US 20220301736A1

(19) **United States**
(12) **Patent Application Publication**
Piefer et al.

(10) **Pub. No.: US 2022/0301736 A1**
(43) **Pub. Date: Sep. 22, 2022**

(54) **AQUEOUS ASSEMBLY AND CONTROL METHOD**

(71) Applicant: **SHINE Technologies, LLC**, Janesville, WI (US)

(72) Inventors: **Gregory Piefer**, Janesville, WI (US); **Eric N. Van Abel**, Oregon, WI (US)

(21) Appl. No.: **17/745,637**

(22) Filed: **May 16, 2022**

Related U.S. Application Data

(63) Continuation of application No. 14/390,658, filed on Oct. 3, 2014, now Pat. No. 11,361,873, filed as application No. PCT/US13/31837 on Mar. 15, 2013.

(60) Provisional application No. 61/620,735, filed on Apr. 5, 2012.

Publication Classification

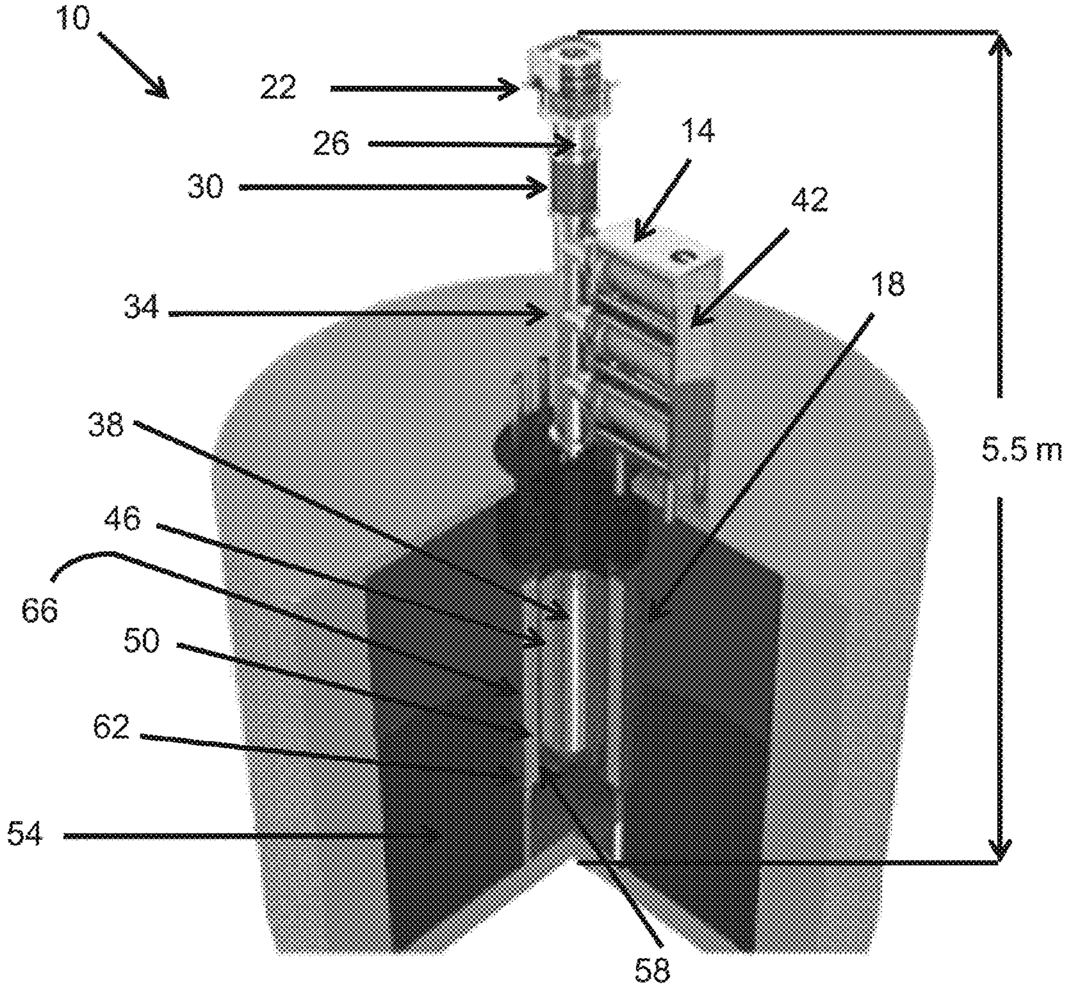
(51) **Int. Cl.**

G21G 1/00	(2006.01)
G21G 1/08	(2006.01)
G21C 3/42	(2006.01)
G21C 1/26	(2006.01)
G21C 7/34	(2006.01)
G21C 1/30	(2006.01)
G21C 7/02	(2006.01)

(52) **U.S. Cl.**
CPC ***G21G 1/0005*** (2013.01); ***G21G 1/08*** (2013.01); ***G21C 3/42*** (2013.01); ***G21C 1/26*** (2013.01); ***G21C 7/34*** (2013.01); ***G21C 1/30*** (2013.01); ***G21C 7/02*** (2013.01); *Y02E 30/30* (2013.01); *G21C 1/24* (2013.01)

(57) **ABSTRACT**

An aqueous assembly has a negative coefficient of reactivity with a magnitude. The aqueous assembly includes a vessel and an aqueous solution, with a fissile solute, supported in the vessel. A reactivity stabilizer is disposed within the aqueous solution to reduce the magnitude of the negative coefficient of reactivity of the aqueous assembly during operation of the aqueous assembly.



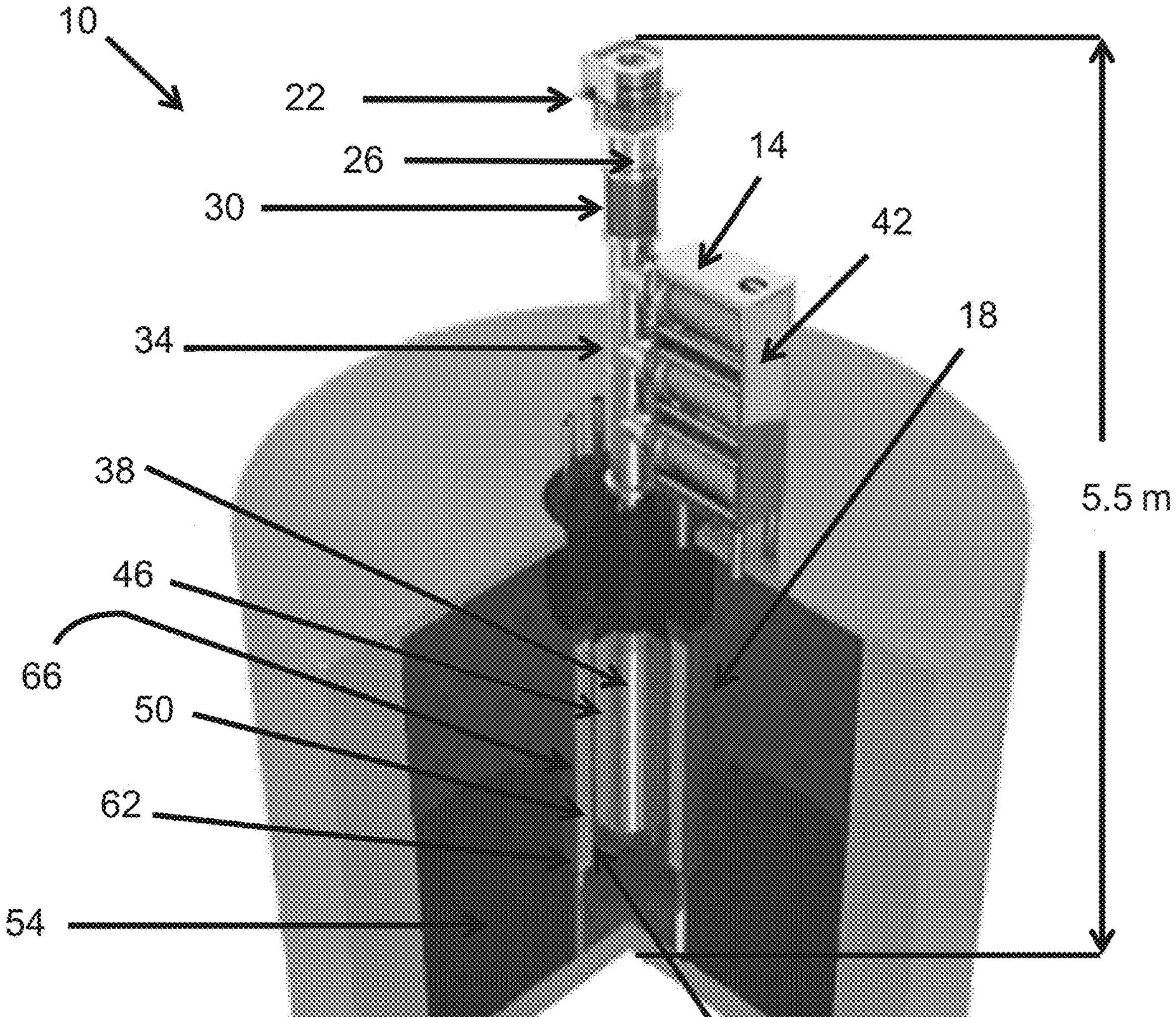


FIG. 1

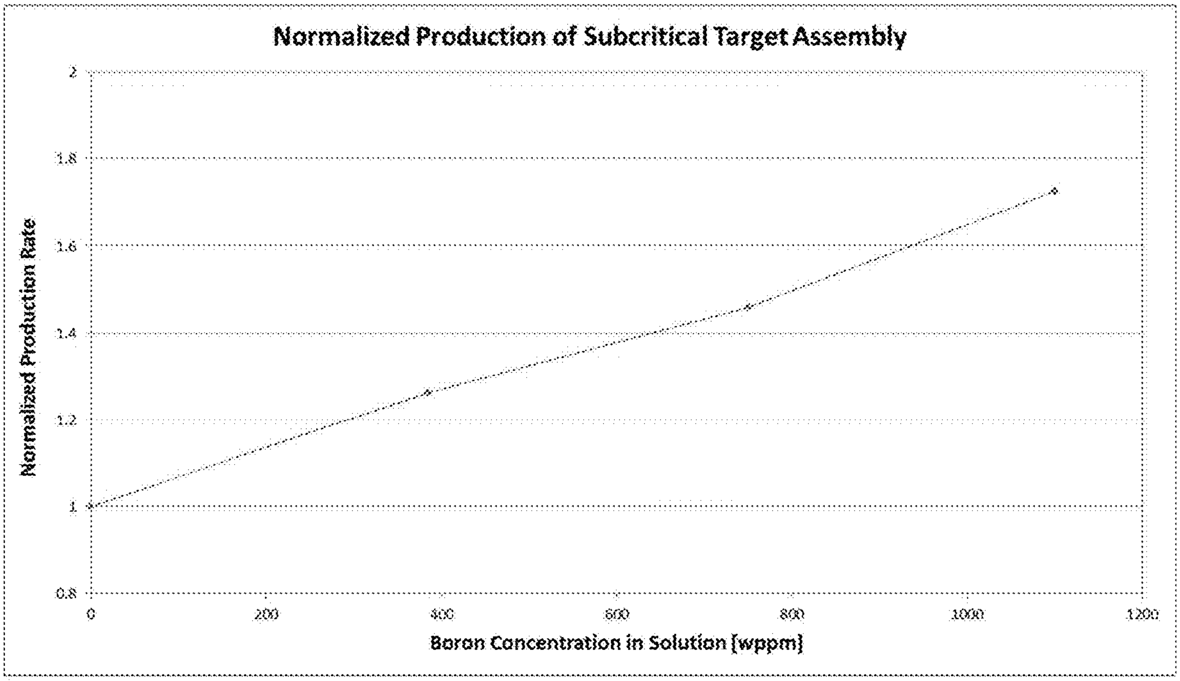

Normalized Production of Subcritical Target Assembly
Normalized Production Rate
2
1.8
1.6
1.4
1.2
1
0.8
0
200
400
600
800
1000
1200
Boron Concentration in Solution [wppm]

FIG. 2

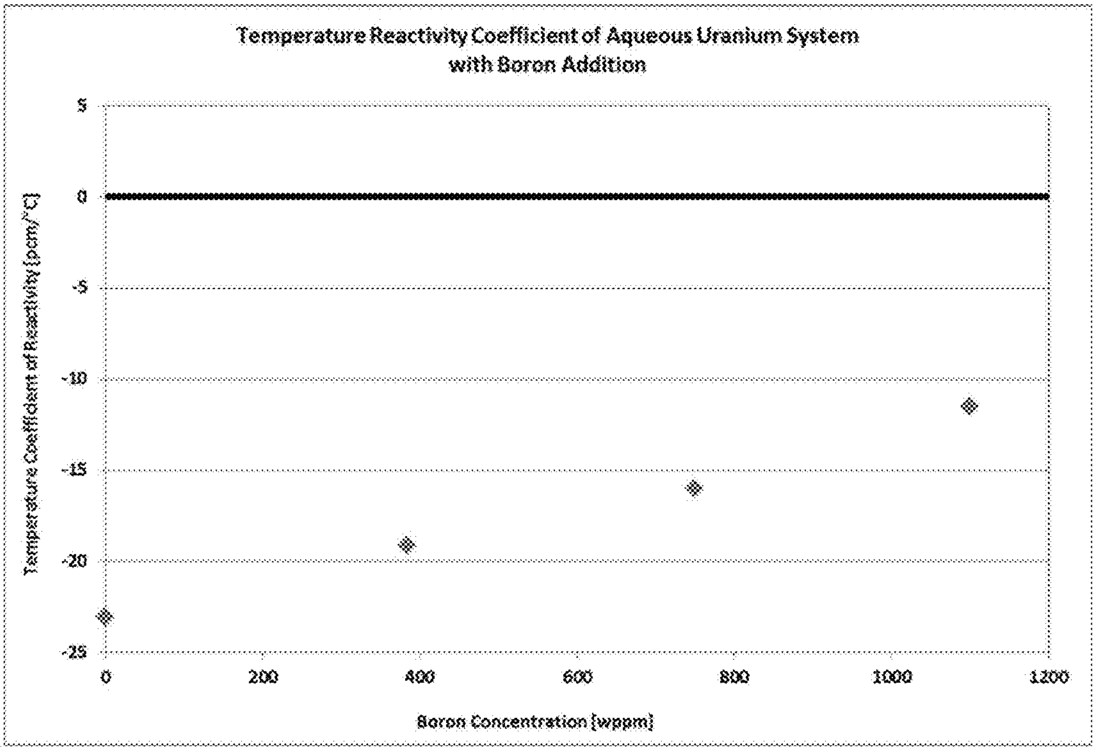

Temperature Reactivity Coefficient of Aqueous Uranium System
with Boron Addition
Temperature Coefficient of Reactivity [pcm/°C]
5
0
-5
-10
-15
-20
-25
0
200
400
600
800
1000
1200
Boron Concentration [wppm]

FIG. 3

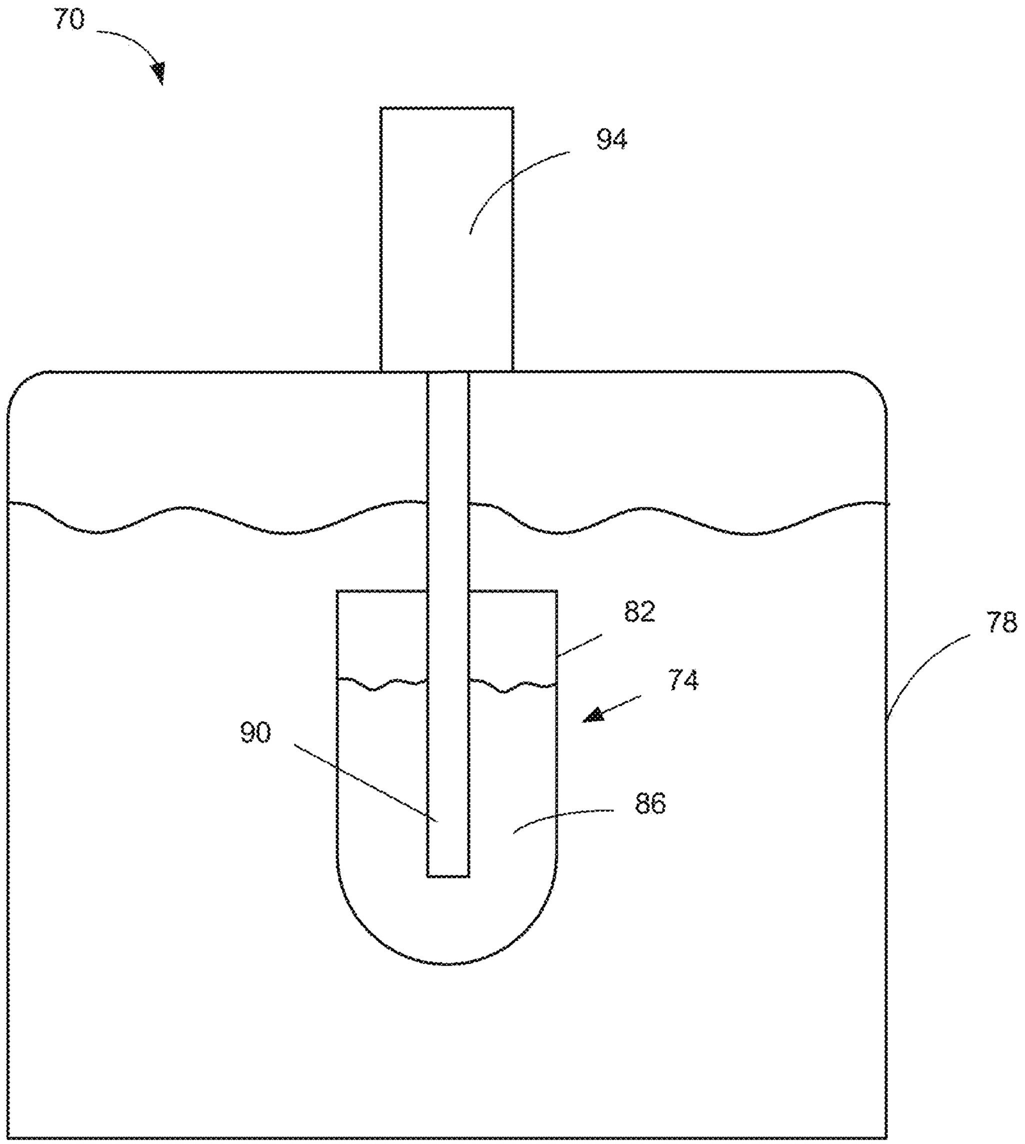


FIG. 4

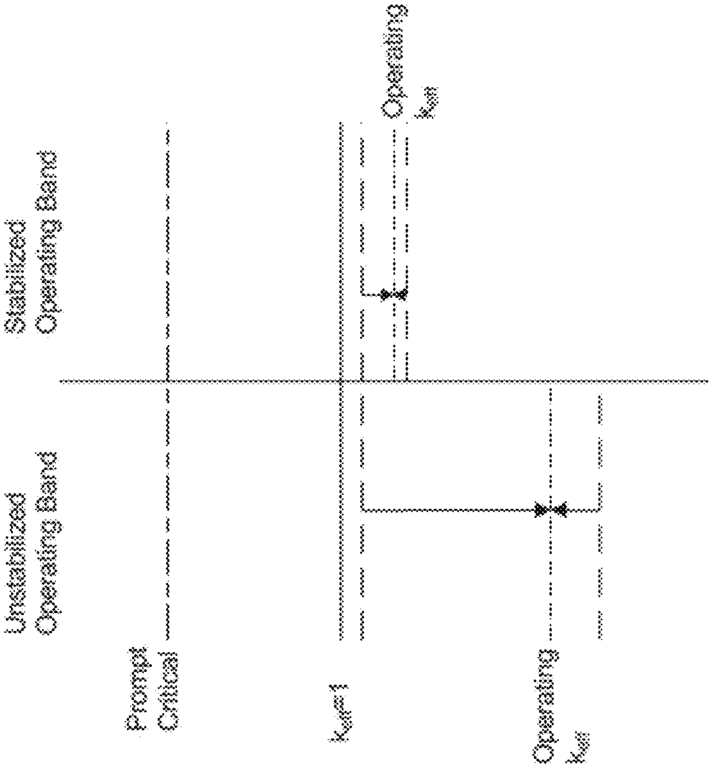

Unstabilized Operating Band
Stabilized Operating Band
Prompt Critical
k_eff=1
Operating k_eff
Operating k_eff

FIG. 5

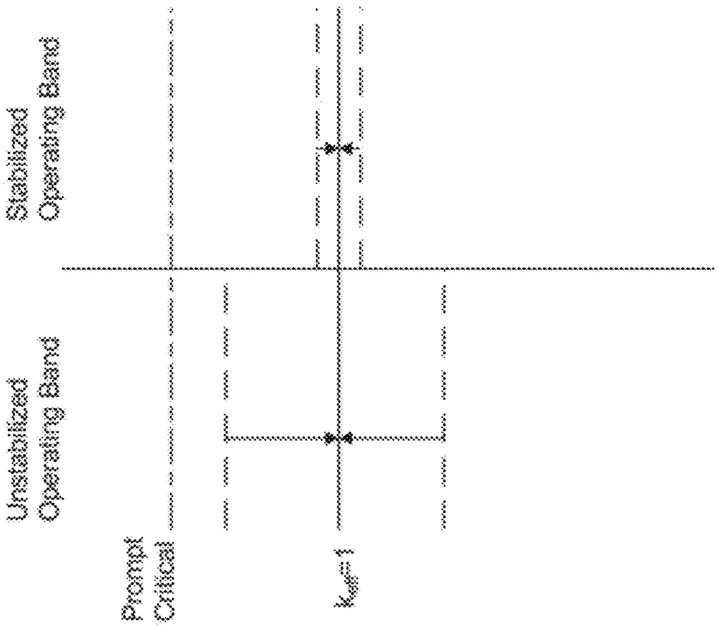

Unstabilized Operating Band
Stabilized Operating Band
Prompt Critical
k_eff=1

FIG. 6

AQUEOUS ASSEMBLY AND CONTROL METHOD

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This patent application is a continuation of prior U.S. patent application Ser. No. 14/390,658, filed Oct. 3, 2014, which is a national stage filing under 35 U.S.C. 371 of International Patent Application No. PCT/US2013/031837, filed Mar. 15, 2013, which claims priority to U.S. Provisional Patent Application No. 61/620,735, filed Apr. 5, 2012, the entire contents of all of which are incorporated by reference herein. Priority to these applications is hereby claimed.

INTRODUCTION

[0002] The invention relates to aqueous assemblies.

[0003] In an aqueous assembly, a vessel contains a fissile material dissolved in an aqueous solution. Because the fissile material is dissolved in solution, these assemblies tend to have large negative temperature and void coefficients of reactivity caused by the expansion of the solution. Where an aqueous assembly is used in the production of medical isotopes, for example, it is desirable to operate the aqueous assembly at relatively high power levels and, where subcritical, at relatively high neutron multiplication factors. However, the large negative temperature and void coefficients of reactivity can cause undesirable reactivity loss and/or power oscillations, thereby limiting the operating parameters of the aqueous assembly.

SUMMARY

[0004] In some embodiments, provided is an aqueous assembly having a negative coefficient of reactivity with a magnitude. The aqueous assembly includes a vessel and an aqueous solution, with a fissile solute, supported in the vessel. A reactivity stabilizer is disposed within the aqueous solution to reduce the magnitude of the negative coefficient of reactivity of the aqueous assembly.

[0005] In other embodiments, provided are methods of operating an aqueous assembly having a coefficient of reactivity with a magnitude. A vessel is provided. An aqueous solution, including a fissile solute, is added to the vessel. A reactivity stabilizer is added to the aqueous solution, thereby reducing the magnitude of the coefficient of reactivity. A fission reaction is sustained within the aqueous solution.

[0006] Other aspects of the invention will become apparent by consideration of the detailed description and accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] FIG. **1** is a cutaway view of a subcritical hybrid, including a neutron source assembly and an aqueous assembly.

[0008] FIG. **2** is a graph of boron concentration in a target solution versus a normalized isotope production rate of a subcritical aqueous assembly.

[0009] FIG. **3** is a graph of boron concentration in an aqueous uranium solution versus a temperature coefficient of reactivity of the aqueous assembly.

[0010] FIG. **4** is a cross sectional view of an aqueous reactor.

[0011] FIG. **5** is a graph comparing subcritical operating bands of stabilized and unstabilized subcritical aqueous assemblies.

[0012] FIG. **6** is a graph comparing operating bands of stabilized and unstabilized critical aqueous assemblies.

DETAILED DESCRIPTION

[0013] Before any embodiments are explained in detail, it is to be understood that the invention is not limited in its application to the details of construction and the arrangement of components set forth in the following description or illustrated in the following drawings. The invention is capable of other embodiments and of being practiced or of being carried out in various ways. Also, it is to be understood that the phraseology and terminology used herein is for the purpose of description and should not be regarded as limiting. The use of "including," "comprising," or "having" and variations thereof herein is meant to encompass the items listed thereafter and equivalents thereof as well as additional items. Unless specified or limited otherwise, the terms "mounted," "connected," "supported," and "coupled" and variations thereof are used broadly and encompass direct and indirect mountings, connections, supports, and couplings. Further, "connected" and "coupled" are not restricted to physical or mechanical connections or couplings. It also is specifically understood that any numerical range recited herein includes all values from the lower value to the upper value, e.g., all possible combinations of numerical values between the lowest value and the highest value enumerated are to be considered to be expressly stated in this application. For example, if a concentration range is stated as 1% to 50%, it is intended that values such as 2% to 40%, 10% to 30%, or 1% to 3%, etc., or if a parameter is stated as 0.95-0.99, it is intended that values such as 0.96-0.98, 0.95-0.98, etc. are expressly enumerated in this specification. These are only examples of what is specifically intended.

[0014] The devices and methods presented herein may be used with various types and configurations of aqueous assemblies, including, for example, both critical and subcritical aqueous assemblies.

[0015] Referring to FIG. **1**, a subcritical hybrid **10** includes a neutron source assembly **14** and an aqueous assembly, more specifically, an aqueous target assembly **18**.

[0016] The neutron source assembly **14** includes an RF-driven plasma ion source **22**. The ion source **22** receives a feed gas, such as a tritium (T) and deuterium (D) mixture. The ion source **22** generates and collimates an ion beam, including D^+ and T^+ ions, directed along a predetermined pathway **26**.

[0017] An accelerator **30** receives the D^+ and T^+ ion beam and accelerates the ion beam to yield an accelerated D^+ and T^+ ion beam. The accelerator **30** may include a series of acceleration electrodes, or electrostatic plates, for accelerating the D^+ and T^+ ion beam.

[0018] An accelerator target portion **34** of the neutron source assembly **14** receives the accelerated ion beam. The accelerator target portion **34** includes a gas target chamber **38** and, in the illustrated embodiment, a differential pumping system **42**. The gas target chamber **38** contains a nuclear particle-deriving target gas that is reactive with the accelerated beam and, in turn, emits nuclear particles, i.e., protons or neutrons. In one construction, the target gas chamber **38** is filled with an approximately equal mix of D and T gas.

[0019] Gases that leak from the gas target chamber **38** into the differential pumping section **42** pass through high speed pumps, through a cold trap, and back into the target chamber. The cold traps remove heavier gasses that in time can contaminate the system due to very small leaks.

[0020] The accelerated D^+ and T^+ ion beam striking a mixed target gas of D and T produces D-T and T-D reactions, resulting in the emission of neutrons.

[0021] In some constructions of the invention, a neutron multiplier **46** substantially surrounds the gas target chamber. The neutron multiplier **46** may be substantially formed of beryllium or uranium. Multiplication occurs when energetic neutrons from the gas target chamber split beryllium atoms into two helium nuclei and an additional neutron via (n,2n) reactions or when neutrons undergo (n,2n), (n,3n), or (n,f) reactions with uranium. For example, a 14.1 MeV neutron has enough energy to react this way a few times before dropping below the multiplication threshold.

[0022] The aqueous target assembly **18** includes a target solution vessel (TSV) **50** and is surrounded by a shield tank **54**. The TSV **50** includes an inner wall **58** and an outer wall **62**, with an annular target solution volume **66** defined between the inner wall **58** and the outer wall **62**. The TSV **50** may be formed, for example, of zircaloy, stainless steel, or aluminum. The TSV **50** substantially surrounds the gas target chamber **38** and, where applicable, the neutron multiplier **46**.

[0023] The TSV **50** receives an aqueous solution, including a fissile solute, in the annular target solution volume **66**. The fissile solute may include U-235 in the form of low enriched uranium (LEU), natural uranium, or other fissionable materials. The uranium may be converted into a salt (e.g., uranyl nitrate, uranyl sulfate, uranyl phosphate, uranyl carbonate, or uranyl fluoride) to increase the solubility, and the pH may be adjusted to further increase solubility. The aqueous solution may include uranium in a concentration of at least about 10 grams-U/liter, at least about 20 grams-U/liter, at least about 30 grams-U/liter, at least about 40 grams-U/liter, at least about 60 grams-U/liter, at least about 80 grams-U/liter, at least about 100 grams-U/liter, at least about 120 grams-U/liter, at least about 140 grams-U/liter, at least about 160 grams-U/liter, at least about 180 grams-U/liter, at least about 200 grams-U/liter, at least about 220 grams-U/liter, at least about 240 grams-U/liter, at least about 260 grams-U/liter, at least about 280 grams-U/liter, or at least about 300 grams-U/liter. The aqueous solution may include uranium in a concentration of less than about 800 grams-U/liter, less than about 750 grams-U/liter, less than about 700 grams-U/liter, less than about 650 grams-U/liter, less than about 600 grams-U/liter, less than about 550 grams-U/liter, less than about 500 grams-U/liter, less than about 450 grams-U/liter, or less than about 400 grams-U/liter. The aqueous solution may include uranium in a concentration of 10 grams-U/liter to about 800 grams-U/liter, about 20 grams-U/liter to about 700 grams-U/liter, about 40 grams-U/liter to about 600 grams-U/liter, about 40 grams-U/liter to about 500 grams-U/liter, or about 50 grams-U/liter to about 400 grams-U/liter. In some embodiments, uranium concentrations in the aqueous solution may be in the range of 10 grams-U/liter to 800 grams-U/liter. In some embodiments, uranium concentrations in the aqueous solution may be in the range of 40 grams-U/liter to 500 grams-U/liter.

[0024] In order to substantially maximize the production of medical isotopes with the subcritical hybrid, while substantially ensuring that subcriticality is maintained, an effective neutron multiplication factor (k_{eff}) of the system is calculated for a given uranium concentration and enrichment using neutronics computer codes. Neutronics codes that can be used for this analysis included MCNPS, HELIOS, VARIANT, PN2ND, PHOENIX/ANC, KENO, DENOVO, and many others. Desired uranium concentrations and enrichments may then be calculated for a desired k_{eff}.

[0025] The k_{eff} is a measure of a system's proximity to criticality, where:

[0026] $k_{eff}<1.0$ is subcritical

[0027] $k_{eff}=1.0$ is critical

[0028] $k_{eff}>1.0$ is supercritical

In order to substantially maximize the productivity of medical isotopes, while substantially ensuring that subcriticality is maintained, it is desirable to operate the subcritical hybrid **10** with k_{eff} of the aqueous target assembly **18** close to 1.0 (e.g., 0.9500-0.9995), because higher k_{eff} values increase the efficiency of the system due to increased subcritical multiplication. The hybrid **10** may be operated with k_{eff} of at least about 0.7000, at least about 0.7500, at least about 0.8000, at least about 0.8500, at least about 0.9000, or at least about 0.9500. The hybrid **10** may be operated with k_{eff} of less than about 0.9995, less than about 0.9990, less than about 0.9980, less than about 0.9970, less than about 0.9960, less than about 0.9950, or less than about 0.9900. The hybrid **10** may be operated with k_{eff} of 0.7000 to 0.9995, 0.7500 to 0.9995, 0.8000 to 0.9995, 0.9000 to 0.9995, 0.9500 to 0.9995, or 0.9900 to 0.9995.

[0029] FIG. **4** is a cross-sectional view of an aqueous reactor **70**. The aqueous reactor **70** includes an aqueous assembly **74** (e.g., an aqueous assembly capable of criticality) disposed within a shield tank **78**. The aqueous assembly **74** includes a reactor vessel **82** supporting a volume of aqueous solution **86**. The aqueous solution **86** includes a fissile solute. The fissile solute may include U-235 in the form of low enriched uranium (LEU), natural uranium, or other fissile materials. The uranium may be converted into a salt (e.g., uranyl nitrate, uranyl sulfate, or uranyl fluoride) to increase the solubility, and the pH may be adjusted to further increase solubility. The aqueous solution **86** includes at least a critical mass of the fissile solute. The critical mass of the fissile solute depends upon its nuclear properties (e.g. the fission cross-section), the fissile solute's enrichment and concentration within the solution, the density of the solution, the shape of the solution within the reactor vessel, the solution temperature, neutron reflectivity of the surroundings, and other factors.

[0030] A control rod **90** is selectively positionable within the aqueous assembly **74**. The control rod **90** includes a material having a high neutron capture cross section. This material may include silver, indium, and cadmium. Other elements that can be used include, for example, boron, cobalt, hafnium, dysprosium, gadolinium, samarium, erbium, and europium, or their alloys and compounds, e.g., high-boron steel, silver-indium-cadmium alloy, boron carbide, zirconium diboride, titanium diboride, hafnium diboride, gadolinium titanate, and dysprosium titanate.

[0031] The control rod **90** is positioned within the aqueous assembly **74** by a control rod drive mechanism (CRDM) **94**. Inserting the control rod **90** deep within aqueous solution **86** of the reactor vessel **82** reduces the reactivity of the aqueous assembly **74**, thereby keeping the aqueous assembly **74** from becoming inadvertently critical (i.e., the control rod maintains k_{eff}<1.0). As the control rod **90** is controllably withdrawn from the solution by the CRDM **94**, fewer neutrons are captured, and the reactivity within the aqueous assembly **74** increases until k_{eff}=1.0 (i.e., the aqueous assembly **74** is critical). Continuing to withdraw the control rod **90** would continue to insert positive reactivity. If the control rod **90** is withdrawn rapidly, and sufficient positive reactivity is inserted into the aqueous assembly **74**, the aqueous assembly **74** could become prompt critical: the point where fission can be sustained utilizing prompt neutrons alone. However, this positive rod reactivity may be counteracted by other effects that result in negative reactivity, including warming of the solution and the formation of voids within the solution due to radiolysis, or even boiling.

[0032] Since the fissile atoms (e.g., uranium-235) are in solution in an aqueous assembly (e.g., the subcritical aqueous target assembly **18** or the aqueous assembly **74**), the mass concentration of uranium decreases as the solution expands with increasing temperature. This expansion displaces uranium from the more neutronically important "high-worth" central region of the TSV **50** (FIG. **1**) or the reactor vessel **82** (FIG. **4**), and moves the uranium to a free surface of the solution, which is a "low-worth" region.

[0033] The thermal expansion effect is compounded by the increase in average neutron energy as the solution's temperature is increased. The increase in thermal neutron temperature decreases the probability of causing fission of uranium-235 relative to the other events that could occur (e.g., escape from the system, capture in low-lying resonances, etc.). This effect may result in a strongly negative temperature coefficient of reactivity. The temperature coefficient of reactivity (α_T) is a measure of the change in the reactivity of the system per unit increase in temperature. α_T predicts the change in k_{eff} for a change in temperature of the aqueous solution. α_T of embodiments of the subcritical hybrid **10** or of the aqueous reactor **70** are estimated to be approximately −10 pcm/° F. at 100° F. Values of α_T may be calculated with a neutronics computer code. The value of α_T may be at least about −100, at least about −90, at least about −80, at least about −70, at least about −60, or at least about −50. The value of α_T may be less than about −1, less than about −2, less than about −3, less than about −4, less than about −5, less than about −6, less than about −7, less than about −8, less than about −9, or less than about −10. The value of α_T may be −100 to −1, −90 to −2, −80 to −3, −70 to −4, or −60 to −5.

[0034] In addition to the negative α_T, aqueous assemblies, such as the subcritical aqueous target assembly **18** (FIG. **1**) or aqueous assembly **74** (FIG. **4**), also have a strong negative void coefficient (α_{void}). α_{void} is a measure of the change in the reactivity of the system per unit increase of gas or void. Aqueous systems have a negative void coefficient due to a similar effect as described for thermal expansion (as void is added to the solution, it displaces uranium from the high-worth central region to the low-worth region at the solution surface). Values of α_{void} may be calculated with a neutronics computer code. The value of α_{void} may be at least about −500 pcm/(% void), at least about −450, at least about −400, at least about −350, at least about −300, at least about −250, at least about −200, at least about −150, or at least about −100. The value of α_{void} may be less than about −10, less than about −20, less than about −30, less than about −40, or less than about −50. The value of α_{void} may be −500 to −10, −450 to −20, −400 to −30, −350 to −40, or −300 to −50 pcm/(% void).

[0035] The large negative α_T and α_{void} can cause two potential issues with aqueous systems: reactivity oscillations and reduced output. Reactivity oscillations can occur as a result of any transients induced on the system (e.g., power change, or pressure change) or due to natural oscillations (e.g., turbulent flow). For example, if the temperature increases, the reactivity feedback mechanisms will cause power to drop, which will lead to a temperature decrease and a subsequent power increase. The cycle will continue until it is externally damped by control systems or until it naturally decays.

[0036] The second potential issue is reduced output. For the subcritical aqueous target assembly **18**, the output may be reduced because the strong negative temperature and void coefficients result in lower k_{eff} values, thereby reducing the subcritical multiplication of the system. The strong negative α_T and α_{void} may result in a reduction in the operating power level of the system to ensure that there is enough safety margin in the design to account for the power oscillations.

[0037] By reducing the magnitude of α_T and α_{void}, one can reduce the impact of both of these issues.

[0038] Certain isotopes have very large capture cross sections for neutrons while also decreasing in density and/or absorbance with a temperature increase, and these isotopes may be called reactivity stabilizers. Reactivity stabilizers absorb neutrons from a nuclear system, preventing the neutrons from causing fission. Some examples of reactivity stabilizers include, but are not limited to, boron-10, gadolinium-155, and gadolinium-157. Boron-10 may be added to the aqueous solution in the form of boric acid (i.e., H_3BO_3 or $B(OH)_3$). Boric acid may be particularly desirable due to high solubility and low pH. In addition to using soluble boric acid, other physical placements of the boron could be used. Such devices include fixed plates or rods containing boron. Commercial boron-aluminum alloys may be used due to their chemical and radiation stability. Another option would be to place the boron in separate tubes filled with concentrated boric acid.

[0039] By adding these reactivity stabilizers to the aqueous solution in the TSV **50** (FIG. **1**) or the reactor vessel **82** (FIG. **4**), the relative importance of the uranium in the solution can be reduced since the reactivity stabilizer competes for neutrons with the uranium. As such, when the solution temperature is increased (or increases), the solution expansion not only removes some of the uranium from the high-worth central region, but also removes some of the reactivity stabilizer. The net effect is that the strong negative α_T is reduced in magnitude.

[0040] A similar response is achieved with α_{void}. An increase in solution void displaces the reactivity stabilizer as well as the uranium. Therefore, the reactivity impact of an additional bubble in the solution is reduced due to the competing effects of loss of uranium and loss of reactivity stabilizer.

[0041] By adjusting the concentration of the reactivity stabilizers, one can shape the reactivity feedback coefficients α_T and α_{void} to any desired levels. For example, the reactivity stabilizer concentration may be chosen to lessen the magnitude of α_T and α_{void}, while still keeping them negative. Negative coefficients help ensure that an increase in system power leads to a decrease in reactivity (self-limiting device); however, coefficients that are too negative lead to the power oscillations described above. FIG. **3** illustrates temperature coefficient of reactivity (α_T) of a subcritical aqueous target assembly at several selected boron concentrations, showing the reduced magnitude of the temperature coefficient as the boron concentration increases.

[0042] Ultimately, the decreased reactivity coefficients offer increased stability (α_T and α_{void}) when operating the subcritical hybrid assembly **10**, due to the reduced reactivity oscillations. This increased stability also allows for increased production rates of medical isotopes. Because reactivity oscillations are minimized, the subcritical hybrid assembly may be operated with a higher effective neutron multiplication factor (k_{eff}). FIG. **2** is a graph of boron concentration in a target solution versus a normalized production rate of a subcritical assembly, showing the increase in productivity as the boron concentration increases.

[0043] FIG. **5** illustrates k_{eff} operating bands of a subcritical aqueous assembly. For a subcritical aqueous assembly without the use of reactivity stabilizers, the k_{eff} operating band is wide, due to oscillations in temperature and void reactivity as a result of the large α_T and α_{void}. In order to reduce the chance of criticality, a typical operating k_{eff} value of the unstabilized operating band is undesirably far from k_{eff}=1.0, which reduces the efficiency of operating the subcritical aqueous assembly due to reduced subcritical multiplication. In comparison, an aqueous assembly including reactivity stabilizers has a narrower k_{eff} operating band due to reduced oscillations in temperature and void reactivity, as a result of the reducing the magnitudes of α_T and α_{void}. Moreover, the typical operating k_{eff} value of the stabilized operating band is closer to k_{eff}1.0, while still maintaining the same margin from criticality in the operating band, thereby increasing the efficiency of operating the subcritical aqueous assembly by increasing subcritical multiplication.

[0044] FIG. **6** illustrates k_{eff} operating bands of a critical aqueous assembly. For a critical aqueous assembly without the use of reactivity stabilizers, the k_{eff} operating band is wide due to oscillations in temperature and void reactivity as a result of the large α_T and α_{void}. When operating critically, the upper limit of the operating band is undesirably close to prompt criticality. In comparison, a critical aqueous assembly including reactivity stabilizers has a narrower k_{eff} operating band due to reduced oscillations in temperature and void reactivity as a result of reducing the magnitudes of α_T and α_{void}. Moreover, the margin to prompt criticality is greater, thereby increasing a safety margin of the critical aqueous assembly.

Example 1

[0045] The subcritical hybrid is provided, including the neutron source assembly, neutron multiplier, and aqueous assembly. An aqueous solution is provided in the TSV. The aqueous solution includes a fissile solute, including LEU.

[0046] Desired concentrations of boron, or other reactivity stabilizers, may be calculated using a neutronics computer code. An operator may select desired values of k_{eff}, α_T, and α_{void}, and then calculate a boron concentration. Other input values to the neutronics code include operating conditions of the hybrid assembly, e.g., the geometries of the TSV, shield tank, and neutron multiplier, as well as the volumes, solution chemistry, densities of all materials, source particle energies, nuclear cross section data, and temperatures of all materials.

[0047] Once a desired boron concentration is calculated, a boron or boric acid addition is prepared and added to the aqueous solution.

[0048] α_T and α_{void} are calculated for a desired soluble reactivity stabilizer concentration. A first k_{eff} value (k_{eff1}) is determined to a high degree of accuracy using a base case. Then a small perturbation is made in the variable of interest (e.g., solution temperature), and the new k_{eff} value (k_{eff2}) is calculated. Optionally, a second perturbation is then made in the opposite direction from the base case, and a third k_{eff} value is calculated.

[0049] The reactivity coefficient (α_T or α_{void}) is then calculated from $(k_{eff1}-k_{eff2})/(k_{eff1}*k_{eff2})/\Delta Z$, where ΔZ is the perturbation in the variable of interest. The two perturbations are used to confirm the calculated reactivity coefficient (α_T or α_{void}), to determine the slope of the reactivity coefficient, and to provide better statistics through averaging.

[0050] Once the subcritical hybrid is operating, α_T and α_{void} are measured through a combination of instrumentation and calculation. For instance, α_T can be inferred by observing the effects of temperature on the power of the system. The temperature of the solution will be measured (at a few specific locations in the solution), and this measured temperature is then mapped to a bulk temperature using fluid dynamics calculations. The power or neutron flux is then measured at that temperature. By knowing the source neutron term, this neutron flux or power can be correlated to a known k_{eff} in the system. Then a change in temperature (or change in void) is imposed on the system (such as by altering cooling flow), and the process is repeated. The reactivity coefficient (α_T or α_{void}) is then calculated using the same formula as above.

Example 2

[0051] The aqueous reactor is provided, including the aqueous assembly. An aqueous solution is provided in the reactor vessel. The aqueous solution includes fissile solute of known concentration and enrichment.

[0052] Desired concentrations of boron, or of other reactivity stabilizers, may be calculated using a neutronics computer code. An operator may select desired values of α_T, and α_{void}, and then calculate a boron concentration. Other input values to the neutronics code may include operating conditions of the aqueous reactor, e.g., the geometries of the reactor vessel and shield tank, as well as the volumes, solution chemistry, densities of all materials, source particle energies, nuclear cross section data, and temperatures of all materials.

[0053] Once a desired boron concentration is calculated, a boron or boric acid addition is prepared and added to the aqueous solution.

[0054] α_T and α_{void} are calculated for a desired soluble reactivity stabilizer concentration. The two perturbations are used to confirm the calculated reactivity coefficient (α_T or α_{void}) to determine the slope of the reactivity coefficient and to provide better statistics through averaging.

[0055] Once the aqueous reactor is operating, α_T and α_{void} are measured through a combination of instrumentation and calculation. For instance, α_T can be inferred by observing the effects of temperature on the power of the system. The temperature of the solution will be measured (at a few specific locations in the solution), and this measured temperature is then mapped to a bulk temperature using fluid dynamics calculations. The power or neutron flux is then measured at that temperature. The reactivity coefficient (α_T or α_{void}) is then calculated using the same formula as above.

[0056] Thus, the invention provides, among other things, an aqueous assembly and a control method for the same. Various features and advantages of the invention are set forth in the following claims.

What is claimed is:

1. An aqueous assembly having a negative coefficient of reactivity, the aqueous assembly comprising:

a vessel;

an aqueous solution, including a fissile solute, supported in the vessel; and

a reactivity stabilizer disposed within the aqueous solution to reduce a magnitude of the negative coefficient of reactivity of the aqueous assembly during operation of the aqueous assembly, wherein the reactivity stabilizer is a solute of the aqueous solution.

2. The aqueous assembly of claim **1**, wherein the coefficient of reactivity is a solution temperature coefficient of reactivity.

3. The aqueous assembly of claim **1**, wherein the coefficient of reactivity is a solution void coefficient of reactivity.

4. The aqueous assembly of claim **1**, wherein the fissile solute includes uranium.

5. The aqueous assembly of claim **1**, wherein the fissile solute includes at least one of uranyl nitrate, uranyl sulfate, and uranyl fluoride.

6. The aqueous assembly of claim **1**, wherein the reactivity stabilizer includes boron-10.

7. The aqueous assembly of claim **1**, wherein the reactivity stabilizer includes at least one of boric acid, gadolinium-155, and gadolinium-157.

8. The aqueous assembly of claim **1**, wherein the aqueous assembly is subcritical, the aqueous assembly further comprising a neutron source for sustaining a fission reaction within the vessel.

9. The aqueous assembly of claim **1**, wherein the aqueous assembly is capable of critical operation.

10. A method of operating an aqueous assembly having a coefficient of reactivity with a magnitude, the method comprising:

adding an aqueous solution, including a fissile solute, to a vessel;

adding a reactivity stabilizer to the aqueous solution; and

subsequent to adding the reactivity stabilizer, sustaining a fission reaction within the aqueous solution at an effective neutron multiplication factor (k_{eff}) of 0.9 or greater, wherein the reactivity stabilizer reduces the magnitude of the coefficient of reactivity while the fission reaction is sustained within the aqueous solution.

11. The method of claim **10**, further comprising operating a neutron source to sustain the fission reaction with the aqueous solution.

12. The method of claim **10**, wherein adding the reactivity stabilizer includes adding at least one of boric acid, gadolinium-155, and gadolinium-157.

13. The method of claim **10**, wherein the reactivity stabilizer is a solute of the aqueous solution.

14. The method of claim **10**, wherein reducing the magnitude of the coefficient of reactivity includes reducing a magnitude of a negative temperature coefficient of reactivity.

15. The method of claim **10**, wherein reducing the magnitude of the coefficient of reactivity includes reducing a magnitude of a negative void coefficient of reactivity.

16. The method of claim **10**, further comprising withdrawing a control rod until the aqueous solution achieves criticality.

17. A subcritical aqueous assembly having a negative coefficient of reactivity, the subcritical aqueous assembly comprising:

a vessel;

an aqueous solution, including a fissile solute including uranium, supported in the vessel;

a neutron source for sustaining a fission reaction with the fissile solute at a subcritical level within the vessel; and

a reactivity stabilizer disposed within the aqueous solution to reduce a magnitude of the negative coefficient of reactivity of the subcritical aqueous assembly during operation of the subcritical aqueous assembly.

18. The subcritical aqueous assembly of claim **17**, wherein the reactivity stabilizer includes at least one of boron-10, gadolinium-155, and gadolinium-157.

19. A method of operating a subcritical aqueous assembly having a negative coefficient of reactivity with a magnitude, the method comprising:

adding an aqueous solution, including a fissile solute including uranium, to a vessel;

adding a reactivity stabilizer to the aqueous solution;

operating a neutron source to sustain a fission reaction with the fissile solute of the aqueous solution at a subcritical level; and

reducing the magnitude of the negative coefficient of reactivity of the subcritical aqueous assembly during operation of the subcritical aqueous assembly.

20. The method of claim **19**, wherein the reactivity stabilizer is added to the aqueous solution before operating the neutron source.

* * * * *