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UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

April 14, 1999

MEMORANDUM TO: Chairman Jackson
Commissioner Dicus
Commissioner Diaz
Commissioner McGaffigan
Commissioner Merrifield

FROM: William D. Travers
Executive Director for Operations

SUBJECT: MIXED-OXIDE FUEL USE IN COMMERCIAL LIGHT WATER REACTORS

In a Commission briefing on high-burnup fuel on March 25, 1997, the staff said that they would prepare a white paper on mixed-oxide (MOX) fuel in anticipation of a DOE program to burn excess weapons plutonium in commercial reactors. This memorandum and its attachment comprise that paper and are provided to inform the Commissioners of technical issues associated with such a program. More recently, on February 5, 1999, I was contacted by the Nuclear Control Institute regarding a paper they have written on this subject. They presented that paper to the staff in a public meeting on April 7, 1999. The Nuclear Control Institute's written paper had been provided to the staff earlier, and we have taken the paper into consideration in preparing this memorandum.

Background

In January 1997, the U.S. Department of Energy released a record of decision for the storage and disposition of weapons-usable fissile materials. In this record, DOE recommended that excess weapons-grade plutonium be disposed of by two methods: (1) reconstituting the plutonium into mixed-oxide (MOX) fuel rods and burning it in current light water reactors, and (2) immobilizing the plutonium in glass logs with appropriate radioactive isotopes to deter theft prior to geologic disposal. Based on current information, it now appears that, if the MOX fuel method is utilized, fuel fabrication will take place at the Savannah River site in South Carolina with burning in nearby Westinghouse-type PWRs. Although DOE will probably not receive funding in FY 2000 for developing a license application, Congress has already given its approval for NRC licensing authority over a MOX fuel fabrication facility operated under contract with DOE (PL 105-261, October 17, 1998).

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In the 1970s, the NRC investigated the environmental impact of using recycled MOX fuel in commercial LWRs. That study was documented as the *Final Generic Environmental Statement on the Use of Recycle Plutonium in Mixed Oxide Fuel in Light Water Cooled Reactors* (GESMO, NUREG-0002, 1976). Although results of that environmental study were favorable, licensing-type safety analyses were not performed. Some related test reactor programs and commercial reactor demonstrations were also carried out in the U.S. Shortly after the publication of GESMO, however, the U.S. abandoned plans for recycling plutonium although several other countries continued this approach.

Today, recycled (i.e., reactor-grade) MOX fuel is routinely used in Belgium, France, Germany, and Switzerland, and commercial use of MOX fuel is planned in Japan. Thus, technical and regulatory issues associated with reactor-grade MOX fuel utilization have been addressed in other countries. Nevertheless, there are recent questions in Europe and Japan about the possible effects of plutonium inhomogeneities on reactivity transients, and there are differences between weapons-grade MOX fuel and reactor-grade MOX fuel. Together, these raise key technical issues that need to be considered in order for NRC to be prepared to review the commercial use of MOX fuel. The relevant issues are described below, along with some indication of the preparation that would be needed, and additional details are given in the Attachment.

Discussion:

Weapons-grade MOX fuel has a different mix of plutonium isotopes than reactor-grade MOX fuel and this affects all the neutronic properties of the fuel. MOX fuel of any isotopic composition has physical properties that are somewhat different from UO_2 fuel and this affects the thermal and mechanical performance of the fuel rods. These differences affect fabrication, transportation, and storage of MOX fuel. The most important of these issues are discussed below.

- Control rod and absorber worths are reduced as a result of the higher thermal absorption cross sections of plutonium compared with uranium, and this can reduce reactor shut-down margin. Based on European experience, this effect can probably be accommodated without modification of the control systems by limiting the number of MOX fuel assemblies to about 30% of the core inventory.

- The coolant void coefficient of reactivity is less negative for MOX fuel than for UO_2 fuel. This is the result of larger fission cross sections at higher neutron energies and, hence, a need for less neutron moderation. Void coefficients can be kept in an acceptable range by limiting the concentration of plutonium in MOX fuel rods. Core designs expected in the weapons disposal program use relatively low concentrations of plutonium and therefore should not present a problem.

- The neutron energy spectrum is harder for the reason just mentioned, and higher neutron energies could enhance irradiation damage in the reactor pressure vessel. This effect can be managed with appropriate loading patterns that keep MOX assemblies away from the periphery of the core.

- Reactor kinetics computer codes used in safety analyses need to be modified for MOX fuel to account for the larger cross sections, changes in the energy dependence of the cross sections, smaller delayed neutron fraction, increased energy per fission, and other basic neutronic parameters that are altered by the plutonium isotopes in weapons-grade MOX fuel. Validated codes are necessary to deal with the neutronic issues mentioned above and other aspects of core design and safety analysis.

- For a given fuel rod power, MOX fuel rods operate with higher centerline temperatures because of the reduced thermal conductivity of the mixed oxides compared with UO_2. This will increase the initial fuel rod stored energy for a loss-of-coolant accident and could result in the need for reduced power limits for MOX assemblies. Higher temperatures also increase gas release from fuel pellets and, hence, the fission product gap inventory. The related gap activity may impact some offsite dose calculations.

- Inhomogeneities (plutonium clusters) in MOX fuel may affect fuel behavior during reactivity accidents, especially at high burnups. This could necessitate the modification of fuel damage criteria in Regulatory Guide 1.77 (Assumptions used for Evaluating a Control Rod Ejection Accident for PWRs). If there are any burnup limits for MOX fuel that are different from UO_2 fuel, they would probably be related to this event. This is an issue that has not been resolved in Europe and appears to be the only issue that might require new experimental data for MOX fuel.

- Plutonium from nuclear weapons contains some gallium. While the normal fabrication process will reduce the amount to part-per-million levels, its effects on fuel and cladding behavior have not yet been fully assessed. DOE is performing experimental studies at this time, and the effects of this impurity will have to be considered in any licensing assessment.

- Fuel rod computer codes used in safety analyses will have to be modified for MOX fuel to account for altered physical properties such as thermal conductivity, thermal expansion, and creep rates. Validated codes are necessary to deal with the fuel behavior issues mentioned above and other aspects of fuel design and safety analysis.

- Fission product and actinide concentrations are somewhat different in MOX fuel and UO_2 fuel, and this could affect the potential consequences of a severe accident. However, it is not likely that severe accident progression, insofar as we understand it, would be different or that source terms (fractions) would be altered. Therefore consequence analyses, rather than full probabilistic risk assessments, may be sufficient to assess the changes due to the different inventory of radionuclides.

- Criticality analysis will be altered for MOX fuel fabrication, transportation, and storage because of the different isotopes and material forms. Criticality data will have to be obtained so that methods can be revised to support the required analysis.

- For cooling times of one year or greater, the decay heat is higher for MOX fuel because of its larger inventory of actinides. This higher decay heat will have to be accommodated by the design of spent fuel storage and transportation casks.

It can be noted that, in the paper by the Nuclear Control Institute, the main body of work addressed the higher content of transuranic elements in mixed-oxide fuel and the health consequences these might have in the event of beyond-design-basis severe accidents. Increases of about 32% were found in latent cancer fatalities for MOX cores being considered in comparison with uranium-based cores. The NRC staff has not performed similar calculations and therefore was not in a position to comment on these results. However, statements about greater vulnerability to reactivity insertions and pressurized-thermal shock of the reactor vessel were questioned by the staff. The issues described by the Nuclear Control Institute have all been identified in the above list and discussed further in the attachment as appropriate.

Conclusion:

Experience in Europe with the technical and regulatory issues of using MOX fuel suggests that these issues can be resolved here as well. Nevertheless, the NRC and the U.S. industry must also deal with these issues, and some of the technical issues will be unique because of the difference between weapons-grade MOX fuel and the reactor-grade MOX fuel being used elsewhere. Resources for MOX activities have not been included in the FY 2000 budget. However, there are technical areas that need relatively long lead times (3-5 years) for resolution. In one of these areas concerning plutonium inhomogeneities and their effects on reactivity accidents, the staff intends to initiate discussions with DOE regarding research programs on which we might cooperate. The staff will develop a plan for addressing the MOX issues, and the plan will be sufficiently complete in time to consider extra funding needs in the FY 2001-2002 budget. We will advise the Commissioners of significant developments related to these activities.

Attachment:
Mixed-Oxide Fuel Use in Commercial Light Water Reactors

Note: This memorandum and its attachment were originally drafted in RES by Undine Shoop, who is now in NRR.

cc: SECY
OCA
OGC
OPA
CFO
CIO
ACRS

ATTACHMENT

MIXED-OXIDE FUEL USE IN COMMERCIAL LIGHT WATER REACTORS

INTRODUCTION

In January 1997, the U.S. Department of Energy released a record of decision for the storage and disposition of weapons-usable fissile materials. In this record, DOE recommended that excess weapons-grade plutonium be disposed of by two methods: first, reconstituting the plutonium into mixed-oxide (MOX) fuel rods and burning it in current light water reactors, and second, immobilizing the plutonium in glass logs with appropriate radioactive isotopes to deter theft prior to geologic disposal. Based on current information, it now appears that, if the MOX fuel method is utilized, fuel fabrication will take place at the Savannah River site in South Carolina with burning in nearby Westinghouse-type PWRs. Although DOE may not begin developing a license application right away, Congressional approval has already been given for NRC facility regulation and a number of issues will eventually need to be considered.

This paper provides an overview of the technical issues associated with the use of MOX fuel in light water reactors. The majority of relevant U.S. experience is from experiments that were performed during the time when reprocessing was considered an option for the future. These experiments are described below. Additionally, the experience from other countries, which continue to pursue the use of MOX fuel, is highlighted, including the lessons learned and experimental results gained from their programs. The basics of plutonium are discussed and the differences between uranium-based fuel and MOX fuel are described. The specific issues that will need to be considered prior to the fabrication and use of weapons-grade plutonium in U.S. reactors are also discussed.

BACKGROUND

In the beginning of the U.S. nuclear reactor program, it was anticipated that the fuel cycle would be closed by reprocessing spent fuel to recover the usable plutonium and uranium for use as MOX fuel in thermal or fast reactors. Spent fuel reprocessing would perform the dual function of recycling the fissile isotopes that have enough energy to be reused and reducing the long-lived actinides by incorporating them into the MOX fuel and burning them in a reactor. This would significantly reduce the decay time for the remaining wastes. Programs to determine the economic and practical feasibility of using MOX fuel were developed to obtain a practical MOX fabrication process and reactor implementation method. In the early 1970's, the major obstacles to plutonium recycle were thought to be solved; therefore, testing programs began to be phased out while a reprocessing plant at Barnwell started the licensing process and was partially constructed. To study the environmental impact of using MOX fuel, NRC continued developing the Final Generic Environmental Statement on the Use of Recycle Plutonium in Mixed Oxide Fuel in Light Water Cooled Reactors (GESMO, NUREG-0002, 1976) that had been started by its predecessor, the U.S. Atomic Energy Commission.

On April 7, 1977, the U.S. announced a decision to defer indefinitely the commercial reprocessing and recycling of the plutonium. France, Belgium, the United Kingdom, Germany, and Japan all continued to pursue the recycle option, and routine burning of MOX fuel is now carried out in most of those countries.

The use of plutonium to fuel commercial reactors in the U.S. is again being considered following the 1994 U.S. agreement with Russia to reduce the inventory of fissile material from nuclear weapons. To evaluate the desirability of utilizing weapons-grade plutonium in U.S. LWRs will require revisiting previous information and investigating new MOX technologies that have been developed and used in other countries.

Basics of Plutonium

Plutonium is the 94th element of the periodic table and is composed of more than a dozen different isotopes. It exists in extremely limited quantities in nature; therefore, most of the world's current inventory of plutonium has been created by man. The isotope with the mass number 239 is the easiest to produce and the most useful for nuclear chain reactions. Pu-239 is produced by neutron capture in U-238, the most abundant uranium isotope. Because current reactor fuel contains large quantities of U-238, this conversion process occurs over the lifetime of the fuel in thermal reactors, providing a self-generating fuel source. Plutonium-239 is a radioactive isotope which decays primarily by alpha emission. It has a half-life of 24,100 years. Five other plutonium isotopes have half lives greater than 10 years, with the longest being 80,000,000 years for the naturally occurring Pu-244.

Differences between weapons-grade plutonium and reactor-grade plutonium

The primary difference between reactor-grade plutonium and weapons-grade plutonium is the isotopic composition. Reactor-grade plutonium is created by irradiating normal LWR uranium-based fuel and then reprocessing the spent fuel at the end of its life to extract the plutonium isotopes. Weapons-grade plutonium is created by irradiating U-238 to an optimally low burnup and then separating the isotopes to produce a different isotopic mixture. DOE defines the different plutonium grades by the amount of plutonium-240 that the mixture contains because the most desirable plutonium mixture would be composed of only the odd-numbered fissile isotopes. Weapons-grade plutonium, which is the most purified of the grades, contains less than 7% Pu-240, followed by fuel-grade plutonium with 7-19% Pu-240, and the least purified reactor-grade plutonium with greater than 19% Pu-240. Table A gives typical concentrations of the most abundant plutonium isotopes. For the purposes of this paper, all grades containing more than 7% Pu-240 will be called reactor-grade plutonium.

Table A. Typical isotopic composition of weapons-grade and reactor-grade plutonium (wt%)

Isotope	Weapons grade	Reactor grade
Pu-238	0.05	1.0
Pu-239	94.3	59.0
Pu-240	5.0	24.0
Pu-241	0.6	11.0
Pu-242	0.05	5.0

There are several practical differences between reactor-grade and weapons-grade MOX fuel. Weapons-grade plutonium, with its higher Pu-239 content, creates a harder neutron spectrum. It is also expected that the weapons-grade MOX fuel will contain up to 7 wt% plutonium, whereas the European reactor-grade MOX fuel has approximately 4 wt% plutonium. These differences will have to be taken into account.

In addition to the different isotopic compositions, weapons-grade MOX fuel will have traces of gallium that might react with zirconium alloy cladding. Gallium was added to the weapons-grade plutonium to act as a stabilizer for the plutonium metal used in the production of nuclear weapons. This element can be removed chemically, but this is an expensive process; thus, weapons-grade MOX fuel may contain some gallium.

Differences between MOX and Uranium-based fuel

Table B shows approximate isotopic compositions at the beginning of life and the end of life for a typical uranium-based fuel and a comparable low enrichment weapons-grade MOX fuel. The values shown are for illustration only as actual amounts will vary depending on the particular core design and power history, but the general trend is clear. Both fuels contain a lot of U-238, but the uranium-based fuel has no plutonium isotopes at the beginning of life (BOL) and less of the plutonium isotopes at the end of life (EOL).

Table B. Approximate isotopic composition of a uranium-based fuel and a MOX fuel (wt%)

Isotope	BOL U-Fuel	EOL U-Fuel[a]	BOL MOX-Fuel	EOL MOX-Fuel[a]
U-235	3.25	0.72	0.19	0.06
U-238	96.75	94.0	96.3	94.1
Pu-239	--	0.56	3.31	1.0
Pu-240	--	0.23	0.176	0.40
Pu-241	--	0.11	0.021	0.30
Other Pu Isotopes	--	0.07	0.003	0.14
Other Nuclides	--	4.31	--	4.0

[a]Burnup of 37.6 MWd/kg used for this example

The isotopic compositions of the two fuel types produce different cross section parameters, which impact the characteristics of the reactor core. Plutonium has a higher thermal absorption cross section than uranium, and this reduces the reactivity worth of the control blades, burnable poisons, and liquid absorbers used to control the reactor. The reduction is caused by competition for neutrons between the fuel and the absorber materials. The greater absorption in plutonium results in less neutron absorption by the absorber materials in a core with MOX fuel. The fission cross sections of the two fuels also differ. MOX fuel has a higher fission cross section, which means that, of the neutrons absorbed in the fuel, a greater percentage result in fissions. The higher fission cross sections of the MOX fuel create more flux depression across a fuel assembly from self shielding, and they cause power peaks when MOX fuel rods are close

to UO_2 fuel rods. These changes in cross sections have to be accommodated in core design.

Added to the cross section effects are other nuclear characteristics that change core behavior. One is the lower delayed neutron fraction (beta) of MOX fuel. The beta value gives the percentage of neutrons released after fission from the decay of fission products. These neutrons make it possible to control the reaction during normal operation and transient conditions, and the lower beta value makes reactor control more difficult. Another significant neutronic effect is the harder neutron spectrum produced by MOX fuel. That is, there are more high energy neutrons in a core with MOX fuel than with uranium-based fuel. This harder spectrum results in more U-238 reactions since U-238 is a high energy absorber. The harder spectrum can also increase the vessel fluence depending on the fuel management techniques used in the core reload. However, the reactivity of MOX fuel decreases at a slower rate with burnup in comparison to uranium-based fuel such that less excess reactivity is needed for MOX fuel at the beginning of core life. Finally, the energy released per fission is slightly higher for MOX fuel, and the decay heat, which is smaller at first, becomes larger after one year compared with irradiated UO_2 fuel. All of these factors have to be taken into account in core design and safety analyses.

The two fuel types differ in material properties as well. The thermal conductivity of MOX fuel is approximately 10% lower than standard UO_2 fuel. Thus, for a given fuel rod power, MOX fuel pellets will operate at somewhat higher temperatures during normal operation. This will have an effect on the initial conditions for loss-of-coolant accidents. It will also increase fission gas release during normal operation, and this will affect the radionuclide inventory in the pellet-to-cladding gap, the fuel rod internal pressure, and the thermal conductivity of the gap (i.e., the gap conductance). Fresh MOX fuel has a fuel melting temperature that is about 10 °C lower than uranium-based fuel. Fuel melting is not approached during normal operation or design-basis accidents, but this might have some effect on severe accidents. The thermal expansion coefficient of MOX fuel is approximately 1% higher than that for uranium-based fuel and this would increase the pellet-to-cladding mechanical interaction (PCMI). However, MOX fuel pellets have a higher creep rate than UO_2, which would tend to decrease PCMI because the porous pellet can be compressed.

Finally, MOX pellets are usually fabricated by mechanically blending UO_2 and PuO_2 powders, then pressing and sintering them. This results in a ceramic that is not homogeneous on a microscopic scale, and the little islands of high plutonium concentration act as hot spots because of their high fissile content. This may affect the behavior of the pellets during reactivity transients. Technical issues related to these differences between MOX fuel and uranium-based fuel are discussed later in this paper.

PREVIOUS U.S. STUDIES AND RESEARCH ON MOX FUEL

Previous efforts focused primarily on recycled thermal reactor spent fuel to investigate the feasibility of using MOX fuel in thermal and fast reactors. It was originally envisioned that the fuel cycle would be closed by reprocessing the spent fuel, thus reducing the amount of high-level waste, burning the long-lived actinides, and recovering the usable energy left after discharge from the reactors. Thus, fuel performance and characteristics of reactor-grade MOX fuel have been rather extensively explored and documented in previous U.S. efforts. Most of the tests were eventually phased out because it was believed that the feasibility of using MOX

fuel in reactors had been demonstrated, and other tests were ended following the decision that MOX fuel would not be used in the U.S. The following is a brief overview of some of the programs sponsored by the AEC, the NRC, and EPRI to investigate the feasibility of using MOX fuel.

Saxton

The Saxton Plutonium project was conducted by Westinghouse Electric Company for the AEC in the mid 1960's. It was the first plutonium fuel project; therefore, the basic characteristics of MOX fuel were hypothesized from the plutonium elemental characteristics but had not been verified by actual reactor irradiation when the program was initiated. The purpose of the program was to develop basic information about the use of plutonium fuel in a standard PWR including the fuel performance characteristics and irradiation-induced behavior.

The program consisted of two phases. The first phase was to develop methods of fuel fabrication and design, perform critical experiments and power operations, and then conduct post-irradiation examinations of the fuel. The second phase of the program was to irradiate the fuel to higher burnup levels to evaluate the feasibility of utilizing reprocessing and MOX fuel to close the fuel cycle.

The Saxton PWR reactor core consisted of 21 fuel assemblies of which the center nine were composed of MOX fuel, which had an isotopic composition similar to weapons-grade plutonium. The remaining surrounding fuel assemblies were of standard uranium-based fuel. For the program's first phase, the MOX fuel assemblies were constructed of fuel rods that contained a similar isotopic composition and burnup, while in the program's second phase the fuel assemblies were constructed of fuel rods with various burnups.

These post-irradiation tests provided the first glimpse of the characteristics of irradiated MOX fuel. It was found that the diameter of the fuel rods decreased after irradiation, although the change in length was negligible. Examination of the fuel pellets showed that fuel restructuring phenomena was limited, pellet-to-cladding mechanical interaction (PCMI) was absent in all MOX fuel pins, and densification of MOX fuel occurred under irradiation. The observations indicated that the overall performance of the MOX fuel tested under the operating conditions of the Saxton PWR was similar to that of UO_2 fuel and was satisfactory.

Plutonium Recycle Test Reactor (PRTR)

The PRTR was utilized as the irradiation facility for the Plutonium Utilization Program conducted by Pacific Northwest Laboratory for the AEC. The purpose of the study was to develop technologies for the use of plutonium in commercial reactors. The test facility was used to irradiate various mixed-oxide fuel types under steady-state conditions to determine which fuel types provide the best performance and the greatest economic advantage. The tests were performed at high linear heat generation rates and progressed to burnups greater than 18 MWd/kg to capture effects over a wide range of operating conditions. Following irradiation, post-irradiation tests were conducted to assess the fuel's performance.

The fuel types differed by the methods of preparation, which included vibrationally compacted particles, compacted and swaged particles, hot-pressed pellets, and cold-pressed-and-sintered pellets. During fabrication, some cladding defects were intentionally incorporated into some

fuel elements. These intentionally defective fuel elements, along with other unintentional defects, provided an opportunity to observe the consequences of MOX fuel defects under operating conditions. Fuel assessment was completed with post-irradiation measurements. Those measurements included visual inspections, dimensional changes, gamma scans, fission gas release, fuel and cladding microscopy, and burnup analysis. The PRTR program concluded that these mixed-oxide fuel types performed well throughout the range of steady-state operating conditions, even when defects were present.

GESMO

The Generic Environmental Statement on the Use of Recycle Plutonium in Mixed Oxide Fuel in Light Water Cooled Reactors (GESMO) project was started in 1974 by the AEC to explore the scope, health, safety, and environmental impacts of widespread use of MOX fuel in U.S. reactors. The final GESMO report was published in 1976 as NUREG-0002. The safeguards portion of the GESMO report was superseded in 1978 by NUREG-0414, which focused exclusively on the safeguarding of reactor recycle plutonium MOX fuel against a domestic threat. The GESMO program was indefinitely postponed before public comments and an ongoing hearing were completed. It was halted following the decision that the U.S. would not pursue recycling of any spent fuel generated within the U.S.

The GESMO program concluded that the most favorable option for the treatment of spent fuel, after a cost-benefit analysis of six different options including no recycle, was the full recycle option. When the health effects attributed to the recycle of MOX fuel were assessed, this program concluded that the recycle option would not significantly increase the health effects compared with the no-recycle option. This assessment included the analysis of particle sizes of MOX fuel following a transportation accident and the determination that the particles would be too large to be inhaled. Thus it was concluded that transportation accidents would not increase the threat of plutonium toxicity from inhalation. It was further observed that the nonradiological impacts were lower for the recycle option than the no-recycle option. On the basis on these findings, the GESMO report recommended that the recycle of plutonium and uranium from spent fuel and subsequent use of MOX fuel should be pursued.

EPRI Tests

The Electric Power Research Institute (EPRI) conducted a number of MOX fuel experiments in operating commercial reactors after the feasibility of using MOX fuel had been established. In-core irradiations were performed to increase the experience with MOX fuel and determine the methodologies needed to assess MOX fuel. For these tests, MOX fuel assemblies were loaded into selected cores at Quad Cities, San Onofre, and Big Rock Point. After irradiation, the fuel assemblies and individual fuel rods were examined and the isotopic compositions of the fuel were measured. After assessing the in-core performance of these test assemblies, it was concluded that MOX fuel performance was similar to uranium-based fuel performance in commercial LWRs, though some differences between the two types were observed. The significant differences noted between the two fuel types included reactivity effects, which decrease reactor control, and a higher decay heat at long cooling times with MOX fuel.

EPRI also sponsored a study at Pacific Northwest Laboratory to investigate the densification behavior of mechanically blended MOX fuel. The study also looked at thermal resintering, irradiation effects on the MOX fuel structure, and inter-diffusion of uranium and plutonium

(homogeneity). The project consisted of pellet fabrication, pre-irradiation pellet characterization, resintering tests, irradiation in the General Electric Test Reactor (GETR), and detailed post-irradiation examination. The study concluded that MOX fuel shows similar densification behavior to that observed in uranium-based fuels, and that the presence of plutonium up to about 6 wt% and particle size up to 500 microns did not affect the physical behavior of the fuel.

EXPERIENCE WITH MOX FUEL

Some countries continue to pursue a closed fuel cycle utilizing reprocessed spent fuel. The experience they have gained from the use of MOX fuel in their commercial reactors and from tests performed with MOX fuel provides additional information on the characteristics and behavior of reactor-grade MOX fuel.

Current use and fabrication of MOX fuel

Belgium was the first country to pursue the plutonium recycle option beginning in 1963 with the loading of 12 MOX fuel rods into the BR3 reactor, an 11 MWe PWR. To produce the fuel needed for this reactor, in which the MOX fraction was progressively increased to 48% and for other reactors projected to begin using MOX fuel, Belgonucleaire built the Dessel fabrication plant, known as DEMOX. This plant was the first commercial fabrication facility in the world and continues to be the world leader in MOX fuel fabrication. In 1988, when France decided to pursue the MOX fuel option in their PWRs, they contracted the DEMOX plant to provide the fuel fabrication. To facilitate the reprocessing of spent fuel into new MOX fuel pellets, the Belgians pioneered a new method of blending the MOX fuel powder called the MIMAS process. This process improved the method of incorporating the plutonium into the uranium matrix which provides better fuel characteristics and chemical separation of the fuel during reprocessing. This method is currently the industry standard for MOX fuel powder blending. Since 1995, MOX fuel has been used in 2 Belgian PWRs.

Considering the increasing delays in development of the fast breeder reactor in France, Electricité de France (EdF) decided to start recycling MOX fuel in PWRs in 1985. Of the 54 PWRs in France, 16 are now loaded with MOX fuel and more will be loaded in the future. Spent fuel is reprocessed at La Hague, now the largest reprocessing plant in the world, and the fissile material is fabricated into fuel rods in a Cogema facility at Cadarache and the Melox plant at Marcoule. To accommodate the reactivity effects and decreased shutdown margin incurred from using MOX fuel, the French have limited the reactor core loading of MOX fuel to 30%, added an additional four control rod assemblies to each core, and increased the amount of boron in the reactor water storage tank and boron makeup tank. To reduce localized power peaking and improve reactor control of a MOX-fueled core, the French try to avoid loading MOX assemblies in control rod locations and use a scatter-load fuel management technique.

The United Kingdom began experimenting with the use of MOX fuel in the 1960's. British Nuclear Fuels Limited (BNFL) began production of MOX fuel in 1963. Initially, the United Kingdom explored the use of MOX fuel in their advanced gas reactors (AGRs), but later redirected their efforts to the use of MOX fuel in fast reactors. There is no MOX fuel in the British LWR at the present time. BNFL initially built a small production facility, which has been recently supplemented with the newly constructed Sellafield facility. The fabrication facility at Sellafield is adjacent to a reprocessing facility which minimizes the transportation of

reprocessed plutonium.

Germany is currently using MOX fuel in more than a dozen of its 20 LWRs. Initially, Germany reprocessed its spent fuel at a reprocessing facility in Hanau, which produced all the MOX fuel assemblies for the German recycle program. That facility was closed in 1991 and current MOX fuel is produced in the Cadarache plant in France. Switzerland also uses MOX fuel in three of its five nuclear power plants.

Japan began looking into the reprocessing of spent fuel in 1979 with a focus on using recycled fuel in their Advanced Thermal Reactor (ATR), which is a heavy-water-moderated, light-water-cooled boiling reactor. To date, more than 670 MOX fuel assemblies have been irradiated in the Fugen ATR. Full scale utilization of MOX will be started soon in Japan's LWRs, and safety reviews are currently underway. Japan does not currently have its own reprocessing facility and must rely on reprocessing and fabrication in other countries; however, a reprocessing plant is currently under construction in Japan and will become operational in the year 2000.

CURRENT RESEARCH ON MOX FUEL

Because a number of countries are using reprocessed spent fuel, related test programs are being conducted at several laboratories. These programs have investigated physical and neutronic characteristics of MOX fuel along with its operational performance. A brief synopsis of these programs and their findings is given in this section.

Halden

The Halden Project in Norway is an undertaking of national organizations in 19 countries sponsoring jointly financed research. Tests in the Halden reactor are designed to provide basic data on how fuel performs in commercial reactors, both under normal operating and transient conditions, with emphasis on extended fuel utilization. In a 1995 Halden Project report, Turnbull reviewed MOX fuel properties measured in various programs in Europe, including measurements in the Halden reactor itself. Significant conclusions were (a) for a given linear heat generation rate, centerline temperature in MOX fuel is slightly higher (~40°C) than in UO_2 fuel as a consequence of reduced thermal conductivity, (b) there is no evidence that fission gas release from MOX fuel is any worse than from UO_2 fuel except as a result of temperature differences, and (c) MOX fuel has a greater resistance to failure from pellet-cladding mechanical interaction (PCMI) than UO_2 fuel because the creep rate of MOX fuel pellets is greater. Because of a need of participating regulatory bodies for qualifying models and codes, the Halden Project initiated new tests on MOX fuel in 1998. MOX fuel rod segments with burnups as high as 78 MWd/kg are being tested to generate data on thermal properties, fission gas release, and PCMI.

Cabri

The Cabri test reactor in France is operated by the Institute for Protection and Nuclear Safety (IPSN) and is used to test nuclear fuel rods under reactivity-initiated accident (RIA) conditions. The facility currently uses a sodium-coolant test loop instead of a water loop, which would be more representative of PWR designs. Studies of highly irradiated UO_2 and MOX fuels were begun in 1993. Seven tests have been completed with UO_2 fuel and three with MOX fuel. One

of the three MOX fuel tests experienced cladding failure (the MOX rod with the highest burnup). While this rod failed at a somewhat higher energy than high-burnup UO_2 rods, fuel dispersal from the failed rod and sodium ejection from the vicinity of the rod were more pronounced than with the UO_2 rods. It is believed that the softer pellets and enhanced fission gas release from the high concentration Pu agglomerates caused the MOX fuel to behave differently from the UO_2 fuel under these conditions. IPSN plans to replace the sodium loop with a water loop to more accurately simulate PWR core conditions. Additional tests are planned with very high-burnup UO_2 fuel and MOX fuel in this facility.

NSRR

The Nuclear Safety Research Reactor (NSRR) of the Japan Atomic Energy Research Institute (JAERI) is being used to investigate the behavior of fuel rods under RIA conditions. Studies to determine the behavior of fresh MOX fuel were initially performed to provide baseline information. These initial tests repeated the conditions of previous tests performed with uranium-based fuel. It was found that the cladding failure mechanism and threshold for fresh MOX fuel were consistent with those for fresh UO_2 fuel and that an effect of plutonium particles (inhomogeneities) was not detected. More recently, JAERI has tested four irradiated MOX fuel rods (20 MWd/kg). Up to the limits of energy deposition tested to date (140 cal/g fuel enthalpy), no cladding failures have occurred in these relatively low-burnup specimens. However, the NSRR tests with irradiated MOX have shown higher fission gas release and larger fuel swelling compared with UO_2 fuel (in agreement with Cabri results), indicating the existence of MOX effects for RIAs.

Current Studies

The OECD/NEA Nuclear Science Committee set up a working group to study the current status and nuclear effects of recycling plutonium. These studies were undertaken by gathering operational and research information into a collective work and performing benchmark studies to augment the information. The information gathered was published as a series titled the *Physics of Plutonium Recycling*.

One benchmark study of particular interest is a study on the effect of increasing the (reactor grade) plutonium concentration in each fuel rod and the resulting effect on the void coefficient. It was expected that, at some higher concentration of plutonium, the void coefficient might become positive. As the moderator density decreases, the fission neutrons are not slowed down as much. Pu-239 becomes more efficient as a fission source when there are more neutrons in the low epithermal resonance region and at high energies, in contrast to uranium which becomes less efficient. Hence, a loss of coolant would increase core reactivity or equivalently, the void coefficient of reactivity would become positive when there is a high Pu-239 content.

The participants in the study utilized various computer codes to predict the resultant void coefficient, and the results were compared to the reference solution that was generated by a continuous energy Monte Carlo calculation. The results of the benchmark demonstrated that the void coefficient of MOX fuel becomes positive between 9.7 and 14.4 wt% loading in each fuel rod. This suggests that an upper limit on plutonium content might be needed for MOX fuel. The study was done for reactor-grade plutonium, but the general conclusion should be applicable to weapons grade plutonium at slightly lower concentrations taking into account that

there is a higher fraction of Pu-239 in this material relative to reactor-grade plutonium. Nevertheless, the upper limit with either type of MOX fuel appears to be at a concentration above the level of current interest.

TECHNICAL ISSUES

Although NRC's General Design Criteria (10 CFR 50, Appendix A) are general enough to apply to all types of reactor fuel, some specific licensing requirements were developed for uranium-based fuels. There are, therefore, technical issues that should be addressed to ensure that specific licensing requirements and related analytical methods are adequate for MOX fuel, and that LWRs loaded with MOX fuel meet all the requirements.

Reactor Physics

The reduction in the effectiveness of the reactor control system is perhaps the most important technical issue that must be addressed for the plutonium disposition program. Control rod worth is reduced by MOX fuel because the increased thermal neutron cross section of plutonium allows the fuel to compete more effectively with the control materials and absorb a greater number of neutrons. Additionally, the lower delayed neutron fraction (beta value) of MOX fuel lets a smaller reactivity insertion make the reactor go prompt critical; thus, there is less time for rod insertion to provide reactor control. European MOX experience has shown that, with a MOX core loading of 30% or less, the core will remain controllable without any modifications to the control system. With increased core loadings of MOX fuel above 30%, two alterations were found to restore the effectiveness of the control system in PWRs: increasing the B-10 content of the soluble boron and using control rods with hafnium and boron carbide instead of the current silver-indium-cadmium type. Alternately, additional control rods could be added to the MOX-fueled cores. Some reactors (Combustion Engineering) were initially designed to hold extra control rods for MOX cores, and other reactors have control rod positions that are not currently used. Whichever method is used, a thorough assessment will be needed to ensure that the reactor will continue to meet the requirements of General Design Criteria 26-28 (10 CFR 50, Appendix A) when it is using MOX fuel.

The fission cross sections in MOX fuel are also larger than those in UO_2 fuel, and this can result in steep flux gradients between adjacent MOX and UO_2 fuel rods. This effect can be reduced with enrichment variations and core design. Another consequence of the differences in cross sections between plutonium and uranium are the changes in the moderator temperature coefficient, the Doppler (fuel temperature) coefficient, and the coefficient of reactivity for coolant voids. Core design and safety analysis will have to take into account these changes in reactivity coefficients.

Plutonium fissioning in MOX fuel produces a harder (higher energy) neutron energy spectrum and this would increase the flux of high energy neutrons in the reactor vessel if MOX assemblies were loaded near the core periphery. A higher flux of energetic neutrons would accelerate the embrittlement process caused by neutron damage to the material. This effect would be similar to putting fresh uranium fuel on the edge of the core, which is avoided in current practice. Thus, renewed attention will have to be paid to core loading patterns to avoid excessive vessel fluence.

The increased energy released per plutonium fission, compared with uranium fission, and the early decrease in decay heat for MOX fuel will affect the analysis of loss-of-coolant-accidents (10 CFR 50, Appendix K). These reductions will tend to offset the increased stored energy that is mentioned below. These changes in energy release and decay heat will also affect the thermal-hydraulics of cooldown events, and these events will be analyzed to fully understand the potential impact.

Most or all of these reactor physics issues require quantitative analysis with computer codes. Therefore, NRC analytical codes will have to be upgraded to include MOX-specific parameters, and industry codes will have to be reviewed for use in licensing. Some of the most critical models that need to be added to the kinetics codes include multiple energy groups (four or more) with upscatter, a modeling capability to capture the harder spectrum effects, improved delayed-neutron precursor calculations, a revised decay heat model, and a method to handle local power peaking.

Fuel Behavior

Uranium dioxide and PuO_2 are very similar ceramics, and MOX fuel behaves very much like UO_2 fuel during normal steady-state operation. Nevertheless, subtle differences caused by somewhat different physical properties have a significant effect. The reduced thermal conductivity in MOX fuel causes the fuel pellets to operate at somewhat higher temperatures than in UO_2 fuel of the same linear power rating. While the higher operating temperatures would not be a problem for normal operation, the fuel temperatures determine the amount of stored heat present at the beginning of a loss-of-coolant accident (LOCA). LOCA analysis is so strongly dependent on this stored heat that it must be calculated accurately, and steady-state fuel rod computer codes are therefore carefully reviewed in a licensing safety assessment. NRC and industry codes will have to be modified to model MOX fuel adequately, and data to support these modifications will have to be obtained from the Halden test reactor and other programs.

In addition to considering normal operation, which sets up the initial conditions for a transient, two types of large transients are addressed in a safety analysis. One is the loss-of-coolant accident and the other is a prompt-critical reactivity accident. Other transients of lesser severity are also considered, but these two are the most challenging. Fuel behavior during a LOCA is determined almost entirely by the cladding. Ballooning, rupture, oxidation, embrittlement, and fragmentation have been studied and quantified in licensing safety analyses (see 10 CFR 50.46 and Appendix K). All of the early work on LOCA behavior was conducted with empty Zircaloy tubes, so the type of fuel pellet would not have made a difference. However, recent NRC studies of LOCA behavior in high-burnup fuel are being conducted with intact segments of fuel rods (i.e., with the fuel left inside) because the chemical bonding between the pellets and the cladding may affect the ballooning process. Chemical bonding may be different for MOX pellets and UO_2 pellets, and the effect could be investigated. However, at this time a major effect is not expected.

In a PWR, which is the type of reactor now anticipated for plutonium disposition, the prompt-critical reactivity accident is a rod-ejection accident that is often referred to generically as a reactivity-initiated accident (RIA). Several of the differences between UO_2 and MOX fuel will directly affect this event. The higher creep rate of MOX fuel may reduce the severity of the pellet-cladding mechanical interaction that causes cladding failure at higher burnups. On the

other hand, the higher fission gas release associated with plutonium hot spots may increase the severity of the interaction, and the higher gas inventory may also cause greater entrainment and expulsion of fuel particles after cladding failure. The one RIA test-to-failure with MOX fuel in the Cabri test program suggests that this difference is significant. If there are any burnup limitations for MOX fuel that are different from UO_2 fuel, they would probably be related to this event. More testing of this type may have to be done with MOX fuel specimens to determine adequate regulatory criteria for MOX fuel for the rod-ejection accident (see Regulatory Guide 1.77).

Gallium is used in concentrations up to 1 wt% as an alloying element in the manufacture of plutonium pits for nuclear weapons. While gallium is not a good neutron absorber and therefore would not interfere with the chain reaction, gallium metal chemically attacks zirconium. Since fuel rod cladding is made of zirconium alloys, efforts will be made to remove gallium from the weapons plutonium. While the fabrication process to be used for making PuO_2 will reduce the concentration of gallium to part-per-million levels, its effects on fuel and cladding behavior have not yet been fully assessed. DOE is performing experimental studies at this time, and the effects of this impurity will have to be considered in any licensing assessment.

Source Terms

A radioactive source term is used to assess offsite dose consequences from postulated reactor accidents. The source term is derived from a severe accident (i.e., an accident with core melt) or a group of severe accidents and is determined by the progression of the accident and the natural processes that retain fission products in the plant. The progression of the accident is affected by melting of the core, formation of crusts, expulsion of core debris from a breached vessel, hydrogen generation from metals, heat transfer to the containment, etc. The addition of a few percent extra plutonium in the core, with a reduction of only about 10°C in melting temperature, will not have a big effect on accident progression. Also, the processes that remove fission products, like agglomeration, settling, and scrubbing by water, will not be affected by the small change in composition of the core debris. Further, the source term itself is given in terms of fractions of initial inventory, so these fractions should not be changed significantly. Only the gap release may increase (marginally) because of the elevated operating temperatures in MOX fuel compared with UO_2 fuel. The gap release is used in the analysis of design-basis accidents, but it will not have a large effect on severe accident source terms.

However, the consequences of a severe accident might change because the inventory of radionuclides is different. At any given time, MOX fuel will have more plutonium than UO_2 fuel, and the inventory of other actinides and fission products will also be somewhat different. Those changes could have an effect on offsite consequences. It can be noted, however, that consequences such as cancer fatalities are caused by a range of actinides and fission products, not just plutonium. The health consequences, which would depend on the type and amount of radionuclides inhaled or ingested, will have to be assessed.

In addition to possible changes in consequences, the changes in reactor physics and fuel behavior discussed above could in principle have an effect on the probability of occurrence of a severe accident, and this should also be assessed. It should be noted, though, that the net outcome may not be obvious. For example, the discussion about reactivity-initiated accidents suggests that the behavior of MOX fuel during an RIA may be worse than that of UO_2 fuel. However, these reactivity accidents do not make a contribution to current risk assessments

because they are terminated by a natural process (Doppler feedback). From the discussion above about accident progression, it appears likely that the probability of severe accidents will not change and that consequence analyses, rather than full probabilistic risk assessments, may be sufficient to assess the changes due to the different inventory of radionuclides.

Fuel Fabrication

Because plutonium is a strong alpha emitter and its specific activity is much higher than uranium, a minute quantity of plutonium, if inhaled, could present a health hazard. Therefore, a MOX fuel fabrication facility will have remote handling requirements not found in uranium fabrication facilities, and these requirements need to be addressed prior to licensing. In addition, the design of a MOX fabrication facility will be subject to more stringent requirements than a uranium fuel fabrication facility. Required design criteria need to be evaluated and modified if necessary prior to any licensing actions.

There may be two issues related to criticality in the weapons-grade MOX fuel fabrication process. Because it is uncertain what the initial, intermediate, and final forms and compositions of the special nuclear material will be in the fabrication process, the first issue is that there may be a lack of publicly available peer-reviewed critical experiments using those forms and compositions. Because it is also uncertain what the processing steps will be, the second issue is that there may be a lack of cross-section data for those forms and compositions at the temperatures and energy ranges of interest (e.g., the resonance region). A study now being performed for NRC at Oak Ridge National Laboratory regarding the areas of applicability of critical experiments may help address this issue.

Fuel Storage and Disposal

It is expected that the final disposal of the spent MOX fuel will be in the geological repository for high level radioactive waste that is being studied and evaluated by DOE. Prior to that, if the MOX spent fuel needs to be stored in dry storage instead of in a water pool, dry storage casks can be developed and then certified by the NRC. The staff has not identified any unique dry cask storage issues at this time.

CONCLUSION

Experience in Europe with the technical and regulatory issues of using MOX fuel suggests that these issues can be resolved here as well. Nevertheless, the NRC and the U.S. industry must also deal with these issues, and some of the technical issues will be unique because of the difference between weapons-grade MOX fuel and the reactor-grade MOX fuel that is being used elsewhere.

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