Appendix A

Examination of Mixed Enrichment Core Loading for the NCSU PULSTAR Reactor

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Summary

MCNP6 simulations were performed of the 1 MWth North Carolina State University (NCSU) PULSTAR reactor core to quantify the potential for the utilization of UO_2 fuel assemblies that are enriched to 6% in ^{235}U within the currently licensed Technical Specifications. The fuel assemblies belonged to the "sister" PULSTAR reactor that was located at the Buffalo Materials Research center (BMRC) at the State University of New York (SUNY) at Buffalo. Except for enrichment, these assemblies are identical in materials and configuration to the assemblies that are currently in use at the NCSU PULSTAR. Moreover, their utilization at BMRC was demonstrated up to a power of 2 MWth. The constructed MCNP6 model was found to yield good agreement with operational PULSTAR data including measurements of excess reactivity (Figure 3.2), rod worth (Table 3.2) and assembly peaking factors (Figure 3.3). Using this model, key technical specification parameters were predicted for representative core configurations that include mixed enrichment (4% and 6%) loading of fuel assemblies (see Figures 4.3 – 4.9 and Tables 4.1 – 4.3). The examined mixed enrichment configurations based on the loading of one 6% assembly or two 6% assemblies (e.g., reflected core 9-1 and 9-2) have been found to meet such limits with substantial margin. In addition, for configurations such as cores 9-1 and 9-2 the pin power peaking factor remains below the limit by a set 15% margin. In all cases, the PULSTAR was shown to maintain its overall negative feedback behavior with a power coefficient of less than -300 pcm/MW. Consequently, these results indicate that the insertion of 6% fuel in pre-selected locations of the PULSTAR core should meet the limits set by the current Technical Specifications.

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1.0 Introduction

1.1 Objective

The objective of this work is to examine the use of a mixed enrichment core design that utilizes unirradiated 6% enriched fuel from the BMRC at SUNY Buffalo with 4% enriched fuel (currently resident in the core) to operate the NCSU PULSTAR reactor. A total of nine 6% fuel assemblies are available for utilization in the PULSTAR core. All mixed enrichment core configurations are required to be analyzed and shown to meet the current licensed Technical Specifications (TS) of the PULSTAR before loading in the core and utilization in reactor operations.

1.2 Background

The PULSTAR reactor is an open-pool 1 MWth reactor. Its core is composed of an array of 5×5 fuel assemblies with 6×6 available fuel positions. The empty assembly positions have traditionally been used to house either graphite or beryllium reflectors (see Figure 1.1 below). Each assembly is composed of a 5x5 array of UO_2 fuel pins that are enriched to 4% in ^{235}U. The reactor has been operated under eight core configurations for 1541 MWd with a core average burn-up of less than 5 GWd/MTU and a corresponding maximum fuel burn-up and assembly average burn-up of no more than 15 GWd/MTU and 10 GWd/MTU, respectively. Control of the core is achieved through the movement of three Ag-In-Cd (80%-15%-5%) control rods. A fourth control rod of the same composition exists; however, this rod was designed for reactor pulsing in the original core configuration and has since been disabled, remaining locked in position above the core. The core is surrounded by six experimental beam tubes which penetrate the concrete reactor biological shield into the pool and may be emptied of water to permit the streaming of neutrons to experimental facilities external to the reactor pool. Of these beam ports three are empty, and lower the available excess reactivity of the core. During operation the reactor is generally at full power; however, most reactivity properties, specifically excess reactivity and control rod worths, are referenced to the cold clean state. The reactor states are defined in Table 1.1.

Table 1.1 Definition of reactor states

Reactor State	Power (MW)	Bulk Moderator Temperature (°F)	Average Fuel Temperature (°F)
Cold Clean	0	70	70
Hot Zero Power	< 0.0001	100	100
Full Power	1	105	293

1.3 Methods

The MCNP6 Monte Carlo code was used for this work to simulate the PULSTAR reactor [1]. The results of the MCNP simulations were compared to historically measured data collected during the operation of the PULSTAR starting in 1972. Subsequently, the MCNP model was used to predict core characteristics for the current core and for potential core configurations that include 6% enriched assemblies. The MCNP6 code was selected due to its capability to model with high fidelity three dimensional geometries, which is of particular importance to modeling small heterogeneous cores, and for its ability to account for core depletion in the analysis. Details of the MCNP6 analysis are given in Section 3.

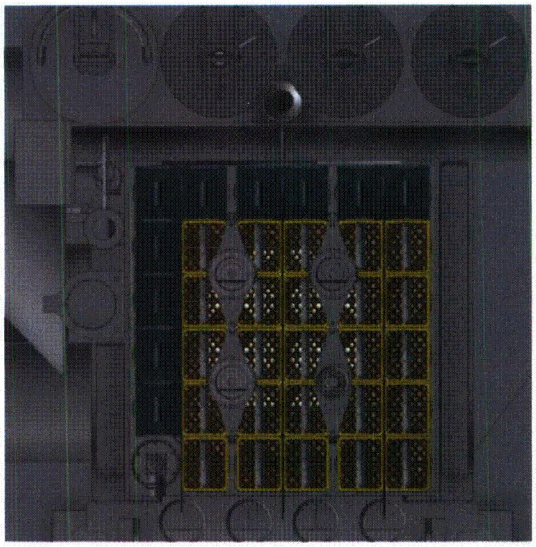

Figure 1.1. A schematic of the PULSTAR reactor core and surroundings in its current configuration (i.e., reflected core 8). The dark squares on the top and left sides of the core represent the beryllium reflectors.

1.4 Excess Reactivity History

The initial 5×5 unreflected core, the standard core, had a measured excess reactivity of 2047 percent milli-rho (pcm). To date reflected core 8 has a measured excess reactivity of 2442 pcm. The core has demonstrated an excess reactivity below the licensed limit of 3970 pcm over the entire power history from September 1972 to the current date [2]. A brief overview of the historical core configurations is listed in Table 1.2 (see layouts in Figure 3.1). The measured excess reactivity over the power history is summarized in Figure 1.2. Each core in the excess reactivity history is labeled by a number corresponding chronologically to the core name in Table 1.2. Current reactivity consumption is estimated to be 0.2 pcm/MWhr.

1.5 Excess Reactivity Needs

Operational demand for experimentation requires that the reactor be maintained at full power for 30-40 hours per week, resulting in a burn-up of approximately 300 pcm per year. To continue operation of the PULSTAR, fresh fuel must be loaded in the core to ensure sufficient excess reactivity. To satisfy the operational need for excess reactivity, it is proposed to utilize the nine 6% enriched UO_2 assemblies from the Buffalo PULSTAR reactor [3,4], currently in the possession of the NCSU PULSTAR facility. The current net operational excess reactivity is approximately 692 pcm accounting for experiments, feedback, and equilibrium xenon effects. The minimum excess reactivity required for routine operation of 6-8 hours daily at 1 MW is nearly 1750 pcm, as summarized in Table 1.3. A drop below this value will prevent the reactor from achieving criticality. Therefore, the PULSTAR is expected to become xenon limited in approximately 2.3 years.

Table 1.2 Summary of core configurations of the NCSU PULSTAR research reactor

Core Name	Operation	Core Configuration/Modifications	Operation Dates
1-Standard Core	0-95 MWd	5x5 array of 4% enriched assemblies	Aug-1972 to Feb-1977
2-Reflected Core 1	95-162 MWd	5 Graphite reflectors inserted in row A6-E6	Apr-1977 to Jun-1979
3-Reflected Core 3	162-861 MWd	Fuel movement from A1-A5 to F2-F6; 5 Graphite reflectors inserted in A1-A5	Jun-1979 to Mar-1999
4-Reflected Core 4	861-969 MWd	Graphite reflectors in A1-A5 replaced with 5 Beryllium reflectors	Mar-1999 to Jun-2005
5-Reflected Core 5	969-1186 MWd	Beryllium reflectors moved to A2-A6; Graphite reflectors moved to A1, B1 and D1-F1; Fuel reconfigured and 5 fresh 4% enriched assemblies inserted in C1 and B6-E6	Jun-2005 to Jun-2009
6-Reflected Core 6	1186-1241 MWd	3 Graphite reflectors in D1-F1 moved to C1-E1; Fission chamber moved from F6 to A6; Fuel reconfigured and assemblies removed in reflected core 5 inserted into C3-C5 and E3-E4	Jun-2009 to Oct-2010
7-Reflected Core 7	1241-1425 MWd	Fuel reconfigured and 4 assemblies replaced with fresh 4% assemblies inserted into C3 and D3-D5	Oct-2010 to Nov-2011
8-Reflected Core 8	1425-Current MWd	Graphite reflectors in A1-E1 replaced with Beryllium reflectors	Nov-2011 to Current

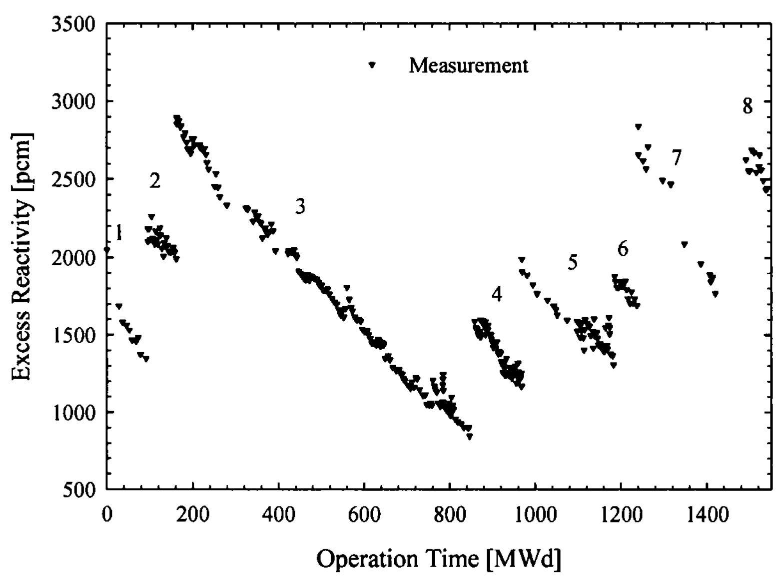

Figure 1.2. NCSU PULSTAR reactor core and excess reactivity history. The labels for each region correspond to the core configurations in chronological order, as listed in Table 1.2.

Table 1.3 Estimated minimum excess reactivity – routine operations

Xenon	300 pcm
Isothermal Temperature Coefficient	120 pcm
Power Defect (1 MW)	330 pcm
Beam-Tube 4&5 (present core)	150 pcm
Beam-Tube 6 (positron array)	750 pcm
Rotating Exposure Ports	100 pcm
TOTAL	1750 pcm

2.0 PULSTAR Core Configurations

Available historical data from measurements of excess reactivity, control rod worth values, shutdown margin, and power peaking factors for each core configuration provide information for confirming neutronic calculations and models including the effects of fuel burn-up and core shuffling. The fuel and reflector positions for each core configuration listed in Table 1.2 are illustrated in chronological order in Figure 3.1 below. Each fuel assembly is labeled according to its numeric index in the upper right corner, enrichment in the lower right, and core position in the upper left. This labeling allows the movement of individual assemblies to be modeled and tracked during burn-up calculations while including the core configuration changes. Although the nominal fuel enrichment is specified as 4%, the enrichment specified by the fuel manufacturer is 4.026% [2,5]. This value was used to simulate the starting composition of the original 1972 "Standard" PULSTAR core.

3.0 MCNP Core Modeling and Comparison to Historical Data

3.1 Core Model

MCNP6 was utilized to model the steady-state neutronic characteristics of PULSTAR reactor [1]. The model geometry and material compositions were set according to OEM specifications (i.e. manufacturer datasheets) and recent measurements of core components. For all materials the ENDF/B-VII cross-sections libraries were used [6]. The temperatures of the moderator and fuel materials were modified using the TMP card of MCNP to the temperature corresponding to the simulated core state, as defined in Table 1.1. Cross-section libraries were modified using the NJOY99 code to capture the thermal neutron scattering in light water and Doppler broadening for the resonances in ^{235}U and ^{238}U [7]. The hydrogen library for H_2O was generated using the standard "H in H_2O" input available for the NJOY99 package [7]. The moderator density was set to the corresponding value at 1 atm at the temperature for the core state, as define in Table 1.1, using the NIST database [8,9]. The corresponding parameters and processed ENDF/B-VII library for each defined core state are listed in Table 3.1.

3.2 Methods for Calculation of Core Reactivity Parameters

The PULSTAR reactor MCNP model was compared to the historical measurements of excess reactivity (as illustrated in Figure 1.2), rod worth values, shutdown margin, and power peaking factors. Modeling of the PULSTAR over the power history included the effects of burn-up and fuel movement, as illustrated by the core configurations in Figure 3.1. Additional comparisons were made for reflected core 8 by comparing measurements of assembly worth performed in May 2014 to MCNP6 calculations.

Table 3.1 MCNP parameters and data library processing for defined core states

Reactor State	Power (MW)	Temperature (°F)		ENDF/B-VII Temperature (MeV)		Moderator Density (g/cm^3)
		Moderator	Fuel	Moderator (H in H_2O)	Fuel (^{235}U, ^{238}U)	
Cold Clean	0	70	70	2.516×10^{-08}	2.516×10^{-08}	0.99797134
Hot Zero Power	< 0.0001	100	100	2.536×10^{-08}	2.536×10^{-08}	0.99304969
Full Power	1	105	293	2.703×10^{-08}	3.602×10^{-08}	0.99200516

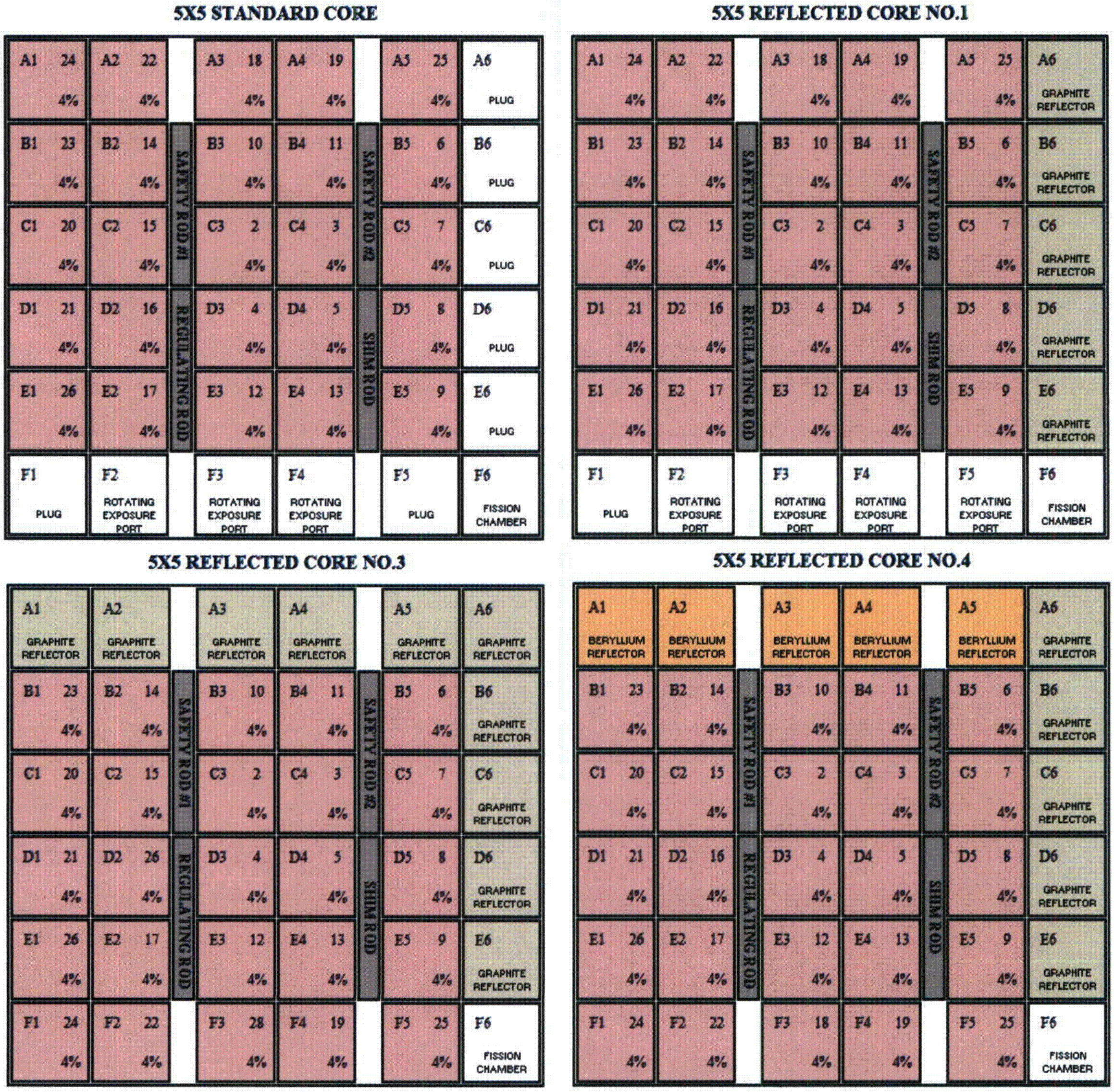

Figure 3.1. PULSTAR core configurations. Each grid position is labeled by its alpha-numeric index (upper left). Assemblies (pink) are labeled by assembly number (upper right) and enrichment (lower right).

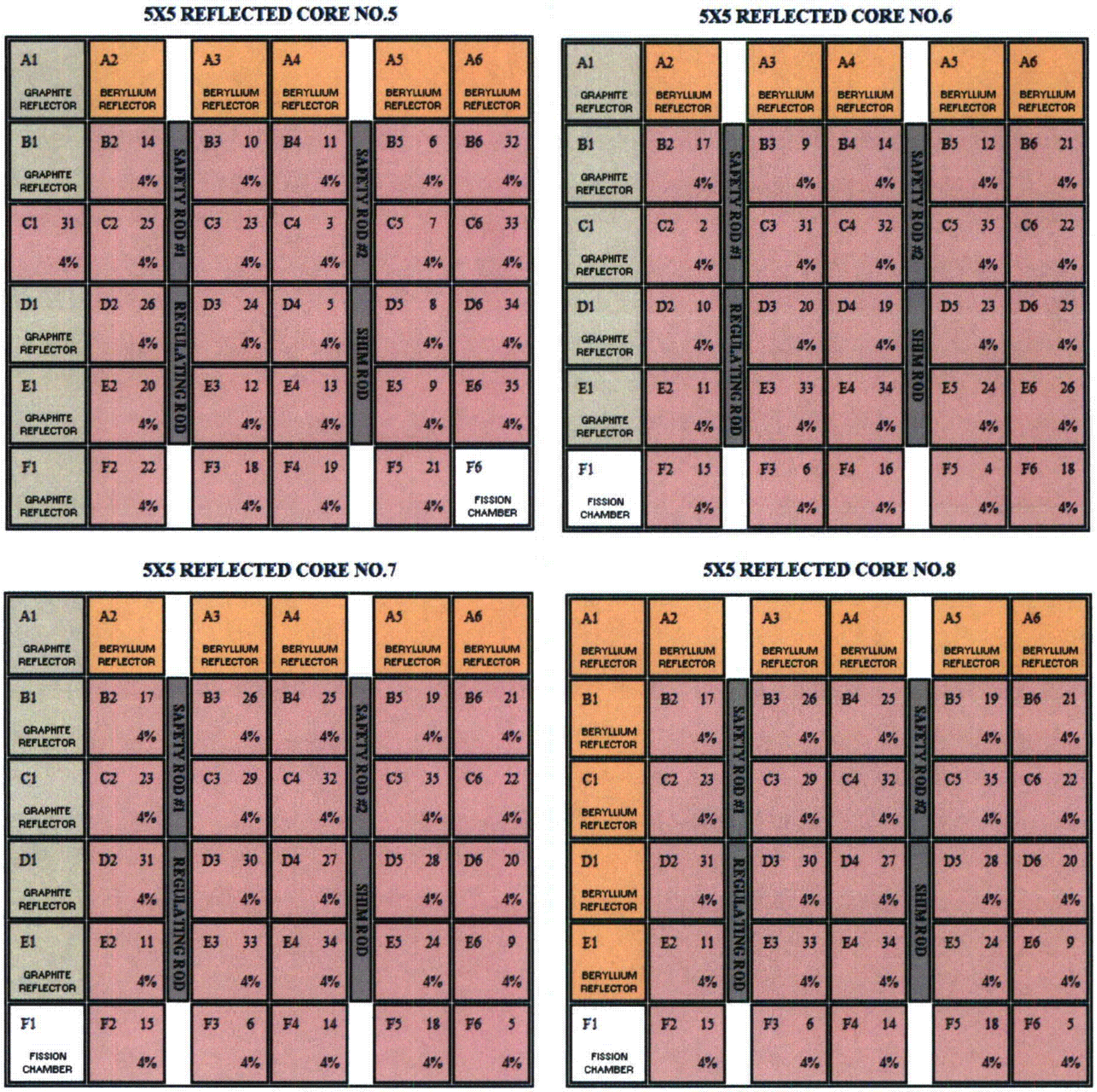

Figure 3.1 (continued)

Burn-up Calculations

The PULSTAR burn-up was performed sequentially for all the historical configurations of the reactor starting from the standard core through the current operational time of reflected core 8. Each configuration was depleted through three successive steps:

1. Burn for 3 days at 1 MW with all rods withdrawn to establish equilibrium xenon
2. Burn for the remainder of the cycle length (MWd) for the given core configuration at 1 MW with all rods withdrawn
3. Burn for 30 days at zero power to allow the fission products, specifically xenon, to decay

This three step procedure was adopted after it was shown through sensitivity analysis that changing the number of burn-up steps (e.g., 10 steps of 10 days vs. 1 step of 100 days) did not affect the change in k_{eff} over the operation period.

To simulate full power (1 MW) in MCNP during depletion, the temperatures, density, and processed data libraries of the fuel and moderator were set according to Table 3.1 (as defined in Section 3.1). The PULSTAR has an asymmetrical geometry and assembly positions have been shuffled periodically over the core history. As a result of these core changes and lack of symmetry, the isotopic inventory of the PULSTAR may vary as a function of core position. Accurate tracking of the fuel inventory as a function of core was achieved by defining an array of 6250 cells for the fuel –10 axial sub-divisions for each fuel pin– and explicitly defining a material card for each cell. The isotope inventory of each of these materials was tracked for each depletion step. During core reconfigurations (e.g., shuffling) each fuel cell was appropriately moved with its corresponding assembly and axial position. To ensure an accurate fuel inventory during the burn, all second tier actinides and fission products contained within the MCNP CINDER database were tracked by utilizing the "BOPT 1 14" card [10]. At each core reconfiguration, the density of each fuel cell was renormalized to the mass output from the MCNP burn-up of the previous core configuration to account for isotopes that were not tracked by MCNP.

Each burn step used the kcode card:

```
kcode  500  1.00000  50  550  100000  0
```

such that 250,000 particles are generated per burn-up step, which corresponds to more than 30,000,000 collisions per step. The k_{eff} calculated at each burn-up step has a statistical uncertainty of less than ±160 pcm, and the rate of change of fuel composition was found to be insensitive to an increase of particles per burn-up step beyond 250,000.

Excess Reactivity (ρ_{excess})

In MCNP the excess reactivity may be estimated directly by modeling the reactor with all rods withdrawn in the cold clean condition, as defined in Table 1.1. To model this state, the fuel and moderator temperatures, density and processed ENDF/B-VII data libraries are set according to Table 3.1 (as defined in Section 3.1). The excess reactivity is calculated as the relative deviation of the MCNP k_{eff} estimate from the critical state ($k_{eff} = 1$) in the cold clean condition, as given below

$$\rho_{excess} = (k_{eff} - 1)/k_{eff} \,. \qquad \text{Equation 3-1}$$

Acceptable results with errors of around 8 pcm in the k_{eff} calculation were obtained using the kcode card

```
kcode 100000 1.017 200 1000 300000 0
```

The measured excess reactivity is estimated using the measured rod worth curves. In these measurements the reactivity insertions due to rod withdrawal are typically small and the reactor is operated with a period, τ, of around 30 seconds. The reactivity is calculated in these measurements using the following expression for the inhour equation,

$$\rho = \sum_{i=1}^{6} \frac{\beta_i}{1 + \lambda_i \tau},$$

Equation 3-2

where β_i are the delayed neutron fractions, λ_i are delayed neutron decay constants and τ is the reactor period. The measured reactivity was estimated using delayed neutron fraction for each group that were scaled from the reference value [11]. The scaling factor was set such that the sum of the delayed neutron fraction for each group (i.e., β_{eff}) was equal to the average MCNP β_{eff} over the core history (i.e., 745 pcm).

Beta Effective (β_{eff})

Beta effective defines the impact of delayed neutrons on the reactivity of the core. The total k_{eff} of the reactor must be equal to sum of the prompt and delayed neutron components which may be expressed as

$$k_{eff} = k_{eff,prompt} + k_{eff}\beta_{eff}, \quad \text{Equation 3-3}$$

where $k_{eff,prompt}$ is the multiplication factor due to prompt neutrons, k_{eff} is the total effective multiplication factor and β_{eff} is the effective delayed neutron factor (i.e., beta effective). Beta effective has been estimated to be 745 pcm. In MCNP the delayed neutron factor was determined by utilizing the TOTNU card to calculate k_{eff} under the cold-clean condition (see Tables 1.1 and 3.1) with and without delayed neutrons. Beta effective was estimated directly using the following expression

$$\beta_{eff} = \frac{k_{eff} - k_{eff,prompt}}{k_{eff}}. \quad \text{Equation 3-4}$$

Control Rod Worth

For estimation of control rod worth using MCNP, the core is modeled in the cold-clean condition. The reactivity worth of a given control rod is calculated as the reactivity difference of the model in the cold clean condition with all rods withdrawn and with the corresponding rod or rods fully inserted. For each core configuration the control rod worth values were calculated for each rod. In addition to the control rod worth, the shutdown margin (SDM) was estimated, where the SDM is defined as the amount of reactivity by which the reactor would be subcritical from its present condition assuming all control rods are fully inserted except for the rod of highest reactivity worth that is assumed to be fully withdrawn [2]. This quantity may be estimated for the PULSTAR as

$$\mathrm{SDM} = \rho_{excess} - \rho_{gang} + \rho_{high}, \quad \text{Equation 3-5}$$

where ρ_{high} is the rod worth of the highest worth rod. The gang rod worth (ρ_{gang}) was estimated as the sum of the worth of the safety 1 (ρ_{s1}), safety 2 (ρ_{s2}), and regulating rods (ρ_{reg}). The highest worth rod is selected from safety 1, safety 2 and regulating rod, and excludes the non-operational shim rod. The SDM must be less than -400 pcm.

Assembly Worth

The worth of a single assembly is the change in excess reactivity of the reactor when that assembly is removed. In MCNP the reactivity worth of an assembly is calculated as the difference in excess reactivity predicted for the model with all rods withdrawn, and for the model with all rods withdrawn and that assembly re-defined as water (moderator).

Power Peaking Factor Calculations

The power peaking factors in the PULSTAR are traditionally measured by inserting a neutron probe in each assembly and measuring the neutron flux as the probe is withdrawn from the assembly. In this case the power peaking factor is taken as the ratio of the highest axial neutron flux in an assembly to the average of all measured neutron flux values in the core. In MCNP the estimation of power peaking factors may be performed by calculating the fission energy deposition rate within each discrete fuel unit in the core. In this case, each fuel pin was divided into 10 axial cells resulting in 6250 fuel cells in the core. An F7 fission energy deposition tally was calculated in each of the 6250 cells used to model the fuel with the cross-sections, moderator density, and temperatures corresponding to the cold-clean condition, and with the control rods in the MCNP predicted gang critical position. The power peaking factor for each pin was calculated as the ratio of the maximum fission energy deposition, F7 tally, of the 10 axial cells in the pin to the average fission rate of the 6250 fuel material cells in the core. The pin power peaking factor, $\mathrm{F}_{\mathrm{Q}}^{n}$, may be defined as

$$\mathrm{F}_{\mathrm{Q}}^{n} = \frac{\text{power of hotest cell in pin } n}{\text{average power of all cells in the core}} = \mathrm{P}_{n}^{\mathrm{hot}}/\langle \mathrm{P}\rangle_{\mathrm{cell}},$$

Equation 3-6

where $\mathrm{P}_{n}^{\mathrm{hot}}$ is the power of the hottest axial cell in pin *n* and $\langle \mathrm{P}\rangle_{\mathrm{cell}}$ is the average power of all 250 axial layers in the core. The greatest pin power peaking factor is the power peaking factor for the core, F_{Q}, and is compared to the Technical Specifications limit of 2.92. Assembly averaged power peaking factors were calculated by first averaging the fission rate in each pin within each axial zone and within a single assembly. Subsequently the assembly power peaking factor, $\mathrm{F}_{\mathrm{Q}}^{a}$ for each assembly was calculated as the ratio of the maximum fission rate of the 10 axial layers to the average fission rate of all 250 axial layers in the core. The assembly power peaking factor may be defined as

$$\mathrm{F}_{\mathrm{Q}}^{a} = \frac{\text{power of hotest axial layer assembly in } a}{\text{average power of all layers in the core}} = \mathrm{P}_{a}^{\text{hot layer}}/\langle \mathrm{P}\rangle_{\mathrm{layer}},$$

Equation 3-7

where $\mathrm{P}_{a}^{\text{hot layer}}$ is the sum of the pin powers in the hottest axial layer of assembly *a* and $\langle \mathrm{P}\rangle_{\mathrm{layer}}$ is the average power of all 250 axial layers in the core. The greatest assembly averaged power peaking factor is the assembly power peaking factor for the core, $\mathrm{F_Q}^{\mathrm{A}}$. The assembly power peaking factors estimated from MCNP may be considered analogous to the measured flux peaking factors, and as such provide a basis for comparison of the measured and calculated power distribution in the PULSTAR.

3.3 Comparison of MCNP and Measured Data

Before using the MCNP model to predict safety related parameters for future core configurations, comparison to historical data was performed. This included data for excess reactivity, rod worth values, and assembly peaking factors. Each parameter was calculated as described above. The excess reactivity as a function of operational time, illustrated in Figure 3.2, demonstrates that the measured values are in reasonable agreement with those predicted using MCNP6. The MCNP6 estimated rod worth values, SDM, and assembly averaged peaking factors are compared to measurement in Table 3.2. The rods are listed as safety 1 (S1), safety 2 (S2), regulating (Reg), shim, and gang. The right value for each configuration column is the MCNP6 estimate whereas the left value is the measurement. The peaking factors listed are the assembly peaking factor for the core, with the exception of the standard core where the comparison is based on the pin power peaking factor due to the availability of such experimental data. As was found for the excess reactivity, the MCNP6 predicted parameters are within reasonable agreement with measurement. The power peaking factor distribution was also used for comparing MCNP6 predictions and measurement, as demonstrated in Figure 3.3 for reflected core 8. Each fuel assembly is labeled according to its numeric index in the upper right and core position in the upper left. The assembly peaking factor calculated using MCNP6 is listed in the lower right of each cell and the measured peaking factor is listed in the lower left. The assembly peaking factors predicted by MCNP6 were within 10% of measurements near the core interior and within 30% near the core periphery.

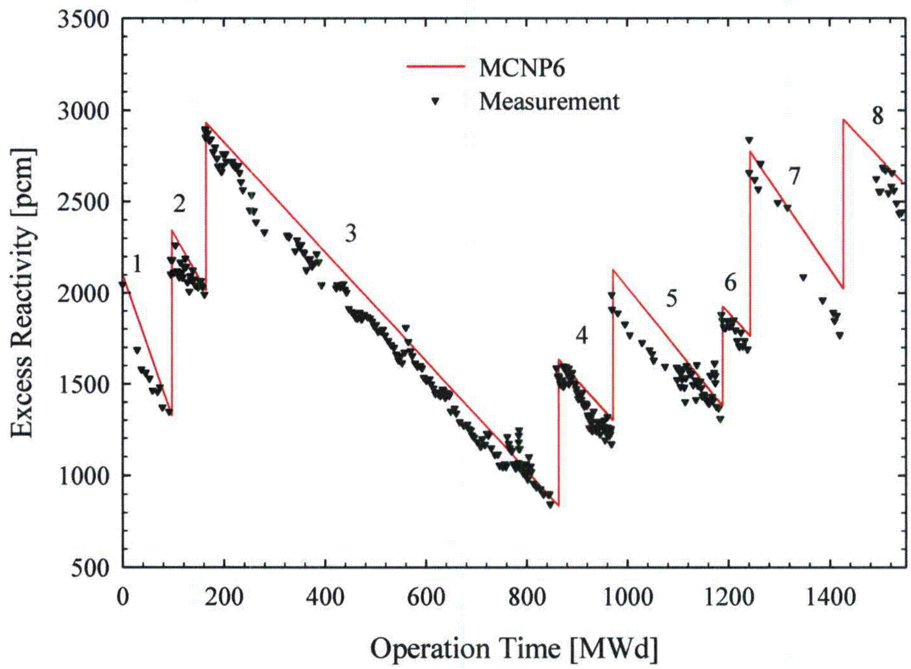

Figure 3.2. A comparison of the measured and calculated PULSTAR excess reactivity history. The labels for each region correspond to the core configurations in chronological order, as listed in Table 1.2.

Table 3.2. Summary of parameters for historic core configurations (For each core the right column is the MCNP value and the left column is the measured value). For the standard core the comparison is made based on pin power peaking factors as the measurement is more representative of this parameter.

	Standard Core		Reflected Core 1		Reflected Core 3		Reflected Core 4		Reflected Core 5		Reflected Core 6		Reflected Core 7		Reflected Core 8	
	Meas	Calc	Meas	Calc	Meas	Calc	Meas	Calc	Meas	Calc	Meas	Calc	Meas	Calc	Meas	Calc
S1 (pcm)	4165	4596	4084	4286	2655	2910	2943	3193	2348	2665	2583	2460	2246	2499	1991	2713
S2 (pcm)	2631	2933	3185	3297	2267	2326	2502	2504	2961	3199	2808	3314	2695	3275	2246	3048
Reg (pcm)	2521	2769	2379	2623	3982	4029	3664	3784	2787	2982	2757	2842	2634	2927	2297	3135
Shim (pcm)	1644	1867	1899	2091	2961	3062	2696	2891	3727	3537	4492	3906	3982	3956	3522	3596
Gang (pcm)	9316	10299	9648	10205	8903	9265	9110	9481	8096	8846	8168	8616	7576	8701	6534	8895
SDM (pcm)	-3104	-3621	-3462	-3578	-2301	-2307	-3858	-4066	-3145	-3521	-3459	-3380	-2041	-2655	-1612	-2812
F_Q^A	2.8	2.69	2.07	1.84	2.1	1.84	1.80	1.71	1.62	1.71	1.90	1.76	1.89	1.90	1.76	1.84

In addition to rod worth values, excess reactivity, and power peaking factors, recent assembly worth measurements allow for further comparison between MCNP calculations and measurement for reflected core 8. The assembly worth values of F6 and F2 in reflected core 8 were measured and found to be 200 pcm and 610 pcm respectively. The MCNP predicted assembly worth values are 270 pcm and 650 pcm for F6 and F2 respectively.

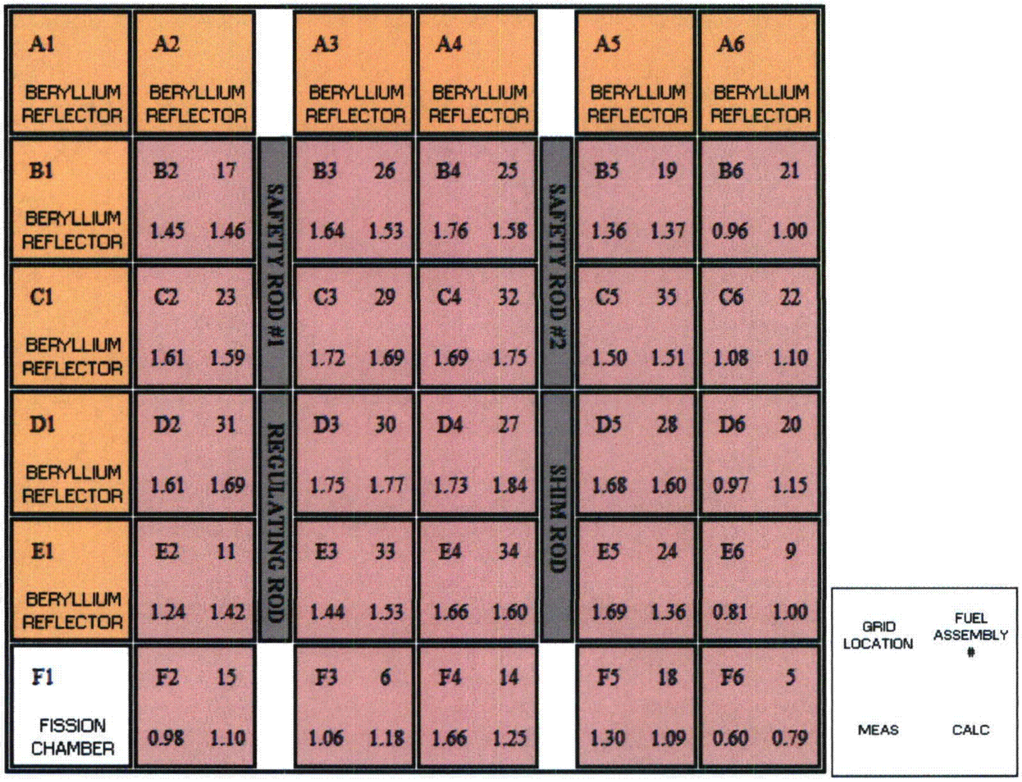

Figure 3.3. Reflected core 8 assembly power peaking map. Assembly peaking factors in fuel assemblies (pink) are listed for measurement (lower left) and calculation (lower right)

4.0 MCNP Modeling of Mixed Enrichment Cores

4.1 Calculation of Core Kinetic Parameters

Mixed enrichment configurations of the PULSTAR reactor were evaluated by changing the enrichment and density in the reflected core 8 model for each assembly loaded with 6% enriched fuel. The excess reactivity, assembly worth, and power peaking factor were calculated using MCNP6 for the case of loading a single 6% assembly to establish the positions in which "single" assemblies may be loaded without violating Technical Specifications limits. The excess reactivity (Equation 3-1) and assembly worth are computed as described in Section 3.2. In addition to excess reactivity, assembly worth, power peaking factor, rod worths, shutdown margin, and core kinetics were evaluated for representative mixed enrichment core configurations and for reflected core 8 (e.g., see Figures 4.1 and 4.2 below). The rod worth values and shutdown margins are calculated as described in Section 3.2. The calculation of core kinetics are described below and include the moderator feedback coefficient, reactivity insertion rate, void coefficient, Doppler feedback coefficient, power defect, and β_{eff}. Additional calculations were performed for pin power and assembly power peaking factor maps using the approach described in Section 3.2.

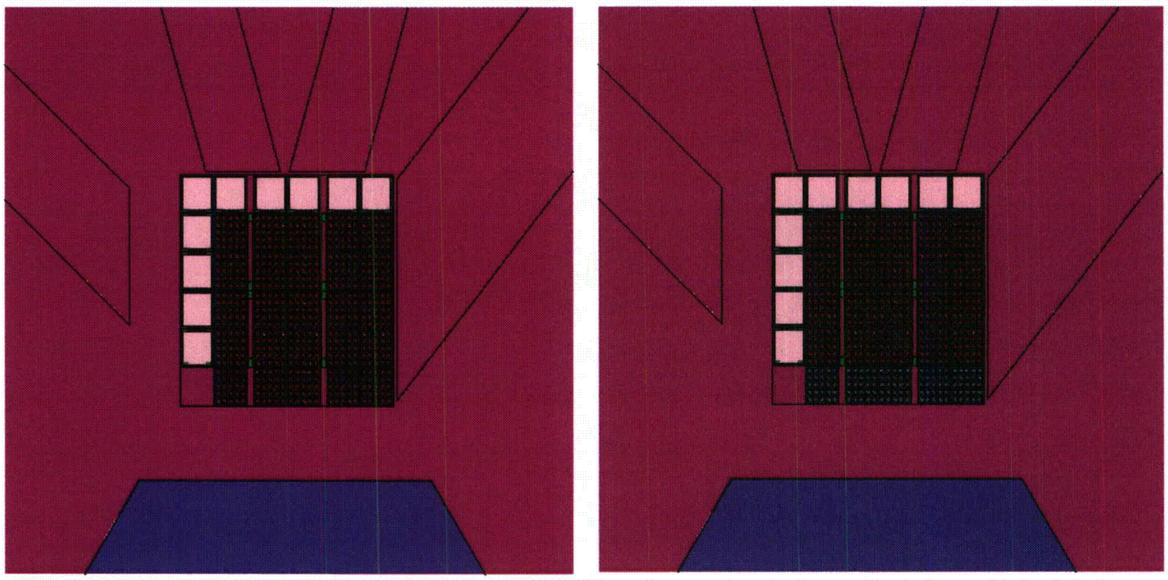

Figure 4.1. MCNP models of reflected core 8 (left) and a representative reflected core 9-4 (right).

Reactivity Parameter Calculations

The PULSTAR has various characteristic reactivity parameters which may be estimated by Monte Carlo methods, including excess reactivity, rod worth, assembly worth, reactivity insertion rate, beta effective, and feedback coefficients. The feedback coefficients of interest were the moderator, Doppler, and void coefficients. The procedure for calculating each parameter is described in its specified section below. In general, all reactivity effects were calculated under similar conditions to those of the excess reactivity. The reactivity calculated for a simulated core condition is the sum total of the excess and the change in reactivity due to changes from the cold clean condition; where the cold clean condition is a xenon free core at 70 °F. This estimation may be expressed more concisely as,

$$\rho = \rho_{excess} + \Delta\rho, \qquad \text{Equation 4-1}$$

where ρ is the calculated reactivity for a particular state, ρ_{excess} is the reactivity in the cold clean condition with all rods withdrawn, and $\Delta\rho$ is the effect on reactivity of a change in the core state from cold clean condition. The calculated reactivity ρ is the output of MCNP and may be used to determine the reactivity feedback of changes in the core state. All feedback coefficients were determined assuming a linear model between reactivity and the varied parameter expressed as,

$$\rho = \rho_{excess} + \alpha_G \Delta G, \qquad \text{Equation 4-2}$$

where ρ is the reactivity, ΔG is the change in a parameter which describes the core state (e.g., fuel temperature) and α_G is the linear feedback coefficient corresponding to the parameter G. If ρ is estimated for multiple values of G then under the assumption the of a linear feedback, the slope of a linear least squares regression of ρ and G is considered the estimate of α_G. As in the case of the previous calculations all materials were modeled with ENDF/B-VII cross-section libraries, which were treated with NJOY99 for Doppler broadening or to produce thermal scattering kernels when necessary (see Section 3.1). The kcode line used in the calculation of reactivity feedback coefficients was

```
kcode 100000 1.017 200 1000 300000 0
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The total number of particles run (80,000,000 tracked; 20,000,000 skipped) produced a value of k_{eff} value with a statistical uncertainty of approximately 8 pcm. Unless otherwise specified all rods are assumed fully extruded in all the calculations described below.

Rod Reactivity Insertion Rate

The operation of the reactor requires the direct insertion of reactivity through withdrawal of control rods, most commonly in a gang configuration. To model the reactivity insertion rate resulting from control rod movement in MCNP, the k_{eff} of the core was estimated in the cold clean condition with the rods in two gang positions, 12" and 15" insertion. These values were chosen as they bound the critical position at cold clean where the sensitivity or reactivity to rod position is both linear and greatest. The resulting reactivity insertion rate, $\dot{\rho}$, is calculated as

$$\dot{\rho} = \frac{\Delta\rho}{\Delta h}\dot{h}, \qquad \text{Equation 4-3}$$

where $\Delta\rho$ is the change in reactivity between the rod positions, Δh is the 3" change in rod position, and $\dot{h}$ is the rod withdraw rate of 7.5"/min. The reactivity insertion rate due to rod withdrawal has a limit of 100 pcm/s.

Moderator Coefficient

The isothermal temperature coefficient (α_T), referred to operationally as the moderator feedback coefficient, measures the effect of core temperature on reactivity. Operationally this effect is measured by varying the flow rate in the secondary side of the heat exchanger at low core powers (<1 kW). When the core is in an isothermal condition both moderator temperature and fuel temperature are approximately the same such that the isothermal coefficient measures the combined effect of the moderator and fuel. In MCNP this coefficient was estimated with a linear comparison between the cold clean condition and the zero power condition (see Tables 1.1 and 3.1).

Void Coefficients
Voids occur in the moderator of the PULSTAR as either microscopic cavities or by the insertion of in core probes. To simulate voids, the water in two channels was re-defined as void. The channels chosen were the two right of center in assembly D4. These pins correspond to positions that may be measured using in-core probes. The void coefficient was calculated per Equation 4-2, using the channel volume of 56.9 cm^3. The reactivity difference was taken as that between the excess reactivity and the reactivity of the core with the voided channels.

Doppler Coefficient
The Doppler coefficient in the PULSTAR is a measure of the negative reactivity insertion due to the rise in fuel temperature from the hot zero power state to the full power state (see Table 1.1). Doppler broadening in a low-burn-up core such as the PULSTAR occurs primarily in ^{238}U; however, effects from ^{235}U may also be present. To examine the effect of Doppler broadening on the reactivity of the MCNP model, ACER libraries for ^{238}U and ^{235}U were prepared using NJOY99 and the corresponding ENDF/B-VII libraries. The fuel temperature input card, TMP card, and corresponding Doppler broadened libraries for U-235 and U-238 were varied homogenously for all fuel cells as function of temperature (100 °F, 142 °F, 179 °F, 217 °F, 293 °F) while maintaining a homogeneous moderator temperature, using the thermal cross-sections of H in H_2O and density appropriate for 100 °F (see hot zero power in Table 3.1). The Doppler coefficient of reactivity (α_F) is the slope between the reactivity and fuel temperature, per Equation 4-2.

Power Defect
The change in operation state from hot zero power to full power in the NCSU PULSTAR is associated with a distinct change in reactivity, which is both a combination of the moderator and Doppler feedback effects known as the power defect, (α_P). This power defect may be calculated per Equation 4-2 by comparing the reactivity with all rods withdrawn in the hot zero power and full power states as described in Table 3.1.

Power Peaking Factor Calculations
As discussed in Section 3.2, the MCNP estimation of power peaking factors may be determined by calculating the fission energy deposition rate within each discrete fuel unit in the core. An F7 fission energy deposition tally was calculated in each of the 6250 cells used to model the fuel with the cross-sections, moderator density, and temperatures corresponding to the cold clean condition, and with the control rods in the MCNP predicted gang critical position. The cold clean condition is considered to be the most conservative case with respect to axial power peaking as including the reactivity losses due to power defect results in withdrawal of control rods and thus a more uniform power distribution. The pin power peaking for each pin was calculated as the ratio of the maximum fission energy deposition, F7 tally, of the 10 axial cells in the pin to the average fission rate of the 6250 fuel material cells in the core. The highest pin power peaking factor is the power peaking factor for the core, F_Q, and has a Technical Specifications limit of 2.92.

4.2 Mixed Enrichment Core Configurations

Core configurations containing a single 6% enriched assembly were considered. MCNP6 calculations were performed where a single 6% assembly was inserted in a selected position that originally contained a 4% enriched assembly in reflected core 8 to examine the core limits using such fuel loading patterns. Multiple 6% loading patterns were considered for positions that did not violate safety limits for single 6% assembly loading, and are shown in Figure 4.2. Each fuel assembly is labeled according to its numeric index in the upper right corner, enrichment in the lower right, and core position in the upper left. The 6% assemblies have not yet been given a numeric designation.

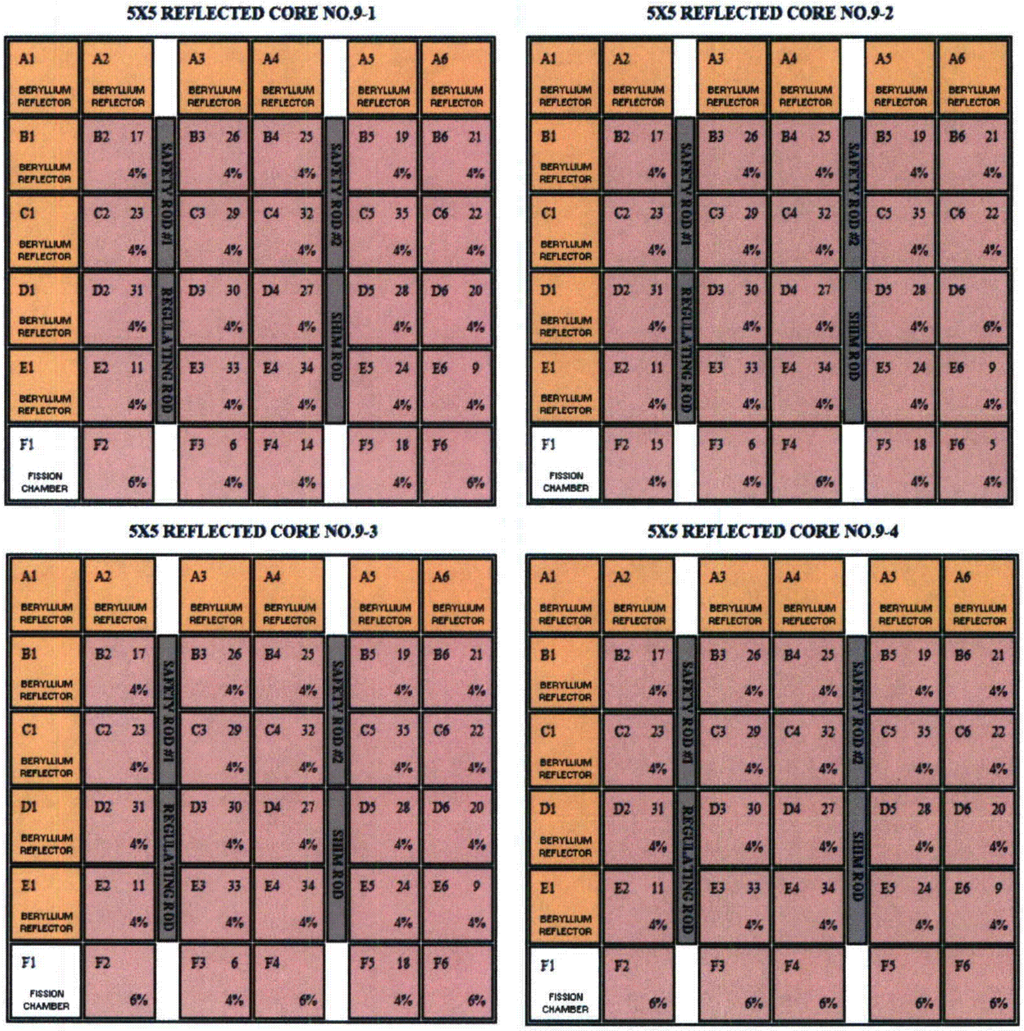

Figure 4.2. PULSTAR mixed enrichment core configurations based on the insertion of 6% assemblies in selected positions of row F and/or column 6. Each grid position is labeled by its alpha-numeric index (upper left). Assemblies (pink) are labeled by assembly number (upper right) and enrichment (lower left).

4.3 Results

The MCNP6 model was used to characterize the reactivity behavior of the PULSTAR in its current configuration (reflected core 8), and possible configurations for reflected core 9 with 6% enriched fuel assemblies. The excess reactivity, 6% assembly worth, and power peaking factors for each single 6% assembly loading is summarized in Table 4.1. The license limit for excess reactivity, assembly worth, and power peaking factors are 3970 pcm, 1590 pcm, and 2.92 respectively. Permitted and non-permitted single 6% assembly loading positions are illustrated in Figure 4.3. The core position is designated in the upper left corner of each cell. Each assembly location designates a 6% assembly loaded in that position with the core excess reactivity in the upper right corner, the assembly worth in the lower left corner, and the power peaking factor, F_Q, in the lower right. Positions where single 6% assembly loading is permitted based on Technical Specifications limits are green, whereas positions where single 6% assembly loading is not permitted are red.

Table 4.1. Summary of single 6% assembly loading.

Core Position Loaded	Excess Reactivity (pcm)	6% Assembly Worth (pcm)	F_Q
B2	3010	1812	2.62
B3	3112	1917	2.73
B4	3135	2036	2.87
B5	3008	1564	2.76
B6	2789	714	2.57
C2	3127	2143	2.63
C3	3061	1856	2.70
C4	3147	2030	2.91
C5	2990	1559	2.81
C6	2847	773	2.53
D2	3048	2282	2.82
D3	3092	1963	2.91
D4	3145	2191	3.15
D5	2986	1706	3.07
D6	2858	803	2.56
E2	3036	1673	2.76
E3	3005	1477	2.83
E4	3025	1634	3.09
E5	2997	1302	3.01
E6	2797	590	2.56
F2	2779	825	2.52
F3	2865	936	2.53
F4	2916	1075	2.55
F5	2829	848	2.52
F6	2701	367	2.52

Figure 4.3. Permitted single 6% fuel loading positions (green). The excess reactivity, greatest assembly worth and core power peaking factor are listed for single 6% fuel loaded in that position. Positions considered not permitted for 6% loading are red.

As described in Section 4.3, mixed enrichment core configuration with multiple 6% enriched assemblies were considered where the 6% assemblies were loaded into permitted core positions indicated in Figure 4.2. The excess reactivity, rod worth values, SDM, reactivity insertion rate, and core pin peaking factors are tabulated in Table 4.2 for representative mixed enrichment cores with multiple 6% assemblies as illustrated in Figure 4.2. The rods are listed as safety 1 (S1), safety 2 (S2), regulating (Reg), shim, and gang. The power peaking factor is the maximum pin power peaking factor in the core. The license limits (as specified in the technical specifications) for excess reactivity, SDM, reactivity insertion rate, and power peaking factor are less than 3970 pcm, less than -400 pcm, less than 100 pcm/s, and less than 2.92 respectively. These core parameters are estimated to be within the safety limits for all multiple 6% assembly mixed enrichment core configurations considered (see Figure 4.2). A sensitivity analysis of the power peaking factor to the critical rod position demonstrated that the power peaking factor predicted by MCNP6 varies by no more than 5% for ganged rod positions within 50 pcm of the critical position. Assembly averaged power peaking factors maps for reflected core 8 and representative reflected core 9 configurations loaded with multiple 6% assemblies are illustrated in Figure 4.4-4.8. Pin Power peaking factor maps for reflected core 8 and the representative reflected core 9 mixed enrichment configurations are illustrated in Figure 4.9. Core positions are indicated in the upper left of each cell while the assembly numeric index for 4% enriched assemblies is indicated in the upper right. The 6% enriched assemblies from the SUNY Buffalo PULSTAR have not yet been given a numeric index. Assembly peaking factors are indicated in the lower right of each cell and the assembly worth of 6% enriched assemblies is indicated in lower left. The MCNP6 calculated peaking factors for all reflected core 9 cases are within 10% of those calculated for reflected core

8. The predicted worth of a single 6% enriched fuel in multiple loading reflected core 9 configurations considered were determined to be below the 1590 pcm license limit for reactivity insertion by a single fuel assembly.

Table 4.2 Summary of MCNP6 core parameters for representative mixed enrichment core configurations

	limit	Reflected Core 8	Reflected Core 9-1	Reflected Core 9-2	Reflected Core 9-3	Reflected Core 9-4
ρ_{excess} (pcm)	3970	2604	2895	3160	3214	3735
S1 (pcm)		2713	2621	2534	2532	2357
S2 (pcm)		3048	2935	2930	2839	2630
Reg (pcm)		3135	3171	3043	3162	3133
Shim (pcm)		3596	3594	3698	3642	3651
Gang (pcm)		8895	8728	8507	8533	8120
SDM (pcm)	-400	-2812	-2661	-2304	-2156	-1253
$\dot{\rho}$ (pcm/s)	100	68	68	65	65	62
F_Q	2.92	2.56	2.51	2.54	2.59	2.78

Based on the above table, representative cores 9-1 and 9-2 are considered acceptable for loading. The ρ_{excess} and SDM are comfortably within the set technical specifications limits. Cores 9-3 and 9-4 would be precluded based on the power peaking factor (F_Q) as its value falls outside a margin of 15% that is set to be greater than the maximum deviation between the calculated and experimentally estimated values (see Table 3.2). In this case, if F_Q for cores 9-3 and 9-4 is multiplied by 1.15 it would yield a value greater than 2.92.

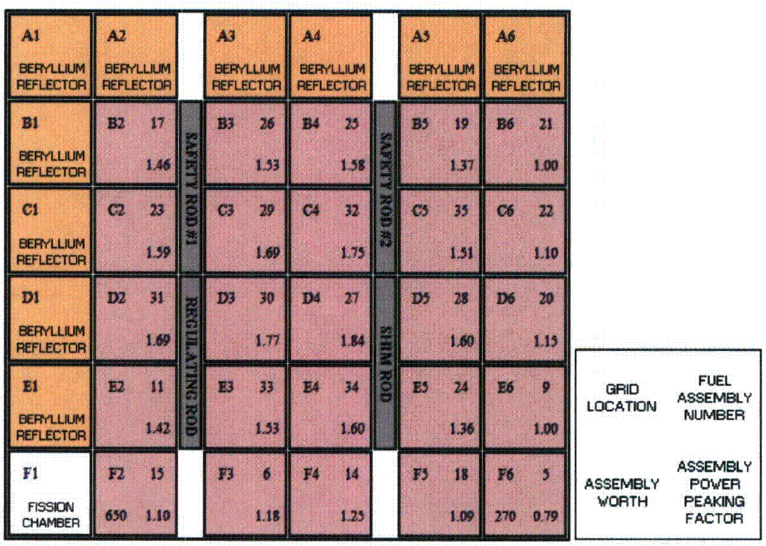

Figure 4.4. Reflected core 8 assembly power peaking factor map. Each grid position is labeled by its alpha-numeric index (upper left). Assemblies (pink) are labeled by assembly number (upper right) for 4% enriched fuel only. Assembly power peaking factor (lower right) and measured assembly worth (lower left) are listed.

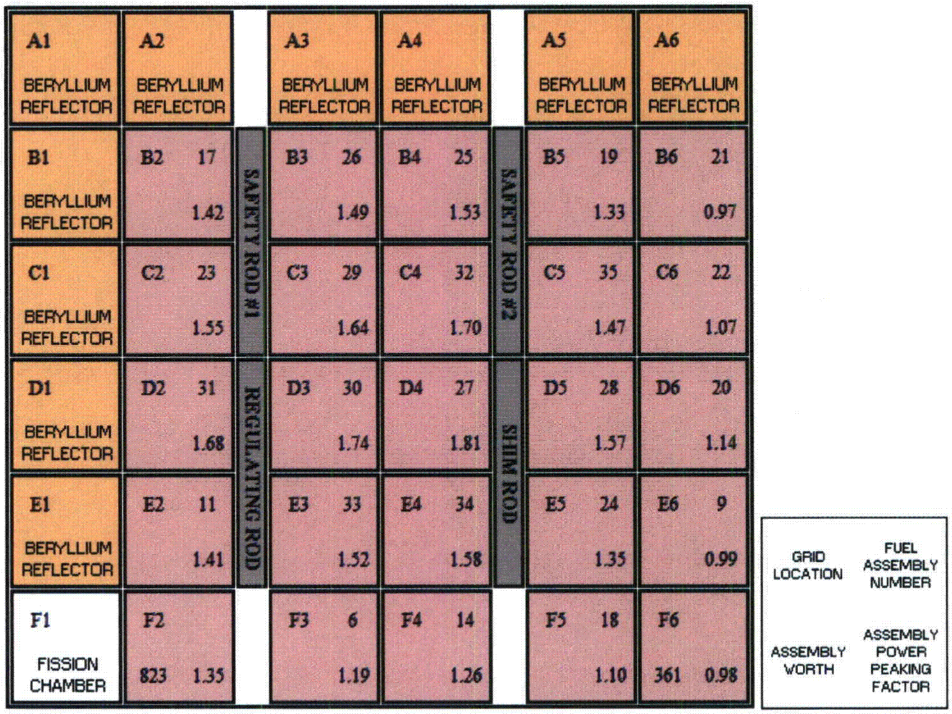

Figure 4.5. Reflected core 9-1 assembly power peaking factor map. Assembly power peaking factor (lower right) and assembly worth for 6% enrich fuel (lower left) are listed.

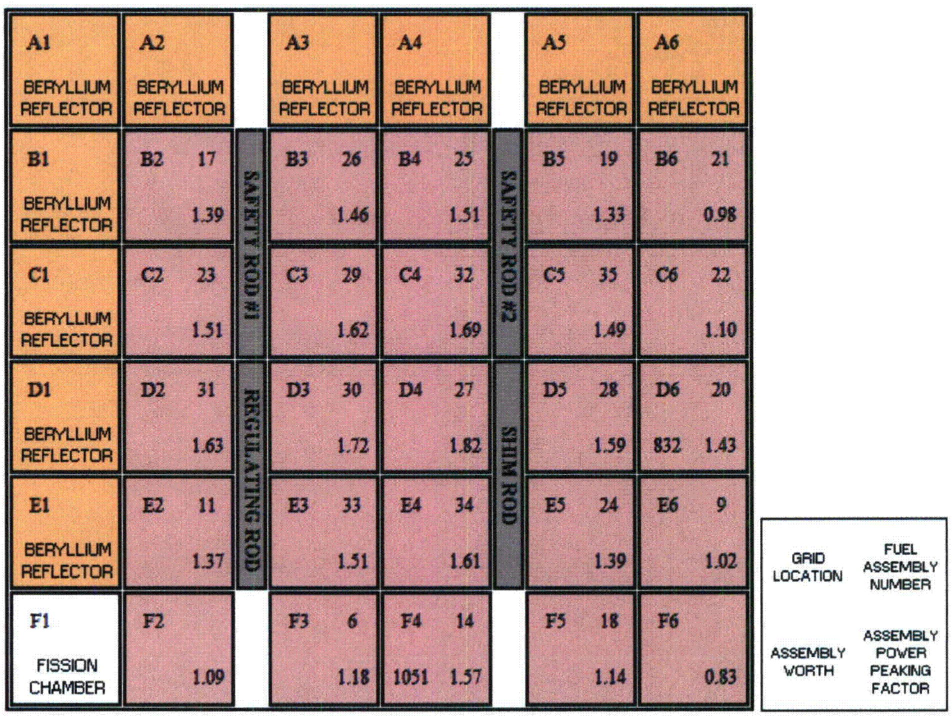

Figure 4.6. Reflected core 9-2 assembly power peaking factor map. Assembly power peaking factor (lower right) and assembly worth for 6% enrich fuel (lower left) are listed.

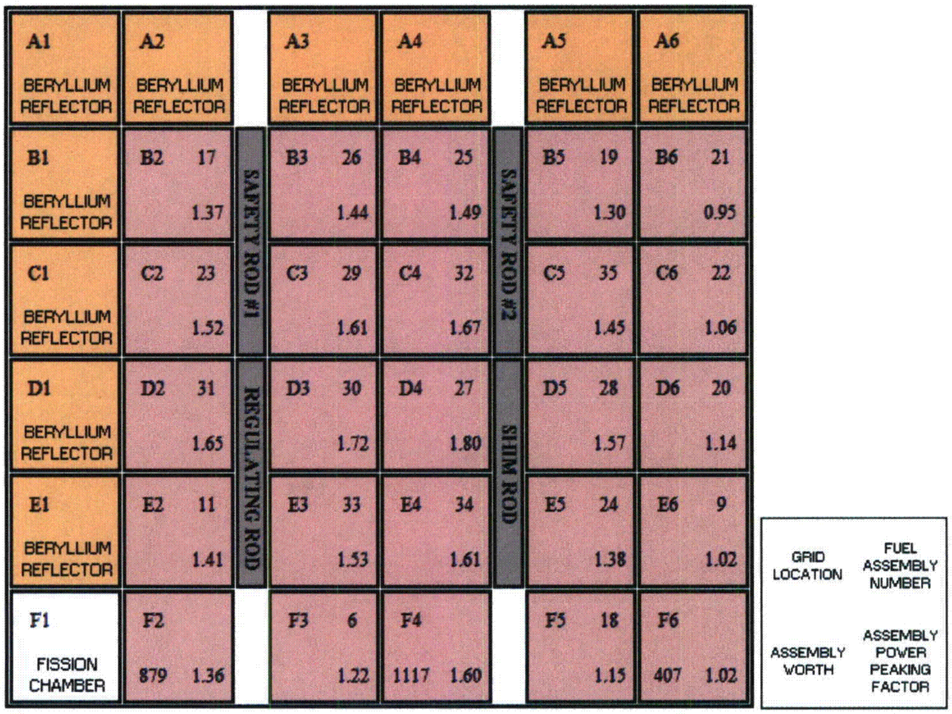

Figure 4.7. Reflected core 9-3 assembly power peaking factor map. Assembly power peaking factor (lower right) and assembly worth for 6% enrich fuel (lower left) are listed.

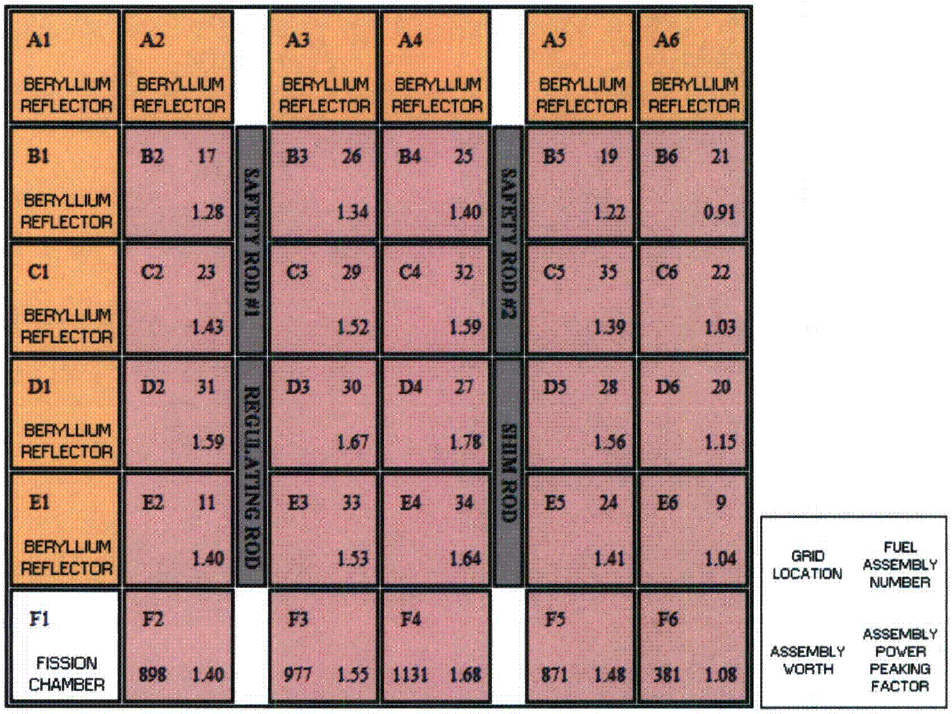

Figure 4.8. Reflected core 9-4 assembly power peaking factor map. Assembly power peaking factor (lower right) and assembly worth for 6% enrich fuel (lower left) are listed.

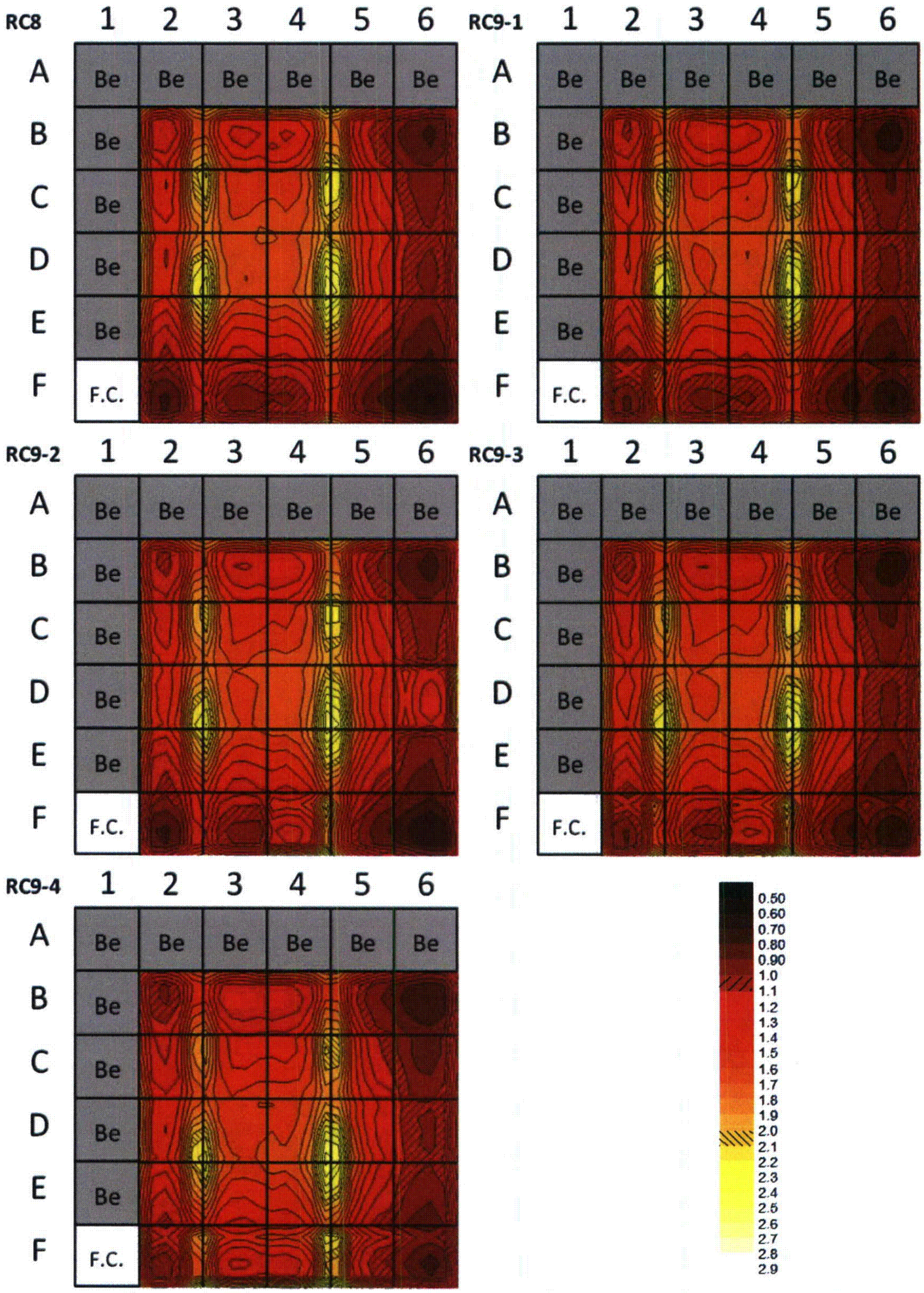

Figure 4.9. Pin power peaking factor map of reflected cores 8, 9-1, 9-2, 9-3 and 9-4.

The reactivity feedback coefficients were computed for core 8 and the various configurations of reflected core 9. The calculation of the Doppler coefficient for reflected core 8 using linear regression with Equation 4-2, is illustrated in Figure 4.10 for both beginning of cycle (1425 MWd) and the current state (1541 MWd). The calculated feedback coefficients and β_{eff} are tabulated in Table 4.3. The Doppler and moderator coefficients have a relative uncertainty due to the statistical uncertainty in k_{eff} of nearly 5% and 10% respectively. The void coefficients have a relative uncertainty of nearly 10%. The power defect for each configuration has a statistical uncertainty of around 20 pcm. With the exception of the moderator feedback coefficient, all feedback coefficients and β_{eff} were calculated to change by less than 10% between different core configurations.

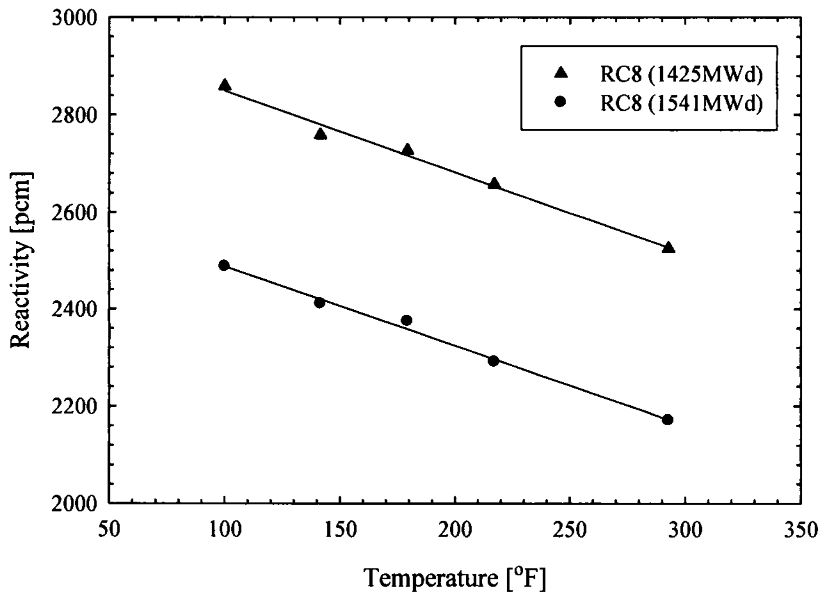

Figure 4.10. Reflected core 8 linear regression for calculation of Doppler coefficient. Operation times of 1425 MWd (begging of cycle) and 1541 MWd (current cycle state) for reflected core 8 are given, as illustrated in Figure 3.2

Table 4.3 Summary of MCNP6 core kinetics for representative mixed enrichment configurations.

	Reflected Core 8	Reflected Core 9-1	Reflected Core 9-2	Reflected Core 9-3	Reflected Core 9-4
α_T (pcm/°F)	-3.44	-2.96	-3.44	-3.28	-2.38
α_F (pcm/°F)	-1.66	-1.68	-1.64	-1.65	-1.58
α_V (pcm/cm^3)	-1.09	-1.09	-1.13	-1.16	-1.08
α_P (pcm/MW)	-335	-341	-334	-341	-349
β_{eff} (pcm)	742	716	733	740	738

5.0 Conclusions

An MCNP6 Monte Carlo model was created to simulate the NCSU PULSTAR reactor's neutronic characteristics. Using this model, it was demonstrated that reasonable agreement exists between measured and calculated excess reactivity (as a function of operating time), rod worth values, and assembly averaged power peaking factors. Furthermore, the model was shown to reliably predict the historic PULSTAR core behavior in comparison to measurements. Therefore, based on this model, analysis was performed of the current reflected core 8, with the insertion of fuel assemblies that are enriched to 6% (by weight) with ^{235}U. Such assemblies were obtained from the decommissioned PULSTAR reactor at the BMRC of SUNY Buffalo and are currently stored at the NCSU PULSTAR facility.

The performed MCNP analysis showed that, for several representative "reflected core 9" configurations, no reactivity parameters associated with the safe insertion of fuel and safe start-up of the core violate the PULSTAR's Technical Specifications. This includes the total core excess reactivity (limited to less than 3970 pcm), the worth of a single inserted assembly (limited to less than 1590 pcm), the shutdown margin for the cold clean condition (limited to less than -400 pcm), the maximum reactivity insertion rate through rod withdrawal (limited to less than 100 pcm/s), and the maximum core pin power peaking factor (limited to less than 2.92). The examined mixed enrichment configurations based on the loading of one 6% assembly or two 6% assemblies (e.g., reflected core 9-1 and 9-2) have been found to meet such limits with substantial margin. In addition, for configurations such as cores 9-1 and 9-2 the pin power peaking factor remains below the limit by a set 15% margin. In all cases, the PULSTAR maintained its overall negative feedback behavior as demonstrated by a power coefficient of reactivity that is less than -300 pcm/MW.

6.0 References

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