



HU000035511T2

(19) **HU**(11) Lajstromszám: **E 035 511**(13) **T2****MAGYARORSZÁG****Szellemi Tulajdon Nemzeti Hivatala**

## EURÓPAI SZABADALOM SZÖVEGÉNEK FORDÍTÁSA

(21) Magyar ügyszám: **E 16 154148**(22) A bejelentés napja: **2011. 05. 11.**

(96) Az európai bejelentés bejelentési száma:

**EP 20110154148**

(97) Az európai bejelentés közzétételi adatai:

**EP 3038112 A1** **2016. 06. 29.**

(97) Az európai szabadalom megadásának meghirdetési adatai:

**EP 3038112 B1** **2017. 10. 25.**(51) Int. Cl.: **G21C 3/08**

(2006.01)

**G21C 3/322**

(2006.01)

**G21C 21/10**

(2006.01)

**G21C 3/60**

(2006.01)

**G21C 3/64**

(2006.01)

**G21C 3/06**

(2006.01)

**G21C 3/326**

(2006.01)

(30) Elsőbbségi adatok:

**333467 P** **2010. 05. 11.** **US****393499 P** **2010. 10. 15.** **US****201161444990 P** **2011. 02. 21.** **US**

(73) Jogosult(ak):

**Thorium Power, Inc., McLean, VA 22102 (US)**

(72) Feltaláló(k):

**Bashkirtsev, Sergey Mikhailovich, 125080 Moscow (RU)****Kuznetsov, Valentin Fedorovich, 111402 Moscow (RU)****Kevrolev, Valery Vladimirovich, 123368 Moscow (RU)****Morozov, Alexey Glebovich, 123423 Moscow (RU)****Montgomery, Michael H, Hamilton, Virginia 20158 (US)**

(74) Képviselő:

**ARINOVA Szabadalmi és Védjegy Iroda,  
Budapest**

(54)

**Fűtőelem egység**

Az európai szabadalom ellen, megadásának az Európai Szabadalmi Közlönyben való meghirdetésétől számított kilenc hónapon belül, felszólalást lehet benyújtani az Európai Szabadalmi Hivatalnál. (Európai Szabadalmi Egyezmény 99. cikk(1))

A fordítást a szabadalmas az 1995. évi XXXIII. törvény 84/H. §-a szerint nyújtotta be. A fordítás tartalmi helyességét a Szellemi Tulajdon Nemzeti Hivatala nem vizsgálta.



(11) **EP 3 038 112 B1**

(12) **EUROPEAN PATENT SPECIFICATION**

(45) Date of publication and mention  
of the grant of the patent:  
**25.10.2017 Bulletin 2017/43**

(51) Int Cl.:  
**G21C 3/08** (2006.01) **G21C 3/322** (2006.01)  
**G21C 3/326** (2006.01) **G21C 21/10** (2006.01)  
**G21C 3/60** (2006.01) **G21C 3/64** (2006.01)  
**G21C 3/06** (2006.01)

(21) Application number: **16154148.7**

(22) Date of filing: **11.05.2011**

(54) **FUEL ASSEMBLY**  
**BRENNELEMENT**  
**ASSEMBLAGE DE COMBUSTIBLE**

(84) Designated Contracting States:  
**AL AT BE BG CH CY CZ DE DK EE ES FI FR GB**  
**GR HR HU IE IS IT LI LT LU LV MC MK MT NL NO**  
**PL PT RO RS SE SI SK SM TR**

(30) Priority: **11.05.2010 US 333467 P**  
**15.10.2010 US 393499 P**  
**21.02.2011 US 201161444990 P**

(43) Date of publication of application:  
**29.06.2016 Bulletin 2016/26**

(62) Document number(s) of the earlier application(s) in  
accordance with Art. 76 EPC:  
**11735927.3 / 2 569 776**

(73) Proprietor: **Thorium Power, Inc.**  
**McLean, VA 22102 (US)**

(72) Inventors:  
• **Bashkirtsev, Sergey Mikhailovich**  
**125080 Moscow (RU)**  
• **Kuznetsov, Valentin Fedorovich**  
**111402 Moscow (RU)**  
• **Kevrolev, Valery Vladimirovich**  
**123368 Moscow (RU)**  
• **Morozov, Alexey Glebovich**  
**123423 Moscow (RU)**

• **Montgomery, Michael H**  
**Hamilton, Virginia 20158 (US)**

(74) Representative: **Beck Greener**  
**Fulwood House**  
**12 Fulwood Place**  
**London WC1V 6HR (GB)**

(56) References cited:  
**GB-A- 876 399** **GB-A- 904 140**  
**GB-A- 1 031 678** **GB-A- 1 126 396**  
**GB-A- 1 282 767** **RU-C1- 2 389 089**  
**US-A- 3 275 564** **US-A- 5 737 375**  
**US-A1- 2009 252 278**

• **V. V. BOL'SHAKOV ET AL: "Experimental study  
of burnout in channels with twisted fuel rods",  
THERMAL ENGINEERING, vol. 54, no. 5, 1 May  
2007 (2007-05-01), pages 386-389, XP055006454,  
ISSN: 0040-6015, DOI:  
10.1134/S0040601507050096**  
• **D D Keiser ET AL: "The Development of Metallic  
Nuclear Fuels for Transmutation Applications:  
Materials Challenges", Journal of The Minerals,  
Metals & Materials Society, 12 January 2008  
(2008-01-12), pages 29-32, XP055360303,  
Retrieved from the Internet:  
URL:<http://www.springerlink.com/index/XG14562L28723435.pdf> [retrieved on 2017-03-30]**

Note: Within nine months of the publication of the mention of the grant of the European patent in the European Patent Bulletin, any person may give notice to the European Patent Office of opposition to that patent, in accordance with the Implementing Regulations. Notice of opposition shall not be deemed to have been filed until the opposition fee has been paid. (Art. 99(1) European Patent Convention).

**EP 3 038 112 B1**

**Description**

## BACKGROUND OF THE INVENTION

## 1. Field of the Invention

**[0001]** The present invention relates generally to nuclear fuel assemblies used in the core of a nuclear reactor, and relates more specifically to metal nuclear fuel elements.

## 2. Description of Related Art

**[0002]** U.S. Patent Application Publication No. 2009/0252278 A1 discloses a nuclear fuel assembly that includes seed and blanket sub-assemblies. The blanket sub-assembly includes thorium-based fuel elements. The seed sub-assembly includes Uranium and/or Plutonium metal fuel elements used to release neutrons, which are captured by the Thorium blanket elements, thereby creating fissionable U-233 that burns in situ and releases heat for the nuclear power plant.

**[0003]** Conventional nuclear power plants typically use fuel assemblies that include a plurality of fuel rods that each comprise uranium oxide fuel in a cylindrical tube.

## SUMMARY OF EXAMPLES OF THE DISCLOSURE

**[0004]** The surface area of the cylindrical tube of conventional fuel rods limits the amount of heat that can be transferred from the rod to the primary coolant. To avoid overheating the fuel rod in view of the limited surface area for heat flux removal, the amount of fissile material in these uranium oxide fuel rods or mixed oxide (plutonium and uranium oxide) fuel rods has conventionally been substantially limited.

**[0005]** According to the invention, there is provided a fuel assembly according to claim 1 and a method of manufacturing a fuel assembly according to claim 28. More specific embodiments are defined in the additional dependent claims.

## BRIEF DESCRIPTION OF THE DRAWINGS

**[0006]** For a better understanding of examples of the present disclosure as well as other objects and further features thereof, reference is made to the following description which is to be used in conjunction with the accompanying drawings, where:

FIG. 1 is a cross-sectional view of a fuel assembly according to an example, the cross-section being taken in a self-spacing plane;

FIG. 2 is a cross-sectional view of the fuel assembly of FIG. 1, the cross-section being taken in a plane that is shifted by 1/8 of a twist of the fuel elements from the view in FIG. 1;

FIG. 3 is a cross-sectional view of the fuel assembly of FIG. 1, taken in a plane that is parallel to the axial direction of the fuel assembly;

FIG. 4 is a perspective view of a fuel element of the fuel assembly of FIG. 1;

FIG. 5 is a cross-sectional view of the fuel element in FIG. 3;

FIG. 6 is a cross-sectional view of the fuel element in FIG. 3, circumscribed within a regular polygon;

FIG. 7A is an end view of a fuel assembly according to an alternative example, for use in a pressurized heavy water reactor;

FIG. 7B is a partial side view of the fuel assembly of FIG. 7A;

FIG. 8 is a diagram of a pressurized heavy water reactor using the fuel assembly illustrated in FIGS. 7A and 7B

FIG. 9 is a cross-sectional view of the fuel element in FIG. 3; and

FIG. 10 is a cross-sectional view of a fuel assembly according to an additional example.

## DETAILED DESCRIPTION

**[0007]** FIGS. 1-3 illustrate a fuel assembly 10. As shown in FIG. 3, the fuel assembly 10 comprises a plurality of fuel elements 20 supported by a frame 25.

**[0008]** As shown in FIG. 3, the frame 25 comprises a shroud 30, guide tubes 40, an upper nozzle 50, a lower nozzle 60, a lower tie plate 70, an upper tie plate 80, and/or other structure(s) that enable the assembly 10 to operate as a fuel assembly in a nuclear reactor. One or more of these components of the frame 25 may be omitted without deviating from the scope of the disclosure.

**[0009]** As shown in FIG. 3, the shroud 25 mounts to the upper nozzle 50 and lower nozzle 60. The lower nozzle 60

(or other suitable structure of the assembly 10) is constructed and shaped to provide a fluid communication interface between the assembly 10 and the reactor 90 into which the assembly 10 is placed so as to facilitate coolant flow into the reactor core through the assembly 10 via the lower nozzle 60. The upper nozzle 50 facilitates direction of the heated coolant from the assembly 10 to the power plant's steam generators (for PWRs), turbines (for BWRs), etc. The nozzles 50, 60 have a shape that is specifically designed to properly mate with the reactor core internal structure.

**[0010]** As shown in FIG. 3, the lower tie plate 70 and upper tie plate 80 are preferably rigidly mounted (e.g., via welding, suitable fasteners (e.g., bolts, screws), etc.) to the shroud 30 or lower nozzle 60 (and/or other suitable structural components of the assembly 10).

**[0011]** Lower axial ends of the elements 20 form pins 20a that fit into holes 70a in the lower tie plate 70 to support the elements 20 and help maintain proper element 20 spacing. The pins 20a mount to the holes 70a in a manner that prevents the elements 20 from rotating about their axes or axially moving relative to the lower tie plate 70. This restriction on rotation helps to ensure that contact points between adjacent elements 20 all occur at the same axial positions along the elements 20 (e.g., at self-spacing planes discussed below). The connection between the pins 20a and holes 70a may be created via welding, interference fit, mating non-cylindrical features that prevent rotation (e.g., keyway and spline), and/or any other suitable mechanism for restricting axial and/or rotational movement of the elements 20 relative to the lower tie plate 70. The lower tie plate 70 includes axially extending channels (e.g., a grid of openings) through which coolant flows toward the elements 20.

**[0012]** Upper axial ends of the elements 20 form pins 20a that freely fit into holes 80a in the upper tie plate 80 to permit the upper pins 20a to freely axially move upwardly through to the upper tie plate 80 while helping to maintain the spacing between elements 20. As a result, when the elements 20 axially grow during fission, the elongating elements 20 can freely extend further into the upper tie plate 80.

**[0013]** As shown in FIG. 4, the pins 70a transition into a central portion of the element 20.

**[0014]** FIGS. 4 and 5 illustrate an individual fuel element/rod 20 of the assembly 10. As shown in FIG. 5, the elongated central portion of the fuel element 20 has a four-lobed cross-section. A cross-section of the element 20 remains substantially uniform over the length of the central portion of the element 20. Each fuel element 20 has a fuel kernel 100, which includes a refractory metal and fuel material that includes fissile material.

**[0015]** A displacer 110 that comprises a refractory metal is placed along the longitudinal axis in the center of the fuel kernel 100. The displacer 110 helps to limit the temperature in the center of the thickest part of the fuel element 20 by displacing fissile material that would otherwise occupy such space and minimize variations in heat flux along the surface of the fuel element. The displacer 110 may be eliminated altogether.

**[0016]** As shown in FIG. 5, the fuel kernel 100 is enclosed by a refractory metal cladding 120. The cladding 120 is preferably thick enough, strong enough, and flexible enough to endure the radiation-induced swelling of the kernel 100 without failure (e.g., without exposing the kernel 100 to the environment outside the cladding 120). The entire cladding 120 is at least 0.3 mm, 0.4 mm, 0.5 mm, and/or 0.7 mm thick. The cladding 120 thickness is at least 0.4 mm in order to reduce a chance of swelling-based failure, oxidation based failure, and/or any other failure mechanism of the cladding 120.

**[0017]** The cladding 120 may have a substantially uniform thickness in the annular direction (i.e., around the perimeter of the cladding 120 as shown in the cross-sectional view of FIG. 5) and over the axial/longitudinal length of the kernel 100 (as shown in FIG. 4). Alternatively, as shown in FIG. 5, the cladding 120 is thicker at the tips of the lobes 20b than at the concave intersection/area 20c between the lobes 20b. For example, the cladding 120 at the tips of the lobes 20b is at least 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 100%, 125%, and/or 150% thicker than the cladding 120 at the concave intersections/areas 20c. The thicker cladding 120 at the tips of the lobes 20b provides improved wear resistance at the tips of the lobes 20b where adjacent fuel elements 20 touch each other at the self-spacing planes (discussed below).

**[0018]** The refractory metal used in the displacer 110, the fuel kernel 100, and the cladding 120 comprises zirconium. As used herein, the term zirconium means pure zirconium or zirconium in combination with other alloy material(s). However, other than for the fuel kernel 100, other refractory metals may be used instead of zirconium (e.g., niobium, molybdenum, tantalum, tungsten, rhenium, titanium, vanadium, chromium, zirconium, hafnium, ruthenium, osmium, iridium, and/or other metals). As used herein, the term "refractory metal" means any metal/alloy that has a melting point above 1800 degrees Celsius (2073K).

**[0019]** In certain examples, not falling under the scope of the present invention, the refractory metal may be replaced with another non-fuel metal, e.g., aluminum. However, the use of a non-refractory non-fuel metal is best suited for reactor cores that operate at lower temperatures (e.g., small cores that have a height of about 1 meter and an electric power rating of 100 MWe or less). Refractory metals are preferred for use in cores with higher operating temperatures.

**[0020]** As shown in FIG. 5, the central portion of the fuel kernel 100 and cladding 120 has a four-lobed profile forming spiral spacer ribs 130. The displacer 110 may also be shaped so as to protrude outwardly at the ribs 130 (e.g., corners of the square displacer 110 are aligned with the ribs 130). According to alternative examples, the fuel elements 20 may have greater or fewer numbers of ribs 130 without deviating from the scope of the present invention. For example, as generally illustrated in FIG. 5 of U.S. Patent Application Publication No. 2009/0252278 A1, a fuel element may have

three ribs/lobes, which are preferably equally circumferentially spaced from each other. The number of lobes/ribs 130 may depend, at least in part, on the shape of the fuel assembly 10. For example, a four-lobed element 20 may work well with a square cross-sectioned fuel assembly 10 (e.g., as is used in the AP-1000). In contrast, a three-lobed fuel element may work well with a hexagonal fuel assembly (e.g., as is used in the VVER).

**[0021]** FIG. 9 illustrates various dimensions of the fuel element 20. Any of these dimensions, parameters and/or ranges, as identified in the below table, can be increased or decreased by up to 5%, 10%, 15%, 20%, 25%, 30%, 40%, 50%, or more.

| Fuel Element 20 Parameter                         | Symbol          | Example Values                                                                                                                                       | Unit              |
|---------------------------------------------------|-----------------|------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------|
| Circumscribed diameter                            | D               | 9-14 (e.g., 12.3, 12.4, 12.5, 12.6)                                                                                                                  | mm                |
| Lobe thickness                                    | $\Delta$        | 2.5-3.8 (e.g., 2.5, 2.6, 2.7, 2.8, 2.9, 3.0, 3.1, 3.2, 3.3, 3.4, 3.5, 3.6, 3.7, 3.8), variable                                                       | mm                |
| Minimum cladding thickness                        | $\delta$        | 0.4-1.2 (e.g., 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.1, 1.2)                                                                                          | mm                |
| Cladding thickness at the lobe                    | $\delta^{\max}$ | 0.4-2.2 (e.g., 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, 1.8, 1.9, 2.0, 2.1, 2.2), $1.5\delta$ , $2\delta$ , $2.5\delta$ | mm                |
| Average cladding thickness                        |                 | 0.4 - 1.8 (e.g., 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, 1.8), at least 0.4, 0.5, or 0.6                               | mm                |
| Curvature radius of cladding at lobe periphery    | r               | $\Delta/2$ , $\Delta/1.9$ , variable                                                                                                                 | mm                |
| Curvature radius of fuel kernel at lobe periphery | $r_f$           | 0.5-2.0 (e.g., 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, 1.8, 1.9, 2.0), $(\Delta-2\delta)/2$ , variable                      | mm                |
| Radius of curvature between adjacent lobes        | R               | 2-5 (e.g., 2, 3, 4, 5), variable                                                                                                                     | mm                |
| Central displacer side length                     | a               | 1.5-3.5 (e.g., 1.5, 1.6, 1.7, 1.8, 1.9, 2.0, 2.1, 2.2, 2.3, 2.4, 2.5, 2.6, 2.7, 2.8, 2.9, 3.0, 3.1, 3.2, 3.3, 3.4, 3.5)                              | mm                |
| Fuel element perimeter                            |                 | 25-60 (e.g., 25, 30, 35, 40, 45, 50, 55, 60)                                                                                                         | mm                |
| Fuel element area                                 |                 | 50-100 (e.g., 50, 60, 70, 80, 90, 100)                                                                                                               | 2 mm <sup>2</sup> |
| Fuel kernel area, mm <sup>2</sup>                 |                 | 30-70 (e.g., 30, 40, 50, 60, 70)                                                                                                                     | mm <sup>2</sup>   |
| Enrichment                                        |                 | $\leq 19.7$                                                                                                                                          | w/o               |
| U fraction                                        |                 | $\leq 25$                                                                                                                                            | v/o               |

**[0022]** As shown in FIG. 4, the displacer 110 has a cross-sectional shape of a square regular quadrilateral with the corners of the square regular quadrilateral being aligned with the ribs 130. The displacer 110 forms a spiral that follows the spiral of the ribs 130 so that the corners of the displacer 110 remain aligned with the ribs 130 along the axial length of the fuel kernel 100. In alternative examples with greater or fewer ribs 130, the displacer 110 preferably has the cross-sectional shape of a regular polygon having as many sides as the element 20 has ribs.

**[0023]** As shown in FIG. 6, the cross-sectional area of the central portion of the element 20 is preferably substantially smaller than the area of a square 200 in which the tip of each of the ribs 130 is tangent to one side of the square 200. In more generic terms, the cross-sectional area of an element 20 having n ribs is preferably smaller than the area of a regular polygon having n sides in which the tip of each of the ribs 130 is tangent to one side of the polygon. A ratio of the area of the element 20 to the area of the square (or relevant regular polygon for elements 20 having greater or fewer than four ribs 130) is less than 0.7, 0.6, 0.5, 0.4, 0.35, 0.3. As shown in FIG. 1, this area ratio approximates how much of the available space within the shroud 30 is taken up by the fuel elements 20, such that a lower ratio means that more space is advantageously available for coolant, which also acts as a neutron moderator and which increases the moderator-to-fuel ratio (important for neutronics), reduces hydraulic drag, and increases the heat transfer from the elements 20 to the coolant. The resulting moderator to fuel ratio is at least 2.0, 2.25, 2.5, 2.75, and/or 3.0 (as opposed to 1.96 when conventional cylindrical uranium oxide rods are used). The fuel assembly 10 flow area is increased by over 16% as compared to the use of one or more conventional fuel assemblies that use cylindrical uranium oxide rods. The increased flow area may decrease the coolant pressure drop through the assembly 10 (relative to conventional uranium oxide assemblies), which may have advantages with respect to pumping coolant through the assembly 10.

**[0024]** As shown in FIG. 4, the element 20 is axially elongated. In the illustrated example, each element 20 is a full-length element and extends the entire way from lower tie plate 70 at or near the bottom of the assembly 10 to the upper tie plate 80 at or near the top of the assembly 10. This may result in elements 20 that are anywhere from 1 meter long (for compact reactors) to over 4 meters long. Thus, for typical reactors, the elements 20 may be between 1 and 5 meters long. However, the elements 20 may be lengthened or shortened to accommodate any other sized reactor without deviating from the scope of the present invention.

**[0025]** While the illustrated elements 20 are themselves full length, the elements 20 may alternatively be segmented, such that the multiple segments together make a full length element. For example, 4 individual 1 meter element segments 20 may be aligned end to end to effectively create the full-length element. Additional tie plates 70, 80 may be provided at the intersections between segments to maintain the axial spacing and arrangement of the segments.

**[0026]** The fuel kernel 100 comprises a combination of a refractory metal/alloy and fuel material. The refractory metal/alloy may comprise a zirconium alloy. The fuel material may comprise low enriched uranium (e.g., U235, U233), plutonium, or thorium combined with low enriched uranium as defined below and/or plutonium. As used herein, "low enriched uranium" means that the whole fuel material contains less than 20% by weight fissile material (e.g., uranium-235 or uranium-233). The uranium fuel material is enriched to between 1% and 20%, 5% and 20%, 10% and 20%, and/or 15% and 20% by weight of uranium-235. The fuel material comprises 19.7% enriched uranium-235.

**[0027]** The fuel material may comprise a 3-10%, 10-40%, 15-35%, and/or 20-30% volume fraction of the fuel kernel 100. According to various embodiments, the refractory metal may comprise a 60-99%, 60-97%, 70-97%, 60-90%, 65-85%, and/or 70-80% volume fraction of the fuel kernel 100. Volume fractions within one or more of these ranges provide an alloy with beneficial properties as defined by the material phase diagram for the specified alloy composition. The fuel kernel 100 comprises a Zr-U alloy that is a high-alloy fuel (i.e., relatively high concentration of the alloy constituent relative to the uranium constituent) comprised of either  $\delta$ -phase  $\text{UZr}_2$ , or a combination of  $\delta$ -phase  $\text{UZr}_2$  and  $\alpha$ -phase Zr. The  $\delta$ -phase of the U-Zr binary alloy system may range from a zirconium composition of approximately 65-81 volume percent (approximately 63 to 80 atom percent) of the fuel kernel 100. These examples have been found to result in low volumetric, irradiation-induced swelling of the fuel element 20. Fission gases are entrained within the metal kernel 100 itself, such that the fuel element 20 can omit a conventional gas gap from the fuel element 20. Such swelling may be significantly less than would occur if low alloy ( $\alpha$ -phase only) compositions were used (e.g., at least 10%, 20%, 30%, 50%, 75%, 100%, 200%, 300%, 500%, 1000%, 1200%, 1500%, or greater reduction in volume percent swelling per atom percent burnup than if a low alloy  $\alpha$ -phase U-10Zr fuel was used). Irradiation-induced swelling of the fuel element 20 or kernel 100 thereof may be less than 20, 15, 10, 5, 4, 3, and/or 2 volume percent per atom percent burnup. Swelling is expected to be around one volume percent per atom percent burnup.

**[0028]** According to alternative examples, not falling under the scope of the present invention, the fuel kernel may be replaced with a plutonium-zirconium binary alloy with the same or similar volume percentages as with the above-discussed U-Zr fuel kernels 100, or with different volume percentages than with the above-discussed U-Zr fuel kernels 100. For example, the plutonium fraction in the kernel 100 may be substantially less than a corresponding uranium fraction in a corresponding uranium-based kernel 100 because plutonium typically has about 60-70% weight fraction of fissile isotopes, while LEU uranium has 20% or less weight fraction of fissile U-235 isotopes. The plutonium volume fraction in the kernel 100 may be less than 15%, less than 10%, and/or less than 5%, with the volume fraction of the refractory metal being adjusted accordingly.

**[0029]** The use of a high-alloy kernel 100 may also result in the advantageous retention of fission gases during irradiation. Oxide fuels and low-alloy metal fuels typically exhibit significant fission gas release that is typically accommodated by the fuel design, usually with a plenum within the fuel rod to contain released fission gases. The fuel kernel 100 according to one or more examples of the present disclosure, in contrast, does not release fission gases. This is in part due to the low operating temperature of the fuel kernel 100 and the fact that fission gas atoms (specifically Xe and Kr) behave like solid fission products. Fission gas bubble formation and migration along grain boundaries to the exterior of the fuel kernel 100 does not occur. At sufficiently high temperatures, small (a few micron diameter) fission gas bubbles may form. However, these bubbles remain isolated within the fuel kernel 100 and do not form an interconnected network that would facilitate fission gas release. The metallurgical bond between the fuel kernel 100 and cladding 120 may provide an additional barrier to fission gas release.

**[0030]** The fuel kernel 100 (or the cladding 120 or other suitable part of the fuel element 20) of one or more of the fuel elements 20 can be alloyed with a burnable poison such as gadolinium, boron, erbium or other suitable neutron absorbing material to form an integral burnable poison fuel element. Different fuel elements 20 within a fuel assembly 10 may utilize different burnable poisons and/or different amounts of burnable poison. For example, some of fuel elements 20 of a fuel assembly 10 (e.g., less than 75%, less than 50%, less than 20%, 1-15%, 1-12%, 2-12%, etc.) may include kernels 100 with 25, 20, and/or 15 weight percent or less Gd (e.g., 1-25 weight percent, 1-15 weight percent, 5-15 weight percent, etc.). Other fuel elements 20 of the fuel assembly 10 (e.g., 10-95%, 10-50%, 20-50%, a greater number of the fuel elements 20 than the fuel elements 20 that utilize Gd) may include kernels 100 with 10 or 5 weight percent or less Er (e.g., 0.1-10.0 weight percent, 0.1 to 5.0 weight percent etc.).

**[0031]** The burnable poison displaces the fuel material (rather than the refractory metal) relative to fuel elements 20 that do not include burnable poison in their kernels 100. For example, according to one example of a fuel element 20 whose kernel 100 would otherwise include 65 volume percent zirconium and 35 volume percent uranium in the absence of a poison, the fuel element 20 includes a kernel 100 that is 16.5 volume percent Gd, 65 volume percent zirconium, and 18.5 volume percent uranium. The burnable poison instead displaces the refractory metal, rather than the fuel material. The burnable poison in the fuel kernel 100 displaces the refractory metal and the fuel material proportionally. Consequently, the burnable poison within the fuel kernel 100 may be disposed in the  $\delta$ -phase of  $\text{UZr}_2$  or  $\alpha$ -phase of Zr such that the presence of the burnable poison does not change the phase of the  $\text{UZr}_2$  alloy or Zr alloy in which the burnable poison is disposed.

**[0032]** Fuel elements 20 with a kernel 100 with a burnable poison may make up a portion (e.g., 0-100%, 1-99%, 1-50%, etc.) of the fuel elements 20 of one or more fuel assemblies 10 used in a reactor core. For example, fuel elements 20 with burnable poison may be positioned in strategic locations within the fuel assembly lattice of the assembly 10 that also includes fuel elements 20 without burnable poison to provide power distribution control and to reduce soluble boron concentrations early in the operating cycle. Similarly, select fuel assemblies 10 that include fuel elements 20 with burnable poison may be positioned in strategic locations within the reactor core relative to assemblies 10 that do not include fuel elements 20 with burnable poison to provide power distribution control and to reduce soluble boron concentrations early in the operating cycle. The use of such integral burnable absorbers may facilitate the design of extended operating cycles.

**[0033]** Alternatively and/or additionally, separate non-fuel bearing burnable poison rods may be included in the fuel assembly 10 (e.g., adjacent to fuel elements 20, in place of one or more fuel elements 20, inserted into guide tubes in fuel assemblies 10 that do not receive control rods, etc.). Such non-fuel burnable poison rods can be designed into a spider assembly similar to that which is used in the Babcock and Wilcox or Westinghouse designed reactors (referred to as burnable poison rod assemblies (BPRA)). These then may be inserted into the control rod guide tubes and locked into select fuel assemblies 10 where there are no control banks for the initial cycle of operation for reactivity control. When the burnable poison cluster is used it may be removed when the fuel assembly is relocated for the next fuel cycle. According to an alternative example in which the separate non-fuel bearing burnable poison rods are positioned in place of one or more fuel elements 20, the non-fuel burnable poison rods remain in the fuel assembly 10 and are discharged along with other fuel elements 20 when the fuel assembly 10 reaches its usable life.

**[0034]** The fuel elements 20 are manufactured via powder-metallurgy co-extrusion. Typically, the powdered refractory metal and powdered metal fuel material (as well as the powdered burnable poison, if included in the kernel 100) for the fuel kernel 100 are mixed, the displacer 110 blank is positioned within the powder mixture, and then the combination of powder and displacer 110 is pressed and sintered into fuel core stock/billet (e.g., in a mold that is heated to varying extents over various time periods so as to sinter the mixture). The displacer 110 blank may have the same or similar cross-sectional shape as the ultimately formed displacer 110. Alternatively, the displacer 110 blank may have a shape that is designed to deform into the intended cross-sectional shape of the displacer 110 upon extrusion. The fuel core stock (including the displacer 110 and the sintered fuel kernel 100 material) is inserted into a hollow cladding 120 tube that has a sealed tube base and an opening on the other end. The opening on the other end is then sealed by an end plug made of the same material as the cladding to form a billet. The billet may be cylindrically shaped, or may have a shape that more closely resembles the ultimate cross-sectional shape of the element 20, for example, as shown in FIGS. 5 and 9. The billet is then co-extruded under temperature and pressure through a die set to create the element 20, including the finally shaped kernel 100, cladding 110, and displacer 120. According to various examples that utilize a non-cylindrical displacer 110, the billet may be properly oriented relative to the extrusion press die so that corners of the displacer 110 align with the lobes 20b of the fuel element 20. The extrusion process may be done by either direct extrusion (i.e., moving the billet through a stationary die) or indirect extrusion (i.e., moving the die toward a stationary billet). The process results in the cladding 120 being metallurgically bonded to the fuel kernel 100, which reduces the risk of delamination of the cladding 120 from the fuel kernel 100. The tube and end plug of the cladding 120 metallurgically bond to each other to seal the fuel kernel 100 within the cladding 120. The high melting points of refractory metals used in the fuel elements 10 tend to make powder metallurgy the method of choice for fabricating components from these metals.

**[0035]** The fuel core stock of the fuel elements 20 may be manufactured via casting instead of sintering. Powdered or monolithic refractory metal and powdered or monolithic fuel material (as well as the powdered burnable poison, if included in the kernel 100) may be mixed, melted, and cast into a mold. The mold may create a displacer-blank-shaped void in the cast kernel 100 such that the displacer 110 blank may be inserted after the kernel 100 is cast, in the same manner that the cladding 120 is added to form the billet to be extruded. The remaining steps for manufacturing the fuel elements 20 may remain the same as or similar to the above-discuss embodiment that utilizes sintering instead of casting. Subsequent extrusion results in metallurgical bonding between the displacer 110 and kernel 100, as well as between the kernel 100 and cladding 120.

**[0036]** The fuel elements 20 are manufactured using powdered ceramic fuel material instead of powdered metal fuel material. The remaining manufacturing steps may be the same as discussed above with respect to the embodiments using powdered metal fuel material. The manufacturing process may result in a fuel kernel 100 comprising fuel material

disposed in a matrix of metal non-fuel material. In one or more of the metal fuel examples, the resulting fuel kernel 100 comprises a metal fuel alloy kernel comprising an alloy of the metal fuel material and the matrix of metal non-fuel material (e.g., a uranium-zirconium alloy). In one or more of the ceramic fuel examples, the kernel 100 comprises ceramic fuel material disposed in (e.g., interspersed throughout) the matrix of metal non-fuel material. According to various embodiments, the ceramic fuel material used in the manufacturing process may comprise powdered uranium or plutonium oxide, powdered uranium or plutonium nitride, powdered uranium or plutonium carbide, powdered uranium or plutonium hydride, or a combination thereof. In contrast with conventional  $\text{UO}_2$  fuel elements in which  $\text{UO}_2$  pellets are disposed in a tube, the manufacturing process results in ceramic fuel being disposed in a solid matrix of non-fuel material (e.g., a zirconium matrix).

**[0037]** As shown in FIG. 4, the axial coiling pitch of the spiral ribs 130 is selected according to the condition of placing the axes of adjacent fuel elements 10 with a spacing equal to the width across corners in the cross section of a fuel element and may be 5% to 20% of the fuel element 20 length. The pitch (i.e., the axial length over which a lobe/rib makes a complete rotation) is about 21.5 cm, while the full active length of the element 20 is about 420 cm. As shown in FIG. 3, stability of the vertical arrangement of the fuel elements 10 is provided: at the bottom - by the lower tie plate 70; at the top - by the upper tie plate 80; and relative to the height of the core - by the shroud 30. As shown in FIG. 1, the fuel elements 10 have a circumferential orientation such that the lobed profiles of any two adjacent fuel elements 10 have a common plane of symmetry which passes through the axes of the two adjacent fuel elements 10 in at least one cross section of the fuel element bundle.

**[0038]** As shown in FIG. 1, the helical twist of the fuel elements 20 in combination with their orientation ensures that there exists one or more self-spacing planes. As shown in FIG. 1, in such self spacing planes, the ribs of adjacent elements 20 contact each other to ensure proper spacing between such elements 20. Thus, the center-to-center spacing of elements 20 will be about the same as the corner-to-corner width of each element 20 (12.6 mm in the element illustrated in FIG. 5). Depending on the number of lobes 20b in each fuel element 20 and the relative geometrical arrangement of the fuel elements 20, all adjacent fuel elements 20 or only a portion of the adjacent fuel elements 20 will contact each other. For example, in the illustrated four-lobed embodiment, each fuel element 20 contacts all four adjacent fuel elements 20 at each self-spacing plane. However, in a three-lobed fuel element in which the fuel elements are arranged in a hexagonal pattern, each fuel element will only contact three of the six adjacent fuel elements in a given self-spacing plane. The three-lobed fuel element will contact the other three adjacent fuel elements in the next axially-spaced self-spacing plane (i.e., 1/6 of a turn offset from the previous self-spacing plane).

**[0039]** In an n-lobed element 20 in which n fuel elements are adjacent to a particular fuel element 20, a self-spacing plane will exist every 1/n helical turn (e.g., every 1/4 helical turn for a four-lobed element 20 arranged in a square pattern such that four other fuel elements 20 are adjacent to the fuel element 20; every 1/3 helical turn for a three-lobed element in which three fuel elements are adjacent to the fuel element (i.e., every 120 degrees around the perimeter of the fuel element)). The pitch of the helix may be modified to create greater or fewer self-spacing planes over the axial length of the fuel elements 20. Each four-lobed fuel element 20 includes multiple twists such that there are multiple self-spacing planes over the axial length of the bundle of fuel elements 20.

**[0040]** All of the elements 20 twist in the same direction. However, adjacent elements 20 may twist in opposite directions.

**[0041]** The formula for the number of self-spacing planes along the fuel rod length is as follows:

$$N=n*L/h,$$

where:

L - Fuel rod length

n - Number of lobes (ribs) and the number of fuel elements adjacent to a fuel element

h - Helical twist pitch

The formula is slightly different if the number of lobes and the number of fuel elements adjacent to a fuel element are not the same.

**[0042]** As a result of such self-spacing, the fuel assembly 10 may omit spacer grids that may otherwise have been necessary to assure proper element spacing along the length of the assembly 10. By eliminating spacer grids, coolant may more freely flow through the assembly 10, which advantageously increases the heat transfer from the elements 20 to the coolant. However, the assembly 10 may include spacer grid(s).

**[0043]** As shown in FIG. 3, the shroud 30 forms a tubular shell that extends axially along the entire length of the fuel elements 20 and surrounds the elements 20. However, the shroud 30 may comprise axially-spaced bands, each of which surrounds the fuel elements 20. One or more such bands may be axially aligned with the self-spacing planes.

Axially extending corner supports may extend between such axially spaced bands to support the bands, maintain the bands' alignment, and strengthen the assembly. Alternatively and/or additionally, holes may be cut into the otherwise tubular/polygonal shroud 30 in places where the shroud 30 is not needed or desired for support. Use of a full shroud 30 may facilitate greater control of the separate coolant flows through each individual fuel assembly 10. Conversely, the use of bands or a shroud with holes may facilitate better coolant mixing between adjacent fuel assemblies 10, which may advantageously reduce coolant temperature gradients between adjacent fuel assemblies 10.

**[0044]** As shown in FIG. 1, the cross-sectional perimeter of the shroud 30 has a shape that accommodates the reactor in which the assembly 10 is used. In reactors such as the AP-1000 that utilize square fuel assemblies, the shroud has a square cross-section. However, the shroud 30 may alternatively take any suitable shape depending on the reactor in which it is used (e.g., a hexagonal shape for use in a VVER reactor (e.g., as shown in FIG. 1 of U.S. Patent Application Publication No. 2009/0252278 A1).

**[0045]** The guide tubes 40 provide for the insertion of control absorber elements based on boron carbide ( $B_4C$ ), silver indium cadmium (Ag, In, Cd), dysprosium titanate ( $Dy_2O_3 \cdot TiO_2$ ) or other suitable alloys or materials used for reactivity control (not shown) and burnable absorber elements based on boron carbide, gadolinium oxide ( $Gd_2O_3$ ) or other suitable materials (not shown) and are placed in the upper nozzle 50 with the capability of elastic axial displacement. The guide tubes 40 may comprise a zirconium alloy. For example, the guide tube 40 arrangement shown in FIG. 1 is in an arrangement used in the AP-1000 reactor (e.g., 24 guide tubes arranged in two annular rows at the positions shown in the 17x17 grid).

**[0046]** The shape, size, and features of the frame 25 depend on the specific reactor core for which the assembly 10 is to be used. Thus, one of ordinary skill in the art would understand how to make appropriately shaped and sized frame for the fuel assembly 10. For example, the frame 25 may be shaped and configured to fit into a reactor core of a conventional nuclear power plant in place of a conventional uranium oxide or mixed oxide fuel assembly for that plant's reactor core. The nuclear power plant may comprise a reactor core design that was in actual use before 2010 (e.g., 2, 3 or 4-loop PWRs; BWR-4). Alternatively, the nuclear power plant may be of an entirely new design that is specifically tailored for use with the fuel assembly 10.

**[0047]** As explained above, the illustrated fuel assembly 10 is designed for use in an AP-1000 or EPR reactor. The assembly includes a 17x17 array of fuel elements 20, 24 of which are replaced with guide tubes 40 as explained above for a total of 265 fuel elements 20 in EPR or 264 fuel elements 20 in AP-1000 (in the AP-1000, in addition to the 24 fuel elements being replaced with the guide tubes, a central fuel element is also replaced with an instrumented tube).

**[0048]** The elements 20 preferably provide 100% of the overall fissile material of the fuel assembly 10. Alternatively, some of the fissile material of the assembly 10 may be provided via fuel elements other than the elements 20 (e.g., non-lobed fuel elements, uranium oxide elements, elements having fuel ratios and/or enrichments that differ from the elements 20). According to various such alternative embodiments, the fuel elements 20 provide at least 50%, 60%, 70%, 75%, 80%, 85%, 90%, and/or 95% by volume of the overall fissile material of the fuel assembly 10.

**[0049]** Use of the metal fuel elements 20 facilitate various advantages over the uranium oxide or mixed oxide fuel conventionally used in light water nuclear reactors (LWR) (including boiling water reactors and pressurized water reactors) such as the Westinghouse-designed AP-1000, AREVA-designed EPR reactors, or GE-designed ABWR. For example, the power rating for an LWR operating on standard uranium oxide or mixed oxide fuel could be increased by up to about 30% by substituting the all-metal fuel elements 20 and/or fuel assembly 10 for standard uranium oxide fuel and fuel assemblies currently used in existing types of LWRs or new types of LWRs that have been proposed.

**[0050]** One of the key constraints for increasing power rating of LWRs operating on standard uranium oxide fuel has been the small surface area of cylindrical fuel elements that such fuel utilizes. A cylindrical fuel element has the lowest surface area to volume ratio for any type of fuel element cross-section profile. Another major constraint for standard uranium oxide fuel has been a relatively low burnup that such fuel elements could possibly reach while still meeting acceptable fuel performance criteria. As a result, these factors associated with standard uranium oxide or mixed oxide fuel significantly limit the degree to which existing reactor power rating could be increased.

**[0051]** One or more examples of the all-metal fuel elements 20 overcome the above limitations. For example, as explained above, the lack of spacer grids may reduce hydraulic resistance, and therefore increase coolant flow and heat flux from the elements 20 to the primary coolant. The helical twist of the fuel elements 20 may increase coolant intermixing and turbulence, which may also increase heat flux from the elements 20 to the coolant.

**[0052]** Preliminary neutronic and thermal-hydraulic analyses have shown the following :

- The thermal power rating of an LWR reactor could be increased by up to 30.7% or more (e.g., the thermal power rating of an EPR reactor could be increased from 4.59 GWth to 6.0 GWth).
- With a uranium volume fraction of 25% in the uranium-zirconium mixture and uranium-235 enrichment of 19.7%, an EPR reactor core with a four-lobe metallic fuel element 20 configuration could operate for about 500-520 effective full power days (EFPDs) at the increased thermal power rating of 6.0 GWth if 72 fuel assemblies were replaced per batch (once every 18 months) or 540-560 EFPDs if 80 fuel assemblies were replaced per batch (once every 18

months).

- Due to the increased surface area in the multi-lobe fuel element, even at the increased power rating of 6.0 GWth, the average surface heat flux of the multi-lobe fuel element is shown to be 4-5% lower than that for cylindrical uranium oxide fuel elements operating at the thermal power rating of 4.59 GWth. This could provide an increased safety margin with respect to critical heat flux (e.g., increased departure from nucleate boiling margin in PWRs or maximum fraction limiting critical power ratio in BWRs). Further, this could allow a possibility of using 12 fuel elements per assembly with burnable poisons. Burnable poisons could be used to remove excess reactivity at the beginning of cycle or to increase the Doppler Effect during the heat-up of the core.
- Thus, the fuel assemblies 10 may provide greater thermal power output at a lower fuel operating temperature than conventional uranium oxide or mixed oxide fuel assemblies.

**[0053]** To utilize the increased power output of the assembly 10, conventional power plants could be upgraded (e.g., larger and/or additional coolant pumps, steam generators, heat exchangers, pressurizers, turbines). Indeed, the upgrade could provide 30-40% more electricity from an existing reactor. Such a possibility may avoid the need to build a complete second reactor. The modification cost may quickly pay for itself via increased electrical output. Alternatively, new power plants could be constructed to include adequate features to handle and utilize the higher thermal output of the assemblies 10.

**[0054]** Further, one or more examples of the disclosure could allow an LWR to operate at the same power rating as with standard uranium oxide or mixed oxide fuel using existing reactor systems without any major reactor modifications. For example:

- An EPR would have the same power output as if conventional uranium-oxide fuel were used: 4.59 GWt;
- With a uranium volume fraction of 25% in the uranium-zirconium mixture and uranium-235 enrichment of approximately 15%, an EPR reactor core with a four-lobe metallic fuel element 20 configuration could operate for about 500-520 effective full power days (EFPDs) if 72 fuel assemblies were replaced per batch or 540-560 EFPDs if 80 fuel assemblies were replaced per batch.
- The average surface heat flux for the elements 20 is reduced by approximately 30% compared to that for cylindrical rods with conventional uranium oxide fuel (e.g., 39.94 v. 57.34 W/cm<sup>2</sup>). Because the temperature rise of the coolant through the assembly 10 (e.g., the difference between the inlet and outlet temperature) and the coolant flow rate through the assembly 10 remain approximately the same relative to conventional fuel assemblies, the reduced average surface heat flux results in a corresponding reduction in the fuel rod surface temperature that contributes to increased safety margins with respect to critical heat flux (e.g., increased departure from nucleate boiling margin in PWRs or maximum fraction limiting critical power ratio in BWRs).

**[0055]** Additionally and/or alternatively, fuel assemblies 10 according to the present disclosure can be phased/laddered into a reactor core in place of conventional fuel assemblies. During the transition period, fuel assemblies 10 having comparable fissile/neutronic/thermal outputs as conventional fuel assemblies can gradually replace such conventional fuel assemblies over sequential fuel changes without changing the operating parameters of the power plant. Thus, fuel assemblies 10 can be retrofitted into an existing core that may be important during a transition period (i.e., start with a partial core with fuel assemblies 10 and gradually transition to a full core of fuel assemblies 10).

**[0056]** Moreover, the fissile loading of assemblies 10 can be tailored to the particular transition desired by a plant operator. For example, the fissile loading can be increased appropriately so as to increase the thermal output of the reactor by anywhere from 0% to 30% or more higher, relative to the use of conventional fuel assemblies that the assemblies 10 replace. Consequently, the power plant operator can choose the specific power uprate desired, based on the existing plant infrastructure or the capabilities of the power plant at various times during upgrades.

**[0057]** One or more examples of the fuel assemblies 10 and fuel elements 20 may be used in fast reactors (as opposed to light water reactors). In fast reactors, the non-fuel metal of the fuel kernel 100 is preferably a refractory metal, for example a molybdenum alloy (e.g., pure molybdenum or a combination of molybdenum and other metals), and the cladding 120 is preferably stainless steel (which includes any alloy variation thereof) or other material suitable for use with coolant in such reactors (e.g., sodium). Such fuel elements 20 may be manufactured via the above-discussed co-extrusion process or may be manufactured by any other suitable method (e.g., vacuum melt).

**[0058]** As shown in FIGS. 7A, 7B, and 8, fuel assemblies 510 may be used in a pressurized heavy water reactor 500 (see FIG. 8) such as a CANDU reactor.

**[0059]** As shown in FIGS. 7A and 7B, the fuel assembly 510 comprises a plurality of fuel elements 20 mounted to a frame 520. The frame 520 comprises two end plates 520a, 520b that mount to opposite axial ends of the fuel elements 20 (e.g., via welding, interference fits, any of the various types of attachment methods described above for attaching the elements 20 to the lower tie plate 70). The elements 20 used in the fuel assembly 510 are typically much shorter than the elements 20 used in the assembly 10. According to various embodiments and reactors 500, the elements 20

and assemblies 510 used in the reactor 500 may be about 18 inches long.

**[0060]** The elements 20 may be positioned relative to each other in the assembly 510 so that self-spacing planes maintain spacing between the elements 20 in the manner described above with respect to the assembly 10. Alternatively, the elements 20 of the assembly 510 may be so spaced from each other that adjacent elements 20 never touch each other, and instead rely entirely on the frame 520 to maintain element 20 spacing. Additionally, spacers may be attached to the elements 20 or their ribs at various positions along the axial length of the elements 20 to contact adjacent elements 20 and help maintain element spacing 20 (e.g., in a manner similar to how spacers are used on conventional fuel rods of conventional fuel assemblies for pressurized heavy water reactors to help maintain rod spacing).

**[0061]** As shown in FIG. 8, the assemblies 510 are fed into calandria tubes 500a of the reactor 500 (sometimes referred to in the art as a calandria 500). The reactor 500 uses heavy water 500b as a moderator and primary coolant. The primary coolant 500b circulates horizontally through the tubes 500a and then to a heat exchanger where heat is transferred to a secondary coolant loop that is typically used to generate electricity via turbines. Fuel assembly loading mechanisms (not shown) are used to load fuel assemblies 510 into one side of the calandria tubes 500a and push spent assemblies 510 out of the opposite side of the tubes 500a, typically while the reactor 500 is operating.

**[0062]** The fuel assemblies 510 may be designed to be a direct substitute for conventional fuel assemblies (also known as fuel bundles in the art) for existing, conventional pressurized heavy water reactors (e.g., CANDU reactors). In such an example, the assemblies 510 are fed into the reactor 500 in place of the conventional assemblies/bundles. Such fuel assemblies 510 may be designed to have neutronic/thermal properties similar to the conventional assemblies being replaced. Alternatively, the fuel assemblies 510 may be designed to provide a thermal power uprate. In such uprate examples, new or upgraded reactors 500 can be designed to accommodate the higher thermal output.

**[0063]** The fuel assembly 10 is designed to replace a conventional fuel assembly of a conventional nuclear reactor. For example, the fuel assembly 10 illustrated in FIG. 1 is specifically designed to replace a conventional fuel assembly that utilizes a 17x17 array of  $\text{UO}_2$  fuel rods. If the guide tubes 40 of the assembly 10 are left in the exact same position as they would be for use with a conventional fuel assembly, and if all of the fuel elements 20 are the same size, then the pitch between fuel elements/rods remains unchanged between the conventional  $\text{UO}_2$  fuel assembly and one or more examples of the fuel assembly 10 (e.g., 12.6 mm pitch). In other words, the longitudinal axes of the fuel elements 20 may be disposed in the same locations as the longitudinal axes of conventional  $\text{UO}_2$  fuel rods would be in a comparable conventional fuel assembly. According to various embodiments, the fuel elements 20 may have a larger circumscribed diameter than the comparable  $\text{UO}_2$  fuel rods (e.g., 12.6 mm as compared to an outer diameter of 9.5 mm for a typical  $\text{UO}_2$  fuel rod). As a result, in the self-aligning plane illustrated in FIG. 1, the cross-sectional length and width of the space occupied by the fuel elements 20 may be slightly larger than that occupied by conventional  $\text{UO}_2$  fuel rods in a conventional fuel assembly (e.g., 214.2 mm for the fuel assembly 10 (i.e., 17 fuel elements 20 x 12.6 mm circumscribed diameter per fuel element), as opposed to 211.1 mm for a conventional  $\text{UO}_2$  fuel assembly that includes a 17 x 17 array of 9.5 mm  $\text{UO}_2$  fuel rods separated from each other by a 12.6 mm pitch). In conventional  $\text{UO}_2$  fuel assemblies, a spacer grid surrounds the fuel rods, and increases the overall cross-sectional envelope of the conventional fuel assembly to 214 mm x 214 mm. In the fuel assembly 10, the shroud 30 similarly increases the cross-sectional envelope of the fuel assembly 10. The shroud 30 may be any suitable thickness (e.g., 0.5 mm or 1.0 mm thick). In an embodiment that utilizes a 1.0 mm thick shroud 30, the overall cross-sectional envelope of an embodiment of the fuel assembly 10 may be 216.2 mm x 216.2 mm (e.g., the 214 mm occupied by the 17 12.6 mm diameter fuel elements 20 plus twice the 1.0 mm thickness of the shroud 30). As a result, the fuel assembly 10 may be slightly larger (e.g., 216.2 mm x 216.2 mm) than a typical  $\text{UO}_2$  fuel assembly (214 mm x 214 mm). The larger size may impair the ability of the assembly 10 to properly fit into the fuel assembly positions of one or more conventional reactors, which were designed for use with conventional  $\text{UO}_2$  fuel assemblies. To accommodate this size change, according to one or more embodiments of the present invention, a new reactor may be designed and built to accommodate the larger size of the fuel assemblies 10.

**[0064]** According to an alternative, the circumscribed diameter of all of the fuel elements 20 may be reduced slightly so as to reduce the overall cross-sectional size of the fuel assembly 10. For example, the circumscribed diameter of each fuel element 20 may be reduced by 0.13 mm to 12.47 mm, so that the overall cross-sectional space occupied by the fuel assembly 10 remains comparable to a conventional 214 mm by 214 mm fuel assembly (e.g., 17 12.47 mm diameter fuel elements 20 plus two 1.0 mm thickness of the shroud, which totals about 214 mm). Such a reduction in the size of the 17 by 17 array will slightly change the positions of the guide tubes 40 in the fuel assembly 10 relative to the guide tube positions in a conventional fuel assembly. To accommodate this slight position change in the tube 40 positions, the positions of the corresponding control rod array and control rod drive mechanisms in the reactor may be similarly shifted to accommodate the repositioned guide tubes 40. Alternatively, if sufficient clearances and tolerances are provided for the control rods in a conventional reactor, conventionally positioned control rods may adequately fit into the slightly shifted tubes 40 of the fuel assembly 10.

**[0065]** Alternatively, the diameter of the peripheral fuel elements 20 may be reduced slightly so that the overall assembly 10 fits into a conventional reactor designed for conventional fuel assemblies. For example, the circumscribed diameter of the outer row of fuel elements 20 may be reduced by 1.1 mm such that the total size of the fuel assembly is 214 mm

x 214 mm (e.g., 15 12.6 mm fuel elements 20 plus 2 11.5 mm fuel elements 20 plus 2 1.0 mm thicknesses of the shroud 30). Alternatively, the circumscribed diameter of the outer two rows of fuel elements 20 may be reduced by 0.55 mm each such that the total size of the fuel assembly remains 214 mm x 214 mm (e.g., 13 12.6 mm fuel elements 20 plus 4 12.05 mm fuel assemblies plus 2 1.0 mm thicknesses of the shroud 30). In each example, the pitch and position of the central 13x13 array of fuel elements 20 and guide tubes 40 remains unaltered such that the guide tubes 40 align with the control rod array and control rod drive mechanisms in a conventional reactor.

**[0066]** FIG. 10 illustrates a fuel assembly 610 according to an alternative example. The fuel assembly 610 is designed to replace a conventional  $\text{UO}_2$  fuel assembly in a conventional reactor while maintaining the control rod positioning of reactors designed for use with various conventional  $\text{UO}_2$  fuel assemblies. The fuel assembly 610 is generally similar to the fuel assembly 10, which is described above and illustrated in FIG. 1, but includes several differences that help the assembly 610 to better fit into one or more existing reactor types (e.g., reactors using Westinghouse's fuel assembly design that utilizes a 17 by 17 array of  $\text{UO}_2$  rods) without modifying the control rod positions or control rod drive mechanisms.

**[0067]** As shown in FIG. 10, the fuel assembly includes a 17 by 17 array of spaces. The central 15 by 15 array is occupied by 200 fuel elements 20 and 25 guide tubes 40, as described above with respect to the similar fuel assembly 10 illustrated in FIG. 1. Depending on the specific reactor design, the central guide tube 40 may be replaced by an additional fuel element 20 if the reactor design does not utilize a central tube 40 (i.e., 201 fuel elements 20 and 24 guide tubes 40). The guide tube 40 positions correspond to the guide tube positions used in reactors designed to use conventional  $\text{UO}_2$  fuel assemblies.

**[0068]** The peripheral positions (i.e., the positions disposed laterally outward from the fuel elements 20) of the 17 by 17 array/pattern of the fuel assembly 610 are occupied by 64  $\text{UO}_2$  fuel elements/rods 650. As is known in the art, the fuel rods 650 may comprise standard  $\text{UO}_2$  pelletized fuel disposed in a hollow rod. The  $\text{UO}_2$  pelletized fuel may be enriched with U-235 by less than 20%, less than 15%, less than 10%, and/or less than 5%. The rods 650 may have a slightly smaller diameter (e.g., 9.50 mm) than the circumscribed diameter of the fuel elements 20, which slightly reduces the overall cross-sectional dimensions of the fuel assembly 610 so that the assembly 610 better fits into the space allocated for a conventional  $\text{UO}_2$  fuel assembly.

**[0069]** In the illustrated example, the fuel rods/elements 650 comprise  $\text{UO}_2$  pelletized fuel. However, the fuel rods/elements 650 may alternatively utilize any other suitable combination of one or more fissile and/or fertile materials (e.g., thorium, plutonium, uranium-235, uranium-233, any combinations thereof). Such fuel rods/elements 650 may comprise metal and/or oxide fuel.

**[0070]** According to one or more alternative examples, the fuel rods 650 may occupy less than all of the 64 peripheral positions. For example, the fuel rods 650 may occupy the top row and left column of the periphery, while the bottom row and right column of the periphery may be occupied by fuel elements 20. Alternatively, the fuel rods 650 may occupy any other two sides of the periphery of the fuel assembly. The shroud 630 may be modified so as to enclose the additional fuel elements 20 in the periphery of the fuel assembly. Such modified fuel assemblies may be positioned adjacent each other such that a row/column of peripheral fuel elements 650 in one assembly is always adjacent to a row/column of fuel elements 20 in the adjacent fuel assembly. As a result, additional space for the fuel assemblies is provided by the fact that the interface between adjacent assemblies is shifted slightly toward the assembly that includes fuel elements 650 in the peripheral, interface side. Such a modification may provide for the use of a greater number of higher heat output fuel elements 20 than is provided by the fuel assemblies 610.

**[0071]** A shroud 630 surrounds the array of fuel elements 20 and separates the elements 20 from the elements 650. The nozzles 50, 60, shroud 630, coolant passages formed therebetween, relative pressure drops through the elements 20 and elements 650, and/or the increased pressure drop through the spacer grid 660 (discussed below) surrounding the elements 650 may result in a higher coolant flow rate within the shroud 630 and past the higher heat output fuel elements 20 than the flow rate outside of the shroud 630 and past the relatively lower heat output fuel rods 650. The passageways and/or orifices therein may be designed to optimize the relative coolant flow rates past the elements 20, 650 based on their respective heat outputs and designed operating temperatures.

**[0072]** According to the invention, the moderator:fuel ratio for the fuel elements 20 of the fuel assembly 610 is less than or equal to 2.4. The moderator:fuel ratio equals a ratio of

(1) the total area within the shroud 630 available for coolant/moderator (e.g., approximated by the total cross-sectional area within the shroud 630 minus the total cross-sectional area taken up by the fuel elements 20 (assuming the guide tubes 40 are filled with coolant)) to (2) the total cross-sectional area of the kernels 100 of the fuel elements 20 within the shroud 630.

**[0073]** The shroud 630 may be replaced with one or more annular bands or may be provided with holes in the shroud 630, as explained above. The use of bands or holes in the shroud 630 may facilitate cross-mixing of coolant between the fuel elements 20 and the fuel elements 650.

**[0074]** As shown in FIG. 10, the fuel elements 650 are disposed within an annular spacer grid 660 that is generally comparable to the outer part of a spacer grid used in a conventional  $\text{UO}_2$  fuel assembly. The spacer grid 660 may rigidly connect to the shroud 630 (e.g., via welds, bolts, screws, or other fasteners). The spacer grid 660 is preferably sized so as to provide the same pitch between the fuel elements 650 and the fuel elements 20 as is provided between the central fuel elements 20 (e.g., 12.6 mm pitch between axes of all fuel elements 20, 650). To provide such spacing, the fuel elements 650 may be disposed closer to the outer side of the spacer grid 660 than to the shroud 630 and inner side of the spacer grid 660. The fuel assembly 610 and spacer grid 660 are also preferably sized and positioned such that the same pitch is provided between fuel elements 650 of adjacent fuel assemblies (e.g., 12.6 mm pitch). However, the spacing between any of the fuel elements 20, 650 may vary relative to the spacing between other fuel elements 20, 650 without deviating from the scope of the present invention.

**[0075]** The fuel elements 20 provide at least 60%, 65%, 70%, 75%, and/or 80% of a total volume of all fissile-material-containing fuel elements 20, 650 of the fuel assembly 610. For example, according to one or more examples in which the fuel assembly 610 includes 201 fuel elements 20, each having a cross-sectional area of about  $70 \text{ mm}^2$ , and 64 fuel elements 650, each having a 9.5 mm diameter, the fuel elements 20 provide about 75.6% of a total volume of all fuel elements 20, 650 ( $201 \text{ fuel elements } 20 \times 70 \text{ mm}^2 \text{ equals } 14070 \text{ mm}^2$ ;  $64 \text{ fuel elements } 650 \times \pi \times (9.5/2)^2 = 4534 \text{ mm}^2$ ; fuel element 20, 650 areas are essentially proportional to fuel element volumes;  $(14070 \text{ mm}^2 / (14070 \text{ mm}^2 + 4534 \text{ mm}^2) = 75.6\%$ )).

**[0076]** The height of the fuel assembly 610 matches a height of a comparable conventional fuel assembly that the assembly 610 can replace (e.g., the height of a standard fuel assembly for a Westinghouse or AREVA reactor design).

**[0077]** The illustrated fuel assembly 610 may be used in a 17x17 PWR such as the Westinghouse 4-loop design, AP1000, or AREVA EPR. However, the design of the fuel assembly 610 may also be modified to accommodate a variety of other reactor designs (e.g., reactor designs that utilize a hexagonal fuel assembly, in which case the outer periphery of the hexagon is occupied by  $\text{UO}_2$  rods, while the inner positions are occupied by fuel elements 20, or boiling water reactors, or small modular reactors). While particular dimensions are described with regard to particular embodiments, a variety of alternatively dimensioned fuel elements 20, 650 and fuel assemblies 10 may be used in connection with a variety of reactors or reactor types.

**[0078]** Depending on the specific reactor design, additional rod positions of a fuel assembly may be replaced with  $\text{UO}_2$  rods. For example, while the fuel assembly 610 includes  $\text{UO}_2$  rods only in the outer peripheral row, the assembly 610 could alternatively include  $\text{UO}_2$  rods in the outer two rows.

**[0079]** The portion of the fuel assembly 610 that supports the fuel elements 650 is inseparable from the portion of the fuel assembly 610 that supports the fuel elements 20. The fuel elements 20 are not separable as a unit from the fuel elements 650 of the fuel assembly 610 (even though individual fuel elements 20, 650 may be removed from the assembly 610, for example, based on individual fuel element failure). Similarly, there is not a locking mechanism that selectively locks the fuel element 650 portion of the fuel assembly to the fuel element 20 portion of the fuel assembly 610. The fuel elements 20 and fuel elements 650 of the fuel assembly 610 have the same designed life cycle, such that the entire fuel assembly 610 is used within the reactor, and then removed as a single spent unit.

**[0080]** The increased heat output of the fuel elements 20 within the fuel assembly 610 can provide a power uprate relative to the conventional all  $\text{UO}_2$  fuel rod assembly that the assembly 610 replaces. The power uprate is at least 5%, 10%, and/or 15%. The uprate may be between 1 and 30%, 5 and 25%, and/or 10 and 20%. The fuel assembly 610 provides at least an 18-month fuel cycle, but may also facilitate moving to a 24+ or 36+ month fuel cycle. The fuel assembly 610, which uses fuel elements 20 having the example parameters discussed above with respect to the element 20 shown in FIG. 10, the assembly 17 provides a 17% uprate relative to a conventional  $\text{UO}_2$  fuel assembly under the operating parameters identified in the below tables.

| Operating Parameter for AREVA EPR Reactor   |  | Value       | Unit   |
|---------------------------------------------|--|-------------|--------|
| Reactor power                               |  | 5.37        | GWt    |
| Fuel cycle length                           |  | 18          | months |
| Reload batch size                           |  | 1/3         | core   |
| Enrichment of Fuel Element 20               |  | $\leq 19.7$ | w/o    |
| Enrichment of $\text{UO}_2$ of the Rods 650 |  | $\leq 5$    | w/o    |
| Coolant flow rate                           |  | 117%        | rv     |
| Fuel Assembly Parameter                     |  | Value       | Unit   |
| Fuel assembly design                        |  | 17x17       |        |

(continued)

| Fuel Assembly Parameter                                         | Value | Unit |
|-----------------------------------------------------------------|-------|------|
| Fuel assembly pitch                                             | 215   | mm   |
| Fuel assembly envelope                                          | 214   | mm   |
| Active fuel height                                              | 4200  | mm   |
| Number of fuel rods                                             | 265   |      |
| Fuel element 20 pitch (i.e., axis to axis spacing)              | 12.6  | mm   |
| Average outer fuel element 20 diameter (circumscribed diameter) | 12.6  | mm   |
| Average minimum fuel element 20 diameter                        | 10.44 | mm   |
| Moderator to fuel ratio, seed region (around elements 20)       | 2.36  |      |
| Moderator to fuel ratio, blanket (around the fuel rods 650)     | 1.9   |      |
| * $r_V$ = reference value                                       |       |      |

**[0081]** The fuel assemblies 10, 510, 610 are preferably thermodynamically designed for and physically shaped for use in a land-based nuclear power reactor 90, 500 (e.g., land-based LWRS (including BWRs and PWRs), land-based fast reactors, land-based heavy water reactors) that is designed to generate electricity and/or heat that is used for a purpose other than electricity (e.g., desalinization, chemical processing, steam generation, etc.). Such land-based nuclear power reactors 90 include, among others, VVER, AP-1000, EPR, APR-1400, ABWR, BWR-6, CANDU, BN-600, BN-800, Toshiba 4S, Monju, etc. However, the fuel assemblies 10, 510, 610 may be designed for use in and used in marine-based nuclear reactors (e.g., ship or submarine power plants; floating power plants designed to generate power (e.g., electricity) for onshore use) or other nuclear reactor applications.

**[0082]** The foregoing illustrated examples are provided to illustrate the structural and functional principles of the present disclosure and are not intended to be limiting. To the contrary, the principles of the present invention are intended to encompass any and all changes, alterations and/or substitutions within the scope of the following claims.

## Claims

1. A fuel assembly (10) for use in a core of a nuclear power reactor, the assembly comprising:

a frame (25) comprising a lower nozzle (60) that is shaped and configured to mount to the nuclear reactor internal core structure; and  
a plurality of elongated, extruded fuel elements (20) supported by the frame, each of said plurality of fuel elements comprising:

a fuel kernel (100) comprising fuel material disposed in a matrix of metal non-fuel material, the fuel material comprising fissile material, and  
a cladding (120) surrounding the fuel kernel, **characterised in that**  
a moderator:fuel ratio in a region of the fuel elements is 2.4 or less,

wherein the moderator:fuel ratio is an area ratio within a cross-section that is perpendicular to longitudinal axes of the plurality of elongated, extruded fuel elements and extends through the plurality of elongated, extruded fuel elements, the ratio being a ratio of a total area available for moderator flow for the plurality of fuel elements to a total area of the fuel kernels of the plurality of fuel elements; and  
wherein the kernel comprises  $\delta$ -phase UZr<sub>2</sub>.

2. The fuel assembly of claim 1, wherein:

the plurality of elongated, extruded fuel elements comprise a plurality of elongated, extruded metal fuel elements; the fuel material comprises metal fuel material; and  
the fuel kernel comprises a metal fuel alloy kernel comprising an alloy of the metal fuel material and the metal non-fuel material.

3. The fuel assembly of claim 1, wherein the fuel material comprises ceramic fuel material disposed in the matrix of metal non-fuel material.

4. The fuel assembly of claim 1, wherein:

the plurality of elongated, extruded fuel elements provide at least 60% of a total volume of all fuel elements of the fuel assembly.

5. The fuel assembly of claim 4, wherein said total volume of all fuel elements of the fuel assembly includes the total volume of all fuel elements that are supported by the lower nozzle.

6. The fuel assembly of claim 1, wherein an average thickness of the cladding is at least 0.6 mm.

7. The fuel assembly of claim 1, wherein the respective fuel kernels of the plurality of elongated, extruded fuel elements are formed via sintering of the fuel material and metal non-fuel material.

8. The fuel assembly of claim 1, wherein, with respect to a plurality of said plurality of fuel elements:

the fuel material of the fuel kernel is enriched to 20% or less by uranium-235 and/or uranium-233 and comprises between a 20% and 30% volume fraction of the fuel kernel; and  
the non-fuel metal comprises between a 70% and 80% volume fraction of the fuel kernel.

9. The fuel assembly of claim 8, wherein, with respect to the plurality of said plurality of elongated, extruded fuel elements, the fuel material enrichment is between 15% and 20%.

10. The fuel assembly of claim 8, wherein, with respect to the plurality of said plurality of elongated, extruded fuel elements, the non-fuel metal of the fuel kernel comprises zirconium.

11. The fuel assembly of claim 1, wherein, with respect to a plurality of said plurality of fuel elements:

the fuel material of the fuel kernel comprises plutonium;  
the non-fuel metal of the fuel kernel comprises zirconium; and  
the non-fuel metal of the fuel kernel comprises between a 70% and 97% volume fraction of the fuel kernel.

12. The fuel assembly of claim 1, wherein the fuel material comprises a combination of: uranium and thorium; plutonium and thorium; or uranium, plutonium, and thorium.

13. The fuel assembly of claim 1, wherein the cladding of a plurality of said plurality of fuel elements is metallurgically bonded to the fuel kernel.

14. The fuel assembly of claim 1, wherein the non-fuel metal of a plurality of said plurality of fuel elements comprises aluminum.

15. The fuel assembly of claim 1, wherein the non-fuel metal of a plurality of said plurality of fuel elements comprises a refractory metal.

16. The fuel assembly of claim 1, wherein the cladding of a plurality of said plurality of fuel elements comprises zirconium.

17. The fuel assembly of claim 1, wherein a plurality of said plurality of fuel elements each has a spirally twisted, multi-lobed profile that defines a plurality of spiral ribs.

18. The fuel assembly of claim 17, wherein the spiral ribs of adjacent ones of said plurality of fuel elements periodically contact each other over the axial length of the fuel elements, such contact helping to maintain the spacing of the fuel elements relative to each other.

19. The fuel assembly of claim 17, wherein the multi-lobed profile comprises concave areas between adjacent lobes.

20. The fuel assembly of claim 17, wherein:

the multi-lobed profile comprises lobe tips and intersections between adjacent lobes, and with respect to said plurality of said plurality of fuel elements, the cladding is thicker at the tips than at the intersections.

21. The fuel assembly of claim 1, wherein the fuel assembly comprises a burnable poison.
22. The fuel assembly of claim 21, wherein at least one of the plurality of elongated, extruded fuel elements comprises the burnable poison.
23. The fuel assembly of claim 1, further comprising a plurality of UO<sub>2</sub> fuel elements supported by the frame, each of said plurality of UO<sub>2</sub> fuel elements comprising UO<sub>2</sub> fuel.
24. The fuel assembly of claim 23, wherein at least some of the plurality of elongated UO<sub>2</sub> fuel elements are positioned laterally outwardly from the plurality of elongated, extruded fuel elements.
25. The fuel assembly of claim 24, further comprising a shroud that separates coolant flow past the plurality of elongated UO<sub>2</sub> fuel elements from coolant flow past the plurality of elongated, extruded fuel elements.
26. The fuel assembly of claim 25, wherein a ratio of (1) a total area within the shroud available for moderator to (2) a total cross-sectional area of the kernels of the plurality of elongated, extruded fuel elements within the shroud is 2.4 or less.
27. The fuel assembly of claim 23, wherein the UO<sub>2</sub> fuel has less than 15% U-235 enrichment.
28. A method of manufacturing a fuel assembly (10) for use in a core of a nuclear power reactor, the method comprising:  
manufacturing each of a plurality of elongated fuel elements (20) by:  
mixing fuel material with metal non-fuel material, wherein the fuel material comprises fissile material,  
creating a fuel core stock from the mixed fuel material and metal non-fuel material wherein the fuel core stock comprises  $\delta$ -phase UZr<sub>2</sub>,  
surrounding the fuel core stock with a cladding material, and  
co-extruding the fuel core stock and cladding material to create the fuel element; and  
mounting the plurality of elongated fuel elements to a frame (25) of the fuel assembly  
wherein a moderator:fuel ratio in a region of the fuel elements is 2.4 or less, the moderator:fuel ratio being an area ratio within a cross-section that is perpendicular to longitudinal axes of the plurality of elongated, extruded fuel elements and extends through the plurality of elongated, extruded fuel elements, the ratio being a ratio of a total area available for moderator flow for the plurality of fuel elements to a total area of the fuel kernels of the plurality of fuel elements.
29. The method of claim 28, wherein the fuel material comprises powdered fuel material and the metal non-fuel material comprises powdered metal non-fuel material, wherein creating the fuel core stock comprises sintering the mixed powdered fuel material and the powdered metal non-fuel material to create the fuel core stock.
30. The method of claim 28, wherein creating the fuel core stock comprises melt-casting the mixed fuel material and the metal non-fuel material to create the fuel core stock.
31. The method of any one of claims 28, 29 or 30, wherein:  
the plurality of elongated fuel elements comprise a plurality of elongated metal fuel elements; and  
the fuel material comprises metal fuel material; and  
the fuel core stock comprises a metal fuel core stock comprising an alloy of the metal fuel material and the metal non-fuel material.
32. The method of claim 29 or 30, wherein the fuel material comprises ceramic fuel material.

33. The method of any one of claims 28, 29 or 30, wherein the plurality of elongated fuel elements provide at least 60% of a total volume of all fuel elements of the fuel assembly.

34. The method of any one of claims 28, 29 or 30, wherein an average thickness of the cladding after co-extrusion is at least 0.6 mm.

35. The method of claim 29, further comprising positioning a displacer within the mixed powdered fuel material and metal non-fuel material before said sintering such that said sintering results in a fuel core stock that includes the displacer.

36. The method of any one of claims 28, 29 or 30, wherein:

the frame comprises a lower nozzle that is shaped and configured to mount to a core of a land-based nuclear power reactor; and

the fuel assembly is thermodynamically designed and physically shaped for operation in the land-based nuclear power reactor.

37. The method of claim 36, further comprising placing the fuel assembly into the land-based nuclear power reactor.

38. A land based nuclear reactor including a fuel assembly according to any of claims 1 to 28.

39. A land based nuclear reactor according to claim 38, wherein the reactor is a heavy water reactor.

40. The land-based nuclear power reactor of claims 38 or 39, in which the reactor comprises a conventional nuclear power plant having a reactor design that was in actual use before 2010; and the frame of the fuel assembly is shaped and configured to fit into the land-based nuclear power reactor in place of a conventional uranium oxide fuel assembly for said reactor.

## Patentansprüche

### 1. Brennstoffanordnung (10)

zur Verwendung in einem Kern eines Kernkraftreaktors, wobei die Anordnung Folgendes umfasst: einen Rahmen (25), der eine untere Düse (60) umfasst, die bemessen und konfiguriert ist, um an der inneren Kernstruktur des Kernkraftreaktors angebracht zu werden; und

eine Vielzahl von länglichen extrudierten Brennstoffelementen (20), die durch den Rahmen gestützt werden, wobei jedes der Vielzahl von Brennstoffelementen Folgendes umfasst: einen Brennstoffkernel (100), der Brennstoffmaterial umfasst, das in einer Matrix eines metallischen Nichtbrennstoffmaterials angeordnet ist, wobei das Brennstoffmaterial spaltbares Material umfasst, und

eine Verkleidung (120), die den Brennstoffkernel umfasst, **dadurch gekennzeichnet, dass** ein Moderator:Brennstoff-Verhältnis in einem Bereich des Brennstoffelements 2,4 oder weniger beträgt, wobei es sich bei dem Moderator:Brennstoff Verhältnis um ein Bereichsverhältnis in einem Querschnitt handelt, der senkrecht zu Längsachsen der Vielzahl von länglichen extrudierten Brennstoffelementen steht und sich durch die Vielzahl von länglichen extrudierten Brennstoffelementen erstreckt, wobei es sich bei dem Verhältnis um ein Verhältnis von einem Gesamtbereich, das für einen Moderatorstrom für die Vielzahl von Brennstoffelementen zur Verfügung steht, zu einem Gesamtbereich der Brennstoffkernel der Vielzahl von Brennstoffelementen handelt; und wobei der Kernel  $\alpha$ -Phasen-UZr<sub>2</sub> umfasst.

### 2. Brennstoffanordnung nach Anspruch 1, wobei:

die Vielzahl von länglichen extrudierten Brennstoffelementen eine Vielzahl von länglichen extrudierten metallischen Brennstoffelementen umfasst;

das Brennstoffmaterial metallisches Brennstoffmaterial umfasst; und

der Brennstoffkernel einen Brennstoffkernel aus einer Metalllegierung umfasst, der eine Legierung aus dem metallischen Brennstoffmaterial und dem metallischen Nichtbrennstoffmaterial umfasst.

### 3. Brennstoffanordnung nach Anspruch 1, wobei das Brennstoffmaterial keramisches Brennstoffmaterial umfasst, das

in der Matrix des metallischen Nichtbrennstoffmaterials angeordnet ist.

4. Brennstoffanordnung nach Anspruch 1, wobei:

die Vielzahl von länglichen extrudierten Brennstoffelementen zumindest 60 % des Gesamtvolumens aller Brennstoffelemente der Brennstoffanordnung bereitstellt.

5. Brennstoffanordnung nach Anspruch 4, wobei das Gesamtvolumen aller Brennstoffelemente der Brennstoffanordnung das Gesamtvolumen aller Brennstoffelemente beinhaltet, die durch die untere Düse gestützt werden.

6. Brennstoffanordnung nach Anspruch 1, wobei eine Durchschnittsdicke der Verkleidung zumindest 0,6 mm beträgt.

7. Brennstoffanordnung nach Anspruch 1, wobei die entsprechenden Brennstoffkernel der Vielzahl von länglichen extrudierten Brennstoffelementen durch Sintern des Brennstoffmaterials und des metallischen Nichtbrennstoffmaterials gebildet sind.

8. Brennstoffanordnung nach Anspruch 1, wobei Folgendes in Bezug auf eine Vielzahl der Vielzahl von Brennstoffelementen gilt:

Das Brennstoffmaterial des Brennstoffkerns ist durch Uran 235 und/oder Uran 233 auf 20 % oder weniger angereichert und umfasst einen Volumenanteil des Brennstoffkerns zwischen 20 % und 30 %; und das Nichtbrennstoffmetall umfasst einen Volumenanteil des Brennstoffkerns zwischen 70 % und 80 %.

9. Brennstoffanordnung nach Anspruch 8, wobei die Brennstoffmaterialanreicherung in Bezug auf die Vielzahl der Vielzahl von länglichen extrudierten Brennstoffelementen zwischen 15 % und 20 % liegt.

10. Brennstoffanordnung nach Anspruch 8, wobei das Nichtbrennstoffmetall des Brennstoffkerns in Bezug auf die Vielzahl der Vielzahl von länglichen extrudierten Brennstoffelementen Zirkonium umfasst.

11. Brennstoffanordnung nach Anspruch 1, wobei Folgendes in Bezug auf eine Vielzahl der Vielzahl von Brennstoffelementen gilt:

Das Brennstoffmaterial des Brennstoffkerns umfasst Plutonium; das Nichtbrennstoffmetall des Brennstoffkerns umfasst Zirkonium; und das Nichtbrennstoffmetall des Brennstoffkerns umfasst einen Volumenanteil des Brennstoffkerns zwischen 70 % und 97 %.

12. Brennstoffanordnung nach Anspruch 1, wobei das Brennstoffmaterial eine Kombination aus Folgendem umfasst; Uran und Thorium; Plutonium und Thorium; oder Uran, Plutonium und Thorium.

13. Brennstoffanordnung nach Anspruch 1, wobei die Verkleidung einer Vielzahl der Vielzahl von Brennstoffelementen metallurgisch mit dem Brennstoffkernel verbunden ist.

14. Brennstoffanordnung nach Anspruch 1, wobei das Nichtbrennstoffmetall einer Vielzahl der Vielzahl von Brennstoffelementen Aluminium umfasst.

15. Brennstoffanordnung nach Anspruch 1, wobei das Nichtbrennstoffmetall einer Vielzahl der Vielzahl von Brennstoffelementen ein hochschmelzendes Metall umfasst.

16. Brennstoffanordnung nach Anspruch 1, wobei die Verkleidung einer Vielzahl der Vielzahl von Brennstoffelementen Zirkonium umfasst.

17. Brennstoffanordnung nach Anspruch 1, wobei eine Vielzahl der Vielzahl von Brennstoffelementen jeweils ein spiralförmig gedilltes, mehrfach gelapptes Profil aufweist, das eine Vielzahl von Spiralrippen definiert.

18. Brennstoffanordnung nach Anspruch 17, wobei die Spiralrippen von benachbarten der Vielzahl von Brennstoffelementen einander über die axiale Länge der Brennstoffelemente periodisch berühren, wobei die Berührung ein Beibehalten der Beabstandung der Brennstoffelemente bezogen aufeinander unterstützt.

19. Brennstoffanordnung nach Anspruch 17, wobei das mehrfach gelappte Profil konkave Bereiche zwischen benachbarten Lappen umfasst.

20. Brennstoffanordnung nach Anspruch 17, wobei:

das mehrfach gelappte Profil Lappenspitzen und Schnittpunkte zwischen benachbarten Lappen umfasst und die Verkleidung in Bezug auf die Vielzahl der Vielzahl von Brennstoffelementen an den Spitzen dicker ist als an den Schnittpunkten.

21. Brennstoffanordnung nach Anspruch 1, wobei die Brennstoffanordnung ein brennbares Gift umfasst.

22. Brennstoffanordnung nach Anspruch 21, wobei zumindest eines der Vielzahl von länglichen extrudierten Brennstoffelementen das brennbare Gift umfasst.

23. Brennstoffanordnung nach Anspruch 1, die ferner eine Vielzahl von UO<sub>2</sub>-Brennstoffelementen umfasst, die durch den Rahmen gestützt wird, wobei die Vielzahl von UO<sub>2</sub>-Brennstoffelementen UO<sub>2</sub>-Brennstoff umfasst.

24. Brennstoffanordnung nach Anspruch 23, wobei zumindest einige der Vielzahl von länglichen UO<sub>2</sub>-Brennstoffelementen von der Vielzahl von länglichen extrudierten Brennstoffelementen lateral nach außen angeordnet sind.

25. Brennstoffanordnung nach Anspruch 24, die ferner eine Ummantelung umfasst, die einen Kühlmittelstrom an der Vielzahl von länglichen UO<sub>2</sub>-Brennstoffelementen vorbei von einem Kühlmittelstrom an der Vielzahl von länglichen extrudierten Brennstoffelementen vorbei trennt.

26. Brennstoffanordnung nach Anspruch 25, wobei ein Verhältnis von (1) einem Gesamtbereich in der Ummantelung, die einem Moderator zur Verfügung steht, zu (2) einem Gesamtquerschnittsbereich der Kern der Vielzahl von länglichen extrudierten Brennstoffelementen in der Ummantelung 2,4 oder weniger beträgt.

27. Brennstoffanordnung nach Anspruch 23, wobei der UO<sub>2</sub>-Brennstoff eine Anreicherung von weniger als 15 % U 235 aufweist.

28. Verfahren zur Herstellung einer Brennstoffanordnung (10) zur Verwendung in einem Kern eines Kernkraftreaktors, wobei das Verfahren Folgendes umfasst:

Herstellen jedes von einer Vielzahl von länglichen Brennstoffelementen (20) durch:

Mischen von Brennstoffmaterial mit metallischen Nichtbrennstoffmaterial, wobei das Brennstoffmaterial spaltbares Material umfasst,  
Erzeugen eines Brennstoffkerngrundmaterials aus dem gemischten Brennstoffmaterial und dem metallischen Nichtbrennstoffmaterial, wobei das Brennstoffkerngrundmaterial cf-Phasen-UZr<sub>2</sub> umfasst,  
Umgeben des Brennstoffkerngrundmaterials mit einem Verkleidungsmaterial und Koextrudieren des Brennstoffkerngrundmaterials und Verkleidungsmaterials, um das Brennstoffelement zu erzeugen; und  
Anbringen der Vielzahl von länglichen Brennstoffelementen an einem Rahmen (25) der Brennstoffanordnung,

wobei ein Moderator:Brennstoff-Verhältnis in einem Bereich des Brennstoffelementes 2,4 oder weniger beträgt, wobei es sich bei dem Moderator:Brennstoff-Verhältnis um ein Bereichsverhältnis in einem Querschnitt handelt, der senkrecht zu Längsachsen der Vielzahl von länglichen extrudierten Brennstoffelementen steht und sich durch die Vielzahl von länglichen extrudierten Brennstoffelementen erstreckt, wobei es sich bei dem Verhältnis um ein Verhältnis von einem Gesamtbereich, der einem Moderatorstrom für die Vielzahl von Brennstoffelementen zur Verfügung steht, zu einem Gesamtbereich der Brennstoffkern der Vielzahl von Brennstoffelementen handelt.

29. Verfahren nach Anspruch 28, wobei das Brennstoffmaterial pulverförmiges Brennstoffmaterial umfasst und das metallische Nichtbrennstoffmaterial pulverförmiges metallisches Nichtbrennstoffmaterial umfasst, wobei das Erzeugen des Brennstoffkerngrundmaterials Sintern des gemischten pulverförmigen Brennstoffmaterials und des pulverförmigen metallischen Nichtbrennstoffmaterials umfasst, um das Brennstoffkerngrundmaterial zu erzeugen.

30. Verfahren nach Anspruch 28, wobei das Erzeugen des Brennstoffkerngrundmaterial Schmelzgießen des gemischten Brennstoffmaterials und des metallischen Nichtbrennstoffmaterials umfasst, um das Brennstoffkerngrundmaterial zu erzeugen.

31. Verfahren nach einem der Ansprüche 28, 29 oder 30, wobei:

die Vielzahl von länglichen Brennstoffelementen eine Vielzahl von länglichen metallischen Brennstoffelementen umfasst; und

das Brennstoffmaterial metallisches Brennstoffmaterial umfasst; und

das Brennstoffkerngrundmaterial ein metallischen Kerngrundmaterial umfasst, das eine Legierung aus dem metallischen Brennstoffmaterial und dem metallischen Nichtbrennstoffmaterial umfasst.

32. Verfahren nach Anspruch 29 oder 30, wobei Brennstoffmaterial ein Keramikbrennstoffmaterial umfasst.

33. Verfahren nach einem der Ansprüche 28, 29 oder 30, wobei die Vielzahl von länglichen Brennstoffelementen zumindest 60 % des Gesamtvolumens aller Brennstoffelemente der Brennstoffanordnung bereitstellt.

34. Verfahren nach einem der Ansprüche 28, 29 oder 30, wobei eine Durchschnittsdicke der Verkleidung zumindest 0,6 mm beträgt.

35. Verfahren nach Anspruch 29, das ferner Anordnen eines Verdrängungskörpers in dem gemischten pulverförmigen Brennstoffmaterial und metallischen Nichtbrennstoffmaterial vor dem Sintern umfasst, sodass das Sintern zu einem Brennstoffkerngrundmaterial führt, das den Verdrängungskörper beinhaltet.

36. Verfahren nach einem der Ansprüche 28, 29 oder 30, wobei:

der Rahmen eine untere Düse umfasst, die bemessen und konfiguriert ist, um an einem Kern eines landgestützten Kernkraftreaktors angebracht zu werden; und

die Brennstoffanordnung zum Betrieb in dem landgestützten Kernkraftreaktor thermodynamisch ausgebildet und physikalisch bemessen ist.

37. Verfahren nach Anspruch 36, das ferner Anordnen der Brennstoffanordnung in dem landgestützten Kernkraftreaktor umfasst.

38. Landgestützter Kernkraftreaktor, der eine Brennstoffanordnung nach einem der Ansprüche 1 bis 28 beinhaltet.

39. Landgestützter Kernkraftreaktor nach Anspruch 38, wobei es sich bei dem Reaktor um einen Schwerwasserreaktor handelt.

40. Landgestützter Kernkraftreaktor nach Anspruch 38 oder 39, wobei der Reaktion ein herkömmliches Kernkraftwerk umfasst, das ein Reaktordesign aufweist, das vor 2010 in Gebrauch war; und der Rahmen der Brennstoffanordnung bemessen und konfiguriert ist, um in den landgestützten Kernkraftreaktor anstelle einer herkömmlichen Uranoxid-Brennstoffanordnung für den Reaktor zu passen.

## Revendications

1. Assemblage combustible (10)

pour l'utilisation dans un coeur de réacteur d'une centrale nucléaire, l'assemblage comprenant :

un cadre (25) comprenant une buse inférieure (60) façonnée et configurée pour être montée sur la structure du coeur intérieur du réacteur nucléaire ; et

une pluralité de crayons combustibles extrudés allongés (20) soutenus par le cadre, chacun de ladite pluralité de crayons combustibles comprenant :

un noyau de combustible (100), comprenant le matériau combustible disposé dans une matrice de matériau non combustible métallique, le matériau combustible comprenant une matière fissile, et une gaine (120) revêtant le noyau de combustible (100),

**caractérisé par**

un ratio modérateur/combustible dans la zone des crayons combustibles égal à 2,4 ou moins,  
 le ratio modérateur/combustible étant un rapport de zone au sein d'une section transversale perpendiculaire à  
 des axes longitudinaux de la pluralité de crayons combustibles extrudés allongés, et s'étendant à travers la  
 pluralité de crayons combustibles extrudés et allongés, ce ratio étant un ratio de la superficie totale disponible  
 pour le flux de modérateur pour la pluralité de crayons combustibles sur une superficie totale de noyaux de  
 combustible de la pluralité de crayons combustibles ; et  
 le noyau comprenant de l'UZr2 en phase

**2. Assemblage combustible selon la revendication 1, dans lequel :**

la pluralité de crayons combustibles extrudés et allongés comprend une pluralité de crayons combustibles  
 allongés en métal extrudé ;  
 le matériau combustible comprenant un matériau combustible métallique ; et  
 le noyau combustible comprenant un noyau en alliage de combustible métallique comprenant un alliage de  
 matériau combustible métallique et de matériau non combustible métallique.

**3. Assemblage combustible selon la revendication 1, dans lequel le matériau combustible comprenant un matériau  
 combustible de céramique disposé dans la matrice de matériau non combustible métallique.**

**4. Assemblage combustible selon la revendication 1, dans lequel :**

la pluralité de crayons combustibles extrudés allongés fournit au moins 60% du volume total de tous les crayons  
 combustibles de l'assemblage combustible.

**5. Assemblage combustible selon la revendication 4, ledit volume total de tous les crayons combustibles de l'assem-  
 blage combustible comprenant le volume total de tous les crayons combustibles supportés par la buse inférieure.**

**6. Assemblage combustible selon la revendication 1, l'épaisseur moyenne de la gaine mesurant au moins 0,6 mm.**

**7. Assemblage combustible selon la revendication 1, les noyaux combustibles respectifs de la pluralité de crayons  
 combustibles extrudés et allongés étant formés par frittage du matériau combustible et du matériau non combustible  
 métallique.**

**8. Assemblage combustible selon la revendication 1, dans lequel, relativement à une pluralité de ladite pluralité de  
 crayons combustibles,  
 le matériau combustible du noyau combustible est enrichi jusqu'à 20% ou moins par de l'uranium-235 et/ou de  
 l'uranium-233, et comprend de 20% à 30% de la fraction du volume du noyau combustible ; et le métal non com-  
 bustible comprend de 70% à 80% de la fraction du volume du noyau combustible.**

**9. Assemblage combustible selon la revendication 8, dans lequel, relativement à la pluralité de ladite pluralité de  
 crayons combustibles extrudés allongés, l'enrichissement du matériau combustible est compris entre 15% et 20%.**

**10. Assemblage combustible selon la revendication 8, dans lequel, relativement à la pluralité de ladite pluralité de  
 crayons combustibles extrudés allongés, le métal non combustible du noyau combustible comprend du zircon.**

**11. Assemblage combustible selon la revendication 1, dans lequel, relativement à une pluralité de ladite pluralité de  
 crayons combustibles :**

le matériau combustible du noyau combustible comprend du plutonium ;  
 le métal non combustible du noyau combustible comprend du zircon ; et  
 le métal non combustible du noyau combustible comprend de 70% à 97% d'une fraction du volume de noyau  
 combustible.

**12. Assemblage combustible selon la revendication 1, le matériau combustible comprenant une combinaison de : ura-  
 nium et thorium ; plutonium et thorium ; ou uranium, plutonium, et thorium.**

13. Assemblage combustible selon la revendication 1, la gaine d'une pluralité de ladite pluralité de crayons combustibles est liée par voie métallurgique au noyau combustible.
- 5 14. Assemblage combustible selon la revendication 1, le métal non combustible d'une pluralité de ladite pluralité de crayons combustibles comprend de l'aluminium.
15. Assemblage combustible selon la revendication 1, le métal non combustible d'une pluralité de ladite pluralité de crayons combustibles comprend un métal réfractaire.
- 10 16. Assemblage combustible selon la revendication 1, la gaine d'une pluralité de ladite pluralité de crayons combustibles comprend du zircon.
17. Assemblage combustible selon la revendication 1, une pluralité de ladite pluralité de crayons combustibles comprend chacune un profil multilobé en spirale définissant une pluralité de nervures spiralées.
- 15 18. Assemblage combustible selon la revendication 17, les nervures spiralées de crayons adjacents de ladite pluralité de crayons combustibles étant périodiquement en contact l'une avec l'autre sur la longueur axiale des crayons combustibles, ce contact contribuant au maintien de l'espacement des crayons combustibles entre eux.
- 20 19. Assemblage combustible selon la revendication 17, le profil multilobé comprenant des zones concaves entre les lobes adjacents.
- 25 20. Assemblage combustible selon la revendication 17, le profil multilobé comprenant des extrémités de lobes et des intersections entre lobes adjacents, et, relativement à ladite pluralité de ladite pluralité de crayons combustibles, la gaine est plus épaisse aux extrémités qu'aux intersections.
- 30 21. Assemblage combustible selon la revendication 1, l'assemblage combustible comprenant un poison combustible.
22. Assemblage combustible selon la revendication 21, au moins un de la pluralité de crayons combustibles extrudés allongés comprend le poison combustible.
- 35 23. Assemblage combustible selon la revendication 1, comprenant en outre une pluralité de crayons combustibles UO<sub>2</sub> supportés par le cadre, chacun de ladite pluralité de crayons combustibles UO<sub>2</sub> comprenant du combustible UO<sub>2</sub>.
24. Assemblage combustible selon la revendication 23, au moins certains de la pluralité de crayons combustibles UO<sub>2</sub> allongés étant positionnés latéralement vers l'extérieur depuis la pluralité de crayons combustibles extrudés allongés.
- 40 25. Assemblage combustible selon la revendication 24, comprenant en outre une enveloppe séparant le débit de réfrigérant au-delà de la pluralité de crayons combustibles UO<sub>2</sub> allongés du débit de réfrigérant au-delà de la pluralité de crayons combustibles extrudés allongés.
- 45 26. Assemblage combustible selon la revendication 25, un ratio de (1) une superficie totale, au sein de l'enveloppe, disponible pour le modérateur sur (2) une surface transversale totale des noyaux de la pluralité de crayons combustibles extrudés allongés au sein de l'enveloppe est égal à 2,4 ou moins.
27. Assemblage combustible selon la revendication 23, l'enrichissement du combustible UO<sub>2</sub> à l'U-235 étant inférieur à 15%.
- 50 28. Méthode de fabrication d'un assemblage combustible (10) pour être utilisé dans le coeur d'un réacteur nucléaire, la méthode comprenant :  
  
la fabrication de chacun d'une pluralité de crayons combustibles allongés (20) par :  
  
55 le mélange du matériau combustible avec du matériau non combustible métallique, le matériau combustible comprenant une matière fissile,  
la création d'un stock de coeur combustible à partir du matériau combustible et du matériau non combustible

métallique mélangés, le stock de coeur combustible comprenant de l'UZr2 en phase  $\alpha$ ,  
l'enveloppement du stock de coeur combustible avec un matériau de gainage, et la co-extrusion du stock  
de coeur combustible et de la gaine pour créer le crayon combustible ; et  
le montage de la pluralité de crayons combustibles allongés sur un cadre (25) de l'assemblage combustible,

un ratio modérateur/combustible dans une zone des crayons combustibles est égal à 2,4 ou moins, le ratio  
modérateur/combustible étant un ratio de superficies au sein d'une section transversale perpendiculaire à des  
axes longitudinaux de la pluralité de crayons combustibles extrudés et allongés, et s'étendant à travers la  
pluralité de crayons combustibles extrudés et allongés, ce ratio étant un ratio de la superficie totale disponible  
pour le flux de modérateur pour la pluralité de crayons combustibles sur une superficie totale de noyaux de  
combustible de la pluralité de crayons combustibles.

**29.** Méthode selon la revendication 28, le matériau combustible comprenant du matériau combustible en poudre, et le  
matériau non combustible métallique comprenant du matériau non combustible métallique en poudre, la création  
du stock de coeur combustible comprenant le frittage du matériau combustible en poudre et du matériau non  
combustible métallique en poudre mélangés pour créer le stock de coeur combustible.

**30.** Méthode selon la revendication 28, la création du stock de coeur combustible comprenant le moulage en phase  
fondue du matériau combustible et du matériau non combustible métallique mélangés pour la création du stock de  
coeur combustible.

**31.** Méthode selon une quelconque des revendications 28, 29 ou 30, dans laquelle :

la pluralité de crayons combustibles allongés comprend une pluralité de crayons combustibles métalliques  
allongés ; et  
le matériau combustible comprend du matériau combustible métallique ; et  
le stock de coeur combustible comprend un stock de coeur combustible métallique comprenant un alliage du  
matériau combustible métallique et de matériau non combustible métallique.

**32.** Méthode selon la revendication 29 ou 30, le matériau combustible comprenant du matériau combustible de céra-  
mique.

**33.** Méthode selon une quelconque des revendications 28, 29 ou 30, la pluralité de crayons combustibles allongés  
comprendant au moins 60% du volume total de tous les crayons combustibles de l'assemblage combustible.

**34.** Méthode selon une quelconque des revendications 28, 29 ou 30, l'épaisseur moyenne de la gaine après la co-  
extrusion mesurant au moins 0,6 mm.

**35.** Méthode selon la revendication 29, comprenant en outre le positionnement d'un déplaceur au sein du mélange du  
matériau combustible en poudre et de matériau non combustible en poudre mélangés préalablement au frittage,  
de sorte que ledit frittage produise un stock de coeur de combustible comprenant le déplaceur.

**36.** Méthode selon une quelconque des revendications 28, 29 ou 30, dans laquelle :

le cadre comprend une buse inférieure façonnée et configurée pour se monter sur un coeur d'un réacteur  
nucléaire terrestre ; et  
l'assemblage combustible étant conçu du point de vue thermodynamique et façonné physiquement pour son  
utilisation dans le réacteur nucléaire terrestre.

**37.** Méthode selon la revendication 36, comprenant en outre l'installation de l'assemblage combustible dans le réacteur  
nucléaire terrestre.

**38.** Réacteur nucléaire terrestre comprenant un assemblage combustible selon une quelconque des revendications 1  
à 28.

**39.** Réacteur nucléaire terrestre selon la revendication 38, le réacteur étant un réacteur à eau lourde.

- 40.** Réacteur nucléaire terrestre selon la revendication 38 ou 39, dans lequel le réacteur comprend une centrale nucléaire classique possédant un modèle de réacteur en exploitation antérieurement à 2010 ; et le cadre de l'assemblage combustible étant façonné et configuré pour être monté dans le réacteur nucléaire terrestre au lieu d'un assemblage combustible classique à oxyde d'uranium pour ledit réacteur.

5

10

15

20

25

30

35

40

45

50

55

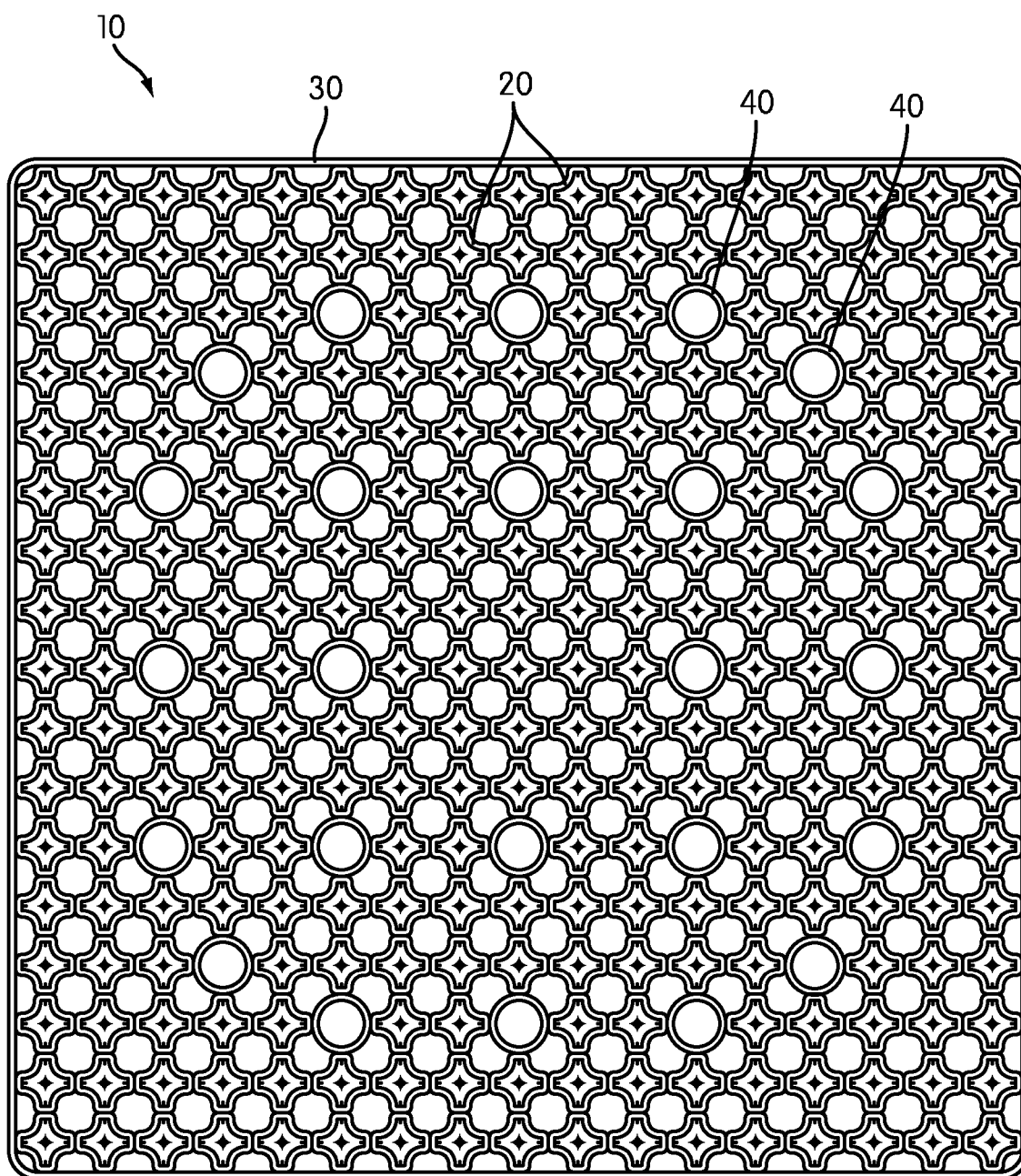


FIG. 1

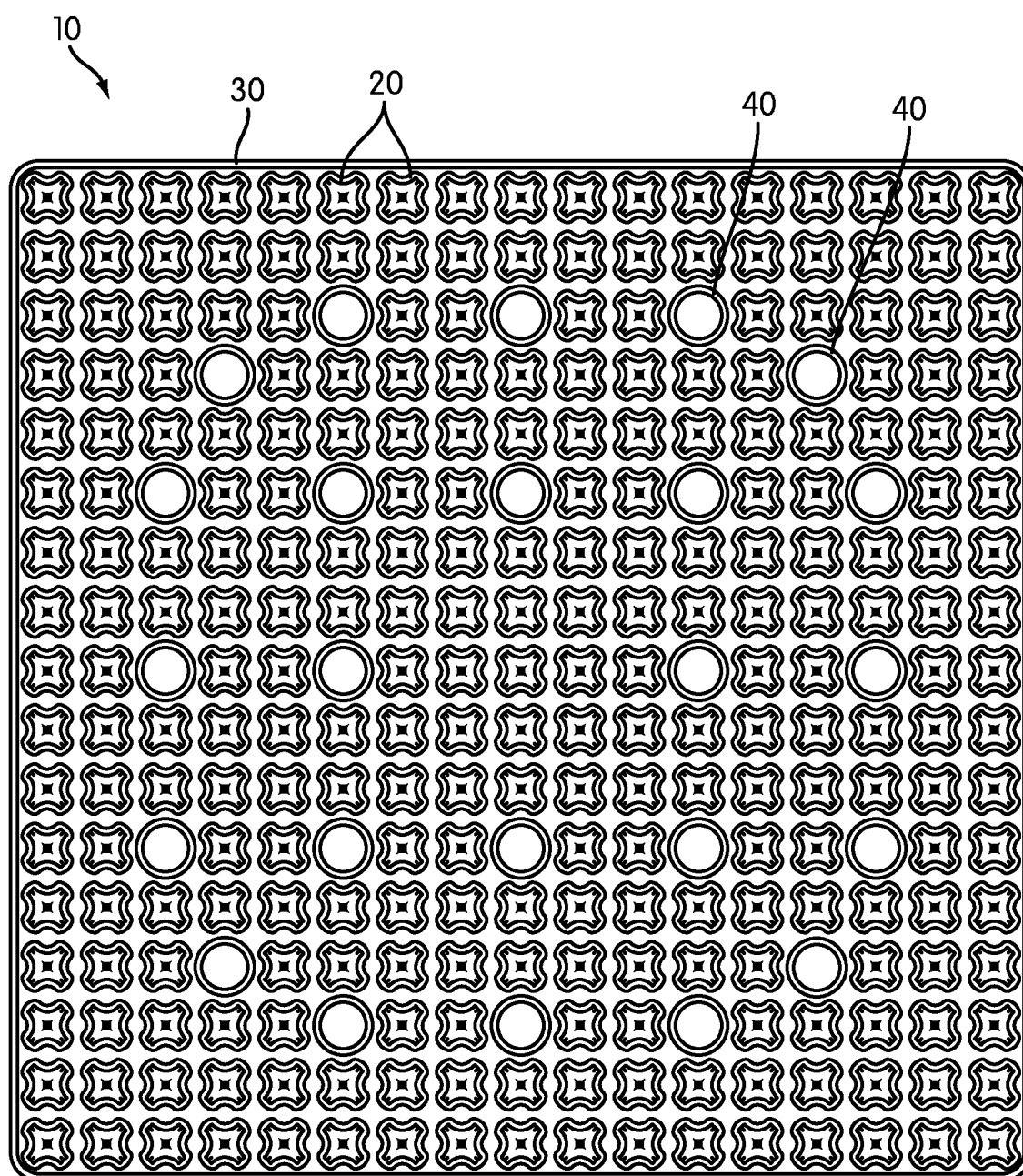


FIG. 2

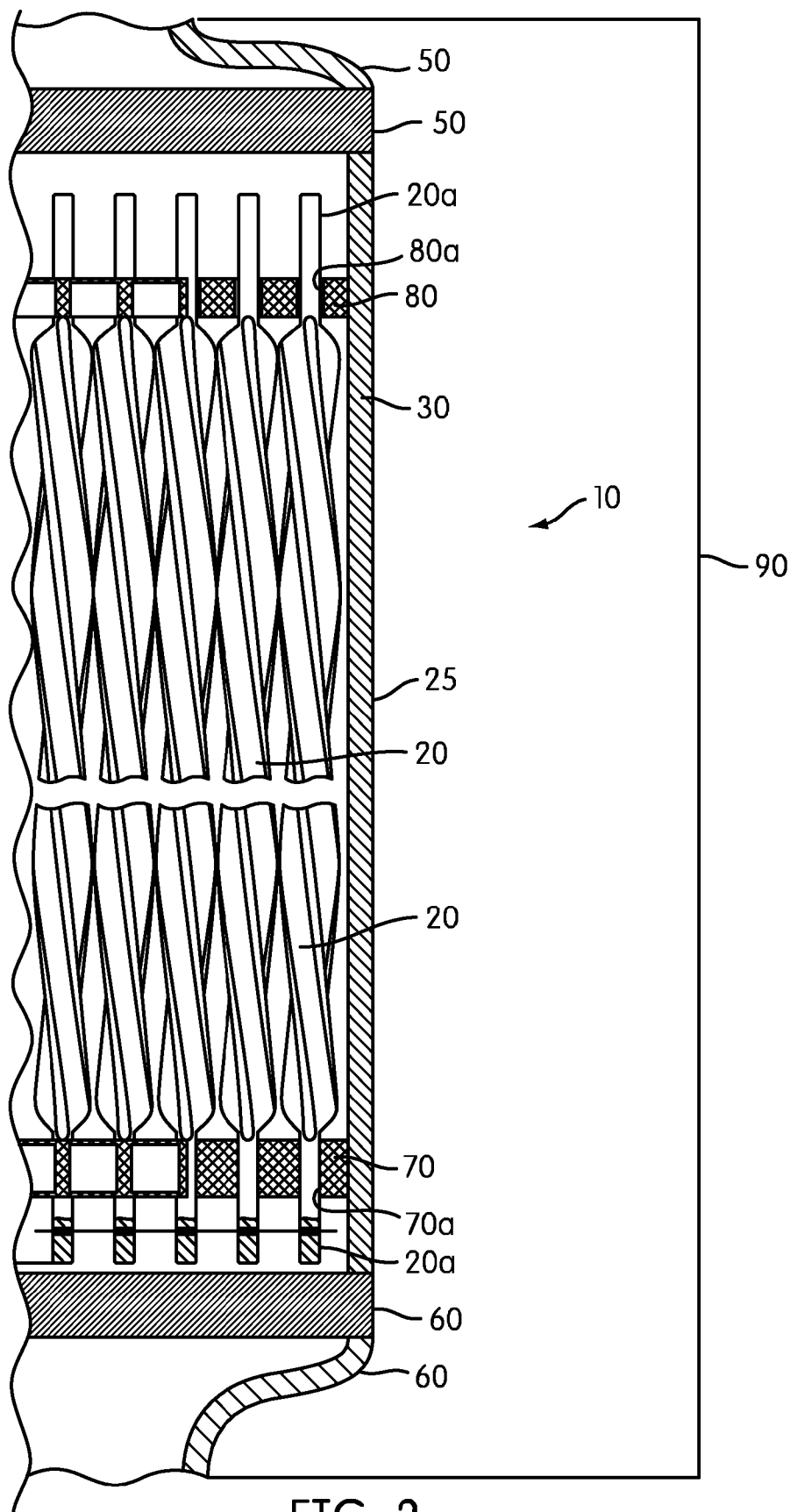


FIG. 3

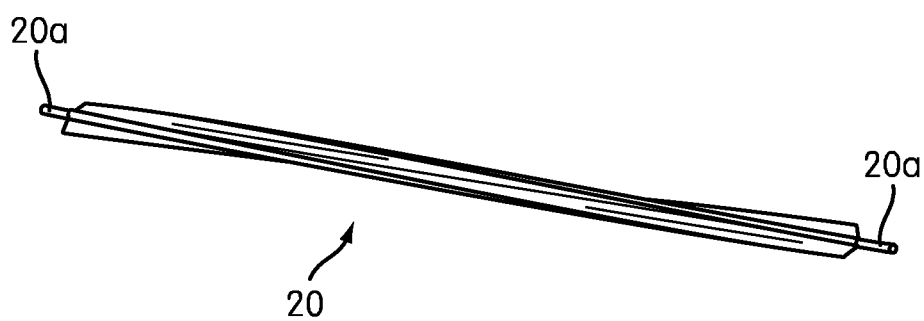


FIG. 4

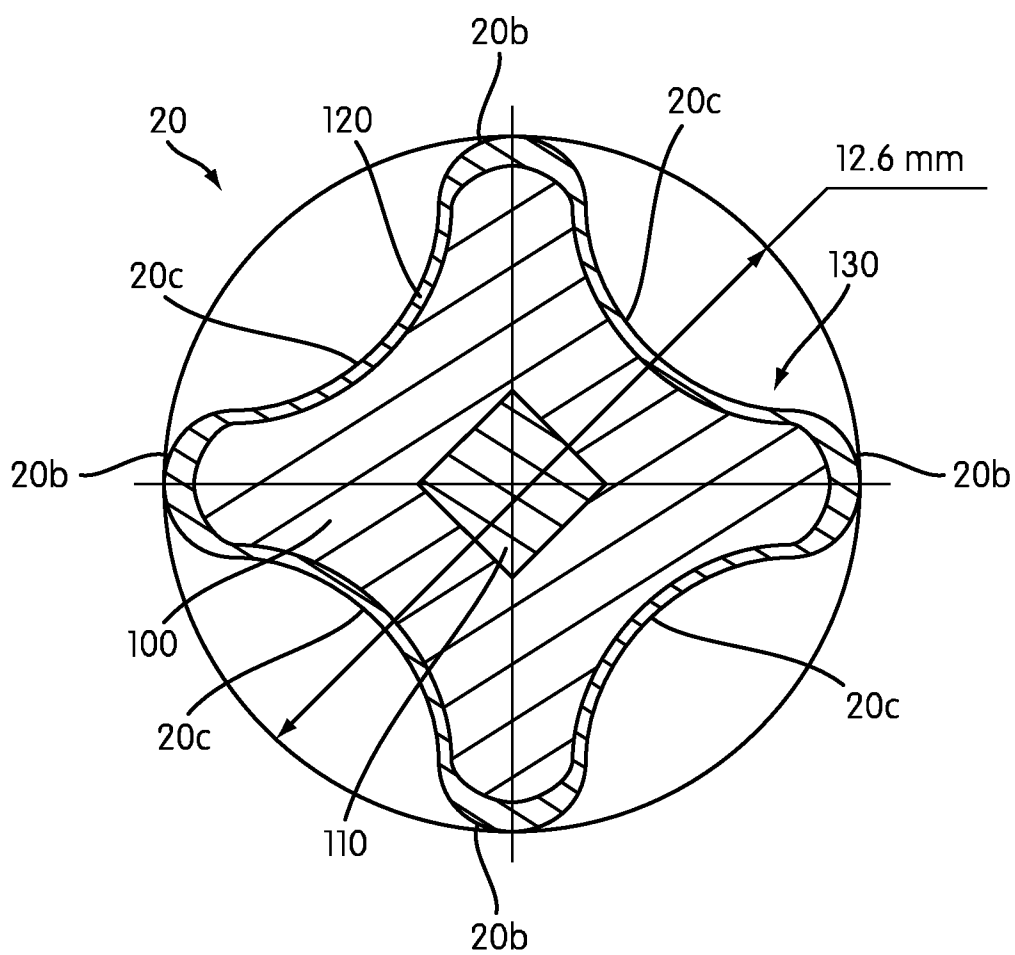


FIG. 5

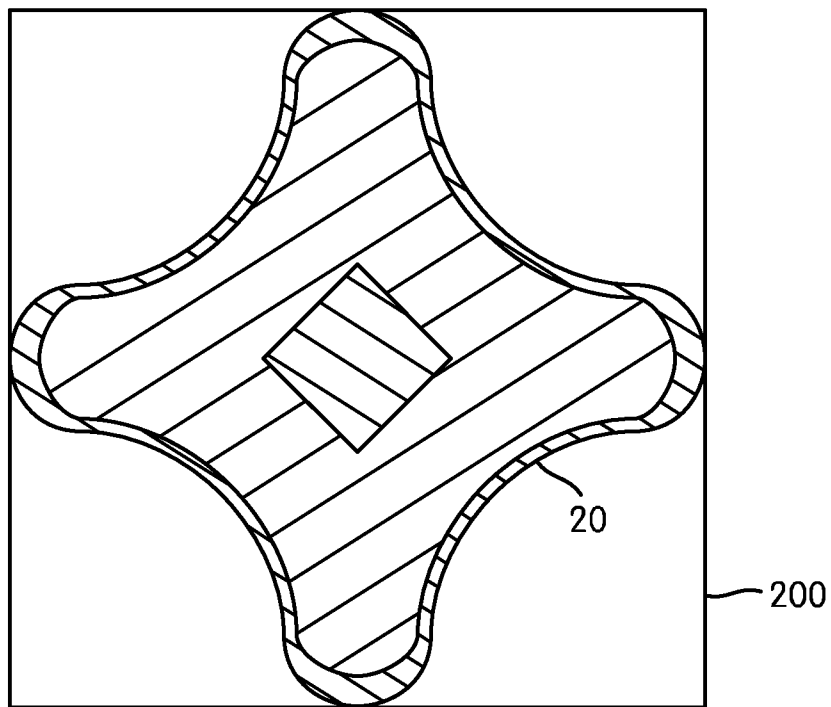


FIG. 6

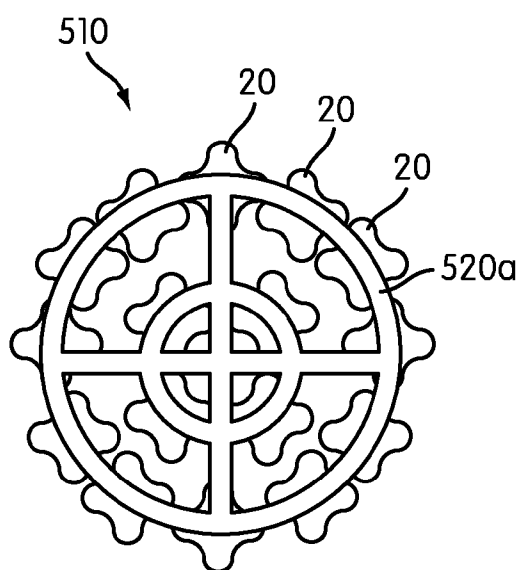


FIG. 7A

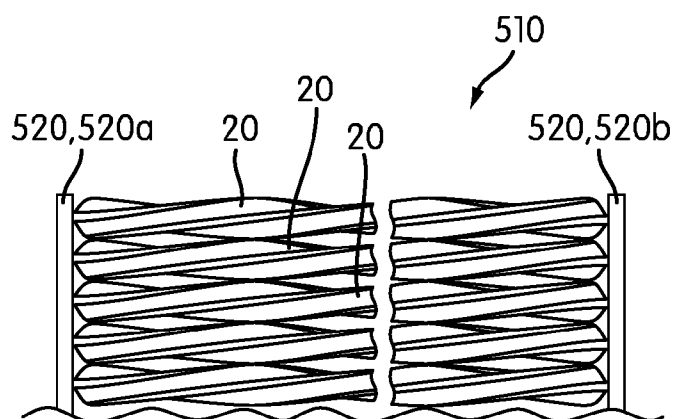


FIG. 7B

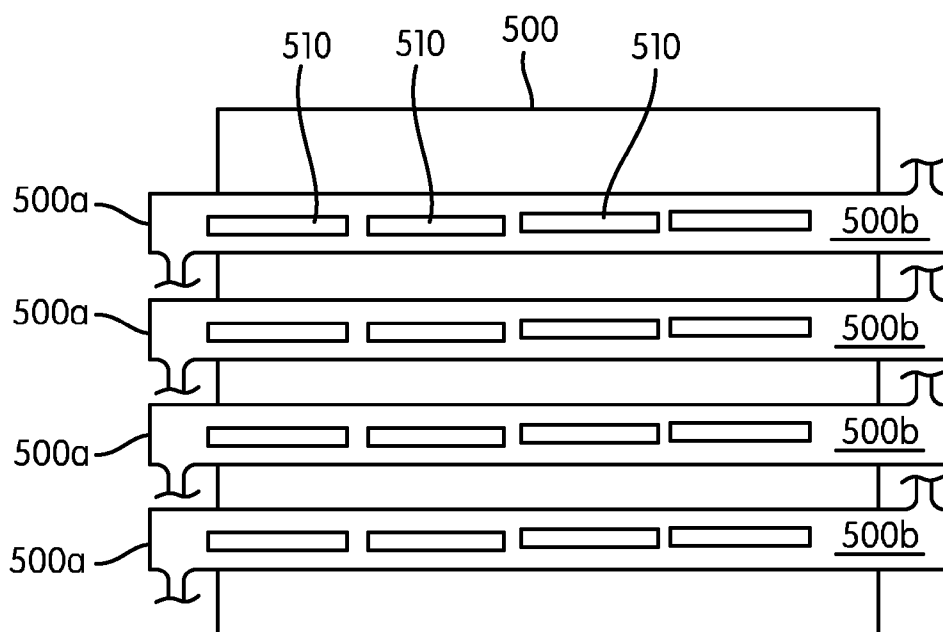


FIG. 8

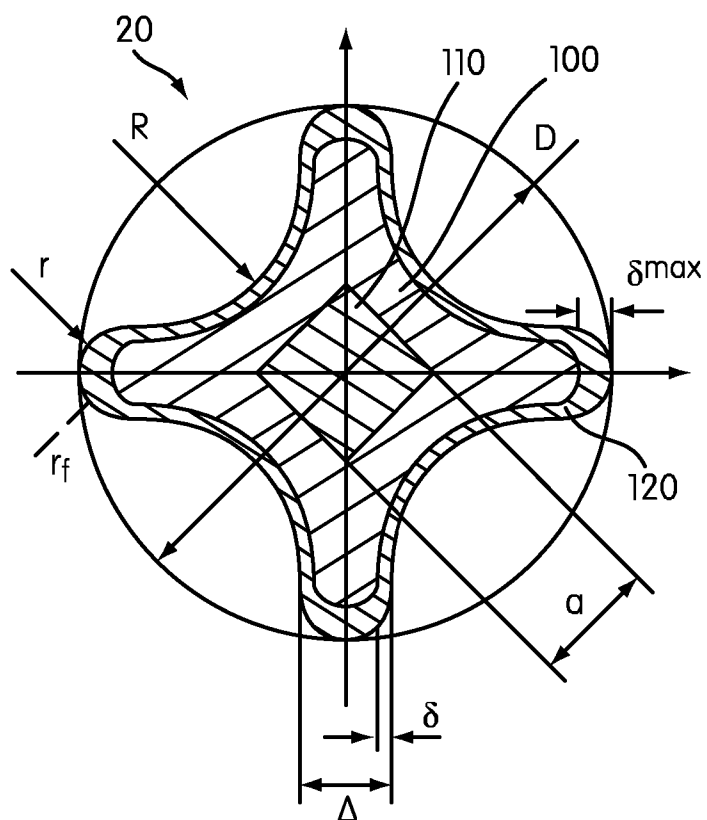


FIG. 9

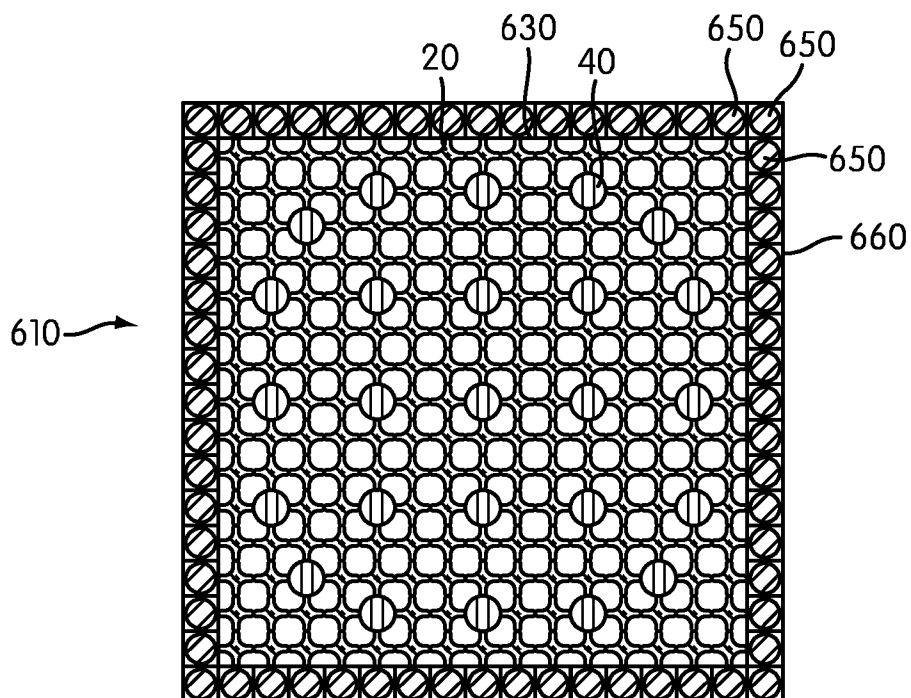


FIG. 10

**REFERENCES CITED IN THE DESCRIPTION**

*This list of references cited by the applicant is for the reader's convenience only. It does not form part of the European patent document. Even though great care has been taken in compiling the references, errors or omissions cannot be excluded and the EPO disclaims all liability in this regard.*

**Patent documents cited in the description**

- US 20090252278 A1 [0002] [0020] [0044]

## FŰTŐELEM-EGYSÉG

### Szabadalmi igénypontok

1. Fűtőelem-egység (10) egy nukleáris erőmű-reaktor (atomerőmű-reaktor, angolul: „nuclear power reactor”) egy magjában történő alkalmazásra, ahol az egység magában foglalja a következőket:
  - egy keretet (25), amely magában foglal egy alsó fűvókát (60), amely úgy van formálva és kialakítva, hogy a nukleáris reaktor (atomreaktor) belső mag-szerkezetére legyen rögzítve (felszerelve); és
  - több hosszúkás, extrudált fűtőelemet (20), amely a keret által van megtámasztva (tartva), ahol a nevezett több fűtőelem közül mindegyik magában foglalja a következőket:
    - egy fűtőelem-magot (angolul: „fuel kernel”) (100), amely fűtőanyagot tartalmaz, amely egy fém nem-fűtőanyag mátrixban (angolul: „matrix of metal non-fuel material”) van elrendezve, ahol a fűtőanyag hasadóanyagot tartalmaz, és
    - egy burkolatot (120), amely körülzárja a fűtőelem-magot,
  - azzal jellemezve, hogy
  - egy moderátor:fűtőanyag arány a fűtőelemek egy régiójában 2,4 vagy annál kisebb, ahol a moderátor:fűtőanyag arány egy területi arány egy keresztmetszeten belül, amely merőleges a több hosszúkás, extrudált fűtőelem hosszúsági irányú tengelyeire és a több hosszúkás, extrudált fűtőelemen keresztül terjed, ahol az arány a következő: a több fűtőelem számára szolgáló moderátor-áramláshoz (angolul: „moderator flow”) rendelkezésre álló egy teljes terület aránya a több fűtőelem fűtőelem-magjainak egy teljes területéhez képest; és
  - ahol a mag tartalmaz  $\alpha$ -fázisú  $\text{UZr2-t}$ .
2. Fűtőelem-egység az 1. igénypont szerint, ahol:
  - a több hosszúkás, extrudált fűtőelem magában foglal több hosszúkás, extrudált fém-fűtőelemet;
  - a fűtőanyag tartalmaz fém fűtőanyagot; és
  - a fűtőelem-mag magában foglal egy fém fűtőanyag ötvözet magot (angolul: „metal fuel alloy kernel”), amely tartalmaz egy ötvözetet, amely a fém fűtőanyagból és a fém nem-fűtőanyagból áll.
3. Fűtőelem-egység az 1. igénypont szerint, ahol a fűtőanyag tartalmaz keramikus fűtőanyagot (angolul: „ceramic fuel material”), amely a fém nem-fűtőanyag mátrixban van elrendezve.
4. Fűtőelem-egység az 1. igénypont szerint, ahol:
  - a több hosszúkás, extrudált fűtőelem a fűtőelem-egységhez tartozó összes fűtőelem egy teljes térfogatának legalább 60%-át teszi ki (adja).
5. Fűtőelem-egység a 4. igénypont szerint, ahol a fűtőelem-egységhez tartozó összes fűtőelemnek a nevezett teljes térfogata magában foglalja azon összes fűtőelemnek a teljes térfogatát, amely az alsó fűvóka által van megtámasztva (tartva).
6. Fűtőelem-egység az 1. igénypont szerint, ahol a burkolat egy átlagos vastagsága legalább 0,6 mm.
7. Fűtőelem-egység az 1. igénypont szerint, ahol a több hosszúkás, extrudált fűtőelemhez tartozó megfelelő fűtőelem-magok a fűtőanyag és a fém nem-fűtőanyag szinterelése (angolul: „sintering”) révén vannak kialakítva.



8. Fűtőelem-egység az 1. igénypont szerint, ahol a nevezett több fűtőelem közül többre vonatkozóan a következők vannak érvényben:
  - a fűtőelem-magnak a fűtőanyaga 20%-ra vagy annál kevesebbre van dúsítva a következőkkel: urán-235 (uránium-235) és/vagy urán-233 (uránium-233), és az tartalmazza a fűtőelem-mag egy olyan térfogat-frakcióját (térfogatrészt), amely 20% és 30% között van (tartalmazza a fűtőelem-mag 20-30 térfogatszázalékát); és
  - a nem-fűtőanyag fém tartalmazza a fűtőelem-mag egy olyan térfogat-frakcióját (térfogatrészt), amely 70% és 80% között van (tartalmazza a fűtőelem-mag 70-80 térfogatszázalékát).
9. Fűtőelem-egység a 8. igénypont szerint, ahol a nevezett több hosszúka, extrudált fűtőelem közül a többre vonatkozóan, a fűtőanyag-dúsítás 15% és 20% között van.
10. Fűtőelem-egység a 8. igénypont szerint, ahol a nevezett több hosszúka, extrudált fűtőelem közül a többre vonatkozóan, a fűtőelem-magnak a nem-fűtőanyag fémje tartalmaz cirkóniumot (cirkont).
11. Fűtőelem-egység az 1. igénypont szerint, ahol a nevezett több fűtőelem közül többre vonatkozóan a következők vannak érvényben:
  - a fűtőelem-magnak a fűtőanyaga tartalmaz plutóniumot;
  - a fűtőelem-magnak a nem-fűtőanyag fémje tartalmaz cirkóniumot (cirkont); és
  - a fűtőelem-magnak a nem-fűtőanyag fémje tartalmazza a fűtőelem-mag egy olyan térfogat-frakcióját (térfogatrészt), amely 70% és 97% között van (tartalmazza a fűtőelem-mag 70-97 térfogatszázalékát).
12. Fűtőelem-egység az 1. igénypont szerint, ahol a fűtőanyag tartalmazza a következők egy kombinációját: urán (uránium) és tórium; plutónium és tórium; vagy urán (uránium), plutónium és tórium.
13. Fűtőelem-egység az 1. igénypont szerint, ahol a nevezett több fűtőelem közül többnek a burkolata kohászati úton össze van kapcsolva a fűtőelem-maggal (kötve van ahhoz).
14. Fűtőelem-egység az 1. igénypont szerint, ahol a nevezett több fűtőelem közül többnek a nem-fűtőanyag fémje tartalmaz alumíniumot.
15. Fűtőelem-egység az 1. igénypont szerint, ahol a nevezett több fűtőelem közül többnek a nem-fűtőanyag fémje tartalmaz egy tűzálló (magas olvadáspontú) fémot.
16. Fűtőelem-egység az 1. igénypont szerint, ahol a nevezett több fűtőelem közül többnek a burkolata tartalmaz cirkóniumot (cirkont).
17. Fűtőelem-egység az 1. igénypont szerint, ahol a nevezett több fűtőelem közül több esetben mindegyik egy spirálisan csavart, több-karéjos (több-lebenyes, angolul: „multi-lobed”) profillal rendelkezik, amely meghatároz több spirális bordát.
18. Fűtőelem-egység a 17. igénypont szerint, ahol a nevezett több fűtőelem közül az egymással szomszédosoknak a spirális bordái periodikusan érintkeznek egymással a fűtőelemeknek a tengelyirányú hosszában, ahol az ilyen érintkezés által elő van segítve, hogy legyen megtartva a fűtőelemeknek a térközökkel történő elhelyezése egymáshoz viszonyítva.
19. Fűtőelem-egység a 17. igénypont szerint, ahol a több-karéjos (több-lebenyes) profil magában foglal konkv területeket szomszédos karéjok (lebenyek) között.
20. Fűtőelem-egység a 17. igénypont szerint, ahol:
  - a több-karéjos (több-lebenyes) profil magában foglal karéj-csúcsokat (lebeny-csúcsokat) és metszéspontokat szomszédos karéjok (lebenyek) között, és
  - a nevezett több fűtőelem közül a nevezett többre vonatkozóan, a burkolat vastagabb a csúcsoknál, mint a metszéspontoknál.

21. Fűtőelem-egység az 1. igénypont szerint, ahol a fűtőelem-egység tartalmaz egy kiégő mérget (angolul: „burnable poison”).
22. Fűtőelem-egység a 21. igénypont szerint, ahol a több hosszúkás, extrudált fűtőelem közül legalább az egyik tartalmazza a kiégő mérget.
23. Fűtőelem-egység az 1. igénypont szerint, amely továbbá magában foglal több UO<sub>2</sub>-fűtőelemet, amely a keret által van megtámasztva (tartva), ahol a nevezett több UO<sub>2</sub>-fűtőelem közül mindegyik tartalmaz UO<sub>2</sub>-fűtőanyagot.
24. Fűtőelem-egység a 23. igénypont szerint, ahol a több hosszúkás UO<sub>2</sub>-fűtőelem közül legalább néhány oldalirányban kifelé van elhelyezve a több hosszúkás, extrudált fűtőelemtől (azokhoz képest).
25. Fűtőelem-egység a 24. igénypont szerint, amely továbbá magában foglal egy védőburkolatot (angolul: „shroud”), amely által a hűtőközeg-áramlás (angolul: „coolant flow”), amely áthalad a több hosszúkás UO<sub>2</sub>-fűtőelemen, el van választva a hűtőközeg-áramlástól, amely áthalad a több hosszúkás, extrudált fűtőelemen.
26. Fűtőelem-egység a 25. igénypont szerint, ahol (1) egy moderátor számára rendelkezésre álló egy a védőburkolaton belüli teljes terület aránya (2) a több hosszúkás, extrudált fűtőelemhez tartozó magok egy a védőburkolaton belüli teljes keresztmetszeti területéhez képest 2,4 vagy annál kisebb.
27. Fűtőelem-egység a 23. igénypont szerint, ahol az UO<sub>2</sub>-fűtőanyag 15%-nál kisebb U-235 dúsítással rendelkezik.
28. Eljárás egy fűtőelem-egység (10) előállítására, amely egy nukleáris erőmű-reaktor (atomerőmű-reaktor, angolul: „nuclear power reactor”) egy magjában történő alkalmazására szolgál, ahol az eljárás magában foglalja a következőket:

több hosszúkás fűtőelem (20) közül mindegyik előállítása a következők révén:

fűtőanyag összekeverése fém nem-fűtőanyaggal, ahol a fűtőanyag hasadóanyagot tartalmaz,

egy fűtőelem-mag alapanyag (angolul: „fuel core stock”) előállítása az összekevert fűtőanyagból és fém nem-fűtőanyagból, ahol a fűtőelem-mag alapanyag tartalmaz  $\alpha$ -fázisú UZr<sub>2</sub>-t,

a fűtőelem-mag alapanyag körülzárása egy burkolóanyaggal, és

a fűtőelem-mag alapanyag és burkolóanyag koextrudálása (együtt extrudálása), hogy legyen előállítva a fűtőelem-egység; és

a több hosszúkás fűtőelem rögzítése (felszerelése) a fűtőelem-egység egy keretére (25),

ahol egy moderátor:fűtőanyag arány a fűtőelemek egy régiójában 2,4 vagy annál kisebb, ahol a moderátor:fűtőanyag arány egy területi arány egy keresztmetszeten belül, amely merőleges a több hosszúkás, extrudált fűtőelem hosszúsági irányú tengelyeire és a több hosszúkás, extrudált fűtőelemen keresztül terjed, ahol az arány a következő: a több fűtőelem számára szolgáló moderátor-áramláshoz (angolul: „moderator flow”) rendelkezésre álló egy teljes terület aránya a több fűtőelem fűtőelem-magjainak egy teljes területéhez képest.

29. Eljárás a 28. igénypont szerint, ahol a fűtőanyag tartalmaz por alakú fűtőanyagot és a fém nem-fűtőanyag tartalmaz por alakú fém nem-fűtőanyagot, ahol a fűtőelem-mag alapanyag előállítása magában foglalja az összekevert por alakú fűtőanyag és por alakú fém nem-fűtőanyag szinterelését (angolul: „sintering”), hogy legyen előállítva a fűtőelem-mag alapanyag.

30. Eljárás a 28. igénypont szerint, ahol a fűtőelem-mag alapanyag előállítását magában foglalja az összekevert fűtőanyag és fém nem-fűtőanyag olvasztásos öntését (olvadék fázisban történő öntését, angolul: „melt-casting”), hogy legyen előállítva a fűtőelem-mag alapanyag.
31. Eljárás a 28., 29. vagy 30. igénypontok bármelyike szerint, ahol:
  - a több hosszúkás fűtőelem magában foglal több hosszúkás fém-fűtőelemet; és
  - a fűtőanyag tartalmaz fém fűtőanyagot; és
  - a fűtőelem-mag alapanyag tartalmaz egy fém fűtőanyag-mag alapanyagot, amely tartalmaz egy ötvözetet, amely a fém fűtőanyagból és a fém nem-fűtőanyagból áll.
32. Eljárás a 29. vagy 30. igénypont szerint, ahol a fűtőanyag tartalmaz keramikus fűtőanyagot (angolul: „ceramic fuel material”).
33. Eljárás a 28., 29. vagy 30. igénypontok bármelyike szerint, ahol a több hosszúkás fűtőelem a fűtőelem-egységhez tartozó összes fűtőelem egy teljes térfogatának legalább 60%-át teszi ki (adja).
34. Eljárás a 28., 29. vagy 30. igénypontok bármelyike szerint, ahol a burkolat egy átlagos vastagsága a koextrudálás (együtt extrudálás) után legalább 0,6 mm.
35. Eljárás a 29. igénypont szerint, amely továbbá magában foglalja egy kiszorító test (angolul: „displacer”) elhelyezését az összekevert por alakú fűtőanyagon és fém nem-fűtőanyagon belül a nevezett szinterelés előtt, oly módon, hogy a nevezett szinterelés által egy olyan fűtőelem-mag alapanyag van eredményezve, amely tartalmazza a kiszorító testet.
36. Eljárás a 28., 29. vagy 30. igénypontok bármelyike szerint, ahol:
  - a keret magában foglal egy alsó fűvókát, amely úgy van formálva és kialakítva, hogy egy szárazföldi nukleáris erőmű-reaktor (atomerőmű-reaktor) egy magjára legyen rögzítve (felszerelve); és
  - a fűtőelem-egység termodinamikailag úgy van kialakítva és fizikailag úgy van formálva, hogy a szárazföldi nukleáris erőmű-reaktorban (atomerőmű-reaktorban) legyen üzemeltetve (működtetve).
37. Eljárás a 36. igénypont szerint, amely továbbá magában foglalja a fűtőelem-egység behelyezését a szárazföldi nukleáris erőmű-reaktorba (atomerőmű-reaktorba).
38. Szárazföldi nukleáris reaktor (atomreaktor), amely magában foglal egy az 1.-től 28.-ig igénypontok bármelyike szerinti fűtőelem-egységet.
39. Szárazföldi nukleáris reaktor (atomreaktor) a 38. igénypont szerint, ahol a reaktor egy nehézvízes reaktor.
40. Szárazföldi nukleáris erőmű-reaktor (atomerőmű-reaktor) a 38. vagy 39. igénypontok szerint, ahol a reaktor magában foglal egy konvencionális (hagyományos) nukleáris erőművet (atomerőművet), amely egy olyan reaktor-kialakítással rendelkezik, amely 2010 előtt volt aktuális használatban; és
  - a fűtőelem-egységnek a kerete úgy van formálva és kialakítva, hogy legyen beillesztve (beszerelve) a szárazföldi nukleáris erőmű-reaktorba (atomerőmű-reaktorba) egy konvencionális (hagyományos) urán-oxid (uránium-oxid) fűtőelem-egység helyett, amely a nevezett reaktor számára szolgál.