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PROCESS FOR MAKING A CERAMIC COMPOSITION FOR

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IMMOBILIZATION OF ACTINIDES

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5 PROCESS FOR MAKING A CERAMIC COMPOSITION FOR
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STATEMENT OF GOVERNMENT INTEREST

The United States Government has rights in this invention pursuant to
10 Contract No. W-7405-ENG-48 between the U.S. Department of Energy and the
University of California.

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Application No. 60/090,312,
15 filed 6/23/98 , entitled " Ceramic Composition and Process for Immobilization of
Actinides", which is incorporated herein by this reference.

BACKGROUND OF THE INVENTION

Field of the Invention

20 The present invention relates generally to a process for making a ceramic
composition suitable for immobilizing actinides, in particular plutonium, thorium and
uranium. The ceramic composition comprises pyrochlore, brannerite and rutile. The
ceramic composition is attractive for immobilization of excess plutonium because of
its extremely low leachability, the existence of natural mineral analogues that have
25 demonstrated actinide immobilization over hundreds of millions of years in wet
geological environments, and the high solid solubility of actinides in the ceramic thus

providing a relatively low overall waste volume. Incorporation of plutonium into ceramic provides a form that is relatively easy to store but renders retrieval of the plutonium to be more difficult than other immobilized forms . The process relates particularly to a cold pressing and sintering process for making said ceramic composition, which allows for impurities in the actinides feedstock.

Description of Related Art

Because of their extreme durability, ceramic forms have been studied extensively since the late 1970s for the immobilization of high level waste (HLW). The material called Synthetic Rock (SYNROC) is a titanate-based ceramic composed approximately of 30% zirconolite, 30% hollandite, 30% perovskite and 10% rutile. In the HLW application, actinides partition into the zirconolite and perovskite phases. U.S. Patents 4,274,976 (Ringwood), 4,329,248 (Ringwood), 4,645,624 (Ramm, Ringwood) and 4,808,337 (Ramm et al) disclose the immobilization of HLW in synthetic rock.

A form of synthetic rock to immobilize spent fuel (SYNROC-F) was reported by S.E. Kesson and A.E. Ringwood, "Safe Disposal of Spent Nuclear Fuel", Radioactive Waste Management and the Nuclear Fuel Cycle, Vol. 4(2), pp. 159-174, October 1983. This form of SYNROC consisted of 90 wt% uranium pyrochlore, 5 wt% hollandite and 5 wt% rutile.

A variant of SYNROC-F, namely SYNROC-FA was reported by A.G. Solomah, P.G. Richardson and A.K. McIlwain, "Phase Identification, Microstructural Characterization, Phase Microanalyses and Leaching Performance Evaluation of SYNROC-FA Crystalline Ceramic Waste Form", Journal of Nuclear Materials 148, pp. 157-165, 1987. This form of SYNROC consisted of uranium pyrochlore, perovskite, uraninite and hollandite.

A cold press and sinter process is used in the production of mixed oxide

(MOX) fuel from uranium and plutonium. The MOX process uses pressing pressures in excess of 20,000 psi and sintering temperatures of 1,700 deg C in a 4% H₂ atmosphere on a 24 hour cycle. Because the final product is to be used as fuel, impurities in the feedstock cannot be tolerated.

5

SUMMARY OF THE INVENTION

An object of this invention is to provide a process for making a ceramic material for immobilization of actinides, including plutonium, uranium, thorium, americium and neptunium, said immobilized actinides then being suitable for storage
10 in an underground repository.

The desired characteristics of such a ceramic material include: a) low leachability, b) high solid solubility of actinides in the ceramic, c) ability to incorporate "high-fired" PuO₂ of nominal particle size of 20 microns and less than 50 microns, d) sufficient compositional flexibility to incorporate significant
15 concentrations of Pu and neutron absorbers (such as gadolinium and hafnium) as well as varying impurities in the feed streams, e) thermal stability during high level waste glass pouring in can-in-canister configurations, f) high chemical durability in the geologic repository environments both before and after undergoing radiation damage from alpha decay, g) difficult recoverability of plutonium from the ceramic to impede
20 proliferation.

The ceramic composition comprises pyrochlore, brannerite and rutile. A pyrochlore matrix provides the means to incorporate a higher concentration of plutonium than a zirconolite matrix. SYNROC compositions have contained hollandite, which the present composition does not. Other compositions have utilized
25 reactive plutonium (such as dissolved plutonium) whereas the present composition starts with unreactive ("high fired") plutonium. The present composition also tolerates

greater than 50 wt% impurities in the actinide feedstocks. The present composition has been found to be stable when subjected to high level waste glass pouring in a storage canister. More specifically the mineralogical composition remains unchanged and the pellets retain their physical integrity.

5 The present invention also relates to a process for making said ceramic composition which involves milling the actinides to a fine powder, blending the actinide powder with ceramic precursors, granulating the blend to facilitate flow into the press and die set, cold pressing the blend, followed by sintering. This is in contrast to the SYNROC process, which involves hot uniaxial or isostatic pressing. In
10 addition, processes producing SYNROC have formed hollandite, which the present process does not. The production of mixed oxide (MOX) fuel also uses a cold press and sinter process, however there are critical differences in process parameters, which lead to differences in the end products. In addition, the MOX process cannot tolerate
15 (up to 55.7 wt% in the actinide feedstock).

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 illustrates the processing regime for the inventive ceramic;

FIG. 2 illustrates the phase boundaries in the zirconolite, and plutonium, uranium
20 pyrochlore system;

FIG. 3 illustrates the actinide oxidation process;

FIG. 4 illustrates the immobilization process utilizing actinide already in oxidized
form; and

FIG. 5 illustrates the ceramic precursor fabrication process.

25

DETAILED DESCRIPTION OF THE INVENTION

Abbreviations

Al — aluminum

Am — americium

ANSTO — Australian Nuclear Science and Technology Organization

5 Ba — barium

Ca — calcium

Ce — cerium

cm — centimeter

Cr — chromium

10 deg C — temperature measured in degrees Celsius

DWPF — Defense Waste Processing Facility

EDS — energy dispersive spectrometry

Ga — gallium

Gd — gadolinium

15 H — hydrogen

Hf — hafnium

HLW — High Level Waste

LLNL — Lawrence Livermore National Laboratory

Mo — molybdenum

20 MOX — mixed oxides

MPa — megaPascals

MT — metric ton

Na — sodium

Ni — nickel

Np — neptunium

O — oxygen

P — phosphorus

ppm — parts per million

5 psi — pounds per square inch

Pu — plutonium

PUREX — plutonium-uranium extraction

SEM — scanning electron microscopy

Si — silicon

10 Sm — samarium

SRS — Savannah River Site

SYNROC — synthetic rock

Ta — tantalum

Th — thorium

15 Ti — titanium

U — uranium

vol % — volume percent

W — tungsten

wt % — weight percent

20 ZPPR — Zero Power Physics Reactor

Zn — zinc

Zr — zirconium

Definitions

actinide oxide — a mineral phase of the form AnO_2 , where An is generally U, but can include Th, Np, Pu and Am

alkalis — lithium, sodium, potassium, rubidium, cesium

alkaline earths — magnesium, calcium, strontium, barium

5 brannerite — a mineral phase of the form CTi_2O_6 where C is an actinide selected from the group consisting of U, Pu, Th, Np, and Am.

calcining — heating materials to high temperatures to drive off water and other volatile substances

hafnia — HfO_2

10 halides — fluorides, chlorides, bromides, iodides

high fired — heated or fired at temperatures greater than 650 deg C

hollandite — a mineral phase having the approximate composition $BaAl_2Ti_6O_{16}$

monazite — a mineral phase having the approximate composition $CePO_4$

perovskite — a mineral phase having the approximate composition $CaTiO_3$

15 pyrochlore — a cubic mineral phase of the form: $A_2Ti_2O_7$, where A can be a range of ions, including Ca, Gd, Hf, Sm, U, Pu, Th, Np and Am.

reactive sintering — reacting a particulate material, agglomerate, or product by heating or firing close to but below the melting point, resulting in a densified, crystallized, bonded and/or stabilized final product.

20 rutile — TiO_2

simulated DWPF thermal cycle — a thermal cycle that simulates the pouring and cooling of high level waste glass around cans containing the ceramic, in the DWPF as part of the DOE disposition process

whitlockite — a mineral phase having the approximate composition $Ca_3(PO_4)_2$

25 zirconolite — $CaATi_2O_7$, where A is selected from the group consisting of Zr, Hf, Gd

and Sm

Ceramic Formulation

A novel formulation of titanate-based minerals has been discovered to be capable of effectively immobilizing actinides. Said actinides include plutonium, uranium, thorium, americium and neptunium, preferably uranium and plutonium. Other radioactive materials such as transuranic and high-level wastes that contain significant amounts of actinides may be immobilized in this ceramic composition where said actinides in the waste have been concentrated prior to immobilization in the ceramic form.

This formulation consists primarily of pyrochlore, brannerite and rutile. Immobilization in the baseline formulation is accomplished by elemental substitution of the plutonium into lattice sites of pyrochlore. Pyrochlore provides the means to incorporate higher quantities of actinides than with zirconolite. This formulation demonstrates the ability to incorporate a high uranium and plutonium concentration (elemental up to 32 wt%, in oxides form up to 36 wt%) without significant changes in properties or mineralogy. Neutron absorber loadings (gadolinium, hafnium, samarium) are not affected by interchanging uranium for plutonium. Pyrochlore is less susceptible than zirconolite to long term, radiation induced damage effects from alpha decay of the plutonium that would lead to enhanced dissolution of the waste form during exposure to groundwater. Naturally occurring pyrochlores can retain actinides for billions of years even when extensive secondary alteration due to contact with fluids at temperatures less than 100 deg C has occurred. The composition is further described in patent application entitled "Ceramic Composition for Immobilization of Actinides", by inventors: Bartley B. Ebbinghaus, Richard A. Van Konynenburg, Eric R. Vance, Martin W. Stewart, Adam Jostsons, Jeffrey S. Allender, and D. Thomas Rankin, which is incorporated herein by reference.

The ceramic form has been found to be two to four orders of magnitude more durable than alternate glass forms as measured by dissolution rates in aqueous solution. Plutonium in the immobilized form cannot be extracted and purified by currently existing standard processes, such as the PUREX process. Significant changes in the head end processing would be required.

The immobilization form is capable of incorporating "high-fired" plutonium oxide with nominal particle sizes less than 2 millimeters, preferably less than 150 microns, in diameter, directly into the form. The immobilization form is capable of incorporating a wide variety of impurities relevant to the plutonium disposition mission, up to 55.7 wt %. Compositions with impurities up to 13 wt% in the product form were tested with no apparent detriment to the form.

Figure 1 shows a preliminary processing regime that defines the compositional space in which the ceramic is generated. The amount of pyrochlore is greater than 50% volumetric fraction, preferably 80% volumetric fraction. The amount of brannerite is up to 50% volumetric fraction, preferably 12%. The amount of zirconolite is up to 50% volumetric fraction, preferably 0%. The amount of rutile is up to 20% volumetric fraction, preferably 8%. The amount of actinide oxide is up to 1% volumetric fraction, preferably less than 0.5%. Other phases may also be present, up to 10% volumetric fraction, preferably 0%. Said other phases can be silicate, whitlockite, monazite, perovskite, magnesium titanate, ilmenite, pseudobrookite, corundum, calcium uranium vanadate, hafnium titanate, magnesium aluminum titanate, magnetoplumbite, or calcium aluminum titanate.

To maintain criticality control, especially where the actinide is plutonium, the ceramic should contain an adequate amount of neutron absorbers (such as hafnium, gadolinium and samarium). The preferred amounts are defined as overall molar ratios of Hf-to-Pu and Gd-to-Pu such that both are equal to or greater than unity.

To depict on a ternary phase diagram the processing regime in which the ceramic is formed (See Figure 1), the number of variables had to be reduced from 6 (the number of oxide components) to 3. Since UO_2 and PuO_2 are known to be interchangeable in the formulation without changing the compositional phase boundaries, they can be considered as one oxide (AnO_2), thus reducing the number of variables to 5. The form is designed to contain excess rutile, which is essentially pure TiO_2 , so its activity is fixed at unity, thus reducing the number of variables to 4. Gd is known to partition relatively evenly between the three primary actinide-bearing phases, pyrochlore, zirconolite, and brannerite. Consequently, the Gd can be factored out without inducing too much error, thus reducing the number of variables to the desired value of 3. The resulting ternary phase diagram is depicted in Figure 1. Perovskite is abbreviated as "Pe." Pyrochlore is abbreviated as "Py." Zirconolite is abbreviated as "Z." Brannerite is abbreviated as "B," and HfTiO_4 is abbreviated as "Hf." The "acceptable" processing regime is identified by the diagonal lined region in Figure 1. In the process planned for actual disposition, UO_2 and PuO_2 will be added to a preblended mixture of the other components. The composition of the preblended mixture would fall at approximately 0.25 units of HfO_2 and 0.75 units of CaO . Addition of UO_2 and/or PuO_2 would cause the resulting mixture to fall on a straight line between this point and the AnO_2 point. The intersection of this imaginary line with the identified "acceptable" processing range indicates that there is a fairly wide range of UO_2 and/or PuO_2 compositions that lie within the "acceptable" range.

Process For Forming Ceramic

Actinides, preferably uranium and plutonium, are first oxidized. The actinides may be oxidized via a process which involves hydriding the actinides to a fine powder, nitriding the hydride powder, and then oxidizing the powder. Those actinide oxides that have not been previously calcined are preferably calcined to remove

moisture and other volatile substances. Calcination temperature is greater than 750 deg C, preferably 950 deg C, in an air or inert atmosphere. The actinides are preferably calcined for about one hour. Preferably a halide removal step to remove halide impurities follows the calcination step. The oxidation process is shown in FIG.

5 3.

The overall immobilization process for actinide oxides is shown in FIG. 4. The actinide oxides, preferably oxides of uranium (UO_2 , U_3O_8 , UO_3) and plutonium (PuO_2), are milled to a fine powder of particle sizes less than 50 microns, preferably nominally 20 microns in diameter. Reduction to this particle size is necessary to ensure essentially complete reaction of the actinide oxides with the ceramic precursors in subsequent sintering operations. Larger particles will only partially react, leaving islands of actinide-rich minerals or unreacted actinide oxide encased in the mineral structure. While this may be acceptable for the desired repository performance, it complicates the form characterization and acceptance for the repository if present in significant quantities. Various means may be used to mill the actinide oxides, ball mills, jet mills and attritor mills being preferred, with attritor mills being the most preferred. The ratio of uranium oxide to plutonium oxide is preferably about 2:1 to ensure the dominant formation of the desired pyrochlore mineral phase.

20 The actinide oxide powder then undergoes a mixing-blending step. During this mixing-blending step, ceramic precursors are blended in. Blending should be on the micro-scale to ensure uniform reaction of the actinides and precursors. If this blending is not adequately performed on the micro-scale, then islands of actinide-rich and actinide-lean mineral forms can result. While these non-uniform products may well be acceptable with regard to repository performance, they will complicate the licensing and repository acceptance process.

25

The above mentioned ceramic precursors comprise neutron absorbers, oxides of titanium, and hydroxides of calcium, preferably TiO_2 and Ca(OH)_2 , respectively. The anatase form of TiO_2 is preferred. Said neutron absorbers comprise hafnium, gadolinium and samarium, preferably hafnium (HfO_2) and gadolinium (Gd_2O_3) in combination. Amounts of Gd_2O_3 and HfO_2 are preferably 8.0 wt% and 10.6 wt %. It is also preferred that the ratio of Gd_2O_3 to PuO_2 and the ratio of HfO_2 to PuO_2 each be greater than or equal to unity. The neutron absorbers are present to ensure criticality control in the final material. More reactive forms of the actinides and ceramic precursors may be used as starting materials, including nitrates, alkoxides and carbonates. However, when these materials are used, they should be converted to oxides in a calcination step before sintering in the final form.

Two different methods of precursor fabrication can be performed depending on the desired final form. For large-scale, production-sized forms, the precursor materials, nominally consisting of TiO_2 , Ca(OH)_2 , Gd_2O_3 , and HfO_2 , are wet mixed, dried, size reduced, and then calcined. For small-scale, development testing forms, the precursor materials may be added to the pre-sized actinide feed and then wet mixed, dried, size reduced, and then calcined. In both cases, the following specifications are applied. The preferred method for wet mixing the precursor materials involves wet ball milling in a high-alumina milling jar with stabilized zirconia grinding media for a minimum of 2 hours. Dry mixing and other methods of wet mixing have been demonstrated, but the process stated above is preferred. After wet mixing, the wet slurry is separated from the grinding media and dried in a oven set at 105°C for approximately 16 hours. Other methods of drying have been demonstrated, but convection drying is preferred. After drying, the material is size reduced to a nominal size less than 1 mm and to ensure reactivity during calcining. The material is then calcined in air between 700 and 800°C , preferably 750°C , for 1

hour for large-scale forms. The overall process is shown in FIG. 5. When small-scale forms are desired and the actinides have already been blended with the precursor materials, the materials are calcined between 600 and 750°C for 1 hour in air. Some classification of the material is required to obtain a flowable powder, the preferred size range is less than 1 mm but greater than 150 μm. In some applications, it is desirable to add the preferred binder to the precursors before they are mixed with the actinides.

Sintering aids in amounts ranging from 0.1 to 5 wt% may be blended with the precursors and actinides to facilitate the sintering process. Preferred sintering aids include B₂O₃, Al₂O₃, SiO₂, and Alkali and Alkaline earth oxides, halides, sulfates, and hydroxides. Halides include fluorides, chlorides, bromides and iodides. Alkalis include lithium, sodium, potassium, rubidium and cesium. Alkaline earths include magnesium, calcium, strontium and barium. High loadings of ²³⁸U are intended to ensure additional criticality control in the ceramic form through limitation of ²³⁵U/²³⁸U ratio as ²³⁹Pu decays to ²³⁵U in the long term.

Blending of the ceramic precursors with the actinide oxides can be accomplished in several ways. One way is to use ball-milling with an aqueous vehicle. Good blend has been achieved on the scale necessary to ensure uniform mineral products. However, the addition of water to the process complicates criticality control and necessitates additional processing steps. An alternate technique, which is being developed for plant use for ceramic formation, is the use of a high-energy device such as an attritor mill. The mill provides the additional energy necessary to break up the agglomerated particles of the plutonium and uranium oxide for blending on a micro-scale. Additives (dispersants) are preferably added to enhance flowability and reduce holdup of the mill. Examples of these additives include ethylene bis-stearamide, polyolefin, stearic acid, citric acid and monoisopropanol-

amine.

Two methods of mixing the precursors with the actinides have been tested. The first method involves first grinding the actinides and then mixing in the precursors in a separate attritor mill. The second method utilizes one large mill to

5 grind the actinides and mix them with precursor material at the same time. In a one-gallon high-speed attritor mill, which has been used for most of the testing, agitator speeds range from 600 to 1100 rpm with a preferred running speed of approximately 950 rpm. Acceptable milling media size is two to five-millimeter spheres, preferably five-millimeter media. The milling media is zirconia, aluminum oxide, depleted

10 uranium, stainless steel, or ceramic, preferably stabilized zirconia, most preferably zirconia stabilized with yttria. To scale up the process for use in larger attritor mills, the parameter to be held constant is the tip speed. For a given rpm, the edge of the agitator arm in the larger mill will be moving faster than in the smaller mill. This will affect how the powder is worked. Thus it is important that the tip speed of the agitator

15 arms is matched when using larger mills. Milling and/or mixing times range from three to twelve minutes with a preferred run time of five minutes. Generally, the run time is increased by two to three minutes if the material is being milled and mixed in the same attritor. The five-minute run time has been used for batches ranging from five hundred grams to one thousand grams of material. Higher milling rpms will

20 generally result in greater uniformity of particle size and shorter run times. Milling and mixing times need to be sufficiently long to achieve the desired particle size and for a homogenous mix. Excessively long mixing times may result in demixing, wherein the constituents begin to separate. Each time the attritor is run a small amount of dispersant is added to the powder to maintain powder flowability. The

25 amount is dependent upon the type used, but ranges from one-tenth of a percent to five percent based on the batch weight, preferably in the range of 0.5 to 3%.

Preferably, either one-half weight percent of ethylene bis-stearamide or three weight percent of polyolefin are used. The additive is used in the same amounts whether the actinides are milled independently and then mixed, or co-milled and mixed.

The mixture is then granulated to facilitate uniform flow into a press die set.

5 During the granulation step, binder and lubricant materials are added. Acceptable granules have been formed with hydroxy-propyl methylcellulose and/or polyethylene glycol added in a water emulsion as the binder. The preferred binder will have the following proportions: 0.5 to 2 wt% hydroxy-propyl methylcellulose, 0.5 to 5 wt% polyethylene glycol, and 0.5 to 10 wt% water. The preferred lubricants include

10 ethylene bis-stearamide and polyolefin. Granulation is preferred because of the tendency for the finely milled blend to clump, and the milled blend is difficult to meter and transfer to the press system. In addition, handling of such finely milled powder presents the possibility of excess dusting when the milled and blended powder is removed from the contained powder preparation unit. Once granulated, the

15 blended milled product is easily transferred, metered, and stored and is relatively dust-less during handling. A "V" shell blender, a blade granulator, a fluid bed, a pin mixer, a slant double cone blender, and a roll compactor have been used for granulation and have all been shown to meet the flowability criteria. In some applications, lubricants are not added to the powders and are instead applied to the die

20 walls. Studies have shown that ten weight percent oleic acid added to acetone is an acceptable external lubricant.

The granulated mixture is then poured into a press die set and cold pressed at a pressure range of 1,000 - 20,000 psi, preferably at 2,000 psi for large-scale ceramic forms. This greatly minimizes die wear and press operation difficulties. However,

25 due to the low pressing force, the resulting green ceramic materials can be relatively fragile until they are sintered, and some care should be taken in handling. Since the

sintering used for ceramic formation is reactive sintering, relatively low green densities are required for the cold pressing operation product. Theoretical maximum sintered density is about 5.91 g/cm^3 . Actual densities obtained are usually greater than 90% of theoretical .

5 When binders or lubricants are used, a binder burn-out stage should be used in the sintering cycle. The preferred temperature range of this step is 100 to 300°C and the preferred time is one-half to 3 hours. This stage is necessary to thoroughly dry the ceramic and decompose the binder and lubricants added.

10 The pressed mixture is reactively sintered at a temperature in the range of 1200 - 1500 deg C, for 1 - 8 hours. The sintering atmosphere should be air, or an inert atmosphere such as helium, neon, argon, krypton or xenon, or a reducing atmosphere comprising 5%CO and 95% CO₂. It is preferred that the sintering occur in an air atmosphere. It is preferred that the sinter temperature be 1350 deg C and the temperature held for four hours. The sintered ceramic may then be cooled to room
15 temperature. The sintering process results in densification of the material and formation of the desired microstructure and mineral phases.

 Following immobilization of the actinides in ceramic form, the ceramic may be loaded into cans. The cans may then be loaded into canisters, with high level waste glass poured into the canisters around the cans.

20 Experimental Results and Discussion

 The starting materials are research-grade oxide powders (hydroxide powder, in the case of calcium) in the micrometer size range. The composition of the baseline ceramic (in weight %) is as follows: CaO-10.0; TiO₂-35.8; HfO₂-10.6; Gd₂O₃-8.0; UO₂-23.7; and PuO₂-11.9. Note that the anatase form of TiO₂ is used. On a molar
25 basis the following substitutions can be made without significantly affecting the product mineralogy or product properties:

PuO_2 can be replaced with CeO_2 , UO_2 , and/or ThO_2

UO_2 can be replaced with PuO_2 , CeO_2 and/or ThO_2

HfO_2 can be replaced with ZrO_2

Gd_2O_3 can be replaced with Sm_2O_3 .

5 In small-scale, form development testing, these powders are wet-mixed for one hour using a ball mill with Al_2O_3 or ZrO_2 grinding media and deionized water. They are then separated by sieving and flushing with water and are dried overnight at about 90 deg C in air. The dried powder is then size-reduced and calcined at 750 deg C for one hour in either argon or air atmosphere. It is then cold-pressed in a steel die
10 at about 11,400 psi into cylindrical pellets, typically 1.27 cm in diameter, with length-to-diameter ratio less than one. Between pressings, the steel die is coated with a thin layer of about 10 wt % oleic acid in acetone as a die lubricant. No binders are used. The pellets are placed on platinum foil (recent practice) or on a thin layer of alumina or zirconia powder (earlier practice) and are then reaction-sintered in argon
15 atmosphere (commercial purity) at 1350 deg C for 4 hours. Some samples are fired in an air atmosphere or 5% CO in a balance of CO_2 . The fired densities are routinely evaluated using weight and geometric size, and are typically 90% of the calculated theoretical maximum density or higher. Phase composition is routinely evaluated by X-ray diffraction analysis (XRD) and scanning electron microscopy (SEM)—energy
20 dispersive spectrometry (EDS). Detailed analysis by electron microprobe is performed on select samples.

 In large-scale, production form testing, the precursor powders are wet-mixed for a minimum of two hours using a ball mill with ZrO_2 grinding media and deionized water. They are then separated by sieving and flushing with water and are dried
25 overnight at about 105 deg C in air. The dried powder is then size-reduced and calcined at 750 deg C for one hour in an air atmosphere. The calcined precursors are

then blended with the actinide oxides using either wet ball milling for a minimum of two hours or dry attritor milling for a minimum of three minutes. When wet ball milling is used, the powder is dried again at 105°C and size reduced. Granulation of the blended material is then performed with addition of binders. Lubricants may also be added during the granulation step. The granulated powder is then cold-pressed in a steel die at about 2,000 psi into pucks, typically 8.89 cm in diameter and 3.18 cm in thickness. When an internal lubricant is not used, the steel die is coated with a thin layer of about ten weight percent oleic acid in acetone between pressing. The pucks are placed on refractory with a thin layer of alumina or zirconia powder or on zirconia coated refractory. The pucks are then reaction-sintered in an air atmosphere at 1350 deg C for 4 hours. The fired densities are routinely evaluated using weight, geometric size, and immersion volume, and are typically 90% of the calculated theoretical maximum density or higher. Phase composition is routinely evaluated by X-Ray Diffraction analysis (XRD). Detailed analysis by Scanning Electron Microscopy (SEM)-Energy Dispersive Spectrometry (EDS) and electron microprobe is performed on select samples.

Unsintered disc sizes range from 1.27 to 8.89 cm in diameter, and 0.25 to 3.18 cm in thickness. Sintered disc sizes range from 0.5 to 6.67 cm, and 0.12 to 2.39 cm in thickness.

20 Baseline Formulation Chemistry

The pyrochlore-based baseline product form is observed to be composed of about 80 vol % pyrochlore, about 12 vol % brannerite, and about 8 vol % rutile. Zirconolite can also be present, but it is not generally observed when the sample is well reacted and when there are no feed impurities present. Pyrochlore and zirconolite are very closely related minerals. The primary difference in the structures arises from the way the characteristic layers of TiO_6 octahedra are stacked. Zirconolite actually

has several structural polytypes that also differ in the way the characteristic layers are stacked: zirconolite-2M, zirconolite-3T, and zirconolite-4M (polymygnite) to name those that have actually been observed in this ceramic form. The number corresponds to the number of layers before the stacking repeats itself and the letter stands for the
5 crystal symmetry, M for monoclinic and T for trigonal. When the layers are aligned in a body-centered fashion, the pyrochlore phase is formed.

The phase relationship between pyrochlore and zirconolite and its polytypes is one important part of defining the baseline formulation. To depict the phase relationships, a pseudo-ternary diagram is given in Figure 2. The end points are
10 zirconolite ($\text{CaZrTi}_2\text{O}_7$ or $\text{CaHfTi}_2\text{O}_7$), Pu-pyrochlore ($\text{CaPuTi}_2\text{O}_7$ or its surrogate $\text{CaCeTi}_2\text{O}_7$), and U-pyrochlore (CaUTi_2O_7). The open points are data from Ce-loaded samples, and the solid points are data from the Pu-loaded samples. The squares contain Hf and Zr and the diamonds contain U only. The circles are data from the Zr-loaded samples, and the triangles are from the Hf-loaded samples. Many of the
15 samples contain Gd, which had to be factored out in order to depict all the data on one ternary diagram. For simplicity the Gd was all assumed to be entirely on the Ca site, which is accurate in many cases. As a result of this assumption, Figure 2 is more correctly described as a ternary plot consisting of the three components, (1) Pu or Ce, (2) Hf or Zr, and (3) U. The baseline composition in this diagram is at approximately
20 0.49 units of U, 0.25 units of Pu, and 0.26 units of Hf.

Figure 2 clearly shows that the equilibrium phase behavior of Hf and Zr and of Ce and Pu are for all practical purposes indistinguishable. Closer inspection reveals that the equilibrium phase behavior of U is also identical to that of Ce and Pu, i.e. the pyrochlore phase boundary is independent of the total U, Pu, and Ce composition.
25 Note that with a comparable offset adjustment in the U-loading, the Pu-loading in the form can be adjusted anywhere from 0 to about 32% without appreciably changing

the mineralogy in the baseline form. The regime above 0.7 units of Ce, Pu, and U is the pyrochlore single-phase regime. The region above about 0.8 units of Hf and Zr is the single phase zirconolite regime (-2M). There is some scatter in the zirconolite boundary. This is due at least in part to a temperature effect. At around 1400 deg C, the boundary appears to be closer to about 0.75 formula units, and at around 1200 deg C, the boundary appears to be closer to about 0.85 formula units. An intermediate phase generally occurs at about 0.5 formula units of Hf or Zr. This is the zirconolite-4M phase. This phase is generally not observed in samples with impurities.

Microprobe analyses on a number of samples have been averaged to give the nominal atomic compositions of the primary phases in the ceramic form. The nominal atomic compositions are given in Table I. For zirconolite and pyrochlore, the total metal composition is normalized to 4. For brannerite, the total metal composition is normalized to 3, and for rutile and actinide oxide, it is normalized to unity. The corresponding amount of oxygen based on the assumed oxidation states shown is given in the O equivalent column. In the ideal structures, the oxygen equivalents for pyrochlore, zirconolite, brannerite, rutile, and actinide oxide are 7, 7, 6, 2, and 2, respectively.

Table I.
Elemental compositions in baseline form

Phase	Ca	Gd	Hf	U	Pu	Ti	Al	Total Metal	O equiv.
Pyrochlore	0.905	0.217	0.265	0.432	0.237	1.905	0.037	4.00	6.964
Zirconolite	0.741	0.147	0.839	0.133	0.116	1.842	0.181	4.00	7.093
Brannerite	0.071	0.110	0.135	0.534	0.212	1.888	0.050	3.00	5.849
Rutile	0.000	0.000	0.083	0.010	0.000	0.900	0.007	1.00	1.997
Actinide oxide	0.079	0.045	0.029	0.426	0.381	0.015	0.025	1.00	1.886
Assumed oxidation state	2+	3+	4+	4+	4+	4+	3+		

5 One of the interesting features in the compositions shown in Table I is that although the phase boundaries appear to be the same for the use of either UO_2 or PuO_2 in the formulation, the elemental partitioning between the phases is different. Notice that U is enriched relative to Pu in the brannerite phase and depleted relative to Pu in the zirconolite phase. These enriched and depleted relationships are based on
10 comparison to the approximate 2-to-1 ratio of U-to-Pu in the dominant pyrochlore phase, which corresponds to the U-to-Pu ratio in the ceramic composition as a whole.

Actinide Oxide Dissolution Kinetics

15 Dissolution of "high-fired" PuO_2 or PuO_2/UO_2 into the ceramic form seems to be affected significantly by temperature, process impurities, and thoroughness of mixing, and to a lesser extent by the relative abundance of the primary phases. Note that all "high-fired" PuO_2 used in these tests was heated to 1000 deg C for 4 hours in an air atmosphere and all the "high-fired" PuO_2/UO_2 was heated to 950 deg C for 2 hours in an argon atmosphere.

In earlier formulation work, a zirconolite-rich formulation was being developed, and data on actinide dissolution kinetics was obtained for this formulation. In addition to the matrix phase of zirconolite, the form contained Ba-hollandite, rutile, and pyrochlore. In this set of experiments performed at LLNL, the "high-fired" PuO₂ was sieved through a 600 mesh sieve (i.e., the particles were less than 20 microns diameter) and the precursors were then dry mixed by hand in a V-shaped mixer. A half dozen pellets were pressed at between 30 and 80 MPa and fired at 1300 deg C for 4 hours. After the first firing, the product densities varied from about 89 to 96% of the theoretical maximum (4.9 g/cm³). The samples were then separated into 3 pairs and fired at 1300, 1350, or 1400 deg C for 4 hours. One of each pair was then subjected to a simulated DWPF thermal cycle. Results of the thermal treatment tests are discussed later. All of the product pellets were analyzed using the SEM/microprobe. The pellets with the 1300 deg C final firing temperature had large chunks of "unreacted" PuO₂ up to about 20 microns in diameter. The PuO₂ is termed "unreacted" in this case since it was found to be essentially pure PuO₂. The pellets fired at 1350 deg C had a small amount of "reacted" PuO₂, typically 3 microns in diameter or less. The PuO₂ is termed "reacted" in this case because it was found to contain significant and consistent amounts of Gd and Zr. Only one "reacted" PuO₂ grain barely larger than 2 microns diameter was found in the sample with the final firing temperature of 1400 deg C. From these data it is clear that 1300 deg C is an inadequate temperature to achieve PuO₂ dissolution into the zirconolite-rich ceramic form. However, 4 hours at 1350 deg C appears to be adequate time and temperature to achieve dissolution of PuO₂ particles up to about 20 microns in diameter into the zirconolite-rich ceramic matrix. Apparently, the reaction kinetics increase significantly between 1300 and 1350 deg C. It is not known for certain, but the significant increase in reaction kinetics is believed to be the result of a minor liquid phase that forms at temperatures

greater than about 1325 deg C.

The current baseline formulation is pyrochlore-rich not zirconolite-rich. In more recent work performed at ANSTO, a mixture of "high-fired" PuO_2/UO_2 (1 part Pu per 2 parts U) was dry-milled with ceramic precursors, pressed into pellets at
5 about 90 MPa and fired at temperatures ranging from 1275 to 1400 deg C for 4 hours. The PuO_2/UO_2 feed material was composed of a number of large agglomerates greater than 10 microns but less than about 20 microns in diameter. Most firings were performed in an argon atmosphere, but some were performed in air. The results suggest that the particle size requirements for the pyrochlore-based form are less
10 stringent than for the previously mentioned zirconolite-rich form. Enhanced dissolution was generally observed as the temperature was increased, but even at 1300 deg C the PuO_2/UO_2 dissolution was satisfactory, much better than in the previously mentioned work on the zirconolite-rich formulation. All residual PuO_2/UO_2 in the pyrochlore-rich ceramic form fell into the category of "reacted," i.e.,
15 it contained significant and relatively consistent amounts of Gd and Hf.

Two other important general observations have been made. First, the residual "reacted" PuO_2/UO_2 in the pyrochlore-rich formulation is essentially always observed to be encapsulated within the brannerite grains. This indicates that by decreasing the amount of the brannerite component in the formulation, enhanced PuO_2 and/or UO_2
20 dissolution can be obtained. Second, feed impurities such as silica enhance PuO_2 and/or UO_2 dissolution considerably. Since feed impurities can also aid densification, their presence in limited quantities can be advantageous to the ceramic form. Note that although a reactive "low-fired" PuO_2 was never tested, it has been found that a sufficiently small PuO_2 and/or UO_2 particle size and good mixing are more than
25 sufficient to achieve dissolution of PuO_2 and/or UO_2 into the ceramic form. Therefore, any enhanced dissolution into the ceramic form that could be gained by using "low-

fired" PuO₂ is not required.

Feed Impurity Tolerances

Tolerance of the ceramic form to the range of feed impurities expected is an
5 important part of making the ceramic form a viable and attractive candidate for Pu
disposition. A relatively large amount of work was conducted in this area at LLNL,
SRS, and ANSTO. A set of 10 Pu-sample compositions and 10 Ce-sample
compositions were prepared according to the general procedure described in the
experimental section. Pu-sample compositions are given in Table II. Composition A-0
10 is the baseline ceramic form. Compositions A-1 to A-6 correspond to various general
categories of feed material that are expected. A-1 corresponds to typical impure
oxides. Nominally about 5 metric ton (MT) of currently declared U.S. excess Pu falls
into this category. A-2 corresponds to the composition of Pu from the Zero Power
Physics Reactor (ZPPR) plates. Nominally about 3 MT of current excess Pu falls into
15 this category. A-3 corresponds to the composition of atypical impure metal.
Nominally about 2 MT of current excess Pu falls into this category. A-4 corresponds
to the composition of atypical clean metal. Nominally about 1 MT of current excess
Pu falls into this category. A-5 corresponds to the composition of U/Pu oxides.
Nominally about 1 MT of current excess Pu falls into this category. A-6 corresponds
20 to the composition of Pu alloys. Nominally about 1 MT of current excess Pu falls
into this category. A-7 is an overall estimated average composition for the 17 MT
excess Pu case. A-8 is an estimated most extreme case. A-9 is an intermediate case
between A-7 and A-8 that corresponds roughly to one of the extreme compositions
tested in the competing glass formulation work.

Table II.

Compositions of samples fabricated in the feed impurity tests.

(Totals may not exactly equal 100% because of rounding)

5

	A-0	A-1	A-2	A-3	A-4	A-5	A-6	A-7	A-8	A-9
	wt %	wt %	wt %	wt %	wt %	wt %	wt %	wt %	wt %	wt %
Base Feed Materials										
CaO	9.95	9.67	9.89	9.73	9.92	9.85	9.83	9.80	8.65	9.44
TiO ₂	35.87	34.88	35.64	35.08	35.77	35.50	35.43	35.34	31.20	34.04
HfO ₂	10.65	10.35	10.58	10.41	10.62	10.54	10.52	10.49	9.26	10.11
Gd ₂ O ₃	7.95	7.73	7.90	7.77	7.93	7.87	7.85	7.83	6.91	7.54
UO ₂	23.69	23.03	23.54	23.17	23.63	23.45	23.40	23.34	20.60	22.48
PuO ₂	11.89	11.56	11.81	11.63	11.86	11.77	11.75	11.71	10.34	11.28
Impurities										
Al ₂ O ₃		0.63	0.20	0.22		0.11	1.04	0.32	1.59	0.50
MgO		0.19		0.23	0.02	0.46	0.18	0.13	0.87	0.44
CaCl ₂		0.37						0.16	2.19	0.66
Ga ₂ O ₃				1.27	0.14			0.14		0.57
Fe ₂ O ₃		0.17		0.14		0.16		0.08	0.50	0.15
Cr ₂ O ₃		0.04		0.02				0.02	0.13	0.08
NiO		0.08		0.09				0.04	0.33	0.13
CaF ₂		0.21						0.12	1.30	0.44
K ₂ O		0.15		0.04				0.07	1.05	0.32
Na ₂ O		0.16						0.06	0.47	0.14

MoO ₂		0.05	0.44			0.30		0.11	0.47	0.28
SiO ₂		0.51						0.19	1.50	0.46
Ta ₂ O ₅		0.05		0.15				0.06	0.64	0.19
B ₂ O ₃		0.04							0.34	0.17
WO ₂		0.14		0.06					1.64	0.49
ZnO					0.11			0.01		0.07

Sample preparation and characterization work was shared among the various participating sites. Samples A-1 to A-6 were generally prepared only at one site, whereas samples A-0, A-7, A-8, and A-9 were prepared at two or three different sites.

5 At least one Ce-sample and one Pu-sample of each composition were successfully prepared. All of the Ce-samples and most of the Pu-samples have since been characterized to determine the product phase assemblages. All of the samples reacted well and formed pyrochlore as the dominant phase, even sample A-8 which had 13 wt % total impurities in the product. Several trends were observed. Si could not be

10 incorporated significantly into any of the primary ceramic phases. SiO₂ forms a separate glassy phase that contains significant amounts of Ca, Al, Ti, and other impurities but little or no Pu or U. Excess amounts of Al in the feed also increase the likelihood of the glass phase formation. The same effect seems to be observed for P. P₂O₅ was not intentionally added to the form, but was found to be present at about

15 200 ppm in the TiO₂ starting material. P₂O₅ forms a separate phase (presumably whitlockite) that is rich in Ca and P. In general, all other impurities were either vaporized or accommodated into at least one of the primary ceramic phases.

Compositions that were low in impurities produced ceramics that were for the most part rich in brannerite and lean in zirconolite, and compositions that were rich in

20 impurities produced ceramics that were for the most part lean in brannerite and rich in

zirconolite. As mentioned earlier, the impurities seem to enhance the reaction kinetics considerably. Compositions with the highest impurity levels had the least amount of actinide oxide in the product, as low as 0.04 vol %, and compositions with the lowest impurity levels had the greatest amount of actinide oxide in the product, as high as 0.6 vol %. Based on image analysis of the SEM images obtained, the compositional range observed in the suite of impurities tests was as follows: pyrochlore-62 to 90 vol %, brannerite-0 to 22 vol %, zirconolite-0 to 25 vol %, rutile-0 to 16 vol %, actinide oxide-0.004 to 0.6 vol %, and silicate glass-0 to 6 vol % as shown in Table III.

Note that these samples were fired at 1350 deg C for 4 hours in an argon atmosphere. Sample compositions with CeO₂ used 0.634 times the PuO₂ mass listed in order to keep the molar compositions the same.

TABLE III
Product Mineralogy

Mineralogy	Baseline	Observed Range	Acceptable Range
	(vol %)	(vol %)	(vol %)
Pyrochlore	80	62 - 90	> 50
Brannerite	12	0 - 22	0 - 50
Zirconolite	0	0 - 25	0 - 50
Rutile	8	0 - 16	0 - 20
Actinide Oxide	0.5	0.04 - 0.6	0 - 1
Silicate and other phases	0	0 - 6	0 - 10

Many of the samples were analyzed by electron microprobe analysis. These data were used to generate the preliminary partitioning coefficients given in Table IV. As is readily seen, the more common impurities, namely Al, Cr, Fe, Ni, Ga, and Mg,

partition preferentially into zirconolite. A few impurities partition preferentially into the pyrochlore phase, namely Mo, Ta, and W. Na, K, and Zn tend to vaporize and/or to partition into the silica-rich glassy phase, but the little that remains in the primary phases does seem to partition selectively. Some data are also given for the relative partitioning of impurities into brannerite compared to pyrochlore. With the possible exception of Ni and Zn, the impurities do not seem to partition significantly into the brannerite phase.

Table IV.

Approximate partitioning coefficients for various impurities.

10

Element	$X_{\text{zirconolite}}/X_{\text{pyrochlore}}$	$X_{\text{brannerite}}/X_{\text{pyrochlore}}$
Al	16	2.3
Cr	15	---
Fe	3	1
Ga	>30	---
K	<0.05	---
Mg	3.0	<0.1
Mo	0.10	0.20
Na	<0.1	0.2
Ni	1.5	2
Ta	<0.1	<0.1
W	0.020	---
Zn	4	5

The partitioning coefficient is given as the mole fraction of the element in the phase of interest divided by the mole fraction of the element in the pyrochlore phase

The maximum impurity levels demonstrated are as shown in Table V.

Table V

Maximum Impurity Levels Demonstrated

Impurity	Product Concentration (wt %)	Equivalent Feed Concentration (wt %)
Al ₂ O ₃	10.0	48.3
B ₂ O ₃	1.0	7.8
BaO	2.3	16.3
CaCl ₂	2.19	15.8
CaF ₂	10.0	48.3
CaO	10.0	48.3
Cr ₂ O ₃	10.0	48.3
Cu ₂ O	10.0	48.3
Fe ₂ O ₃	10.0	48.3
Ga ₂ O ₃	15.3	60.2
K ₂ O	1.05	8.9
MgO	10.0	48.3
MnO ₂	10.0	48.3
MoO ₃	10.9	50.7
Na ₂ O	0.47	4.3
Nb ₂ O ₅	10.7	50.2
NiO	10.0	48.3
P ₂ O ₅	5.1	31.0
PbO	0.5	4.2
SiO ₂	1.50	12.7
SnO ₂	4.1	26.6
Ta ₂ O ₅	13.0	55.8
WO ₃	16.4	62.3
ZnO	10.0	48.3
Max. Tot.	13.0	55.7

- 5 Max. Tot. is the maximum combined total of impurities that was tested. Product concentration is the concentration of the impurity in the immobilized product. Equivalent feed concentration is the equivalent feed concentration of the impurity in

the PuO₂ feed.

Stability with Respect to the DWPF Pour

Since it is planned that cans containing the ceramic will be enveloped in molten glass during the glass pouring operation at the DWPF, it is important to know
5 that the ceramic will remain stable during this process. Tests in this area fell into two basic areas, evaluation of potential mineralogical and compositional changes during the heating and the slow cool-down, and evaluation of potential cracking during the rapid heat-up.

The heating and slow cool-down process was simulated by heating the product
10 forms to between 1000 and 1200 deg C and cooling at between 1 and 2 deg C per minute. In every case, no mineralogical change was observed. Phase compositions before and after thermal treatment were analyzed by electron microprobe or quantitative EDS analysis. In every case, there was little or no compositional change. Any small compositional differences observed were well within the statistical
15 variations expected. Compositions before and after one of the thermal treatment tests are given in Table VI. In this particular test, the previously mentioned zirconolite-rich samples were used. These were the samples with the final firing temperature of 1350 deg C. One of the two samples was then subjected to a simulated DWPF thermal heating and cooling cycle: heat to 1000 deg C, hold for 15 minutes, cool to 500 deg C
20 at 2 deg C per minute, then cool to ambient at 1 deg C per minute or slower. There were five phases in the sample: zirconolite, pyrochlore, rutile, hollandite, and "reacted" PuO₂. Only the compositions for the Pu-bearing phases are given in Table IV. Under the column of DWPF, a "no" means that the data are from the sample that was not subjected to the simulated DWPF thermal cycle and a "yes" means that the
25 data are from the sample that was subjected to the simulated DWPF thermal cycle. Note that the compositional analyses are surprisingly close, even for the "reacted"

PuO₂.

A test was also performed in which molten DWPF-type glass was heated to about 1100 deg C and was then poured directly onto bare non-radioactive ceramic pellets to determine qualitatively how badly the ceramic would crack because of the thermal shock. In short, the cracking was minimal. Out of 7 pellets, ranging from 2.5 to 4 cm in diameter, only one pellet cracked into two separate pieces. All the other pellets remained intact, with little or no observed cracking.

Table VI

10 Effect of DWPF heating and cooling cycle on mineralogical composition.
(Compositions determined by electron microprobe analysis. Totals may not exactly match final column because of rounding))

Phase	DWPF	CaO	BaO	GdO _{1.5}	ZrO ₂	PuO ₂	TiO ₂	AlO _{1.5}	Total
Zirconolite	No	0.612	0.000	0.238	0.799	0.194	1.757	0.399	4.000
Zirconolite	Yes	0.633	0.000	0.234	0.805	0.201	1.732	0.394	4.000
Pyrochlore	No	0.713	0.022	0.255	0.225	0.617	2.131	0.037	4.000
Pyrochlore	Yes	0.739	0.037	0.238	0.230	0.622	2.089	0.045	4.000
PuO ₂	No	0.000	0.007	0.044	0.188	0.717	0.044	0.000	1.000
PuO ₂	Yes	0.000	0.008	0.044	0.186	0.724	0.040	0.000	1.000

15 From the data on impurity effects it is possible to generate a preliminary set of feed impurity specifications. It was learned that most impurities fell into one of four

categories: (1) volatiles, (2) zirconolite stabilizers, (3) pyrochlore stabilizers, and (4) glass formers. The preliminary specification limits are given in Table VII. The limits given are all based on impurity sample A-9 (5.1 wt % impurities in the product) except for the limit on pyrochlore stabilizers, which is based on sample A-8 (13 wt % impurities in the product). The limits are reported in total moles per mole of PuO_2 . Molar ratio is used rather than weight ratio since the impurities substitute into the ceramic form on an atomic basis and not on a weight basis. It is expected with further testing that the draft limits given in Table VII can be relaxed considerably.

10

Table VII.

Preliminary specification limits on feed impurities.

Category	Moles per mole PuO_2	Impurities
Volatiles	0.60	NaCl , KCl , CaCl_2 , CaF_2 , MgF_2 , etc.
Zirconolite stabilizers	0.75	$\text{AlO}_{1.5}$, $\text{FeO}_{1.5}$, $\text{GaO}_{1.5}$, $\text{CrO}_{1.5}$, MgO , ZrO_2 , HfO_2 , etc.
Pyrochlore stabilizers	0.40	WO_2 , MoO_2 , $\text{TaO}_{2.5}$, $\text{NbO}_{2.5}$
Glass formers	0.30	SiO_2 , $\text{BO}_{1.5}$

15

Obviously numerous modifications and variations of the present invention are possible in the light of the above teachings. It is therefore to be understood that within the scope of the appended claims the invention may be practiced otherwise than as specifically described therein.

PROCESS FOR MAKING A CERAMIC COMPOSITION FOR
IMMOBILIZATION OF ACTINIDES

ABSTRACT OF THE DISCLOSURE

Disclosed is a process for making a ceramic composition for the immobilization of actinides, particularly uranium and plutonium. The ceramic is a titanate material comprising pyrochlore, brannerite and rutile. The process comprises oxidizing the actinides, milling the oxides to a powder, blending them with ceramic precursors, cold pressing the blend and sintering the pressed material.

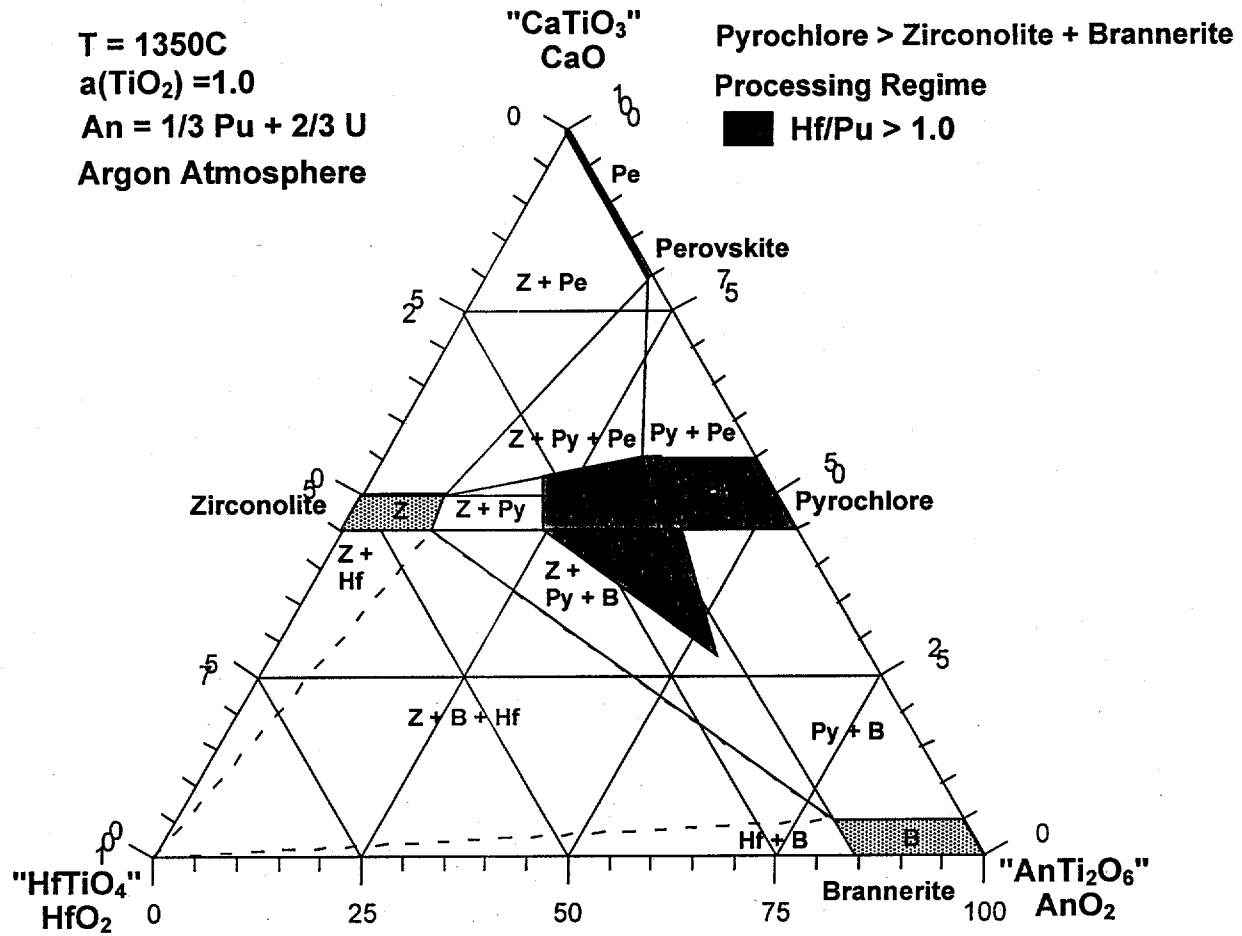


FIG. 1
 Depiction of the processing regime.

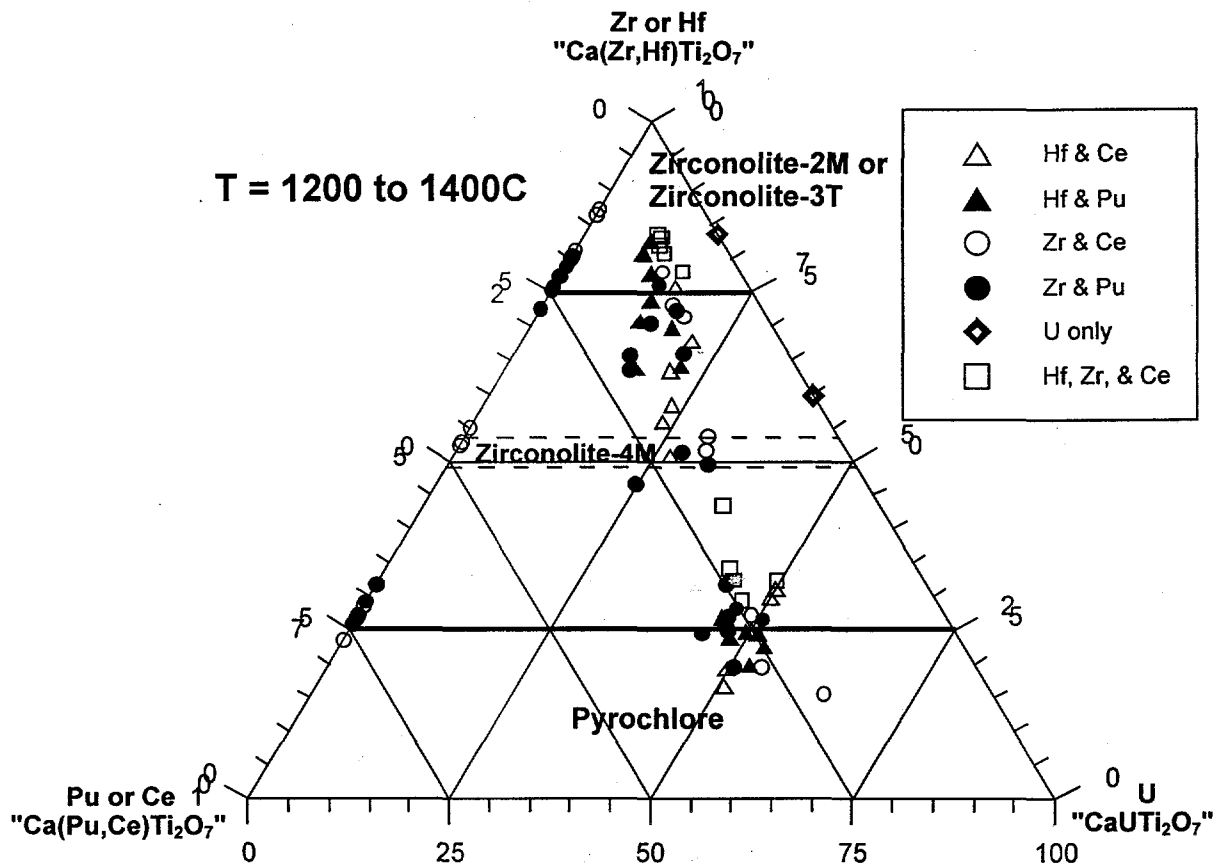


FIG. 2
Phase boundaries in the system Ca(Hf,Zr)Ti₂O₇-Ca(Pu,Ce)Ti₂O₇-
CaUTi₂O₇.

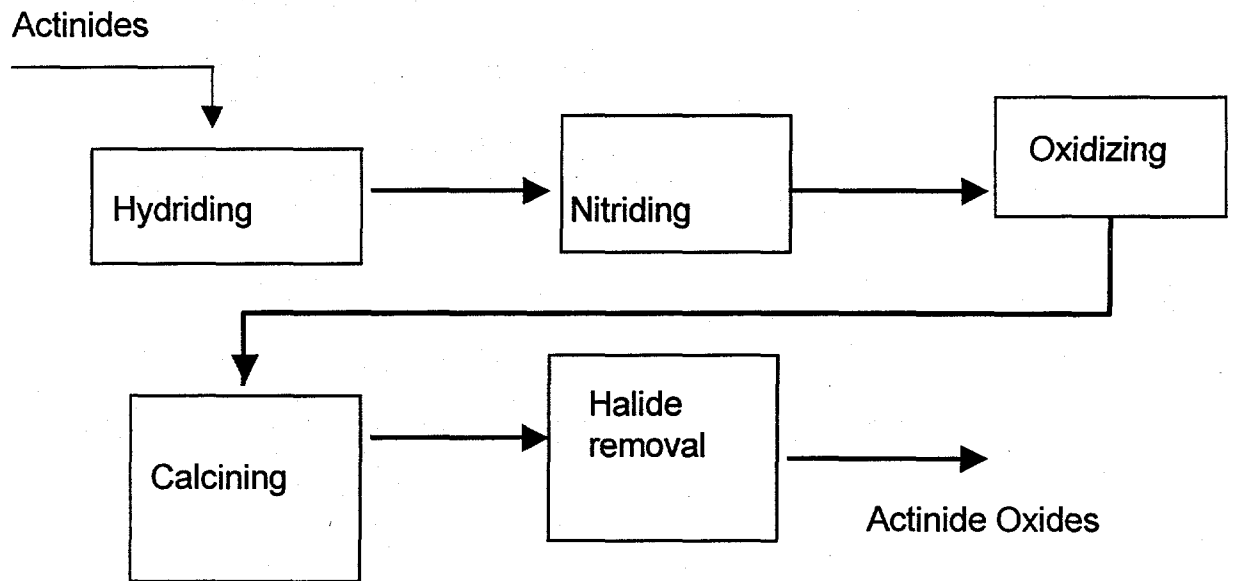


FIG. 3
Flow Diagram of Actinide Oxidation Process

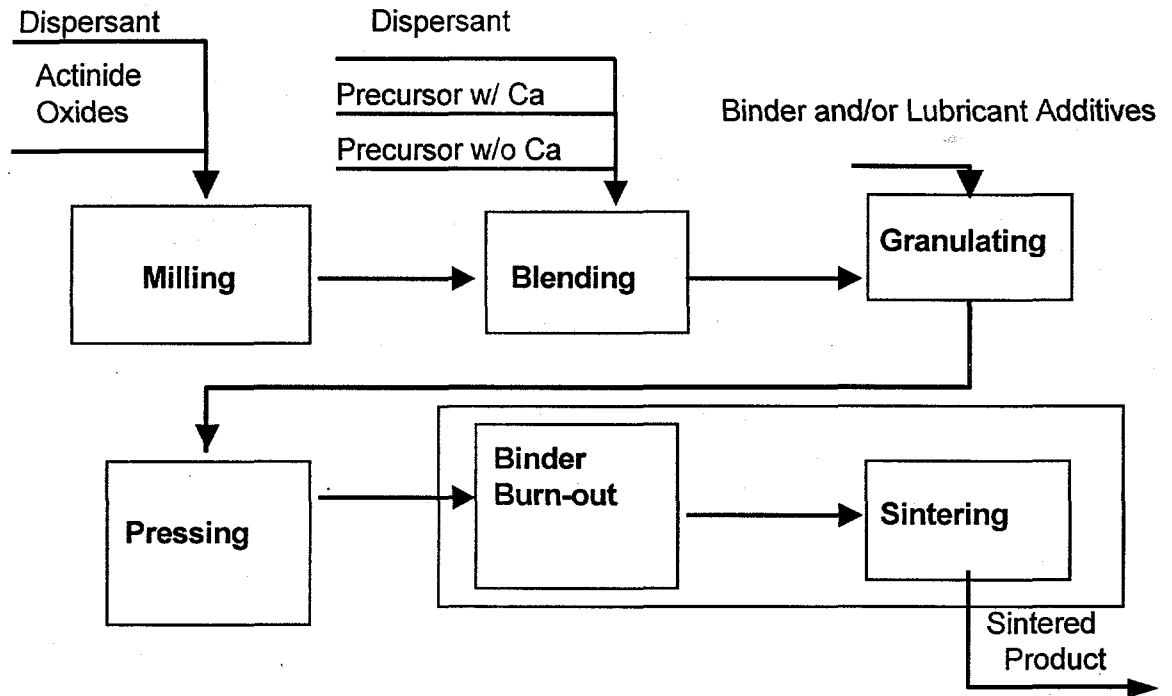


FIG. 4
Flow Diagram of Immobilization Process
(Actinide Oxides)

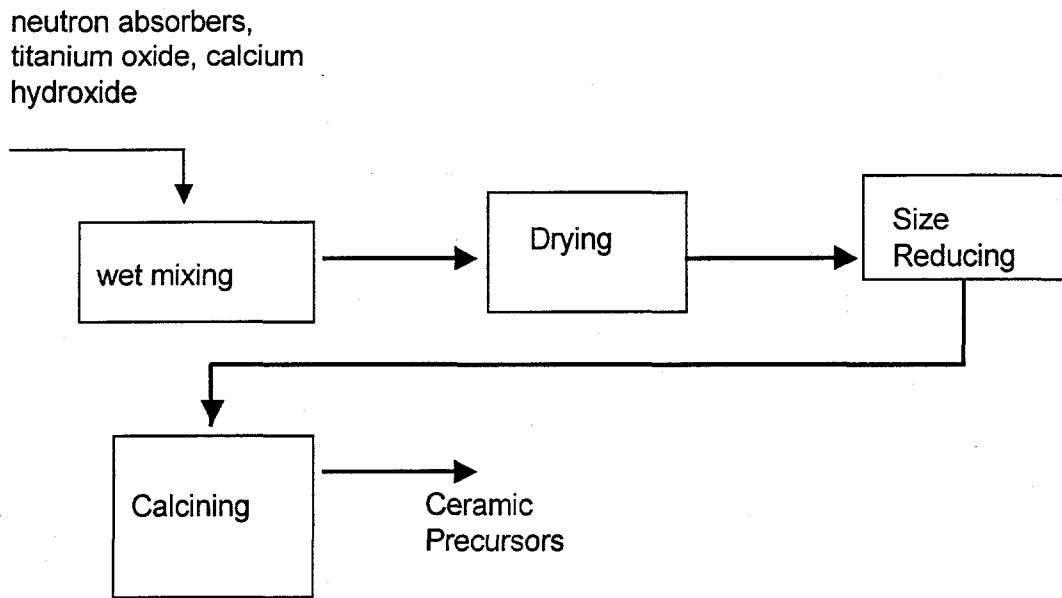


FIG. 5
Flow Diagram of Ceramic Precursor Fabrication