STARTUP REPORT

FOR THE

WASHINGTON STATE UNIVERSITY

NUCLEAR RADIATION CENTER

TRIGA REACTOR

APRIL 20, 2009

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WASHINGTON STATE UNIVERSITY

Nuclear Radiation Center

John Nguyen
U.S. Nuclear Regulatory Commission
Mailstop O12 D00
11555 Rockville Pike
Rockville, MD 20852-2738

April 17, 2009

Dear Mr. Nguyen,

Washington State University recently completed converting the WSU TRIGA reactor from operating on a mixed HEU/LEU core to a core fueled entirely by low enriched uranium. WSU is required to submit a Reactor Startup Report within six months of the return of the reactor to normal operation. The reactor was returned to steady-state operation in October 2008. Since that time the reactor has been operated at steady-state in order to build up ^{149}Sm to a relatively constant level before conducting pulse testing of the reactor. The pulse testing was performed in March, 2009 and the results were used to calculate pulsing limits. After pulse testing was completed it was determined that the reactor could be returned to normal operation, i.e. both steady-state and pulsing operations, as of April 13, 2009.

Please feel free to contact me anytime if there are any questions.

Respectfully Submitted

Donald Wall

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Washington State University
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1. EXECUTIVE SUMMARY

The Washington State University Nuclear Radiation Center (WSUNRC) converted its 1 MW TRIGA open pool research reactor from an HEU/LEU mixed core to a low enriched uranium (LEU) core. As part of the Global Threat Reduction Intuitive (GTRI), the HEU fuel that partially comprised the WSUNRC 1 MW reactor Core 34A was replaced with 30/20 LEU fuel. The new core is designated as Core 35A, an all LEU core composed of both new 30/20 fuel and the 8.5/20 fuel that comprised the LEU portion of the previous 34-A mixed core.

Core 34A was shutdown for the last time on Friday, September 19, 2008. All fuel was removed from the grid plate. On September 29, 2008, the U.S. Nuclear Regulatory Commission issued the order to convert, and the first 30/20 LEU cluster went on the grid plate at 1553 hours, thereby completing the U.S. Department of Energy conversion milestone for the WSU Reactor (WSUR).

Subsequent loading of LEU Core 35A commenced shortly thereafter, reaching criticality on October 7, 2008 at 1526 hrs. The LEU core was declared steady-state operational on October 17, 2008 after extensive testing and measurements prescribed in the Conversion Safety Analysis Report (2007 CSAR). Pulse testing on Core 35A was completed on March 6, 2009 utilizing the procedures outlined the 2007 CSAR. A timeline of the events is provided in Table 1.1.

Table 1.1 Summary timeline of conversion related events.

Date	Event
9/19/08	HEU/LEU Core 34A shutdown
9/23/08	Core 34A fuel and reflector unload complete
9/29/08	Graphite reflectors loaded into core Neutron source installed USDOE conversion milestone complete (1553 hrs)
10/7/08	LEU Core 35A goes critical (1526 hrs)
10/8/08	LEU Core 35A fuel loading complete
10/10/08	Graphite/fuel optimization complete
10/10/08	Final SDM and core excess complete
10/15/08	125% power scram test
10/17/08	Final power calibrations complete Core 35A Steady-State Operational
3/6/09	Pulse testing complete
4/15/09	Core 35A Pulse Operational

Steady-state operations have continued since the conversion date with all tests and measurements consistent with predicted behavior; however, the burn-in period required to establish steady-state samarium concentration in the new fuel is about 371 MWH. It is for this reason that flux measurements and core characteristics have not been measured at this time, and will be included in our 2008-2009 annual report to the USNRC. The experimentally measured and calculated values for the EOL Core 34A and BOL Core 35A are summarized in Table 1.2.

Table 1.2 Comparison table for Cores 34A and 35A with measured and calculated values.

	Core Number	35A (BOL)	35A (calculated)	34A (EOL)	34A (calculated)
Core Information	Core Type	30/20; 8.5/20; mixed LEU	30/20; 8.5/20; mixed LEU	8.5/70; 8.5/20; mixed HEU/LEU	8.5/70; 8.5/20; mixed HEU/LEU
	Critical Mass (g U-235)	[redacted]	[redacted]	[redacted]	[redacted]
Reactivity Parameters	SDM	(\$0.91)	(\$0.98)	(\$1.76)	(\$1.70)
	Core Excess	\$7.44	\$6.37	\$6.42	\$6.65
	Blade 1	\$1.44	\$1.34	\$1.60	\$1.32
	Blade 2	\$3.71	\$2.99	\$3.50	\$2.89
	Rod 3	\$3.20	\$3.19	\$3.08	\$3.22
	Blade 4	\$3.97	\$3.02	\$3.81	\$2.86
	Blade 5	\$0.16	\$0.43	\$0.16	\$0.40
	$\Delta\rho$ (1 MW)	\$2.38	\$2.52	\$2.20	\$1.45
Axial Average Thermal Flux[b] ($x10^{12}$ $n/cm^2 s$)	D8	N/A[a]	4.95	3.22	4.92 (5.18)
	D9	N/A[a]	1.44	N/A[a]	1.45 (2.10)
	E8	N/A[a]	4.35	3.33	4.35 (4.39)
	E9	N/A[a]	1.29	N/A[a]	1.30 (1.75)
Reactor Physics	β_{eff}	0.0075	0.0075	0.0070	0.0076
	void coeff. (per 1% H_2O)	N/A[a]	-0.135% $\Delta k/k$	N/A[a]	-0.080% $\Delta k/k$
	PNTC (-$\Delta k/k$-°C, 23-1000 °C)	N/A[a]	0.6×10^{-4} to 1.27×10^{-4}	N/A[a]	0.54×10^{-4} to 1.51×10^{-4}

(a) No data are available at this time.

(b) Values given for the axial average thermal neutron flux calculations are from MCNP5 and in parentheses, calculated from our WSUR in house Exterminator II code.

2. INITIAL CORE LOADING

2.1 Overview

The initial core loading process was carried out in accordance with the 2007 CSAR and our conversion SOP (CSOP). The procedure comprised a stepwise plan to refuel the WSUR with LEU fuel in core positions (CPs) where the FLIP fuel was located in Core 34A.

2.2 Core Loading

New graphite reflector elements were first installed in the same positions from which the old graphite reflector elements were removed CP F4 and F5, where used graphite reflectors were placed. The IFE cluster was installed into CP C4 and the IFE was inserted into C4NW and connected to the temperature indication units in the console. The pulse rod fuel assembly was installed into CP D5, followed by the new pulse rod in D5NW. The pulse rod system was completed, tested, and declared operational.

Calculations showed that criticality would occur with 11 partially burned 8.5/20 LEU clusters (44 fuel elements) and 10 new 30/20 LEU clusters (39 fuel elements) for a total of 21 LEU clusters (83 fuel elements) as detailed in the MCNP diagram, Figure 2.1 and Figure 2.2.

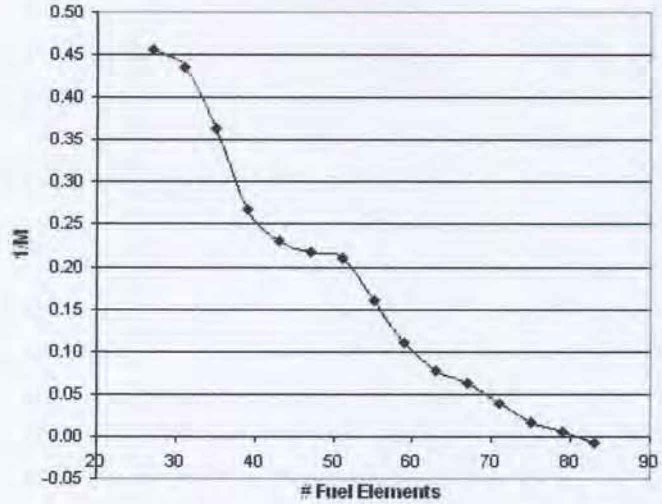

Figure 2.1 MCNP calculated Core 35A criticality assessment performed by GA.

[redacted]

Figure 2.2 MCNP plot of the GA predicted critical core configuration for Core 35A.

It was found that the neutron source, which was originally positioned in CP B6, did not have enough fuel between it and the detector to give a measurable increase in counts after loading each cluster. The problem was addressed after 12 clusters were initially put into the grid plate by moving the neutron source to CP G2. Criticality count rate measurements were then taken from a scaler in line with the fission detector as fuel was added to the core. The results are presented in Table 2.1.

Table 2.1 Subcritical multiplication data for Core 35A.

Elements added	Count rate (cpm)	1/M	Predicted total elements needed for criticality
51	14.8	1	
55	34.8	0.4253	58
59	57.6	0.2569	65.1
67	267.2	0.0554	69.2
71	613.2	0.0241	74.2
75	4377.2	0.0034	75.5

The loading of Core 35A continued and subcritical multiplication data were taken to determine the number of fuel elements required to achieve criticality. Core 35A went critical on October 7, 2008 at 1526 hrs. The criticality plot and corresponding core map are seen in Figure 2.3 and Figure 2.4. Calculations performed with MCNP at GA estimated 83 elements needed to achieve criticality, while experimentally; criticality was achieved with 79 elements, comprising a single 4-rod cluster difference. The number of elements to call the reactor *at least* critical was taken as 76 elements; however, the number of clusters needed to achieve at least a critical assembly required 79 elements.

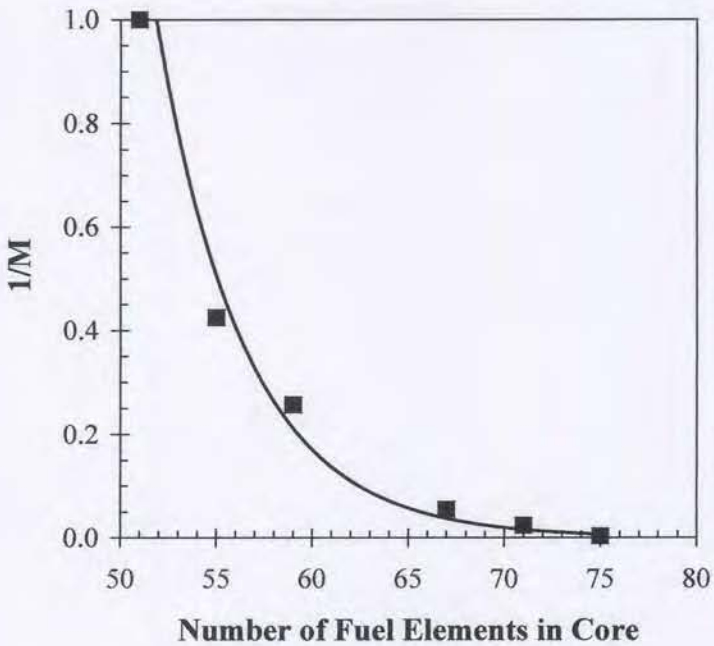

Figure 2.3 Measured criticality data from the initial core loading of Core 35A.

[redacted]

Figure 2.4 Core 35A map representing the point at which the WSUR went critical.

3. CRITICAL MASS

3.1 Overview

The critical mass is calculated from the number of elements needed to achieve criticality. In the case of WSUR Core 35A, this number is 79 elements, composed of partially burned 8.5/20 and fresh 30/20 fuel. The amount of uranium-235 comprising those specific elements is delineated as the critical mass. The amount of U-235 remaining in the 8.5/20 section of the core (44 elements total) was computed from the last SNM core inventory completed for the HEU/LEU core, for the period ending September 30, 2008.

3.2 Results

The inventory in the critical assembly for the 8.5/20 section of the core is [redacted] grams of U-235. The rest of the core is fresh 30/20 fuel, and the amount contained in this critical assembly is [redacted] g of U-235. Therefore, the total critical mass for WSUNRC Core 35A is [redacted] g of U-235. The calculations in the 2007 CSAR suggested that 83 elements were required to achieve criticality, accounting for [redacted] g U-235. This is a difference of only one 4-rod 30/20 fuel cluster.

4. SHUTDOWN MARGIN & EXCESS OPERATIONAL REACTIVITY

4.1 Overview

This section outlines the characteristics of the core excess as calculated by MCNP5 and actual measured values for Cores 34A and 35A. In addition, the calculated optimal configuration for Core 35A was found to exceed the maximum allowable excess reactivity value of 5.6% $\Delta k/k$ once assembled, because the new β_{eff} value of 0.0075 reduced the limit from \$8.00 for Core 34A to \$7.46 for Core 35A.

To resolve the situation, seven standard LEU fuel elements with a higher burn-up and lower U-235 content were moved into higher flux positions to reduce the overall reactivity of the core. Seven new reflectors were replaced by old reflectors, in postulating that they would be less efficient, and standard fuel was moved such that less reactive clusters were in higher power factor core positions.

Once a satisfactory core excess was obtained for the fueled core itself, four experimental rotator tubes, and experimental facilities were installed. Core 35A was then operated to accumulate enough burn up to build in samarium thereby allowing the flux distribution and poison levels to reach steady-state concentration. The amount of time required is 371 MWH on the new fuel.

4.2 Results

Core 34A was originally calculated to have an excess reactivity of \$6.65 by MCNP5. When this value was measured just prior to disassembly for the conversion, it was found to be \$6.31. This was an acceptable value, and was within the previous limit of \$8.00.

Core 35A was calculated by MCNP5 to have a core excess of $6.35. This value was experimentally determined to be $7.69 after Core 35A achieved criticality. The large discrepancy between the actual and calculated values is due to the discrepancy in the MCNP5 calculated and experimentally measured values for the control element reactivity worths.

Immediately following the core reload and once criticality was achieved with a completely fueled core on October 8, 2008, a shutdown margin was performed and the core excess was found to be $7.69. Calibrations were then performed on all four control blades and one control rod to ensure a precise core excess was calculated. The following day on October 9, 2008 a shutdown margin was performed with the freshly calibrated control elements and the core excess was calculated to be $7.65, still in excess of the acceptable value.

The following day, October 10, 2008 a combination of solutions was determined by the Facility Director, Reactor Supervisor, and the GA consultant assigned to the project. Old reflectors, which were thought to be less efficient, were placed into core positions B4, B5, B7, B8, G5, and G6 and a shutdown margin was performed. The core excess value was found to be higher at $7.75, and the new reflectors were replaced in these positions.

Standard elements S21 were moved from B1 to C2, and S03 from C2 to B1. The core excess was determined to be $7.60. Standard elements S26 were moved from F1 to E2, and S06 from E2 to F1. The core excess was determined to be $7.54. Standard elements S22 were moved from F3 to E2, and S27 from E2 to F3, S26 from E2 to F2.

The core excess was determined to be \$7.44 and which is below the upper limit in the technical specification of \$7.46.

With the core excess within acceptable limits, a power calibration at 750 kW, 1 MW, and two initial approaches to 1 MW were performed. The fission products produced by these actions further reduced the core excess to \$7.35 as determined on October 20, 2008. With the core now designated operational the four experimental rotator tubes were installed in positions E8, D8, E9, D9, with the cadmium lined tube in position E9. The final core excess of the operable core 35A was determined to be \$7.12 on October 20, 2008.

Core 35A was then operated at one megawatt on a regular basis to build up samarium in the core, which was estimated to require 371 megawatt hours to reach steady-state within 1% of the final value. Figure 4.1 traces the core excess from October 10, 2008 to February 17, 2009 and shows the build-in of fission product poisons, mainly ^{149}Sm, as the WSUNRC procedures for SDM measurements to be with a cold-clean core, free of xenon poisoning. The ^{149}Sm buildup accounts for approximately \$7.44 – \$6.86 = \$0.58 ($k_{ex(BOL)} - k_{ex(current)}$) of negative reactivity contribution from neutron poisons in the core. It is important to note that the core as of February 17, 2009 has 367 MWH of burn up, and as such the equilibrium between samarium production and removal has not been achieved, seen in Figure 4.1.

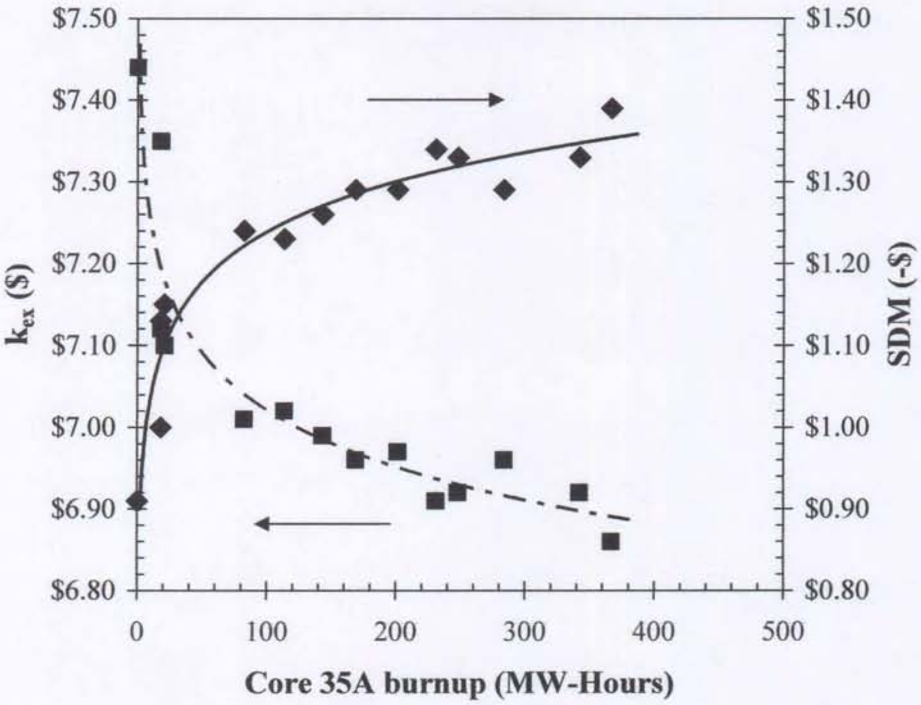

Figure 4.1 Core excess (■, – — –) and shutdown margin (♦, —) calculations based on experimental data taken after Core 35A was loaded and brought to an acceptable core excess value of $7.44.

5. REGULATING AND SAFETY CONTROL ROD CALIBRATIONS

5.1 Overview

Control elements are calibrated at the WSUR by taking the reactor critical at ten watts with the blade that is undergoing calibration fully inserted. The blade is sufficiently withdrawn to achieve a stable period of 30 seconds, and the doubling time from 200-400 watts and 300-600 watts is measured. This data is used to calculate the integral worth of each control element.

5.2 Results

Following the conversion from Core 34A to Core 35A there were some minor changes in blade worth for each of the five control elements, shown in Table 5.1.

Table 5.1 Measured and calculated control element worths for Cores 34A and 35A.

	Core 35A BOL		Core 34A EOL	
	Measured	Calculated	Measured	Calculated
Blade 1	$1.44	$1.34	$1.60	$1.32
Blade 2	$3.71	$2.99	$3.50	$2.89
Rod 3	$3.20	$3.19	$3.08	$3.22
Blade 4	$3.97	$3.02	$3.81	$2.86
Blade 5	$0.16	$0.43	$0.16	$0.40
Total	$12.48	$10.97	$12.15	$10.69

The calculated values shown in Table 5.1 reflect deviations in the measured values from MCNP5 calculated blade worths in Core 35A, resulting in the discrepancies reported in Section 4.2. From these values it is clear that the MCNP models under-predict control element worths for control elements 1, 2, 3, 4 and over-predict the worth of control element 5 for BOL Core 35A.

6. REACTOR POWER CALIBRATION

6.1 Overview

The Washington State University TRIGA reactor is calibrated using a calorimetric process. Per the WSUNRC SOPs, the reactor was isolated on the west side of the pool by placing a large divider door over the pool divider opening. A stable, homogenous pool temperature was then obtained utilizing the primary coolant loop and a pool mixer. The coolant temperature was monitored and plotted in five minute intervals until stable (< 0.1 °C/h). The reactor was then brought quickly to one megawatt and maintained at this power level by control element manipulation for forty minutes, while recording the primary coolant temperature at five minute intervals.

After forty minutes, the condition of the reactor was recorded in the reactor log, and the reactor was shut down by manual SCRAM forty five minutes after achieving power. The coolant temperature continued to be monitored and plotted in five minute intervals. After a time period sufficient to provide indication of relatively constant rate of pool temperature decrease, the reactor power level was calculated using the plotted data.

The initial and final pool temperatures were extrapolated from the calculated mid-time on the graph of coolant temperature vs. time. Change in pool temperature was determined and the heating time (startup to SCRAM) was recorded. From this data the temperature rise per hour was calculated by dividing the average rise in temperature by the heating time.

To obtain the actual power level of the reactor, the temperature rise per hour was divided by the tank constant for the WSUR (5.90 °C/Hr/MW). The positions of the in-core detectors are adjusted to obtain a correct reading if the observed and calculated power levels differ by more than 5%.

Power calibrations were performed for Core 35A in its pre-operational and operational core configurations, illustrated in Figure 6.1 and Figure 6.2. This was done to characterize the core in its most basic configuration, as well as the configuration most utilized at the WSUR for experiments and irradiations.

[redacted]

Figure 6.1 Core 35A in its pre-operational arrangement, without experimental or irradiation facilities installed.

[redacted]

Figure 6.2 Operational Core 35A arrangement containing experimental and irradiation facilities installed into or around the grid plate.

6.2 Pre-Operational Power Calibrations: 25%, 75%, and 100% Power

Power calibrations were performed on Core 35A with the neutron source in core position G2, no rotator tubes, experimental or irradiation facilities installed, except for the H-position iridium irradiation location holders H-2 through H-7. These holders were left empty for all of the pre-operational calibrations. Figure 6.3 shows the temperature traces for pre-operational calibrations at 25%, 75%, and 100% power.

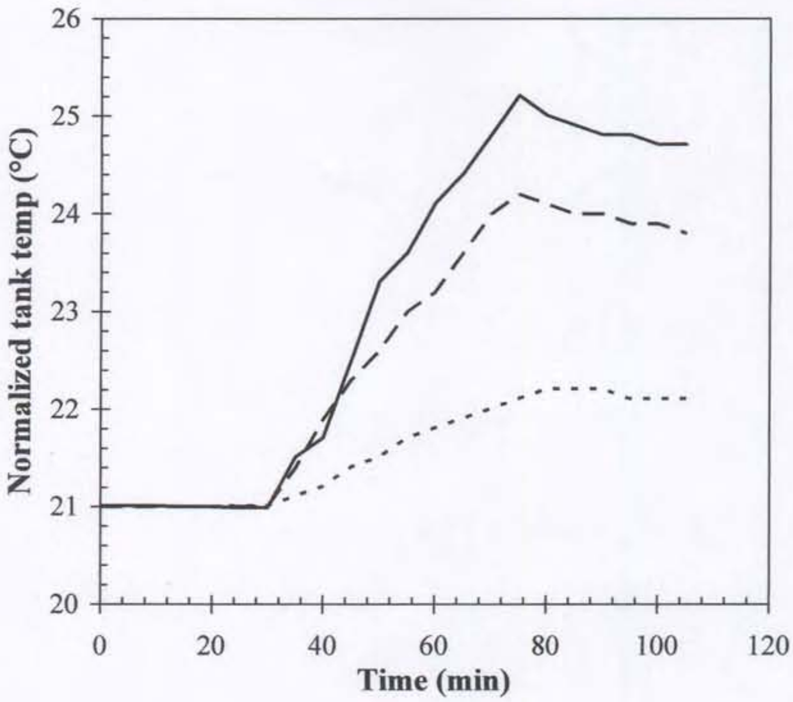

Figure 6.3 Reactor power calibrations for pre-operational Core 35A at 25% (calculated 24.9%, - - -), 75% (calculated 70.6%, — —) and 100% (calculated 102%, ——) power. Initial temperatures and times are offset to the lowest temperature recorded and the first rise in temperature, respectively.

6.2.1 25% Power Calibration

Table 6.1 Power calibration at 25% of full power on nuclear instrumentation.

	Control element positions (in)					**Power channel indications (% 1 MW)**			**Fuel Temp. (°C)**
	No.1	No.2	No.3	No.4	No.5	CIC	UIC	Log-N	
Start:	7.17	6.54	14.99	6.62	13.06	25	24	25	144
Finish:	6.72	6.76	14.99	6.75	12.20	25	25	26	149

Calculated Power: 0.249 MW

The channels were providing accurate information of the core at lower power levels. This determination allowed for the continuation of the calibrations with a second power calibration at 75% power.

6.2.2 75% Power Calibration

Table 6.2 Power calibration at 75% of full power on nuclear instrumentation.

	Control element positions (in)					Power channel indications (% 1 MW)			Fuel Temp. (°C)
	No.1	No.2	No.3	No.4	No.5	CIC	UIC	Log-N	
Start:	8.05	8.05	15.11	8.04	11.12	76	74	75	273
Finish:	7.80	8.10	15.11	8.10	9.80	74	70	75	268

Calculated Power: 0.706 MW

This calibration confirmed that the channels were providing reasonably accurate information of the core at intermediate power levels. This determination allowed the staff to continue with a third power calibration at 100% power.

6.2.3 100% Power Calibration

Table 6.3 Power calibration at 100% of full power on nuclear instrumentation.

	Control element positions (in)					Power channel indications (% 1 MW)			Fuel Temp. (°C)
	No.1	No.2	No.3	No.4	No.5	CIC	UIC	Log-N	
Start:	8.26	8.25	15.11	8.27	11.05	100	94	100	302
Finish:	8.26	8.25	15.11	8.25	11.49	100	94	100	301

Calculated Power: 1.02 MW

The reactor was brought to the same power level for calibration adjustments. The UIC position was adjusted to read 100% at the corresponding power channel in the console.

6.3 Initial 100% Power Calibration for Operational Core 35A

6.3.1 Operational Power Calibration at 100%

Another power calibration was deemed necessary with all the experimental and irradiation facilities installed in the core to see how the additional in-core material would affect flux and change channel readings at full power, illustrated in Figure 6.1. The attempted power calibration at 100% power showed that the core was actually reaching only 90.2% power, shown in Table 6.4. Upon completion of this calibration each of the detectors were raised out of core until each channel read the correct level of 90% power.

Table 6.4 Power calibration at 100% of full power on nuclear instrumentation. Calculated power from measured data shows actual core power at 90.2% power.

	Control element positions (in)					Power channel indications (% 1 MW)			Fuel Temp. (°C)
	No.1	No.2	No.3	No.4	No.5	CIC	UIC	Log-N	
Start:	8.62	8.60	15.11	8.57	11.09	100	98	100	303
Finish:	8.43	8.61	15.11	8.57	9.80	100	98	100	302

Calculated Power: 0.902 MW

6.3.2 Operational Power Calibration at 90% for Verification

After consulting with GA, another power calibration was performed at 90% power to verify the accuracy of our nuclear instrumentation, as the last power calibration showed 100% power when the reactor was actually at 90%.

Table 6.5 Power calibration at 90% of full power for verification on nuclear instrumentation after detector adjustment.

	Control element positions (in)					Power channel indications (% 1 MW)			Fuel Temp. (°C)
	No.1	No.2	No.3	No.4	No.5	CIC	UIC	Log-N	
Start:	8.54	8.54	15.13	8.52	11.69	92	92	90	301/271
Finish:	8.52	8.49	15.12	8.55	9.97	92	92	90	304/276

Calculated Power: 0.905 MW

This power calibration confirmed that the reactor was operating at 90% power with the experiment facilities installed and that the current power channel settings adequately indicated power level.

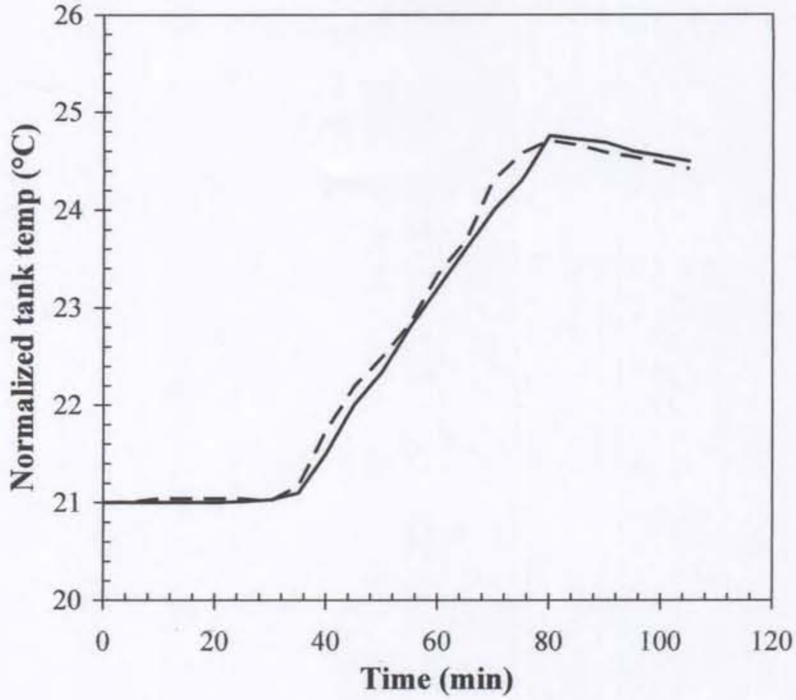

Figure 6.4 Reactor power calibrations for pre-operational Core 35A at 100% (calculated 90.2%, ——) and then again at 90% power (calculated 90.1%, — —) after detector movement. Initial temperatures and times are offset to the lowest temperature recorded and the first rise in temperature, respectively.

6.3.3 Final BOL Core 35A Operational Power Calibration at 100%

One more power calibration at full power was performed to confirm proper channel operation at 100% of 1 MW. For this power calibration, the AIIF and C8 and F8 irradiation baskets as well as all H positions and rotator tubes were in core with the neutron source remaining in position G2.

Table 6.6 Final power calibration at 100% of full power on nuclear instrumentation.

	Control element positions (in)					Power channel indications (% 1 MW)			Fuel Temp. (°C)
	No.1	No.2	No.3	No.4	No.5	CIC	UIC	Log-N	
Start:	8.53	8.52	15.12	8.55	11.06	100	100	100	314/283
Finish:	8.48	8.48	15.12	8.49	12.60	100	100	100	314/284

Calculated Power: 1.002 MW

Successful completion of this calibration at full power with all pertinent experimental facilities installed confirmed the operational status of the power channels.

6.4 Post-Conversion Calibrations

All post-conversion power calibrations have been within specifications for operational Core 35A.

7. THERMAL FLUX DISTRIBUTIONS

Preliminary measurements of thermal neutron flux in irradiation position D8 have been made. This was done by neutron activation of ^{63}Cu, ^{58}Fe, ^{59}Co, and ^{197}Au. The value was found to be 7.3×10^{12} n/cm^2/s. This is higher than a previously determined value of 4×10^{12} n/cm^2/s in the same irradiation position. However, it should be pointed out that the uncertainty associated with the Core 34A value is not known. Flux values for the other irradiation positions in Core 34A are unknown.

8. REACTOR PHYSICS MEASUREMENTS

Reactor physics measurements have not been made at this time. The measurements will be completed shortly. Table 1.2 provides the results for the calculated and measured values that we do have for BOL Core 35A and EOL Core 34A.

9. PRIMARY COOLANT MEASUREMENTS

The primary coolant bulk pool water was analyzed by gamma spectrometry. A 500 mL water sample was taken after at least four hours of operation at 1 MW. It was then counted on a GeLi gamma detector for 80,000 seconds.

The primary coolant pool water was analyzed on October 29, 2008 and November 24, 2008 for sealed source radioactivity. In addition, an analysis was performed on the same samples to look for evidence of fission product release that might occur at levels not picked up by the continuous air monitor (CAM). There was no indication of a release.

10. PULSE MEASUREMENTS

10.1 Overview

The variable heat capacity, along with the rod power factors, radial, and axial peaking factors can be used to predict peak temperatures for fuel rods. Previously, the WSU mixed core utilized standard TRIGA and FLIP fuels that had the same uranium loading (8.5% by weight), and thus both fuel types had very similar heat capacities. At present, the WSU reactor has fuels with significantly different uranium loadings (8.5% and 30%) which leads to fuels with heat capacities that discernibly different. However, for the purpose of calculating temperature peaking in the hot rod position, and in the central core region, which is populated only by 30/20 fuel, it is sufficient to use the heat capacity value for 30/20 fuel. This will establish temperature peaking values for two reasons: first, power peaking takes place in the 30/20 region, and second, the 30/20 fuel has a smaller heat capacity, and thus will reach higher peak temperatures than the standard TRIGA fuel for the same energy and peaking factors.

10.2 Calculation of Pulsing Limit

The heat capacity for 30/20 TRIGA fuel may be determined by the same means used to calculate the heat capacity for 8.5/20 standard TRIGA fuel. The expression used to determine the heat content for values greater than 25 °C for δ-phase ZrH_x for various stoichiometries (i.e. values of $x < 1.65$) is:

$$0.03488T^2 + (34.446 + 14.8071(x - 1.65)T - 882.95 - 370.18(x - 1.65)) \text{ joules/mole} \quad (1)$$

For 30/20 TRIGA fuel, x = 1.6, which yields the following equation:

$$0.03488T^2 + 33.706T - 864.44 \text{ J/mol} \quad (2)$$

The enthalpy for uranium metal that has been previously used to calculate standard TRIGA heat capacity is given by

$$6.483 \times 10^{-5} T^2 + 0.1087T - 2.758 \text{ J/g} \quad (3)$$

Using a density of 5.610 g/mL for $ZrH_{1.6}$ and 19.05 g/mL for the density of uranium metal, the density of 30% U/ZrH1.6 is calculated as follows.

$$0.70 \text{ g } ZrH_{1.6} / 5.610 \text{ g/mL} = 0.1248 \text{ mL } ZrH_{1.6} \quad (4)$$

$$0.30 \text{ g U}/19.05 \text{ g/mL} = 0.0157 \text{ mL} \quad (5)$$

Therefore, the total volume of 1 gram of 30/20 TRIGA fuel is 0.1405 mL, giving a density of 7.115 g/mL. The volumetric heat content is given by the sum of the heat contents for the $ZrH_{1.6}$ and uranium metal contributions. For 1 mL of fuel the number of moles of $ZrH_{1.6}$ is given by

$$(7.115 \text{ g})0.70/ 92.83 \text{ g/mol} = 0.05365 \quad (6)$$

And the number of grams of uranium metal in 1 mL of fuel is given by

$$7.115 \text{ g fuel} \times 0.30 \text{ g U/g fuel} = 2.1345 \text{ g U} \quad (7)$$

The volumetric heat content of the $ZrH_{1.6}$ phase is given by

$$0.05365 \text{ mol/mL}(0.03488T^2 + 33.706T - 8.64.44 \text{ J/mol}) =$$

$$= 1.871 \times 10^{-3}T^2 + 1.808T - 46.377 \text{ J/mL} \quad (8)$$

The volumetric heat content of the uranium metal is given by

$$(2.1345 \text{ g U/mL fuel}) \times (6.483 \times 10^{-5} T^2 + 0.1087T - 2.758 \text{ J/g}) =$$

$$= 1.384 \times 10^{-4}T^2 + 0.2320T - 5.887 \text{ J/mL fuel} \quad (9)$$

Adding the volumetric heat content for $ZrH_{1.6}$ and uranium metal gives the volumetric heat content for the fuel:

$$2.009 \times 10^{-3}T^2 + 2.04T - 52.264 \text{ J/mL} \quad (10)$$

Taking the derivative with respect to temperature gives the heat capacity

$$2.04 + 4.018 \times 10^{-3}T \text{ J/mL °C} \quad (11)$$

By comparison, the heat capacity value for standard TRIGA fuels that was previously calculated at WSU is $2.17 + 4.36 \times 10^{-3}T$ J/mL °C. Thus, the heat capacity of 30/20 fuel is about 6% less than standard TRIGA (and FLIP) fuel at low temperature, and increases at a lower rate with increasing temperature, due to the higher uranium loading.

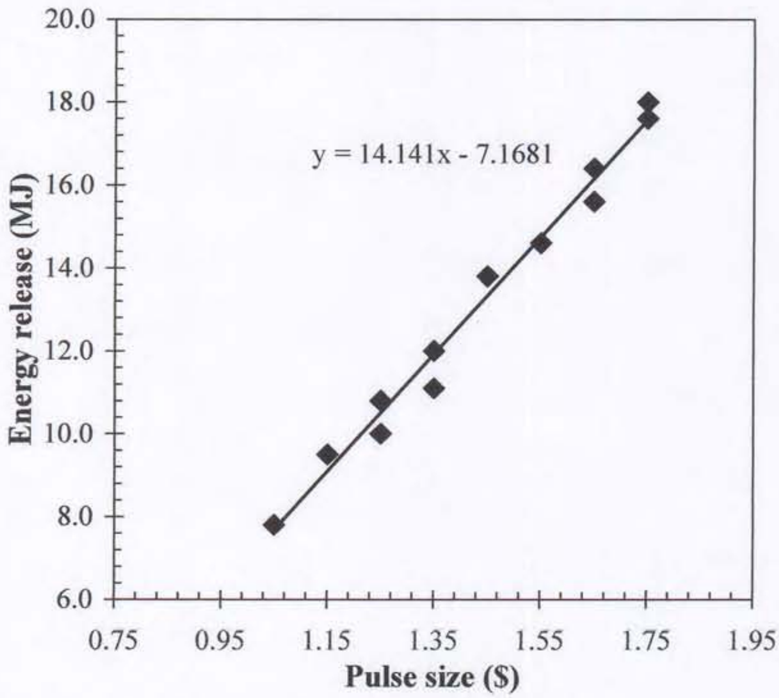

Figure 10.1 Energy release versus pulse size for Core 35A.

The equation in Figure 10.1 for the best fit line is y = 14.14x – 7.17; it should be noted that the energy release drops very rapidly for reactivity insertions less than $1, to the point where they become difficult to accurately measure. Rod power factors, radial and axial peaking factors for the hot rod position, D4NE, and the IFE position, C4NW, are given in Table 10.1.

Table 10.1 Power factors for Core 35A.

	D4NE (25 °C)	D4NE (280 °C)	C4NW (280 °C)	C4NW (280 °C)
RPF	2.56	2.47	1.56	1.56
Radial	1.27	1.19	Not available	Not available
Axial	1.35	1.29	1.454	1.454
RPF × R × A	4.39	3.78	2.70[a]	3.51[b]

(a) The product of RPF × R × A was determined by using the radial peaking factor for the hot rod in D4NE, i.e. 1.19.

(b) The product of RPF × R × A was determined by using the radial peaking factor for the core average, i.e. 1.55.

WSU has historically used a peak allowable fuel temperature of 795 °C for pulse limit calculations in order to account for measurement uncertainty—the Technical Specification limit for peak fuel temperature is 830 °C for pulsing. Using a starting temperature of 30 °C, (giving $T_f - T_i = 765$ °C) one may calculate the peak allowable energy density using equation 12, when heat the variable heat capacity equation takes the form illustrated in equation 11.

$$Cp = C_0 + C_1 T \quad (11)$$

$$E = C_0\left(T_f - T_i\right) + \frac{C_1}{2}\left(T_f - T_i\right)^2 \quad (12)$$

$$(2.04 \text{ J/mL °C} \times 765 \text{ °C}) + (4.018 \times 10^{-3} \text{ J/mL °C}^2 \times (765 \text{ °C})^2)/2 =$$

$$= 1560.6 + 1175.7 = 2736 \text{ J/mL} \quad (13)$$

Using total fuel volume of 343.42 mL/rod × 119 rods = 40,867 mL, the peak allowable energy density of 2736 J/mL and a peaking factor of 4.39, one can calculate the peak allowable energy release:

$$\frac{2736 J/mL \times 40{,}867 mL fuel}{1\times10^{6} J/MJ \times 4.39} = 25.47 MJ \tag{14}$$

Given the relationship between energy release and pulse size, i.e.

$$\text{Energy release (MJ)} = 14.14\ \text{MJ/\$} \times \text{pulse size (\$)} - 7.17\ \text{MJ} \tag{15}$$

one can calculate the maximum allowable pulse size:

$$\frac{25.47 MJ + 7.17 MJ}{14.14 MJ/\$} = \$2.31 \tag{16}$$

10.3 Conclusions

The similarity of pulsing limits arises because the energy output of Core 35A is smaller for a given pulse size than was the case with Core 34A. A comparison of the energy release by Cores 34A and 35A is given in Figure 10.2.

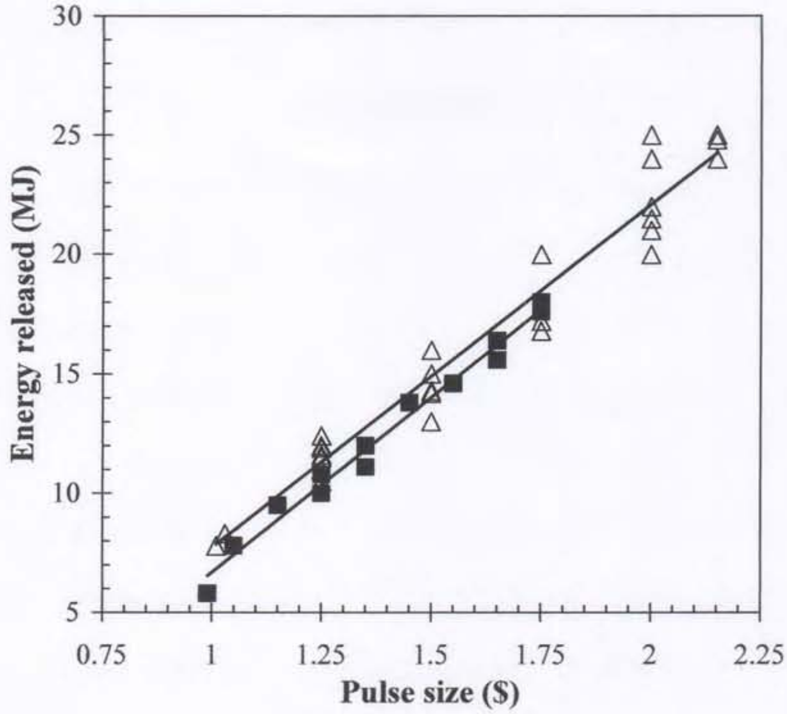

Figure 10.2 Energy release versus pulse size comparisons for Core 34A (Δ) and 35A (■).

WSU has an administrative pulsing limit of $2.00, which requires any pulse larger than $2.00 to be approved by both the Reactor Supervisor and Facility Director. Pulsing limits for Core 34A and Core 35A are similar, even though the heat capacity of the 30/20 fuel is about 6% smaller than FLIP fuel.

It is evident that Core 35A has a consistently lower energy release than Core 34A, for the same size pulses. Coupled with the difference in heat capacities therefore causes similar temperature peaking between the two cores. As a result, the WSUR calculated maximum pulse will be set at $2.31, and our administrative pulsing limit for Core 35A will remain at $2.00. Pulse testing will continue to confirm the pulsing limit calculations.

11. DISCUSSION OF RESULTS

The WSUR is the only mixed core comprising 8.5/20 and 30/20 fuel in existence. Moreover, the calculations done for this conversion were unique because the 8.5/20 fuel was partially burned, while the 30/20 fuel was fresh. Error is to be expected here due to fuel burn up calculations in preparation for predicting BOL Core 35A; however, all of the calculations were within reason when compared to the measured values for the new mixed core. The codes used were benchmarked by comparisons with the previous mixed FLIP/STD Core 34A measured and calculated values.

In all aspects, the conversion went relatively smoothly, with no major setbacks. Problems did arise with a higher than predicted (and allowed) core excess, which was fixed by rearranging graphite and fuel into different orientations within the same core arrangement. That is, no 8.5/20 fuel was switched for 30/20 fuel or graphite, and vice versa. With the conversion is now complete, LEU Core 35A is completely steady-state and pulse operational.