MOX FUEL IRRADIATION PROGRAM

FOR DISPOSITION OF SURPLUS UNITED STATES PLUTONIUM

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ABSTRACT

This paper describes the plan developed by Duke COGEMA Stone & Webster (DCS) to dispose of 33 tonnes of excess weapons grade plutonium by using mixed oxide (MOX) fuel in McGuire 1 and 2 and Catawba 1 and 2, operated by Duke Power; and Virginia Power's North Anna 1 and 2. A discussion of the assumptions and constraints imposed by DOE and the utilities is presented along with the fuel assembly neutronic design, the software used for core design, and the resulting in-core fuel management schemes which would accomplish the mission objective.

I. INTRODUCTION

The Duke COGEMA Stone & Webster (DCS) team is under contract to the Department of Energy (DOE) to dispose of surplus plutonium by fabricating the plutonium into mixed oxide (MOX) fuel and using the fuel in commercial nuclear reactors. As a part of the project, Duke Engineering & Services, COGEMA and Stone & Webster will design, construct and operate a MOX Fuel Fabrication Facility (MFFF) on the DOE's Savannah River Site. Six commercial nuclear power reactors, referred to as mission reactors, will use the MOX fuel produced by the MFFF. Irradiating the MOX fuel will destroy much of the weapons grade plutonium and leave the remaining material no longer attractive for weapons use. At the same time, the reactors will be producing a beneficial product, electricity.

The six mission reactors are McGuire 1 and 2 and Catawba 1 and 2, operated by Duke Power; and Virginia Power's North Anna 1 and 2. All six mission reactors are Westinghouse-designed pressurized water reactors (PWRs). The 2893 MW_{th} North Anna units are located in Virginia's Louisa County, while the 3411 MW_{th} McGuire and Catawba units are located near Cornelius, North Carolina, and Clover, South Carolina, respectively. All of the mission reactors use 17x17 PWR fuel in operating cycles of approximately eighteen months.

DCS has developed a Mission Reactors Irradiation Plan (MRIP) that describes how Duke Power and Virginia Power will incorporate MOX fuel into the fuel supply of the six mission reactors. The MRIP demonstrates the feasibility of disposing of 33 tonnes of surplus plutonium between 2007 and 2022. The MRIP is the first of several complementary deliverables related to the irradiation services area of the MOX fuel project. The Mission Reactors System Modification Plan (MRSMP) will describe plant and facility modifications that are required to accomplish the MRIP. The MRIP and its associated analyses will serve as one of the bases for the MRSMP. The Mission Reactors Licensing Plan will establish the approach taken to obtain the Nuclear Regulatory Commission (NRC) approvals that are needed to carry out the MRIP. The Mission Reactors Permitting

Plan will identify any other required regulatory approvals. The following discussion summarizes the MRIP and its associated analyses.

II. DESCRIPTION OF WORK

DCS developed the MRIP in a three-step process. First, DCS identified key fuel management objectives, based on project requirements and utility constraints.

A. Fuel Management and Operational Assumptions and Constraints

1. The MOX Fuel Fabrication Facility (MFFF) will be designed, constructed, and started up in time to produce batch quantities of MOX fuel to support batch implementation (incorporation of significant quantities of MOX fuel in reload batches) in September 2007.

2. The NRC will issue all necessary regulatory approvals for MFFF operation and mission reactor operation with MOX fuel in time to support batch implementation in September 2007.

3. The required modifications to the mission reactors to receive and utilize MOX fuel will be completed to support batch implementation in September 2007.

4. The mission reactors have received no reactor operating license extensions, and will therefore cease operation at or near the end of their 40 year licensed operating period.

5. The mission reactors will operate substantially in accordance with current plans for cycle length.

6. The mission reactors will experience no significant unplanned outages or shutdowns.

7. Availability of MOX fuel will not constrain the MRIP at any time once the irradiation campaign has begun.

8. 33 tonnes of plutonium will be made available for fabrication into MOX fuel.

9. Duke Power and Virginia Power will minimize technical and licensing risks by using MOX fuel designs and core designs based on contemporary European MOX fuel experience.

10. Duke Power and Virginia Power will perform the program in a cost efficient manner.

Second, Duke Power and Virginia Power established a fuel management strategy to accomplish those objectives. Major assumptions and constraints associated with the MOX fuel core designs are listed below.

B. Core Design Assumptions and Constraints

1. MOX fuel assembly designs that are compatible with and mechanically similar to current low enriched uranium (LEU) fuel assembly designs will be used at Catawba, McGuire and North Anna.

2. MOX fuel burnup will be limited to 45 GWD/MThm (assembly average) and 50 GWD/MThm (peak rod).

3. Uranium fuel burnup will be limited to 60 GWD/MThm (lead rod).

4. MOX fuelwill be discharged after two cycles.

5. MOX fuel peaking limits will be identical to uranium fuel.

6. Fuel cycles will be consistent with uranium fuel management plans (currently 18 month cycles).

7. MOX fuel core fractions will be approximately 40% or less.

8. Low leakage core designs will be used.

9. MOX fuel will receive a minimum of 20 GWD/MThm burnup.

10. The MOX fuel will contain no integral burnable absorbers.

11. The plutonium isotopic concentrations are characteristic of weapons grade material (<7% Pu^{240}).

12. The uranium portion of the MOX fuel is composed of depleted uranium with a nominal enrichment of 0.25% U^{235}.

Third, Duke Power and Virginia Power performed fuel cycle studies to verify that the core designs developed could accomplish the program objectives and meet all of the assumptions and constraints. Typical pressurized water reactor cores are a mixture of fuel assemblies that are in their first, second, or third cycle of irradiation. Cores are designed to produce the desired energy output with the minimum fuel cost. Core designs are constrained by a number of factors, including energy requirements (cycle length), individual assembly and fuel rod peaking limits, reactivity coefficient limits, soluble boron limits (maximum boron concentrations), burnup limits, and maximum enrichment limits. Core designers manipulate loading patterns, enrichments, and integral and lumped burnable poison to obtain core designs that meet applicable constraints in the most economical and practical manner.

MOX fuel core designs require analytical methods that are capable of accurately modeling mixed LEU and MOX cores (e.g., the neutron flux gradients between uranium and MOX fuel assemblies). Duke Power performed its nuclear analyses using the CASMO-4 and SIMULATE-3 MOX computer codes. Virginia Power performed its nuclear analyses using the MCNP and PDQ computer codes. Those analytical methods are consistent with the current nuclear analyses methodologies used by the respective utilities. Both methodologies have already been validated to some extent for MOX fuel applications. Duke Power and Virginia Power will perform additional validation as part of the MOX fuel qualification and licensing process. The use of reference analytical MOX fuel calculations, critical experiments containing plutonium and partial MOX fuel core operating data will be used to demonstrate the acceptability of neutronics codes for partial MOX fuel core analyses.

Other members of the DCS team have extensive uranium and MOX fuel expertise, including Framatome Cogema Fuels (FCF), an experienced domestic nuclear fuel vendor; one of FCF's parent companies, Framatome S.A., the world's leading MOX fuel designer; and EDF, the world's leading MOX fuel user. FCF, Framatome, and EDF supported Duke Power and Virginia Power in the development of the MRIP.

III. RESULTS

There is considerable experience using reactor grade MOX fuel in commercial PWRs. Typically, "mixed" cores are used with 30% or less MOX fuel and the remainder low enriched uranium (LEU) fuel. MOX fuel assemblies are mechanically and hydraulically similar to LEU fuel assemblies. However, PWR MOX fuel assemblies employ an enrichment zoning approach in which the outermost fuel rods contain less fissile material (plutonium) than the inner fuel rods. Enrichment zoning in MOX fuel assemblies is necessary due to the relatively higher thermal flux in adjacent LEU fuel assemblies. Without enrichment zoning, this thermal flux gradient would lead to unacceptably high power in the outermost MOX fuel assembly rods. Duke Power and Virginia Power built upon the extensive European MOX fuel experience base in developing fuel assembly and core designs for the surplus plutonium disposition program.

The fuel cycle studies utilized two baseline MOX fuel assembly designs, which are referred to as High MOX and Low MOX. These names refer to the amount of plutonium that is loaded per fuel assembly, relative to each other. The overall plutonium enrichments of the High MOX and Low MOX designs were chosen to provide initial reactivities that are characteristic of fresh LEU fuel in eighteen month fuel cycles. Using two MOX fuel assembly designs provides additional flexibility with respect to core design.

The overall plutonium enrichment for each baseline MOX fuel assembly design is obtained from a weighted average of the plutonium enrichments of each of the fuel pins in the assembly. The plutonium enrichments of the individual enrichment zones and the resulting High MOX and Low MOX plutonium enrichments are provided in Table 1. The MOX fuel assembly zoning is shown in Figure 1. The High MOX and Low MOX designs share common enrichments for the low and medium zones, thereby limiting to four the nominal number of different enrichments required from the MFFF.

Table 1
MOX Fuel Assembly Plutonium Enrichments

Enrichment Zone	**Number of Fuel Rods**	**High MOX w/o Pu**	**Low MOX w/o Pu**
Low (corners)	12	2.316	2.316
Medium (edges)	68	3.583	3.583
High (interior)	184	4.794	4.364
Total or Average	264	4.37	4.07

Beginning with the all-uranium fuel cores expected to be characteristic of mission reactor fuel cycles in 2007, Duke Power and Virginia Power developed a series of transition MOX fuel cycles. After several transition cycles, the plants achieved "equilibrium" partial MOX fuel cores with close to 40% MOX fuel assemblies in the cores. For McGuire and Catawba, the "equilibrium" partial MOX fuel cores would vary each cycle between 36 and 40 feed MOX fuel assemblies [out of 84 total feed (LEU + MOX) assemblies]. For North Anna, the "equilibrium" partial MOX fuel cores would vary each cycle between 28 and 29 feed MOX fuel assemblies [out of 68 or 69 total feed (LEU + MOX) assemblies respectively]. The term equilibrium cycle will be used for either of these alternating cycles. Figures 2 and 3 show the first equilibrium partial MOX fuel core loading patterns for McGuire/Catawba and North Anna respectively.

The core design analyses indicated that acceptable core designs, satisfying anticipated peaking limits, could be developed for such mixed LEU/MOX fuel cores. The analyses also indicated that plant reactivity control enhancements (e.g., higher worth B_4C control rods versus silver (Ag)–indium (In)–cadmium (Cd) control rods, enriched soluble boric acid) may be required to compensate for the lower thermal neutron absorber reactivity worth in partial MOX fuel cores. The neutronic analyses performed will be used to support the development of the MRSMP and the identification of any required plant modifications, as noted previously.

The core design analyses demonstrated that 51 planned operating cycles for the six mission reactors between 2007 and 2022 are capable of disposing of 34.8 tonnes of surplus weapons plutonium. This corresponds to 1743 MOX fuel assemblies in the six reactors. Plutonium disposition amounts by year, and cumulatively, are shown on Figure 4.

IV. CONCLUSION

In conclusion, the DCS team has established a baseline plan for accomplishing the mission of disposing of 33 tonnes of surplus weapons plutonium by irradiating MOX fuel in the McGuire, Catawba, and North Anna reactors. The plan has been validated by preliminary nuclear fuel and core analyses. These analyses indicate that the plan is feasible, although enhanced reactivity control mechanisms may be needed to maintain plant operating margins. The baseline MRIP will serve to establish interface requirements with fuel qualification, fuel fabrication, and transportation areas of the MOX fuel project.

Over the next several years Duke Power and Virginia Power will refine fuel and core designs, evaluate the need for plant modifications, and apply for the license amendments from the Nuclear Regulatory Commission that are necessary to receive and utilize MOX fuel. DCS will adjust the baseline MRIP as necessary to reflect these internal activities and external programmatic factors.

ACKNOWLEDGEMENTS

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REFERENCES

1. DUKE COGEMA STONE & WEBSTER, “Mission Reactors Irradiation Plan”, DCS – IS – 1999 – 001, Revision 1, January, 2000

Figure 1
Proposed MOX Fuel Assembly Design

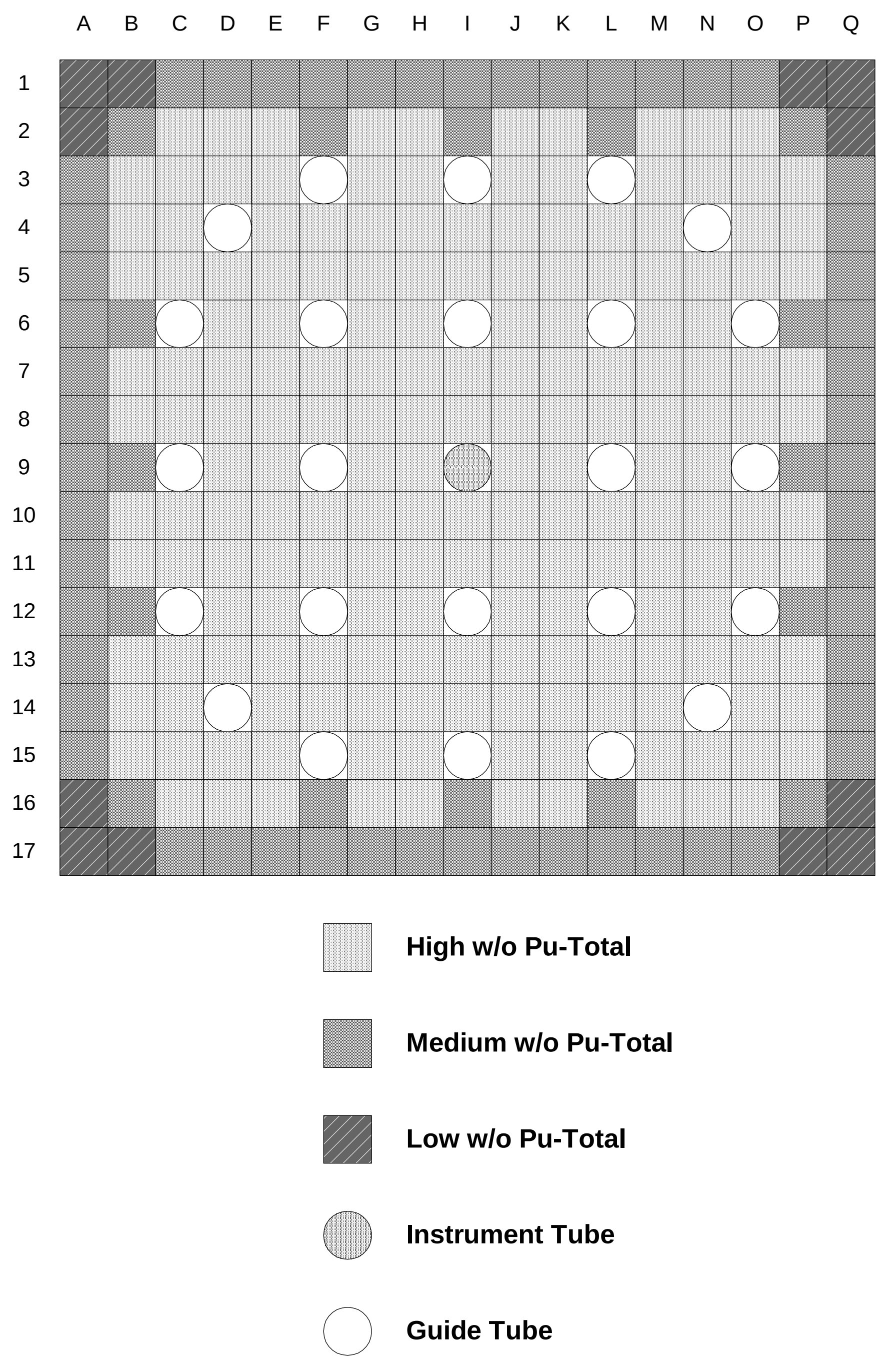

Figure 2

Typical McGuire & Catawba Partial MOX Fuel Core Loading Pattern
1st Equilibrium Core

	H	G	F	E	D	C	B	A
8	U 4.16 2	U 4.23 24/3.5 0	U 4.37 1	U 4.23 24/3.5 0	U 4.37 1	Pu 4.07 24/4.0 0	U 4.23 I 128 0	Pu 4.37 1
9	U 4.23 24/3.5 0	U 4.24 1	U 4.23 20/4.0 0	U 4.24 1	U 4.23 24/3.5 0	Pu 4.07 1	Pu 4.37 16/3.0 0	U 4.24 1
10	U 4.37 1	U 4.23 20/4.0 0	U 4.24 1	Pu 4.07 24/4.0 0	U 4.24 1	Pu 4.37 1	U 4.45 I 128 0	Pu 4.37 1
11	U 4.23 24/3.5 0	U 4.24 1	Pu 4.07 24/4.0 0	U 4.37 1	Pu 4.37 1	U 4.45 I 128 0	Pu 4.37 4/2.0 0	U 3.92 2
12	U 4.37 1	U 4.23 24/3.5 0	U 4.24 1	Pu 4.37 1	U 4.24 1	Pu 4.37 20/3.5 0	U 3.92 2	
13	Pu 4.07 24/4.0 0	Pu 4.07 1	Pu 4.37 1	U 4.45 I 128 0	Pu 4.37 20/3.5 0	Pu 4.37 4/2.0 0	U 4.24 1	
14	U 4.23 I 128 0	Pu 4.37 16/3.0 0	U 4.45 I 128 0	Pu 4.37 4/2.0 0	U 3.92 2	U 4.16 2	Enrichment wt % # BP fingers/wt% # cycles burned	
15	Pu 4.37 1	U 4.24 1	Pu 4.37 1	U 3.92 2				

Note: 'I xxx' ≡ # of IFBA coated fuel pins in the assembly (UO_2 assemblies with IFBA only).

Figure 3

Typical North Anna Partial MOX Fuel Core Loading Pattern
1st Equilibrium Core

	H	G	F	E	D	C	B	A
8	Pu 4.07 1	Pu 4.37 16/0.95 1	Pu 4.37 1	U 4.3 24/2.5 0	U 4.55 1	U 4.55 24/2.0 0	U 4.3 1	Pu 4.37 0
9	Pu 4.37 16/0.95 1	Pu 4.37 1	Pu 4.37 12/0.95 1	U 4.55 1	U 4.3 24/2.5 0	U 4.3 1	Pu 4.37 24/0.95 0	U 4.3 2
10	Pu 4.37 1	Pu 4.37 12/0.95 1	U 4.55 1	U 4.3 24/2.5 0	Pu 4.07 1	U 4.55 24/2.0 0	Pu 4.07 0	
11	U 4.3 24/2.5 0	U 4.55 1	U 4.3 24/2.5 0	U 4.55 1	U 4.55 24/2.0 0	Pu 4.37 8/2.5 0	U 4.3 1	
12	U 4.55 1	U 4.3 24/2.5 0	Pu 4.07 1	U 4.55 24/2.0 0	U 4.45 2	U 4.3 2		
13	U 4.55 24/2.0 0	U 4.3 1	U 4.55 24/2.0 0	Pu 4.37 8/0.95 0	U 4.3 2			
14	U 4.3 1	Pu 4.37 24/0.95 0	Pu 4.07 0	U 4.3 1				
15	Pu 4.37 0	U 4.3 2						

Enrichment wt %
BP fingers/wt%
cycles burned

FIGURE 4

Yearly and Cumulative Plutonium Loading