

Sulfur Blanket

I. Priority

[0001] This application claims the benefit of U.S. Provisional Patent Application No. 63/036,029, Titled: "Sulfur Blanket," filed June 8, 2020. This U.S. Provisional Patent Application No. 63/036,029 is hereby incorporated by reference in its entirety as if fully restated herein.

II. Background

[0002] Nuclear fusion is generally defined as the process by which lighter nuclei are merged to form heavier nuclei. For lighter nuclei the fusion process liberates energy in the form of kinetic energy in the residual particles. The vast majority of past attempts at generating electrical power from fusion reactions have contemplated boiling water to drive conventional turbines (an example of a means approximated by a Carnot cycle). These past attempts have often utilized strong magnetic fields to constrain plasmas of electrons and ions until the ions collide and fuse. Such magnetic containment is prone to instabilities and particle leakage, causing inadvertent and often catastrophic loss of energy that would otherwise be needed to sustain fusion reactions.

[0003] The electrons within the plasma present their own set of difficulties. First, because electrons are much lighter than ions, electromagnetic collisions between electrons and ions tend to rob the ions of the kinetic energy needed for the fusion process. Second, these scattered electrons tend to be relativistic, emitting photonic radiation when they collide or accelerate. This photonic radiation is also a large source of energy leakage, robbing the plasma of the energy needed to sustain fusion reactions. The elimination of electrons from nuclear fusion reactions is taught in U.S. Provisional Patent Application No. 62/811,485 filed February 27, 2019 and titled "Direct Nuclear Power Conversion" by one of the applicants of this instant application. The PCT application PCT/US20/19449 titled "Direct Nuclear Power Conversion" was filed February 24, 2020 and claims the benefit of U.S. Provisional Patent Application No. 62/811,485. Both 62/811,485 and PCT/US20/19449 are incorporated by reference into this instant application.

[0004] There is a class of nuclear fusion reactions referred to as aneutronic. In these reactions very little of the energy liberated by the reactions is in the form of kinetic energy in neutrons. Aneutronic fusion reactions are also taught in 62/811,485 and PCT/US20/19449.

[0005] There are other nuclear fusion reactions that generate neutrons wherein a significant or majority of the released reaction energy is in the form of neutron kinetic energy. This neutron kinetic energy is converted into electrical power through their absorption in material in the form of heat which can be carried away by a working fluid in order to generate electrical power. A specific case is the mutual fusion of deuterium nuclei to generate neutrons with a kinetic energy of approximately 2.5 MeV. The mutual fusion of deuterium nuclei and the absorption of neutron kinetic energy in a working fluid is taught in U.S. Provisional Patent Application No. 62/995,168 filed January 14, 2020 and titled "Transient Beam Compression Fusion" by one of the applicants of this instant application. Provisional patent 62/995,168 is incorporated by reference into this instant application.

[0006] In addition, the mutual fusion of deuterium nuclei and the amplification of energy release due to neutron moderation and absorption in a working fluid is taught in U.S. Provisional Patent Application No. 63/070,587 filed August 26, 2020 and titled "Mixed Nuclear Power Conversion". Provisional patent 63/070,587 is incorporated by reference into this instant application.

[0007] The production of ion beams, such as deuteron beams, is taught in U.S. Provisional Patent Application No. 63/036,073 filed June 8, 2020 and titled "Ion Source". Provisional patent 63/036,073 is incorporated by reference into this instant application.

[0008] Higher kinetic energy neutrons such as those emanating from the fusion of tritium and deuterium ions (DT fusion) pose a significant radiological risk to nearby personnel and are very difficult to shield. Large doses of DT fusion neutrons in metals cause embrittlement and dimensional changes, compromising the functionality and integrity of the reactor. Another problem with DT fusion is the need to produce the fuel component tritium.

[0009] Another form of nuclear interaction is antimatter annihilation reactions. Take for example a negatively charged antiproton drifting into uranium, even depleted uranium U238. Note that 99% of antiprotons that stops in uranium induces fission. When a low kinetic energy antiproton strikes a target, it quickly decelerates due to scattering against electrons in the target. At thermal energies the antiproton will only penetrate a few atomic layers into the target. When the negatively-charged antiprotons decelerate to kinetic energies of a few electron-Volts they displace an orbiting outer-shell electron. Because antiprotons are fermions with different quantum numbers than electrons, they quickly cascade down to the ground state and annihilate against one of the nucleons (proton or neutron) in the nucleus. The absorption by the nucleus of one of the pi-mesons that emanate from this annihilation induces the nuclear fission. Unlike neutron induced fission, the isotope of uranium is irrelevant. Depleted uranium U238 undergoes antiproton-induced fission just as easily as fissile U235. Unlike weapons-grade fissile materials such as U235, there are minimal regulatory controls on the handling of U238. This significantly reduces research costs and administrative overhead, allowing development of the technology to progress much faster than otherwise possible. One aspect of antimatter annihilation reactions as a trigger for nuclear fission is that an

average of 16 neutrons are generated per fission event. If it were possible to harvest 8.64 MeV of energy per neutron, this would generate 138 MeV of energy in addition to the approximately 240 MeV generated by the fission event itself.

[0010] Antimatter annihilation reactions are also useful for other purposes such as the elimination of unwanted biological cells. United State patent 9,630,021 invented by an inventor of the instant application Gerald Jackson titled “Antiproton Production and Delivery for Imaging and Termination of Undesirable Cells” describes such an application. Patent 9,630,021 is hereby incorporated by reference as if fully stated herein.

[0011] Another type of nuclear reaction that produces neutrons is the reaction Li7(p,n)Be7 , wherein an incident proton at a kinetic energy above the threshold of 1.9 MeV on a lithium-7 target produces a very low energy neutron and a residual beryllium-7 atom.

[0012] The exchange of protons for neutrons on targets is the basis of energy amplifiers, which are described in International Patent Application PCT/EP94/02467 titled “An Energy Amplifier for Clean Nuclear Energy Production Driven by a Particle Beam Accelerator” invented by Nobel Prize winner Carlo Rubbia. PCT/EP94/02467 is hereby incorporated by reference as if fully stated herein. Accordingly, there is a need for improvement over such past approaches.

III. Summary

[0013] The disclosure below uses different prophetic embodiments to teach the broader principles with respect to articles of manufacture, apparatuses, processes for using the articles and apparatuses, processes for making the articles and apparatuses, and products produced by the process of making, along with necessary intermediates, directed to nuclear power multiplication and conversion.

[0014] This Summary is provided to introduce the idea herein that a selection of concepts is presented in a simplified form as further described below. This Summary is not intended to identify key features or essential features of subject matter, nor this Summary intended to be used to limit the scope of claimed subject matter. Additional aspects, features, and/or advantages of examples will be indicated in part in the description which follows and, in part, will be apparent from the description, or may be learned by practice of the disclosure.

[0015] References cited herein are incorporated by reference as if fully stated herein. The following description and drawings are illustrative and are not to be construed as limiting. Numerous specific details are described to provide a thorough understanding of the disclosure. However, in certain instances, well-known or conventional details are not described in order to avoid obscuring the description. References to one or an embodiment in the present disclosure can be, but not necessarily are, references to the same embodiment; and, such references mean at least one of the embodiments.

[0016] Reference in this specification to "one embodiment" or "an embodiment" means that a particular feature, structure, or characteristic described in connection with the embodiment is included in at least one embodiment of the disclosure. The

appearances of the phrase "in one embodiment" in various places in the specification are not necessarily all referring to the same embodiment, nor are separate or alternative embodiments mutually exclusive of other embodiments. Moreover, various features are described which may be exhibited by some embodiments and not by others. Similarly, various requirements are described which may be requirements for some embodiments but not for other embodiments.

[0017] The terms used in this specification generally have their ordinary meanings in the art, within the context of the disclosure, and in the specific context where each term is used. Certain terms that are used to describe the disclosure are discussed below, or elsewhere in the specification, to provide additional guidance to the practitioner regarding the description of the disclosure. For convenience, certain terms may be highlighted, for example using italics and/or quotation marks. The use of highlighting has no influence on the scope and meaning of a term; the scope and meaning of a term is the same, in the same context, whether or not it is highlighted. It will be appreciated that same thing can be said in more than one way.

[0018] Consequently, alternative language and synonyms may be used for any one or more of the terms discussed herein, nor is any special significance to be placed upon whether or not a term is elaborated or discussed herein. Synonyms for certain terms are provided. A recital of one or more synonyms does not exclude the use of other synonyms. The use of examples anywhere in this specification including examples of any terms discussed herein is illustrative only, and is not intended to further limit the scope and meaning of the disclosure or of any exemplified term. Likewise, the disclosure is not limited to various embodiments given in this specification.

[0019] Without intent to limit the scope of the disclosure, examples of instruments, apparatus, methods and their related results according to the embodiments of the present disclosure are given below. Note that titles or subtitles may be used in the examples for convenience of a reader, which in no way should limit the scope of the disclosure. Unless otherwise defined, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this disclosure pertains. In the case of conflict, the present document, including definitions will control.

[0020] With the foregoing in mind, consider an apparatus (method of making, method of using) including power plant of output electrical power constructed so as to produce more of said output electrical power than electrical power input to the apparatus, e.g., by bringing into collision ions so as to induce fusion reactions. In some embodiments herein, the power plant: (1) can be devoid of a magnetic field that constrains a plasma; (2) can be such that energy released from the fusion reactions is amplified by secondary nuclear reactions in a material surrounding said fusion reactions caused by neutrons; (3) or can be both. Illustratively, consider the reaction of deuterium-deuterium (DD) fusion surrounded by a region of sulfur to teach the broader concepts of producing such electrical power. In other embodiments, fusion reactions are replaced by antimatter-induced nuclear fission or other nuclear reactions that also produce neutrons, said reactions also surrounded by a region of sulfur.

IV. Industrial Applicability

[0021] Industrial applicability is representatively directed to that of apparatuses and devices, articles of manufacture - particularly electrical - and processes of making and using them. Industrial applicability also includes industries engaged in the foregoing, as well as industries operating in cooperation therewith, depending on the implementation.

V. Drawings

[0022] In the non-limiting examples of the present disclosure, please consider the following:

[0023] Figure 1 is an illustration of a method of producing electrical power [026] from a process creating [002] neutrons [004].

[0024] Figure 2 is a list of nuclear reaction [102] that produce neutrons [004] in a creating [002] process or that absorb neutrons [004] in a capturing [016] process.

[0025] Figure 3 is a list of isotopes of sulfur atoms [030] found in nature on Earth including for each isotope the natural abundance and the thermal neutron capture cross section.

[0026] Figure 4 is a plot of published experimental data showing the (n,g) [088] neutron [004] capture cross section as a function of neutron kinetic energy.

[0027] Figure 5 is an illustration of the isotope sulfur-32 [032] capturing [016] a neutron [004] via the (n,g) [088] reaction to form sulfur-33 [033] and emit 8.64 MeV of electromagnetic radiation [008].

[0028] Figure 6 is an illustration of the isotope sulfur-33 [033] capturing [016] a neutron [004] via the (n,g) [088] reaction to form sulfur-34 [034] and emit 11.42 MeV of electromagnetic radiation [008].

[0029] Figure 7 is an illustration of the isotope sulfur-34 [034] capturing [016] a neutron [004] to form sulfur-35 [035] and emit 6.99 MeV of electromagnetic radiation [008]. Sulfur-35 [035] then undergoes beta decay with a half-life of 87 days to form

chlorine-35 [040] with the additional release of 0.17 MeV of electromagnetic radiation [008].

[0030] Figure 8 is an illustration of the isotope sulfur-36 [036] capturing [016] a neutron [004] to form sulfur-37 [037] and emit 4.30 MeV of electromagnetic radiation [008]. Sulfur-37 [037] then undergoes beta decay with a half-life of 5 minutes to form chlorine-37 [042] with the additional release of 4.87 MeV of electromagnetic radiation [008].

[0031] Figure 9 is a plot of published experimental data showing the (n,a) [090] neutron [004] capture cross section as a function of neutron kinetic energy.

[0032] Figure 10 is a plot of published experimental data showing the (n,p) [092] neutron [004] capture cross section as a function of neutron kinetic energy.

[0033] Figure 11 is a plot of published experimental data showing the DD fusion cross section for the reaction channel yielding a neutron [004].

[0034] Figure 12 is a plot of published experimental data showing the DD fusion cross section for the reaction channel yielding a proton [061].

[0035] Figure 13 is a plot of the calculated neutron [004] kinetic energy generated by a DD fusion reaction as a function of the kinetic energy of each deuteron [062] beam that are in direct head-on collision.

[0036] Figure 14 is an illustration of an embodiment of a power plant [200] harvesting energy from fusion reactions [072] and nuclear reactions [102] within a surrounding sulfur blanket [104] in order to generate [028] electrical power [026].

[0037] Figure 15 is an illustration of an embodiment of harvesting energy from nuclear reactions [102] within a surrounding sulfur blanket [104] in order to generate [028] electrical power [026].

[0038] Figure 16 is an illustration of an embodiment of harvesting energy from nuclear reactions [102] in order to produce electrical power [026].

[0039] Figure 17 is an illustration of a turbine [134] powered by the thermal energy in steam [020] employed to turn a drive shaft [136] which turns a generator [128] that produces electrical power [026].

[0040] Figure 18 is an illustration of a sulfur containment vessel [140] and a heat exchanger [118] that are heater by nuclear reactions [102].

[0041] Figure 19 is an illustration of the addition of an electrical battery [120] between the generator [128] and an electrical load [158] wherein the electrical battery [120] is also fed electrical power [026] by external power sources [160].

[0042] Figure 20 is an illustration of an embodiment wherein a sulfur containment vessel [140] is utilized simultaneously as a sulfur blanket [104] and a sulfur-sodium battery [156].

[0043] Figure 21 is a plot of the sulfur-sodium battery [156] voltage as a function of sulfur [030] concentration in the sulfur-sodium mixture [150].

[0044] Figure 22 is an illustration of the isotope sodium-23 [162] capturing [016] a neutron [004] to form sodium-24 [164] and emit 6.96 MeV of electromagnetic radiation [008]. Sodium-24 [164] then undergoes beta decay with a half-life of 15 hours to form magnesium-24 [166] with the additional release of 5.52 MeV of electromagnetic radiation [008].

VI. Detailed Disclosure of Modes

[0045] The following detailed description is directed to concepts and technologies for direct nuclear power conversion into electrical power by fusion reactions, teaching by way of prophetic illustration. The disclosure includes an apparatus comprising a generator of output electrical power in a construction to bring into collision ions so as to induce nuclear fusion reactions and thereby produce more of said output electrical power than electrical power input to the apparatus. Similarly, the following disclosure teaches a method of generating electrical power, the method comprising generating more output electrical power than electrical power input to an apparatus by bringing into collision, in said apparatus, one or more species of ions so as to induce nuclear fusion reactions. These are indicative of how to make such an apparatus as well as necessary intermediates produced in the methods.

[0046] In contrast to past attempts at nuclear fusion for the purposes of electrical power generation, this disclosure teaches an apparatus comprising an electrical power plant that can be devoid of a magnetic field that contains a plasma comprised of said ions brought into said collisions. It also describes a method of bringing ions into collision in ways that can be devoid of constraining a plasma with a magnetic field.

A. Harvesting Energy with Neutrons

[0047] One teaching embodiment for teaching broader concepts is directed to a method of harvesting energy with neutrons from a sulfur blanket [104] surrounding a region in which neutrons [004] created, sometimes in conjunction with the creation of ions [006] and electromagnetic radiation [008]. Electromagnetic radiation [008] is generally

defined as electrons [054], positrons [056], and gamma-rays [058] across the entire electromagnetic spectrum. The process of creating [002] neutrons [004] and the subsequent method of harvesting energy from said neutrons [004], ions [006], and electromagnetic radiation [008] is illustrated in Figure 1.

[0048] After the process of creating [002] the neutrons generally undergo a process of moderating [010] wherein the kinetic energy carried by the neutrons [004] is reduced. The lost kinetic energy is generally converted into heat [116] and subsequent heat transmission [014]. The vast majority of neutrons undergo the process of moderating [010] before they undergo a subsequent process of capturing [016], wherein a neutron [004] is absorbed by an atom via nucleon exchange reactions [076] such as neutron [004] absorption with a subsequent emission of a gamma-ray [058] (referred to as a (n,g) reaction [088]. Other relevant neutron capture channels are neutron-proton (n,p) [092] and neutron-alpha (n,a) [090] exchanges. It is sometime possible for the capturing [016] process by an atom to be immediately preceded by transfer of neutron [004] kinetic energy to that same atom, also deemed moderating [010]. The process of capturing [016] generates more heat [116] and subsequent heat transmission [014] and additional electromagnetic radiation [008].

[0049] In parallel, the process of creating [002] may also generate ions [006]. These ions will generally undergo the process of stopping [012], wherein the kinetic energy lost by the ions is also converted into heat [116] and subsequent heat transmission [014]. The heat transmission [014] and electromagnetic radiation [008] from the processes of creating [002], moderating [010], capturing [016], and stopping [012] are all then subjected to the process of heat exchanging [018].

[0050] The process of creating [002] neutrons [004] is generally, but not necessarily, the result of nuclear reactions [102]. Such nuclear reactions [102] may comprise nuclear fission [070], nuclear fusion [072], radioisotope decay [074], antimatter annihilation reactions [098], or nucleon exchange reactions [076] such as proton-neutron (p,n) reactions [078]. Nucleon exchange reactions [076] that produce neutrons [004] are generally induced by bombarding atoms with energetic particles such as the protons in the (p,n) reactions [078] or energetic photons [008] in the (g,n) reactions [086]. There are dozens of possible nucleon exchange reactions [076], including gamma-neutron (g,n) [086], alpha-neutron (a,n) [084], deuteron-neutron (d,n) [080], triton-neutron (t,n) [082], or even neutron multiplication reactions such as (n,2n) [094] or (n,3n) [096] processes. One of ordinary skill in the art of nuclear physics would be generally familiar with the types of reactions that can create free neutrons. Many of these possible nuclear reactions capable of creating [002] neutrons [004] are summarized in Figure 2.

[0051] In one embodiment, a prophetic teaching, sulfur atoms [030] are used for the step of capturing [016] neutrons [004]. Figure 3 illustrates the abundances and thermal neutron cross sections for stable isotopes found on Earth. Note that the vast majority of naturally occurring sulfur is composed of the isotope sulfur-32 [032]. Most of the remaining naturally occurring sulfur is in the form of isotope sulfur-34 [034]. The isotopes sulfur-33 [033] and sulfur-35 [035] are only found in trace amounts in nature.

[0052] The thermal neutron cross sections specified in Figure 3 are determined by the capturing [016] of neutrons [004] in thermal equilibrium with sulfur atoms [030] at room temperature. The cross section is proportional to the probability of a neutron being absorbed (capturing [016]) by an atom. Room temperature corresponds to a typical

neutron kinetic energy of 0.025 eV. For example, the published data for the (n,g) [088] nucleon exchange reaction [076] for sulfur-32 [032] is plotted in Figure 4. Three published data sets are plotted, with typical experimental errors causing the three sets to diverge in places. The general message is that the lower the temperature, the greater the (n,g) [088] cross section. First, note that upon capturing [016] a neutron [004] the atom changes from the isotope sulfur-32 [032] to the isotope sulfur-33 [033]. Second, note that at the thermal equilibrium kinetic energy of 0.025 eV the plotted cross section of 0.518 barns agrees with the stated value in Figure 3. Also note that for a molten sodium blanket [104] the temperature of the sodium atoms [030] is much higher than room temperature, reducing the actual neutron capture cross section that is observed.

[0053] The prophetic embodiment wherein sulfur atoms [030] are involved in capturing [016] neutrons [004] is of interest because of the large energy release that occurs. As illustrated in Figure 5 for the case of sulfur-32 [032] capturing [016] neutrons [004], the result is the generation of sulfur-33 [033] and the emission of electromagnetic radiation [008]. The mass difference between the initial state (a free neutron [004] and a sulfur-32 [032] atom) and final state (a sulfur-33 [033] atom) is $8.64 \text{ MeV}/c^2$. According to the principle of energy conservation and the famous equation $E=mc^2$, the amount of electromagnetic radiation [008] is equal to this mass difference, or 8.64 MeV. In summary, neutron [004] capturing [016] is performed with sulfur atoms [030] comprising isotope sulfur-32 [032] atoms.

[0054] A similar situation is illustrated in Figure 6 wherein sulfur-33 [033] capturing [016] a neutron [004] yields sulfur-34 [034] and the release of 11.42 MeV of energy. In

summary, neutron [004] capturing [016] is performed with sulfur atoms [030] comprising isotope sulfur-33 [033] atoms.

[0055] As illustrated in Figure 7, a similar reaction takes place upon sulfur-34 [034] capturing [016] a neutron [004] to yield sulfur-35 [035] and the release of 6.99 MeV of energy in the form of electromagnetic radiation [008]. In summary, neutron [004] capturing [016] is performed with sulfur atoms [030] comprising isotope sulfur-34 [034] atoms. Because the isotope sulfur-35 [035] is radioactive, decaying into chlorine-35 [040] via beta decay with a half-life of 87 days, the mass difference between the initial state (sulfur-35 atom [035]) and final state (chlorine-35 atom [040] plus emitted beta particle/electron [054]) results in the emission of another 0.17 MeV of electromagnetic radiation [008].

[0056] As illustrated in Figure 7, a similar reaction takes place upon sulfur-36 [036] capturing [016] a neutron [004] to yield sulfur-37 [037] and the release of 4.30 MeV of energy in the form of electromagnetic radiation [008]. In summary, neutron [004] capturing [016] is performed with sulfur atoms [030] comprising isotope sulfur-36 [036] atoms. Because the isotope sulfur-37 [037] is radioactive, decaying into chlorine-37 [042] via beta decay with a half-life of 5 minutes, the mass difference between the initial state (sulfur-37 atom [037]) and final state (chlorine-37 atom [042] plus emitted beta particle/electron [054]) results in the emission of another 4.87 MeV of electromagnetic radiation [008].

[0057] Because isotopic separation or isotopic enrichment is typically an expensive process, an embodiment is to perform the step of capturing [016] with naturally occurring sulfur. In this case capturing is performed with sulfur atoms [030] consisting of (or in

some cases, having or consisting essentially of) the isotopes sulfur-32 [032], sulfur-33 [033], sulfur-34 [034], and sulfur-36 [036]. Because of its simplicity, an embodiment is to perform the step of moderating [010] also with sulfur atoms [030].

[0058] The capturing [016] of neutrons [004] can also take place because of other nucleon exchange reactions [076]. As a representative example, energetic neutrons [004] impinging on a sulfur-32 [032] atoms can sometimes liberate alpha particles/helium ions [066] via a (n,a) [090] reaction illustrated in Figure 2. As plotted in Figure 9, the (n,a) reaction cross section for producing silicon-29 [044] from sulfur-32 [032] is negligible for neutron kinetic energies below 1.7 MeV. As another representative example, energetic neutrons [004] impinging on a sulfur-32 [032] atoms can sometimes liberate protons/hydrogen ions [061] via a (n,p) [092] reaction. As plotted in Figure 10, the (n,p) reaction cross section for producing phosphorus-32 [050] from sulfur-32 [032] is negligible for neutron kinetic energies below 1.8 MeV. Depending on the neutron kinetic energy during the creating [002] step, the impact of these other nucleon exchange reactions [076] can vary. For high energy neutrons such as those generated by DT fusion these nucleon exchange reactions [076] can be the dominant mechanism for capturing [016] of neutrons [004].

[0059] The moderating [010] of neutrons [004] removes kinetic energy from the neutrons [004] imparted by the creating [002] process. This lost kinetic energy is converted into heat [116] and subsequent heat transmission [014]. The electromagnetic radiation [008] from the creating [002] and capturing [016] step is completely or partially absorbed by the sulfur atoms [030], converting the electromagnetic radiation [008] into heat [116] and subsequent heat transmission [014]. The stopping [012] of ions [006]

emitted by creating [002] converts the ion kinetic energy into heat [116] and subsequent heat transmission [014]. Some or all of this heat transmission [014] and remaining (unconverted) electromagnetic radiation [008] is accumulated in a heat exchanging [018] process.

[0060] The purpose of heat exchanging [018] converting [024] water [022] into steam [020]. The heat [116] and electromagnetic radiation [008] accumulated by heat exchanging [018] is delivered into the water [022] to cause it to boil and produce steam [020]. The steam is then used in the step of electricity generating [028], converting [024] the steam [020] back into liquid water [022]. The result of electricity generating [028] is the output of electrical power [026].

[0061] An embodiment is a method of electricity generating [028] wherein the amount of output electrical power [026] resulting from said electricity generating [028] is greater than the total amount of electricity required (or in some cases, used) to perform the steps of creating [002], moderating [004], stopping [012], transmitting, capturing [016], heat exchanging [018], converting [020], and generating [028]. This condition is generally referred to as breakeven, or breakeven energy production. Another embodiment is a method of electricity generating [028] wherein the amount of output electrical energy resulting from said electricity generating [028] is greater than the total amount of electrical energy required (or in some cases, used) to carry out the steps of creating [002], moderating [004], stopping [012], heat transmission [014], capturing [016], heat exchanging [018], converting [020], and generating [028]. The above two embodiments are equivalent in the absence of a means for storing energy by electrical or thermal means.

[0062] In summary, Figure 1 illustrates a method of producing electrical power [026], the method comprising: creating [002] neutrons [004] via nuclear reactions [102], said neutrons [004] carrying neutron kinetic energy; moderating [010] said neutrons [004] to thermal energies to produce moderated neutrons, converting the neutron kinetic energy into heat, and transmitting [014] said heat to a heat exchanger [118]; creating ions [006] via the nuclear reactions [102], stopping [012] the ions [006] to produce heat, and transmitting [014] to said heat exchanger [118] the heat generated by the stopping [012] of the ions [006]; capturing [016] said moderated neutrons with sulfur atoms [030] to produce heat [116], and transmitting [014] to said heat exchanger [118] energy released by the capturing [016] of said moderated neutrons; transmitting energy from decaying radioisotopes [106] created by the capturing [016] of said moderated neutrons to said heat exchanger [118]; heat exchanging [018] at least some of each said heat and energy in said heat exchanger [118] by converting water [022] into steam [020]; and generating [028] electrical power [026] with said steam [020].

[0063] Figures 15 and 16 illustrates an apparatus to convert energy from nuclear reactions [102] into electrical power, the apparatus including; one or more regions in which nuclear reactions occur and thereby create [002] neutrons [004], ions [006], and electromagnetic radiation [008]; one or more degraders [112], surrounding said one or more regions, that stop [012] the ions [006] and absorbs the electromagnetic radiation [008] emanating from said one or more regions and convert substantially all kinetic energy of the ions [006], and substantially all of the electromagnetic radiation [008], into heat [116]; one or more moderators [110], surrounding said one or more degraders [112], that slow down neutrons [004] emanating from said one or more regions, and that pass

through said one or more degraders [112], that convert substantially all kinetic energy of said neutrons [004] into heat [116]; a plurality of sulfur atoms [030], within said one or more moderators [110], that capture [016] neutrons [004] slowed down in said one or more moderators [110] and that convert energy released by said capture of said neutrons [004] into heat [116]; wherein said one or more moderators [110] is configured to absorb the electromagnetic radiation [008] and absorb heat [116] generated by radioactive decay [074] of said sulfur atoms [030]; one or more heat exchangers [118], in thermal communication [014] with said one or more moderators [110], water [022] flowing through said one or more heat exchangers [118] to produce steam [020]; one or more converters [124], through which said steam [020] flows, adapted to convert [024] thermal energy into another form of energy; one or more couplers [130], connected to said one or more converters [124]; and one or more generators [128], that receive said energy converted [024] in said one or more converters [124] via said one or more couplers [130], and thereby generate [028] electrical power [026].

[0064] Another embodiment is an apparatus to convert energy from nuclear reactions [102] into electrical power [026], the apparatus including: one or more regions in which nuclear reactions [102] occur; one or more degraders [112] that stop ions [006] emanating from said one or more regions by transforming substantially all kinetic energy of said ions [006] into heat [116]; one or more moderators [110] that slow down neutrons [004] emanating from said one or more regions by converting substantially all kinetic energy of said neutrons [004] into heat [116]; a plurality of sulfur atoms [030] that capture neutrons [004] slowed down in said one or more moderators [110] and that convert energy released by said capture of neutrons [004] into heat [116]; one or more

heat exchangers [118] in thermal communication [014] with said one or more degraders [112], said one or more moderators [110], and said sulfur atoms [030], wherein each said heat exchanger [118] is positioned to absorb electromagnetic radiation [008] emanating from said one or more regions; and positioned to absorb electromagnetic radiation [008] and heat [1116] generated by radioactive decay of said sulfur atoms [030]; water [022] flowing through said heat exchanger [118] to produce steam [020]; one or more converters [124], through which said steam [020] flows, and adapted to convert [024] thermal energy into another form of energy; one or more couplers [130] connected to said one or more converters [124]; and one or more generators [128] that receive said energy converted in said one or more converters [124] via said one or more couplers [130] and produce electrical power [026] therefrom.

[0065] In one embodiment of the above apparatus, the said nuclear reactions [102] include nuclear fission [070] reactions. In another embodiment of the above apparatus, the said nuclear reactions [102] include nuclear fusion [072] reactions. Specifically, one embodiment of these nuclear fusion [072] reactions include the fusion of deuterium nuclei [062] with other deuterium nuclei [062]. In another embodiment of the above apparatus, the said nuclear reactions [102] include radioactive decay [074] of one or more isotopes. In another embodiment of the above apparatus, the said nuclear reactions [102] include antimatter annihilation reactions [098]. Specifically, one embodiment of these antimatter annihilation reactions [098] is the annihilation of antiprotons on uranium nuclei. In another embodiment of the above apparatus, the said nuclear reactions [102] include reactions [076] caused by bombarding atoms with

energetic particles such as the protons in the (p,n) reactions [078] or energetic photons [008] in the (g,n) reactions [086].

[0066] In one embodiment of the above apparatus, the said one or more degraders [112] also absorb electromagnetic radiation [008] emanating from said one or more regions. Such electromagnetic radiation [008] can include photons, which those of ordinary skill in the art can be called x-rays or gamma-rays [058]. In one embodiment of the above apparatus, the said sulfur atoms [030] include the isotope sulfur-32 [032], sulfur-33 [033], sulfur-34 [034], or sulfur-36 [036]. In another embodiment of the above apparatus, the said sulfur atoms [030] consisting essentially of the isotope sulfur-32 [032], sulfur-33 [033], sulfur-34 [034], and sulfur-36 [036] atoms.

B. Deuterium-Deuterium Fusion

[0067] One teaching embodiment for teaching broader concepts is directed to the nuclear reaction [102] of deuterium-deuterium (DD) fusion, a reaction in which neutrons [004] are created at much lower kinetic energy than other types of neutronic fusion reactions, such as deuterium-tritium (DT) reactions. DD fusion is employed herein as a prophetic teaching, recognizing that materials other than deuterium can be fused consistent with the prophetic teaching by this example.

[0068] One embodiment for net electrical power generation [028] utilizing nuclear fusion [072] is to induce fusion events by colliding a beam of deuterons [026] (bare deuterium nuclei) with another beam of deuterons [026]. In other words, nuclear fusion reactions [072] comprise fusion of deuterium nuclei with other deuterium nuclei. Bare nuclei are atoms that have had all of their orbiting electrons [054] stripped away. In one

embodiment, the kinetic energy of the two deuteron [062] beams are substantially equal, meaning that the difference between the average kinetic energies of the two deuteron [062] beams is comparable or smaller than the spread of kinetic energies of the individual deuterons [062] within the two said beams.

[0069] When the two beams of deuterons [062] collide with equal kinetic energy, the collisions are said to occur in the center-of-mass frame. Another term employed by those of normal skill in physics is center-of-momentum frame. The probability of deuterons [062] in opposing beams colliding with sufficient energy to induce nuclear fusion [072] is quantified by cross section. There are two fusion cross sections (or fusion channels) associated with DD fusion. In the first channel the deuterons merge to form the nuclear isotope helium-3 [064] plus a neutron [004]. Because the combined mass of the helium-3 nucleus [064] and neutron [004] is less than the mass of two deuterons [062], the helium-3 nucleus [064] and neutron [004] are each created [002] with accompanying kinetic energy. This mass difference between the initial and final states, along with the principles of conservation of momentum and conservation of energy dictate that if fusion could occur with deuterons [062] at rest, the kinetic energies of the helium-3 nuclei [064] and neutron [004] would be 0.082 MeV and 2.45 MeV respectively.

[0070] Because both deuterons possess positive electrical charges, they repel one another. To induce nuclear fusion [072] it is necessary to bring the two deuterons [062] close together. This proximity is achieved by accelerating the deuterons [062] to a sufficiently large kinetic energy. The fusion cross section for this neutronic channel is plotted as a function of deuteron kinetic energy in the center-of-mass frame in Figure 11. Note that the cross section increases with kinetic energy up to a maximum of

approximately 0.1 barns. A barn is a convenient unit of cross section employed by physicists, equivalent to 10^{-28} m^2 .

[0071] The second DD fusion channel is aneutronic. In this second channel the deuterons merge to form the nuclear isotope hydrogen-3 (tritium) [063] plus a proton (hydrogen-1) [061]. Because the combined mass of the hydrogen-3 nucleus [063] and proton [061] is less than the mass of two deuterons [062], the hydrogen-3 nucleus [063] and proton [061] are each created [002] with accompanying kinetic energy. This mass difference between the initial and final states, along with the principles of conservation of momentum and conservation of energy dictate that if fusion could occur with deuterons [062] at rest, the kinetic energies of the hydrogen-3 nucleus [063] and proton [061] would be 1.01 MeV and 3.02 MeV respectively. The fusion cross section for this aneutronic channel is plotted as a function of deuteron kinetic energy in the center-of-mass frame in Figure 12. Note that the cross section increases with kinetic energy up to a maximum of approximately 0.1 barns.

[0072] Therefore, in the context of DD nuclear fusion the step of creating [002] consists of (or consists essentially of) neutrons [004] and the ions hydrogen-1 [061], hydrogen-3 [063], and helium-3 [064]. The step of stopping [012] takes place for the ions the ions hydrogen-1 [061], hydrogen-3 [063], and helium-3 [064]. Because both DD fusion channels have approximately the same dependence of cross section on center-of-mass deuteron kinetic energy, the two channels occur with approximately equal probability. For this reason it is noted that the creating [002] of a neutron [004] occurs in approximately half of all DD fusion events.

[0073] In order to achieve breakeven energy production, DD fusion with deuteron [062] kinetic energies as high as 0.5 MeV is an embodiment. One prophetic teaching is for the center-of-mass deuteron [062] kinetic energies at the time of collision to be larger than 0.1 MeV. Other prophetic teachings are for center-of-mass deuteron [062] kinetic energies at the time of collision to be larger than 0.2 MeV, 0.3 MeV, 0.4 MeV, 0.5 MeV, 0.6 MeV, 0.7 MeV, 0.8 MeV, 0.9 MeV, and 1.0 MeV.

[0074] As the kinetic energy of the two beams of deuterons [062] is increased, the kinetic energy of the neutrons [004] also increases due to conservation of energy. Figure 13 contains a plot of the calculated neutron [004] kinetic energy as a function of center-of-mass deuteron [062] kinetic energy. Note that as previously stated, at a deuteron [062] kinetic energy of zero (at rest) the kinetic energy of the neutron [004] is 2.45 MeV. As the deuteron [062] kinetic energy is increased the neutron [004] kinetic energy also increases. At deuteron [062] beam kinetic energies of 0.5 MeV the neutron [004] kinetic energy increases to 3.2 MeV.

C. Sulfur Blanket

[0075] One prophetic teaching of a power plant [200] that houses a generator [128] of electrical power [026] is illustrated in Figure 14. Note that a basic concept for such embodiments is to suspend the ion accelerator [206] within a vacuum vessel wall [204] maintaining a vacuum sufficient to operate said ion accelerator [206]. The vacuum vessel wall [204] is enclosed, at least in part, by a volume of sulfur atoms [030]. This volume is called a sulfur blanket [104]. The vacuum vessel wall [204] can be composed of aluminum, stainless steel, or titanium.

[0076] In one embodiment, the sulfur blanket [104] is in the form of molten sulfur. The heat [116] and electromagnetic radiation [008] from the steps of creating [002], stopping [0012], moderating [010], and capturing [016] is deposited into the molten sulfur. The purpose heat exchanging [018] is to remove this heat [116] from the sulfur blanket [104], boiling liquid water [022] to produce high pressure steam [020]. In one embodiment the molten sulfur [030] within the sulfur blanket [104] undergoes thermal convection, and pipes containing flowing water [022] near the top of the sulfur blanket remove heat [116] from the sulfur blanket [104] and deliver it into the water [022] to produce steam [020]. The high pressure steam [020] is then converted [024] back into water in a process employing a converter [124] and coupler [123] that ultimately delivers the energy into a generator [128] of electrical power [026].

[0077] Figure 15 illustrates a prophetic teaching wherein nuclear reactions [102] take place within a degrader [112]. In an embodiment the degrader [112] is, at least in part, a vacuum vessel wall [204]. The degrader performs, at least in part, the step of stopping [012] ions and converting electromagnetic radiation [008] from the nuclear reactions [102] into heat [116]. Outside of the degrader [112] is a moderator [110] that is, at least in part, composed of sulfur atoms [030]. The heat exchanger [118] is in thermal contact with the sulfur atoms [030]. In one embodiment the heat exchanger [118] is completely within sulfur blanket [104], communicating energy out of the sulfur blanket [104] via water [022] and steam [020] pipes.

[0078] In a prophetic teaching, the utility of a sulfur blanket [104] is demonstrated by considering DD fusion as the nuclear reaction [102]. DD fusion has two equal probability channels, one neutronic and the other aneutronic. The net energy gain from

the neutronic reaction is 0.082 MeV plus 2.45 MeV for a total of 3.27 MeV. The net energy gain from the aneutronic reaction is 1.01 MeV plus 3.02 MeV for a total of 4.03 MeV. Therefore, the average net energy gain for DD fusion reactions is 3.65 MeV.

Table 1: Calculation of sulfur blanket [104] energy release per captured neutron [004].

Absorbing Isotope	Sulfur-32	Sulfur-33	Sulfur-34	Sulfur-36
Natural Abundance	94.99%	0.75%	4.25%	0.01%
Capture Cross Section (barns)	0.518	0.454	0.256	0.236
Relative Capture Probability	0.49204	0.00341	0.01088	0.00002
Absolute Capture Probability	97.17%	0.67%	2.15%	0.00%
Capture Energy Gain (MeV)	8.641	11.417	6.986	4.303
Radioactive Isotope			Sulfur-35	Sulfur-37
Decay Product			Chlorine-35	Chlorine-37
Decay Energy Release (MeV)			0.167	4.865
Total Energy Release (MeV)	8.641	11.417	7.153	9.169
Weighted Release (MeV)	8.397	0.077	0.154	0.000
Release per Neutron (MeV)				8.628

[0079] Table 1 contains the input and calculated parameters that determine the energy release per captured neutron [004] in a sulfur blanket [104]. The four columns of values contain the calculations parameters associated with reactions illustrated in Figures 5, 6, 7, and 8. The top two parameter values are drawn from the information presented in Figure 3. The relative capture probability is calculated by multiplying the isotope natural abundance by the (n,g) [088] capture cross section. The absolute capture probability is the relative capture probability divided by the sum of all relative capture probabilities across the four table columns. The absolute capture probability is the probability of a capture neutron being captured by that particular isotope assuming natural sulfur atoms [030] abundances. The capture energy gain is simply the mass difference between the final and initial states of each reaction.

[0080] As indicated in Figures 7 and 8, the beta decay of radioactive isotopes sulfur-35 [035] and sulfur-37 [037] into the stable isotopes chlorine-35 [040] and chlorine-37 [042] respectively also contribute to the amount of electromagnetic radiation [008] and hence heat [116] produced within the sulfur blanket [104]. The two right columns contain parameter values calculated for those radioisotope decay [074] reactions.

[0081] In an embodiment wherein the two beams of deuterons [062] collide with equal energies of 0.5 MeV, the data in Figure 13 indicates that neutrons [004] enter the sulfur blanket [104] with kinetic energies as high as 3.2 MeV. According to the data presented in Figures 9 and 10, the cross section for such neutrons [004] captured on sulfur-32 atoms [032] due to the nucleon exchange reactions [076] (n,a) [090] and (n,p) [092] can be as high as 0.16 barns, triple the (n,g) [088] radiative capture cross section of 0.518 barns. Table 2 contains the input and calculated parameters that determine the energy release per captured neutron [004] due to these two nucleon exchange reactions [076].

Table 2: Calculation of sulfur blanket [104] energy release per captured neutron [004] due to nucleon exchange reactions [076] with sulfur-32 [032] atoms.

Decay Product Isotope	Silicon-29	Phosphorus-32
Nucleon Exchange Reaction	(n,a)	(n,p)
Capture Energy Release (MeV)	2.548	0.093
Radioactive Decay Channel	Stable	Beta Decay
Decay Half Life (days)		14.3
Radioactive Decay Product		Sulfur-32
Decay Energy Release (MeV)		1.711
Total Energy Release (MeV)	2.548	1.804
Release per Neutron (MeV)		4.352

[0082] Note that the energy gain from the nucleon exchange reactions [076] in

Table 2 produce about half of the radiative capture (n,g) [088] reaction for sulfur-32 [032] listed in Table 1 and Figure 5. Because the neutrons [004] moderate [010] very quickly while traveling through sulfur atoms [030], the overall probability of these nucleon exchange reactions [076] is relatively low.

D. Electrical Power Generation

[0083] The step of electricity generating [028] in Figure 1 is taught in Figures 14, 15, and 16 as the combination of a converter [124], a coupler [130], and a generator [128]. In one embodiment illustrated in Figure 17, the converter [124] is a turbine [134] that converts thermal energy in the steam into rotational motion of a drive shaft [136] which acts as a coupler [130]. The drive shaft [136] turns a generator [128] to produce electrical power [026]. There are many other types of converters [124], couplers [130], and electrical generators. In one alternative embodiment, the converter [124] is a thermoelectric element utilizing the Peltier-Seebeck effect to convert heat [116] into DC electrical power, the coupler [130] are wires carrying this electrical power, and the generator [128] is a DC to AC transformer circuit.

[0084] In order to generate power, it is necessary to first remove the heat from the sulfur atoms [030]. Figure 18 is an illustration of a sulfur containment vessel [140] surrounded by thermal insulation [138] in order to assure that substantially all of the heat [116] absorbed within the vessel is removed by a heat exchanger [118] that carries water [022] and steam [020] in pipes [132] to the converter [124]. The nuclear reactions [102] occur within a vacuum vessel wall [204] that is immersed within the sulfur atoms [030] within the sulfur containment vessel [140].

[0085] In one embodiment the heat exchanger [118] resides near the top of the sulfur containment vessel [140] where convection currents within the molten sulfur maintain maximum sulfur temperatures in the area around the heat exchanger [118]. In another embodiment the sulfur containment vessel [140] exterior walls (walls in thermal communication with the thermal insulation [138]) are thick enough to absorb electromagnetic radiation [008] that might otherwise escape from the sulfur atoms [030].

E. Sulfur-Sodium Battery

[0086] There is enough sunlight and wind power on the planet to supply all of the energy needs of the world. The problem is that the availability of harvested power does not necessarily coincide with the instantaneous energy demands of consumers. An inexpensive and compact means of storing electrical power is one of the greatest challenges facing humanity.

[0087] Commercial nuclear fission reactors are capable of generating a steady electrical power level, but are not capable of tracking the minute-by-minute demand changes exhibited on electrical grids. A means of steadily charging and then quickly discharging stored energy as demand requires would also provide significant advantages.

[0088] DD nuclear fusion [072] coupled to a sulfur blanket [104] can provide steady electrical power [026] similar to that of a commercial nuclear fission reactor. The apparatus in Figure 14 can be configured to follow hourly demand fluctuations, but cannot source high instantaneous peak electrical powers [026] for such surge loads as starting a large electric motor.

[0089] As illustrated in Figure 19, one embodiment is to place an electrical battery [120] between the generator [128] and an electrical load [158] in order to provide such surge capacity. Another aspect of this embodiment is to store electrical power [026] from external power sources [160] such as wind turbines and solar arrays.

[0090] One type of electrical battery [120] under study for many decades is the sulfur-sodium battery [156]. In an embodiment, the power plant [200] of Figure 14, wherein the sulfur blanket [104] is constructed in a manner similar to the embodiment illustrated in Figure 18, is modified to simultaneously produce a sulfur-sodium battery [156]. An embodiment wherein a sulfur blanket [104] also functions as a sulfur-sodium battery [156] is illustrated in Figure 20.

[0091] A reservoir of molten sodium atoms [038] is separated from a molten sulfur-sodium mixture [150] by a solid electrolyte [146]. In an embodiment this solid electrolyte [146] is composed of the ceramic b''-alumina (BASE). The molten sodium atoms [038] serves as the anode [142] and the molten sulfur-sodium mixture [150] serves as the cathode [144]. The negative terminal [154] of this sulfur-sodium battery [156] is in electrical contact with the molten sodium [038] while the positive terminal [152] of the battery [156] is in electrical communication with the molten sulfur-sodium mixture [150]. In this scenario the sulfur containment vessel [140] walls are not in electrical communication with either the molten sodium [038] or sulfur-sodium mixture [150] or both. The negative terminal [154] and positive terminal [152] pass through the sulfur containment vessel [140] wall utilizing electrical insulators [148]. There can be more than one reservoir of sodium atoms [038], solid electrolyte [148], negative terminal [154], and/or positive terminal [152].

[0092] This embodiment can, in some cases, be advantageous over past embodiments of a sulfur-sodium battery [156] because of the elevated temperature required to operate such a battery [156] and the additional cost and complexity of providing the required heat [116] and thermal insulation [138] as compared to other battery [120] technologies. Because of the existence of the sulfur blanket [104] as a means of increasing the electrical power [026] output of a nuclear fusion [072] power plant [200], all of these additional costs and complexities already existed.

[0093] When the sulfur-sodium battery [156] is fully charged, substantially all of the sodium atoms [038] are in the sodium reservoir. As plotted in Figure 21, at this time the voltage across the positive terminal [152] and negative terminal [154] is 2.076 Volts at a battery temperature of 350°C. As the sulfur-sodium battery [156] discharges electrical current across the terminals [152,154] sodium ions pass through the solid electrolyte [146] and preferentially form the compound Na_2S_5 . Starting near the solid electrolyte [146] this compound gradually forms in progressively large volume into the sulfur-sodium mixture [150] volume. When the percentage of sulfur atoms [030] in the sulfur-sodium mixture [150] reaches approximately 78%, the sulfur-sodium battery [156] voltage begins to decrease as first Na_2S_4 , then Na_2S_3 , and then Na_2S_2 begin to form. At a concentration of 60% sulfur atoms [030] in the sulfur-sodium mixture [150] substantially all of the sulfur-sodium mixture [150] is composed of Na_2S_2 and the sulfur-sodium battery [156] voltage becomes a constant 1.78 Volts.

[0094] The theoretical capacity of a sulfur-sodium battery [156] is 760 Watt-hours per kilogram, but past practical performance has been limited to 110-150 Watt-hours/kg. In an exemplary teaching example, a sulfur blanket that is 2 m in radius and 4 m long

would have a mass of approximately 90,000 kg. Such a sulfur-sodium battery [156] has an expected demonstrated electrical energy storage capacity of 12,000 kW-hrs. This is enough stored electrical power [026] to supply electricity to 500 average homes for a day.

[0095] In the sulfur blanket [104] energetic neutrons [004] are moderated as they travel through the volume of the sulfur blanket [104]. In an embodiment wherein the sulfur blanket [104] also functions as a sulfur-sodium battery [156], some of the sodium atoms [038] are positioned to also moderate [010] and capture [016] neutrons [004]. In other words, the volume of sulfur atoms [030] comprises sodium atoms [038]. Because naturally occurring sodium [038] is composed of only sodium-23 [162] which has a mass lower than the dominant naturally occurring sulfur isotope sulfur-32 [032], the sodium atoms [038] improve the moderating [010] function of the sulfur blanket [104]. Figure 22 is an illustration of the neutron [004] capture [016] and subsequent heat [116] released by sodium-23 [162]. When sodium-23 [162] captures [016] a neutron [004] it becomes the radioactive isotope sodium-24 [164], which undergoes beta-decay with a half-life of 15 hours to become magnesium-24. The total sodium [038] energy release of 12.47 MeV per captured neutron is significantly higher than the 8.68 MeV per neutron released on average by sulfur atoms [030]. The sodium atoms [038] improve the capturing [016] function of the sulfur blanket [104].

F. High Neutron Cross Section Additives

[0096] There are embodiments wherein other elements are added to the sulfur atoms [030] in the sulfur blanket [104] to improve the performance, size, capital cost, and weight of a power plant [200]. There are dozens of such elements that can be utilized

such a way, several that are discussed below exemplifying embodiments that serve specific applications or commercial markets.

[0097] As summarized in Figure 3, the peak thermal neutron capture cross section for sulfur [030] is 0.518 barns. There are embodiments wherein a much higher capture cross section is desired in order to reduce the radius (and hence weight, volume, and cost) of a power plant [200]. Otherwise, too many neutrons [004] pass through the sulfur containment vessel [140] walls, giving up their initial kinetic energy but not inducing the energy release that comes with capture [016].

[0098] In one embodiment, mercury-199 atoms added to the sulfur blanket [104] in the form of mercury sulfide, otherwise known as cinnabar or vermilion when accompanied by the other mercury isotopes found in naturally occurring mercury. Mercury-199 atoms have a thermal neutron capture cross section of 2150 barns, approximately 4000 greater than that of sulfur [030]. For unenriched mercury, doubling the effective capture cross section of the sulfur blanket [104] requires the addition of approximately 0.3% mercury atoms by moles. Because the natural abundance of mercury-199 atoms is 16.87%, 0.3% addition of unenriched mercury atoms would increase neutron capture performance by an order of magnitude. The disadvantage of the use of mercury-199 is the reduction in the amount of energy liberated by neutron capture [016]. Instead of producing 8.63 MeV per neutron with sulfur [030], mercury-199 produces 7.95 MeV. An attractive feature of capturing [016] neutrons [004] with mercury-199 is that mercury-199 typically emits much lower energy gamma-rays [058] which are absorbed by the sulfur blanket [104] in a much shorter distance. This also reduces the

size of the sulfur blanket [104]. The mercury atoms are positioned to also moderate [010] neutrons [004].

[0099] Other embodiments that employ the addition (either in enriched or unenriched form) of alternative isotopes in the sulfur blanket [104] exist. These embodiments include the use of the isotopes beryllium-7, lithium-6, boron-10, sodium-22, chlorine-35 [040], bromine-79, tantalum-179, iodine-125, and isotopes of xenon, cadmium, hafnium, gadolinium, cobalt, samarium, titanium, dysprosium, erbium, europium, molybdenum and ytterbium.

[0100] There are specific applications wherein much higher sulfur blanket [104] energy gains are useful, despite severe difficulties in the areas of safety, radioactive waste, national security, and other non-technical considerations. In such applications an embodiment is the addition of uranium-235 to the sulfur blanket [104]. The uranium in spent commercial fuel rods are composed primarily of uranium-238 (depleted uranium) and uranium-235 (fissile uranium). The fissile uranium in these fuel rods are typically enriched to approximately 3% abundance, and the spent fuel rods have lost typically 6% of that fissile uranium population before they are removed and stored. There is currently a significant issue around the world with the indefinite storage of such spent fuel rods. When such spent fuel rods are utilized in a sulfur blanket [104], the level of fissile uranium depletion is not significant until over 90% of the fissile uranium is consumed. Therefore, such an embodiment provides an alternative destination for such spent fuel rods, and further, the storage of such fuel rods can be alleviated.

[0101] There are alternative embodiments in which the addition of enriched uranium -235 up to 80% is desired. In one such embodiment the enriched fissile uranium is added in the form of uranium sulfide.

[0102] The dominant thermal neutron capture reaction for uranium-235 induces nuclear fission [070] and has a cross section of 583 barns. This is 1000 time greater than the capture cross section of sulfur [030]. Adding uranium-235 to a sulfur blanket [104] dramatically increases energy release. When uranium-235 undergoes fission it releases roughly 1 MeV per amu, or 235 MeV. Most of this energy is in the form of fission daughter kinetic energy, which is stopped [012] by the sulfur [030] and other surrounding material in a distance short compared to the dimensions of the sulfur blanket [104]. This represents an energy release approximately 33 times larger than that of sulfur [030] upon the capture [016] of a neutron [004]. The other aspect of such embodiments is a greater breakeven margin for such a power plant [200].

G. Statement of Scope

[0103] In sum, it is important to recognize that this disclosure has been written as a thorough teaching rather than as a narrow dictate or disclaimer. Reference throughout this specification to "one embodiment", "an embodiment", or "a specific embodiment" means that a particular feature, structure, or characteristic described in connection with the embodiment is included in at least one embodiment and not necessarily in all embodiments. Thus, respective appearances of the phrases "in one embodiment", "in an embodiment", or "in a specific embodiment" in various places throughout this specification are not necessarily referring to the same embodiment. Furthermore, the particular

features, structures, or characteristics of any specific embodiment may be combined in any suitable manner with one or more other embodiments. It is to be understood that other variations and modifications of the embodiments described and illustrated herein are possible in light of the teachings herein and are to be considered as part of the spirit and scope of the present subject matter.

[0104] It will also be appreciated that one or more of the elements depicted in the drawings/figures can also be implemented in a more separated or integrated manner, or even removed or rendered as inoperable in certain cases, as is useful in accordance with a particular application. Additionally, any signal arrows in the drawings/Figures should be considered only as exemplary, and not limiting, unless otherwise specifically noted. Furthermore, the term "or" as used herein is generally intended to mean "and/or" unless otherwise indicated. Combinations of components or steps will also be considered as being noted, where terminology is foreseen as rendering the ability to separate or combine is unclear.

[0105] As used in the description herein and throughout the claims that follow, "a", "an", and "the" includes plural references unless the context clearly dictates otherwise. Also, as used in the description herein and throughout the claims that follow, the meaning of "in" includes "in" and "on" unless the context clearly dictates otherwise. Variation from amounts specified in this teaching can be "about" or "substantially," so as to accommodate tolerance for such as acceptable manufacturing tolerances.

[0106] The foregoing description of illustrated embodiments, including what is described in the Abstract and the Modes, and all disclosure and the implicated industrial applicability, are not intended to be exhaustive or to limit the subject matter to the precise

forms disclosed herein. While specific embodiments of, and examples for, the subject matter are described herein for teaching-by-illustration purposes only, various equivalent modifications are possible within the spirit and scope of the present subject matter, as those skilled in the relevant art will recognize and appreciate. As indicated, these modifications may be made in light of the foregoing description of illustrated embodiments and are to be included, again, within the true spirit and scope of the subject matter disclosed herein.

VII. Claims

1. A method of producing electrical power, the method comprising:
creating neutrons via nuclear reactions, said neutrons carrying neutron kinetic energy;
moderating said neutrons to thermal energies to produce moderated neutrons, converting the neutron kinetic energy into heat, and transmitting said heat to a heat exchanger;
creating ions via the nuclear reactions, stopping the ions to produce heat, and transmitting to said heat exchanger the heat generated by the stopping of the ions;
capturing said moderated neutrons with sulfur atoms to produce heat, and transmitting to said heat exchanger energy released by the capturing of said moderated neutrons;
transmitting energy from decaying radioisotopes created by the capturing of said moderated neutrons to said heat exchanger;
heat exchanging at least some of each said heat and energy in said heat exchanger by converting water into steam; and
generating electrical power with said steam.
2. The method of claim 1, wherein said nuclear reactions includes nuclear fission reactions.
3. The method of claim 1, wherein said nuclear reactions include nuclear fusion reactions.

4. The method of claim 3, wherein said nuclear fusion reactions comprise fusion of deuterium nuclei with other deuterium nuclei.
5. The method of claim 1, wherein said nuclear reactions include radioactive decay of one or more isotopes.
6. The method of claim 1, wherein said nuclear reactions include antimatter annihilation reactions.
7. The method of claim 1, wherein said nuclear reactions include reactions caused by bombarding atoms with energetic particles.
8. The method of claim 1, wherein said nuclear reactions include nucleon exchange reactions.
9. The method of claim 1, wherein said nuclear reactions include reactions caused by energetic photons.
10. The method of claim 1, wherein said moderating is performed by said sulfur atoms.
11. The method of claim 1, wherein said generating produces more electrical power than the total amount of electricity required to perform the steps of creating,

moderating, stopping, transmitting, capturing, heat exchanging, converting, and generating.

12. The method of claim 1, wherein said capturing is performed with sulfur atoms comprising isotope sulfur-32 atoms.

13. The method of claim 1, wherein said capturing is performed with sulfur atoms comprising isotope sulfur-33 atoms.

14. The method of claim 1, wherein said capturing is performed with sulfur atoms comprising isotope sulfur-34 atoms.

15. The method of claim 1, wherein said capturing is performed with sulfur atoms comprising isotope sulfur-36 atoms.

16. The method of claim 1, wherein said capturing is performed with sulfur atoms consisting essentially of the isotopes sulfur-32, sulfur-33, sulfur-34, and sulfur-36 atoms.

17. The method of claim 1, wherein said moderating is also performed with sodium atoms.

18. The method of claim 1, wherein said capturing is also performed with sodium atoms.

19. The method of claim 1, wherein said moderating is also performed with mercury atoms.

20. The method of claim 1, wherein said capturing is also performed with mercury atoms.

21. An apparatus to convert energy from nuclear reactions into electrical power, the apparatus including:

one or more regions in which nuclear reactions occur;

one or more degraders that stop ions emanating from said one or more regions by transforming substantially all kinetic energy of said ions into heat;

one or more moderators that slow down neutrons emanating from said one or more regions by converting substantially all kinetic energy of said neutrons into heat;

a plurality of sulfur atoms that capture neutrons slowed down in said one or more moderators and that convert energy released by said capture of neutrons into heat;

one or more heat exchangers in thermal communication with said one or more degraders, said one or more moderators, and said sulfur atoms, wherein each said heat exchanger is

positioned to absorb electromagnetic radiation emanating from said one or more regions; and

positioned to absorb electromagnetic radiation and heat generated by radioactive decay of said sulfur atoms;

water flowing through said heat exchanger to produce steam;

one or more converters, through which said steam flows, and adapted to convert thermal energy into another form of energy;

one or more couplers connected to said one or more converters; and

one or more generators that receive said energy converted in said one or more converters via said one or more couplers and produce electrical power therefrom.

22. The apparatus of claim 21, wherein said nuclear reactions comprise nuclear fission reactions.

23. The apparatus of claim 21, wherein said nuclear reactions comprise nuclear fusion reactions.

24. The apparatus of claim 23, wherein said nuclear fusion reactions comprise fusion of deuterium nuclei with other deuterium nuclei.

25. The apparatus of claim 21, wherein said nuclear reactions comprise radioactive decay of one or more isotopes.

26. The apparatus of claim 21, wherein said nuclear reactions comprise antimatter annihilation reactions.

27. The apparatus of claim 21, wherein said nuclear reactions comprise reactions caused by bombarding atoms with energetic particles.

28. The apparatus of claim 21, wherein said one or more degraders also absorb electromagnetic radiation emanating from said one or more regions.

29. The apparatus of claim 28, wherein said electromagnetic radiation includes electrons.

30. The apparatus of claim 28, wherein said electromagnetic radiation includes positrons.

31. The apparatus of claim 21, wherein said sulfur atoms comprise isotope sulfur-32 atoms.

32. The apparatus of claim 21, wherein said sulfur atoms comprise isotope sulfur-33 atoms.

33. The apparatus of claim 21, wherein said sulfur atoms comprise isotope sulfur-34 atoms.

34. The apparatus of claim 21, wherein said sulfur atoms comprise isotope sulfur-36 atoms.

35. The apparatus of claim 21, wherein said sulfur atoms comprise isotopes sulfur-32, sulfur-33, sulfur-34, and sulfur-36 atoms.

36. The apparatus of claim 21, wherein said sulfur atoms comprise sodium atoms.

37. The apparatus of claim 21, wherein said sulfur atoms comprise a quantity of unenriched mercury atoms.

38. The apparatus of claim 21, wherein said sulfur atoms comprise a quantity of mercury atoms wherein the concentration of mercury-199 atoms has been enriched.

39. An apparatus to convert energy from nuclear reactions into electrical power, the apparatus including;

one or more regions in which nuclear reactions occur and thereby create neutrons, ions, and electromagnetic radiation;

one or more degraders, surrounding said one or more regions, that stop the ions and absorbs the electromagnetic radiation emanating from said one or more regions and convert substantially all kinetic energy of the ions, and substantially all of the electromagnetic radiation, into heat;

one or more moderators, surrounding said one or more degraders, that slow down neutrons emanating from said one or more regions, and that pass through said one or more degraders, that convert substantially all kinetic energy of said neutrons into heat;

a plurality of sulfur atoms, within said one or more moderators, that capture neutrons slowed down in said one or more moderators and that convert energy released by said capture of said neutrons into heat;

wherein said one or more moderators is configured to absorb the electromagnetic radiation and absorb heat generated by radioactive decay of said sulfur atoms;

one or more heat exchangers, in thermal communication with said one or more moderators,

water flowing through said one or more heat exchangers to produce steam;

one or more converters, through which said steam flows, adapted to convert thermal energy into another form of energy;

one or more couplers, connected to said one or more converters; and

one or more generators, that receive said energy converted in said one or more converters via said one or more couplers, and thereby generate electrical power.

40. The apparatus of claim 39, wherein said degrader is a vacuum vessel wall separating a vacuum within said one or more regions from said moderator.

41. The apparatus of claim 40, where said vacuum vessel wall is composed of stainless steel.