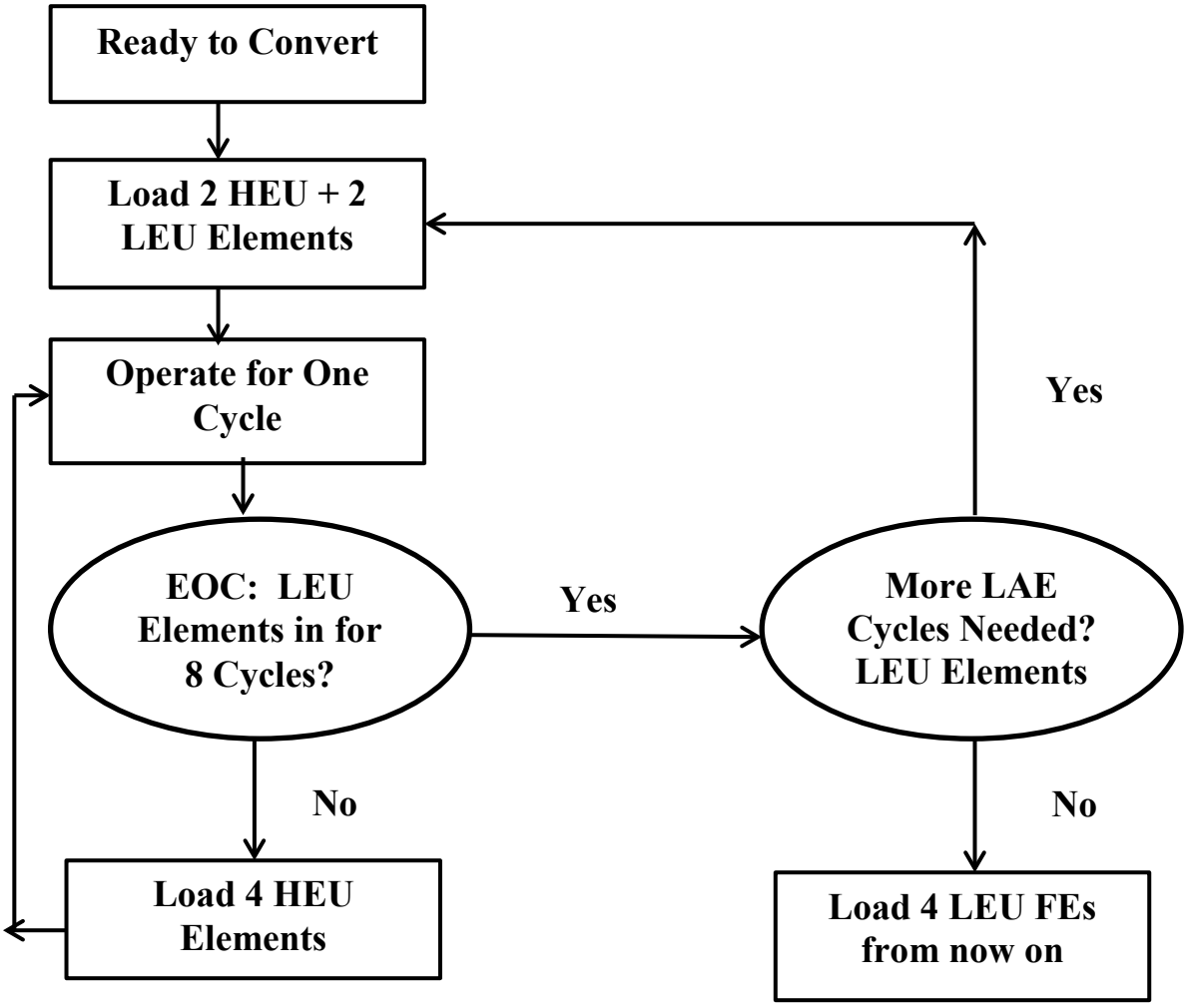

Figure 1. Flow Diagram for the LAE Program

An analysis of two LAE cycles (a total of 16 fuel cycles) was carried out and documented in (Hanson, 2012). It shows that there are no major neutronic or power distribution issues if two LEU fuel elements are inserted into the NBSR core to act as lead acceptance elements. There will be a decrease in the excess reactivity after loading the LEU fuel elements so that the first cycle will not be able to operate for 38.5 days; it is expected to operate for only 37.4 days. All subsequent cycles are expected to be able to last no less than 38 days and most at least 38.5 days. The calculations of the excess reactivity and shutdown margin with the LAEs in the core show compliance with Technical Specification 3.1.2, Reactivity Limitations. There will be a small decrease in the neutron beam performance, the magnitude of which will change as the LAEs are moved through the core. Calculations of shim arm critical position at startup; neutron lifetime and delayed neutron fraction; and moderator temperature coefficient and reactivity; showed that these parameters will not change significantly when the LEU is added to the core during the LAE program.

A similar analysis was carried out where the transition was the insertion of four LEU fuel elements every cycle until (and beyond) when the core was completely loaded with LEU (Hanson, 2013). All neutronic parameters are either not changed significantly or still considered to be within the required safety envelope; similar to the expectation for the LAE cycles discussed above.

3. STARTUP TEST PLAN

3.1 Planning Startup Tests

The NRC guidance for the startup plan [Chapter 18 in Part 1 of (NRC, 1996)] states that the startup plan should contain:

- "a well-planned systematic set of subcritical multiplication measurements or an inverse multiplication approach to critical measurement during new fuel loading, and confirmation that analysis subcritical multiplication or critical fuel loading are within pre-established acceptable limits

- an experimental measurement plan to determine the important operational reactor physics parameters (such as control rod worth, excess reactivity, reactor thermal power, coefficients of reactivity, and power peaking factors) and thermal-hydraulic parameters (such as fuel, cladding, and coolant temperatures, reactor coolant system flow rates, and pressure drops, if appropriate), comparisons with predictions and acceptance criteria …

- measurements of magnitudes of area radiation fields and radioactive effluents, and comparisons with the same parameters for operation of the HEU-fueled reactor and pre-established acceptance criteria …"

For the NBSR, extensive tests are not needed for several reasons. The proposed reload plan (Section 2) shows that the conversion will be gradual, with only either two or four fresh LEU fuel elements (FEs) placed in the core at the beginning of each cycle during the transition.

Hence, each reload fuel cycle is only a perturbation of a well-known core. Subcritical multiplication is normally monitored when the reactor is loaded from a fully unloaded condition—something that might be necessitated by a long shutdown. However, the assumption herein is that the loading of LEU fuel will take place as part of a normal refueling. There are no changes to the thermal-hydraulic design of the core and the impact of a heavier element (the weight of the fuel element increases from 11.4 kg to 12.7 kg) on the bypass flow is being determined by the aforementioned hydraulic tests at Oregon State University.

The objective of the formal startup plan that must be submitted to the NRC is the verification of compliance with license conditions. There are only a few technical specifications (NIST, 2010) ("Tech Specs"; specifically, "limiting conditions for operation") that need reconfirmation as a result of the change in fuel. The Tech Spec on reactivity limitations has a maximum allowable excess reactivity and minimum shutdown margin that must be confirmed. The Tech Spec on reactor control and safety systems has a maximum reactivity insertion rate for the shim arms that must be confirmed.

The excess reactivity is checked by measuring the critical shim angle and then the differential total shim arm worth (which in turn needs the measurement of the regulating rod worth). The shutdown margin is determined by knowing the excess reactivity and measuring the individual shim arm worths. The maximum reactivity insertion rate is known by measuring the maximum differential worth of the shim arms. Each of these measurements is currently part of the normal operating procedures for the NBSR [e.g., (NIST, 2014)]. None of these measurements are expected to show a significant change when the LEU fuel is loaded. For example, the calculated excess reactivity for the current core at startup is 6.7%$\Delta k/k$ and the corresponding number for the equilibrium (totally converted) LEU core is 6.3%$\Delta k/k$. The difference, 0.4%$\Delta k/k$, represents a small change taking place over several cycles.

As described in Section 2, the reload with LEU fuel takes place over a long period of time and includes many different core configurations, however, the formal startup tests need only be done at selected times during this process. One reason for this is that the critical shim arm position is measured at every startup as part of normal operations, and would alert to any reactivity anomalies and the regulating rod and shim arm worths are measured at least once a year--again independent of the fact that LEU is being added to the core.

The recommended times for the formal startup tests are:

- The start of the LAE cycles, i.e., when the first two LEU fuel elements are introduced into the core.
- The start of the final transition cycles, i.e., when the first loading of four LEU fuel elements takes place.
- The start of two cycles later; i.e., when there are 12 LEU fuel elements in the core and the core might be considered significantly fueled with LEU.
- The start of the eighth cycle loading four LEU fuel elements; i.e., when all 30 fuel elements are LEU elements.

Since the NRC requests (NRC, 1996) that a startup report be submitted within six months of startup, it is proposed that two reports be written: one within six months of the initial LEU loading and one after completion of all tests in the plan--possibly several years later, depending on the number of LAE cycles. The tests and the rationale for when they are performed are explained in more detail in the following sections.

3.2 Critical Shim Arm Position

The critical shim arm position is currently recorded at the startup of every fuel cycle when the reactor is at 1 MW. It is a check of the reactivity of the core and hence, it is an obvious part of the startup plan for each time there is significant change to the core loading.

An estimated critical position (ECP) is calculated (Eyers, 2015) every cycle as part of normal operations. It is based on how long the reactor was shut down before startup and the length of previous cycles; indications of the current excess reactivity. It also corrects for regulating rod position, coolant temperature and shim arm burnup. The acceptance criterion currently used for this measurement is ±1.0° (NIST, 2015), i.e., if the measurement is more than one degree away from the ECP the startup test is not acceptable and the reason for the discrepancy must be determined. The acceptance criterion is based on a comparison of the estimated and measured critical positions for many past cycles which showed that the difference was always within that band.

Data from three different shim arm position histories during the period 1995-2008 are shown on Figure 2. Each history corresponds to a different set of shim arms. The measured shim arm angles are at startup (before xenon buildup) and depend on the regulating rod position, the coolant temperature, the length of the previous cycle and, as shown on the graph, the number of cycles that the shim arms have been in the reactor (cycle number 1 corresponds to new shim arms). Also on the graph are calculations (connected by straight lines) for an idealized initial state but taking into account the impact of shim arm burnup. The calculations are based on the Monte Carlo model used to obtain the neutronics information used in the SAR. The data points before the burnup of the shim arms becomes important are within ~±0.5° and the calculation is ~0.5° below the average of the data.

When the first two LEU fuel elements are placed in the core, the excess reactivity is calculated to be reduced by 0.15%Δρ (Hanson, 2012). It is not surprising that this is a small perturbation as the LEU fuel is supposed to support the same operations as did the HEU fuel. The corresponding change in critical shim arm angle is obtained by noting that the calculation of shim arm differential worth with either HEU or LEU fuel is on the order of 0.6-0.7%Δρ/degree (Diamond, 2014). Hence, the LEU fuel would cause an increase in shim arm angle of (0.15/0.65) 0.23°, which is less than the normal expected uncertainty in shim arm position.

The suggested acceptance criterion for the shim arm critical position is that it should be within 1.0º of the normally calculated ECP. It is assumed that the ECP would at that time include a correction for LEU fuel. For the first LAE cycle the correction is +0.23° as calculated above. For the final eight transition cores (four FEs loaded each cycle) an example of the corresponding

changes is shown in (Hanson, 2013) taking into account an assumed, non-standard, cycle length for the first cycle.

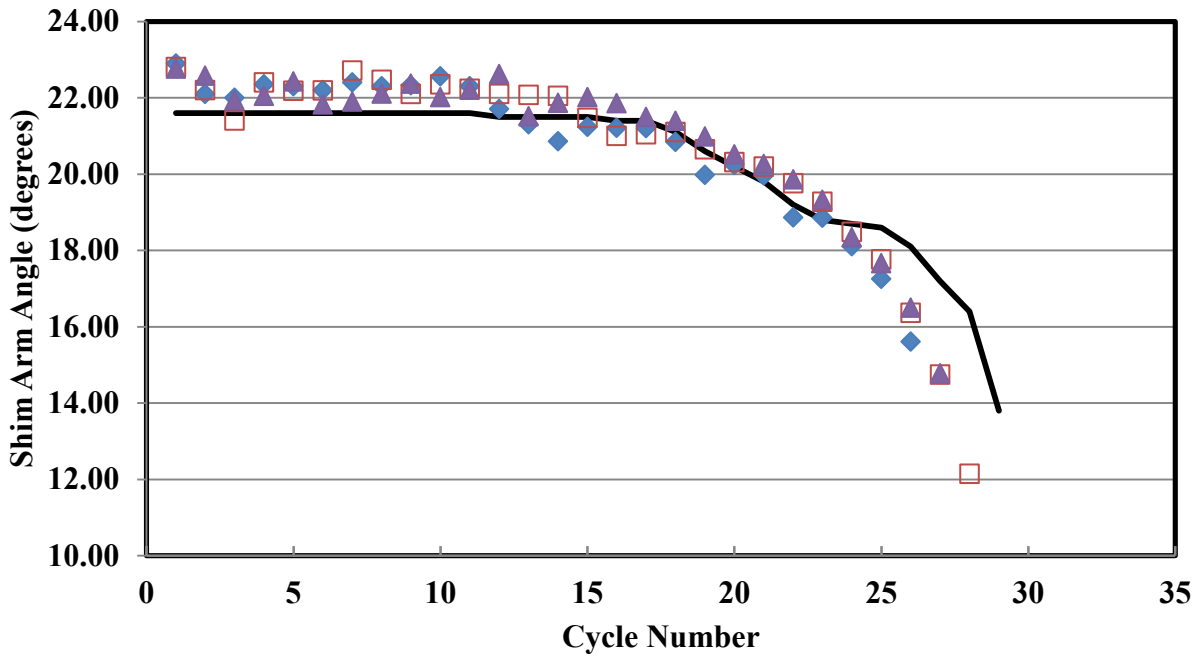

Figure 2. Critical Shim Arm Angle at Startup

3.3 Regulating Rod and Shim Arm Worth

The regulating rod and shim arm worth measurements are normally taken every year to assure that the excess reactivity, shutdown margin, and maximum reactivity insertion rate, are within Tech Spec limits. The procedures are given in (NIST, 2014).

The regulating rod worth is measured in a standard way by moving the rod from a critical state, measuring the resulting period and then using the inhour equation to determine reactivity. This is done with the regulating rod fully inserted and at three other initial positions until the rod is completely withdrawn. Once these data are obtained, the calculated differential shim arm worth can be fit to the measured data.

The shim arm worth measurements are of two types. The first is a measurement of differential shim arm worth at the critical configuration at startup. Differential worth is calculated to be at a maximum near this critical position. The shim arms are moved together, putting the reactor on a period that is used with the inhour equation to determine the worth/degree for that particular movement. This measurement is done with the regulating rod fully inserted and fully withdrawn. The higher of the two measurements, when multiplied by the measured speed of shim arm withdrawal, provides the maximum reactivity insertion rate for the shim arms. The acceptance criterion is the Tech Spec limit of 5×10^{-4} $\Delta\rho$/s.

The second type of measurement is the differential worth of individual shim arms. This is done starting with one shim arm completely inserted, the regulating rod withdrawn and the remaining shim arms at a critical position. The inserted shim arm is withdrawn while maintaining criticality until the regulating rod is fully inserted. The differential worth of the shim arm during that movement is the worth of the regulating rod measured as described above. The regulating rod is then withdrawn, with the three shim arms moving to compensate, so that the reactor is again at criticality and another measurement of a single shim arm movement can be made as before. This measurement is repeated several times until the shim arm being measured is totally withdrawn. This is possible as the regulating rod is only worth ~0.5%Δρ whereas a single shim arm worth is an order of magnitude larger. The core will reach a condition at the end of the set of measurements for a single shim arm when that arm is withdrawn and the regulating rod is inserted and the remaining three shim arms are at a critical position. Before the next shim arm is measured, the regulating rod is withdrawn and the three shim arms are inserted. An acceptance criterion for this condition is that the reactor must be shutdown with the one shim arm withdrawn and the others inserted. The shutdown margin for this condition requires analysis of the test results as explained below.

The results of the above measurements are the differential and total worths of each shim arm and their sum, i.e., the total worth of all shim arms. To determine if the excess reactivity is within the Tech Spec limit, one notes the initial critical position with all shim arms banked together. The worth of the shim arms moving from this critical position to fully withdrawn is defined as the excess reactivity. The acceptance criterion for the maximum excess reactivity is the Tech Spec limit of 15%Δρ.

The shutdown margin is based on the highest worth shim arm being withdrawn along with the regulating rod. Starting again from the just-critical shim arm position, the differential worth measurements of the shim arms provide the data that can be used to obtain the shutdown margin. The acceptance criterion for the minimum shutdown margin is the Tech Spec limit of 0.757%Δρ.

3.4 Other Tests

There are several other measurements that would not be part of the startup test report but are relevant. At every startup there is an extensive radiological survey throughout the reactor building and beyond. Any anomalous reading under normal operation, and certainly with new LEU fuel, would trigger an investigation.

There are also measurements that provide additional validation of the calculations used for operational and safety support. Measurements of neutron flux can be based on foil irradiations such as those used in the past to make measurements in the RT-2 rabbit facility in order to facilitate its use for activation analysis (Lindstrom, 2008 and Şahin, 2014). This provides a local measurement as opposed to a global measurement such as reactivity and is important as the most significant change in the reactor due to the replacement of the HEU with LEU is a shift of the peak flux distribution from the outer core to the inner core. Also of interest is any change in the energy spectrum of the neutron flux, although this is expected to be small (Brown, 2013). These measurements are probably most useful when the core is completely converted or at least no sooner than when there is significant LEU loading. More than ten different foil materials have

been used at the NBSR in the past and these can be used again to compare with the previous measurements in the HEU core. Other foils can be used if desirable and cadmium covered foils can be used to obtain the thermal-to-epithermal flux ratio. All measurements can be compared with the results of calculations.

Two reactivity coefficients that should be relatively easy to measure and will give additional assurance (relative to calculation) t hat the reactor has inherent negative feedback are the power coefficient and the isothermal temperature coefficient. The former is obtained by recording shim arm position (and hence reactivity) during a power ascension. The coefficient is obtained directly if coolant temperature remains constant or is obtained by subtracting out the effect of a coolant temperature coefficient if that temperature also changes. The coolant temperature coefficient measurement requires changing flow and/or heat exchanger conditions in order to increase inlet temperature and measuring shim arm position (and hence reactivity) to maintain constant power. Power would need to be low so that the result is truly an isothermal coefficient.

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