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Program on Technology Innovation: Readiness of Existing and New U.S. Reactors for Mixed-Oxide (MOX) Fuel

1018896

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Technical Update, May 2009

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This document describes research sponsored by the Electric Power Research Institute (EPRI).

This publication is a corporate document that should be cited in the literature in the following manner:

Program on Technology Innovation: Readiness of Existing and New U.S. Reactors for MOX Fuel, EPRI, Palo Alto, CA: 2009. 1018896.

REPORT SUMMARY

Expanding interest in nuclear power and advanced fuel cycles indicate that use of mixed-oxide (MOX) fuel in the current and new U.S. reactor fleet could become an option for utilities in the coming decades. In light of this renewed interest, EPRI has reviewed the substantial knowledge base on MOX fuel irradiation in light water reactors (LWRs). The goal was to evaluate the technical feasibility of MOX fuel use in the U.S. reactor fleet for both existing and advanced LWR designs (Generation III/III+).

Background

Partial MOX fuel cores have been routinely loaded in reactors in France, Germany, Switzerland, Belgium, and India. Japan is actively pursuing commercial use of MOX fuel in its reactor fleet, including plans for one unit to be fueled with a 100% MOX core. In the United States, MOX fuel test assemblies were irradiated at a number of commercial plants in the 1960s, 1970s, and early 1980s. However, MOX commercialization in the United States effectively ended in 1977, with the suspension of federal support for commercial nuclear fuel reprocessing due to proliferation concerns. Active U.S. pursuit of MOX fuel use was revived following the 2000 signing of the Plutonium Management and Disposition Agreement by the United States and the Russian Federation, under which each country intends to irradiate at least 34 metric tons of excess weapons-grade (WG) plutonium (Pu) as fuel in reactors. For its part, the United States is constructing the MOX Fuel Fabrication Facility at DOE's Savannah River Site in South Carolina to produce more than 1700 MOX fuel assemblies for domestic use in commercial pressurized water reactors. Supporting the DOE Pu disposition mission, Duke Energy loaded four MOX lead test assemblies (LTAs)—manufactured in France from U.S.-origin WG Pu—into Catawba Unit 1 in 2005. The LTAs were discharged in 2008 after two 18-month cycles.

Objectives

- To generically evaluate the readiness of existing and new U.S. commercial LWRs to irradiate MOX fuel.
- To identify potentially important knowledge gaps and technology barriers that could impede commercial MOX fuel use by U.S. electric utilities.

Approach

The primary task for this review consisted of collecting and distilling the substantial knowledge and experience base related to LWR use of MOX fuel derived from publicly available reports, manuscripts, and other documentation. The information was verified and augmented through consultations with experts from electric power utilities, reactor vendors, and other organizations, including those connected with the DOE Pu disposition program. The report focuses on generic technical considerations and excludes policy, economic, and social factors. The report assumes the availability of MOX fuel and associated technologies. Current global MOX supplies are considered in terms of overall U.S. reactor fleet capacity and the corresponding potential demand for MOX fuel in LWRs.

Results

The principal technical concerns associated with MOX fuel use include reactivity control and maintenance of adequate shutdown margins due to reduced effectiveness of neutron absorber materials (control rods and soluble boron) in the hardened neutron spectrum, resulting from the presence of Pu. In addition, several facility design and operational issues must be addressed for receipt, handling, and storage of fresh MOX fuel and for the management of spent MOX fuel at the back end due to higher heat loads, increased neutron dose rates, and reduced effectiveness of reactivity control materials in the spent fuel pool and in dry storage systems. MOX fuel performance and reliability is considered to be on par with that of standard uranium oxide fuel. Given the substantial safety margins incorporated into LWR designs, most existing U.S. reactor designs could accommodate partial (30–40%) MOX fuel cores with relatively minor plant modifications and operational changes, setting aside other nontechnical considerations, including cost. Furthermore, the use of lower core fractions would likely obviate the need for most if not all modifications. Regulatory requirements associated with MOX fuel irradiation in U.S. LWRs, including revisions of the reactor design basis and operating license amendment, are substantial but manageable. Transportation of fresh MOX fuel, as Category I material, is one area that could pose serious challenges for commercial MOX usage by U.S. utilities in terms of availability (and cost) of NRC-certified packages and carriers for domestic transportation. DOE served as the exclusive carrier for the MOX fuel LTA shipments to Duke Energy's Catawba Unit 1, but this option may not be available for fresh MOX fuel shipments outside of DOE-sponsored programs. It is worth noting, however, that reactor-grade MOX fuel transportation is routinely addressed abroad, where the need and demand are current, not hypothetical.

EPRI Perspective

In this review of the extensive MOX fuel experience and knowledge base, EPRI has not identified substantial technical barriers that would preclude loading of partial MOX fuel cores in a sizeable fraction of existing U.S. reactors. Higher MOX core loadings should be accommodated in most, if not all, Generation III/III+ LWR designs, although site- and plant-specific features could constrain this flexibility. MOX fuel is currently available commercially, albeit in limited supply—a condition likely to continue in coming decades. In this regard, use of MOX fuel over the next 20–30 years in U.S. LWRs should not be limited by the availability of reactor capacity. Overall, historical and ongoing experience with MOX fuel irradiation in LWRs worldwide provides a sound technical basis for consideration of commercial MOX use as a transitional step in the pursuit of more advanced fuel cycles in the United States.

Keywords

Nuclear Fuel Cycle
Mixed-Oxide (MOX) Fuel
Plutonium Recycling
Light Water Reactor (LWR)

ACKNOWLEDGMENTS

EPRI is grateful to the following individuals who contributed to the preparation of this report:

Ed Wenzinger and Tim Dixon (MPR Associates, Inc.)

Andrew Sowder, Albert Machiels, Jeffrey Hamel, and John Kessler (EPRI)

EPRI also acknowledges the following individuals for their guidance, technical expertise, and feedback on previous draft versions of this report:

Shaw Bien (Energy Northwest)

T.A. Keys and Jim Robert (Tennessee Valley Authority)

Steve Nesbit, Jim Eller, Richard Browder, and Paul Bailey (Duke Energy)

Michel Vidard (Electricité de France)

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1
INTRODUCTION

1.1 Background

With renewed interest in nuclear power as a technology for meeting future electricity generation demand, alternatives to the once-through fuel cycle are once again receiving attention in the United States. Low enrichment uranium oxide fuel (UOX, in the form of UO_2) is used exclusively in the U.S. for commercial nuclear power production. As an alternative to the once-through fuel cycle, a plutonium (Pu) recycling process can be implemented but requires the separation of Pu from the fission products and other materials and the fabrication of mixed uranium-plutonium oxide (MOX) fuel assemblies for re-insertion into light-water reactor (LWR) cores.

Commercial Pu-recycling in LWRs can be considered a mature technology, although its implementation, especially with regard to spent fuel reprocessing, has been and remains challenging. MOX experience in the U.S. to date has been limited to irradiation of lead test assemblies (LTAs) at a number of commercial plants chiefly in the 1960's and 70's (ORNL, 1997e). In 2000, the U.S. and Russian Federation signed the Plutonium Management and Disposition Agreement, which called for the permanent disposal or use as fuel in a reactor of at least 34 metric tons of excess weapons grade (WG) Pu by each country (DOE, 2007). As part of the Agreement, the United States Department of Energy (DOE) is constructing a MOX Fuel Fabrication Facility (MFFF) to enable recycling of WG Pu. The MOX fuel fabricated in the MFFF is expected to substitute for more than 1700 PWR fuel assemblies (DCS, 2002).

The launch of the Global Nuclear Energy Partnership (GNEP) in 2006 formally signaled renewed U.S. interest in pursuing alternative nuclear fuels. And while the GNEP program ended following the 2009 change in the U.S. administration, interest continues in advanced nuclear fuel cycles that offer the benefits of CO_2-free base-load generation while reducing proliferation and waste disposal concerns (Platts, 2009b,c). Reaching the desired end state – a proliferation-resistant closed fuel cycle – requires substantial investment in R&D to realize industrial scale application of reprocessing technology and fast reactors, substantial capital investment in those facilities, and potentially prohibitive levels of risk for industry and capital markets. It can be argued that some sort of bridge between the current LWR-based once-through fuel cycle and a partially- or fully-closed fuel cycle is needed to demonstrate feasibility of key technologies and maintain momentum for expansion and development of nuclear power. DOE reportedly has considered MOX technology as playing such a bridging role (Platts, 2008a). In April 2008, DOE signed a Memorandum of Understanding with the Tennessee Valley Authority for Advanced Fuel Cycle Demonstration Support (DOE, 2008), which included an assessment of MOX use in LWRs (TVA, 2008).

Historical and ongoing experience with MOX fuel utilization in LWRs worldwide provides a technical basis and motivation for reexamining the case for commercial MOX use in the United States. Pu recycling also offers a potential path forward to more advanced fuel cycles.

Given renewed interest in alternative fuel cycles, EPRI has chosen to take a fresh look at the feasibility of MOX fuel use in the current U.S. reactor fleet and in newer (Generation III/III+) advanced LWR designs to identify potential knowledge gaps and technical issues that could impede commercial use of MOX fuel in the U.S. within the coming decades. This review focuses on generic technical considerations and excludes policy, economic, and social factors. The review assumes availability of MOX fuel and associated technologies. However, current global MOX supplies are considered to provide a context for evaluating overall U.S. reactor fleet capacity and corresponding potential demand for MOX fuel use over the next 20 – 30 years.

1.2 MOX versus UOX Fuel

MOX fuel incorporates oxides of Pu and uranium (U) and potentially higher actinides depending on the source of the Pu and U and the reprocessing technology used. The total Pu in LWR fuel varies depending on reactor core design needs, but 13 wt% total Pu represents a practical upper limit, as calculations for infinite lattices yield positive void reactivity coefficients for higher Pu levels (IAEA, 2003; Trellue, 2006). The fact that the bulk fuel matrix remains UO_2 implies that, in general, the physical characteristics of MOX fuel are comparable to that of UOX fuel (Fujishiro et al., 1999; IAEA, 2003). UOX fuel derives a third or more of its energy production from Pu over its in-core life (Graves, 1979), and the differences between UOX and MOX fuel generally decrease with increasing burnup for an equilibrium fuel cycle.

The neutronics properties of MOX fuel differ significantly from that of UOX fuel (Fujishiro et al., 1999; IAEA, 2003; Trellue, 2006; DCS, 2001). The presence of plutonium isotopes in fuel shifts the neutron spectrum to higher energies, which reduces the effectiveness of thermal neutron absorber materials: soluble boron, control/shutdown rods, burnable absorbers, and fission product poisons such as xenon. Shorter neutron lifetimes and fewer delayed neutrons associated with the presence of Pu lead to faster core responses to reactivity transients, such as reactivity insertion accidents. Larger fission cross-sections for Pu isotopes produce power peaking concerns. Greater capture-to-fission ratios for MOX fuel, resulting in production of fissile ^{241}Pu, leads to a slower decrease in reactivity for MOX with increasing burnup. These differences drive the need for safety analyses and licensing activities to ensure that adequate safety and design margins are maintained.

The isotopic composition of plutonium used in MOX fuel (Table 1-1) depends on the manner in which it was produced in terms of reactor design, initial U enrichment, fuel discharge burnup, and spent fuel storage time. For the purpose of this review, reactor grade (RG) Pu refers to recycled Pu obtained from spent UOX fuel that has been irradiated in an LWR at relatively high burnups and contains substantial amounts of Pu isotopes other than ^{239}Pu. Weapons grade Pu is derived from very low burnup uranium fuel to optimize fissile ^{239}Pu content (IAEA, 2003; Trellue, 2006). Table 1-1 compares typical ranges for isotopic compositions for WG and RG plutonium.

Table 1 - 1
Plutonium Isotopic Composition of Weapons Grade and Reactor Grade MOX (Kang et al., 2000; DCS, 2001, 2002; IAEA, 2003; Trellue, 2006)

Isotope	Plutonium Grade	
	Weapons Grade (wt%)	Reactor Grade (wt%)
^{238}Pu	0	1 – 4
^{239}Pu	92 – 95	50 – 60
^{240}Pu	5 – 7	24 – 27
^{241}Pu	0 – 0.5	6 – 11
^{242}Pu	0 – 0.05	5 – 10

Once Pu is formed in LWR UOX fuel, neutron capture and decay reduce the fissile Pu fraction relative to total plutonium with time. As a result, RG Pu extracted from recycled UOX spent fuel has reduced fissile Pu content (<70%) compared with WG Pu (>90%) that has been recovered following a short irradiation period. To compensate for this effect, the Pu content of RG MOX can be increased to provide an equivalent energy content relative to WG MOX (IAEA, 2003). Likewise, it is feasible to tailor the Pu content in MOX fuel for burnup equivalence to UOX fuel. This MOX parity is viewed favorably as it allows for simplified and more flexible core management by eliminating the need for mixed or hybrid batch loading schemes.

2
REVIEW OF MOX EXPERIENCE

The use of MOX fuel in thermal reactors is a mature technology that has been actively pursued and developed since the 1950's. Demonstration of MOX utilization in thermal reactors began in the 1960's with programs in the U.S., Italy, Germany, and Belgium. Subsequently, MOX fuel has been loaded on a routine basis into reactors in France, Germany, Switzerland, Belgium, and India (IAEA, 2003).

2.1 U.S. MOX Experience

While partial or full core loadings with MOX have not occurred in the U.S. reactor fleet, a substantial knowledge base exists from past and recent LTA irradiation experience in commercial reactors. As shown in Table 2-1, MOX LTA demonstrations were performed at a number of U.S. BWRs and PWRs throughout the two decades spanning 1960 – 1980 (ORNL, 1999). The most recent experience with MOX in LWRs in the U.S. has been the irradiation of four WG MOX LTAs in Duke Energy's Catawba Unit 1, a four-loop Westinghouse PWR, as part of the U.S. DOE's Plutonium Disposition Program. The LTAs were manufactured by AREVA in France from U.S. origin Pu and loaded into Catawba Unit 1 in 2005; these were withdrawn in 2008 after two 18 month cycles. A planned third irradiation cycle was deferred due to unexpected fuel assembly growth; this development was not attributed to the presence of MOX, and MOX fuel performance has been characterized as excellent (Duke Energy, 2008, NEI, 2008, Platts, 2008b). These demonstrations and subsequent operational experience have shown MOX fuel performance to be on par with standard UOX fuel performance (IAEA, 2003; Provost and Debes, 2006).

Table 2 - 1
U.S. MOX Lead Test Assembly (LTA) Demonstrations (ORNL, 1999; Duke Energy, 2008)

Reactor	Reactor Design Class	MOX LTA Start	Total Number of Assemblies	Total Number of Fuel Rods
Vallecitos	BWR	1960s	--	≥ 16
Big Rock Point	BWR	1969	16	1248
Dresden-1	BWR	1969	11	103
San Onofre-1	PWR	1970	4	720
Quad Cities-1	BWR	1974	10	48
Ginna	PWR	1980	4	716
Catawba-1	PWR	2005	4	full 17 x 17 assemblies

2.2 International MOX Experience

Perspectives on MOX use in foreign LWRs provide corroborative information regarding MOX use in the U.S. LWR fleet, including those from the Swiss utility KKG (NEA, 2007), Belgonuclaire (Van Vyve, 1996), and Electricité de France (ORNL, 1997b; Fujishiro et al., 1999), and for MOX use in VVER-1000 reactor designs (ORNL, 2004). General consistency among reviews of U.S. and foreign LWR reactor designs indicates that foreign, particularly European, MOX experience is relevant to most BWR and PWR reactor designs.

As in the U.S., MOX fuel testing started in Europe in the 1960s (Table 2-2) but, unlike the U.S. example, continued to develop to commercial scale implementation in the 1980s as shown in Table 2-3 (ORNL, 1999). Currently, there are over 30 units operating with MOX fuel in Europe, most with a one-third MOX core fraction (WNA, 2008b). The first irradiation of LWR MOX fuel was initiated in a Belgian PWR in 1963; commercial MOX use (batch reloads) in two PWRs commenced much later in 1995 (Van Vyve, 1996; IAEA, 2003). In Switzerland, MOX testing in LWRs began in 1978 and was followed by batch loading in three PWRs starting in 1978 (IAEA, 2003).

Germany commenced LWR MOX testing in 1966 and implemented MOX batch reloads in PWR and BWR designs in 1972 and 1974, respectively (IAEA, 2003; WNA, 2008e). An EPRI evaluation of the conversion of seven[1] Siemens-designed PWRs in Germany and Switzerland to enriched boric acid (EBA) for plant borated water systems indicates that PWR conversion to partial MOX cores and EBA systems should be a technically manageable task for many U.S. plants (EPRI, 2001).

In France, 20 of 28 of its 900 MWe PWRs operate with 30% partial MOX cores, and additional reactors are licensed or pending approval for MOX use (NEA, 2007; ORNL, 1997e; WNA, 2009a). Japan is actively pursuing Pu-recycle as part of its energy strategy, including plans to load MOX in up to 20 units (WNA, 2009b). One new Japanese unit at Ohma is being built explicitly for operation with a 100% MOX core load (WNA, 2008a). To date, MOX utilization in LWRs worldwide has been limited to partial core loadings, most at one-third core loadings or less (ORNL, 1999).

[1] Six of the Siemens-designed PWRs evaluated in EPRI (2001) are located in Germany; one is in Switzerland.

Table 2 - 2
LWR MOX LTA Experience Outside of the U.S. (ORNL, 1999; IAEA, 2003; Van Vyve, 2006; Tanaka, 2008)

Country	MOX LTA Start
Belgium	1963
Italy	1968
Netherlands	1971
Sweden	1975
Germany	1966
France	1974
Switzerland	1978
Japan	1986

Table 2 - 3
Summary of Batch MOX Use in Commercial LWRs Worldwide (ORNL, 1999; IAEA, 2003; Van Vyve, 2006; Tanaka, 2008; WNA, 2008e, 2009a,b).[2]

Country	Reactor Type	MOX Reload Start	Number of Reactors Licensed for MOX	Maximum MOX Core Load (%)
Belgium	PWR	1995	2	24
France	PWR	1987	20+*	31
Germany			13 (Total)	
	PWR	1972	≥ 9	50
	BWR	1974	≥ 2	44
India	BWR	1994	2	
Japan	PWR	delayed	8 (Total)	25 – 33
	BWR			
Switzerland	PWR	1984	3	40

*Four more have been or are in the processed of being licensed for MOX use.

2.3 Global MOX Fuel Supply

The global MOX LWR fuel supply represents a few percent of the total LWR fuel demand, and further expansion within the next 20 – 30 years will be limited given the long lead times for

[2] While the UK and Russia have experience with Pu-recycle in other reactor designs, their LWRs have not seen MOX use (ORNL, 1999).

licensing and construction of facilities. Nevertheless, the technology exists, is presently deployed on a commercial scale, and global MOX capacity is expected to grow modestly in the coming decades (Table 2-4). Two operational facilities, in France and the UK, currently represent a total worldwide commercial MOX production capacity of 235 metric tons of heavy metal (MTHM) per year (WNA, 2008e), although the UK facility has continued to operate well below capacity (Platts, 2009d). France is the world leader in LWR fuel recycling with a reprocessing capacity of 1700 metric tons of spent fuel per year and an annual RG MOX fuel production capacity of approximately 150 metric tons out of an annual licensed capacity of 195 metric tons; approximately 100 metric tons of this capacity supports the 20 French 900 MWe PWR reactors operating with 30% MOX cores (ORNL, 1999). Japanese plans include a new MOX production facility at Rokkasho with an annual capacity of 130 MTHM to support 16 – 18 reactors (IAEA, 2003, WNA, 2008b, 2009b).

The U.S. DOE Plutonium Disposition Program is slated to produce approximately 1700 MOX PWR fuel assemblies from WG Pu, equivalent to a total 790 MTHM of fuel over 15 years, with a peak capacity of 70 MTHM of fuel per year projected to support up six 1000 MWe PWR reactors operating with 40% equilibrium cores, 2-cycle MOX irradiations, and 20 GWd/MTHM minimum discharge burnups (DCS, 2002, 2008).

In October 2008, Shaw-Areva MOX Services issued a letter to all U.S Nuclear Utilities soliciting their interest in providing MOX fuel irradiation services (DCS, 2008) based on a known excess fuel capacity of 750 fuel assemblies above and beyond the 950 reserved for the Duke Energy irradiation schedule. The letter of interest reiterated incentives for MOX fuel use under the DOE program:

- Reactor Licensing and modification activities would be done under a cost plus fixed fee contract with MOX Services.
- Utility proposes the pricing for the MOX fuel reloads.
- Depending upon utility requirements, DOE may provide a LEU fuel inventory as a backup should any delays occur in the MOX fuel delivery.

Initiation of MOX reloads at Catawba and McGuire was originally scheduled for 2007; however, fuel fabrication facility construction delays have pushed the earliest MOX fuel deliveries to 2018. Duke Energy's contract for irradiation of a majority of MFFF MOX production expired at the end of 2008 and, as of May 2009, the contract has not been extended or renewed (Platts, 2009a). With or without continued participation of Duke Energy in the DOE MOX irradiation mission, a limited supply of DOE-supplied WG MOX continues to be an option for U.S. utilities in the near future.

Table 2 - 4
Recent, Current, and Anticipated LWR MOX Fuel Production Capacity (ORNL 1999; IAEA, 2003; DCS, 2008; WNA 2008b)

Country	Facility	Production Capacity MTHM/yr	Production Status
Belgium	Dessel/P0	40	Plant closed in 2006
United Kingdom	Sellafield	40	Commissioned in 2001 and downrated from 128 to 40 MTHM/yr in 2007
France	MELOX	195	Production increased from 145 to 195 MTHM/yr in 2007
Japan	Plutonium Fuel Production Facility (PFPF)	130	Planned for 2012
U.S.	MOX Fuel Fabrication Facility (MFFF)	4 – 70* (~790 total over 15 year production schedule; WG MOX only)	Planned for 2018

*Based on 0.463 MTHM per 17x17 PWR fuel assembly (DCS, 2008).

3
EXISTING U.S. REACTOR FLEET

3.1 Overview of Current U.S. Reactor Fleet

The current U.S commercial nuclear generating fleet comprises 104 reactor units - 69 PWRs and 35 BWRs. A breakdown of the fleet by reactor type, license expiration date range, and size range are provided for PWRs and BWRs in Table 3-1.

Table 3 - 1
Breakdown of Operational Reactors in the U.S. by Manufacturer, Design, Size, and Operational Lifespan (EIA, 2008a; NRC, 2008c)

Reactor Vendor	PWR/ BWR	Number of units in operation	Number of units >750MWe	Number of units with 60 year operational lifespans beyond 2039	Number >750MWe with 60 year operational lifespans beyond 2039
Westinghouse	PWR	48	39	28	28
Combustion Engineering	PWR	14	13	7	7
Babcock and Wilcox	PWR	7	7	0	0
Total PWRs		**69**	**59**	**35**	**35**
GE BWR2	BWR	2	0	0	0
GE BWR3	BWR	6	4	0	0
GE BWR4	BWR	19	17	6	6
GE BWR5	BWR	4	4	4	4
GE BWR6	BWR	4	4	4	4
Total BWRs		**35**	**29**	**14**	**14**
Total		**104**	**88**	**49**	**49**

Evaluation of a reactor's suitability for MOX fuel use is case-specific and is beyond the scope of this evaluation. However, a ballpark estimate of the number of potential candidates can be generated based on reactor ages and projected life spans. Fig. 3-1 provides the number of operational LWR reactors in the current U.S. fleet versus year and projects this number out to 2060 based on the assumption that all reactors operate for 60 years. Assuming that (1) newer generation II reactors (circa 1980 and later) are better able to accommodate MOX use (as a result of core flexibility, size, and lifetime, among other factors); (2) commercial scale MOX use would not become a reality until the year 2020 or later; and (3) that a nominal minimum

remaining reactor lifetime of around 20 years is needed to justify the cost and effort associated with licensing and plant modifications, almost 50% of the current 104 operational reactors appear to be potential candidates for partial MOX core loads. Likewise, screening the current U.S. reactor fleet based on output (>750 MWe) and anticipated operational lifetime (2040 and beyond (assuming 60 year lifetimes) yields a candidate population of 49 reactors among the current 104 operating in the U.S. today (Table 3-1).

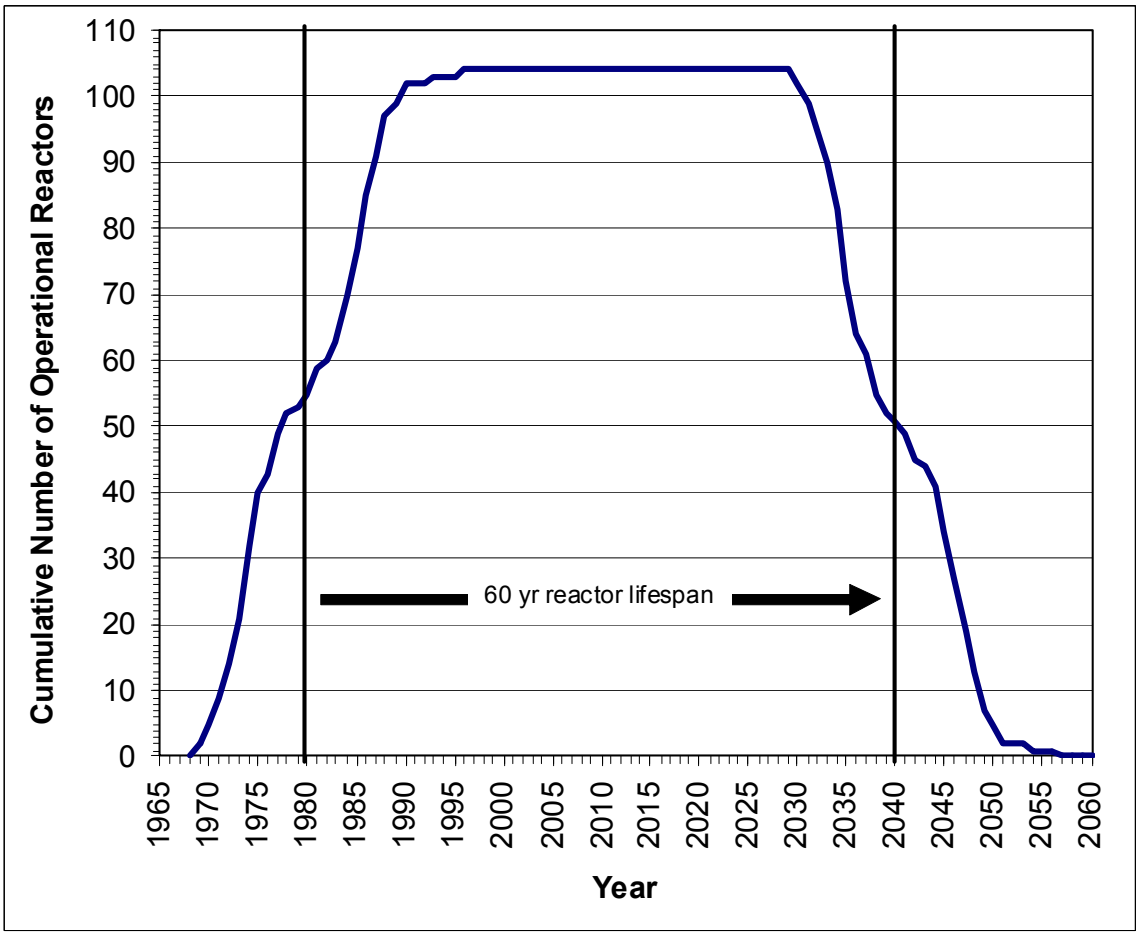

Figure 3 - 1
Projected Number of Operational Reactors by Year for the Existing U.S. Fleet Assuming a 60-year Operating Life. Reactors that became operational in 1980 and later would begin to shut down in 2040, as indicated on the graph (Data from NRC, 2008c)

These approaches do not account for design-specific features and limitations, overall benefits or disadvantages of reactor design classes, i.e., PWRs vs. BWRs, or a number of other site- and utility-specific factors. However, such estimates are useful for highlighting the potential capacity and/or demand for MOX fuel in existing reactors in the event that the future conditions were to favor Pu recycle in LWRs. It is also instructive to compare this candidate population with the French fleet of 20 reactors supported by 100 MTHM/yr of MOX (ORNL 1997e; WNA, 2009a) and the planned DOE WG MOX fuel supply of 70 MTHM/yr expected to support 6 (nominally 1000 MWe) LWRs operating on partial MOX cores (30 – 40%) over the projected 15-year life of the program (DCS, 2002; 2008). The potential capacity for MOX use by the current U.S. fleet is large relative to current and anticipated global MOX fuel supplies.

3.2 Reviews and Analyses of MOX Use in LWRs

An early comprehensive review of MOX experience and associated issues, "*Final Generic Environmental Statement on the Use of Recycle Plutonium in Mixed Oxide Fuel in Light Water Cooled Reactors*," was published just before the 1977 Executive Order on nonproliferation halted commercialization of MOX in the U.S. (NRC, 1976). This work has served as a technical foundation for subsequent reviews and analyses for the U.S. reactor fleet. In the 1990's, DOE efforts to reestablish the technical basis for MOX use in support of its surplus WG Pu disposition program included outreach to the vendors of existing U.S. reactor systems for a review of relevant reactor systems with respect to WG MOX utilization (ORNL 1997a-g; 1999). This documentation provides generic and design specific information on plant modifications and licensing approaches from ABB-Combustion Engineering, General Electric, and Westinghouse required for MOX use (ORNL, 1997b,e). Summaries of these reactor specific reviews with respect to WG MOX use are presented in Appendix A. Extensive documentation supporting the MOX irradiation testing phase of the Plutonium Disposition Program describes key issues including fuel qualification, core and fuel design, plant modifications, and fuel management for WG MOX irradiation in Duke Energy's Catawba and McGuire 1100 MWe, four-loop Westinghouse PWRs (ANRCP, 1998; DCS 2001, 2002).

In April 2008, the Tennessee Valley Authority (TVA) and the U.S. DOE signed a memorandum of understanding to support the demonstration of advanced fuel cycles. This work includes assessing the technical, regulatory and business challenges of MOX use in commercial reactors. The agreement also has provisions for conceptual design development for advanced fuel cycle facilities. As part of this collaboration with DOE, TVA completed a detailed design, licensing, and cost analysis for operation of its Sequoyah Westinghouse PWRs on partial RG MOX cores (TVA, 2008).

3.3 Considerations for MOX Use in Existing U.S. Reactors

Except for the three CE-System 80 units at Palo Verde, the current operating reactors in the U.S. were not explicitly designed for MOX use. However, as all uranium-fueled LWRs end up generating a substantial amount of energy from the fission of ^{239}Pu produced throughout irradiation from ^{238}U activation, it is reasonable to expect that a significant fraction of existing U.S. reactor designs could accommodate partial MOX core loadings with only minor physical and operational plant modifications. Previous and recent LTA irradiation experience in commercial reactors and the sizeable body of reviews and analyses bolster this conclusion.

3.3.1 Reactor Design Class

MOX fuel has been tested and batch loaded into PWRs and BWRs worldwide (for example, Tables 2-1 and 2-3). While the majority of MOX experience has involved PWRs, neither design class has been shown to offer an overall advantage (ORNL, 1997e, IAEA, 2003). Accordingly, both PWRs and BWRs are considered equally appropriate for MOX use.

3.3.2 Reactor Core Operating Characteristics and Reactivity Control

Review of the available knowledge base, including the DOE technical basis for its Pu disposition program, finds reactivity control to be the primary technical issue associated with operation of

LWRs with MOX fuel. The differences in neutronics for Pu and U result in important issues for core reactivity due to (1) overall decreased effectiveness of materials that serve to reduce or suppress reactivity (control/shutdown rods, soluble boron, gadolinium, xenon) and (2) changes in fuel and moderator temperature responses that reduce key safety margins - notably shutdown margins (ORNL, 1997b,e; ANRCP, 1998; Fujishiro et al., 1999; DCS, 2001, 2002, IAEA, 2003, Trellue, 2006). While important, these issues can be addressed through modifications and flexible design for existing and new reactors, respectively. The reduced effectiveness of reactivity control materials for Pu-based fuels, notably control/shutdown rods and soluble boron, means that MOX use will likely require one or more enhancements to reactivity control. However, the nature and extent of such modifications will depend on existing margins, which can vary widely among and within reactor designs and design classes (Duke Energy, 2009).

For MOX-loaded PWRs, reactivity control modifications would include increasing soluble boron concentrations or using enriched boron in coolant systems. Conversion to enriched boron for borated systems is the preferred approach for PWRs to maintain adequate reactivity control while avoiding solubility limits and enhanced corrosion associated with increased natural boron concentrations in reactor coolant water (DCS, 2002; EPRI, 2001; TVA, 2008; Duke Energy, 2009). In the U.S., conversion to enriched boron can require installation or upgrades of plant boron management systems (for recovery and recycle of costly enriched boric acid) and will require onsite analytical capabilities for monitoring and verifying ^{10}B enrichments in borated water systems throughout the plant cycle (EPRI, 2001; TVA, 2008). Use of EBA also permits operations at higher coolant pHs, which provides benefits in terms of radiological exposure and mitigation of fuel crud formation.

Additional reactivity control can be achieved by replacing partial length control rods with full length rods, employing integral burnable absorbers, and using higher worth control rods (ORNL, 1997b,e). It is worth noting that burnable absorber materials and applications were primary developed for UOX cores. Further development of burnable absorber technology optimized for the MOX core environment could greatly improve core design flexibility, fuel utilization, and overall commercial viability of MOX use in existing LWRs (Duke Energy, 2009).

To offset the impact of MOX fuel on control rod worth, MOX fuel assemblies can be located away from rod control cluster positions in PWR cores to preserve control rod worth. Traditional fuel management in partial cores included the use of “island designs” in which MOX fuel rods were isolated from control rod locations by surrounding them with UOX fuel within a fuel assembly (ORNL, 1997e). However, all-MOX fuel assemblies are preferred for PWRs and BWRs for simplicity of manufacturing and lifecycle fuel management (IAEA, 2003). For BWRs, the impact of MOX fuel on control rod worth is less severe due to relatively large water gaps between bundles, which allows for recovery of thermal neutron fluxes. Accordingly, BWR cores can be designed by scattering all-MOX fuel assemblies throughout the core and limiting the number of MOX assemblies assigned to a control blade location to one or two (IAEA, 2003).

Other reactivity control measures for MOX-loaded LWRs include incorporation of burnable absorbers or poisons such as gadolinium to provide additional reactivity control early in the irradiation cycle to counteract the effect of fresh fuel, including power peaking. Burnable absorbers can be inserted into the fuel assembly as discrete elements/rods or incorporated into the fuel itself as integral burnable absorbers applied as coatings on fuel pellet surfaces. While DOE specifically excluded the use of integral burnable absorbers in MOX fuel as part of its Pu

Disposition Program due to concerns over schedule delays accompanying fuel development (ORNL, 1997a; ANRCP, 1998; DCS, 2002), both discrete and integral burnable absorbers in MOX cores provide flexibility for controlling early cycle reactivity. GE highlighted its gadolinium-based integral burnable absorber technology as a promising application under active commercial development for use in its international BWR designs, including designs supporting full MOX cores (GE, 1993; ORNL, 1997b,e).

Westinghouse recommended the application of integral burnable absorbers and enriched boron in the coolant for enhanced reactivity control and higher worth control rods for increased shutdown margin for use of partial or full MOX core loads in its reactors. Westinghouse recommendations specific to full MOX cores included increasing safety injection flow capabilities, boron concentration, and/or boron enrichment; these modifications were deemed necessary for ensuring long-term sub-criticality in the event of an anticipated transient without scram (ORNL, 1997b,e; ANRCP, 1998).

The ABB-Combustion Engineering input to DOE on its System 80 PWR design highlighted the fact that the three Palo Verde reactors were designed and built to accommodate full MOX cores; accordingly, no major plant modifications would be required for loading of MOX fuel. Two options for additional reactivity control to support full MOX core use included increasing the boron concentration in the refueling water storage tank and safety injection system and replacement of 13 installed part-length control rod assemblies with full length control rod assemblies (CE, 1994; ORNL, 1997b,e).

Key MOX impacts on core design and analysis are briefly summarized as follows for Westinghouse 4-Loop PWR (Table 3-2) and General Electric ABWR (Table 3-3) designs based on vendor-derived WG MOX evaluations for the DOE Pu disposition program.

Table 3 - 2
Impacts of MOX Use on Core Design and Analysis for a Generation II Westinghouse 4-Loop PWR (DOE, 1998)

Core Design or Analysis Factor	Design Action / Assessment
MOX Fuel Rods	No axial zoning or integral poisons used All pellets in a given rod contain same weight percent Pu
MOX to LEU interface increased local peaking factors	MOX Enrichment zones within fuel assembly used to limit peaking
MOX reactivity hold down	Burnable poison elements added
Reduced control rod worth	MOX fuel located away from rod cluster control assembly (RCCA) locations
Reduced soluble boron worth	Increased boron concentration from partial cores up to approx 30 - 45% MOX Enriched ^{10}B may be required for moderate to high MOX core loadings to provide adequate reactivity control and shutdown margin
Reduced shutdown margin	Above approximately 30 – 45% MOX additional control rods required and/or enriched ^{10}B may be required.
Moderator Temperature Coefficient more negative for WG-MOX	Consideration for rapid cooling events and cold shutdown margin
WG-MOX Doppler coefficient more negative	Performance comparable or better than for UOX core
Xenon worth reduced in WG-MOX core	Performance comparable or better than for UOX core
Delayed neutron faction and prompt neutron lifetimes reduced for WG-MOX core	Accelerated core response to transients and reactivity insertion accidents
Rod ejection event	Performance comparable or better than for UOX core
Uncontrolled Boron dilution event	Performance comparable or better than for UOX core
Anticipated Transients Without Scram	Accelerated core response to ATWS events
Loss of Coolant Accident	Expect acceptable performance for partial and full MOX cores
Reactor coolant flow loss transient	Similar to 100% UOX core
Main steam line break transient	Similar to 100% UOX core

Table 3 - 3
Impacts of MOX Use on Core Design and Analysis for a Generation III General Electric BWR (GE, 1993)

Core Design or Analysis Factor	Design Action / Assessment
MOX Fuel Rods	No axial zoning used/required All pellets in a given rod contain same weight percent Pu Depending on the design alternatives studied one or more rods contain integral gadolinia poison
MOX reactivity hold down	Integral gadolinia poison used
Reduced control rod worth - MOX / LEU fuel assembly interchangeability	One assembly design with MOX fuel pins located in center of fuel assembly away from control blades and water gaps. UOX rods located on the periphery of the assembly. The reference assembly spiking and spent fuel disposition designs both utilize all MOX rods with gadolinia used in the lattice interior rods to reduce the fission rate on the interior of the assembly similar to that of LEU fuel. The ABWR cell design provides reactivity and shutdown margin through the assembly pitch design with the water gaps aiding in mitigating assembly spectral interactions
Reactivity and Thermal Margins	Reactivity and thermal margins satisfied by reference fuel assembly and cores studied
Dynamic Void Coefficient	Within ABWR generic licensing basis
Doppler Coefficient	Larger than ABWR generic upper limit – addressed in transient analysis
Reactor pressure increase transients	Load rejection with failure of bypass valves most limiting for MOX core. Large margin for MOX fuel with ABWR design
Reactivity and power distribution events – rod ejection	Avoided by ABWR design features
Anticipated Transients Without Scram	Not a limiting ABWR overpressure event
Loss of Coolant Accident	MOX core performance expected to be similar to UOX core
Reactor coolant flow loss transient	Similar to UOX core
Main steam line break transient	Similar to UOX core

3.3.3 Fuel Characteristics and Performance

Compared to ^{235}U in a thermal neutron spectrum, ^{239}Pu has much larger fission and neutron absorption microscopic cross-sections, a larger number of neutrons produced per fission, fewer neutrons generated per absorption, and smaller delayed neutron fractions. These differences in nuclear characteristics between MOX and UOX can be addressed through fuel and core design (ORNL, 1997e, 2004; ANRCP, 1998; IAEA, 2003; Trellue, 2006).

In partial MOX cores, differences between Pu and U result in large thermal flux gradients at the interfaces between the MOX and low-enriched uranium oxide fuel bundles. This localized flux condition is addressed by varying the Pu content in the fuel rods at the edge and corners of the MOX fuel assemblies. PWRs typically employ three different MOX fuel rod types, each with a different Pu content, arranged to mitigate the thermal flux gradients. BWR fuel assembly arrangements have wider water gaps and larger water structures, which can require up to ten different variations in Pu content in fuel rods to mitigate thermal flux issues (IAEA, 2003).

Differences in fuel performance include higher MOX centerline temperatures, greater fission gas release, and lower fission induced swelling of MOX fuel. These differences are considered to be relatively minor and manageable, falling within fuel design margins. Historically, the fission gas release late into fuel irradiation was found to be the most challenging concern (ORNL, 1999). Extensive testing and modeling in the U.S. combined with the extensive commercial MOX experience in Europe have demonstrated MOX fuel performance to be on par with that of UOX fuel (EPRI, 1978; ORNL, 1997b,e, 1999, ANRCP, 1999, Fukuda et al., 1999). French experience with load following operation has also shown better Pellet Clad Interaction performance for MOX fuel than for UOX. Physical tests and post irradiation examination of MOX fuel has confirmed satisfactory performance. As of 2006, MOX fuel failures associated with the EDF experience were reported to be limited to four assemblies out of over 2400 assemblies - all resulting from debris (Fujishiro et al., 1999).

In general, MOX fuel assemblies are completely interchangeable with current standard fuel assembly designs in terms of dimensions and weight. Thus, spatial and weight limits for all aspects of fuel management (transport, handling, refueling, wet storage, and dry storage) should be met (DCS, 2002, ORNL, 1997e).

3.3.4 Reactor Aging and Materials Degradation

Introduction of MOX fuel in LWRs leads to hardening of neutron energies and may result in increased reactor pressure vessel embrittlement (ORNL, 2004). A review commissioned by the Belgian utility Electrabel found that low Pu recycling ratios (20 – 30% partial cores) did not result in increased fast neutron fluence at the pressure vessel for the proposed MOX core management strategies (Van Vyve & Resteigne, 1995; Van Vyve, 1996, ORNL, 1997c). Other studies have shown that core design can mitigate effects of MOX on pressure vessel fluence (ORNL, 2004). For example, the proposed loading scheme for the McGuire and Catawba reactors calls for loading of fresh MOX fuel into the interior core positions, while later cycle and higher burnup assemblies are located in the periphery (DCS, 2002). Accordingly, for partial core loadings, anticipated low leakage core designs, and current structural integrity margins, the resulting impacts of MOX use on pressure vessel integrity are expected to be manageable and minor with respect to safety and reliability (ORNL, 1997c). The Palo Verde CE System 80

reactor design included increased pressure vessel thickness to address higher neutron fluences associated with high MOX core loadings (ORNL, 1997e).

3.3.5 Fuel Handling, Operations, and On-Site Spent Fuel Management

Fresh WG and RG MOX fuel (manufactured using depleted or natural uranium) will exhibit higher dose rates relative to fresh UOX fuel due to elevated neutron and gamma radiation from Pu and other transuranic elements present, but these increases are relatively modest. Handling of fresh MOX fuel will likely require additional radiation and contamination monitoring due to the presence of Pu isotopes, and in some cases, higher actinides (IAEA, 2003).

Identical physical dimensions and similar weight and mechanical properties for MOX and UOX fuel assemblies limit impacts of MOX usage on most aspects of fuel handling and core loading/unloading (ORNL, 1997e). However, higher decay heat following reactor shutdown may delay core offloading during refueling outages.

In terms of spent MOX fuel management, several issues arise due to the resulting higher heat generation and substantially different actinide composition. The minimum cooling period for spent MOX fuel can be anywhere from 2 to 6 times greater than for standard uranium fuel, which may result in challenges where spent fuel storage capacity is limited (ORNL, 1997e; IAEA, 2003). The increased heat loads associated with spent MOX fuel can be addressed by distributing the MOX assemblies among UOX assemblies in the pool and enhancing the spent fuel pool cooling system. Enhanced core and spent fuel pool cooling to accommodate increased decay heat was reported by ABB-CE as a MOX specific design features of the System 80 Palo Verde reactors (ORNL, 1997b,e).

Higher concentrations of Pu, Am, and Cm in spent MOX fuel relative to spent UOX fuel result in significantly higher neutron doses (primarily from ^{238}Pu, ^{242}Cm, and ^{244}Cm), and higher gas pressures from helium production. Due to the higher fissile content and associated differences in neutronic properties, criticality concerns need to be evaluated for wet storage of MOX in the spent fuel pool. Criticality issues in the spent fuel pool can generally be addressed by distributing MOX assemblies among the UOX assemblies (IAEA, 2003, Kryuchkov, et al., 2005).

Loading of MOX into dry storage, relative to UOX fuel, is limited primarily by heat load considerations. Used MOX fuel also exhibits a significantly higher neutron radiation field, while gamma emissions are comparable with that from comparably burned UOX fuel. Higher heat loads from spent MOX fuel mean that a considerable delay may be needed before spent MOX assemblies can be transferred out of the spent fuel pool into dry storage (NEA, 2007). Once moved to dry storage, MOX fuel assemblies can be loaded into canisters along with standard uranium fuel assemblies in dry storage systems (IAEA, 2003). Qualification and licensing of dry cask storage systems is required for MOX fuel storage. Several systems are licensed for spent MOX fuel storage in the U.S. and abroad, and some of these systems have been loaded with MOX fuel at operating and decommissioned plants in the U.S. where MOX LTAs were previously irradiated and discharged (EnergySolutions, 2006; Holtec, 2008; AREVA, 2009).

3.3.6 Transportation and Security

Transportation of fresh MOX fuel, as a Category I or strategic special nuclear material, requires substantial security measures above and beyond those for fresh UOX fuel shipments. Likewise,

under the DOE's Pu disposition program, the domestic transportation of fresh MOX fuel from the fabrication facility at Savannah River to commercial nuclear plants using will be conducted exclusively by the DOE National Nuclear Security Administration's Office of Secure Transportation using its safe-secure trailer (SST) system and special NRC certified Type B transportation packages for fissile material (ORNL, 1997c). The 2005 transport of imported fresh WG-MOX fuel assemblies from Charleston, South Carolina, to Duke's Catawba Unit 1 in York County, South Carolina, for LTA testing demonstrated this approach; however, this option may not be available to utilities for MOX shipments that are not government owned or do not fall under a DOE-sponsored program. Accordingly, MOX transport within the U.S. could present a serious challenge for commercial MOX usage in terms of availability and cost of approved (Type-BF) packages and commercial carriers. However, reactor-grade MOX fuel is routinely transported in other countries, such as France, where the need is a reality rather than a future concern. In general, MOX transportation is conducted under governmental control per domestic laws and in accordance with national obligations under the Convention on the Physical Protection of Nuclear Material and the physical protection guidance provided in INFCIRC 225/Rev.4 (IAEA, 1980, 1999, 2003).

Introduction of fresh MOX fuel to a nuclear plant also brings additional security measures beyond those required for fresh UOX fuel, which would likely include changes to the security plan and staffing. The NRC Commission approved a final rulemaking on December 17, 2008, which establishes security requirements for reactor licensees using MOX fuel with less than 20 wt% PuO_2 consistent with those implemented for the 2005 LTA irradiation at Catawba. These measures are less onerous than called for in 10 CFR 73 for strategic special nuclear material (NRC, 2008b,e). Following irradiation, security requirements for spent MOX fuel are the same as those for spent UOX fuel.

3.3.7 Reversion to 100% UOX Cores

The modifications for MOX use are fully compatible with operations using a 100% UOX core. Should there be an interruption or shortfall in the availability of MOX fuel, the transition from a partial MOX core back to a full UOX core should not pose any technical or safety issues (DCS, 2002). The reactor modifications that are required to use MOX fuel are compatible with either reduced MOX fuel core fractions or all-LEU cores. Cores with reduced MOX fuel core fractions behave more like all-LEU cores, which are currently operating at the plants. Core fractions less than planned for equilibrium cores should be technically feasible.

3.3.8 Licensing Considerations for MOX Use

Regulatory compliance and licensing are significant but manageable challenges for implementing MOX fuel use on a commercial scale at reactors not explicitly designed and/or licensed for MOX fuel use (ORNL, 1997c,e,f; NRC, 1999). Except for the security ramifications of accepting and storing fresh MOX fuel onsite, the licensing process should be similar to that for any change in reactor fuel. Specific nuclear plant license amendments to the NRC would be required. Assuming that the fuel vendor will have received generic NRC approval of the MOX fuel design, significant effort in demonstrating performance of MOX fuel through a lead use assembly program may be necessary. An important challenge for MOX use in U.S. LWRs will be the development of methods and models acceptable to NRC for the evaluation of plant design basis for operation on partial MOX cores, particularly large and small break loss of coolant

accidents, reactivity insertion transients, and anticipated transients without scram. The NRC staff has expressed confidence in the feasibility of licensing commercial MOX use in the U.S. in light of the extensive European experience (NRC, 1999).

At the time of the active MOX testing programs in the 1970s, the NRC was preparing for the apparently impending initiation of commercial MOX implementation. The NRC issued NUREG-0002, Final Generic Environmental Statement on the Use of Recycle Plutonium in Mixed Oxide Fuel in Light Water Cooled Reactors, in August 1976 (NRC, 1976).

Although the physical characteristics of MOX fuel are very similar to that of UOX fuel, some important differences in nuclear characteristics can potentially impact core design and reload analysis as well as the core operational performance under transient and accident conditions. These impacts must be evaluated and addressed through the licensing process, as summarized below (ORNL, 1997b,c,e,f; NRC, 1999).

- MOX fuel will undergo a licensing process like any other change of fuel for a light water reactor. The licensing inputs are applied to provide demonstrations that both the impact of using MOX and mitigating system analyses will enable acceptable performance for the fuel, reactor, and associated systems. The nuclear characteristic differences between MOX and traditional UOX fuel can impact core design, reload analysis, and core performance with operational transients. The modified fuel and modified core design will require that the Technical Specifications and licensing basis be updated. These updates and other licensing considerations will be discussed in this section.
- In order to supply MOX fuel, it is expected that the fuel vendor would prepare and submit topical reports that address fuel assembly design and materials, MOX fuel design, fuel performance, and typical core performance and response. It is further expected that the fuel vendor would receive generic NRC approval for the MOX fuel design.
- A fuel rod design model could be applied to determine whether MOX utilization presents any un-reviewed safety questions, in accordance with 10CFR50.59, or changes to the operating license (NRC, 1986). It would be incumbent on the licensee to make these determinations.
- A lead test assembly program is used to validate MOX fuel performance evaluations from computer models. Consequently, the LTA program is the first step toward a MOX fuel cycle program. The LTA program requires Technical Specification and License amendment requests be prepared for submittal to the NRC.
- The Technical Specification amendment requests include the assessments of MOX fuel influence on the core operating limits, set point changes, and the spent fuel pool criticality analysis. These assessments will involve thermal-hydraulic and nuclear analyses and require development of methods and models to evaluate plant design bases for operation on a partial MOX core. The assessments include large and small break loss of coolant accidents (LOCAs), reactivity insertion transients, and anticipated transients without scram (ATWS). For the large and small break LOCA analyses, it will be necessary to have a LOCA licensing calculation capability.
- License amendment requests will be necessary to have Final Safety Analysis Report (FSAR) updates reviewed. The safety analyses will require that modified fuel and core designs be evaluated for normal reactor operation, transients, and whether accidents are mitigated or fall

under the reactors design basis. Fuel performance will be evaluated against licensing criteria for fuel rod clad cracking, rod bowing, and peaking factors. Similarly, core-reload analyses, source term calculations and fission product inventory evaluations are performed. Reactor kinetics computer models are used in safety analyses and can be modified for larger capture and fission cross sections for MOX fuel.

- The modified fuel and core designs must be evaluated to update the technical specifications and licensing bases and submitted as licensing amendments for U.S. NRC approval. Fuel thermal performance changes are evaluated against acceptance criteria for fuel rod clad cracking, rod bowing, and peaking factors. Core-reload analyses, source term calculations and fission product inventory evaluations are performed. The Technical Specifications and FSAR Sections are updated to document the design changes and bases as well as the accident analyses and mitigating system performance analyses. Specific FSAR chapters and analyses to address include:
  - Chapter 4 - Reactor
  - Chapters 5 and 6 - Emergency core cooling
  - Chapter 9 - Fuel pool cooling systems
  - Chapters 11 and 12 - Radioactive waste and radiation protection systems
  - Chapter 15 - Accident Analyses
  - Severe accident response (NUREG-1150) implications
  - Impacts on resolution of generic issues (NUREG-0933)
  - Impacts on Safeguards and Security for fresh MOX handling and storage
  - Impacts on D&D issues.
- For PWRs, the MOX core design characteristics compared to full UO2 cores warrant evaluation of the following design basis transient events (DOE, 1998):
  - Control assembly ejection
  - Uncontrolled boron dilution
  - Loss of forced reactor coolant flow
  - Loss of coolant accidents
  - Main steam line break
  - Anticipated transient without scram
- In addition to the Technical Specification and License amendment requests, justifications to the NRC are also necessary. For example, the plans for conducting post irradiation examinations of the lead element assembly that is intended to support transitioning to the equilibrium MOX fuel cycle will require NRC review. The post irradiation examinations are important in that they are used to confirm accurate computer model predictions of fuel performance.

- The plant physical security plan will need to be updated and reviewed by the NRC. The sections pertaining to the security of fuel receipt and storage will probably be modified as well as interfaces with the Department of Energy and state and local authorities. Similarly, updates will be required to the environmental assessment, which is intended to determine if there are significant increases in the amounts or changes to types of effluents that are released off-site. The licensee environmental evaluation is provided to the NRC, who authors an environmental evaluation as well.
- The MOX fuel cycle program follows a successful lead test assembly program with MOX fuel loads to an equilibrium quantity of fuel assemblies. The License and Technical Specification Amendment requests prepared for submittal to the NRC follow those prepared for the lead test assembly qualification. In addition the station must submit proposed revisions to the pressure, temperature, and limits report (PTLR) as well as demonstrate compliance with the dry fuel cask vendor's safety analysis.

As an example, MOX-related Licensing assessments and docketed licensing amendment correspondence specific supporting Duke Energy's MOX LTA testing campaign are presented in Appendix B, Table B-1, that ultimately led to irradiation of four MOX assemblies in Catawba Unit 1. These submittals also address part of the licensing changes needed to support the planned partial MOX core reloads.

3.3.9 Potential Conflicts between MOX Use and Power Uprates

Utilities have been using power uprates since the 1970s as a means to increase power output of nuclear plants. The power output increase is typically accomplished by using more highly enriched uranium and/or more fresh fuel in the core, resulting in greater core reactivity. This increase in reactivity, coupled with the inherent reduced reactivity control for a MOX fueled reactor, places a greater control burden on reactor control/shutdown systems and increases demands for maintenance of shutdown margin. Consequently, greater reactivity control requirements are levied for a MOX-fueled reactor with or undergoing a power uprate relative to a UOX fueled reactor (ORNL, 2004).

4
NEW (GENERATION III/III+) U.S. REACTOR FLEET

4.1 Overview of Anticipated Designs for New U.S. Reactor Fleet

In addition to the current U.S. reactor fleet, 17 combined construction and operating license (COL) applications have been received by NRC as of May 2009 representing a total of 26 new Generation III and III+ (GEN III/III+) designs. Table 4-1 summarizes the five GEN III/III+ designs under consideration by U.S. utilities: the GE designed Advanced Boiling Water Reactor (ABWR), the Westinghouse Advanced Passive 1000 (AP1000), AREVA's US-Evolutionary Power Reactor (US-EPR), Mitsubishi Heavy Industries' (MHI) US-Advanced Pressurized Water Reactor (USAPWR), and GE-Hitachi's Economic and Simplified Boiling Water Reactor (ESBWR) (NRC 2009b, WNA 2008d, NEI, 2009, NRC, 2008a,d). The ABWR, now marketed by General Electric-Hitachi (GEH) and Toshiba, is currently the only advanced LWR design in operation, with 4 units built in Japan.

Table 4 - 1
Generation III and III+ Reactor Designs (NRC, 2008a,d, 2009a,b; EIA, 2008b)

Generation	Design	Vendor	Output	Under NRC Review	Certified NRC Design
GEN III	ABWR	GEH	1300		✓
	US-APWR	MHI	1700	✓	
GEN III+	AP1000	Westing-house	1100	✓*	✓
	US-EPR	AREVA	1600	✓	
	ESBWR	GEH	1520	✓	

* The AP1000 has been NRC certified; however, Westinghouse is currently seeking to amend that certification.

The GEN III/III+ reactor designs generally offer standardized and simplified designs, higher availability, longer lifetimes, and expanded safety margins. Some also offer greater reliance on passive safety systems. The trend in new reactor designs is towards fuel flexibility. The European Utility Requirements explicitly call for all advanced LWRs operating in Europe to accommodate at least 50% MOX cores (EUR, 2001). The EPRI Utility Requirements Document calls on designers to consider reactor modifications required by foreseeable changes in fuel technology and fuel cycles that may prove difficult to retrofit (EPRI, 2009). While publicly available design information is limited, it is anticipated that all GEN III/III+ designs for the U.S. market will support high (50 – 100%) MOX core loads.

As shown in Table 4-2, GEN III/III+ reactors designs that are reported to accept MOX fuel include the Westinghouse AP-1000, the Areva NP European Pressurized Water Reactor (EPR), and GE's Advanced Boiling Water Reactor (ABWR) (MHI, 2007, WNA, 2008d, EPDC, 2007). In addition, full MOX core capability has been reported in the open literature for the ABWR, AP1000, US-EPR, and US-APWR designs (WNA, 2008d, AREVA, 2007a, GE, 1993, Ito et al., 1996, MHI, 2008, Matzie, and Worrall, 2004). Japanese plans include construction of an ABWR at Ohma for operation on 100% MOX cores (WNA, 2008a).

Table 4 - 2
Reported MOX Capability for Advanced Light Water Reactor Designs

Reactor	Reported MOX Capacity*	References
Westinghouse AP1000	High MOX core capacity up to 100% reported.	DOE, 1998 Demetri and Saiu, 2004 Matzie and Worrall, 2004 MHI, 2008 WNA, 2008d
Areva EPR	Flexible operation with UOX fuel and/or MOX fuel, including 100% MOX cores.	WNA, 2008d AREVA, 2007b
MHI APWR	Capacity to use MOX cores.	IET, 2008 MHI, 2007 Suzuki et al., 2008
GE ABWR	Designed to utilize full core loading of MOX fuel	Ito et al., 1996 GE, 1993 WNA, 2008a
GE ESBWR	Unknown	GE, 2005

*While vendor information, independent evaluations, and other information sources refer to MOX utilization in advanced LWRs, the reactor designs submitted for NRC approval for the U.S. market reference only the use of UOX cores.

4.2 Considerations for MOX Utilization in New U.S. Reactors

While GEN III/III+ reactors designs do not appear to be limiting with respect to high MOX core utilization, many of the same considerations for existing U.S. reactors will apply. Use of MOX in a new reactor will require NRC approval, either through the original operating license or via license amendment. And while the U.S. and international designs appear to accommodate MOX use, the final design selected for construction in the U.S. may introduce some challenges or limitations with respect to MOX use in the as-built plant. For example, sizing of a spent fuel pool for spent UOX fuel may lead to inadequate wet storage capacity for extensive MOX use due to the longer residence times required for cooling (EUR, 2001).

5
U.S. REACTOR FLEET READINESS FOR MOX FUEL SUMMARY

5.1 General Observations

There is considerable information available that indicates the maturity of MOX fuel technology and the feasibility of MOX fuel use in current and future U.S. reactors. General observations derived from review of the technical literature and discussions with experts from the utility, vendor, and government sectors include:

- Historically, the U.S. has had substantial experience with MOX fuel irradiation in PWRs and BWRs as part of LTA programs. Most recently, four WG MOX fuel assemblies were irradiated at Duke Energy's Catawba Unit 1 over two 18-month cycles spanning 2005 – 2008. MOX fuel performance was characterized as excellent. Assembly growth issues encountered during the test were not linked to MOX fuel use.
- MOX fuel performance is on par with UOX fuel. Historical MOX fuel concerns such as fission gas release are considered manageable. Demonstration of MOX fuel performance at higher burnups is essential for achieving parity of UOX fuel and optimizing core designs and improving commercial viability. In partial MOX cores, large thermal neutron flux gradients at MOX/UOX interfaces are problematic but can be addressed by varying the Pu content in the fuel rods located at the edge and corners of MOX assemblies.
- Evaluations of existing U.S. PWR and BWR reactor designs for MOX use conducted by vendors in support of the DOE Pu Disposition Program found that typical U.S. reactors should support partial MOX core loads (30 – 40%) with limited reactor modifications and some plants could conceivably support full core MOX loads with significant reactor and plant modifications.
- In light of the current and anticipated global supply of MOX fuel, the available reactor capacity for partial MOX core loading (30 – 40%) far exceeds any surplus MOX fuel supply in the global market anticipated for the near future. Consequently, feasibility of MOX use appears to be limited by the fuel supply, not the current reactor technology.
- As of May 2009, there were 17 COL applications submitted to NRC representing a total of 26 advanced LWRs slated for construction in the U.S. These Generation III/III+ reactors are expected to accommodate high MOX core capacities.
- Spent fuel reprocessing, MOX fuel production, and batch irradiation have been commercially implemented in Europe since the 1980s, and over 30 units operate with partial MOX cores (generally 30%). This successful European MOX experience provides a technical basis for the commercial use of MOX fuel in the U.S. reactor fleet. The NRC staff has previously indicated a favorable position on MOX use in light of the European MOX experience.

- Successful licensing of the MOX LTA testing program at Catawba Unit 1 and a large body of regulatory analyses performed in support of MOX feasibility studies indicate that the regulatory burden associated with MOX licensing is substantial but manageable.
- The U.S. DOE is currently constructing a MOX Fuel Fabrication Facility (MFFF) with a planned production of over 1700 MOX PWR fuel assemblies from WG Pu to be irradiated in commercial power reactors. MFFF construction delays have set MOX fuel production back to 2018 at the earliest, and the Duke Energy contract to irradiate a majority of the WG MOX fuel from the DOE program expired in 2008 and was not renewed as of May 2009. A 2008 solicitation seeks expression of interest in some or all of the MFFF output from interested U.S. utilities.
- Renewed interest in nuclear energy as a CO_2-free source of base-load electricity generation and recent shifts in U.S. policy suggest that Pu recycle in LWRs via MOX fuel irradiation may warrant consideration as a technology bridge to more advanced fuel cycles. In April 2008, the Tennessee Valley Authority (TVA) and the U.S. DOE signed a memorandum of understanding to support the demonstration of advanced fuel cycles. This work includes assessing the technical, regulatory and business challenges of MOX use in commercial reactors.
- Transportation of fresh MOX fuel, as a Category I strategic special nuclear material, requires substantial security measures above and beyond those for fresh UOX fuel shipments. While domestic shipments of fresh MOX fuel, such as the Catawba LTAs, that fall under a DOE program are managed exclusively by the DOE's secure transport program, and fresh MOX fuel transportation is generally under government control internationally. However, such options may not be available to U.S. utilities for the commercial transport of fresh RG MOX fuel that is not associated with a DOE mission or program. Spent MOX fuel security requirements are the same as for spent UOX fuel.

5.2 Existing U.S. Reactors

A review of the international MOX experience, extensive U.S. LTA irradiation history in PWRs and BWRs, and design specific reviews and analyses for U.S. reactors in support of the DOE Pu Disposition Program has revealed the following key factors and considerations related to MOX use in the current U.S. reactor fleet:

- Most if not all current reactors in U.S. are capable of accommodating some low MOX core fractions (< 30%) with minimal or no modifications and operational changes. Both PWR and BWR design classes are suitable candidates for MOX loading.
- No technical barriers have been identified that would preclude moderate MOX core loadings (30 – 40%) in at least half of the existing U.S. reactor fleet.
- High MOX core loadings (> 50%) generally require MOX-specific designs. Accordingly, retrofitting of the existing U.S. fleet for high MOX loading does not appear to be a feasible option, except for the three Palo Verde CE System 80 PWRs, which were explicitly designed for full MOX core loads.
- Amendment of reactor operating licenses for MOX use represents a substantial but manageable undertaking that requires demonstration of fuel performance, maintenance of

safety margins, and re-evaluation of plant design basis. Conversion to MOX use could complicate (or be complicated by) prior and future power uprates.

- Conversion to moderate MOX core loadings (30 – 40%) invariably requires additional reactivity control due to the hardening of neutron energy spectra, which leads to significant reductions in the effectiveness of neutron absorbing materials, including: control and shutdown rods, soluble boron, burnable absorbers, and xenon and other fission product poisons. The nature and extent of reactor system modifications can vary widely among and within plant designs to maintain adequate safety margins, most notably shutdown margins; accordingly, required changes must be evaluated on a plant/reactor/core specific basis. These reactivity control measures include the following considerations:
  - Enhancement of the borated water systems is universally recognized as a prerequisite for conversions to partial MOX cores, and can be accomplished through increases in boric acid concentrations, increases in injection rates for standby/emergency liquid control systems, and/or the use of enriched soluble boron. In light of corrosion and solubility concerns associated with high boric acid concentrations, use of enriched soluble boron is the preferred option for PWRs, in spite of the costs and boron recovery requirements, due to the reliance on soluble boron as a chemical shim in the reactor coolant water for core reactivity control throughout the irradiation cycle.
  - Decreased worth of control/shutdown rods in LWRs may also warrant use of higher worth rods, and if necessary and feasible, addition of control rods in PWRs.
  - Core design strategies can also be used to limit MOX impacts on core reactivity control. Common approaches include isolating MOX fuel relative to control rod locations in PWRs and limiting the number of MOX fuel assemblies assigned to each control blade in BWRs.
  - Introduction or increased use of burnable absorber materials in the core can also provide additional reactivity control to counteract the effects of MOX, especially at the beginning of cycle.
- Plant wide changes are also needed to address enhanced security requirements associated with fresh MOX fuel, increased radiation protection and shielding requirements, increased cooling capacity and periods for the core at shutdown and the spent fuel pool after discharge, and spent fuel criticality concerns.
- Hardening of neutron flux energies can exacerbate reactor vessel embrittlement; however, this impact can be mitigated or eliminated through core design and management.
- In terms of fuel flexibility and MOX supply concerns, plant and core modifications for MOX use do not negatively affect the ability to return to 100% UOX cores.

5.3 New U.S. Reactors (Generation III/III+)

Based on the review of available vendor information and the open literature, the following conclusions are drawn regarding the use of MOX fuel in advanced LWR designs comprising a new U.S. reactor fleet:

- All advanced LWR (GEN III/III+) designs, including those targeting the U.S. market, should accommodate high (50 – 100%) MOX core loadings.
- The general trend in utility requirements is toward fuel flexibility and the European Utility Requirements explicitly call for a 50% MOX core capability for new reactors built in the European Union.
- Full MOX core capacity is reported in the open literature for the GEH ABWR, the Westinghouse AP1000, the AREVA EPR, and the MHI APWR. However, information is limited regarding specific design capabilities regarding MOX loading and the differences between U.S. and international designs.
- MOX loading in advanced LWRs may also be restricted by plant-specific design aspects and modifications, such as spent fuel pool capacity.

5.4 Technology and Regulatory Gaps

While MOX fuel use in LWRs is a mature technology, a number of technical and regulatory areas can be identified that warrant further consideration and possible development or represent important challenges for the use of MOX fuel in the commercial U.S. LWR fleet. Three specific areas identified in this review are:

- Development of burnable poisons optimized for the higher neutron energies encountered in LWR MOX cores could improve the feasibility of commercial MOX use in the U.S. reactor fleet.
- Demonstration of MOX fuel performance for higher burnups followed by licensing of MOX fuel for parity with UOX fuel would improve core design flexibility in mixed MOX/UOX cores and would enhance commercial attractiveness of MOX fuel use. Lower MOX burnup limits (50 GWd/t for the Duke MOX LTA program at Catawba) relative to UOX fuel represents a major constraint for core management and fuel utilization, especially UOX fuel performance continues to improve and UOX burnup limits increase.
- Resolution of fresh MOX fuel transportation issues would greatly improve commercial prospects for MOX use in U.S. reactors. At present, the DOE Office of Secure Transport is the only option available for fresh MOX fuel transport, and this option may not be available to or cost effective for the transportation of RG MOX or any MOX material not owned by the U.S. Government or falling under a DOE program.

6
CONCLUSIONS

There is a substantial amount of experience with, and knowledge of, MOX irradiation in LWRs, both internationally and domestically in the U.S. While experience in the U.S. has been limited to demonstrations, the anticipated availability of WG MOX fuel from the DOE Pu disposition programs and possible recycling of RG Pu suggests that MOX loading into current and new U.S. reactors may become an option for the utility industry in the next 20 – 30 years. The principal technical issues associated with MOX use are reactivity control and maintenance of adequate shutdown margins. In addition, there are facility design and operational issues that must be addressed for the receipt, handling, and storage of fresh MOX fuel and for the management of spent MOX fuel at the backend due to higher heat loads, higher neutron dose rates, and reduced effectiveness of reactivity control measures. All of the issues identified over the course of five decades of MOX experience have been shown to be manageable from technical and licensing perspectives. MOX performance and reliability is on par with that of UOX fuel. Other associated concerns, including security and transportation are non-trivial, but have been addressed abroad, and in the U.S. on a limited basis for WG MOX LTAs under DOE auspices.

Given the substantial safety margins incorporated into LWR designs, most existing U.S. reactor designs can accommodate partial (30–40%) MOX fuel cores with relatively minor plant modifications and operational changes, setting aside other nontechnical considerations such as cost. The use of lower core fractions (< 30%) would likely obviate the need for most if not all modifications. Regulatory requirements associated with MOX fuel irradiation in U.S. LWRs, including revisions of the reactor design basis and operating license amendment, are substantial but manageable. Transportation of fresh MOX fuel, as Category I material, is one area that could present serious challenges for commercial MOX usage by U.S. utilities in terms of availability (and cost) of NRC-certified packages and domestic transportation options. Currently, DOE is the exclusive carrier for fresh MOX fuel shipments, as in the case of the Duke Energy LTA irradiation program at Catawba, but this option may not be available for fresh MOX fuel shipments not owned by DOE or not falling under a DOE-sponsored program. It is worth noting, however, that fresh RG MOX fuel transportation occurs routinely on a commercial basis.

Following an extensive review of the international MOX experience and knowledge base, EPRI has not identified substantial technical barriers to use of partial MOX fuel cores in a sizeable fraction of existing U.S. reactors. High MOX core loading capacities (50 – 100%) are anticipated for the advanced Generation III/III+ LWR designs, although site- and plant-specific features could constrain this flexibility. A limited supply of MOX fuel is currently available on the global market, and only incremental increases in this supply are expected over the next several decades. From a technical perspective, the use of MOX fuel in U.S. LWRs over the next 20–30 years appears to be supply, and not reactor, limited. The addition of Generation III/III+ reactors will further expand the capability of U.S. fleet to consume commercial quantities of MOX. Historical and ongoing experience with MOX fuel irradiation in LWRs worldwide provides a sound technical basis for consideration of commercial MOX use as a transitional step in the pursuit of more advanced fuel cycles in the United States.

7
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A
SUMMARY OF REACTOR DESIGN-SPECIFIC CONSIDERATIONS FOR WEAPONS-GRADE MOX USE

Table A - 1
GE Advanced Boiling Water Reactor Plant Design Considerations for Weapons-Grade MOX Use (GE, 1993)

System	MOX Related Issue	Design Feature
Core	MOX Core Fraction	ABWR initially designed for full MOX core capability.
Core	Partial MOX Core	MOX / UO2 Fuel Interchangeability ABWR Assembly Pitch larger water gap provides sufficient reactivity margin
Fuel Assembly	Interchangeability and high MOX Fuel loading	MOX rods can be located in center lattice area with UOX rods at periphery of the assembly to isolate MOX from control blades and fuel assembly interfaces
Spent Fuel Pool	Longer period for decay heat removal from MOX spent fuel than UO2 spent fuel	Addition of a secondary storage pool for discharged assemblies
Lead Test Assembly	Confirm performance of MOX fuel	A lead mixed-oxide bundle test is necessary to provide sufficient data to confirm MOX fuel performance analyses.

Table A - 2
ABB-CE PWR Design Considerations for Weapons-Grade MOX Use (CE, 1994)

System	MOX Related Issue	Design Feature
Core	MOX Core Fraction	System 80 reactors designed with full MOX core capability. Extra Control Rod Worth Greater decay heat removal capacity Increase soluble boron capacity Non-System 80 reactors could run with about a 1/3 MOX core fraction
Plant Cooling System	Increased decay heat	Increased heat removal capacity
Chemical and Volume Control System	Reduced soluble boron worth	Increase in maximum soluble boron concentrations
Safety Injection Systems	Reduced soluble boron worth	Increase in maximum soluble boron concentrations
Control Element Assemblies	Reduce CEA worth	Increased number of CEAs
Fresh Fuel Handling and Storage	MOX Gamma and Neutron source	Added shielding
Spent Fuel Storage	Lower discharge burnup and longer wet storage time Reactivity differences with UO2 fuel	Increase storage capacity
Radwaste System	Higher Tritium Production in reactor coolant	Add tritium removal system

Table A - 3
Four-Loop Westinghouse PWR Design Considerations for Weapons-Grade MOX Use (DOE, 1998)

MOX Loading	Parameter	Issue	Modification/Action
Partial WG-MOX Core	Power Peaking	Local power peaking due to neutron spectrum interface between LEU and MOX fuel assemblies	Reduced Pu content in MOX assembly outer fuel rods
	Reactivity Hold-down	Reduced boron reactivity worth	Wet annular burnable absorbers (WABAs) MOX not placed in control rod positions
	Soluble boron reactivity hold-down	Reduced boron reactivity worth	High Boron Concentration Or Enriched Boron
	Shut-down margin	Reduced control rod worth	MOX not placed in control rod positions Enriched boron or higher worth rods may be required
Full WG-MOX Core	Reactivity Hold-down	Reduced boron reactivity worth	WABAs Integral burnable absorber recommended
	Soluble boron reactivity hold-down	Reduced boron reactivity worth	Enriched Boron Required
	Shut-down margin	Reduced control rod worth	Enriched boron or higher worth rods required
Partial or Full WG-MOX Core	Accident Analyses	MOX Core Differences Reduced delayed neutron fraction More negative moderator temperature coefficient More negative Doppler coefficient Reduced control rod worth Reduced soluble boron worth Increased local power peaking	Transients considered RCCA ejection MSLB Loss of forced Rx flow Uncontrolled boron dilute ATWS Loss of Coolant Accidents No Safety Analysis Issues

MOX Loading	Parameter	Issue	Modification/Action
Partial or Full WG-MOX Core	Licensing	Changes to Technical Specifications	Generic MOX fuel license recommended. License Amendment Licensing basis Hazards analysis required Accident analysis Environmental impact Security Plan
		Fresh MOX Transport and Storage	Evaluate accident consequences

Table A - 4
DOE Mission Reactor Core Design Considerations for MOX Use (DCS, 2002)

System	MOX Related Issue	Modification
Reactor Core	Implement Partial MOX Core – address flux gradient between adjacent UO2 and MOX assemblies	MOX fuel located away from control rod locations Mark-BW/MOX1 17x17 fuel assembly with: central instrument tube 24 control rod guide tubes 264 fuel pins with 3 different Pu contents
Reactor Core	Reactivity Holddown	Integral burnable absorbers (IFBAs) and wet annular burnable absorbers (WABAs) in UOX assemblies Framatome ANP burnable poison rod assemblies (BPRAs) in MOX assemblies Vary boron content and number of burnable poison rods

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B
MOX-RELATED LICENSING INFORMATION FOR DUKE ENERGY REACTORS

Table B - 1
Publicly Available Information from NRC Docketed Submittals Related to MOX Use in Duke Energy's McGuire and Catawba Reactors

Date	Org	Title	Topics	Ref.
July 29, 2004	Duke Energy	McGuire Nuclear Station Units 1 and 2, Docket Numbers 50-369 and 50-370, Technical Specifications Amendment, Request for Additional Information (RAI); TS 3.7.15 - Spent Fuel Assembly Storage, and TS 4.3 – Fuel Storage	RAI Response	Duke Energy, 2004g
June 17, 2004	Duke Energy	Catawba Nuclear Station Units 1 & 2, Docket Nos. 50-413, 50-414 Proposed Amendments to the Facility Operating License and Technical Specifications to Allow Insertion of Mixed Oxide (MOX) Fuel Lead Assemblies (Next Generation Fuel - Response to Request for Additional Information)	RAI Response	Duke Energy, 2004f
May 13, 2004	Duke Energy	Catawba Nuclear Station Units 1 & 2, Docket, Nos. 50-413, 50-414 Proposed Amendments to the Facility Operating License and Technical Specifications to Allow Insertion of Mixed Oxide (MOX) Fuel Lead Assemblies (Correspondence Review),"		Duke Energy, 2004e
April 16, 2004	Duke Energy	Catawba Nuclear Station Units 1 & 2 Proposed Amendments to the FOL and Tech Specs to Allow Insertion of Mixed Oxide Fuel Lead Assemblies (MOX in Catawba 1 Cycle 16)	- Preliminary Core Design for Catawba 1, Cycle 16 - Comparison of Fuel Assembly Design Features (Proprietary) - Technical Basis for Validity of MOX Fuel Lead Assembly Application Analyses - Affidavit Proprietary Information	Duke Energy, 2004d
April 5, 2004	NRC	Safety Evaluation For Proposed Amendments To The Facility Operating License And		NRC, 2004a

Date	Org	Title	Topics	Ref.
		Technical Specifications To Allow Insertion Of Mixed Oxide Fuel Lead Assemblies		
April 5, 2004	NRC	Supplement 1 to Safety Evaluation for Proposed Amendments to the Facility Operating License and Technical Specifications to Allow Insertion of Mixed Oxide Fuel Lead Assemblies	- Request to the NRC for changes to the Catawba Nuclear Station, Units 1 and 2 operating license and physical security plan	NRC, 2004b
Mar 9, 2004	Duke Energy	Catawba Nuclear Station Units 1 & 2 Response to RAI, Mixed Oxide Fuel Lead Assemblies (Security)	RAI Response	Duke Energy, 2004c
March 1, 2004	Duke Energy	Catawba Nuclear Station Units 1 & 2, Docket Nos. 50-413, 50-414, Response to Request for Additional Information (TAC Nos. MB7863, MB7864), Mixed Oxide Fuel Lead Assemblies (Radiological)	RAI Response	Duke Energy, 2004b
Februar y 2, 2004	Duke Energy	Catawba Nuclear Station Units 1 & 2, Docket Nos. 50-413, 50-414, Response to Request for Additional Information (TAC Nos. MB7863, MB7864), Mixed Oxide Fuel Lead Assemblies (Environmental, Radiological and Materials),"	RAI Response	Duke Energy, 2004a
Dec 10, 2003	Duke Energy	Catawba Nuclear Station Units 1 & 2, Docket Nos. 50-413, 50-414 Response to Request for Additional Information dated November 21, 2003 Regarding Mixed Oxide Fuel Lead Assemblies	RAI Response	Duke Energy, 2003h
Nov 13, 2003	Duke Energy	NRC – Duke Energy – Framatome ANP Meeting Slides	REQUIRED REGULATORY APPROVALS - Duke Topical Reports for thermal-hydraulic and nuclear analysis - Framatome Topic Reports (fuel performance, fuel assembly design, MOX fuel design) - Duke license amendment request and exemption requests - Duke security plan changes and exemption requests - DOE export license application	Duke Energy, 2003g

Date	Org	Title	Topics	Ref.
			- Packing Technology transportation package certifications (powder and fuel assemblies) - Lead Assembly License Amendment RAIs	
Nov. 4, 2003	Duke Energy	Catawba Nuclear Station Units 1 and 2; Docket Nos. 50-413, 50-414 McGuire Nuclear Station Units 1 and 2; Docket Nos. 50-369, 50-370 Response to Request for Additional Information Regarding the Use of Mixed Oxide Lead Fuel Assemblies	RAI Response	Duke Energy, 2003f
Oct 3, 2003	Framatome	Catawba Nuclear Station and McGuire Nuclear Station, Partial Response to Request for Additional Information Regarding Use of Mixed Oxide Lead Fuel Assemblies	RAI Response	Framatome, 2003
Oct 1, 2003	Duke Energy	Catawba Nuclear Station Units 1 & 2, Docket Nos. 50-413, 50-414 McGuire Nuclear Station Units 1 & 2, Docket Nos. 50-369, 50-370 Response to Request for Additional Information Regarding the Use of Mixed Oxide Fuel Lead Assemblies	RAI Response	Duke Energy, 2003e
Sept 23, 2003	Duke Energy	Catawba Nuclear Station Units 1 & 2 McGuire Nuclear Station Units 1 & 2 Mixed Oxide Fuel Lead Assembly License Amendment Request	Reduces amendment request from both Catawba and McGuire to only Catawba since the LTA readiness will coincide with Catawba Unit 1 Cycle 16 refueling.	Duke Energy, 2003d
Sept 15, 2003	Duke Energy	McGuire Nuclear Station Units 1 & 2 Catawba Nuclear Station Units 1 & 2 Revision 16 to Duke Energy Corp Physical Security Plan and Request for Exemption from Certain Regulatory Requirements in 10 CFR 11 and 73 to Support MOX Fuel Use	- Revision 16 to the PSP - Description of overall regulatory framework and overview of the submittal. - Proposed security measures for MOX fuel - Lists 10 CFR part 73 requirement exemptions for NRC reactor facilities by the terms of Section 73.6 - Comparison of current and proposed security program to Sections 73.45 & 73.46 - Request for exemptions from select req in 10 CFR	Duke Energy, 2003c

Date	Org	Title	Topics	Ref.
			Parts 11 & 73 in connection with proposed future loading of MOX fuel at McGuire and Catawba	
August 13, 2003	NRC	William B. McGuire Nuclear Station, Units 1 And 2 And Catawba Nuclear Station, Units 1 And 2 Re: Mixed Oxide Lead Fuel Assemblies	RAI - Application For MOX Lead Test Assemblies	NRC, 2003
June 25, 2003	Duke Energy	Duke Energy Corporation, McGuire Nuclear Station, Units 1 and 2, Docket Nos. 50-369 and 50-370, License Amendment Request for Technical Specification 3.3.1, Reactor Trip System Instrumentation, and Technical Specification 4.2.1, Design Features, Fuel Assemblies	- Marked copy of the affected Tech Specs showing the proposed changes - Tech Spec with proposed changes incorporated. - Description of proposed changes and justifications. - No significant hazards consideration - Basis for categorical exclusion form performing an environmental assessment/impact statement.	Duke Energy, 2003b
Feb 27, 2003	Duke Energy	Catawba Nuclear Station Units 1 & 2 McGuire Nuclear Station Units 1 & 2 Proposed Amendments to the FOL and Tech Specs to Allow Insertion of MOX Fuel LTAs and Request for Exemption from Certain Regulation in 10 CFR Part 50	-McGuire Tech Spec Mark-up and Bases - Catawba Tech Spec Mark-up and Bases - Background info, discussion of each proposed change, and supporting tech info to justify the changes. - Duke's no significant hazards consideration analysis per 10 CFR 50.92 - Duke's assessment of environmental consequences of the proposed changes - Request for exemptions from selected NRC regulations in 10 CFR 50	Duke Energy, 2003a

References

Duke Energy, 2003a. "Catawba Nuclear Station Units 1 & 2, McGuire Nuclear Station Units 1 & 2, Proposed Amendments to the FOL and Tech Specs to Allow Insertion of MOX Fuel LTAs and Request for Exemption from Certain Regulation in 10 CFR Part 50." Duke Energy Letter to NRC: February 27, 2003.

Duke Energy, 2003b. "Duke Energy Corporation, McGuire Nuclear Station, Units 1 and 2, Docket Nos. 50-369 and 50-370, License Amendment Request for Technical Specification 3.3.1, Reactor Trip System Instrumentation, and Technical Specification 4.2.1, Design Features, Fuel Assemblies." Duke Energy Letter to NRC: June 25, 2003.

Duke Energy, 2003c. "McGuire Nuclear Station Units 1 & 2, Catawba Nuclear Station Units 1 & 2, Revision 16 to Duke Energy Corp. Physical Security Plan and Request for Exemption from Certain Regulatory Requirements in 10 CFR 11 and 73 to Support MOX Fuel Use." Duke Energy Letter to NRC: September 15, 2003.

Duke Energy, 2003d. "Catawba Nuclear Station Units 1 & 2, McGuire Nuclear Station Units 1 & 2, Mixed Oxide Fuel Lead Assembly License Amendment Request." Duke Energy Letter to NRC: September 23, 2003.

Duke Energy, 2003e. "Catawba Nuclear Station Units I & 2, Docket Nos. 50-413, 50-414, McGuire Nuclear Station Units 1 & 2, Docket Nos. 50-369, 50-370, Response to Request for Additional Information." Duke Energy Letter to NRC: October 1, 2003.

Duke Energy, 2003f. "Catawba Nuclear Station Units 1 and 2; Docket Nos. 50-413, 50-414, McGuire Nuclear Station Units 1 and 2; Docket Nos. 50-369, 50-370, Response to Request for Additional Information Regarding the Use of Mixed Oxide Lead Fuel Assemblies." Duke Energy Letter to NRC: November 4, 2003.

Duke Energy, 2003g. *NRC – Duke Energy – Framatome ANP Meeting Slides*. November 13, 2003.

Duke Energy, 2003h. "Catawba Nuclear Station Units 1 & 2, Docket Nos. 50-413, 50-414, Response to Request for Additional Information dated November 21, 2003, Regarding Mixed Oxide Fuel Lead Assemblies." Duke Energy Letter to NRC: December 10, 2003.

Duke Energy, 2004a. "Catawba Nuclear Station Units 1 & 2, Docket Nos. 50-413, 50-414, Response to Request for Additional Information (TAC Nos. MB7863, MB7864), Mixed Oxide Fuel Lead Assemblies (Environmental, Radiological and Materials)." Duke Energy Letter to NRC: February 2, 2004.

Duke Energy, 2004b. "Catawba Nuclear Station Units 1 & 2, Docket Nos. 50-413, 50-414, Response to Request for Additional Information (TAC Nos. MB7863, MB7864), Mixed Oxide Fuel Lead Assemblies (Radiological)." Duke Energy Letter to NRC: March 1, 2004.

Duke Energy, 2004c. “Catawba Nuclear Station Units 1 & 2, Response to RAI, Mixed Oxide Fuel Lead Assemblies (Security).” Duke Energy Letter to NRC: March 9, 2004.

Duke Energy, 2004d. “Catawba Nuclear Station Units 1 & 2, Proposed Amendments to the FOL and Tech Specs to Allow Insertion of Mixed Oxide Fuel Lead Assemblies (MOX in Catawba 1 Cycle 16).” Duke Energy Letter to NRC: April 16, 2004.

Duke Energy, 2004e. “Catawba Nuclear Station Units 1 & 2, Docket Nos. 50-413, 50-414, Proposed Amendments to the Facility Operating License and Technical Specifications to Allow Insertion of Mixed Oxide (MOX) Fuel Lead Assemblies (Correspondence Review).” Duke Energy Letter to NRC: May 13, 2004.

Duke Energy, 2004f. “Catawba Nuclear Station Units 1 & 2, Docket Nos. 50-413, 50-414, Proposed Amendments to the Facility Operating License and Technical Specifications to Allow Insertion of Mixed Oxide (MOX) Fuel Lead Assemblies (Next Generation Fuel - Response to Request for Additional Information).” Duke Energy Letter to NRC: June 17, 2004.

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