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System Definition Document: Reactor Data Necessary for Modeling Plutonium Disposition in Catawba Nuclear Station Units 1 and 2

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Fissile Materials Disposition Program

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SYSTEM DEFINITION DOCUMENT: REACTOR DATA NECESSARY FOR MODELING PLUTONIUM DISPOSITION IN CATAWBA NUCLEAR STATION UNITS 1 AND 2

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SYSTEM DEFINITION DOCUMENT: REACTOR DATA NECESSARY FOR MODELING PLUTONIUM DISPOSITION IN CATAWBA NUCLEAR STATION UNITS 1 AND 2

R. J. Ellis

ABSTRACT

The U.S. Department of Energy (USDOE) has contracted with Duke Engineering and Services, Cogema, Inc., and Stone & Webster (DCS) to provide mixed-oxide (MOX) fuel fabrication and reactor irradiation services in support of USDOE's mission to dispose of surplus weapons-grade plutonium. The nuclear station units currently identified as mission reactors for this project are Catawba Units 1 and 2 and McGuire Units 1 and 2. This report is specific to Catawba Nuclear Station Units 1 and 2, but the details and materials for the McGuire reactors are very similar. The purpose of this document is to present a complete set of data about the reactor materials and components to be used in modeling the Catawba reactors to predict reactor physics parameters for the Catawba site. Except where noted, Duke Power Company or DCS documents are the sources of these data. These data are being used with the ORNL computer code models of the DCS Catawba (and McGuire) pressurized-water reactors.

1. INTRODUCTION

This system definition document was prepared as part of an Oak Ridge National Laboratory (ORNL) study of the U.S. domestic Duke, Cogema, and Stone & Webster (DCS) weapons-grade plutonium disposition mixed-oxide (MOX) project. This document pertains to the Duke Power Catawba Nuclear Station Units 1 and 2, located near Rock Hill, South Carolina. A photograph of the Catawba site is shown in Fig. 1. The purpose of this report is to provide and present all of the data required to model the nuclear reactors with ORNL physics codes. These data are either documented information or best-estimate assumptions.[1–4] The images and maps presented in this report were obtained from the Web sites for Westinghouse, Duke Energy, and Framatome Technologies.

Figure 1. Catawba Nuclear Station.

Duke Power is responsible for power generation in a large portion of North and South Carolina, as shown in the map in Fig. 2. The Duke Power nuclear stations are indicated on the map as triangles. The Catawba Nuclear Station is 19 miles (30.6 km) southwest of Charlotte, North Carolina, while McGuire Nuclear Station is north of Charlotte. The Catawba Nuclear Station is in a relatively isolated location. The McGuire units are almost identical to the Catawba Westinghouse units. The region surrounding the Catawba site is depicted in Fig. 3.

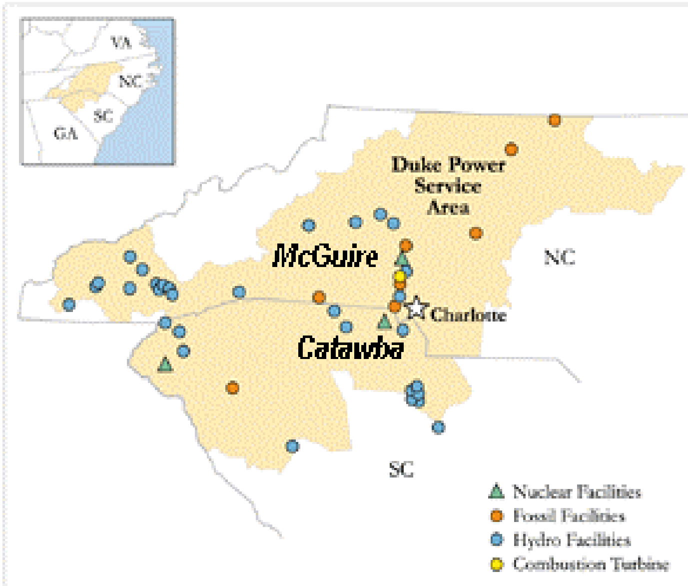


Figure 2. Location of Catawba Nuclear Station.

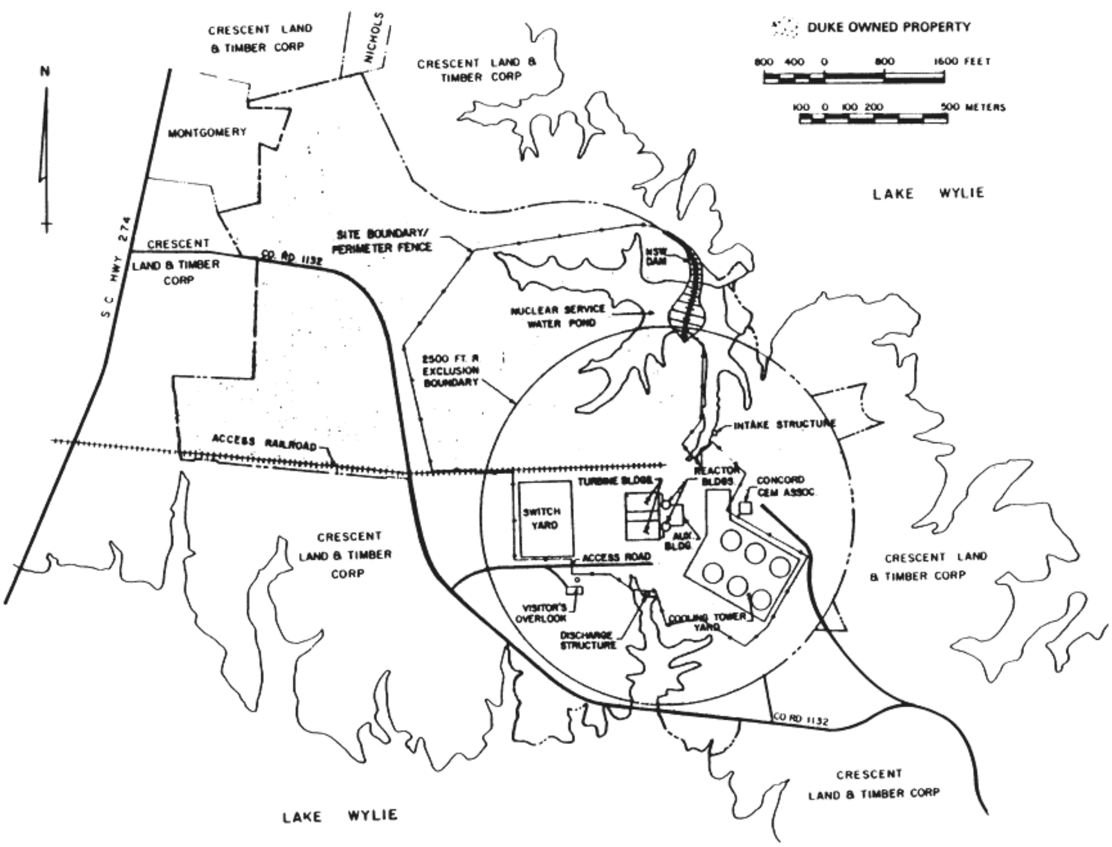


Figure 3. Details of the Catawba Nuclear Station site.

Catawba Unit 1 began commercial operation on June 29, 1985, and Catawba Unit 2 began commercial operation about a year later, on August 19, 1986. The licenses expire on December 6, 2024, and February 24, 2026, respectively.

The Catawba nuclear reactors are both Westinghouse pressurized-water reactors (PWRs) with 4-loop cooling systems (Fig. 4). The reactors are licensed to produce 3411 MW(t), which currently converts to an electrical capacity of 1129 MW(e). The reactor cores comprise 193 fuel assemblies of the 17×17 design, with 264 fuel pins per assembly.

Figure 5 is a three-dimensional (3-D) view of a similar Westinghouse PWR with one-fourth of the core and peripheral components removed. The diagram shows many of the components and regions of the Westinghouse PWR. The control structure ends are prominent at the top of the reactor vessel. The schematic diagram on the right in Fig. 5 identifies the components and devices in the Westinghouse PWR as shown in the open view.

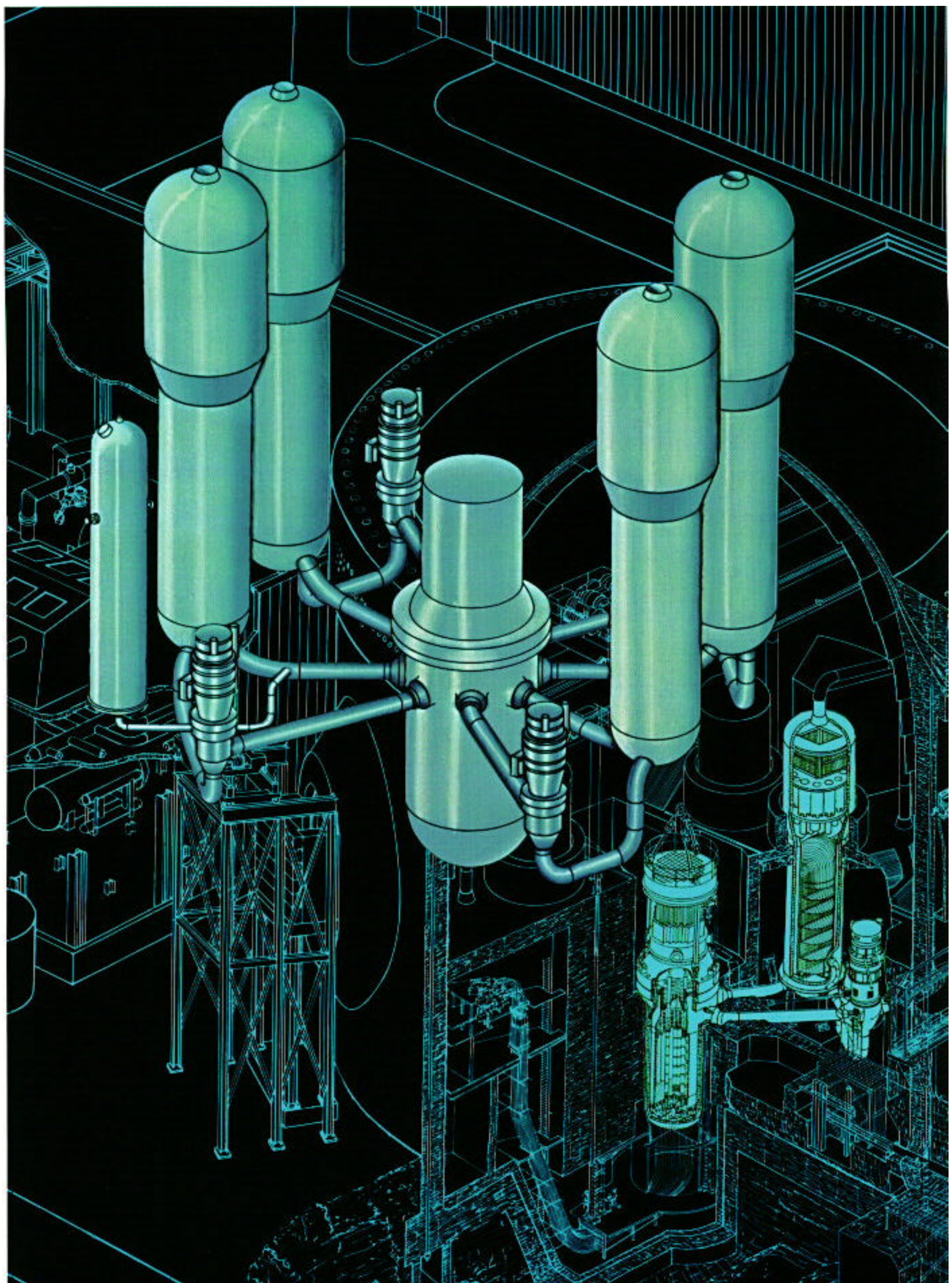


Figure 4. View of the Westinghouse PWR with the 4-loop cooling system.

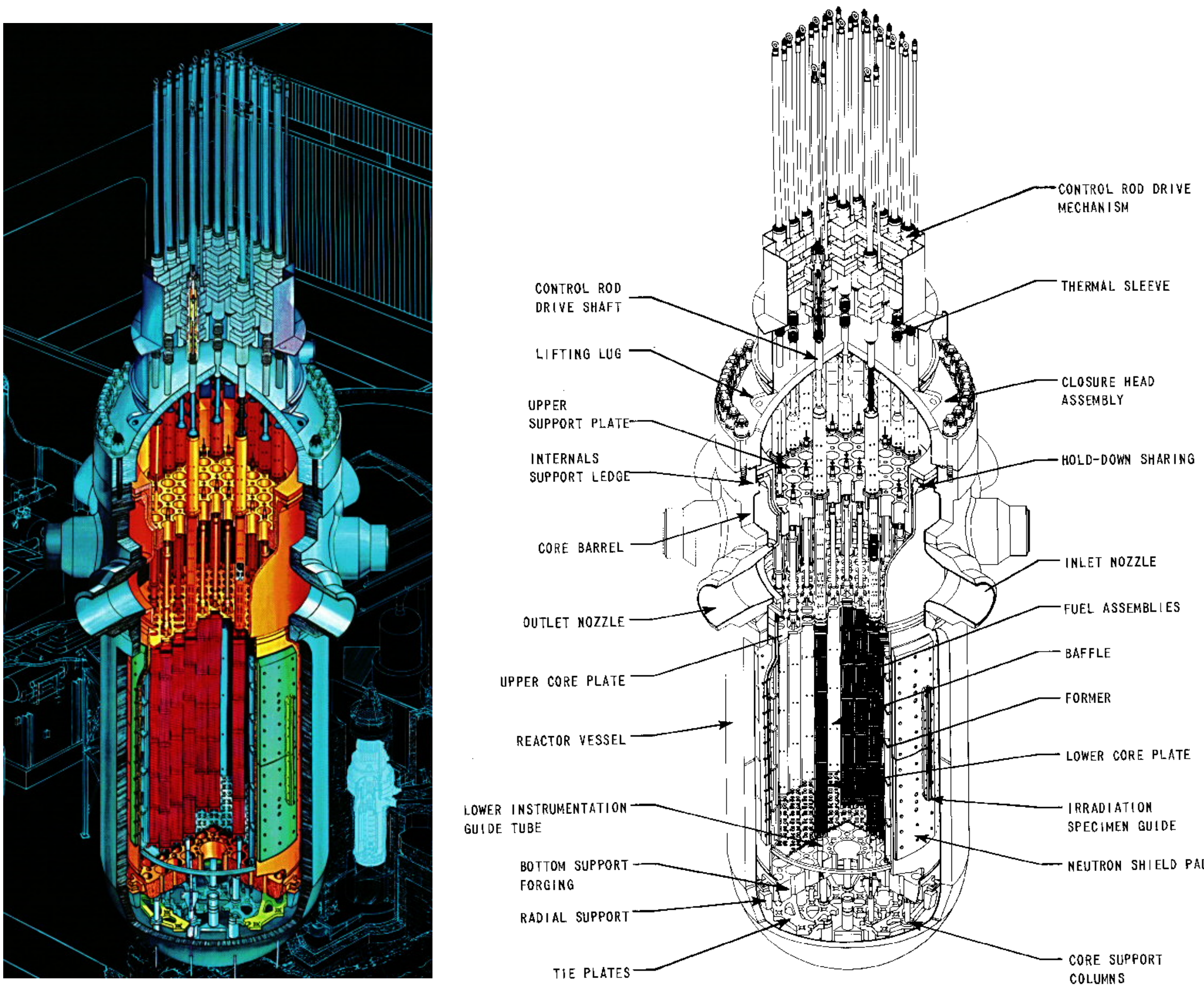


Figure 5. Cross-sectional 3-D view of a similar Westinghouse PWR.

The fuel assembly "vehicle" for the MOX fuel will be based on the state-of-the-art Framatome/ COGEMA Fuels (FCF) Advanced Mark-BW 17 × 17 fuel assembly (see Fig. 6). The Mark-BW was developed as replacement fuel for Westinghouse 17 × 17 plants and has good service records in the McGuire, Catawba, and Trojan nuclear plants. The Mark-BW is licensed for application in Westinghouse 17 × 17 plants to a critical heat flux (CHF) performance level 26% higher than resident fuel. FCF has delivered more than 1100 Mark-BW fuel assemblies. The new MOX assembly is compatible with the FCF Mark-BW fuel assembly design (currently in McGuire and Catawba nuclear stations). DCS will ensure that the weapons-grade (WG) plutonium MOX fuel assembly will be compatible with existing 17 × 17 low-enriched uranium (LEU) fuel assemblies in the reactor core during the lead assembly testing program and then during the production-scale MOX fuel utilization.

The design makes use of European MOX fuel experience of irradiating cores of MOX and LEU fuel assemblies. The advanced micronized master blend (A-MIMAS) process will be used by COGEMA to fabricate WG plutonium MOX fuel as a ceramic PuO_2-and-UO_2 fuel pellet with 2 to 5 wt % fissile plutonium.

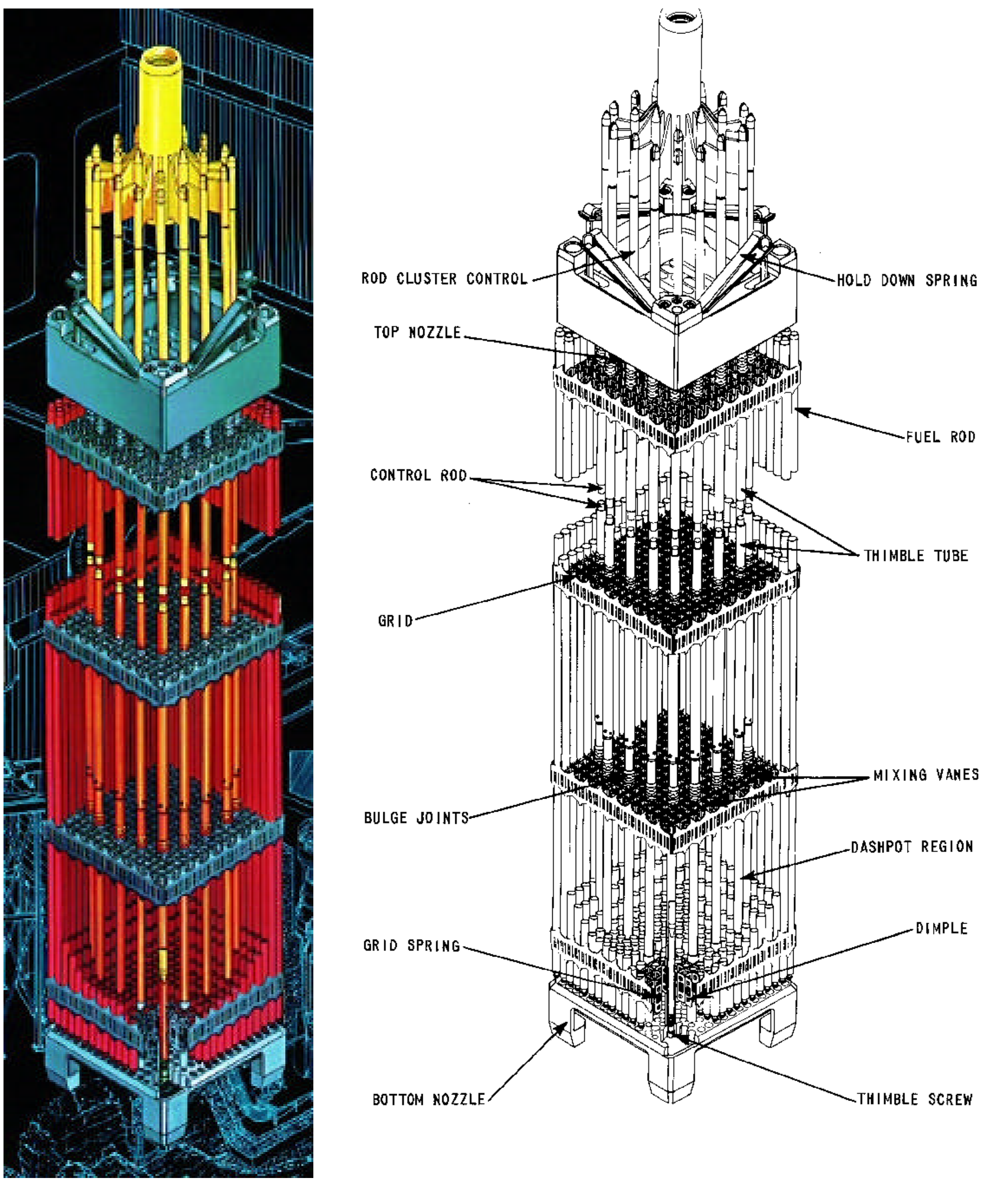


Figure 6. Details of the FCF Mark-BW 17 ´ 17 PWR fuel assembly.

This process is consistent with the MIMAS process currently being used to fabricate reactor-grade MOX fuel.

The nuclear design of the MOX fuel assembly has to account for differences in the nuclear characteristics between MOX and LEU fuel. The thermal absorption cross section for MOX is quite a bit larger than for LEU and results in lower neutron flux levels in MOX fuel assemblies compared to LEU fuel assemblies. This causes a large thermal neutron flux gradient at the MOX/LEU interfaces, which could result in high-power peaking factors in the outermost pins of the MOX fuel assemblies.

Also, the large thermal absorption and fission cross sections of MOX fuel results in a hardened neutron spectrum that reduces the effectiveness of the thermal neutron absorbers, namely, the soluble boron, the burnable poison (BP) rods, and the control rods. The differences between the two fuel types also produce different depletion behavior. The differences in the fuel characteristics are manageable through careful selection of assembly average plutonium enrichments and enrichment zoning within the MOX fuel assembly. Thus, neutronic differences between the MOX and LEU fuel can be minimized to lessen the perturbations associated with substituting one fuel type for the other.

2. SYSTEM DEFINITION

The design details needed for modeling the nuclear reactors at Catawba Nuclear Station Units 1 and 2 include materials and dimensions of reactor components and structures and operating conditions. These actual or assumed data are presented in Tables 1–6. The quantities are presented below both in “engineering” dimensional units and in the International System of Units (SI) or scientific units, as appropriate and necessary for use in computer code input.

Table 1. Reactor operating details and conditions for the Catawba Nuclear Station

Parameter	Value	SI (where appropriate)
Reactor design	Westinghouse PWR, 4-loop cooling system	
Thermal power	3411 MW(t)	
Power density	100.6 kW/L (core)	
Specific power level	38.7 kW/kgHM	
Average linear power/rod	5.44 kW/ft	17.848 kW m^{-1}
Normal peak linear power/rod	13.58 kW/ft	44.554 kW m^{-1}
Core diameter	132.7 in.	337.058 cm
Core “barrel”	ID: 148.0 in. OD: 152.5 in.	ID: 375.92 cm OD: 387.35 cm
Cross-sectional area of core	96.06 ft^2	8.924 m^2
Core height/diameter ratio	1.09	
Ratio of H_2O molecules to U atom	2.68–2.73	
Effective flow area for heat transfer	51.9 ft^2	4.822 m^2
Average heat flux	189400 Btu/h-ft^2	59.748 J s^{-1} cm^{-2}
Maximum heat flux (normal)	440370 Btu/h-ft^2	138.919 J s^{-1} cm^{-2}
Total thermal flow rate	1.412×10^8 lb_m/h	1.779×10^4 kg s^{-1}
Effective flow rate for heat transfer	1.306×10^8 lb_m/h	1.646×10^4 kg s^{-1}
Average coolant velocity along rods	15.166 ft/s	4.623 m s^{-1}
Core coolant flow rate	1.336×10^8 lb_m/h	1.6833×10^4 kg s^{-1}
Average mass velocity	2.516×10^6 lb_m/h-ft^2	0.3413 kg $s^{-1}cm^{-2}$
Number of fuel assemblies in core	193	
Control rods	53	
Core inlet coolant temperature	Unit 1: 556.4°F Unit 2: 558.3°F	Unit 1: 291.33°C Unit 2: 292.39°C

Table 1. (continued)

Parameter	Value	SI (where appropriate)
Average coolant temperature in core	Unit 1: 586.7°F	Unit 1: 308.17°C
	Unit 2: 589.3°F	Unit 2: 309.61°C
Average temperature rise in core	Unit 1: 60.7°F	Unit 1: 33.72°C
	Unit 2: 61.9°F	Unit 2: 34.39°C
Minimum operating pressure	2250 psia	15.513 MPa
Nominal system pressure	2280 psia	15.720 MPa
Fraction of heat generated in the fuel	97.4%	
UO_2 feed assemblies (40% MOX)	48	
MOX feed assemblies (40% MOX)	36	
Fuel cycle duration	495 d (~18 months)	
Assumed capacity factor	85%	

Table 2. Catawba fuel assembly data

Parameter	Value	SI (where appropriate)
Design	FCF Mark-BW, 17 × 17, canless	
Length	159.8 in.	405.8920 cm
Rod length	152.16 in.	386.4864 cm
Dimensions	8.425 in. × 8.425 in.	21.4 cm × 21.4 cm
Assembly pitch	8.466 in.	21.50364 cm
Total number of fuel rods in core	50,952	
Fuel rods per assembly	264	
Number of guide tube thimbles	24	
Number of instrument channels	1	
Rod pitch	0.496 in.	1.25984 cm
Cladding material	M5 or Zircaloy-4 (Zircaloy-4[a])	
Cladding OD	0.374 in.	0.94996 cm
Cladding ID	0.329 in.	0.83566 cm
Cladding thickness	0.0225 in. (0.024[a])	0.05715 cm (0.06096)
Cladding gas gap (radial)	0.00325 in.	0.00826 cm
Fuel pellet diameter	0.3225 in. (0.3195[a])	0.81915 cm (0.81153 cm)
Guide thimble OD	0.482 in.	1.22428 cm
Guide thimble ID	0.450 in.	1.14300 cm
Guide thimble material	Zircaloy-4	
Instrument thimble OD	Upper: 0.482 in.	1.22428 cm
	Lower: 0.429 in.	1.08966 cm
Instrument thimble ID	Upper: 0.450 in.	1.14300 cm
	Lower: 0.397 in.	1.00838 cm
Instrument thimble material	Zircaloy-4	
Grid spacer material per core	2 end grids: Inconel-718 (782 lb)	End: 354.71 kg
	6 intermediate grids: Zircaloy-4 (2928 lb)	Intermed: 1328.12 kg
Heavy metal (HM) loading/assembly	463.3 kg	
Active stack length (cold dimension)	144 in.	365.76 cm
Fuel pellet material	PuO_2 + depleted UO_2 (ceramic, sintered)	
Fuel pellet length	0.400 in. (chamfered) (Mk-BW)	1.016 cm
Volume reduction (pellet chamfer and dish)	1.0%	
Pellet theoretical density	95% (96%[a])	
Weight of fuel if UO_2	220,213 lb	99,887.0 kg
Cladding weight	56,841 lb (of Zircaloy-4)	25,782.7 kg

[a]Reported in the Catawba Final Safety Analysis Report (FSAR).

Table 3. Catawba IFBA pellet data

Parameter	Value	SI
IFBA absorber material	Zirconium diboride, ZrB_2 (enhanced to 30 wt % in ^{10}B to B)	
Absorber density	0.061 lb/in^3	1.688 g cm^{-3}
Coating thickness	1.575 mils	0.0040 cm

Table 4. Catawba burnable poison rod (BPR) data

Parameter	Value	SI
BPR absorber material	Boron carbide/alumina matrix, Al_2O_3-B_4C	
Boron content	Variable	
Rod OD	0.381 in.	0.96774 cm
Cladding material	Stainless steel, SS-304L	
Cladding thickness	0.025 in.[a]	0.06350 cm

[a]This value was estimated; no Catawba data were available.

Table 5. Catawba control rod data

Parameter	Value	SI
Control rod design	Hybrid B_4C	
Absorber material	B_4C	
Number of control rod clusters	53	
Number of absorber rods/cluster	24	
Absorber diameter	0.294 in.	0.74676 cm
Absorber density	0.064 $lb/in.^3$	1.7715 g cm^{-3}
Rod tip material	Ag-In-Cd (80 wt %, 15 wt %, 5 wt %)	
Tip diameter	0.301 in.	0.76454 cm
Tip length	40 in.	101.60 cm
Tip density	0.367 $lb/in.^3$	10.159 g cm^{-3}
Cladding material	Stainless steel 304L and 316, cold worked	
Cladding thickness	0.0385 in.	0.09779 cm
Full length dry weight (per assembly)	94 lb	42.638 kg
Absorber length	142 in.	360.68 cm

Table 6. Catawba reactor core baffle data

Parameter	Value	SI
Baffle material	Carbon steel	
Baffle thickness	1.125 in.	2.8575 cm

Figure 7 is a schematic cross-sectional view of the 17 × 17 Mark-BW fuel assembly with standard LEU fuel. The locations of the guide thimble tubes and the central instrument tube are shown.

Figure 8 is a similar schematic for the Advanced Mark-BW fuel assembly for MOX fuel. The high peaking factors in MOX fuel assemblies placed in the high flux levels near the LEU assemblies are minimized by reducing the enrichment in the outermost fuel pins in the MOX assemblies compared to the enrichment in the innermost fuel pins.

DCS has selected a three-zone design consistent with Framatome's experience in Europe. The assembly average plutonium enrichments of the MOX fuel assemblies were chosen to minimize the peaking and also to improve the interchangeability of the MOX and LEU fuel. This was accomplished by establishing MOX fuel assembly average enrichments of 4.07 and 4.37 wt % plutonium (see Table 7) (based on the distribution of MOX fuel pins with three different levels of plutonium content). These MOX fuel assemblies produce about the same equivalent energy as the LEU fuel assemblies used in the 18-month fuel cycles at the McGuire, Catawba, and North Anna nuclear stations. The isotopic composition vector of the WG plutonium in the MOX fuel is 93.6% ^{239}Pu, 5.9% ^{240}Pu, 0.4% ^{241}Pu, and 0.1% ^{242}Pu. The UO_2 component of the MOX fuel is assumed to have an enrichment of 0.25 wt % ^{235}U.

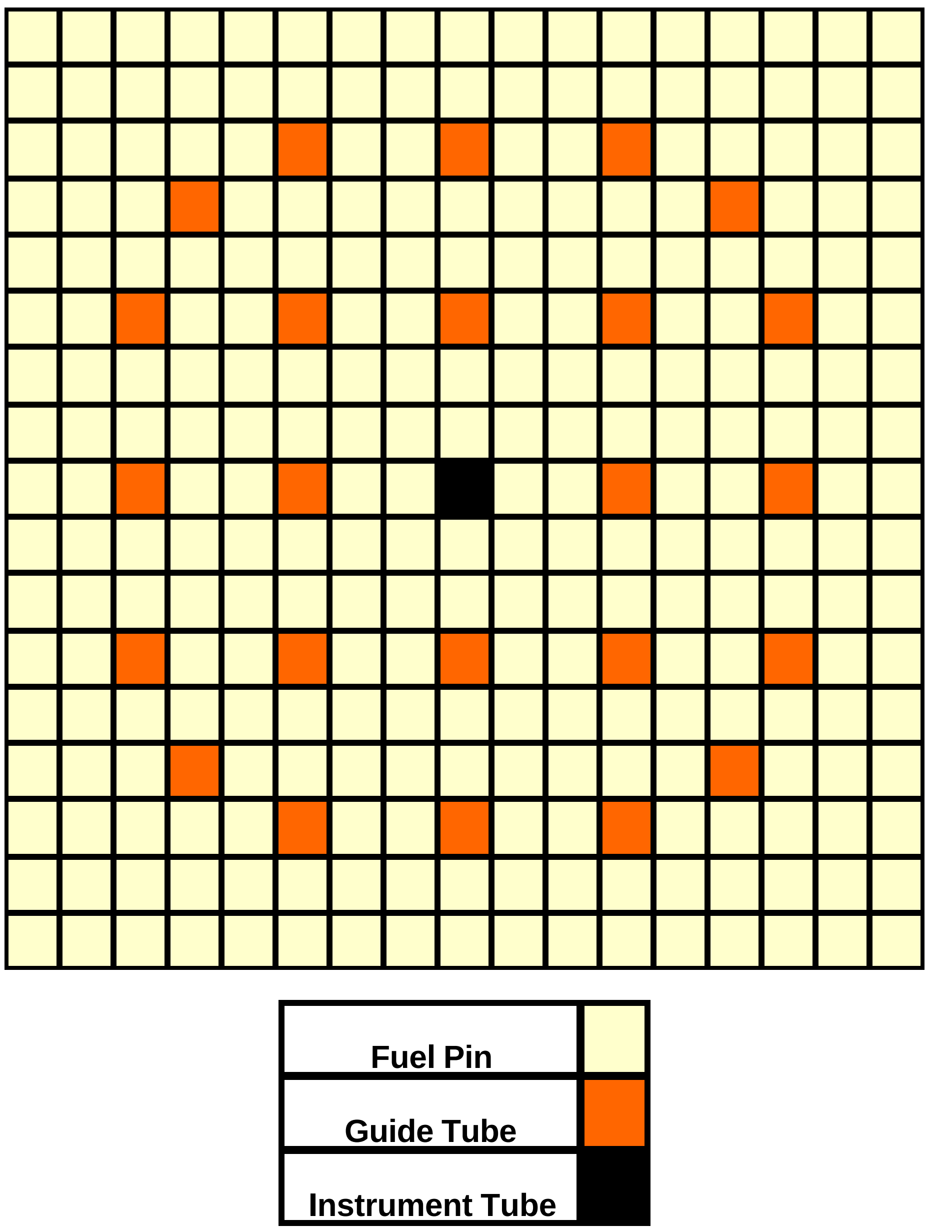


Figure 7. Standard LEU UO_2 assembly (Mark-BW).

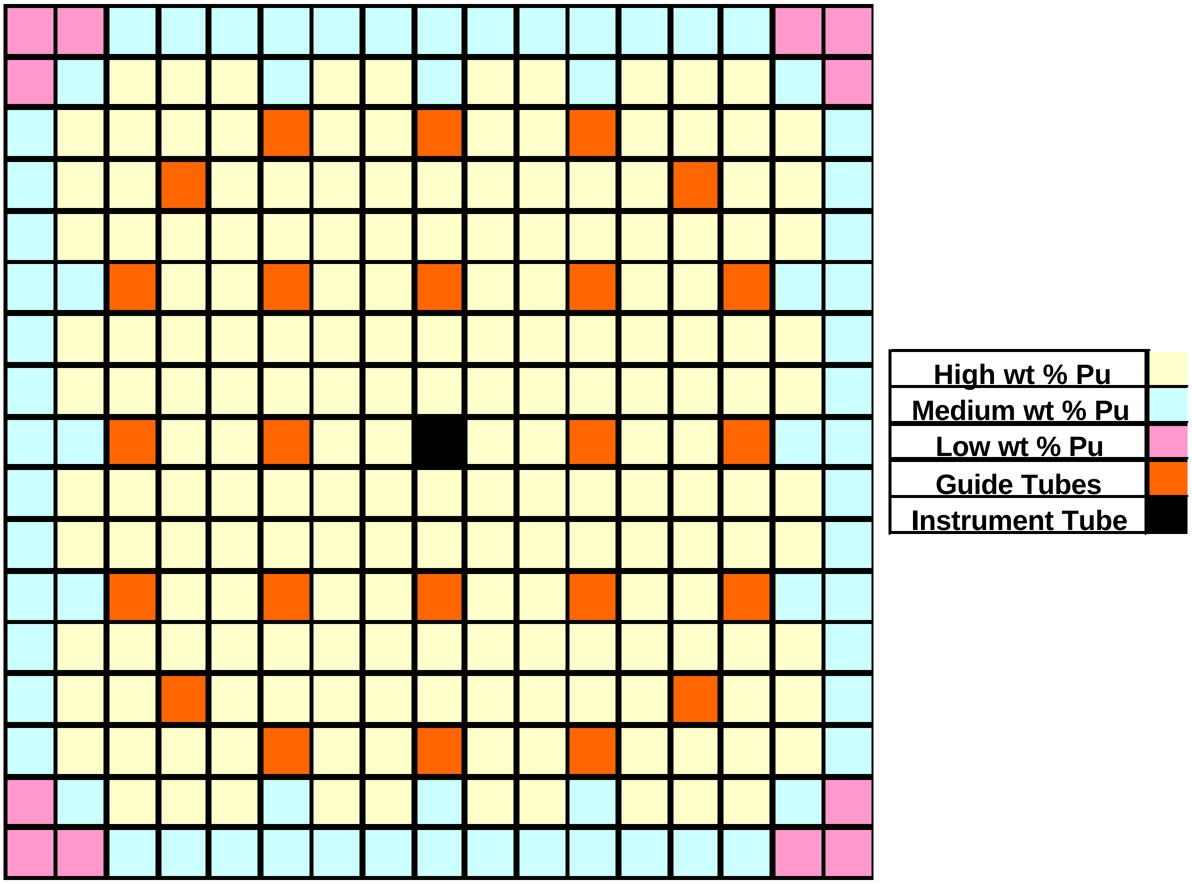


Figure 8. MOX assembly (Advanced Mark-BW MOX).

Table 7. Fuel pin plutonium content (wt %) in the MOX fuel assemblies for use at Catawba Nuclear Station Units 1 and 2

Pin type	4.07 wt % plutonium	4.37 wt % plutonium	Number of fuel pins of each plutonium content
High plutonium content	4.364	4.794	184
Medium plutonium content	3.583	3.583	68
Low plutonium content	2.316	2.316	12

The initial reactivity of a MOX assembly is less than that of the equivalent LEU fuel (which has the same lifetime average reactivity). The reactivity of the MOX fuel decreases at a lower rate than LEU of equivalent enrichment.

Figures 9 to 14 display the various configurations for placement of integral fuel burnable absorbers (IFBAs) in the Mark-BW 17 × 17 PWR fuel assemblies. For the DCS plutonium disposition program, it has not been decided whether IFBAs will be placed in MOX fuel assemblies and in LEU UO_2 fuel assemblies or only in the UO_2 fuel assemblies. The regions and components of the fuel assemblies are color-coded for clarity.

Figures 15 to 20 display the configurations for placing between 4 and 24 burnable poison rods (BPs) in the Mark-BW fuel assemblies. For clarity, the major regions are color-coded as indicated in the legends.

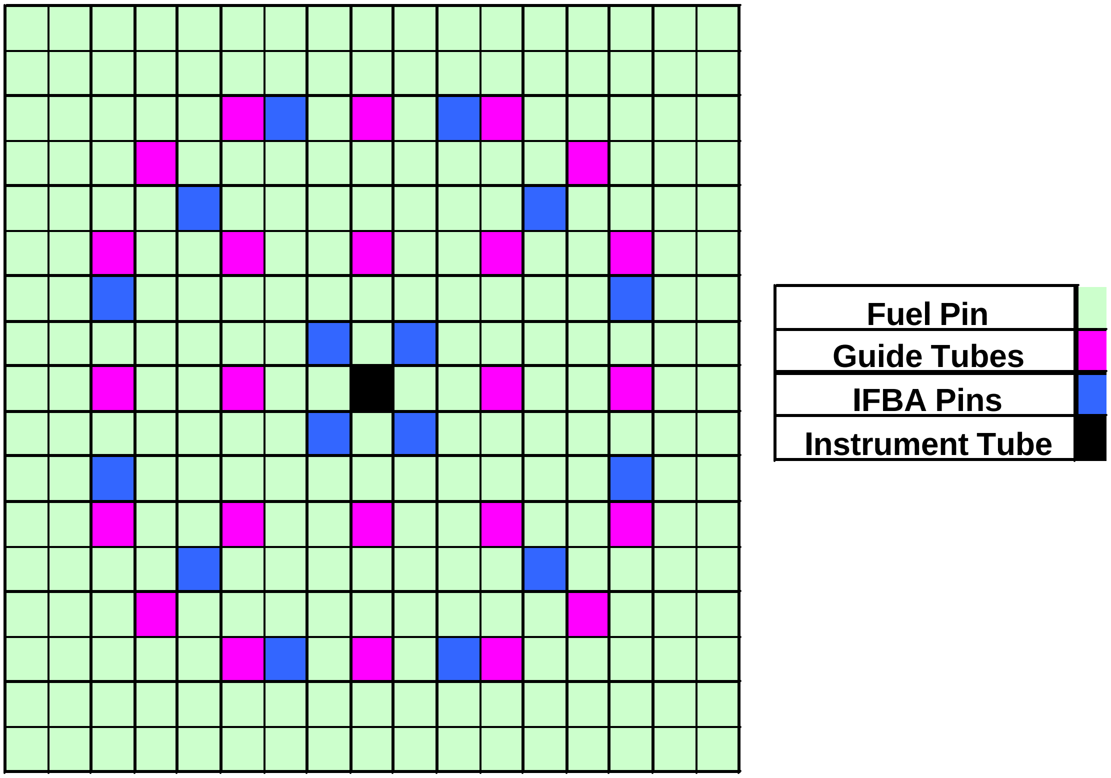


Figure 9. Assembly with 16 IFBAs.

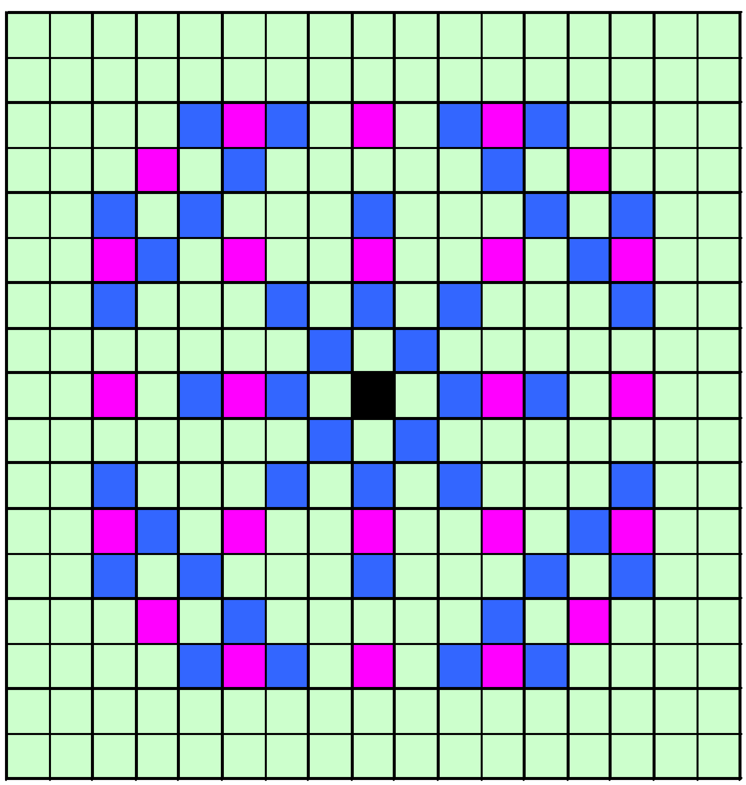


Figure 10. Assembly with 48 IFBAs.

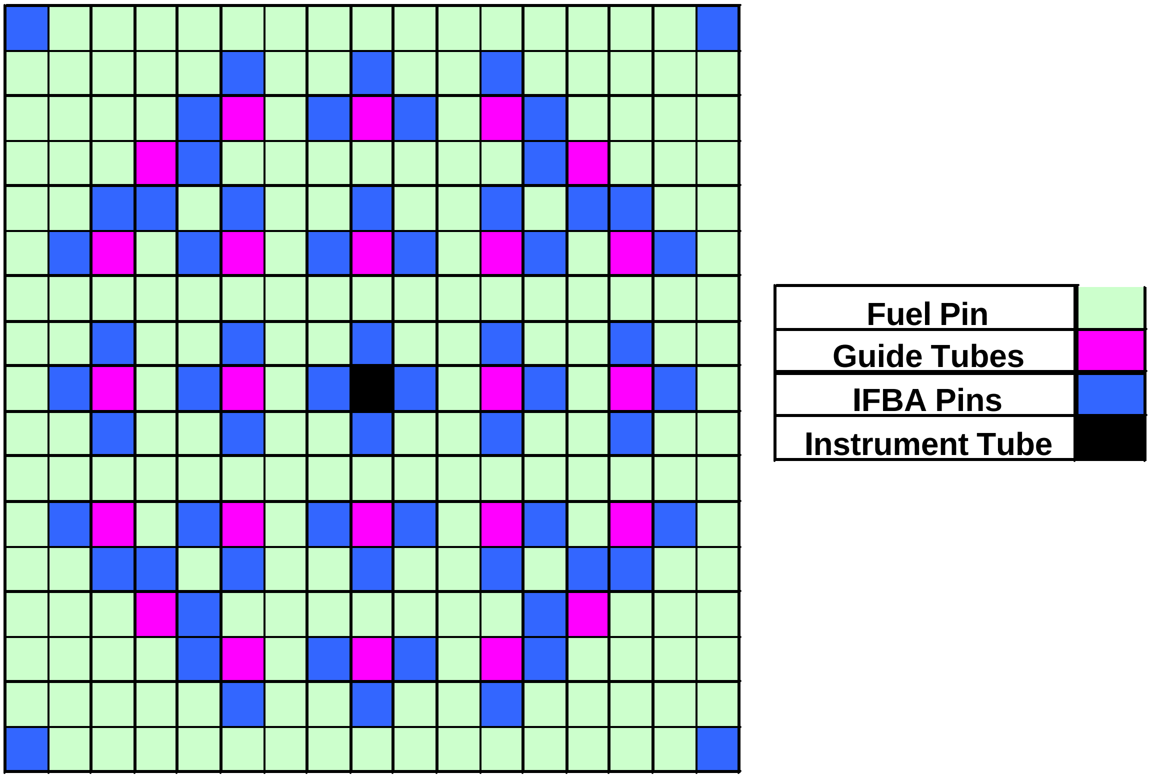


Figure 11. Assembly with 64 IFBAs.

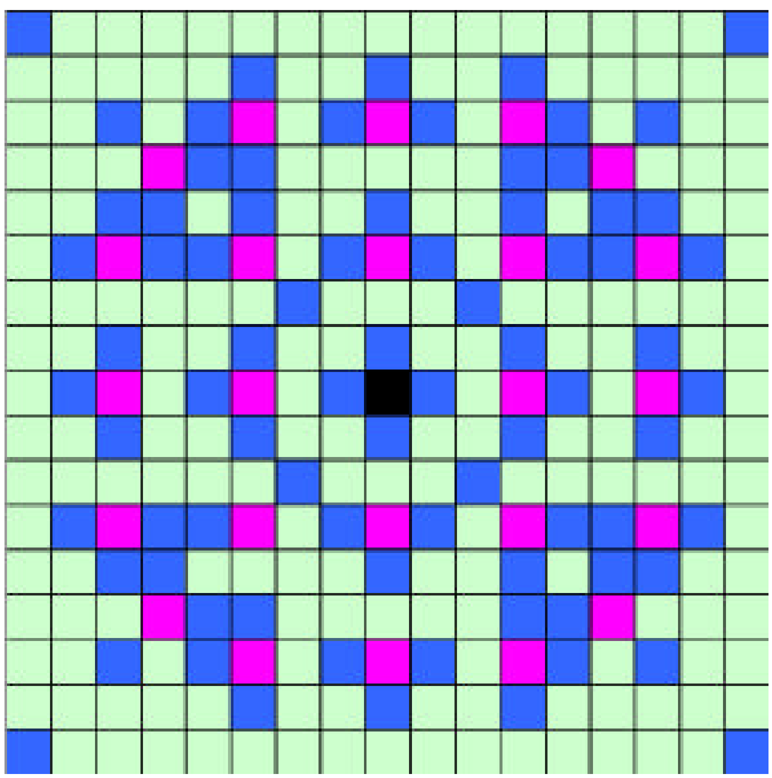


Figure 12. Assembly with 80 IFBAs.

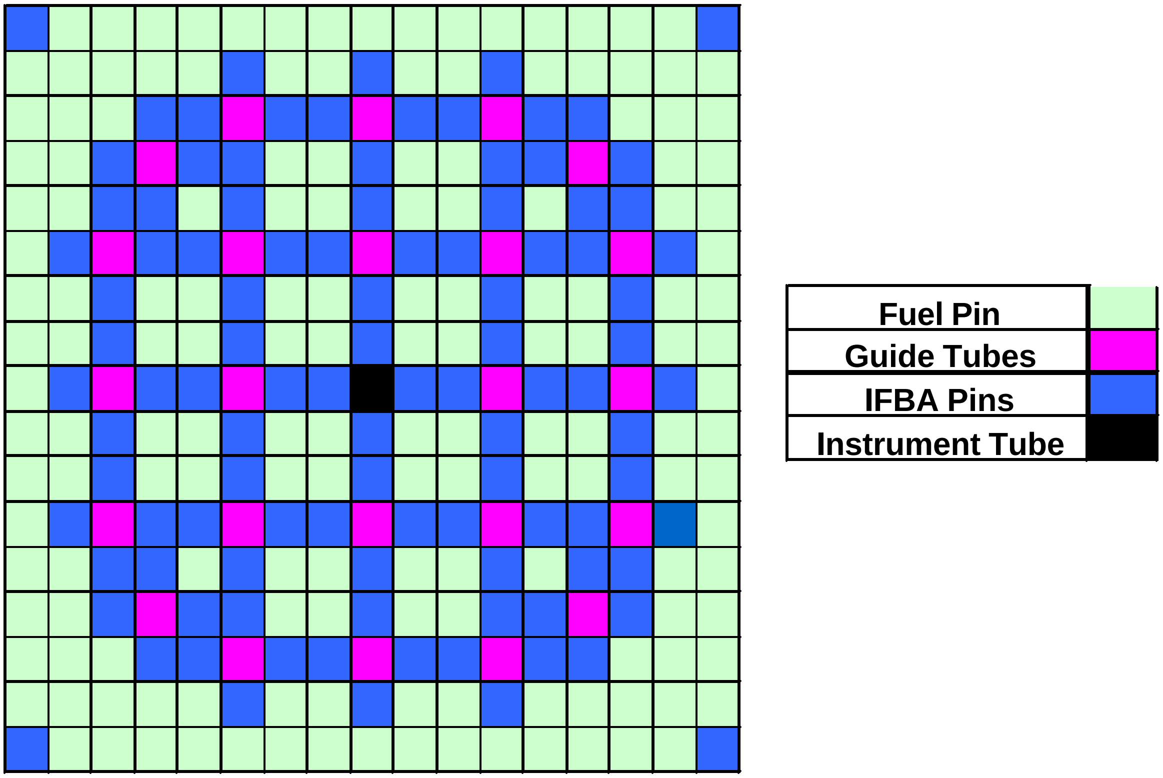


Figure 13. Assembly with 104 IFBAs.

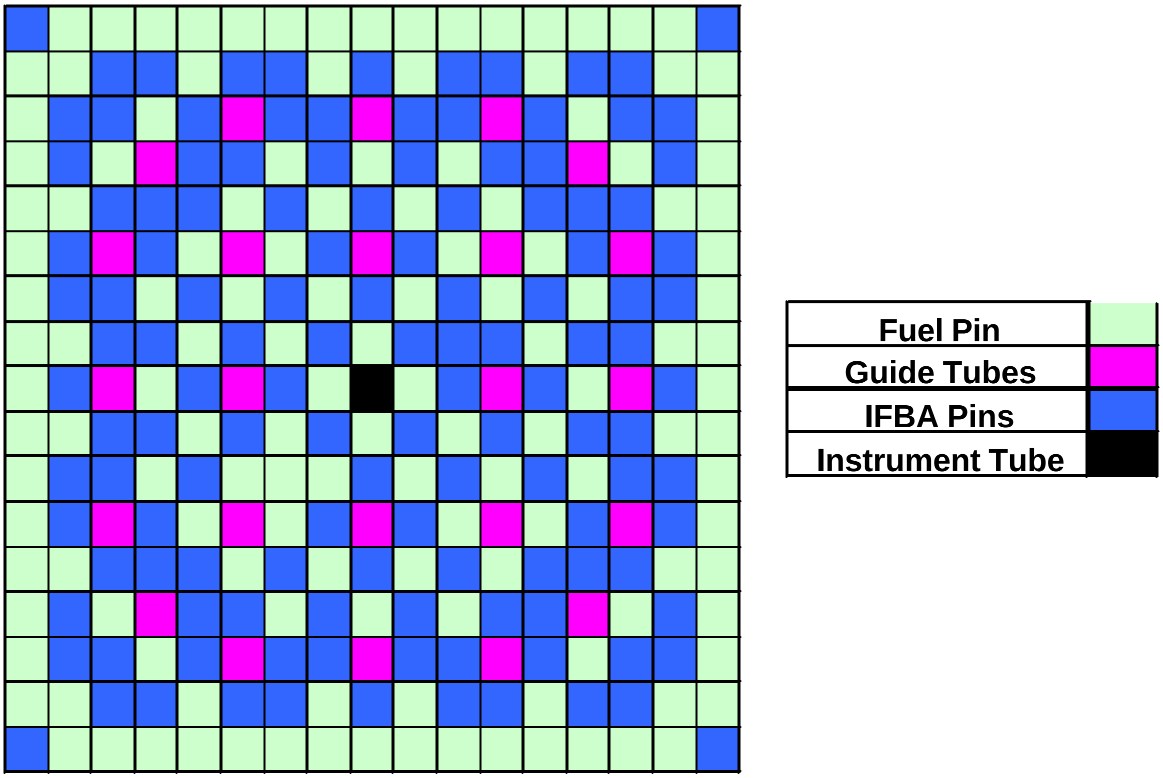


Figure 14. Assembly with 128 IFBAs.

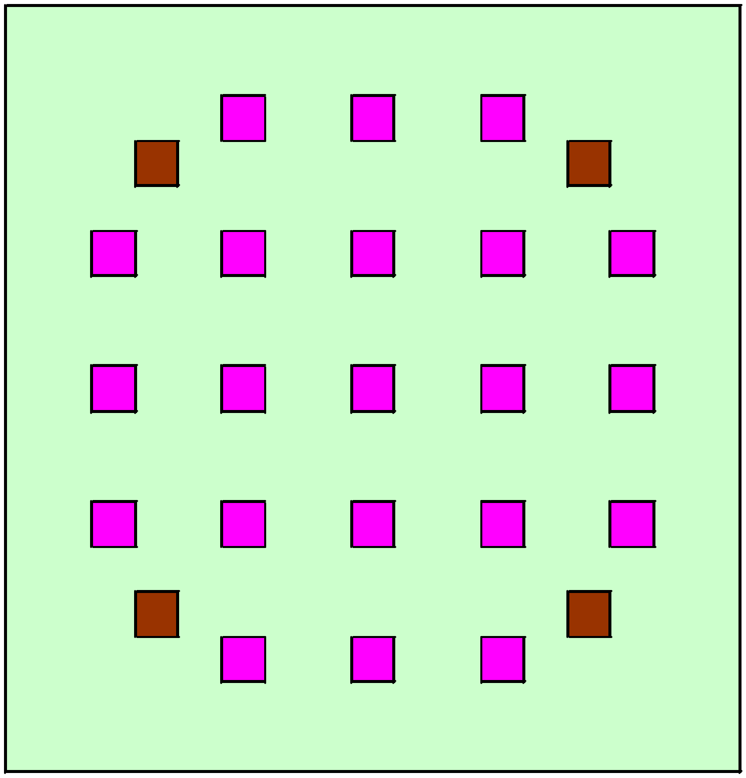


Figure 15. Burnable absorber pin placement for 4 BPs.

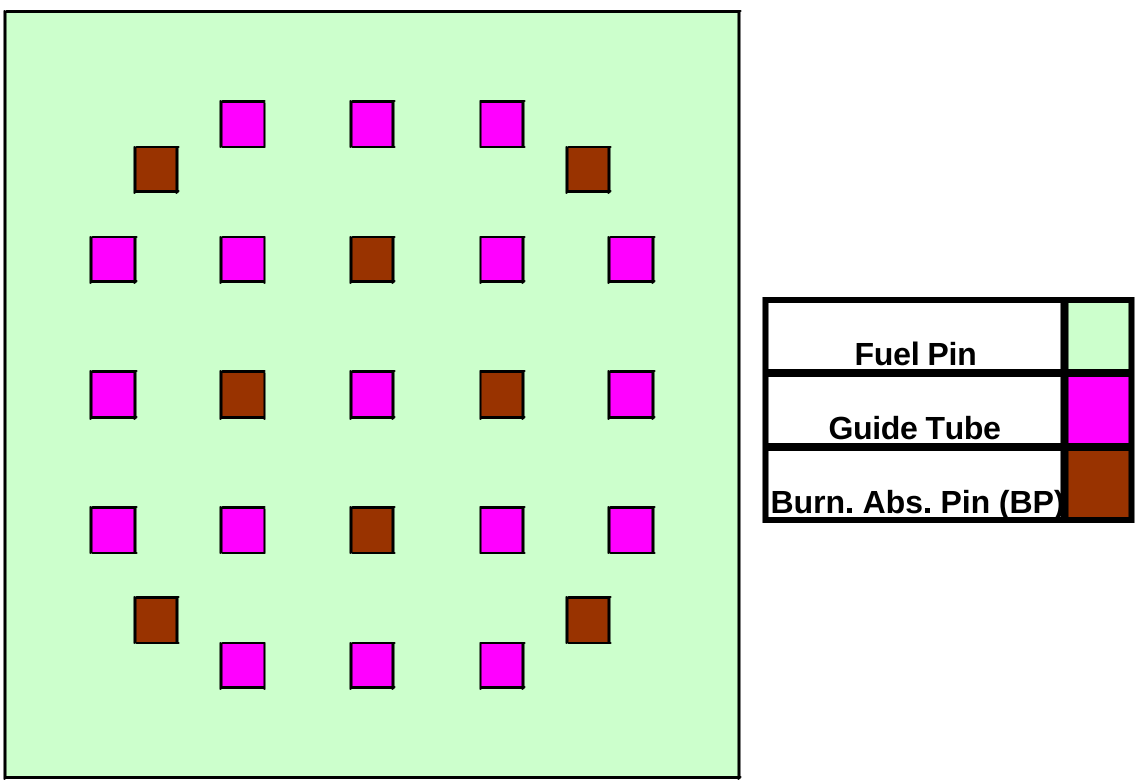


Figure 16. Burnable absorber pin placement for 8 BPs.

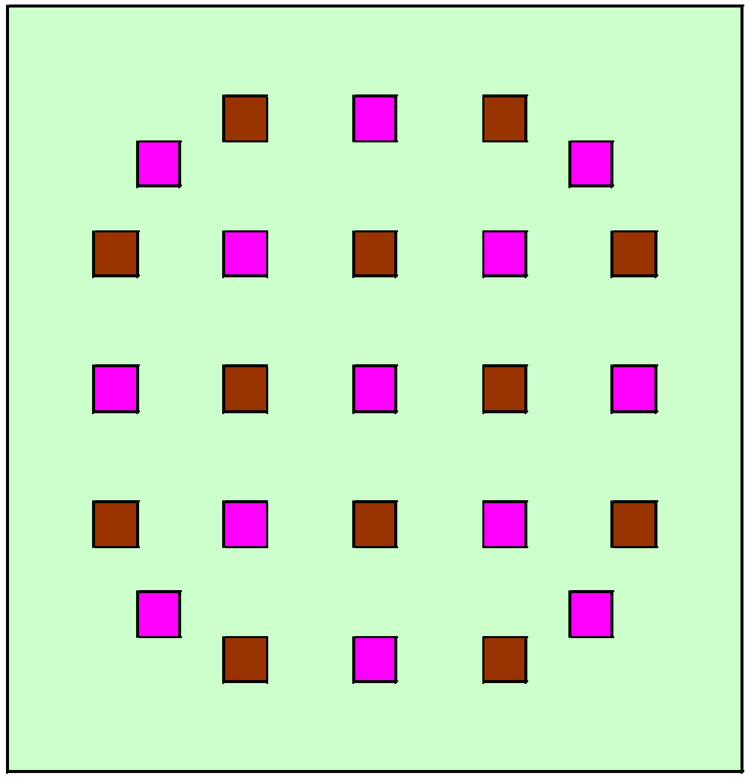


Figure 17. Burnable absorber pin placement for 12 BPs.

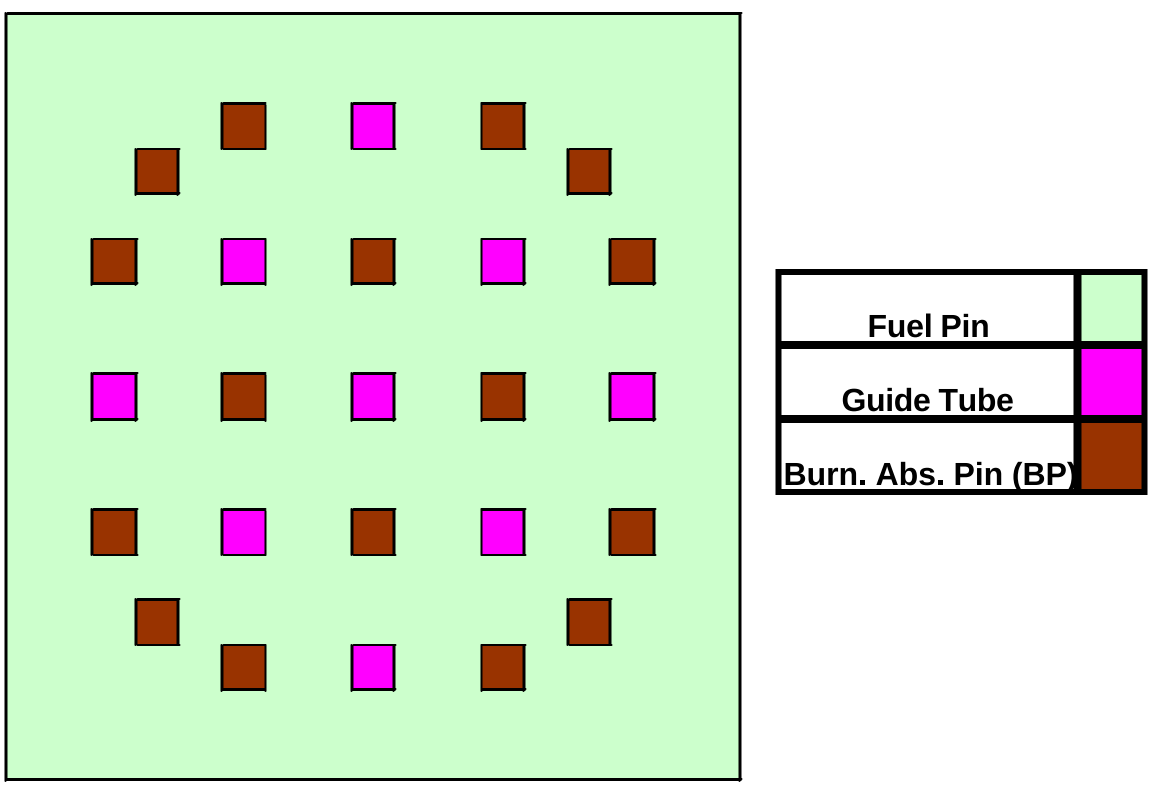


Figure 18. Burnable absorber pin placement for 16 BPs.

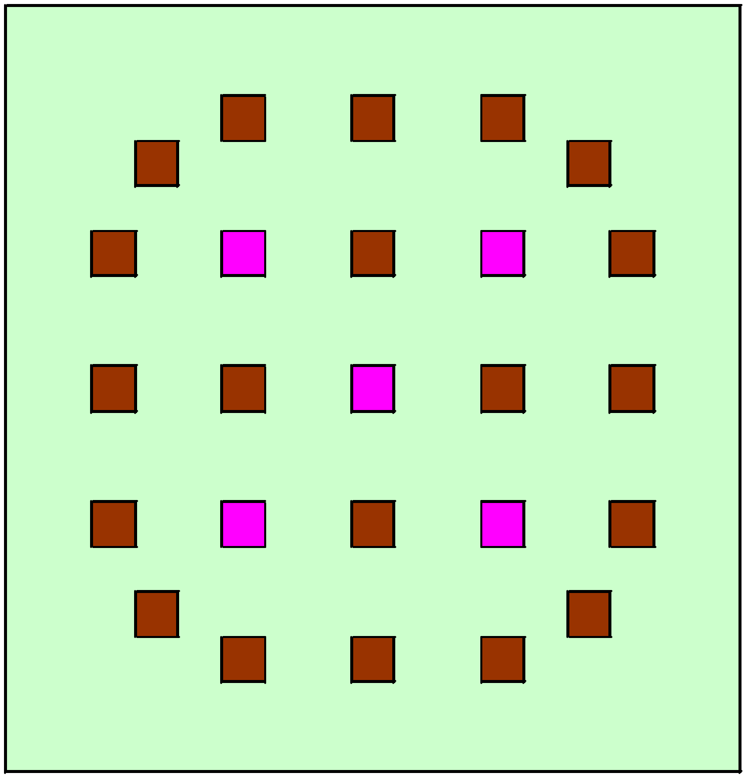


Figure 19. Burnable absorber pin placement for 20 BPs.

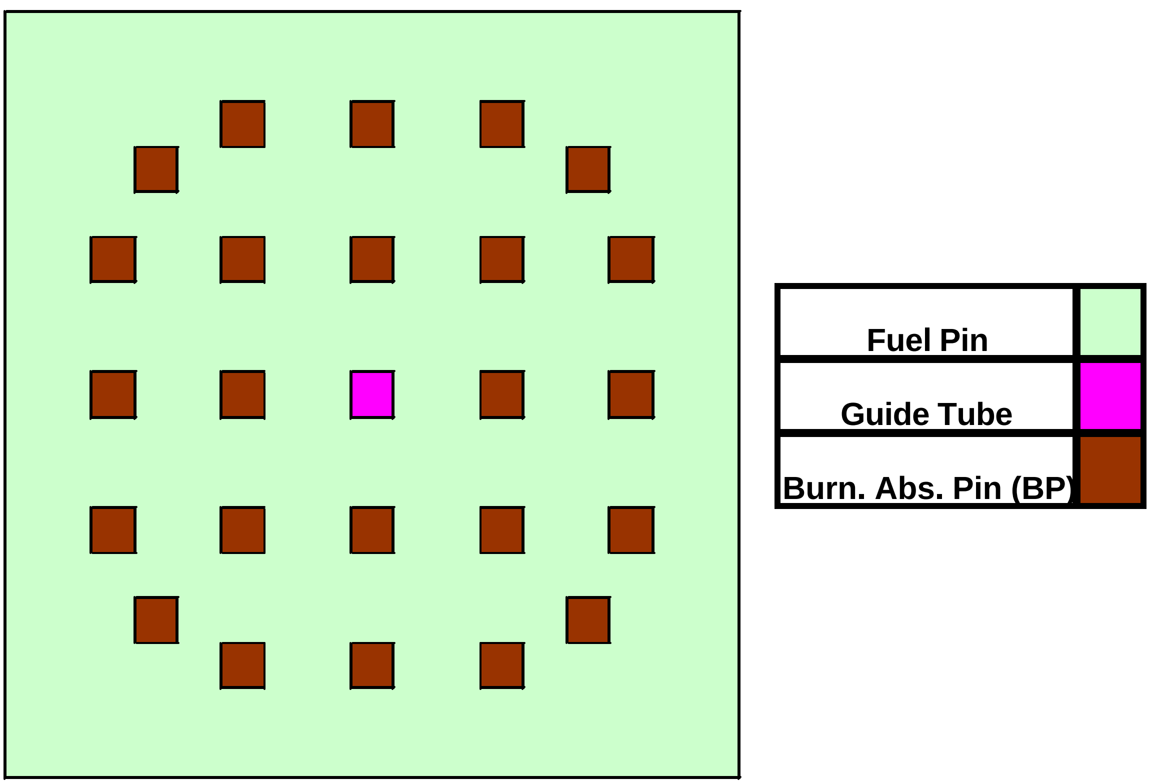


Figure 20. Burnable absorber pin placement for 24 BPs.

3. FUEL MANAGEMENT STRATEGY

The DCS strategy currently calls for an initial irradiation of two MOX lead test assemblies (LTAs). Currently, the MOX LTA irradiation is planned only for the McGuire reactors. After successful irradiation, this will be followed by a controlled transition from an all-LEU fuel core through several partial MOX fuel reloads over several operating cycles. The DCS fuel management plan will irradiate the MOX fuel assemblies for two cycles (average discharge burnup is about 40,000 MWd/kgHM) and LEU fuel assemblies for three cycles. The equilibrium MOX cores at Catawba Units 1 and 2 will have equilibrium MOX core fractions of about 40%. A plausible loading pattern is shown in Fig. 21 for an equilibrium situation. To maintain the MOX core fraction at ~40%, the number of feed MOX assemblies will have to alternate between 36 and 40 assemblies on subsequent reload cycles. The loading pattern depicted in Fig. 21 represents 36 feed MOX assemblies and 40 once-burned MOX assemblies (9 feed MOX assemblies are shown

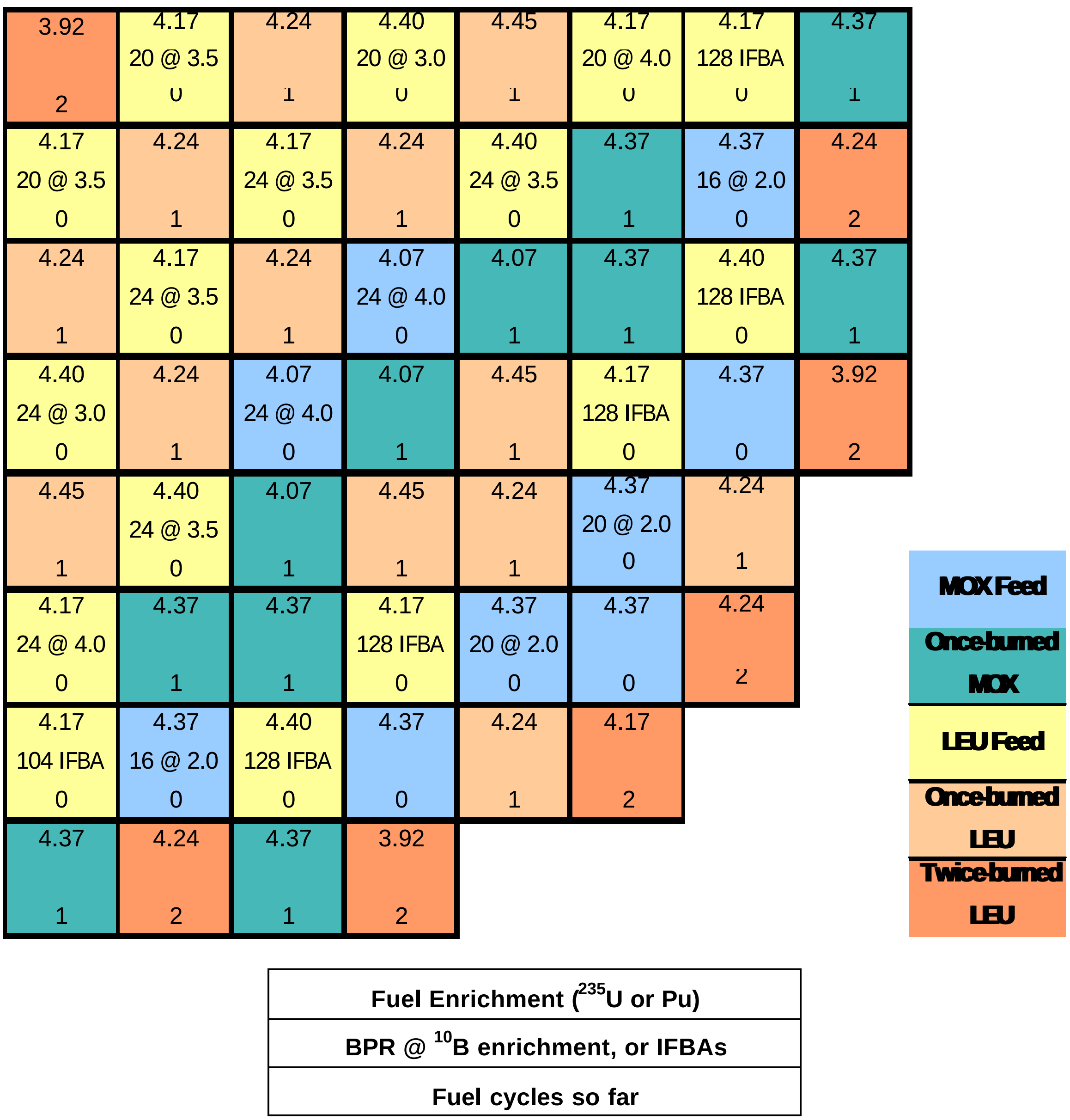


Figure 21. Fuel-loading pattern for equilibrium 40% MOX core (Catawba Units 1 and 2).

in the ¼-core schematic). Specific details of the loading patterns, including LEU assembly fuel enrichments, the number of BPRs, and whether or not IFBAs are used, will most likely change as the DCS loading strategies evolve.

Descriptions of transitional loading patterns are not contained in this document. ORNL studies of possible fuel strategies and loading patterns will be performed using the codes HELIOS and NESTLE and will be the subject of a later report. The LEU equilibrium core-loading pattern is shown in Fig. 22; the LEU assemblies are color-coded by fuel irradiation similar to Fig. 21. The indicated control rod banks (A–D) and shutdown rod banks (SA–SE) are discussed and shown in Fig. 23.

The MOX fuel discharge burnup will be within the 45,000-MWd/kgHM MOX discharge fuel burnup experience in Europe at Belgian, Swiss, and German PWRs. The DCS MOX fuel management strategy should result in minimal perturbations to the existing nuclear fuel management scheme at Catawba.

The DCS strategy aims to reach the mission goal of achieving a burnup of at least 20,000 MWd/MTHM and at least one cycle of reactor irradiation on all the MOX fuel assemblies (33 MT plutonium in total) by the end of 2022.

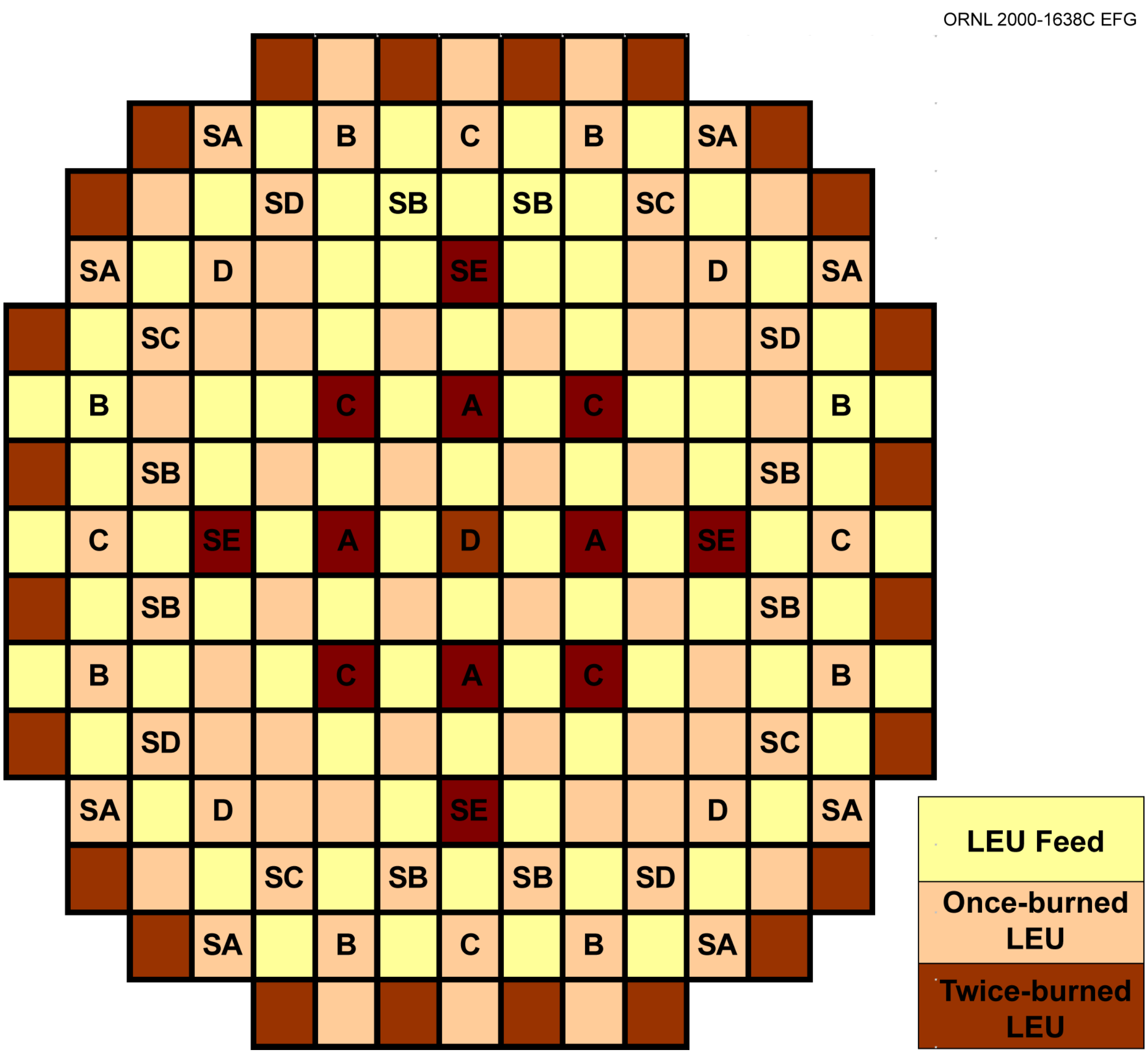
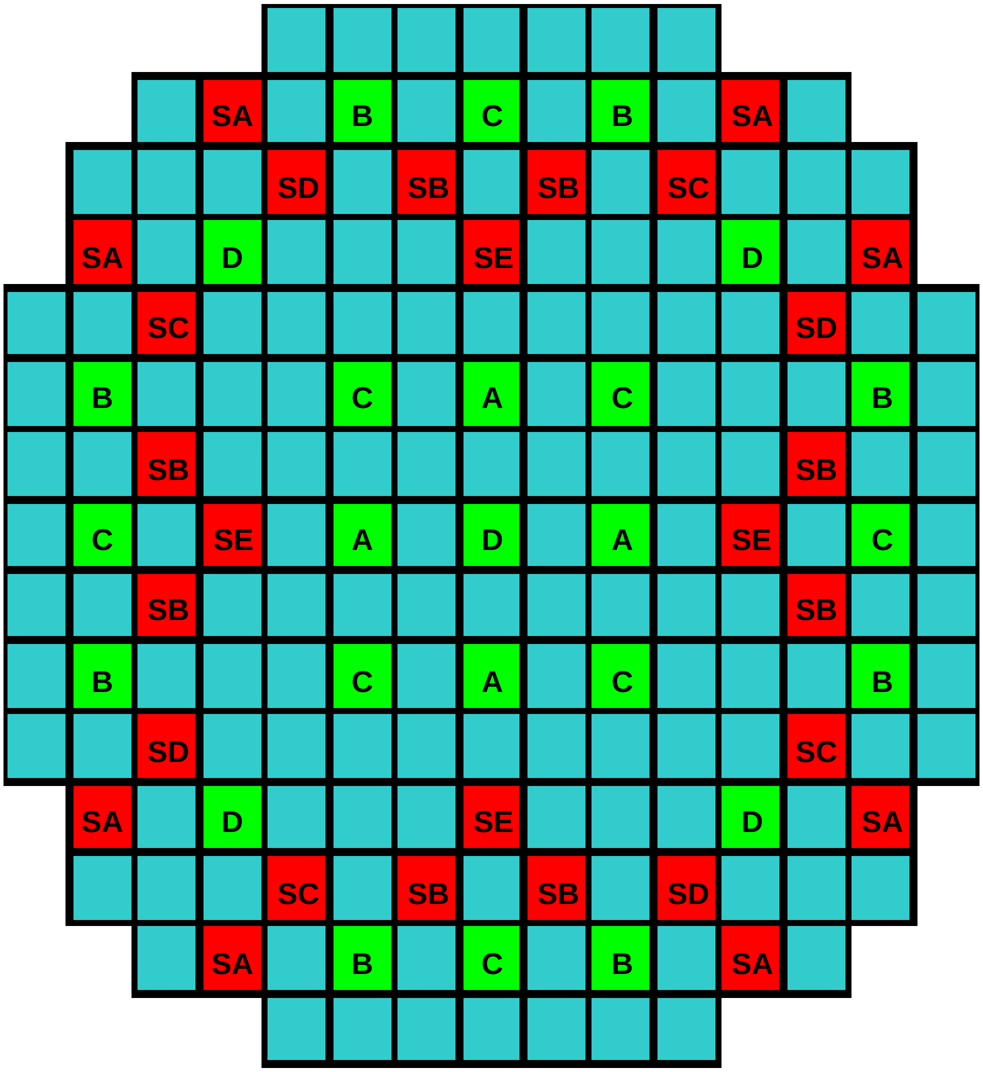


Figure 22. LEU equilibrium fuel-loading pattern.



Control banks	Number of rods	Shutdown banks	Number of rods
A	4	SA	8
B	8	SB	8
C	8	SC	4
D	5	SD	4
Total	**25**	SE	4
		Total	**28**

Figure 23. Location of shutdown and control rod clusters in Catawba Units 1 and 2.

The DCS fuel management strategy encompasses the following constraints, limits, and details:

- 18-month fuel cycles, which are consistent with the LEU situation
- fuel pins for MOX and LEU with cladding OD of 0.374 in. (0.950 cm)—this is consistent with current LEU fuel pins
- MOX fuel assembly consistent with current LEU designs

- MOX fuel burnup limit of 45,000 MWd/MTHM (assembly average) with 50,000 MWd/MTHM (rod)—consistent with Framatome experience
- LEU rod burnup limit of 60,000 MWd/MTU—consistent with current LEU limits
- 35 to 40% MOX fuel core fractions
- MOX fuel will have two cycles of irradiation
- LEU fuel will have three cycles of irradiation
- only three enrichment zones in MOX fuel
- only four different plutonium enrichments from the MOX fabrication plant
- MOX fuel power peaking consistent with LEU fuel peaking and core limits
- "low-leakage" core design
- no integral absorbers in the MOX fuel

The DCS feasibility studies have shown that acceptable transition and equilibrium core designs can be attained for the mission reactors using just two MOX fuel assembly average enrichments. Acceptable loading patterns were modeled using average MOX fuel levels of 4.07 and 4.37 wt % plutonium and LEU fuel enriched to levels needed to reach the desired fuel cycle duration. Multiple enrichments of LEU fuel in conjunction with appropriate placement of the MOX fuel and the use of BP rods were used in DCS modeling to shape the radial power distribution and control the power peaking.

Some details of the DCS fuel-loading strategy are as follows:

- Loading feed MOX fuel is near the core exterior.
- Once-burned MOX fuel is loaded more toward the interior of the core.
- The designs minimize the placement of MOX fuel in locations with control rods to minimize reductions in control rod worth and shutdown margins.
- Designs minimize placement of MOX fuel on the core periphery.

Equilibrium partial MOX fuel core designs require the use of large numbers of BPRs for controlling power peaking and to reduce beginning-of-core (BOC) soluble boron concentration requirements. The necessary increase in BP requirements is the result of the decreased efficiency of thermal absorbers. DCS core designs used the FCF BP assembly design to control power peaking. This design was chosen because the ^{10}B content of the BPRs and the number of BPRs per assembly could be varied.

The harder neutron spectrum associated with MOX fuel decreases the efficiency of thermal neutron absorbers; therefore, it increases the BOC soluble-boron requirements for partial MOX fuel cores compared to those for LEU cores (for both operating and accident situations). Because of reactor coolant system chemistry considerations, there is an upper limit to BOC boron concentrations. The use of additional BPR (above what is needed to control peaking) and the use of enriched soluble boron can reduce the boron concentration requirements to more reasonable levels. The use of additional BPRs results in an economic penalty, and the use of boron enriched in ^{10}B to 25% or more adds cost because it is more expensive than natural boron.

The harder spectrum and the reduced thermal neutron flux in the MOX cores reduces the control rod worth. The Catawba reactors use a hybrid B_4C control rod design, mostly B_4C with a 40-in. (101.6-cm) Ag-In-Cd tip. This hybrid B_4C control rod absorber design is more effective than the full Ag-In-Cd design; the reactivity worth is about 0.2% $\Delta k/k$ at the end of cycle.

4. SUMMARY AND CONCLUSION

Duke Power's four Catawba and McGuire PWRs are to be used by DCS for weapons-grade plutonium disposition. Computer models representing the Catawba and McGuire reactor cores and assemblies have been developed based on the information and assumptions presented as data in this document. The results of fuel-management and core-loading calculations for these reactors will be presented in a later report.

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