

Burn and Bury Option for Plutonium

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One of the most important scientific and political challenges of our era is the safe disposal of plutonium from reactors and nuclear weapons no longer needed for defense purposes. By 2000, the world inventory of plutonium will be between 1600–1700 t.¹

Spent nuclear fuel is the largest source of plutonium, with the 1996 reactor-grade plutonium inventory estimated at 1100 t and increasing by ~70 tpy year.¹

In 1994, a National Academy of Sciences report entitled “Management and Disposition of Excess Weapons Plutonium” made the following recommendation: “Further steps should be contemplated... to reduce the security risks posed by all of the world’s plutonium stocks, military and civilian, separated and unseparated; the need for such steps exists already and will increase with time.”¹

The same report identified two options for plutonium disposition:

- Incorporate plutonium in a glass via a vitrification process and bury the mixture in a geologic repository;
- Burn plutonium in existing nuclear reactors.

In December 1996, the U.S. DOE announced a strategy for managing fissile plutonium obtained from the disassembly of nuclear weapons. The plan calls for “a dual-track plutonium disposition strategy that allows for immobilizing plutonium in glass or ceramic forms and burning plutonium as mixed oxide fuel in existing reactors.”²

This article proposes an option for both reactor- and weapons-grade plutonium disposition that incorporates both aspects of

the dual-track strategy. It details the incorporation of plutonium in a nonfertile, ZrO₂ matrix ceramic fuel that will be burned in an existing light water nuclear reactor (LWR), and then buried in a geologic repository without further reprocessing.

Previous Developments

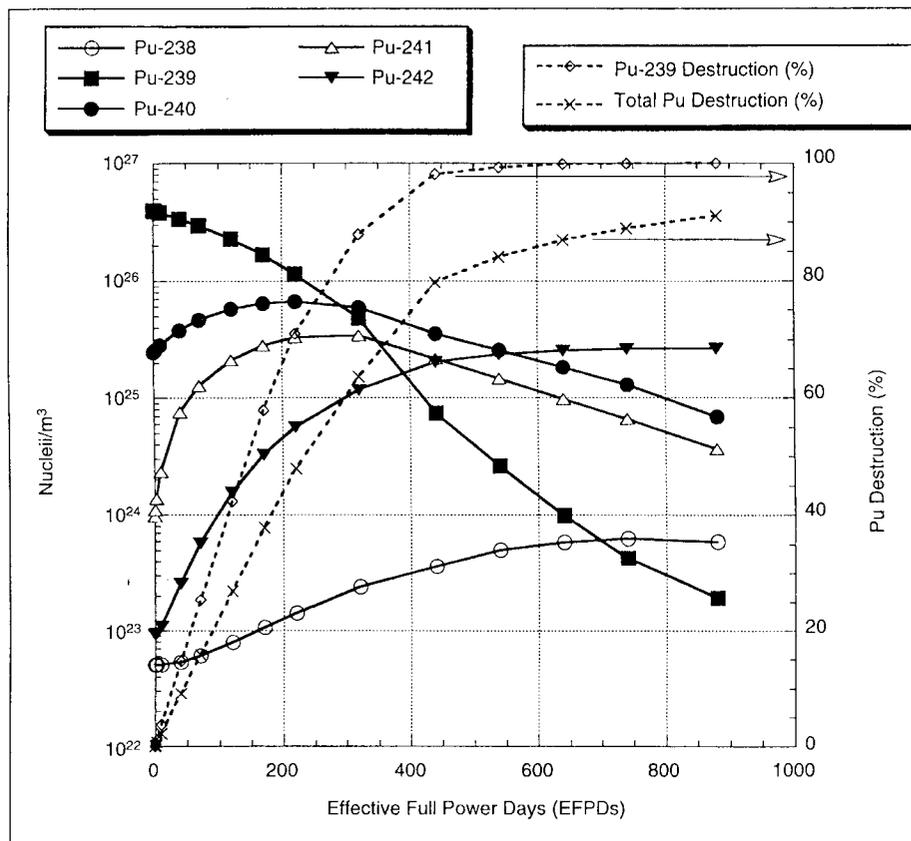
Some aspects of this idea have been developed by others.^{3–10} Burning plutonium in a nonfertile matrix produces a spent fuel with little residual plutonium, since, in contrast to burning a conventional uranium oxide (UO₂) fuel, no new actinides are formed. Moreover, the isotopic composition of the plutonium in the irradiated fuel is degraded to the extent that the spent fuel is of little use as a nuclear explosive material.

Finally, any spent-fuel byproducts (e.g., higher actinides and fission products) reside in an inert ZrO₂ matrix that possesses exceptional chemical durability characteristics and may constitute a viable final waste-form. This “burn and bury” concept offers an efficient means to reduce the world plutonium inventory as well as to reduce security risks.

Properties of ZrO₂

Zirconia is the common name for zirconium dioxide (ZrO₂), a polymorphic oxide that exists in three different crystal structures below its melting point of 2950 K:

- A high-temperature cubic phase (space group *Fm $\bar{3}m$*) from 2640–2950 K;
- An intermediate-temperature tetragonal phase (space group *P4₂/nmc*) from 1440–2640 K;



Calculated plutonium destruction/transmutation was accomplished by burning a nonfertile fuel containing 96.3 wt% ZrO_2 , 2.9 wt% weapons-grade PuO_2 and 0.8 wt% Er_2O_3 for 880 effective full-power days (EFPDs) at a 100% core average power of 17 kW/m. Depletion calculations were performed using a pressurized water reactor (PWR) model with the nonfertile PuO_2 fuel in the peripheral assemblies and conventional low-enriched UO_2 fuel in the interior assemblies.

- A low-temperature, naturally occurring, monoclinic form, known as baddeleyite (space group $P2_1c$) below 1420 K.¹¹⁻¹³

We are interested in the cubic phase of ZrO_2 , which is isostructural with fluorite (CaF_2) and UO_2 . An important property of ZrO_2 is that certain aliovalent oxides (for instance, MgO , CaO , Y_2O_3), when mixed with ZrO_2 , are able to stabilize the cubic fluorite structure from room temperature to the melting point of the compound.¹³

Somewhat smaller additions of these same oxides lead to compounds referred to as partially stabilized ZrO_2 (PSZ), which are characterized by the presence of both cubic and tetragonal forms.¹³

In PSZ-bearing materials, the tetragonal ZrO_2 form is metastable and can be made to transform to the monoclinic phase during deformation. This transformation is accompanied by a

volume expansion of a few percent, an effect that is exploited in transformation-toughened engineering ceramics based on PSZ.^{14, 15, 12}

Nuclear Fuel-, Waste-Form

Cubic zirconia is attractive as both a nuclear fuel-form and a nuclear waste-form because it is an actinide host phase. Compounds such as UO_2 , plutonia (PuO_2), ceria (CeO_2), and thoria (ThO_2) crystallize in the fluorite structure and so are isostructural with cubic ZrO_2 .^{16, 17}

At temperatures >1770 K, complete solid solubility has been reported for ZrO_2 - PuO_2 ¹⁷ and similarly for ZrO_2 - UO_2 at temperatures >2570 K,¹⁸ but at temperatures less than ~ 1470 K, solid solubility between ZrO_2 and actinides is limited (PuO_2 ,¹⁹ UO_2 ,²⁰ ThO_2 ²¹).

However, additions of a cubic stabilizer can enhance actinide solubility in

a cubic fluorite host phase. For instance, additions of 20–30 mol% CaO to ZrO_2 - UO_2 mixtures, combined with sintering in a hydrogen atmosphere, produce complete solid solubility for this ternary system.²²

Rare-earth sesquioxides, (La , Pr , Nd , Sm , Gd , Tb , Dy , Ho , Er , Yb) $_2O_3$, also are effective cubic-phase stabilizers for ZrO_2 .²³ In fact, for additions up to ~ 20 mol%, rare-earths stabilize the cubic phase and they increase the melting point of the compound (by as much as 3% in the case of ZrO_2 - Yb_2O_3), thereby further enhancing the chemical stability of ZrO_2 .²³

Calculations indicate that the cubic phase field of ZrO_2 increases with increasing rare-earth mass.²⁴ Incorporation of rare-earth species in an actinide host phase is a useful waste disposal concept, since rare-earths have large thermal neutron capture cross sections.²⁵ Consequently, they are effective neutron poisons and serve to abate criticality issues during storage.

Rare-earth additives in the design of nuclear fuels also are an important concept because rare-earth constituents are burnable neutron poisons (i.e., depletable neutron absorbers). Adding burnable poisons makes it possible to use fuels with higher initial concentrations of fissile nuclides, and extended fuel burnup is possible.

For instance, addition of the rare-earth element erbium (Er) to a ZrO_2 - PuO_2 fuel makes it feasible to incorporate high plutonium mass loadings in the fuel.⁴ UO_2 fuels incorporating burnable poisons (in particular with Gd_2O_3 additions) have been used in boiling water reactors for longer than 20 years.^{26, 29}

ZrO_2 Matrix Fuel

The concept of a ZrO_2 matrix fuel is not new. A 1962 Westinghouse Electric Co. report documents irradiations performed on 94 fuel elements in the ZrO_2 - UO_2 composition field.³⁰ The elements were irradiated at the National Research Universal (NRU) reactor at Chalk River, Ontario, and at the National Reactor Testing Station in Idaho.

A 1966 report describes a ZrO_2 - UO_2 - CaO fuel burned in the

Power Burst Facility (PBF) at the Idaho National Engineering Facility with no fuel rod failures for temperatures to 2420 K.³¹ Between 1969 and 1974, a ternary fuel consisting of 57 wt% ZrO₂, 38 wt% UO₂ and 5 wt% CaO was successfully irradiated in the Shippingport pressurized water reactor (PWR) in Pennsylvania.³² And a light-water breeder reactor (LWBR) program tested a ternary ZrO₂-UO₂-CaO fuel and achieved high burnup without fuel failure.³²

In 1965, a study was conducted to identify an inert diluent for UO₂-PuO₂ fuel mixtures.³³ ZrO₂ was selected because of its low neutron absorption cross section, which is such that it behaves as an innocuous material in a reactor environment.

The behavior of zirconium in reactor environments is well-known, as it is the majority element in Zircaloy, a corrosion-resistant fuel cladding material with small neutron capture cross section. Zircaloy has been used in thermal reactors for longer than 30 years.³⁴

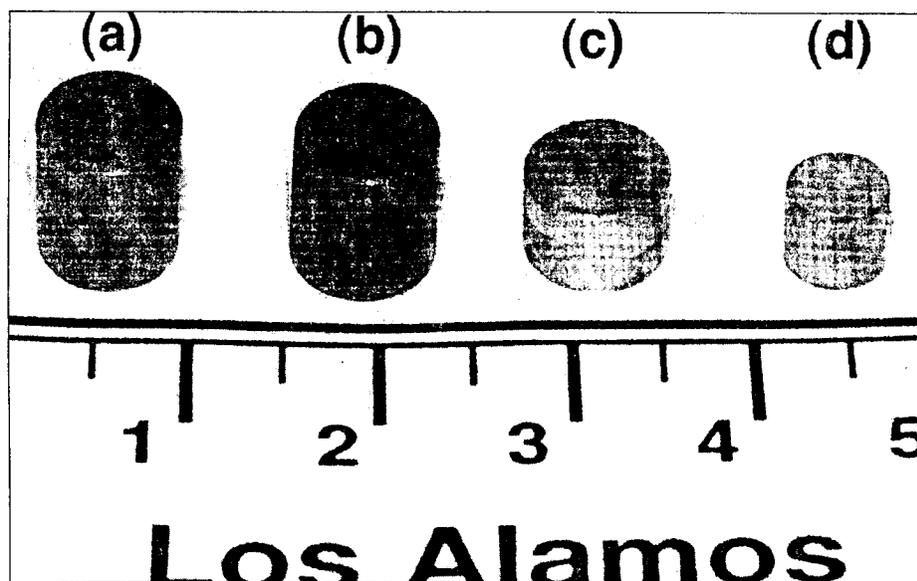
More recently, nuclear fuel design studies have shifted from UO₂-based to PuO₂-bearing, uranium-free fuels.^{3, 4, 8, 10, 35-37} These are called nonfertile fuels; i.e., they do not breed plutonium or other fissionable actinides during use. In contrast, a fertile fuel is any fuel containing nonfissile isotopes that are transmuted into fissile species during irradiation.

Examples of the latter include:

- Mixed oxide (MOX) fuels containing ²³⁸U, which breeds fissionable ²³⁹Pu during irradiation;
- Fuels containing ²³²Th, which breeds fissionable ²³³U upon irradiation.

When PuO₂ is mixed with a neutron-transparent nonfissile material, such as ZrO₂, the fuel often is referred to as an inert-matrix fuel.³⁵ Nonfertile (inert-matrix) fuels have gained popularity in recent years because of concerns regarding the use of MOX fuels for Pu disposition.

A neutronic evaluation has been performed for a ZrO₂-PuO₂ fuel in a boiling water reactor environment. An optimum composition of 80.4 wt% ZrO₂, 8.3 wt% PuO₂, 9.7 wt% CaO and 1.6 wt% Er₂O₃ was identified for a cubic-stabilized fuel including a burnable poison (Er).⁵ For this fuel composition, a nearly 100% burnup of all the plutonium is achieved in a 3-



A series of sintered fuel pellets, incorporating varying amounts of ZrO₂. Pellets were synthesized via a dry-processing route and sintered in an argon-hydrogen (6%) atmosphere for 4 h at 1970 K. The full width of the image is 5 cm.

- (a) Nonfertile, ternary oxide mixture of 87.19 wt% ZrO₂, 2.69 wt% PuO₂ and 10.12 wt% CaO.
 (b) Quaternary oxide mixture consisting of 87.94 wt% UO₂, 10.97 wt% PuO₂, 4.628 wt% ZrO₂ and 0.462 wt% CaO.
 (c) Fully stabilized, binary cubic ZrO₂ mixture with 20 mol% CaO.
 (d) Mixture of 87.19 wt% ZrO₂, 2.69 wt% CeO₂ and 10.12 wt% CaO.

year fuel cycle, assuming 20 kW/m linear heat generation rate for the reactor power level.

A simulation shows the results of a burnup calculation for a fuel with composition 96.3 wt% ZrO₂, 2.9 wt% PuO₂ and 0.8 wt% Er₂O₃, burned for 880 full-power days at a 100% core average power of 17 kW/m (Ref. 37) (codes used for these calculations were MCNP,³⁸ ORIGEN2,³⁹ and MOCUP, a coupled version of the aforementioned codes⁴⁰).

Greater than 90% of the plutonium was destroyed. Moreover, this simulation illustrates that the isotopic composition of plutonium in a nonfertile fuel is drastically altered during burnup and renders the spent fuel useless for nuclear weapons applications.

Nonfertile, ZrO₂ matrix fuel pellets containing PuO₂ were synthesized via a dry-processing route at Los Alamos National Laboratory, N. M.⁴¹

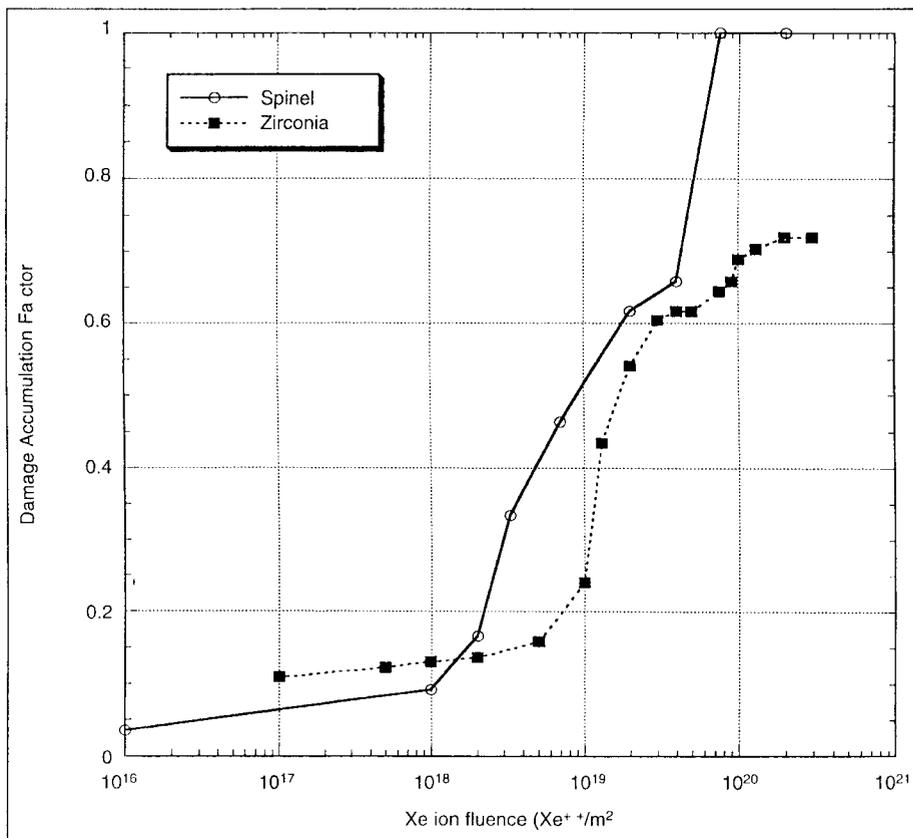
A series of pellets incorporating various amounts of ZrO₂ were photographed: (1) a mixture of ZrO₂, PuO₂ and CaO, to produce a nonfertile, ternary oxide fuel composition; (2) a quaternary oxide mixture of UO₂,

PuO₂, ZrO₂ and CaO, a so-called evolutionary mixed oxide (EMOX), in which a nonfertile species (zirconium) is substituted for uranium; (3) a binary oxide mixture of ZrO₂ and CaO, a fully stabilized pellet containing no fissile material; and (4) a mixture of ZrO₂, CeO₂ and CaO, a ternary oxide fuel, where cerium is added as a surrogate for plutonium.

Irradiation Damage Behavior

An important aspect of fuel performance is the irradiation damage behavior of the fuel. Nuclear fuel pellets are exposed to a high-neutron-flux environment. They suffer self-damage from high-energy, high-mass fission fragments. Ion irradiations of Y₂O₃-stabilized cubic ZrO₂ to high fluence indicate no propensity for amorphization, nor are phase transformations observed.⁴²⁻⁴⁴

Under ambient conditions, no amorphization was observed in ZrO₂ to a peak damage level of 110 displacements per atom (dpa),^{43,45} far greater than the dose necessary to amorphize magnesioaluminatite spinel (MgAl₂O₄), which itself is a radiation-tolerant material.⁴⁶



A comparison of radiation damage accumulation in spinel ($MgAl_2O_4$) and Y_2O_3 -stabilized cubic ZrO_2 (9.5 mol% Y_2O_3). Values of the damage accumulation factor plotted here are derived from ion-channeling measurements performed on single crystals of spinel irradiated with 370 keV Xe^{2+} ions at 170 K and ZrO_2 crystals irradiated with 400 keV Xe^{2+} ions at 180 K.

A comparison was made of radiation damage accumulation in spinel ($MgAl_2O_4$) and Y_2O_3 -stabilized cubic ZrO_2 (ZrO_2 -9.5 mol% Y_2O_3). The data for the comparison were derived from ion-channeling measurements performed on single crystals of spinel irradiated with 370 keV Xe^{2+} ions at 170 K^(Ref. 47) and ZrO_2 crystals irradiated with 400 keV Xe^{2+} ions at 180 K.⁴³ A value of 1 for the damage accumulation factor is indicative of an amount of damage produced by the Xe^{2+} ion irradiation sufficient to render the material fully amorphous.

The comparison indicates that spinel is amorphized by a dose of $\sim 8 \times 10^{19}$ Xe^{2+}/m^2 (370 keV Xe). This was confirmed using transmission electron microscopy (TEM).⁴⁶ For ZrO_2 , no amorphization is observed to a dose of at least 3×10^{20} Xe^{2+}/m^2 (400 keV Xe). TEM observations, again, confirm that the ZrO_2 remains crystalline to this dose.⁴³ In all reported ion-beam

damage studies of ZrO_2 , the cubic fluorite phase survives ion bombardment.

High-temperature neutron irradiations of Y_2O_3 fully-stabilized ZrO_2 samples to a dose equivalent to ~ 1 dpa revealed no phase transformations as well as negligible swelling at 650 and 1025 K.⁴⁸ In a 1 dpa irradiation at an intermediate temperature of 875 K, however, 1.5–2.0% volume swelling of ZrO_2 was observed.⁴⁸ The mechanisms responsible for this swelling must be examined further.

To simulate fission fragment damage, 72 MeV I^+ ion irradiations were performed on Y_2O_3 -stabilized and CaO-stabilized ZrO_2 .⁴⁹ For fluences ranging from 1×10^{19} – 1×10^{20} I^+/m^2 and irradiation temperatures ranging from ambient to 1170 K, no swelling of ZrO_2 samples was observed (based on laser profilometry measurements of surface relief across an implanted area⁴⁹). In summary, the radiation damage properties of cubic ZrO_2

appear quite satisfactory for application of ZrO_2 as a nuclear fuel.

Materials Property Concern

The primary materials property concern regarding the use of cubic ZrO_2 as a nuclear fuel matrix is its poor thermal conductivity. Low thermal conductivity is a general problem in oxide fuels. As a consequence, oxide fuel pellets operate with high internal temperatures.

Typical values of the measured thermal conductivity (k) of UO_2 (for normal operating temperatures for fuel in a pressurized water reactor; i.e., 1900–2100 K^(Ref. 4)) range from 0.15–0.4 W/(m·K).⁵⁰ Measured k values for ZrO_2 range from 0.15–0.3 W/(m·K) in this same temperature range.⁵⁰

Stabilized ZrO_2 does not exhibit any higher thermal conductivity. For instance, measured values of k in CaO-stabilized cubic ZrO_2 (15–20 mol% CaO) range from 0.16–0.17 W/(m·K) in the temperature range 1040–1090 K.⁵¹ The thermal conductivity of PuO_2 is much lower than UO_2 ,⁴ so a ZrO_2 - PuO_2 nonfertile fuel is expected to have lower thermal conductivity than UO_2 .

This implies that ZrO_2 - PuO_2 fuels must be used at lower reactor power levels compared to UO_2 fuels, or they must be situated at the periphery of the reactor core, away from the peak neutron and gamma flux region. There are alternatives, however, that may improve the thermal performance of a nonfertile oxide fuel.

One possibility is to fabricate a fuel with an annulus geometry.^{6,7} In this case, calculations indicate that, if the central hole diameter exceeds 7.5% of the pellet diameter, the centerline pellet temperature can be reduced by more than 100 K.⁶

Another possibility is to mix a high thermal conductivity second phase into the nonfertile fuel; i.e., use a cermet fuel (in this case, the second phase is a metal) or a ceramic composite (here, the second phase is a high thermal conductivity ceramic, such as a nitride).

Nevertheless, the greatest challenge confronting the application of ZrO_2 - PuO_2 -based nonfertile fuels in LWRs is to overcome the poor thermal conductivity of this mixed oxide.

Leachability of Materials

As a nuclear waste-form, ZrO_2 must exhibit minimal susceptibility to leaching in an aqueous environment, even as the material accumulates radiation damage due to self-damage processes (α -decay of radionuclides). Neutral pH studies of ZrO_2 solubility in water have been performed. These indicate extremely low solubility of zirconium (~ 10 – $12M$ zirconium concentration) at ambient temperature.⁵²

In aggressive (highly acidic or alkaline) environments, it is possible to dissolve ZrO_2 . Etchants include hot, concentrated hydrofluoric acid or $HF:NH_4F$ ⁵³ and boiling orthophosphoric acid.⁵⁴ Under ambient conditions, zirconium concentrations in aqueous solutions of maximum acidity and alkalinity (pH 1 and 14, respectively) are $\sim 10^{-4}M$.⁵²

To compare ZrO_2 solubility with other ceramics, it is interesting to note that, of the principal commercial methods for producing pure ZrO_2 , one method is by reaction of natural zircon with sodium hydroxide.¹³ This implies that zircon, a leading candidate ceramic waste-form, appears to be more susceptible to alkaline dissolution than ZrO_2 .

One experimental study revealed that leaching rates in actinide-bearing, fluorite-structure oxides are indeed affected by self-radiation damage (α -decay), even though α -recoil events do not induce metamictization (an amorphization transformation) in these compounds.^{55, 56}

Specifically, in fluorite-structure mineral samples of uraninite ($(U,Th)O_2$) and thoriantite ($(Th,U)O_2$), it was found that leaching rates in radiation-damaged samples were slightly enhanced relative to annealed samples.

The same studies, however, suggested that radiation damage in these materials tends to heal with time by a self-annealing process. By contrast, leachability of materials that are susceptible to metamictization, e.g., natural zircon, exhibit largely increased leachability with increasing radiation dose.⁵⁷

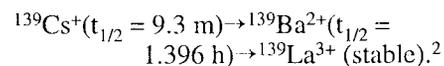
Troublesome Products

There is an additional concern regarding the extent to which transmutation and fission products

from fuel irradiation will be stable in the cubic ZrO_2 lattice. Of the actinides, americium and neptunium have ionic radii similar to uranium and plutonium (at least for 4+ valence ions, where radii range from 0.092–114 nm, depending on coordination^{58, 59}), and should fit similarly in the fluorite structure.

In addition to the actinides, a wide variety of fission product radionuclides form during burnup. Of the possible fission products, smaller ions are generally more compatible with the cubic ZrO_2 lattice.²³ Interestingly, radionuclide natural decay sequences most often involve β^- emission, with one consequence being an evolutionary progression toward smaller ions.^{7, 8}

For instance, the fission product ^{139}Cs undergoes a natural decay chain:



In this sequence, the ion decreases in size from ~ 0.170 nm for Cs^{1+} to 0.138 nm for Ba^{2+} to 0.110 nm for La^{3+} (Refs. 58, 59) (assuming seven-fold coordination for cations in cubic stabilized ZrO_2). The last ion in the series is the most compatible with the ZrO_2 lattice based on size.

The three most troublesome fission products, from a radiotoxicity risk standpoint, are the long-lived radionuclides ^{99}Tc , ^{129}I and ^{135}Cs .⁶⁰ The concern is that technetium, iodine and cesium readily form water soluble compounds and may migrate out of a geologic repository.

In fact, calculations indicate that the predominant long-term repository exposure risk is because of these three species, by comparison to any actinide species in repository waste.⁶⁰ It is not yet clear how technetium, iodine and cesium will behave in a ZrO_2 matrix. It should be noted that, upon extended exposure to the thermal neutron flux of an LWR (e.g., using a fuel designed for high burnup), ^{99}Tc and ^{129}I can be transmuted to stable isotopes ^{100}Ru and ^{130}Xe , respectively. The stability of the latter species in a ZrO_2 matrix also is an open question.

Fuel Fabrication

The final topic for consideration is fuel fabrication. One of the key features of

the ZrO_2 matrix fuel-form and waste-form concept is the relative ease of synthesis of ZrO_2 matrix pellets. ZrO_2 matrix fuels can be fabricated by processes identical to those used to produce UO_2 and MOX fuels.⁴

For MOX fuels, there are two current fabrication processes based on dry mixing: the short binderless route (used in the United Kingdom); the masterblend route, known either as the optimized commilling (OCOM) or as the micronization of master blend (MIMAS) process (used in Belgium, France and Germany).⁶¹ Both procedures involve milling of constituent oxide powders (UO_2 and PuO_2) followed by pressing and sintering of oxide pellets. No technical obstacles are anticipated by replacement of UO_2 with ZrO_2 powders for nonfertile fuel fabrication.

Summary and Conclusions

This paper details a concept for the disposition of reactor-grade or excess weapons-grade plutonium:

- Burn the plutonium in existing nuclear light-water reactors using a ceramic matrix, nonfertile fuel;
- Bury the spent fuel in a geologic repository without further processing.

For the nonfertile fuel matrix, we propose using ZrO_2 . Cubic ZrO_2 has the following distinctive features:

- Cubic-stabilized ZrO_2 is an actinide-host phase in which actinides have high solubilities (over 10 wt% for uranium and plutonium). In fact, cubic ZrO_2 is isostructural with fluorite-structured actinide compounds, such as UO_2 , PuO_2 and ThO_2 ; this implies that a single-phase fuel-form, similar to existing UO_2 nuclear fuels, can be readily fabricated.
- Most rare-earth elements and Groups II–IV elements, have high solubilities (5–30 at.%) in cubic ZrO_2 . This implies that many fission products can readily be incorporated in a cubic ZrO_2 matrix. Examples include rare-earth fission products, which are all effective cubic-phase stabilizers for ZrO_2 . These traits enhance the stability of the fuel during irradiation. The chemical flexibility and stability of cubic ZrO_2 suggest that it also may double as a viable waste-form following irradiation.
- Rare-earth species can play a dual-role in a ZrO_2 -matrix fuel. Many rare-earth

isotopes possess high neutron capture cross sections. These species can be added as cubic phase stabilizers during fuel synthesis, but they then serve a dual purpose as burnable neutron poisons during irradiation. Using rare earths in this way, a nonfertile fuel can accommodate higher concentrations of plutonium than in a MOX fuel.

- Cubic ZrO_2 has a high melting point (2970 K, compared to 2620 K for PuO_2 and 3135 K for UO_2) and high thermal stability (i.e., no thermally activated phase transformations).

- ZrO_2 is chemically inert. The cubic polymorph of ZrO_2 exhibits low solubility in acidic and alkaline solutions under ambient conditions. Consequently, actinides in a ZrO_2 matrix are not easily recovered using conventional reprocessing techniques, such as the PUREX process.³⁴ Hence, a nonfertile fuel based on ZrO_2 has an added positive attribute regarding proliferation resistance. Following reactor irradiation, any residual plutonium is secure in the inert, crystalline ZrO_2 matrix and may be suitable for burial.

- Cubic ZrO_2 has good radiation resistance. Specifically, ZrO_2 exhibits no propensity for amorphization and minimal swelling following significant radiation exposures.

- Neutron capture cross sections in ZrO_2 are small. This ensures acceptable neutron economy in a ZrO_2 -matrix fuel. The behavior of zirconium in LWRs also is well understood, since zirconium is the majority element in corrosion-resistant zircalloy fuel-cladding materials. Zircalloy has been used for 40 years in LWR designs.

- A ZrO_2 -based oxide fuel can be fabricated by conventional MOX fuel synthesis procedures.

- Burning a nonfertile fuel can facilitate the transmutation of plutonium into less-hazardous species, while simultaneously producing energy for commercial consumption.

- ZrO_2 exhibits extremely low solubility in water of neutral pH under ambient conditions. Dissolution of ZrO_2 requires aggressive aqueous mixtures of strong acids or bases. This property suggests that a ZrO_2 waste-disposal form is suitable for long-term storage.

This paper describes a safe and efficient means to dispose of both reactor-

and weapons- grade plutonium. In addition, the burn and bury concept discussed here may be utilized to promote a new idea for future nuclear reactor fuel cycling. Specifically, a ZrO_2 -matrix fuel is a viable final fuel form for a twice-through LWR fuel cycle model.

LWR fuel cycles were originally designed to include multiple reprocessing stages for spent fuel, and, ultimately, fast reactor technology was to be used to close the fuel cycle. Spent UO_2 fuel was not originally intended to be a final waste form, although it is now treated as such. In the twice-through fuel cycle model proposed here, UO_2 fuel is used in the first cycle, then a second LWR burn cycle is initiated using a nonfertile matrix.

This final fuel will incorporate plutonium, possibly long-lived radionuclides (⁹⁹Tc, ¹²⁹I and ¹³⁵Cs) and minor actinides derived from the products of the first fuel cycle. Following the second cycle, the inert-matrix spent fuel (ZrO_2) is buried as a final waste form.

This cradle-to-grave fuel cycle concept represents a new paradigm for globally sustainable nuclear power. ■

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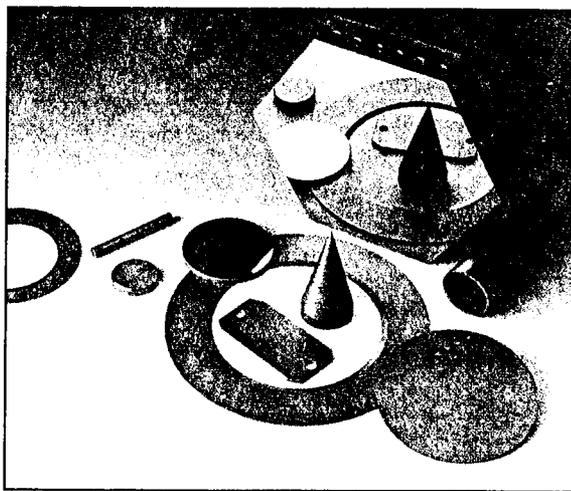
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