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(71) Applicant: **WESTINGHOUSE ELECTRIC COMPANY LLC** [US/US]; 1000 Westinghouse Drive, Suite 141, Cranberry Township, Pennsylvania 16066 (US).

(72) Inventors: **LAHODA, Edward J.**; 116 Washington Street, Edgewood, Pennsylvania 15218 (US). **SHAH, Hemant**; 120 Cowdray Park, Columbia, South Carolina 29223 (US). **XU, Peng**; 1805 Lake Carolina Drive, Columbia, South Carolina 29229 (US). **CAI, Lu**; 1805 Lake Carolina Drive, Columbia, South Carolina 29229 (US).

(74) Agent: **SPADACENE, Joseph C.** et al.; WESTINGHOUSE ELECTRIC COMPANY LLC, 1000 Westinghouse Drive, Suite 141, Cranberry Township, Pennsylvania 16066 (US).

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(54) Title: COMPOSITE FUEL WITH ENHANCED OXIDATION RESISTANCE

(57) Abstract: An improved nuclear fuel that has enhanced oxidation resistance and a process for making it are disclosed. The fuel comprises a composite of U235 enriched U₃Si₂ particles and an amount less than 30% by weight of UO₂ particles positioned along the surface of the U₃Si₂ particles. The composite may be compressed into a pellet form. The process comprises forming a layer of UO₂ on the surface of U₃Si₂ particles, either by exposing U₃Si₂ particles to an atmosphere of up to 15% oxygen by volume dispersed in an inert gas for a period of time and at a temperature sufficient to form UO₂ at the U₃Si₂ particle surface, or by mixing U₃Si₂ particles with an amount up to 30% by weight of UO₂ particles.



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COMPOSITE FUEL WITH ENHANCED OXIDATION RESISTANCE**STATEMENT REGARDING GOVERNMENT RIGHTS**

[0001] This invention was made with government support under Contract No. DE-NE0008222 awarded by the Department of Energy. The U.S. Government has certain rights in this invention.

BACKGROUND OF THE INVENTION**1. Field of the Invention**

[0002] The invention relates to methods for improving water corrosion resistance of triuranium disilicide light water reactor fuel.

2. Description of the Prior Art

[0003] Nuclear reactors are powered by fuel containing fissile material, traditionally uranium dioxide (UO₂) derived from uranium hexafluoride (UF₆) enriched with the isotope uranium-235 (U235). Because the fission process releases high levels of energy in the form of heat, the fuel must be in a form that can withstand both the high operating temperatures and the neutron radiation environment. Fuel is typically in the form of a stack of pellets clad and sealed in a tube made of a material, such as a zirconium alloy, that can contain the radiation. Conventional fuel pellets are typically fabricated by compressing suitable powders into a generally cylindrical mold. The compressed material is sintered, which results in a substantial reduction in volume.

[0004] Conventional fuel pellets can include a maximum of about 5% by weight of U235 (the current licensed limit for many nuclear fabrication facilities) with the remainder of the uranium component composed of one or more other isotopes, typically uranium-238 (U238) with or without trace amounts of other uranium isotopes.

[0005] A higher loading of U235 in the uranium fuel composition as well as a higher thermal conductivity would be economically beneficial owing to higher thermal conductivity and longer fuel cycles (currently about 10 to 24 months). To that end, triuranium disilicide (U₃Si₂) has been advanced as at least a partial replacement for UO₂ as the fuel component. U235 constitutes from about 0.7% to about 5% by weight based on the total weight of the uranium component of U₃Si₂. See for example, U.S. Patent No. 8,293,151 and published application US 2012/0002777, each incorporated herein by reference, wherein fuel compositions having from 50 to 100% U₃Si₂ and zero up to 50% UO₂ are disclosed. In general, the density of U₃Si₂ is greater than the density of UO₂. The density

of U_3Si_2 is 12.2 grams/cm³ and the density of UO_2 is 10.96 grams/cm³. U.S. Patent 8,293,151 posits (without intending to be bound by any particular theory), that the increase in density results in improved nuclear plant performance by enabling longer fuel cycles and/or higher power ratings, and that the use of U_3Si_2 in a nuclear fuel composition can allow the U235 content in a nuclear fuel assembly to increase by about 17% percent by weight with an increase in thermal conductivity of between 3 and 5 times, as compared to that obtained with the use of UO_2 .

- [0006] It has been found that U_3Si_2 has good water corrosion resistance at 300 °C similar to UO_2 . However, tests indicated that as water temperatures increase, the grain boundaries of U_3Si_2 were preferentially attacked by water and steam, especially at 360 °C and above.
- [0007] It has been found that U_3Si_2 suffers from excess oxidation at temperatures higher than 360 °C and will completely oxidize in steam at 450 °C and above in a short period of time. The rapid oxidation could present economic problems for a plant in the event of a leak or significant safety problems in the event of a design basis accident, such as a loss of coolant accident or a reactor initiated accident. Oxidation of U_3Si_2 is a potential safety concern in the implementation of U_3Si_2 fuel in light water reactors, including pressurized water reactors and boiling water reactors.
- [0008] If the benefits of U_3Si_2 as a nuclear fuel are to be realized, the risk of excess oxidation needs to be minimized.

SUMMARY OF THE INVENTION

- [0009] The following summary is provided to facilitate an understanding of some of the innovative features unique to the embodiments disclosed and is not intended to be a full description. A full appreciation of the various aspects of the embodiments can be gained by taking the entire specification, claims, and abstract as a whole.
- [0010] To address the concerns in use of U_3Si_2 as a nuclear fuel, various embodiments of a new more robust fuel designed to enhance oxidation resistance of U_3Si_2 are disclosed herein. Additionally, a process for forming the various embodiments of the more robust fuel with enhanced oxidation resistance is disclosed.
- [0011] The improved fuel comprises a composite of U235 enriched U_3Si_2 and an amount less than 30% by weight of UO_2 . The UO_2 particles may also be enriched with U235 isotopes.
- [0012] In various aspects, the UO_2 may be in the form of a layer of UO_2 particles on the surface of a U_3Si_2 pellet. Alternatively or additionally, the improved nuclear fuel may be in the

form of a pellet formed from compressed U235 enriched U_3Si_2 particles and less than 30% by weight U235 enriched UO_2 particles, wherein the UO_2 particles are predominantly positioned along the grain boundaries of the U_3Si_2 particles.

- [0013] A method is provided for conditioning U_3Si_2 powder and adding UO_2 as secondary phases to U_3Si_2 in the powder form before consolidation to pellets to improve its water corrosion resistance in coolant during operation and in high temperature steam in loss of coolant accident conditions. To improve the water corrosion resistance of U_3Si_2 at temperatures higher than 360 °C, the as fabricated U_3Si_2 powder can be exposed to inert gas atmosphere with a relatively low oxygen partial pressure, such as an amount up to 15% oxygen by volume. Alternatively, UO_2 powder can be added to U_3Si_2 powder in a weight percentage of up to 30% to be consolidated as an U_3Si_2 - UO_2 composite.
- [0014] Also disclosed herein is a process for improving water corrosion resistance of nuclear fuel comprising forming a layer of UO_2 on the surface of U_3Si_2 particles. In certain aspects, the process for forming the UO_2 layer comprises exposing U_3Si_2 particles to an atmosphere of up to 15% oxygen by volume dispersed in an inert gas for a period of time and at a temperature sufficient to form UO_2 at the U_3Si_2 particle surface.
- [0015] Exposing the U_3Si_2 particles to the gaseous atmosphere may in various aspects include flowing the inert gas and oxygen through or over the particles. Alternatively, exposing the U_3Si_2 particles to the gaseous atmosphere may in various aspects include combining the U_3Si_2 particles and the oxygen-inert gas atmosphere in a mixer and mixing at a rate sufficiently slow to avoid raising the temperature of the particles above 200 °C.
- [0016] In certain aspects, the process for forming the UO_2 layer comprises mixing U_3Si_2 particles with an amount up to 30% by weight of UO_2 particles. Thereafter, the mixed particles are pressed into a pellet and the pellet is sintered. In various aspects, the amount of UO_2 particles mixed with the U_3Si_2 particles is sufficient to adhere the layer of UO_2 particles on the grain boundaries of the U_3Si_2 particles.
- [0017] In certain aspects, the process for forming the UO_2 layer comprises layering UO_2 particles over a U_3Si_2 pellet either before or after the U_3Si_2 pellet has been sintered. The U_3Si_2 pellet with the UO_2 layer may be sintered. In various aspects, the UO_2 particles form at the grain boundaries of the U_3Si_2 particles at the surface of the pellet.
- [0018] It is believed that the placement of UO_2 particles at the grain boundaries of the U_3Si_2 particles will slow down the oxidation of U_3Si_2 , especially at higher steam temperatures.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

- [0019] As used herein, the singular form of “a”, “an”, and “the” include the plural references unless the context clearly dictates otherwise. Thus, the articles “a” and “an” are used herein to refer to one or to more than one (i.e., to at least one) of the grammatical object of the article. By way of example, “an element” means one element or more than one element.
- [0020] Directional phrases used herein, such as, for example and without limitation, top, bottom, left, right, lower, upper, front, back, and variations thereof, shall relate to the orientation of the elements shown in the accompanying drawing and are not limiting upon the claims unless otherwise expressly stated.
- [0021] In the present application, including the claims, other than where otherwise indicated, all numbers expressing quantities, values or characteristics are to be understood as being modified in all instances by the term “about.” Thus, numbers may be read as if preceded by the word “about” even though the term “about” may not expressly appear with the number. Accordingly, unless indicated to the contrary, any numerical parameters set forth in the following description may vary depending on the desired properties one seeks to obtain in the compositions and methods according to the present disclosure. At the very least, and not as an attempt to limit the application of the doctrine of equivalents to the scope of the claims, each numerical parameter described in the present description should at least be construed in light of the number of reported significant digits and by applying ordinary rounding techniques.
- [0022] Further, any numerical range recited herein is intended to include all sub-ranges subsumed therein. For example, a range of “1 to 10” is intended to include any and all sub-ranges between (and including) the recited minimum value of 1 and the recited maximum value of 10, that is, having a minimum value equal to or greater than 1 and a maximum value of equal to or less than 10.
- [0023] As used herein, an “inert gas” is a gas which does not undergo chemical reactions under a set of given conditions, such as for example, oxidation reactions. The noble gases often do not react with many substances. Inert gases are used generally to avoid unwanted chemical reactions that would degrade a sample. Purified argon and nitrogen gases are most commonly used as inert gases due to their high natural abundance (78% N₂, 1% Ar in air) and low relative cost. An inert gas is a non-reactive gas under particular conditions. For example, nitrogen at ordinary temperatures and the noble gases (helium,

argon, krypton, xenon and radon) are unreactive toward most species and in various aspects may be used as the inert gas in various embodiments of the process disclosed herein.

[0024] As used herein, the “grain boundary” is the interface or juncture between adjacent grains in a multi-particulate material. The grain boundary is a transition region in which some atoms are not exactly aligned with either grain. Grain boundaries of particles have less density on the atomic scale, a property that implies the presence of atomic holes, into which atoms can diffuse. This makes the zone at the grain boundaries of U_3Si_2 particles, for example, prone to oxidation, but also available for direct interaction with UO_2 particles or with oxygen to form UO_2 at the grain boundaries. It is believed, without intending to be bound by any particular theory, that when UO_2 particles are positioned along the grain boundaries of the U_3Si_2 particles, the higher oxidation resistance of the UO_2 particles shields the U_3Si_2 particles from oxidation.

[0025] As used herein, the term “pre-pelletized” means the particles or powder have previously been compressed into the shape of a pellet and may or may not have been sintered thereafter. Pre-pelletization may be done by any suitable known technique for making pellets and when also sintered, by any suitable known technique for sintering pellets.

[0026] To minimize, and preferably significantly reduce and delay, if not eliminate, the risk of oxidation of U_3Si_2 fuel, the corrosion resistance of U_3Si_2 can be improved. There are several solutions for corrosion resistance improvement for U_3Si_2 . One solution is to condition U_3Si_2 by exposing it to a mixture of inert gas and oxygen to form UO_2 on the surface of U_3Si_2 . An alternative solution is to add UO_2 to U_3Si_2 powder before pressing the green pellets and sintering. The method described herein improves water corrosion resistance of U_3Si_2 by adding an amount of UO_2 to loose or pre-pelletized particles of U_3Si_2 , sufficient to form a layer around the grain boundaries of U_3Si_2 particles. The UO_2 may be added to U_3Si_2 either directly or by reaction with oxygen to form UO_2 . The UO_2 layer may form around a plurality of U_3Si_2 particles, dispersed throughout the particles. Alternatively, the UO_2 layer may be formed around the grain boundaries of U_3Si_2 particles on the outer surface of a U_3Si_2 pellet.

[0027] The improved fuel may, in various aspects comprise a composite of U235 enriched U_3Si_2 particles and an amount less than 30% by weight of UO_2 , which may or may not also be U235 enriched. The UO_2 may be in the form of a layer of particles coating the surface of pre-pelletized U_3Si_2 . The UO_2 may be in the form of particles interspersed throughout U_3Si_2 particles. The UO_2 may be in the form of a layer of particles coating the surface of

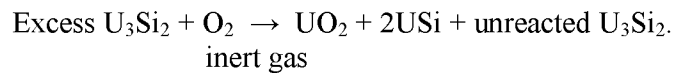
pre-pelletized U_3Si_2 and as particles interspersed throughout U_3Si_2 particles. In each embodiment, the UO_2 particles are positioned along the surface of the U_3Si_2 particles in either a continuous or a discontinuous layer. Some gaps where there is no UO_2 on the surface of some of the U_3Si_2 particles or where only part of the U_3Si_2 particles surface is coated will in practice likely occur resulting in a discontinuous layer.

- [0028] The improved nuclear fuel may, in various aspects, be in the form of a pellet formed from compressed U235 enriched U_3Si_2 particles and less than 30% by weight UO_2 particles, wherein the UO_2 particles are predominantly positioned along the grain boundaries of the U_3Si_2 particles or the U_3Si_2 pellet. The UO_2 particles may also be U235 enriched. provided the combined U235 enrichment is within the limits of the license granted by the controlling regulatory authority.
- [0029] Triuranium disilicide (U_3Si_2) may include various uranium isotopes, such as, but not limited to, uranium-238, uranium-236, uranium-235, uranium-234, uranium-233, uranium-232, and mixtures thereof. In certain aspects, the uranium component of the U_3Si_2 substantially includes uranium-238 and uranium-235, and optionally, trace amounts of uranium-236 and uranium-232. In other aspects, the uranium component of the U_3Si_2 includes uranium-235 in an amount such that it constitutes from about 0.7% to about 7% by weight, and typically about 5% by weight, based on the total weight of the uranium component of the U_3Si_2 .
- [0030] In certain aspects, the percentage of uranium-235 in the U_3Si_2 is at the maximum licensed amount, such as from about 4.95% to about 5.00%.
- [0031] UO_2 has better corrosion resistance than U_3Si_2 and the UO_2 phase in U_3Si_2 is expected to reduce the oxidation of U_3Si_2 and thus improve safety margins for events from fuel leaker events to design basis accidents, such as loss of coolant accidents and reactor initiated accidents.
- [0032] U_3Si_2 has a higher uranium loading than UO_2 , so it is economically more attractive. Licenses issued by the Nuclear Regulatory Commission (NRC) typically limit fuels for light water reactors to no more than 5% but in the future may reach 7% U235 of uranium. Therefore, it is advantageous to get as high a density as possible within the allowable limit. In addition, U_3Si_2 has a much higher thermal conductivity than UO_2 , (about 5-10 times as high) so the use of U_3Si_2 as the fuel leads to lower operating temperatures and lower fission gas release during operation.
- [0033] In the composite disclosed herein, the amount of UO_2 should be as minimal as possible because the more UO_2 added, the lower uranium loading or the density of U235 in the

fuel. For example, U_3Si_2 has a density of 12.2 g/cc whereas UO_2 has a density of 10.96 g/cc. The precise amount of UO_2 to add to U_3Si_2 to form the U_3Si_2 - UO_2 composite may vary, up to 30% by weight, but, in various aspects, UO_2 may be added in the smallest amount one can while still getting the oxidation resistance that UO_2 provides but avoiding lowering the density of U235 as little as possible.

[0034] The improved composite U_3Si_2 - UO_2 fuel can be made, for example, by forming a layer of UO_2 on the surface of U235 enriched U_3Si_2 . The layer of UO_2 may be formed by exposing the U_3Si_2 particles to an amount of oxygen, up to 15% by volume, dispersed in an inert gaseous atmosphere. In various aspects, the method may proceed by flowing oxygen in an inert gaseous atmosphere over a plurality of U_3Si_2 particles or through a plurality of U_3Si_2 particles, or both at a temperature sufficient to form UO_2 . The temperature in various aspects is less than 300 °C. The exposure of U_3Si_2 to the oxygen may last for a sufficient time period to allow the reaction forming UO_2 at the grain boundaries of U_3Si_2 to occur. For example, the flow of oxygen in the inert atmosphere may continue for up to several minutes.

[0035] The oxygen will react with the U_3Si_2 to form UO_2 on the surface of the U_3Si_2 particles in a reaction that is believed to proceed generally as follows:



The USi is more stable in oxygen than the original U_3Si_2 , but may oxidize further to UO_2 and SiO_2 at much higher temperatures. The inert gas does not participate in the reaction except to absorb and carry away heat. The inert gas may be selected from the group consisting of nitrogen, helium, argon, krypton, xenon and radon. Argon and nitrogen are preferred due to their natural abundance and relative low cost. There should be no hydrogen in the gas. The oxygen is present in an amount up to 15% by volume to prevent a runaway reaction by the U_3Si_2 . A runaway reaction will occur if the heat generated by the exothermic reaction of U_3Si_2 with O_2 exceeds the cooling due to the heat capacity of the inert gas components and the mass of the U_3Si_2 .

[0036] The oxygen may be present in an amount ranging from less than one percent up to 15 percent by volume. In various aspects the oxygen is present in an amount greater than zero and less than one percent by volume.

[0037] In various aspects, the method may proceed by combining the U235 enriched U_3Si_2 particles and the atmosphere of up to 15% oxygen and inert gas in a mixer, such as a

ribbon mixer, and mixing at a rate sufficiently slow to avoid raising the temperature of the particles above 200 °C.

[0038] The powder would be mixed by mixing warm U_3Si_2 particles at less than 200 °C with a cool gas mixture, preferably less than 100 °C. Mixing is preferably done slowly to avoid heat from the friction created by mixing. The heating can be controlled by changing the rate of mixing. The gas may be injected into the particles as they are mixing. The temperature should be high enough so that the reaction of the O_2 and U_3Si_2 occurs to form UO_2 at the boundaries of U_3Si_2 , but not so high that oxidation occurs anywhere beyond the edges of the U_3Si_2 particles. The temperature may therefore be monitored with a sensor and adjusted when necessary during mixing to maintain the particles, or powder, at no more than 200 °C. As the temperature approaches 200 °C, the rate of mixing can be reduced to maintain the temperature below 200 °C. A UO_2 surface layer is thereby formed on the U_3Si_2 particles.

[0039] In certain aspects, the atmosphere of up to 15% oxygen and inert gas may flow over the surface of pre-pelletized U235 enriched U_3Si_2 . The oxygen will react with U_3Si_2 to form UO_2 along the grain boundaries of the U_3Si_2 particles at the outer surface of the pellet, thereby forming a layer of UO_2 around the outer surface of the U235 enriched U_3Si_2 pellet.

[0040] In various aspects, the UO_2 particles, in various aspects, U 235 enriched UO_2 particles, may be layered on to pre-pelletized U 235 enriched U_3Si_2 , to cover the outer surface of the U_3Si_2 pellet and form a layer of UO_2 at the grain boundaries of the outermost U_3Si_2 particles on the already formed pellet.

[0041] Layering the UO_2 particles onto the pellet may be performed by any suitable layering technique, such as cold or hot spray, physical deposition or similar coating process.

[0042] In an alternative method, U 235 enriched U_3Si_2 particles may be mixed directly with up to 30% by weight UO_2 particles. In various aspects, the U 235 enriched U_3Si_2 particles may be mixed directly with up to 30% by weight U235 enriched UO_2 particles. The mixing may occur in any suitable mixer, such as, by way of example, commercially available double cone blenders, Turbula® blenders, V-blenders or Nauta® mixers. The rate of mixing should be slow enough to avoid raising the temperature of the particles above 200 °C. The mixer therefore may be equipped with a temperature sensor.

[0043] The UO_2 size particle distribution in various aspects will be less than the U_3Si_2 particle size distribution by a factor of about less than 10. The UO_2 particles may be likened to dust on a layer of U_3Si_2 particles. The higher the number of particles of UO_2 (on a

number basis as opposed to a weight % basis) there are to coat the surface of the U_3Si_2 particles, the more likely it will be that the U_3Si_2 particles are covered, and thereby shielded from oxidation.

[0044] After mixing the U_3Si_2 and the UO_2 particles, the U_3Si_2 - UO_2 composite may be formed into a pellet by the conventional methods for forming nuclear fuel pellets, and sintered.

[0045] For example, in certain aspects, the combined particles may first be homogenized to ensure relative uniformity in terms of particle size distribution and surface area. As stated, the size distribution of the U_3Si_2 particles will be greater than that of the UO_2 particles. In certain aspects, additives, such as lubricants, burnable absorbers and pore-forming agents may be added. The particles may be formed into pellets by compressing the mixture of particles in suitable commercially available mechanical or hydraulic presses to achieve the desired “green” density and strength.

[0046] A basic press may incorporate a die platen with single action capability while the most complex styles have multiple moving platens to form “multi-level” parts. Presses are available in a wide range of tonnage capability. The tonnage required to press powder into the desired compact pellet shape is determined by multiplying the projected surface area of the part by a load factor determined by the compressibility characteristics of the powder.

[0047] To begin the process, the mixture of particles is filled into a die. The rate of die filling is based largely on the flowability of the particles.

[0048] Once the die is filled, a punch moves towards the particles. The punch applies pressure to the particles, compacting them to the geometry of the die. In certain pelletizing processes, the particles may be fed into a die and pressed biaxially into cylindrical pellets using a load of several hundred MPa.

[0049] Following compression, the pellets are sintered by heating in a furnace at about 1750 °C under a controlled reducing atmosphere, usually comprised of argon. Sintering is a thermal process that consolidates the green pellets by converting the mechanical bonds of the particles formed during compression into stronger bonds and greatly strengthened pellets. The compressed and sintered pellets are then cooled and machined to the desired dimensions. Exemplary pellets may be about one centimeter, or slightly less, in diameter, and one centimeter, or slightly more, in length.

[0050] The nuclear fuel composition of the present invention can be in various forms, and are not limited to cylindrical pellets. The pellets are typically vertically stacked in a zirconium

alloy tube, or cladding, and several such fuel rods form the fuel assembly of a light water reactor.

[0051] The present invention has been described in accordance with several examples, which are intended to be illustrative in all aspects rather than restrictive. Thus, the present invention is capable of many variations in detailed implementation, which may be derived from the description contained herein by a person of ordinary skill in the art.

[0052] All patents, patent applications, publications, or other disclosure material mentioned herein, are hereby incorporated by reference in their entirety as if each individual reference was expressly incorporated by reference respectively. All references, and any material, or portion thereof, that are said to be incorporated by reference herein are incorporated herein only to the extent that the incorporated material does not conflict with existing definitions, statements, or other disclosure material set forth in this disclosure. As such, and to the extent necessary, the disclosure as set forth herein supersedes any conflicting material incorporated herein by reference and the disclosure expressly set forth in the present application controls.

[0053] The present invention has been described with reference to various exemplary and illustrative embodiments. The embodiments described herein are understood as providing illustrative features of varying detail of various embodiments of the disclosed invention; and therefore, unless otherwise specified, it is to be understood that, to the extent possible, one or more features, elements, components, constituents, ingredients, structures, modules, and/or aspects of the disclosed embodiments may be combined, separated, interchanged, and/or rearranged with or relative to one or more other features, elements, components, constituents, ingredients, structures, modules, and/or aspects of the disclosed embodiments without departing from the scope of the disclosed invention. Accordingly, it will be recognized by persons having ordinary skill in the art that various substitutions, modifications or combinations of any of the exemplary embodiments may be made without departing from the scope of the invention. In addition, persons skilled in the art will recognize, or be able to ascertain using no more than routine experimentation, many equivalents to the various embodiments of the invention described herein upon review of this specification. Thus, the invention is not limited by the description of the various embodiments, but rather by the claims.

What is claimed is:

1. A nuclear fuel comprising:

a pellet formed from compressed U235 enriched U_3Si_2 particles and less than 30% by weight UO_2 particles, wherein the UO_2 particles are predominantly positioned along the grain boundaries of the U_3Si_2 particles.

2. The fuel recited in claim 1 wherein the particle size distribution of the UO_2 particles is less than the particle size distribution of the U_3Si_2 particles by a factor of ten and the number of UO_2 particles exceeds the number of U_3Si_2 particles.

3. The fuel recited in claim 1 wherein the UO_2 particles are U235 enriched and the combined U235 enrichment is up to seven percent by weight.

4. The fuel recited in claim 1 wherein the UO_2 particles are present in an amount greater than zero and less than one percent by weight.

5. A nuclear fuel comprising:

a composite of U235 enriched U_3Si_2 particles and an amount less than 30% by weight of UO_2 particles positioned along the surface of the U_3Si_2 particles.

6. The fuel recited in claim 5 wherein the composite comprises greater than zero and less than one percent by weight of UO_2 particles.

7. The fuel recited in claim 5 wherein the UO_2 particles are U235 enriched and the total U235 enrichment of the composite is no more than seven percent by weight.

8. The fuel recited in claim 5 wherein the composite is compressed into a pellet and sintered.

9. A process for improving water corrosion resistance of nuclear fuel comprising:

forming a layer of UO_2 on the surface of U_3Si_2 particles.

10. The process recited in claim 9 wherein forming the UO_2 layer comprises

exposing U_3Si_2 particles to an atmosphere of up to 15% by volume oxygen dispersed in an inert gas for a period of time and at a temperature sufficient to form UO_2 at the U_3Si_2 particle surface.

11. The process recited in claim 10 wherein the temperature is less than 300 °C.
12. The process recited in claim 10 wherein the temperature of the atmosphere is 100 °C or less and the temperature of the U_3Si_2 particles is less than 200 °C.
13. The process recited in claim 10 wherein the inert gas is selected from the group consisting of helium, neon, argon, krypton, xenon, nitrogen and combinations thereof.
14. The process recited in claim 10 wherein the inert gas is argon.
15. The process recited in claim 10 wherein the inert gas is nitrogen.
16. The process recited in claim 10 wherein the oxygen content of the atmosphere is one percent or less.
17. The process recited in claim 10 wherein exposing the particles to the atmosphere comprises flowing the inert gas and oxygen through the particles.
18. The process recited in claim 10 wherein exposing the particles to the atmosphere comprises combining the particles and the atmosphere in a mixer and mixing at a rate sufficiently slow to avoid raising the temperature of the particles above 200 °C.
19. The process recited in claim 9 further comprising pressing the UO_2 coated U_3Si_2 particles into one or more pellets and sintering the one or more pellets.
20. The process recited in claim 9 wherein the UO_2 layer is formed on pre-pelletized U_3Si_2 particles.
21. The process recited in claim 20 wherein the UO_2 layer is formed by

exposing at least one U_3Si_2 pellet to an atmosphere of up to 15% oxygen dispersed in an inert gas for a period of time and at a temperature sufficient to form UO_2 at the U_3Si_2 pellet surface.
22. The process recited in claim 20 wherein forming the UO_2 layer comprises applying UO_2 particles to the surface of a U_3Si_2 pellet.

23. The process recited in claim 9 wherein forming the UO_2 layer comprises:
- mixing U_3Si_2 particles with an amount up to 30% by weight of UO_2 particles.
24. The process recited in claim 23 further comprising pressing the mixed particles into a pellet and sintering the pellet.
25. The process recited in claim 24 wherein the amount of UO_2 particles is sufficient to adhere the layer of UO_2 particles on the grain boundaries of the U_3Si_2 particles.
26. The process recited in claim 9 wherein the layer of UO_2 layer is discontinuous.
27. The process recited in claim 9 wherein the layer of UO_2 layer is continuous.
28. The process recited in claim 9 wherein the U_3Si_2 particles and the UO_2 particles are U235 enriched up to a combined total of seven percent by weight.
29. The process recited in claim 9 wherein the U_3Si_2 particles are U235 enriched up to five percent by weight.

A. CLASSIFICATION OF SUBJECT MATTER**G21C 3/62(2006.01)i**

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G21C 3/62; C01B 33/06; C04B 35/65; G21C 3/00; G21C 3/30; G21C 3/58; G21F 1/08; G21F 3/04; G21G 4/00

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Korean utility models and applications for utility models

Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

eKOMPASS(KIPO internal) & keywords: pellet, U235, U3Si2, UO2, particle, boundary, sinter

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2012-0002777 A1 (EDWARD J. LAHODA et al.) 05 January 2012 See paragraphs 4-5, 26, and claims 1, 7-8.	1-29
Y	EP 2539900 B1 (WESTINGHOUSE ELECTRIC SWEDEN AB) 24 December 2014 See paragraphs 16, 37, and claim 1.	1-29
Y	WO 2016-209345 A1 (BATTELLE ENERGY ALLIANCE, LLC) 29 December 2016 See page 18, line 3 - page 19, line 29.	10-18, 21
A	EP 0806046 B1 (LOCKHEED MARTIN IDAHO TECHNOLOGIES COMPANY) 17 May 2000 See paragraphs 47-54, and figures 1-2.	1-29
A	JASON M. HARP et al., 'Uranium silicide pellet fabrication by powder metallurgy for accident tolerant fuel evaluation and irradiation', Journal of Nuclear Materials Volume 466, November 2015, Pages 728-738. See pages 728-733.	1-29



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents:

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

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"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

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International Application Division

Korean Intellectual Property Office

189 Cheongsa-ro, Seo-gu, Daejeon, 35208, Republic of Korea



Facsimile No. +82-42-481-8578

Authorized officer

PARK, Hye Lyun

Telephone No. +82-42-481-3463



INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2018/047954

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