NC STATE UNIVERSITY

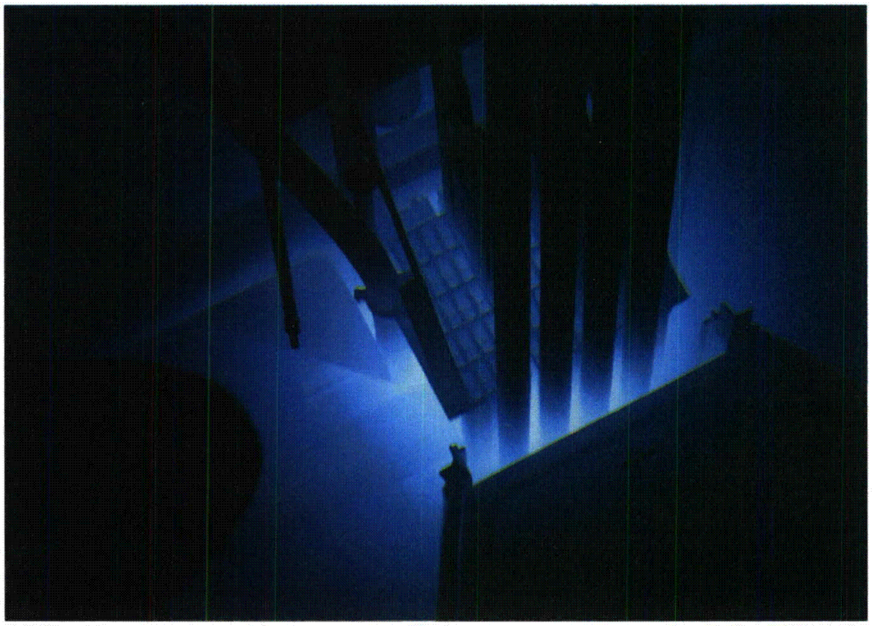
LICENSE AMENDMENT

FOR THE USE OF 6% ENRICHED FUEL

Nuclear Reactor Program

NORTH CAROLINA STATE UNIVERSITY

RALEIGH, NORTH CAROLINA 27695



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AMENDMENT REQUEST

Availability of licensed 4% fuel for the NCSU PULSTAR Reactor is limited to the quantities currently on-hand. NCSU obtained fresh, un-irradiated 6% fuel from the BMRC PULSTAR after it permanently shutdown. In order to continue operations, it is necessary for the NCSU PULSTAR to utilize both the current 4% and the 6% fuel in a mixed enrichment core configuration.

Section 2.B.(2) of the PULSTAR Operating License[1] authorizes the use of reactor fuel that is enriched to less than 20 percent.

Technical Specification 5.1.a[2] requires a change for the use of 6% enriched UO_2. Currently the Specification states:

> *The reactor fuel shall be UO_2 with a nominal enrichment of 4 percent in U-235, zircaloy clad, with fabrication details as described in Section 3 of the Safety Analysis Report.*

The amendment request changes Specification 5.1.a to the following:

> *The reactor fuel shall be UO_2 with a nominal enrichment of 4 percent and/or 6 percent in U-235, zircaloy clad, with fabrication details as described in the Safety Analysis Report.*

Amending this one specification will permit the use of both 4% and 6% enriched fuel while maintaining all other specifications. This ensures that the NCSU PULSTAR can continue to operate safely and reliably while staying within the licensing basis of the current Safety Analysis Report[3].

FACILITY INTRODUCTION

The North Carolina State University PULSTAR Reactor was manufactured by the American Machine and Foundry Company (AMF). The design, fabrication, and installation are based on the proven prototype located at the Buffalo Materials Research Center (BMRC) at the State University of New York at Buffalo that operated through the mid-1990s using uranium dioxide (UO_2) fuel that is 6% enriched in ^{235}U. The NCSU PULSTAR is a light water moderated and cooled thermal reactor that uses UO_2 fuel enriched to 4% in ^{235}U. Initial criticality of the PULSTAR occurred in September 1972. It is operated by the Department of Nuclear Engineering within the College of Engineering. The NCSU PULSTAR operates at steady state power levels up to one megawatt-thermal. The NCSU PULSTAR was originally designed to be pulsed routinely to 2200 MW peak power with a 38 MW·sec total energy release. However, it no longer operates in pulse mode.

The NCSU PULSTAR core is a heterogeneous system of light water and UO_2 fuel, which provides a source of neutrons for research purposes. The core is immersed under twenty feet of water in an open pool. The reactor pool is lined with aluminum and surrounded on the sides and bottom by concrete shielding.

Control of the power level is accomplished by variable positioning of neutron absorbing rods within the core. These control rods as well as the various neutron detecting chambers used for power level measurement, are suspended from a bridge which spans the reactor pool. The reactor is operated from a console located in a control room visible from the bridge.

The NCSU PULSTAR has a number of design features which make it an extremely safe research reactor. The first of these features is the use of low enriched UO_2 in pellet form as fuel. This provides an inherent safety shutdown feature due to the fuel temperature feedback (Doppler effect).

The heat capacity of UO_2 is quite large, permitting a large release of energy in the core under transient conditions without exceeding the melting point of the cladding. The low thermal diffusivity of UO_2 leads to a long thermal time constant for the fuel (approximately 4 seconds). The long time constant prevents the explosive formation of steam experienced in plate-type metallic reactors undergoing severe reactor transients. The time constant for a typical plate-type aluminum alloyed fuel assembly for instance, is on the order of a few milliseconds.

Considerable experience and information has been gathered on the characteristics of UO_2 under irradiation conditions. The chemical and radiation stability of UO_2 is known to be excellent. The ability of UO_2 to retain fission products is also excellent and provides a strong motivation for the use of UO_2 aside from the obvious advantages in performance. Use of the fuel in pellet form ensures against the rapid release of energy which could occur through loss of clad integrity and the subsequent dispersion of fuel into the coolant if the fuel were in powder form.

The nuclear power industry has generated a significant quantity of information on the properties of zircaloy and on operating experience with zircaloy clad UO_2 fuel. Therefore, the clad material is considered a proven material for reactor use. The high melting temperature of zircaloy may be considered a distinct advantage for use in a reactor core.

One of the strongest arguments for the inherent safety of the PULSTAR core is its similarity to the SPERT oxide core, which has undergone extensive testing[4]. Transients releasing as much as 100 MW·sec of energy have been initiated in the SPERT core without causing damage. The use of sintered pellets instead of powdered fuel is an added safety feature. The only serious defect discovered in SPERT tests was the presence of a double peaked pulse caused by coherent bowing of the fuel pins. The coherent bowing was eliminated when the pins were supported in a fashion that provided an 18 inch unsupported length of pin instead of the unsupported length of 6 feet. The PULSTAR fuel is designed to provide an unsupported length of only eight inches so that coherent bowing is not a problem. These supports also serve as wear surfaces to prevent damage to the fuel pin cladding.

As mentioned above, a PULSTAR reactor was operated at a power of 2-MWth at the BMRC in Buffalo, New York, from 1964 to 1995 with UO_2 fuel enriched to 6% in ^{235}U and reaching burnup limits that exceed 15,000 MWD/MTU. Based on the BMRC experience, the operational experience of the NCSU PULSTAR to date, and the supporting analysis (see Appendix A), the performance of the NCSU PULSTAR core under mixed (4% and 6%) enrichment conditions is shown to meet the licensing limits as set forth in its SAR and technical specifications.

FUEL COMPARISON

The North Carolina State University PULSTAR Reactor has been designed to operate for extended periods of time at a power level of 1-MWth, in a manner similar to the pool type reactors fueled with plate type elements. The core is fueled by what is basically light water reactor (LWR) fuel, i.e., four percent enriched UO_2 pellets. The reactor core is comprised of twenty-five fuel assemblies. Each assembly as shown in Figure 1, contains twenty-five fuel pins as shown in Figure 2. Each pin consists of a zircaloy-2 tube of 0.02 inch wall thickness, filled with sintered UO_2 pellets and sealed at the top and bottom. The uranium is enriched to 4 percent by weight in the ^{235}U isotope. Each pellet measures 0.423 inches in diameter and 0.6 inches in length. The finished fuel pin is 0.474 inches in diameter and 26 inches long. Approximately 20.2 grams of ^{235}U are contained in each pin.

Twenty-five pins are fastened mechanically into bundles and are placed in a zircaloy-2 box open at the top and bottom with a cross section measuring 2.74 inches by 3.15 inches. The upper end fittings and the lower end fitting (nosepiece) are attached, bringing the overall length of the assembly to 38 inches. A bail is inserted between side plates at the top of the assembly to serve as a handle for moving the assembly. There are also two alignment holes in the shoulder of the lower end fitting which mate with pins on the grid plate to prevent misalignment of the assemblies in the core. Openings are provided at the sides of each fuel assembly box to allow coolant flow if the top of the fuel assembly should become blocked by a foreign object. The fabrication of the PULSTAR fuel assemblies is in accordance with AMF Specification APR-1[5].

The SUNY BMRC PULSTAR had a 20 fuel assembly core of six percent enrichment, and was licensed to operate at a steady-state power level of 2-MWth and to pulse routinely. The North Carolina State University PULSTAR is a modified version of the BMRC PULSTAR. A comparison of the significant operating parameters for the BMRC and NCSU design is as follows:

TABLE 1 - COMPARISON OF NCSU AND BMRC PULSTAR REACTORS

OPERATING PARAMETER	NCSU	BMRC
Design Steady-state Power (MW)	1	2
Mass UO_2 per core (kg)	359	287
Uranium Enrichment (w% U-235)	4	6
Maximum Specific Energy Release (MW·sec/gram)	310	490
Original Design Pulse Peak Power (MW)	2200	2000
Original Design Pulse Energy Release (MW·sec)	38	40

The NCSU PULSTAR fuel is identical to the BMRC PULSTAR fuel except for the difference in enrichment. The BMRC PULSTAR fuel pin dimensions were verified and documented in procedure HP 11 – Inspection, Shipment, and Receipt of New Fuel Form NCSU/PULSTAR-1A *Fuel Pin Data Sheet* upon receipt of the fuel from BMRC. Refer to Table 2 and Figures 1 and 2 for a comparison of the two fuels. [3,5,6,7,8,9]

TABLE 2 - COMPARISON OF NCSU AND BMRC FUEL PINS		
	NCSU	BMRC
Fuel		
Material	UO_2	
Form	Sintered Pellets	
Enrichment (w% ^{235}U)	4%	6%
Density (gm/cm^3)	10.5 – 10.76	10.3
^{235}U per Fuel Pin (gm)	20.2	30.7
Fuel Pin		
Pellet Diameter (in)	0.423	
Diametrical Gap (in)	0.0085	
Zircaloy-2 clad thickness (in)	0.4725	
Rectangular Spacing (in)	0.606 × 0.524	
Clearance, pin to pin (in)	0.051 × 0.133	
Clearance, pin to box (in)	0.025 × 0.066	
Height of Pellet Stack (in)	24	
Height of Pellet (in)	0.60	

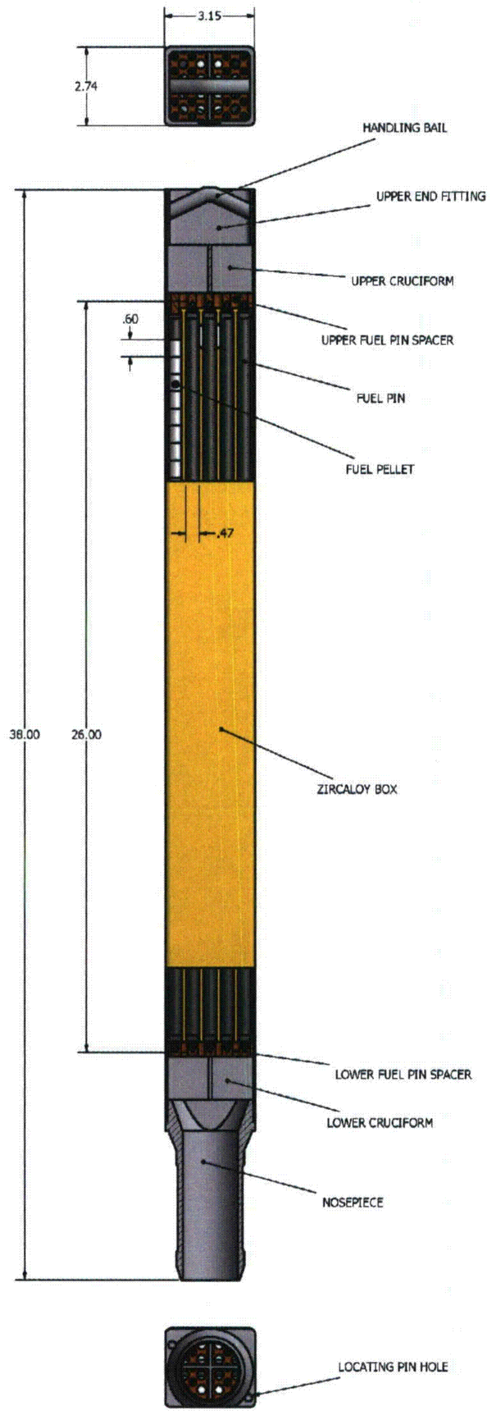

FIGURE 1 - PULSTAR FUEL ASSEMBLY

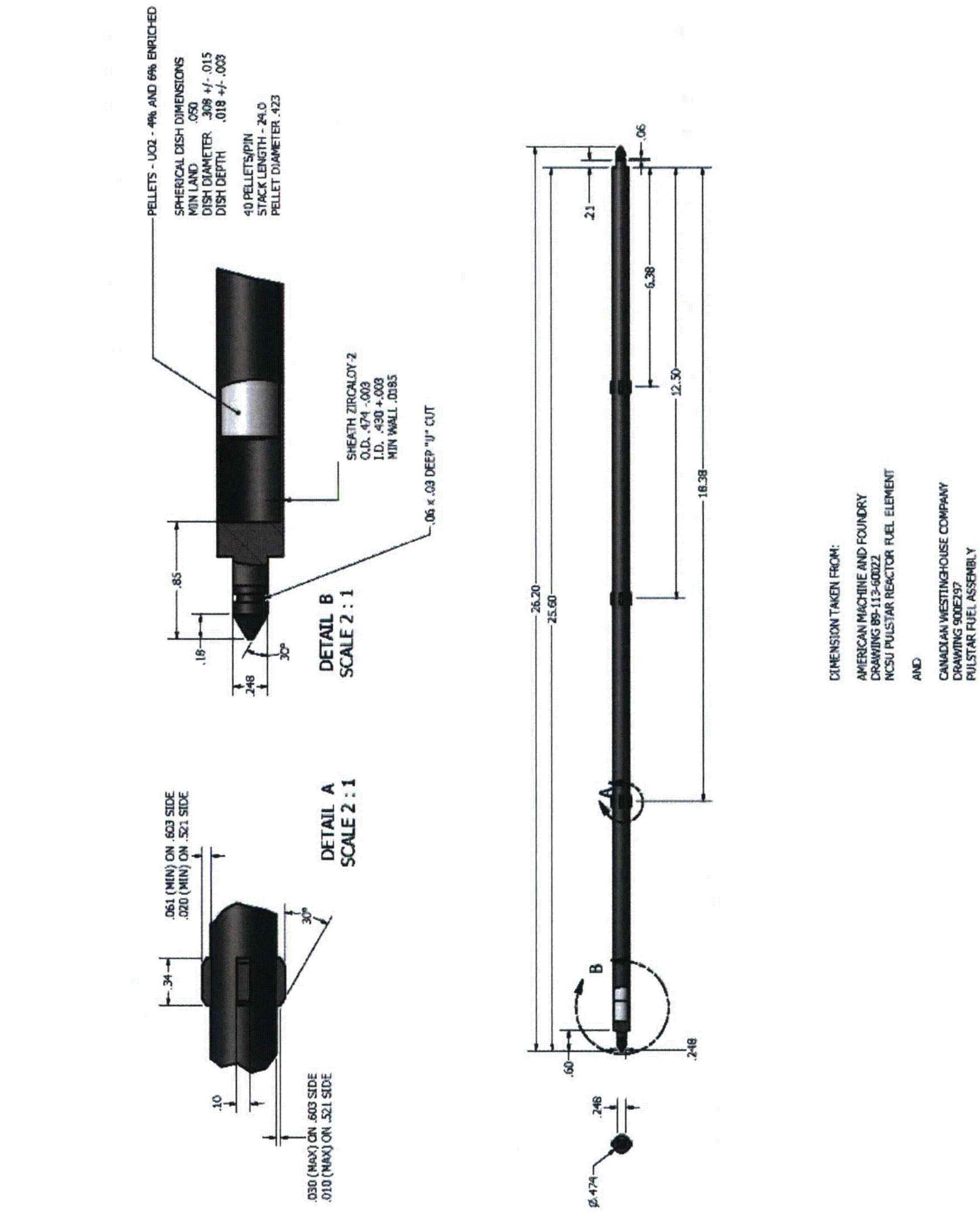

FIGURE 2 - PULSTAR FUEL PIN

SUPPORTING ANALYSIS APPROACH

Simulations using the Monte Carlo code MCNP6 were performed using a model of the NCSU PULSTAR Reactor core to quantify the impact of operating a mixed enrichment core with regard to the limits set forth in the Technical Specifications (see discussion below and Appendix A).

The model was verified and validated against current and historical data and used to predict if the following Technical Specifications would still be satisfied:

SECTION 3.1.e	*The maximum worth of a single fuel assembly shall not exceed 1590 pcm.*
SECTION 3.1.f	*The total nuclear peaking factor in any fuel assembly shall not exceed 2.92.*
SECTION 3.2.a	*The shutdown margin, with the highest worth scrammable control rod fully withdrawn, with the shim rod fully withdrawn, and the experiments at their most reactive condition, relative to the cold critical condition, is greater than 400 pcm.*
SECTION 3.2.b	*The excess reactivity is not greater than 3970 pcm*
SECTION 3.2.d	*The rate of reactivity insertion of the control rods is not greater than 100 pcm per second (critical region only).*

The core grid plate is an array of 6x6 fuel assembly locations that provides maximum flexibility in the arrangement of fuel assemblies, reflectors and experimental locations. Various potential core configurations using 6% fuel were modeled to explore acceptable representative and unacceptable configurations. Due to the flexible design of the NCSU PULSTAR Reactor core several acceptable representative core configurations were found.

The implemented fuel loading approach for new mixed enrichment (4% and 6%) core configurations will be:

1. Use the established MCNP model to predict a core loading pattern that meets the licensed technical specifications limits.
2. Configure the core according to the predicted loading pattern.
3. During startup testing, use existing procedures to confirm the MCNP predictions of *maximum worth of a single fuel assembly, total nuclear peaking factor, shutdown margin, excess reactivity, and rate of reactivity insertion of the control rods.*[10,11,12,13]
4. If any of the quantities in step 3 do not meet the licensed technical specifications limits, the reactor will be shut down.

The above approach will be implemented using established PULSTAR reactor procedures.

SUMMARY OF RESULTS

Methodology

The Monte Carlo code MCNP6 was utilized to model the NCSU PULSTAR reactor core under various configurations and to simulate its steady-state neutronic characteristics. The simulations covered all PULSTAR cores since 1972 and to date. In addition, new configurations using 4% and 6% enriched fuel were simulated. The ENDF/B-VII cross-section libraries were used in the simulations. These libraries were modified using the NJOY code when necessary to generate Doppler broadened and/or thermal scattering cross section libraries. The MCNP neutronic analysis is described in Appendix A.

For confirmation of the MCNP simulation, results were compared to data collected from all historic core configurations including the current core. Resulting values for excess reactivity, rod worth and peaking factors were compared to measured data. Additional calculations were performed to characterize the reactivity coefficients for the current 5x5 Reflected Core Number 8. Various representative core configurations using 6% fuel were modeled and analyzed to identify acceptable and unacceptable configurations.

Reactivity Coefficients

All feedback coefficients are calculated to be sufficiently negative to support an overall negative feedback for the reactor for all credible operating conditions. Table 3 below summarizes the results of the analysis for the current Reflected Core 8 and for representative new (mixed enrichment) cores. It also gives experimentally estimated data for the historical cores.

Moderator Temperature Coefficient

The moderator temperature coefficient in the BMRC PULSTAR core for the temperature range of 100°F to 140°F was measured to be -3 pcm/°F. The actual measured and predicted values for the NCSU PULSTAR cores are listed in Table 3.

Using MCNP results this coefficient was estimated with a linear comparison between the cold clean condition and the zero power condition; where the zero power condition was defined to be at an isothermal core temperature of 100°F.

The moderator temperature coefficient is calculated to be -3.44 pcm/°F for the current Reflected Core Number 8 and between -2.38 pcm/°F and -3.44 pcm/°F for new core configurations

Fuel Temperature Coefficient

The fuel temperature coefficient in the BMRC PULSTAR core for a fuel temperature range of 100°F to 332°F was computed to be -1.5 pcm/°F. The average fuel temperature coefficient for the NCSU PULSTAR was measured to be -1.6 pcm/°F and is based upon a fuel temperature range of 100°F to 193°F. The actual measured and predicted values for the fuel temperature coefficient for the NCSU PULSTAR cores are listed in Table 3.

The fuel temperature coefficient is calculated to be -1.66 pcm/°F for the current Reflected Core Number 8 and between -1.58 pcm/°F and -1.68 pcm/°F for new core configurations.

Void Coefficient

The measured and predicted values for the void coefficient for the NCSU PULSTAR cores are listed in Table 3.

The void coefficient is calculated to be -1.09 pcm/cm^3 for the current Reflected Core Number 8 and between -1.08 and -1.16 pcm/cm^3 for new core configurations.

TABLE 3 - REACTIVITY COEFFICIENTS OF THE NCSU PULSTAR

Core	Moderator Temperature [pcm/°F]	Fuel Temperature [pcm/°F]	Void [pcm/cm^3]
5×5 Standard Core	-3.2	-1.4	-1.03
5×5 Reflected Core No.1	-3.4	-1.8	-1.60
5×5 Reflected Core No.3	-3.9	-1.6	-1.60
5×5 Reflected Core No.4	-3.9	-1.6	
5×5 Reflected Core No.5	-3.9	-1.6	
5×5 Reflected Core No.6	-3.9	-1.6	
5×5 Reflected Core No.7	**	-1.6	
5×5 Reflected Core No.8 – Measured	**	-1.6	
5×5 Reflected Core No.8 – Calculated (see Appendix A, Table 4.2)	-3.44	-1.66	-1.09
Mixed Core Configurations Calculated (see Appendix A, Table 4.2)	-2.38 to -3.44	-1.58 to -1.68	-1.08 to -1.16

**This measurement was not performed for Reflected Core Number 7 and 8

Technical Specification 3.1.e – Maximum fuel assembly worth

The MCNP calculated maximum fuel assembly worth for acceptable core configurations are all below the 1590 pcm limit. The maximum fuel assembly worth for a 6% fuel assembly in permitted representative new core configurations is calculated to be 1075 pcm.

Technical Specification 3.1.f – Total Nuclear Peaking Factor

The peaking factor (F_Q) for the current Reflected Core Number 8 is 2.56. In Table 4, for representative new cores 9-1 and core 9-2 configurations, the calculated peaking factors range from 2.51 to 2.54, which are considered to be within the acceptable margin to the limit of 2.92 (see Appendix A). Also listed in Table 4 are configurations that are considered outside the acceptable margin to the limit (core 9-3 and core 9-4). Appendix A gives details of this analysis.

TABLE 4 - CALCULATED PIN POWER PEAKING FACTORS OF THE NCSU PULSTAR for Core 8 and REPRESENTATIVE LOADINGS of CORE 9

Configuration	Peaking Factor (F_Q)
Current Reflected Core Number 8	2.56
Single 6% assembly added (see Appendix A, Table 4.1, Figure 4.3)	2.52 - 2.57
6% added to F2 and F6 (Core 9-1) (see Appendix A, Table 4.2)	2.51
6% added to F4 and D6 (Core 9-2) (see Appendix A, Table 4.2)	2.54
6% added to F2, F4, F6 (Core 9-3) (see Appendix A, Table 4.2)	2.59
6% added to the entire F row (Core 9-4) (see Appendix A, Table 4.2)	2.78

Technical Specification 3.1.a – Shutdown margin

The shutdown margin of the reactor must be greater than 400 pcm. It is calculated that all new core configurations will meet this criterion. The measured and predicted shutdown margins for the various NCSU PULSTAR cores are listed in Table 5.

Technical Specification 3.1.b – Excess reactivity

The excess reactivity of the reactor is limited to 3970 pcm. The measured and predicted excess reactivity for the various NCSU PULSTAR cores are listed in Table 5. It is calculated that the addition of 6% fuel for the representative new core configurations will raise core excess reactivity to between 2895 pcm and 3735 pcm which is below the limit of 3970 pcm.

Technical Specification 3.2.d – Rate of reactivity insertion of the control rods

The control rods have a withdrawal rate of 7.5 inches per minute. The maximum rate of reactivity insertion by the ganged control rods is limited to 100 pcm/sec. The measured and predicted insertion rates for the various NCSU PULSTAR cores are listed in Table 5. The calculated insertion rate for the control rods for representative new configurations is between 62 and 68 pcm.

TABLE 5 - REACTIVITY PARAMETERS OF THE NCSU PULSTAR			
Core	Shutdown Margin [pcm]	Excess Reactivity [pcm]	Reactivity Insertion Rate [pcm/sec]
5×5 Standard Core Measured	3104	2047	47
5×5 Reflected Core No.1 Measured	3462	2102	52
5×5 Reflected Core No.3 Measured	2031	2890	48
5×5 Reflected Core No.4 Measured	3858	1588	53
5×5 Reflected Core No.5 Measured	3145	1991	55
5×5 Reflected Core No.6 Measured	3459	1881	56
5×5 Reflected Core No.7 Measured	2041	2839	56
5×5 Reflected Core No.8 Measured (current)	1612	2442	57
5×5 Reflected Core No.8 Calculated	2812	2604	68
Mixed Core Configurations Calculated (see Appendix A, section 4.3, Table 4.2)	1253 – 2661	2895 – 3735	62–68

Safety Implications

It is shown that the addition of 6% fuel to the PULSTAR core produces power distributions and kinetic parameters that are within the current operating limits (see Appendix A). Because of this and the fact that this amendment remains within the bounds of the current Safety Analysis Report and its Technical Specifications, the accident analysis and its associated conclusions (as presented in Chapter 13 of the PULSTAR SAR) are considered to remain valid for the anticipated mixed enrichment (4% and 6%) core configurations of the PULSTAR core.

CONCLUSION

Analysis has been performed demonstrating that the PULSTAR reactor can be operated with cores containing fuel enriched to 4% and 6% in 235U while meeting the current Technical Specifications limits and operational objectives. The analysis is detailed in Appendix A. Representative core configurations were identified that utilize both the current NCSU 4% fuel and the BMRC 6% fuel. Furthermore, as the analysis maintained all the licensed safety related limits of the PULSTAR reactor, it is concluded that the BMRC 6% fuel can be used safely and reliably and such activity can be conducted in compliance with all regulations and license requirements.

REFERENCES

1 North Carolina State University PULSTAR Reactor Operating License No. R-120, Docket No. 50-297, April 30, 1997.

2 North Carolina State University PULSTAR Reactor Technical Specifications Amendment 17, Operating License No. R-120, Docket No. 50-297, September 8, 2008.

3 North Carolina State University PULSTAR Reactor Updated Safety Analysis Report, Operating License No. R-120, Docket No. 50-297, 1997.

4 Evaluation of the Qualification of SPERT Fuel for Use in Non-Power Reactors, NUREG-1281, U.S. Nuclear Regulatory Commission, August 1987.

5 Specifications for PULSTAR Fuel Assemblies APR-1 Revision 5, American Machine and Foundry Co., York Division, April 1970.

6 AMF Drawing 89-113-60022 – NCSU PULSTAR Reactor APR Fuel Element, American Machine and Foundry Co., February 1, 1970.

7 Buffalo Materials Research Center Hazards Summary Report, Revision II, September 23, 1963.

8 Buffalo Materials Research Center Safety Evaluation Report, NUREG-0982, U.S. Nuclear Regulatory Commission, May 1983.

9 North Carolina State University PULSTAR Reactor Procedure HP 11 – Inspection, Shipment, and Receipt of New Fuel.

10 NRP-OP-301 Reactor Fuel Handling Rev 2, Approved October 2014.

11 PS-8-3-1 Core Flux Mapping Rev 0, Approved October 2014.

12 SP3.5 Gang Rod Worth Verification Rev 1, Approved January 1998.

13 PS 8-1-1:M1 Excess Reactivity and Shutdown Margin Calculation Rev 0, Approved April 1998.