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Mixed Enrichment Core Design for the NC State University PULSTAR Reactor

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Summary

The NC State University PULSTAR Reactor began operating in 1972 with a core that utilized 25 out of 34 fuel assemblies provided by the U.S. Atomic Energy Commission in 1970. Since then, the facility has continued to use only the same 25 fuel assemblies. This frugal fuel use has been due to operating the reactor only on demand, reflecting two sides of the core with graphite, and scheduling operations as needed to accommodate high negative reactivity worth users and xenon when excess reactivity was low.

In 1988, the facility applied to the U.S. Nuclear Regulatory Commission for a 20 year license renewal. As the result of a fuel utilization review and planning at that time, five beryllium reflector blocks were requested from the U.S. Department of Energy in 1990. At that time it was predicted that these beryllium reflector blocks, the nine spare fuel assemblies, and six additional beryllium reflector blocks to be obtained at a later time would provide sufficient fuel resources for the facility to operate through the second license period.

The NC State University PULSTAR Reactor license was renewed for an additional 20 years of operation on April 30, 1997. The relicensing period added additional years to the to the facility operating time through the end of the second license period, increasing the excess reactivity needs as projected in 1988.

In 1995, the Nuclear Reactor Program developed a strategic plan that addressed the future maintenance, development, and utilization of the facility. Goals resulting from this plan included increased academic utilization of the facility in accordance with its role as a university research facility, and increased industrial service use in accordance with the mission of a land grant university. The strategic plan was accepted, and it is the intent of the College of Engineering to operate the PULSTAR Reactor as a going concern through at least the end of the current license period. In order to reach the next relicensing review without prejudice due to low excess reactivity, it is desired to maintain sufficient excess reactivity so that, if relicensed again, the facility could continue to operate without affecting users until new fuel assistance was provided.

During the NC State University license renewal, the operation of the PULSTAR Reactor at the State University of New York at Buffalo (SUNY Buffalo) was terminated. At that time, the SUNY Buffalo facility had about 240 unused PULSTAR Reactor fuel pins with 6% enrichment. The objective of the work reported here was to develop a mixed enrichment core design for the NC State University PULSTAR reactor which would:

- Demonstrate that 6% enriched SUNY Buffalo fuel could be used in the NC State University PULSTAR Reactor within the existing technical specification safety limits for core physics parameters

- Show that use of this fuel could permit operating the NC State University PULSTAR Reactor to 2017 with increased utilization

- Assure that the decision whether or not to relicense the facility would not be prejudiced by reduced operations due to low excess reactivity

A minimum desirable excess reactivity for routine operations was defined to be 1,920 pcm. This allows for losses due to the moderator temperature coefficient, power defect, approximate equilibrium xenon, the use of two beam tubes, and the use of cadmium lined baskets in two of the four vertical exposure ports. Improvements in the facility capability including increasing the leakage flux to the beam tubes that are being used, using cadmium lined baskets in all four of the vertical exposure ports, and opening a third beam tube for a new instrument increase this total to as much as 2400 pcm.

Maximum utilization of the facility within normal working hours would use about 3690 pcm of excess reactivity over the next twenty years. Counting the present excess reactivity of about 870 pcm, the desired total of incremental excess reactivity increases is 5220 pcm for the second license period.

Existing fuel resources considered for the mixed enrichment core design consist of nine unused 4% enriched fuel assemblies, five beryllium reflector blocks, and at least nine new 6% enriched fuel assemblies. Excess reactivity calculations show that these resources can be used to obtain a total excess reactivity gain of about 5,135 pcm. This gain could be increased by modifying the fuel loading pattern later in the current license period. About 800 pcm of additional excess reactivity could be obtained by changing the remaining six graphite reflector blocks to beryllium.

Excess reactivity, power distribution, shutdown margin, and fuel assembly worth calculations show that the unused SUNY Buffalo fuel pins can be used to operate the NC State University PULSTAR Reactor as a going concern for the next license period without requiring the fabrication of new PULSTAR fuel. These calculations, which gave particular attention 3-D geometric fidelity in modeling the small and highly heterogeneous core, provide a benchmark for using a more efficient code to performing a full range of assembly misloading calculations for use in defining the license basis for using mixed enrichment fuel at the NC State University PULSTAR Reactor.

Considering the results of this work, steps are being taken to prepare for the receipt of the unused 6% enriched fuel pins from the SUNY Buffalo PULSTAR Reactor. Thermal-hydraulic analysis remains to be performed to ensure that safety limits associated with thermal-hydraulic parameters remain acceptable.

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1.0 INTRODUCTION

1.1 Background

The NC State University PULSTAR Reactor achieved initial criticality in September, 1972. At that time, 34 new PULSTAR fuel assemblies had been provided by the U.S. Atomic Energy Commission. Since then, the facility has used only the same 25 fuel assemblies that composed the initial core. This frugal fuel use has been due to operating the reactor only for user requests during regular working hours and the addition of graphite reflector blocks in available locations on two sides of the core. The other nine fuel assemblies remain in reserve along with five beryllium reflector blocks provided by the U.S. Department of Energy in 1992.

PULSTAR Reactor fuel assemblies are relatively unique in that they have been fabricated only for the PULSTAR Reactor at the State University of New York (SUNY) at Buffalo and for the PULSTAR Reactor at NC State University. The SUNY Buffalo PULSTAR Reactor was the prototype PULSTAR reactor and used 6% enriched fuel. NC State University was the second and last PULSTAR Reactor and elected to use 4% enriched fuel.

PULSTAR reactor fuel has attractive features due to its similarity to commercial power reactor fuel in the use of low enrichment UO_2 pellets and zircaloy cladding. The negative reactivity feedback from fuel temperature broadening of ^{238}U absorption resonances is an inherent safety feature of low enrichment fuel. This feedback also makes the PULSTAR Reactor an appealing training reactor due to the similarity of its power feedback to that of commercial power reactors. An additional benefit is that the zircaloy cladding does not have the long term corrosion issues associated with aluminum clad fuel.

In the early 1990's, the State University of New York (SUNY) at Buffalo terminated the operation of their PULSTAR Reactor. This left enough new fuel pins for 9 new PULSTAR fuel assemblies that could potentially be used in the NC State University PULSTAR Reactor. This work to develop a mixed enrichment core design for the NC State University PULSTAR Reactor was begun in 1995 with sponsorship by the U.S. Department of Energy University Reactor Fuel Assistance Program.

Since this work began, the Nuclear Reactor Program completed a detailed program review and strategic plan. The NC State University PULSTAR Reactor also received a new twenty year license on April 30, 1997. As a result, particular attention has been given to how existing fuel resources including the unused SUNY Buffalo fuel pins can be used to operate the NC State University PULSTAR Reactor as a going concern through at least the end of the current license period.

1.2 Strategic Planning

In 1996, the NC State University Nuclear Reactor Program completed a program review and strategic plan. This plan included goals to develop the facility capabilities and to increase its multiple-discipline research and service use as part of its role in the mission of a land grant university. This plan was accepted by the College of Engineering with a statement of intent to operate the PULSTAR Reactor facility as a going concern through at least the end of the next license period.

On April 30, 1997, the NC State University PULSTAR Reactor received its second license for twenty years of operation. The duration of the renewal process introduced additional operating time through the end of the second license period. This additional time increases the excess reactivity needs projected for the second license period in 1988 by about 40% without considering an increase in utilization.

As of September, 1997, the excess reactivity of the current core was only 870 pcm. This low excess reactivity limits the number of hours that the reactor can be operated per week due to xenon buildup. This limitation in turn affects the capacity for beam instrument use and high-worth cadmium shielded fast neutron irradiations.

The excess reactivity reserves of nine spare 4% enriched fuel assemblies and five beryllium reflector blocks has been measured as 2,000 pcm. The excess reactivity utilization rate of the facility has been 0.125 pcm/MWHr or about 125 pcm/year at a representative annual operating rate of 1,000 MWHr/year. If operations continued at the present level, the incremental excess reactivity that is on-hand would be depleted in 16 years, four years before the end of the next license period. Reflecting the second side of the core with beryllium would add about 800 pcm, allowing operation for the full period of the second license with an ending excess reactivity of about 1,000 pcm. This option would cost about $55,000 in 1991 dollars and it would not permit increased research and service utilization. Continued operation would depend on near-term new fuel assistance at about the same time as the decision whether or not to relicense the facility would be made.

The goal of the fuel management strategy is therefore to allow for an increase in facility use while maintaining sufficient excess reactivity to fully support facility operation through the end of the current license period. An additional component of this strategy is that the facility should have sufficient excess reactivity at the end of the current license period so that it could be relicensed and continue to be operated without affecting users until new fuel assistance could be provided.

1.3 Objective

The objective of this work was to identify a mixed enrichment core design using new 6% enriched fuel from the SUNY Buffalo facility and 4% enriched fuel and graphite and beryllium reflector blocks available at NC State University to operate the NC State University PULSTAR Reactor through at least the end of the new license period. Considerations for these designs included the efficient use of the 6% enriched fuel, meeting minimum excess reactivity needs, requirements, and remaining within the licensed technical specifications for total excess reactivity, power distribution, shutdown margin, and maximum fuel assembly worth.

1.4 Methods

Both the DANT-SYS discrete ordinates codes and the MCNP Monte Carlo codes were investigated for this work. The MCNP code was selected and used due to its capability for high fidelity, three-dimensional geometric detail that is of particular significance in modeling a small and highly heterogeneous core.

1.5 Results

The results of this work show that the unused SUNY Buffalo PULSTAR fuel pins can be used to meet the excess reactivity goals for the NC State University PULSTAR Reactor over the new license period. The calculated assembly power distribution for the initial mixed-enrichment core design is more favorable than the present core due to increased symmetry in the reflection and increased symmetry in the fuel placement with respect to water gaps for the control blades. The unreflected mixed enrichment fuel loading pattern defined by this work could be assembled within current technical specifications even if all fuel were new. Reflection can be added to establish and maintain the minimum desired excess reactivity.

These and other results demonstrate the feasibility of implementing a mixed enrichment core or cores using 6% enriched fuel pins at the NC State University PULSTAR Reactor. These calculations provide a basis for benchmarking a more efficient core design code for use in providing a broader range of power distribution and assembly misloading calculations that will be required for licensing the use of mixed enrichment fuel at the NC State University PULSTAR Reactor.

2.0 PULSTAR REACTOR EXCESS REACTIVITY HISTORY AND NEEDS

2.1 Excess Reactivity History

The excess reactivity of the initial 5x5 unreflected core was measured as 1780 pcm in comparison to the licensed excess reactivity of 3970 pcm. After the first 2,500 MW Hrs of operation, the excess reactivity had been depleted down to about 1200 pcm, which is the excess reactivity needed to overcome the xenon peak after 12 hours of operation. Spare positions on the 6x6 core grid plate were used to reflect the 5x5 core with graphite blocks on first one and then two sides. These reflectors produced a total increase in excess reactivity of 1950 pcm. Since that time the facility has been operated with the same core. As of September 1997, the excess reactivity of this core was 870 pcm.

The excess reactivity history of the facility is summarized in Figure 2.1. The excess reactivity changes can be used to show that about 3000 pcm of excess reactivity have been used in the 25 year history of operation (September 1972 - September 1997). A representative annual excess reactivity utilization rate is about 125 pcm/year or about 0.125 pcm/MW Hr of operation.

2.2 Excess Reactivity Needs

The excess reactivity of the NC State University PULSTAR Reactor has always been low in comparison to the licensed value. While the low excess reactivity has not prevented any requested use, at times it has required the scheduling of work so that xenon buildup would not prevent operating at the requested power for the requested time. It clearly would have prevented multiple fast neutron irradiations using cadmium lined baskets at times, and it would have caused availability limitations due to xenon buildup if there had been higher use of the prompt gamma analysis or neutron depth profiling beam instruments. The low excess reactivity in recent years has been a disincentive to further calibrate, develop, and use, beam instruments. This has resulted in not being able to support some recent user requests including semiconductor doping studies, the characterization of materials encountered by airport security systems, and the characterization of materials for use in tritium production.

The minimum desirable excess reactivity for routine operation is summarized in Table 2.1. These limits allow reaching equilibrium xenon if needed for a longer term beam instrument measurement, the standard operational losses, and the capability for simultaneous fast neutron irradiations in two of the four Vertical Exposure Ports (VEPs). This value would increase by about 130 pcm if allowance was made for performing cadmium shielded irradiations in all four VEPs at the same time.

The preferred core design considered in Section 6 increases neutron leakage into the beam tubes that are presently being used, increasing their negative reactivity by 280 pcm. In one concept

North Carolina State University PULSTAR Reactor

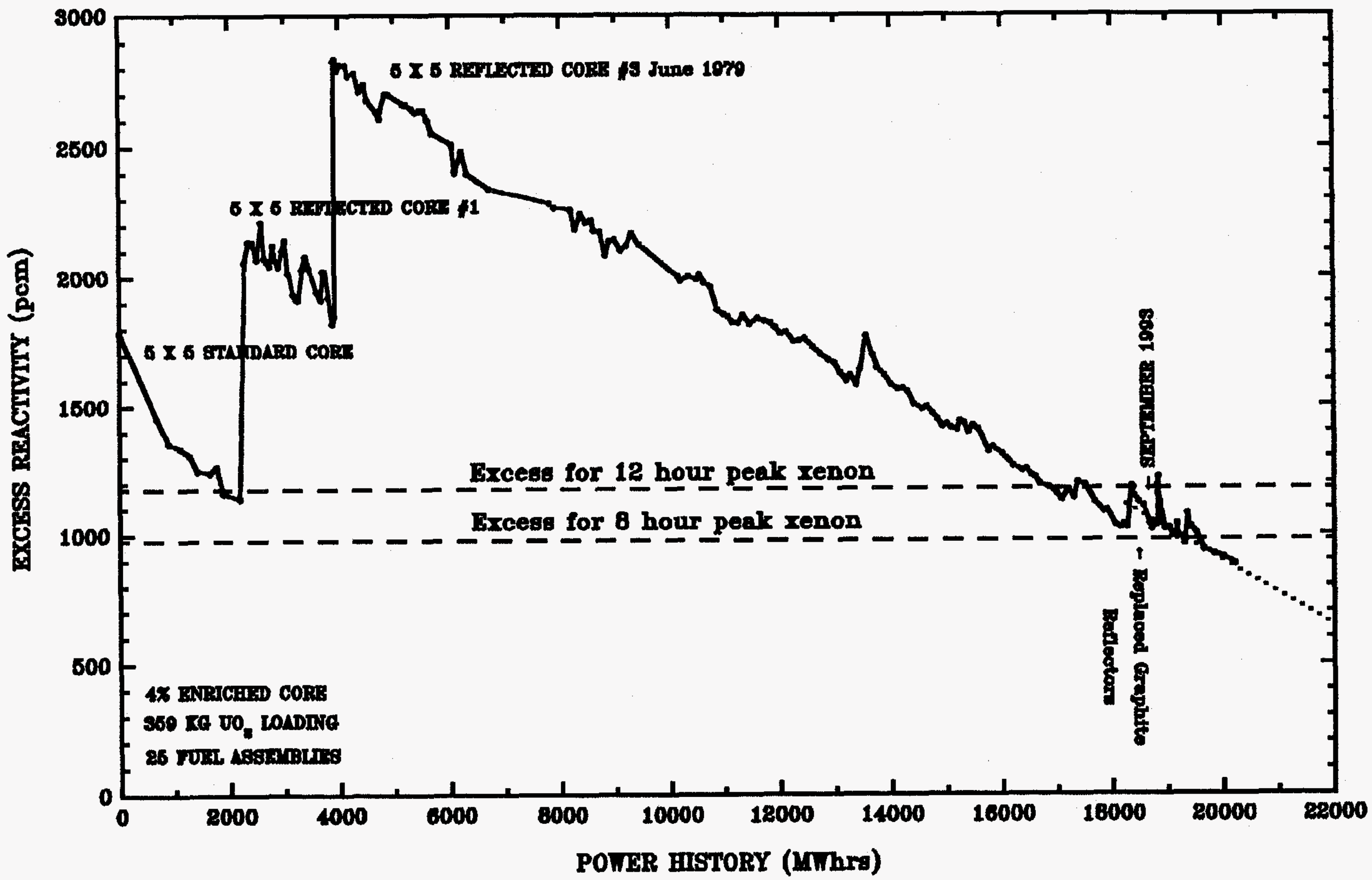

Figure 1.1

Table 2.1 Minimum Desirable Excess Reactivity - Routine Operations

Xenon (approximate equilibrium)	800 pcm
Temperature Coefficient	140 pcm
Power Defect (1 MW)	330 pcm
Beam Tube 4&5 (present core)	130 pcm
Cadmium Line Baskets in VEP (2)	520 pcm
TOTAL	1,920 pcm

for facility development, the neutron radiography would be moved to a different beam tube location and its present location would be used to implement an additional beam instrument such as a diffractometer. The opening of an additional beam tube would introduce an additional excess reactivity loss of about 70 pcm. As a result the total desirable minimum excess reactivity is as much as 2400 pcm.

A representative value for the facility annual operation is about 1,000 full power hours per year. The facility is staffed nine hours per day and can be operated 6.5 hours per day, allowing 2.5 hours for opening the facility, reactor startup, reactor shutdown, and closing the facility. Considering holidays, the facility can be operated up to 50 weeks per year. There is an additional down time of two days per month for routine surveillance and maintenance. Unless justified by a substantial and unexpected demand, there is no intention to increase the facility operation beyond that which can be achieved within nine hour-per-day, five day-per-week staffing.

These operating parameters can be used to calculate that the maximum reactor utilization could be no more than 1475 MW hrs/year. Combining this value with the average rate of reducing excess reactivity by 0.125 pcm/MW Hr gives the result that the maximum total reactivity depletion for the NC State University PULSTAR Reactor would be no greater than about 3690 pcm through the end of the current license period in 20 years.

Full operational capability until the end of the current license in 2017 would require the sum of the total desirable excess reactivity of 2,400 pcm plus the maximum expected excess reactivity depletion of 3690 pcm, or a total of 6090 pcm excess reactivity. Since the existing 4% fuel and reflection has an excess reactivity of 870 pcm, the total incremental excess reactivity needed is 5220 pcm.

The excess reactivity that can be gained with the five beryllium reflector blocks and eight of the unused 4% enriched fuel assemblies on hand has been measured experimentally. These components can provide a 2,000 pcm increase of excess reactivity with about 800 pcm due to five beryllium reflector blocks and about 1200 pcm from the unused 4% enriched fuel assemblies. Counting these resources, a minimum of about 3220 pcm of incremental excess reactivity is desired from the SUNY Buffalo fuel pins.

3.0 MEASURED CORE CONFIGURATIONS FOR EXCESS REACTIVITY BENCHMARK CALCULATIONS

The original critical control blade positions and excess reactivity measurement provide data for a cold, clean excess reactivity and critical control blade position benchmarks. After about 2,000 MWHrs of operation, the original bare core was reflected with graphite on the north side. After about 7,500 MWHr (870 MWd/tonne) of operation, the fuel was moved one row closer to the thermal column nose piece on the east and the west side of the core was also reflected with graphite. After about 17,000 MWHrs (1,972 MWD/tonne) of operation, a test was performed to measure the incremental reactivity obtained by changing the graphite reflector on one side of the core to beryllium.

Startup testing for the first, bare 5x5 core provide initial benchmarks for excess reactivity calculations. The incremental reactivity changes measured for three different changes in reflector configuration provide additional data that can be compared to computed reactivity changes on a fresh fuel basis.

The different measured core configurations are shown in Figure 3.1. A larger scale drawing of the present 5x5 reflected core (Reflected core C-2 in Figure 3.1) is shown in Figure 3.2 to reference the row and column designations of the core base plate. A plan view of the present Reflected 5x5 Core No. 5 is shown in Figure 3.3 to illustrate the relationship between the core grid plate locations, the control blades, the beam tubes, and the thermal column nose piece.

4%	4%	4%	4%	4%
4%	4%	4%	4%	4%
4%	4%	4%	4%	4%
4%	4%	4%	4%	4%
4%	4%	4%	4%	4%

Unreflected Core

4%	4%	4%	4%	4%	C
4%	4%	4%	4%	4%	C
4%	4%	4%	4%	4%	C
4%	4%	4%	4%	4%	C
4%	4%	4%	4%	4%	C

Reflected Core C-1

C	C	C	C	C	C
4%	4%	4%	4%	4%	C
4%	4%	4%	4%	4%	C
4%	4%	4%	4%	4%	C
4%	4%	4%	4%	4%	C
4%	4%	4%	4%	4%	

Reflected Core C-2

Be	Be	Be	Be	Be	C
4%	4%	4%	4%	4%	C
4%	4%	4%	4%	4%	C
4%	4%	4%	4%	4%	C
4%	4%	4%	4%	4%	C
4%	4%	4%	4%	4%	

Reflected Core C-B

Figure 3.1 - Measured Core Configurations for the NC State University PULSTAR Reactor

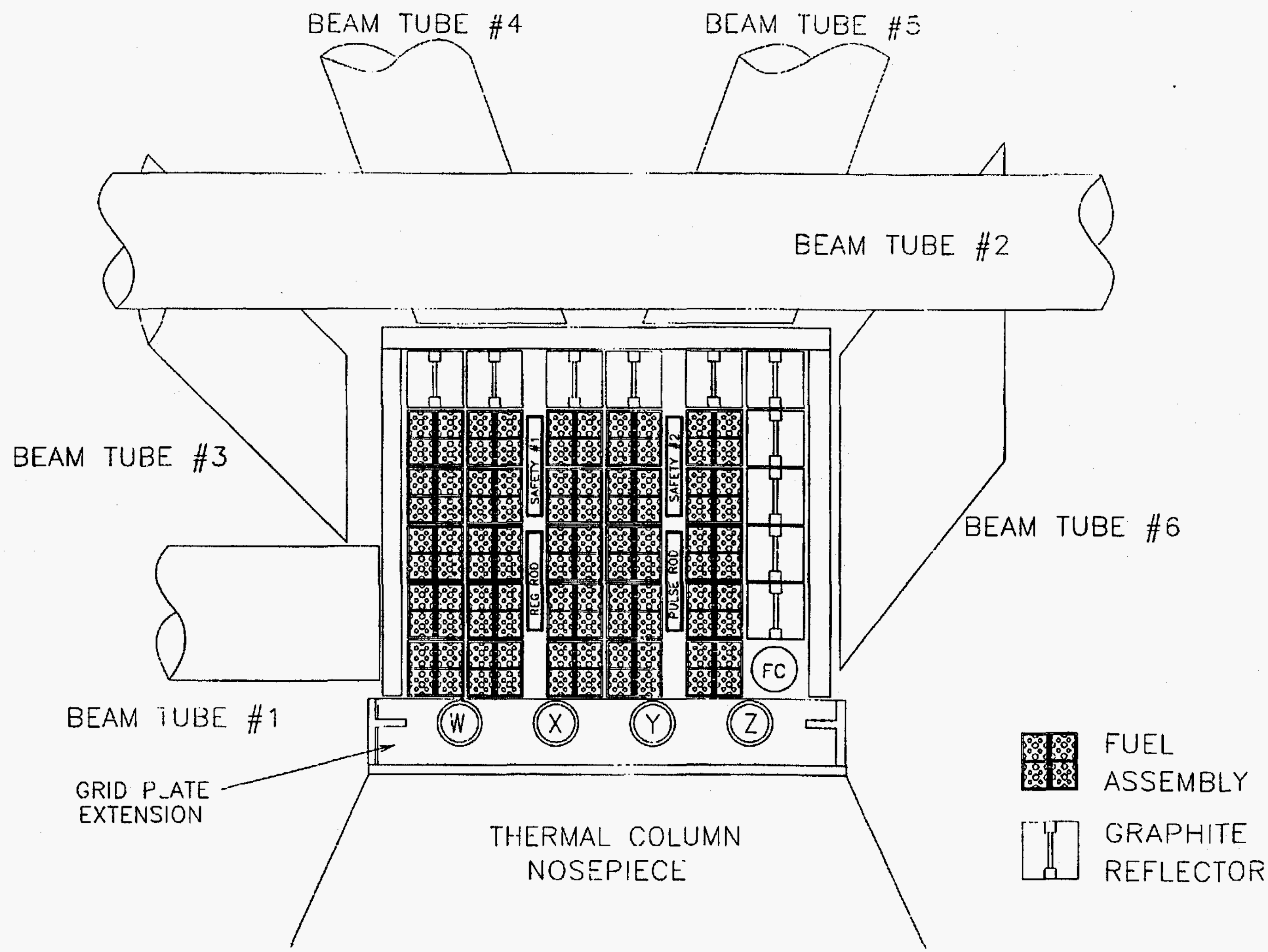
BEAM TUBE #4
BEAM TUBE #5
BEAM TUBE #2
BEAM TUBE #3
BEAM TUBE #6
SAFETY #1
REG ROD
SAFETY #2
PULSE ROD
FC
BEAM TUBE #1
W
X
Y
Z
GRID PLATE EXTENSION
THERMAL COLUMN NOSEPIECE
FUEL ASSEMBLY
GRAPHITE REFLECTOR

Figure 3.2

	1	2	3	4	5	6
A	G-1	G-3	G-5	G-4	G-10	G-2
B	F-18	F-7	F-17	F-15	F-12	G-9
C	F-30	F-31	F-32	F-33	F-34	G-7
D	F-29	F-24	F-21	F-10	F-20	G-6
E	F-28	F-11	F-22	F-14	F-19	G-11
F	F-35	F-26	F-6	F-25	F-23	○

Figure 3.3 - NCSU PULSTAR Reactor Reflected Core 5X5 No. 3 Grid Map

4.0 DANTSYS Core Modeling and Benchmark Calculations

Two and three-dimensional, multigroup core models of the PULSTAR reactor were developed utilizing the DANT-SYS code package. DANT-SYS is a discrete ordinates transport code which uses the multi-group MATXS formatted cross-section library. DANT-SYS was selected for its relative modeling flexibility, availability from the Radiation Shielding Information Center, and computer platform portability. However, it was quickly realized that benchmark cases provided with DANT-SYS were for homogeneous cases or simple heterogenous geometries. In addition, the reference literature contained limited information on the application of DANT-SYS for modeling complex heterogeneous geometries.

The MATXS12-95 cross-section library was obtained directly from LANL and consists of a 69x24 coupled neutron-gamma group from the ENDF/B-VI releases 2 and 3 (334 materials) with P_5 Legendre scattering order. The cross-section library was first processed by the BBC code to select the required elements. The TRANSX code processes MATXS formatted libraries and performs cross-section transport and heterogeneous corrections. These cross-section corrections are extremely important since the DANT-SYS calculation does not include the heterogeneous detail.

The first goal of the model development effort was to obtain excess reactivity predictions for five benchmark cores. These PULSTAR measurements included core-reflector configurations involving water, graphite, beryllium, fuel, and passive core structures. The first model developed was a two-dimensional representation of the current 5x5 Core #3 that is reflected with graphite on two sides. The core material composition was modeled using three material zones:

1. Water
2. Graphite
3. Fuel Mixture

The zones contained the following assigned mixtures:

1. ^{1}H and ^{16}O
2. ^{12}C
3. ^{235}U, ^{238}U, ^{16}O, ^{1}H, tin, nickel, iron, chromium, and Zr_{nat}

The 2-D DANT-SYS model geometry (Figure 4.1) consisted of 169 coarse mesh with over 6000 fine mesh. Atomic densities and volume fractions were used in the mixing calculations. The results from the 2-D calculations are presented in Table 4.1. The control rods out of core excess reactivity numerical results compare well with measured values.

1	1	1	1	1	1	1	1	1	1	1	1	1
1	2	1	2	1	2	1	2	1	2	1	2	1
1	1	1	1	1	1	1	1	1	1	1	1	1
1	3	1	3	1	3	1	3	1	3	1	2	1
1	1	1	1	1	1	1	1	1	1	1	1	1
1	3	1	3	1	3	1	3	1	3	1	2	1
1	1	1	1	1	1	1	1	1	1	1	1	1
1	3	1	3	1	3	1	3	1	3	1	2	1
1	1	1	1	1	1	1	1	1	1	1	1	1
1	3	1	3	1	3	1	3	1	3	1	2	1
1	1	1	1	1	1	1	1	1	1	1	1	1
1	3	1	3	1	3	1	3	1	3	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1

Figure 4.1 - The 2-D DANT-SYS Model NCSU PULSTAR Reactor 5x5 Graphite Reflected Core

5.0 MCNP Core Modeling and Benchmark Calculations

5.1 Core Model

The PULSTAR fuel pins are held by upper and lower fuel assembly grid plates that are in turn held in position by their attachment to a zircaloy channel box that forms the exterior of the fuel assembly. The reactor core is assembled by inserting the nozzle on the lower end of each assembly into a matching hole in the aluminum core grid plate. The fuel assembles are supported and aligned by the lower grid plate and there are no additional structures along the sides or at the tops of the fuel assemblies.

The PULSTAR Fuel pins, fuel assemblies, control blade guides, and the lower grid plate which supports the fuel assemblies were modeled with a high level of geometric detail. Within the active fuel region, the only details omitted were the small dishes in one end of each fuel pellet, minor details in the fuel pin end cap, and small zircaloy bumps on the cladding that assured fuel pin alignment during pulsing.

Above the active fuel height, the fuel pin, upper grid plate, and exterior zircaloy channel were modeled in detail. The only feature omitted at the upper end of the assembly was the aluminum bail that is used for lifting and moving the assembly. Below the active fuel height, the lower grid plate was modeled in detail with only small differences in details in the transition region to the lower nozzle. Aluminum/water ratios were preserved in the adjustments that were made to geometry details.

The graphite and beryllium reflector blocks are held in aluminum frames that provide the same overall dimensions as fuel assemblies. The reflector blocks are installed on the lower grid plate by inserting their dummy nozzle into a hole in the core baseplate. The reflector blocks were modeled in detail with the same minor differences at the upper end and at the lower nozzle as noted for the fuel assemblies.

5.2 Initial Core Excess Reactivity Benchmark

The initial core was an unreflected 5 x 5 array of fuel assemblies. The value of k_{eff} for this core with all rods out was calculated as 1.0181 from control rod position and control rod calibration curves measured during initial start-up testing. The MCNP calculated k_{eff} without the thermal column nose piece was 1.01844 ± 0.00058. The k_{eff} calculated with the thermal column nose piece was 1.01889 ± 0.00092. Both values are within one standard deviation.

As another check, a MCNP calculation was performed with the control rods at a measured critical position during the initial start-up testing. The calculated k_{eff} for this case was 0.99946 ± 0.00083. The difference between the calculated and measured k_{eff} is also less than one standard deviation for this case.

5.3 Sensitivity to Model Parameters

As part of developing the MCNP model for PULSTAR Reactor cores, the sensitivity of the calculated k_{eff} was investigated with respect to several modeling choices that had to be made. These choices were the volume of water surrounding the core, the method used to compensate for not including the fuel pellet end dish, and the effects of using design reference or average as-fabricated values for the fuel enrichment, fuel density, and cladding radius.

The evaluation of the water volume surrounding the core was performed by k_{eff} calculations with 20, 30, and 40 cm of water beyond the core surfaces. The difference in k_{eff} for 30 cm and 40 cm of water was negligible, and 40 cm of water was used in the calculations.

Not modeling the end dish in each fuel pellet was compensated by holding the fuel pellet diameter constant and shortening the active fuel length to conserve fuel mass at constant fuel density. To investigate the effect of this simplification, changes in k_{eff} were calculated for a mass conserving change in fuel density at constant pellet diameter and for a mass conserving change in pellet diameter while keeping the fuel pellet density the same.

Reducing the fuel density by 1% and increasing the active fuel length to hold fuel mass constant gave a calculated k_{eff} of 1.01875 ± 0.00049, or a change in k_{eff} of .00063 that is less than 1.1 times the calculation standard deviation. Reducing the fuel pellet diameter by 1% and increasing the active fuel length to keep the fuel mass constant produced a calculated k_{eff} of 1.01982 ± 0.00048, or a change in k_{eff} of 0.0017 that is 2.9 times the calculation standard deviation. These results indicate that k_{eff} is more sensitive to fractional changes in pellet diameter than fuel density, and that holding the pellet diameter at the actual value and adjusting the active fuel length to conserve fuel mass should give better calculated values of k_{eff}.

For the reported calculations, the difference between design reference values and the actual average fuel density and pellet radius was 0.5%. Using the average actual pellet radius potentially prevented a bias of about one standard deviation for the calculated results.

The design reference value for the fuel pin cladding outer diameter was 1.200 cm (0.4724 in.). As-fabricated measurements for each pin were averaged and the average outer diameter was found to be 1.197 cm (.4712 in.), or 0.27% smaller than the design reference value. The calculated k_{eff} for the initial core with a 1% increase in the as fabricated cladding outer diameter was 1.01032 ± 0.00047, which is 17 standard deviations lower than the initial calculation. Scaling this to the design reference cladding diameter would give a difference in k_{eff} of about 6 times the calculation standard deviation. It was concluded that using as-fabricated fuel pin cladding outer diameter was significant in these calculations.

Fuel pellet assay data indicated an average enrichment of 4.026% in comparison to the design reference value of 4.0%. The difference from the design reference value is 0.65%. The calculated value of k_{eff} for a 1% increase in enrichment was 1.02059 ± 0.00053, or 4.25 times the calculation standard deviation. Scaling this to the as-fabricated difference of 0.65% gives a difference of about 2.7 times the calculation standard deviation. The difference between the specified and average as-measured enrichment for the 6% enriched pins available from the SUNY Buffalo PULSTAR Reactor was negligible. The results of this investigation indicate that as-fabricated fuel measurements are more accurate than the use of as-specified values for the calculation of excess reactivity for PULSTAR Reactor fuel that has been fabricated.

The model used in the benchmark and mixed enrichment core design calculations used actual fuel pellet diameter, density, and enrichment. The active fuel height was calculated to conserve the actual average per-pin fuel mass. The actual average fuel cladding outer diameter was used. The use of average as-fabricated fuel pin dimensions and enrichment can be considered to be best-estimates calculations which are also conservative in comparison to the specified values due to the fact that the largest effect was the fuel cladding diameter and that the slightly smaller average as-fabricated diameter increased the calculated excess reactivity, which is consistent with having an under-moderated core with a negative moderator temperature coefficient of reactivity.

5.4 Incremental Excess Reactivity Changes

Calculated values for k_{eff} with all rods out and cold, clean fuel are shown in Table 5.1 along with a reconstruction of measured k_{eff}. The reconstruction of measured k_{eff} was performed by summing the core initial excess reactivity and the excess reactivity increases associated with each reflector in %Δk/k and converting the result to k_{eff}. Measured values for the core initial excess reactivity and incremental increases in excess reactivity are shown in Table 5.2 along with equivalent values obtained from the calculated values of k_{eff}.

Table 5.1 - Clean Core k_{eff} for Tested Core Configurations

Core	k_{eff} Measured[1]	k_{eff} Calculated[2]	Difference
Unreflected[3]	1.0181 ± .0005	1.01844 ± .0006	.0003 ± .0008
C-1 Reflector	1.0286 ± .0007	1.02868 ± .0006	.0001 ± .0009
C-2 Reflector	1.0387 ± .0009	1.04097 ± .0006	.0023 ± .0011
C-B Reflector	1.0474 ± .0010	1.05042 ± .0006	.0030 ± .0012

[1] Calculations are from incremental increases in Δk/k and do not include reactivity lost due to fuel burn-up over facility history

[2] Calculations for fresh fuel

[3] Initial excess reactivity was 0.0178 Δk/k

The Table 5.1 k_{eff} values agree well for the clean, bare core and for the core with a graphite reflector on one side. The values for the other two reflectors differ by 2 - 3 standard deviations.

The Table 5.2 values for incremental excess reactivity changes associated with each reflector indicate that this difference is due to the measured results for the C-2 Reflector. No physical explanation for indicated discrepancies is known.

Table 5.2 - Measured and Calculated Excess Reactivity Gains For Tested Reflectors

Core	Δk/k Measured	Δk/k Calculated	Difference
C-1 Reflector	.0100 ± .0007	.0100 ± .0008	.0000 ± .0011
C-2 Reflector	.0095 ± .0007	.0116 ± .0008	.0021 ± .0011
C-B Reflector	.0080 ± .0007	.0085 ± .0008	.0005 ± .0011

5.5 Summary

The NC State University PULSTAR Reactor has a small and very heterogenous core. A MCNP model was developed which predicted the initial excess reactivity and $k_{eff} = 1$ at the measured critical rod height within the calculation standard deviation of 58 pcm. Good agreement was obtained for the incremental reactivity associated with two out of three reflector changes over the history of the facility. The worst case agreement, for reflector C-2, had a difference of two standard deviations or about 0.2% Δk/k. These results, combined with the results for calculations for the diverse benchmark cases reported for MCNP give confidence that the reactivity calculations performed for NC State University PULSTAR Reactor core models are correct within the uncertainty of the method.

6.0 Mixed Enrichment Core Analysis

6.1 Introduction

Prior to calculating k_{eff} for a set of selected core loading patterns, several possibilities were investigated for enhancing the leakage flux from the west side of the core into beam tubes 4 and 5. These beam tubes, located on the west side of the core, are used for the neutron radiography and prompt gamma analysis and neutron depth profiling facilities. Having either 4% or 6% enriched fuel on the west side did not make a significant difference in the beam tube flux. However, having fuel instead of reflectors on the west side did increase the beam tube flux some. Since it is desired to keep fuel by the vertical exposure ports on the east side of the core, it was decided to pursue the design of a 4 x 6 core that placed fuel on the east and west sides of the core grid plate and that was reflected on the north and south sides of the core grid plate.

Using the fuel and reflector outline defined above, k_{eff} was calculated for cases having eight 6% enriched fuel assemblies on the east and west sides of the core and for several cases having four 6% assemblies at symmetric locations in the core. Four of these cases are shown in Figure 6-1. The associated calculated values of k_{eff} are summarized in Table 6.1. These calculations were performed with the assumption of all fresh fuel, all rods out, and beam tubes flooded in order to determine the maximum possible excess reactivity. The mixed enrichment Core 4 fuel loading pattern was selected for further analysis due to the excess reactivity being almost as high as the mixed enrichment Core 2 fuel loading pattern while it used only half as many 6% fuel assemblies.

Table 6.1 Mixed Enrichment Core Excess K_{eff}

Core 1	1.06405 ± 0.00056
Core 2	1.06802 ± 0.00055
Core 3	1.06157 ± 0.0056
Core 4	1.06612 ± 0.00056

6.2 Total Excess Reactivity

The excess reactivity for the mixed enrichment Core 4 was calculated to be 1.06612 ± 0.00056 for all fresh fuel. Under subsequent review, it was noted that this calculation was performed without the thermal column nose piece, which places a large volume of graphite within about

C	6%	6%	6%	6%	C
C	4%	4%	4%	4%	C
Be	4%	4%	4%	4%	Be
Be	4%	4%	4%	4%	Be
C	4%	4%	4%	4%	C
C	6%	6%	6%	6%	FC

Core 1

C	6%	6%	6%	6%	C
Be	4%	4%	4%	4%	Be
C	4%	4%	4%	4%	C
Be	4%	4%	4%	4%	Be
C	4%	4%	4%	4%	C
Be	6%	6%	6%	6%	FC

Core 2

C	4%	4%	4%	4%	C
C	6%	4%	4%	6%	C
Be	4%	4%	4%	4%	Be
Be	4%	4%	4%	4%	Be
C	6%	4%	4%	6%	C
C	4%	4%	4%	4%	FC

Core 3

C	4%	4%	4%	4%	C
Be	6%	4%	4%	6%	Be
C	4%	4%	4%	4%	C
Be	4%	4%	4%	4%	Be
C	6%	4%	4%	6%	C
Be	4%	4%	4%	4%	FC

Core 4

Figure 6.1 - Representative Mixed Enrichment Core Designs

three inches of the south side of the core. This calculation was repeated with the thermal column nose piece included, and k_{eff} increased by 0.00220 ± 0.00116. The total excess reactivity for the mixed enrichment Core 4 is 1.06832 ± 0.0018 as summarized in Table 6.2..

Table 6.2 Mixed Enrichment Core 4 Excess Reactivity
With Thermal Column Nose Piece

Initial Calculated Excess Reactivity	1.06612 ± 0.00056
Incremental Nose Piece Reactivity	+ 0.00220 ± 0.00116
Total Excess Reactivity	1.06832 ± 0.00128

The total excess reactivity of this core design, based on all fresh fuel, is much higher than the technical specification limit of 3970 pcm. While this excess reactivity could not be achieved due to the fact that only nine unused 4% fuel assemblies are available, it is not easy to account for the reactivity loss of used 4% fuel assemblies and how they would contribute to the core total excess reactivity as a function of their placement in mixed enrichment core designs. As an alternative to calculating individual 4% enriched fuel assembly burn-up and accounting for their placement in a mixed enrichment core, the possibility for loading an un-reflected, mixed enrichment core on the basis of all fresh fuel was considered. If such a core could clearly be loaded within existing technical specification limits, it could be used for experimental measurements that could justify adding reflection, as needed, to achieve minimum excess reactivity goals while keeping the core design within licensed limits.

6.3 Bare Mixed Enrichment Core

The excess reactivity was calculated for the Mixed Enrichment Core 4 design without the graphite and beryllium reflector blocks. The result was a k_{eff} of 1.01836 ± 0.00074, showing that the unreflected 4x6 mixed enrichment core with all new fuel would have an excess reactivity that is clearly within the facility technical specifications. Startup testing measurements could then be used to add reflection to meet excess reactivity goals within the licensed limit.

The calculated value of k_{eff} for the 5x5 core with fresh 4% fuel was 1.01844 ± 0.00058. While the bare 4x6 mixed enrichment core has four 6% fuel assemblies, it also has one fewer fuel assembly and a less favorable geometry.

6.4 Mixed-Enrichment Core Assembly Power Distribution

MCNP was used to calculate the assembly power distribution for the Mixed Enrichment Core 4 design by counting the fissions in each assembly. Before performing this calculation, a search was performed to find the zero power critical control blade height at 70° F and the blades were set at this position, 9.3 inches above full insertion. Since the pulse blade is held fully withdrawn from the core, this insertion provides the most conservative case with respect to assembly power peaking around the pulse blade location. It also provides the most conservative case with respect to axial power peaking as including excess reactivity losses due to fuel use would result in a higher control blade elevation and a more uniform axial power distribution.

The normalized assembly powers calculated for the mixed enrichment core are shown in Table 7. These data can be compared to the Table 8 relative assembly powers that were determined for the present 4% enriched 5x5 Reflected Core No. 5 by flux mapping and incorporated in the current facility Final Safety Analysis Report (5).

The assembly power distribution for the mixed enrichment core was found to be flatter than that for the present 4% enriched core that is reflected on two adjacent sides with graphite. Comparing the relative assembly powers for the two cores, this flatter distribution appears to be attributable to the use of symmetric reflection and the 6% enriched assemblies picking up some extra power at locations near the core corners. The net result is a more favorable power distribution in comparison to the 5x5 Reflected Core No. 5.

Table 6.3 Assembly Power Distribution for Reflected Mixed Enrichment Core

Column	1	2	3	4	5	6
Row						
A	C	0.713	0.784	0.783	0.712	C
B	Be	1.097	0.999	1.006	1.117	Be
C	C	1.106	1.179	1.201	1.146	C
D	Be	1.125	1.182	1.194	1.144	Be
E	C	1.141	1.012	1.005	1.101	C
F	Be	0.803	0.845	0.830	0.771	FC

Table 6.4 Assembly Power Distribution for 5x5 Core # 5

Column	1	2	3	4	5	6
Row						
A	C	C	C	C	C	C
B	0.664	0.828	0.977	0.980	0.887	C
C	0.753	0.936	1.153	1.076	1.018	C
D	0.863	1.027	1.229	1.326	1.263	C
E	0.801	0.948	1.125	1.216	1.078	C
F	0.690	0.949	1.146	1.088	0.972	FC

6.5 Shutdown Margin

Shutdown margin was investigated for the reflected, mixed enrichment core design by calculating the reactivity for each of the three cases where one of the magnetically coupled control blades is assumed to be fully withdrawn and to remain stuck at that position. The pulse rod was assumed to be fully withdrawn from the core. The results of these calculations were shutdown margins of 804 pcm, 1213 pcm, and 266 pcm for the Mixed Enrichment Core 4 design with the assumption of all fresh fuel.

One of these results, the 266 pcm shutdown margin, is less than the technical specification of 400 pcm. However, as modeled with all fresh fuel, this core would have an excess reactivity of 6385 pcm. If a the same fuel loading pattern was assembled with all fresh fuel but without any reflection, the excess reactivity would be 3818 pcm. The control blade critical position for this core would have an additional 2567 pcm withdrawn from the core. It can therefore be expected that the Mixed Enrichment Core 4 design can be implemented with the required shutdown margin by first loading it as a bare core and then incrementally reflecting it to obtain the desired excess reactivity within shutdown margin limits.

6.6 Fuel Misloading

Excess reactivity was calculated for the four fuel misloading cases shown in Figure 5. The Table 6.5 values show k_{eff} for the misloaded pattern with the control rods at the critical position for the correctly loaded core with all fresh fuel.

C	4%	4%	4%	4%	C
C	4%	4%	4%	4%	C
Be	4%	6%	6%	4%	Be
Be	4%	6%	6%	4%	Be
C	4%	4%	4%	4%	C
C	4%	4%	4%	4%	FC

Case 1

C	4%	4%	4%	4%	C
Be	4%	4%	4%	4%	Be
C	4%	4%	4%	4%	C
Be	4%	6%	6%	4%	Be
C	4%	6%	6%	4%	C
Be	4%	4%	4%	4%	FC

Case 2

C	4%	4%	4%	4%	C
C	4%	4%	4%	4%	C
Be	4%	4%	4%	4%	Be
Be	4%	4%	4%	4%	Be
C	4%	4%	6%	6%	C
C	4%	4%	6%	6%	FC

Case 3

C	4%	4%	4%	4%	C
Be	4%	4%	4%	4%	Be
C	4%	4%	4%	4%	C
Be	4%	4%	6%	6%	Be
C	4%	4%	6%	6%	C
Be	4%	4%	4%	4%	FC

Case 4

Figure 6.2 - Core Misloading Cases

Several conclusions can be obtained from these calculations including:

- Excess reactivity is enhanced when 6% fuel is located adjacent to the water gaps for the control blades

- Excess reactivity enhancement is maximum when all of the 6% fuel faces a control-blade-free water gap

- Minimum shutdown margin will occur when control blade 3 is assumed to be fully withdrawn as this leaves the control blade water gap on the north half of the core without an inserted control blade.

Table 6.5 Fuel Misloading k_{eff}[1]

Case	k_{eff}
1	1.00443 ± 0.00112
2	1.00489 ± 0.00121
3	1.00303 ± 0.00118
4	1.00788 ± 0.00118

[1] Referenced to Initially Critical Core

To address shutdown margin in the most general manner, the worst case excess reactivity and shutdown margin for a misloaded, bare 4x6 mixed-enrichment core show that such a core could be loaded with an adequate shutdown margin. Administrative controls can be used to minimize the probability for a misloading and to detect and correct any misloading prior to power operation.

7.0 Excess Reactivity Enhancement

The total excess reactivity of the mixed enrichment core on a fresh fuel basis was calculated to be 1.06832. The total excess reactivity of the present 5x5 Core No. 5 was calculated to be 1.04097. As a first estimate, converting to the 4x6 mixed-enrichment core design 4 will increase available excess reactivity by about 2735 pcm.

It must also be recognized that the present core has an excess reactivity of about 870 pcm, and that the fission products in four 4% fuel assemblies will be removed from the core during the conversion. As a result, the incremental change in excess reactivity from the present excess reactivity will be greater than that calculated on a fresh-fuel basis.

An experiment was performed in which eight fresh 4% enriched fuel assemblies were loaded in the present 5x5 reflected core No. 5. The total excess reactivity increase was measured as 1200 pcm, or 150 pcm per assembly on the average. An estimate of the minimum excess reactivity reserves can be made as summarized in Table 10 with the assumption that used fuel can be replaced with an increase in excess reactivity of at least 150 pcm per assembly on the average and that no more than four 6% enriched assemblies would be used in the core at any time.

Table 7.1 - Total Incremental Excess Reactivity With Eight New 6% Enriched Fuel Assemblies

Conversion to Mixed Enrichment - Fresh Fuel Basis	2735 pcm
Initial Replacement of Four 4% Assemblies	600 pcm
Subsequent Use of Eight New 4% Assemblies	1200 pcm
Subsequent Use of Four New 6% Assemblies	600 pcm
TOTAL	5135 pcm

These calculations show that the total desirable minimum excess reactivity of 2400 pcm and the maximum excess reactivity use of about 3690 pcm over the next twenty years can be met by incremental reflection of the Mixed Enrichment Core 4 design. It is likely that additional excess reactivity could be obtained by changing the fuel loading pattern after operating with the four initially installed 6% fuel assemblies. For example, it could be possible initially operate with the mixed enrichment core design 4, then move the used 6% assemblies to the core center and, still later, to add four fresh 6% enriched assemblies at the positions used in the initial Mixed Enrichment Core 4 design. This would be expected to produce an additional increase in excess reactivity in relative to the initial design.

8.0 Conclusions

It can be concluded that the use of available 6% enriched fuel pins along with the existing 4% enriched fuel assemblies at NC State University can provide a means for the NC State University PULSTAR Reactor to meet its excess reactivity needs while operating as a going concern for its next license period. It is expected that several different mixed enrichment core designs could be licensed if needed in order to meet this goal.

References

1. Los Alamos Monte Carlo Group, *MCNP - A General Purpose Monte Carlo Code for Neutron and Photon Transport*, LA-7396-M(rev.), Los Alamos National Laboratory, (Apr. 1981)[government report]

2. D.J. Whalen, D.A. Cardon, J.L. Uhle, J.S. Hendricks, *MCNP: Neutron Benchmark Problems*, LA-12212, Los Alamos National Laboratory, (Nov. 1991)[government report]

3. J.C. Wagner, James E. Sisolak, G.W. McKinney, *MCNP: Criticality Safety Benchmark Problems*, LA-12415, Los Alamos National Laboratory, (Oct. 1992)[government report]

4. S. Sitaraman, *MCNP: Light Water Reactor Critical Benchmarks*, NEDO-32028, GE Nuclear Energy (March 1992)[report]

5. North Carolina State University PULSTAR Reactor Updated Final Safety Analysis Report, License No. R-120, Docket No. 50-297, Amendment 11, September 3, 1995

Attachment A

MCNP Reference Benchmark Calculations

MCNP benchmark problems provided by the Los Alamos National Laboratory and the General Electric Company were repeated to demonstrate the performance of the MCNP code and cross sections used in the NC State University PULSTAR Reactor mixed enrichment core design calculations. These benchmark problems included:

1) Fast Neutron Systems

2) Low Enrichment Systems

3) Reflected Systems

4) Small Reactors

These results are summarized below. Additional information about these benchmark problems can be obtained from

- MCNP: Benchmark Problems for Neutrons, LA 12212
- MCNP: Criticality Safety Benchmark Problems, LA-12415m YC 714, October 1992
- MCNP: Light Water Reactor Critical Benchmarks, NEDO-32038, March, 1992

LOS ALAMOS NATIONAL LABORATORY (LANL) BENCHMARK PROBLEMS

No.	LANL MCNP k	Std. Dev.	NCSU MCNP k	Std. Dev.
1	0.9976	0.0011	0.99895	0.00102
2	0.9986	0.0021	0.99981	0.00189
3	1.0075	0.0012	1.01069	0.00100
4	1.0024	0.0013	1.01069	0.00123
5	1.0003	0.0014	1.00143	0.00102
6	0.9981	0.0010	0.99704	0.00219
7	0.9956	0.0022	0.99790	0.00191
8(a14)	0.9991	0.0011	1.00044	0.00111
9(an1)	0.0000	0.0009	0.99833	0.00086
10(an19)	1.0302	0.0013	1.02994	0.00120
11(an20)	0.9960	0.0012	0.99735	0.00142

Attachment A (Cont.)

GE BENCHMARK PROBLEMS

No.	Exp. k	Std. Dev.	MCNP k	Std. Dev.	NCSU MCNP k	Std. Dev.
12	1.0000	0.003	0.9981	0.0011	0.99655	0.00109
13	1.0000	0.003	1.00073	0.0011	0.99929	0.00105
14	1.0000	0.0020	1.0008	0.0013	1.00007	0.00151
15	1.0000		0.9997		1.00091	0.00123