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(54) Title: SEGMENTED REACTION CHAMBER FOR RADIOISOTOPE PRODUCTION

(57) Abstract: A reactor that is operable to produce an isotope includes a region for containing a controlled nuclear fission reaction, the region segmented into a plurality of independent compartments, each of the compartments for containing a parent material in an aqueous solution that interacts with neutrons to produce the isotope via a fission reaction. Also provided are methods of producing an isotope using the same.

SEGMENTED REACTION CHAMBER FOR RADIOISOTOPE PRODUCTION

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. Provisional Patent Application No. 61/299,258, filed January 28, 2010, and incorporated herein by reference in its entirety.

BACKGROUND

[0002] The invention relates to a device and method for producing isotopes. More particularly, the invention relates to a device and method for producing neutron generated medical isotopes with or without a sub-critical reactor and low enriched uranium (LEU).

[0003] Radioisotopes are commonly used by doctors in nuclear medicine. The most commonly used of these isotopes is Mo-99. Much of the supply of Mo-99 is developed fro highly enriched uranium (HEU). The HEU employed is sufficiently enriched to make nucl weapons. HEU is exported from the United States to facilitate the production of the needec 99. It is desirable to produce the needed Mo-99 without the use of HEU.

SUMMARY

[0004] In certain embodiments, provided is a reactor operable to produce an isotope, th reactor comprising a region for containing a controlled nuclear fission reaction, the region segmented into a plurality of independent compartments, each of the compartments for containing a parent material in an aqueous solution that interacts with neutrons to produce t isotope via a fission reaction. The region may be segmented into *n* independent compartmc wherein *n* is an integer greater than or equal to 2.

[0005] In other embodiments, provided is a reactor operable to produce an isotope, the reactor comprising a fusion portion including a target path disposed within a target chambe substantially encircles a space, the fusion portion operable to produce a neutron flux within target chamber; and a fission portion for containing a controlled nuclear fission reaction, th fission portion segmented into a plurality of independent compartments and positioned witl

space for containing a parent material in an aqueous solution that reacts with a portion of th neutron flux to produce the isotope during a fission reaction.

[0006] In other embodiments, provided is a method of producing an isotope, the metho comprising: positioning a parent material in an aqueous solution within a region for contair controlled nuclear reaction, the region segmented into a plurality of independent compartm reacting, in at least one of the compartments over a time period *y*, neutrons with the parent material to produce the isotope; and extracting the aqueous solution comprising the isotope the compartment.

[0007] Other aspects and embodiments of the invention will become apparent by consideration of the detailed description and accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] The invention may be better understood and appreciated by reference to the detc description of specific embodiments presented herein in conjunction with the accompanyin drawings of which:

[0009] FIG. 1 is a first view of the generator with magnetic target chamber.

[0010] FIG. 2 is a second view of the generator with magnetic target chamber.

[0011] FIG. 3 is a first view of the generator with linear target chamber.

[0012] FIG. 4 is a first view of the ion source.

[0013] FIG. 5 is a sectional view of the ion source.

[0014] FIG. 6 is a first view of the accelerator.

[0015] FIG. 7 is a sectional view of the accelerator.

[0016] FIG. 8 is a first view of the differential pumping.

[0017] FIG. 9 is a sectional view of the differential pumping.

[0018] FIG. 10 is a first view of the gas filtration system.

[0019] FIG. 11 is a first view of the magnetic target chamber.

[0020] FIG. 12 is a sectional view of the magnetic target chamber.

[0021] FIG. 13 is a first view of the linear target chamber.

[0022] FIG. 14 is a sectional view of the linear target chamber, showing an exemplary isotope generation system for ^{18}F and ^{13}N production.

[0023] FIG. 15 is a first view of the generator with linear target chamber and synchroni high speed pump.

[0024] FIG. 16 is a sectional view of the synchronized high speed pump in extraction s1 allowing passage of an ion beam.

[0025] FIG. 17 is a sectional view of the synchronized high speed pump in suppression not allowing passage of an ion beam.

[0026] FIG. 18 is a schematic diagram of the generator with linear target chamber and synchronized high speed pump and one embodiment of controller.

[0027] FIG. 19 is a graph of stopping power (keV/μη) versus ion energy (keV) for the stopping power of ^{3}He gas on ^{2}H ions at 10 torr gas pressure and 25°C.

[0028] FIG. 20 is a graph of stopping power (keV/μιη) versus ion energy (keV) for the stopping power of ^{3}He gas on ^{2}H ions at 10 torr gas pressure and 25°C.

[0029] FIG. 21 is a graph of fusion reaction rate (reactions/second) versus ion beam inc energy (keV) for a 100 mA incident ^{2}H beam impacting a ^{3}He target at 10 torr.

[0030] FIG. 22 is a perspective view of a hybrid reactor including a fusion portion and fission portion suited to the production of medical isotopes;

[0031] FIG. 23 is a perspective view of another arrangement of a hybrid reactor includi fusion portion and a fission portion suited to the production of medical isotopes;

[0032] FIG. 24 is a side schematic view of the fission reactor illustrating the various lay material;

[0033] FIG. 25 is a top schematic view of the fission reactor of Fig. 24 illustrating the various layers of material;

[0034] FIG. 26 is a side schematic view of another fission reactor illustrating the variov. layers of material;

[0035] FIG. 27 is a top schematic view of the fission reactor of Fig. 26 illustrating the various layers of material;

[0036] FIG. 28 is a side schematic view of another fission reactor illustrating the variov. layers of material and particularly suited to the formation of Mo-99 from Mo-98; and

[0037] FIG. 29 is a top schematic view of the fission reactor of Fig. 28 illustrating the various layers of material.

[0038] FIG. 30 illustrates the decay of a particularly useful isotope, Mo-99 as created ir day batch process.

[0039] FIG. 31 shows the amount of Mo-99 available during a 5 day batch process wit! segmented reaction chamber in arbitrary units.

[0040] FIG. 32 is a perspective view of a segmented reaction chamber or activation eel

[0041] FIG. 33 is an exploded view of a segmented reaction chamber or activation cell.

[0042] FIG. 34 is a side cross section view of a segmented reaction chamber or activate cell.

[0043] FIG. 35 is a top cross section view of a segmented reaction chamber or activatio cell.

DETAILED DESCRIPTION

Segmented reaction chamber

[0044] Before any embodiments of the invention are explained in detail, it is to be understood that the invention is not limited in its application to the details of construction a arrangement of components set forth in the following description or illustrated in the follow drawings. The invention is capable of other embodiments and of being practiced or of bein carried out in various ways. Also, it is to be understood that the phraseology and terminolo used herein is for the purpose of description and should not be regarded as limiting. The us "including," "comprising," or "having" and variations thereof herein is meant to encompass items listed thereafter and equivalents thereof as well as additional items. Unless specified limited otherwise, the terms "mounted," "connected," "supported," and "coupled" and vari; thereof are used broadly and encompass direct and indirect mountings, connections, suppor and couplings. Further, "connected" and "coupled" are not restricted to physical or mechar connections or couplings.

[0045] Before explaining at least one embodiment, it is to be understood that the invent not limited in its application to the details set forth in the following description as exemplif the Examples. Such description and Examples are not intended to limit the scope of the invention as set forth in the appended claims. The invention is capable of other embodimei of being practiced or carried out in various ways.

[0046] Throughout this disclosure, various aspects of this invention may be presented i1 range format. It should be understood that the description in range format is merely for convenience and brevity, and should not be construed as an inflexible limitation on the sco] the invention. Accordingly, as will be understood by one skilled in the art, for any and all purposes, particularly in terms of providing a written description, all ranges disclosed herei encompass any and all possible subranges and combinations of subranges thereof, as well a integral and fractional numerical values within that range. As only one example, a range oi to 40% can be broken down into ranges of 20% to 32.5% and 32.5% to 40%, 20% to 27.5°/ 27.5% to 40%, etc. Any listed range can be easily recognized as sufficiently describing anc enabling the same range being broken down into at least equal halves, thirds, quarters, fifth

tenths, etc. As a non-limiting example, each range discussed herein can be readily broken d into a lower third, middle third, and upper third, etc. Further, as will also be understood by skilled in the art, all language such as "up to," "at least," "greater than," "less than," "more 1 and the like include the number recited and refer to ranges which can be subsequently brok down into subranges as discussed above. In the same manner, all ratios disclosed herein *ah* include all subratios falling within the broader ratio. These are only examples of what is specifically intended. Further, the phrases "ranging/ranges between" a first indicate numbe a second indicate number and "ranging/ranges from" a first indicate number "to" a second indicate number are used herein interchangeably.

[0047] Terms such as "substantially," "about," "approximately" and the like are used h to describe features and characteristics that can deviate from an ideal or described conditioi without having a significant impact on the performance of the device. For example, "substantially parallel" could be used to describe features that are desirably parallel but thai could deviate by an angle of up to 20 degrees so long as the deviation does not have a signi adverse effect on the device. Similarly, "substantially linear" could include a slightly curve path or a path that winds slightly so long as the deviation from linearity does not significam adversely effect the performance of the device.

[0048] Provided is a segmented reaction chamber for a reactor operable to produce an isotope. The reactor may comprise a region for containing a controlled nuclear fission reac the region segmented into a plurality of independent compartments. Each of the compartm may contain a parent material in an aqueous solution. The parent material may interact wit neutrons to produce an isotope via a fission reaction. The isotope produced may comprise ; least one of the isotopes including, but not limited to, Mo-99, 1-131, 1-125, Xe-133, Cs-137 60, Y-90, Sr-90, and Sr-89.

[0049] In certain embodiments, a reaction chamber 405 comprises an activation cell 4 1 may be segmented, forming a segmented activation cell 600, as shown in Figs. 32-35. It is envisioned that the principles of a segmented approach for a subcritical reactor for isotope production is also applicable to any aqueous reactor system.

[0050] In certain embodiments, the invention provides an aqueous reaction chamber (A filled with an aqueous solution, such as one found in a critical or subcritical aqueous isotop production system. The activation cell may be segmented into multiple pieces or a plurality compartments by dividers 605. The segmented activation cell 600 may be divided or segm into *n* independent compartments by dividers 605. The independent compartments *n* may b integer from 2 to 10, from 3 to 8, or from 4 to 6. The compartments may be assembled or positioned proximate to the target chamber in any suitable orientation. For example, the compartments may be radially symmetrically disposed about a central axis of the activation In certain embodiments, the compartments may be disposed linearly along a central axis, disposed concentrically about a central axis, or disposed radially asymmetrically about a ce axis of the activation cell. The compartments of the activation cell may independently coni parent material for interacting with the protons or neutrons generated in the target chamber produce an isotope. 1-3 solution extraction/fill lines 610 may connect each chamber to an exterior reservoir (not shown) to transport parent material and isotope. A plurality of water cooling pipes 615 may flow fluid to supply a cooling jacket 620 proximal to or surrounding segmented activation cell 600. A lid 625 may cap the segmented activation cell 600 to reta fluid materials within.

[0051] A segmented activation cell may allow for the extraction of isotopes at different periods of time. Separations in the reaction region may also be used to control instabilities might develop in the solution. In some embodiments, the parent material in at least one compartment may be reacted over a time period *y* with at least a portion of the neutrons or protons generated in the target chamber. The time period *y* may be about the half life of the isotope produced. For example, the half life of Mo-99 is about 66 h. As such, the time per may be about 60 h to about 70 h. The time period *y* may be at least about at least about 12 least about 18 h, 24 h, at least about 36 h, at least about 48 h, at least about 72 h, or at least 96 h. The time period *y* may be less than about 2 weeks, less than about 1.5 weeks, less th about 1 week, less than about 5 days, less than about 100 h, less than about 96 h, less than 72 h, or less than about 48 h. The time period *y* may be about 12 h to about 2 weeks, about to about 1 week, about 36 h to about 96 h, or about 48 h to about 80 h.

[0052] Existing systems describing the production of medical isotopes in ARCs may ut single volume to contain the aqueous solution. In such systems, the ARC may be operated periods of minutes to months to produce various isotopes. When the device has operated fc sufficient time to produce the desired quantity of an isotope, the fluid may be drained and tl isotope separated. Suitably, optimal production will have occurred after a period of time ec approximately one half-life of the material being created.

[0053] Many markets for radioisotopes require a continuous supply of material; oversuj may not be sold and undersupply may result in lost revenue. If an oversupply is generated in a period of time and cannot be sold, it may decay away in storage. In order to supply coı market demand, an excess of material may be produced early in the cycle, so that there may ample supply while waiting for the next batch.

[0054] Figure 30 illustrates the decay of a particularly useful isotope, Mo-99 as created day batch process. The dashed line represents hypothetical demand (x-axis reads days, y ax reads supply units). In this system, it may take 5 days to produce 10 units of Mo-99. Once isotope is extracted, irradiation may start on the next 5 day batch. This may result in a tremendous variation in the amount of material available. Due to requirements for high pui isotopes, the ARC may irradiate its solution to near saturation, so shorter batches may not b performed to distribute the production of isotopes over time.

[0055] In other embodiments, the ARC may be cut into physically different sections wi the same device. If a device has x regions in it, the entire system could be irradiated to satu (which occurs at time y), and then one cell may have its isotopes extracted after a period of proportional to the saturation time. Then, every period of time that passes equal to y/x, ano cell may have its isotopes extracted. As soon as isotope extraction is performed on any giv cell, the irradiation process on that cell may begin anew. As such, each cell may always be irradiated to nearly saturation before it is empty.

[0056] Again, considering the case of Mo-99, it may be desirable to have approximatel; day irradiation period. In this case, the ARC may be split into 5 cells. Every day in the 5 d period, 2 units of Mo-99 may be extracted. This may lead to a more uniform supply of the radioisotope, as shown in Fig. 31. Fig. 31 shows the amount of Mo-99 available during a 5

batch process with a segmented reaction chamber in arbitrary units. The dashed line repres hypothetical demand (x-axis reads days, y axis reads supply units).

[0057] In Fig. 30, shown is the hypothetical ARC described may create an oversupply e in the 5 day period, and may not be able to meet demand later. As shown in Fig. 31, the sa ARC, segmented into 5 pieces, may continuously meet demand, which may result in less w product and eliminate the shortage previously experienced.

[0058] A similar effect may be created by producing multiple smaller units, but there n significantly greater expense involved in doing so. The segmented design may offer almos additional cost, but may improve performance dramatically.

[0059] In addition to the utility for smoothing supply to meet demand, the segmented aqueous system may serve to disrupt instabilities that may arise in critical or near critical aqueous systems. These instabilities may lead to control problems that may result in a failu properly operate. Previous experiments with critical aqueous reactors resulted in instabiliti that led to control problems as well as destructive behaviors that caused radiological spills. These instabilities were the result of the solution moving around in unpredictable ways, in s cases forming vortices in the solution.

[0060] The addition of segmentation to the reaction chamber may minimize the extent 1 which these instabilities can propagate, which may greatly increase the controllability of th reaction chamber.

[0061] A segmented reaction chamber may be used with any suitable critical or subcriti fission reactor with an aqueous reaction chamber. For example, a segmented reaction chan may be used with a hybrid reactor described below.

Example of a hybrid reactorfor production of isotopes

[0062] Fig. 22 illustrates an arrangement of a hybrid reactor 5a that is well suited to the production of medical isotopes. Before proceeding, the term "hybrid reactor" as used hereii meant to describe a reactor that includes a fusion portion and a fission portion. In particula illustrated reactor 5a is well suited to the production of Mo-99 from Mo-98 or from a soluti

LEU. The hybrid reactor 5a includes a fusion portion 10 and a fission portion 8 that coopei produce the desired isotopes. In the construction illustrated in Fig. 22, ten distinct fusion portions 10 are employed. Each fusion portion 10 is arranged as a magnetic fusion portion and acts as a neutron source as will be discussed with regard to Figs. 1 and 2. Of course otl arrangements could use fewer fusion portions 10, more fusion portions 10, or other arrange of fusion portions as desired.

[0063] Fig. 23 illustrates another arrangement of a hybrid reactor 5b that is well suited production of medical isotopes. In the construction of Fig. 23, linear fusion portions 11 act neutron sources as will be discussed with regard to Figs. 3 and 4. In the construction of Fig the linear fusion portions 11 are arranged such that five fusion portions 11 are positioned at end of the fission portion 8 and five fusion portions 11 are positioned on the opposite end o fission portion 8. Of course other arrangements that employ other quantities of fusion porti 11, or other arrangements of fusion portions could be employed if desired.

[0064] As illustrated in Figs. 1-3, each fusion portion 10, 11 provides a compact device may function as a high energy proton source or a neutron source. In one embodiment, the i portions 10, 11 utilize ^{2}H-^{3}He (deuterium-helium 3) fusion reactions to generate protons, w may then be used to generate other isotopes. In another embodiment, the fusion portions 1(function as neutron sources by changing the base reactions to ^{2}H-^{3}H, ^{2}H-^{2}H, or ^{3}H-^{3}H reacti

[0065] In view of the disadvantages inherent in the conventional types of proton or neu sources, the fusion portions 10, 11 provide a novel high energy proton or neutron source (sometimes referred to herein generically as an ion source but also considered a particle sou that may be utilized for the production of medical isotopes. Each fusion portion 10, 11 use: small amount of energy to create a fusion reaction, which then creates higher energy proton neutrons that may be used for isotope production. Using a small amount of energy may ali the device to be more compact than previous conventional devices.

[0066] Each fusion portion 10, 11 suitably generates protons that may be used to gener; other isotopes including but not limited to ^{18}F, ^{11}C, $^{15}0$, ^{13}N, ^{63}Zn, ^{124}I and many others. By changing fuel types, each fusion portion may also be used to generate high fluxes of neutro that may be used to generate isotopes including but not limited to 1-131, Xe-133, In-111, 1-

Mo-99 (which decays to Tc-99m) and many others. As such, each fusion portion 10, 11 pr< a novel compact high energy proton or neutron source for uses such as medical isotope generation that has many of the advantages over the proton or neutron sources mentioned heretofore.

[0067] In general, each fusion portion 10, 11 provides an apparatus for generating protc neutrons, which, in turn, are suitably used to generate a variety of radionuclides (or radioisotopes). With reference to Figs. 1 and 2, each magnetic fusion portion 10 includes a plasma ion source 20, which may suitably include an RF-driven ion generator and/or anteni an accelerator 30, which is suitably electrode-driven, and a target system including a target chamber 60. In the case of proton-based radioisotope production, the apparatus may also ir an isotope extraction system 90. The RF-driven plasma ion source 20 generates and collim an ion beam directed along a predetermined pathway, wherein the ion source 20 includes ar for entry of a first fluid. The electrode-driven accelerator 30 receives the ion beam and accelerates the ion beam to yield an accelerated ion beam. The target system receives the accelerated ion beam. The target system contains a nuclear particle-deriving, e.g. a proton-deriving or neutron-deriving, target material that is reactive with the accelerated beam and 1 in turn, emits nuclear particles, i.e., protons or neutrons. For radioisotope production, the ta system may have sidewalls that are transparent to the nuclear particles. An isotope extracti system 90 is disposed proximate or inside the target system and contains an isotope-derivin material that is reactive to the nuclear particles to yield a radionuclide (or radioisotope).

[0068] It should be noted that while an RF-driven ion generator or ion source is describ herein, other systems and devices are also well-suited to generating the desired ions. For example, other constructions could employ a DC arc source in place of or in conjunction w RF-driven ion generator or ion source. Still other constructions could use hot cathode ion sources, cold cathode ion sources, laser ion sources, field emission sources, and/or field evaporation sources in place of or in conjunction with a DC arc source and or an RF-driven generator or ion source. As such, the invention should not be limited to constructions that employ an RF-driven ion generator or ion source.

[0069] As discussed, the fusion portion can be arranged in a magnetic configuration 10 and/or a linear configuration 11. The six major sections or components of the device are connected as shown in FIG. 1 and FIG. 2 for the magnetic configuration 10, and FIG. 3 for linear configuration 11. Each fusion portion, whether arranged in the magnetic arrangemer the linear arrangement includes an ion source generally designated 20, an accelerator 30, a differential pumping system 40, a target system which includes a target chamber 60 for the magnetic configuration 10 or a target chamber 70 for the linear configuration 11, an ion confinement system generally designated 80, and an isotope extraction system generally designated 90. Each fusion portion may additionally include a gas filtration system 50. Ea fusion portion may also include a synchronized high speed pump 100 in place of or in addil the differential pumping system 40. Pump 100 is especially operative with the linear configuration of the target chamber.

[0070] The ion source 20 (FIG. 4 and FIG. 5) includes a vacuum chamber 25, a radio-frequency (RF) antenna 24, and an ion injector 26 having an ion injector first stage 23 and ; injector final stage 35 (FIG. 6). A magnet (not shown) may be included to allow the ion so to operate in a high density helicon mode to create higher density plasma 22 to yield more i current. The field strength of this magnet suitably ranges from about 50 G to about 6000 G suitably about 100 G to about 5000 G. The magnets may be oriented so as to create an axic field (north-south orientation parallel to the path of the ion beam) or a cusp field (north-sou orientation perpendicular to the path of the ion beam with the inner pole alternating betwee north and south for adjacent magnets). An axial field can create a helicon mode (dense pla; whereas a cusp field may generate a dense plasma but not a helicon inductive mode. A gas 21 is located on one end of the vacuum chamber 25, and the first stage 23 of the ion injecto on the other. Gas inlet 21 provides one of the desired fuel types, which may include $^{1}H_2$, ^{2}I $^{3}H_2$, ^{3}He, and ^{11}B, or may comprise ^{1}H, ^{2}H, ^{3}H, ^{3}He, and ^{11}B. The gas flow at inlet 21 is su regulated by a mass flow controller (not shown), which may be user or automatically contn RF antenna 24 is suitably wrapped around the outside of vacuum chamber 25. Alternativel antenna 24 may be inside vacuum chamber 25. Suitably, RF antenna 24 is proximate the vacuum chamber such that radio frequency radiation emitted by RF antenna 24 excites the contents (i.e., fuel gas) of vacuum chamber 25, for example, forming a plasma. RF antenm

includes a tube 27 of one or more turns. RF tube or wire 27 may be made of a conductive ε bendable material such as copper, aluminum, or stainless steel.

[0071] Ion injector 26 includes one or more shaped stages (23, 35). Each stage of the i< injector includes an acceleration electrode 32 suitably made from conductive materials that include metals and alloys to provide effective collimation of the ion beam. For example, th electrodes are suitably made from a conductive metal with a low sputtering coefficient, e.g. tungsten. Other suitable materials may include aluminum, steel, stainless steel, graphite, molybdenum, tantalum, and others. RF antenna 24 is connected at one end to the output of RF impedance matching circuit (not shown) and at the other end to ground. The RF imped matching circuit may tune the antenna to match the impedance required by the generator an establish an RF resonance. RF antenna 24 suitably generates a wide range of RF frequenci including but not limited to 0 Hz to tens of kHz to tens of MHz to GHz and greater. RF an1 24 may be water-cooled by an external water cooler (not shown) so that it can tolerate high power dissipation with a minimal change in resistance. The matching circuit in a turn of R] antenna 24 may be connected to an RF power generator (not shown). Ion source 20, the matching circuit, and the RF power generator may be floating (isolated from ground) at the highest accelerator potential or slightly higher, and this potential may be obtained by an electrical connection to a high voltage power supply. RF power generator may be remotely adjustable, so that the beam intensity may be controlled by the user, or alternatively, by cor system. RF antenna 24 connected to vacuum chamber 25 suitably positively ionizes the fui creating an ion beam. Alternative means for creating ions are known by those of skill in th and may include microwave discharge, electron-impact ionization, and laser ionization.

[0072] Accelerator 30 (FIG. 6 and FIG. 7) suitably includes a vacuum chamber 36, connected at one end to ion source 20 via an ion source mating flange 31, and connected at other end to differential pumping system 40 via a differential pumping mating flange 33. T first stage of the accelerator is also the final stage 35 of ion injector 26. At least one circulc acceleration electrode 32, and suitably 3 to 50, more suitably 3 to 20, may be spaced along axis of accelerator vacuum chamber 36 and penetrate accelerator vacuum chamber 36, whil allowing for a vacuum boundary to be maintained. Acceleration electrodes 32 have holes through their centers (smaller than the bore of the accelerator chamber) and are suitably eac

centered on the longitudinal axis (from the ion source end to the differential pumping end) accelerator vacuum chamber for passage of the ion beam. The minimum diameter of the hc acceleration electrode 32 increases with the strength of the ion beam or with multiple ion b and may range from about 1 mm to about 20 cm in diameter, and suitably from about 1 mn about 6 cm in diameter. Outside vacuum chamber 36, acceleration electrodes 32 may be connected to anti-corona rings 34 that decrease the electric field and minimize corona discr These rings may be immersed in a dielectric oil or an insulating dielectric gas such as SF_6. Suitably, a differential pumping mating flange 33, which facilitates connection to differenti pumping section 40, is at the exit of the accelerator.

[0073] Each acceleration electrode 32 of accelerator 30 can be supplied bias either fron voltage power supplies (not shown), or from a resistive divider network (not shown) as is k by those of skill in the art. The divider for most cases may be the most suitable configurati due to its simplicity. In the configuration with a resistive divider network, the ion source e the accelerator may be connected to the high voltage power supply, and the second to last accelerator electrode 32 may be connected to ground. The intermediate voltages of the accelerator electrodes 32 may be set by the resistive divider. The final stage of the accelerc suitably biased negatively via the last acceleration electrode to prevent electrons from the t chamber from streaming back into accelerator 30.

[0074] In an alternate embodiment, a linac (for example, a RF quadrapole) may be usec instead of an accelerator 30 as described above. A linac may have reduced efficiency and t larger in size compared to accelerator 30 described above. The linac may be connected to i source 20 at a first end and connected to differential pumping system 40 at the other end. L may use RF instead of direct current and high voltage to obtain high particle energies, and 1 may be constructed as is known in the art.

[0075] Differential pumping system 40 (FIG. 8 and FIG. 9) includes pressure reducing barriers 42 that suitably separate differential pumping system 40 into at least one stage. Pr reducing barriers 42 each suitably include a thin solid plate or one or more long narrow tub typically 1 cm to 10 cm in diameter with a small hole in the center, suitably about 0.1 mm t about 10 cm in diameter, and more suitably about 1 mm to about 6 cm. Each stage comprit

vacuum chamber 44, associated pressure reducing barriers 42, and vacuum pumps 17, each a vacuum pump exhaust 41. Each vacuum chamber 44 may have 1 or more, suitably 1 to 4 vacuum pumps 17, depending on whether it is a 3, 4, 5, or 6 port vacuum chamber 44. Tw(the ports of the vacuum chamber 44 are suitably oriented on the beamline and used for ion entrance and exit from differential pumping system 40. The ports of each vacuum chambei may also be in the same location as pressure reducing barriers 42. The remaining ports of i vacuum chamber 44 are suitably connected by conflat flanges to vacuum pumps 17 or may connected to various instrumentation or control devices. The exhaust from vacuum pumps fed via vacuum pump exhaust 41 into an additional vacuum pump or compressor if necessa (not shown) and fed into gas filtration system 50. Alternatively, if needed, this additional vacuum pump may be located in between gas filtration system 50 and target chamber 60 or If there is an additional compression stage, it may be between vacuum pumps 17 and filtrat system 50. Differential pumping section is connected at one end to the accelerator 30 via a accelerator mating flange 45, and at the other at beam exit port 46 to target chamber (60 or via a target chamber mating flange 43. Differential pumping system 40 may also include a turbulence generating apparatus (not shown) to disrupt laminar flow. A turbulence generat apparatus may restrict the flow of fluid and may include surface bumps or other features or combinations thereof to disrupt laminar flow. Turbulent flow is typically slower than lamii flow and may therefore decrease the rate of fluid leakage from the target chamber into the differential pumping section.

[0076] In some constructions, the pressure reducing barriers 42 are replaced or enhance plasma windows. Plasma windows include a small hole similar to those employed as press reducing barriers. However, a dense plasma is formed over the hole to inhibit the flow of g through the small hole while still allowing the ion beam to pass. A magnetic or electric fiel formed in or near the hole to hold the plasma in place.

[0077] Gas filtration system 50 is suitably connected at its vacuum pump isolation valv to vacuum pump exhausts 41 of differential pumping system 40 or to additional compresso: shown). Gas filtration system 50 (FIG. 10) includes one or more pressure chambers or "tra (13, 15) over which vacuum pump exhaust 41 flows. The traps suitably capture fluid impu that may escape the target chamber or ion source, which, for example, may have leaked int<

system from the atmosphere. The traps may be cooled to cryogenic temperatures with liqui nitrogen (LN traps, 15). As such, cold liquid traps 13, 15 suitably cause gas such as atmosj contaminants to liquefy and remain in traps 13, 15. After flowing over one or more LN tra] connected in series, the gas is suitably routed to a titanium getter trap 13, which absorbs contaminant hydrogen gasses such as deuterium that may escape the target chamber or the : source and may otherwise contaminate the target chamber. The outlet of getter trap 13 is suitably connected to target chamber 60 or 70 via target chamber isolation valve 52 of gas filtration system 50. Gas filtration system 50 may be removed altogether from device 10, i] wants to constantly flow gas into the system and exhaust it out vacuum pump exhaust 41, t< another vacuum pump exhaust (not shown), and to the outside of the system. Without gas filtration system 50, operation of apparatus 10 would not be materially altered. Apparatus functioning as a neutron source, may not include getter trap 13 of gas filtration system 50.

[0078] Vacuum pump isolation valves 51 and target chamber isolation valves 52 may facilitate gas filtration system 50 to be isolated from the rest of the device and connected to external pump (not shown) via pump-out valve 53 when the traps become saturated with ga such, if vacuum pump isolation valves 51 and target chamber isolation valves 52 are closed pump-out valves 53 can be opened to pump out impurities.

[0079] Target chamber 60 (FIG. 11 and FIG. 12 for magnetic system 10) or target chan 70 (FIG. 13 and FIG. 14 for the linear system 11) may be filled with the target gas to a pres of about 0 to about 100 torr, about 100 mtorr to about 30 torr, suitably about 0.1 to about 1(suitably about 100 mtorr to about 30 torr. The specific geometry of target chamber 60 or 7(vary depending on its primary application and may include many variations. The target chi may suitably be a cylinder about 10 cm to about 5 m long, and about 5 mm to about 100 cn diameter for the linear system 14. When used in the hybrid reactor, the target chamber is arranged to provide an activation column in its center. The fusion portions are arranged to beams through the target chamber but outside of the activation column. Thus, the beams tr; substantially within an annular space. Suitably, target chamber 70 may be about 0.1 m to a m long, and about 30 to 50 cm in diameter for the linear system 14.

[0080] For the magnetic system 12, target chamber 60 may resemble a thick pancake, a 10 cm to about 1 m tall and about 10 cm to about 10 m in diameter. Suitably, the target cha 60 for the magnetic system 12 may be about 20 cm to about 50 cm tall and approximately i in diameter. For the magnetic target chamber 60, a pair of either permanent magnets or electromagnets (ion confinement magnet 12) may be located on the faces of the pancake, o of the vacuum walls or around the outer diameter of the target chamber (see FIG. 11 and FI 12). The magnets are suitably made of materials including but not limited to copper and aluminum, or superconductors or NdFeB for electromagnets. The poles of the magnets ma oriented such that they create an axial magnetic field in the bulk volume of the target chaml The magnetic field is suitably controlled with a magnetic circuit comprising high permeabi magnetic materials such as 1010 steel, mu-metal, or other materials. The size of the magne target chamber and the magnetic beam energy determine the field strength according to equ (1):

$$r = 1.44\sqrt{E}/B \qquad (1)$$

for deuterons, wherein r is in meters, E is the beam energy in eV, and B is the magnetic fiel strength in gauss. The magnets may be oriented parallel to the flat faces of the pancake an polarized so that a magnetic field exists that is perpendicular to the direction of the beam fr the accelerator 30, that is, the magnets may be mounted to the top and bottom of the chamb cause ion recirculation. In another embodiment employing magnetic target chamber 60, th are suitably additional magnets on the top and bottom of the target chamber to create mirro fields on either end of the magnetic target chamber (top and bottom) that create localized re of stronger magnetic field at both ends of the target chamber, creating a mirror effect that c the ion beam to be reflected away from the ends of the target chamber. These additional m creating the mirror fields may be permanent magnets or electromagnets. It is also desirable provide a stronger magnetic field near the radial edge of the target chamber to create a simi mirror effect. Again, a shaped magnetic circuit or additional magnets could be employed t provide the desired strong magnetic field. One end of the target chamber is operatively connected to differential pumping system 40 via differential pumping mating flange 33, ant gas recirculation port 62 allows for gas to re-enter the target chamber from gas filtration sy

50. The target chamber may also include feedthrough ports (not shown) to allow for variov. isotope generating apparatus to be connected.

[0081] In the magnetic configuration of the target chamber 60, the magnetic field confi: the ions in the target chamber. In the linear configuration of the target chamber 70, the inje ions are confined by the target gas. When used as a proton or neutron source, the target cha may require shielding to protect the operator of the device from radiation, and the shielding be provided by concrete walls suitably at least one foot thick. Alternatively, the device ma; stored underground or in a bunker, distanced away from users, or water or other fluid may 1 used a shield, or combinations thereof.

[0082] Both differential pumping system 40 and gas filtration system 50 may feed into target chamber 60 or 70. Differential pumping system 40 suitably provides the ion beam, v gas filtration system 50 supplies a stream of filtered gas to fill the target chamber. Additior in the case of isotope generation, a vacuum feedthrough (not shown) may be mounted to tai chamber 60 or 70 to allow the isotope extraction system 90 to be connected to the outside.

[0083] Isotope extraction system 90, including the isotope generation system 63, may b number of configurations to provide parent compounds or materials and remove isotopes generated inside or proximate the target chamber. For example, isotope generation system may include an activation tube 64 (Figs. 12 and 14) that is a tightly wound helix that fits jus inside the cylindrical target chamber and having walls 65. Alternatively, in the case of the pancake target chamber with an ion confinement system 80, it may include a helix that cov the device along the circumference of the pancake and two spirals, one each on the top and bottom faces of the pancake, all connected in series. Walls 65 of activation tubes 64 used i: these configurations are sufficiently strong to withstand rupture, yet sufficiently thin so thai protons of over 14 MeV (approximately 10 to 20 MeV) may pass through them while still keeping most of their energy. Depending on the material, the walls of the tubing may be at 0.01 mm to about 1 mm thick, and suitably about 0.1 mm thick. The walls of the tubing are suitably made of materials that will not generate neutrons. The thin-walled tubing may be 1 from materials such as aluminum, carbon, copper, titanium, or stainless steel. Feedthrough shown) may connect activation tube 64 to the outside of the system, where the daughter or

product compound-rich fluid may go to a heat exchanger (not shown) for cooling and a che separator (not shown) where the daughter or product isotope compounds are separated fron mixture of parent compounds, daughter compounds, and impurities.

[0084] In another construction, shown in FIG. 15, a high speed pump 100 is positioned between accelerator 30 and target chamber 60 or 70. High speed pump 100 may replace th differential pumping system 40 and/or gas filtration system 50. The high speed pump suita includes one or more blades or rotors 102 and a timing signal 104 that is operatively connei to a controller 108. The high speed pump may be synchronized with the ion beam flow fro accelerator section, such that the ion beam or beams are allowed to pass through at least on 106 in between or in blades 102 at times when gaps 106 are aligned with the ion beam. Tir signal 104 may be created by having one or more markers along the pump shaft or on at lea of the blades. The markers may be optical or magnetic or other suitable markers known in art. Timing signal 104 may indicate the position of blades 102 or gap 106 and whether or r there is a gap aligned with the ion beam to allow passage of the ion beam from first stage 3 accelerator 30 through high speed pump 100 to target chamber 60 or 70. Timing signal 10⁴ be used as a gate pulse switch on the ion beam extraction voltage to allow the ion beam to i ion source 20 and accelerator 30 and enter high speed pump 100. When flowing through th system from ion source 20 to accelerator 30 to high speed pump 100 and to target chamber 70, the beam may stay on for a time period that the ion beam and gap 106 are aligned and t turn off before and while the ion beam and gap 106 are not aligned. The coordination of tii signal 104 and the ion beam may be coordinated by a controller 108. In one embodiment o controller 108 (FIG. 18), controller 108 may comprise a pulse processing unit 110, a high v isolation unit 112, and a high speed switch 114 to control the voltage of accelerator 30 betv suppression voltage (ion beam off; difference may be 5-10 kV) and extraction voltage (ion on; difference may be 20 kv). Timing signal 104 suitably creates a logic pulse that is passe through delay or other logic or suitable means known in the art. Pulse processing unit 110 alter the turbine of the high speed pump to accommodate for delays, and high speed switch may be a MOSFET switch or other suitable switch technology known in the art. High volti isolation unit 112 may be a fiber optic connection or other suitable connections known in th For example, the timing signal 104 may indicate the presence or absence of a gap 106 only per rotation of a blade 102, and the single pulse may signal a set of electronics via controlle

to generate a set of n pulses per blade revolution, wherein n gaps are present in one blade rotation. Alternatively, timing signal 104 may indicate the presence or absence of a gap 10 each of m gaps during a blade rotation, and the m pulses may each signal a set of electronic controller 108 to generate a pulse per blade revolution, wherein m gaps are present in one b rotation. The logic pulses may be passed or coordinated via controller 108 to the first stage accelerator section 35 (ion extractor), such that the logic pulse triggers the first stage of accelerator section 35 to change from a suppression state to an extraction state and visa ver: the accelerator were +300 kV, for example, the first stage of accelerator 35 may be biased t +295 kV when there is no gap 106 in high speed pump 100, so that the positive ion beam w flow from +295 kV to +300 kV, and the first stage of accelerator 35 may be biased to +310 when there is a gap 106 in high speed pump 100, so that the ion beam travels through accel 30 and through gaps 106 in high speed pump 100 to target chamber 60 or 70. The different voltage between the suppression and extraction states may be a relatively small change, sue about 1 kV to about 50 kV, suitably about 10 kV to about 20 kV. A small change in voltag facilitate a quick change between suppression (FIG. 17) and extraction (FIG. 16) states. Ti: signal 104 and controller 108 may operate by any suitable means known in the art, includin not limited to semiconductors and fiber optics. The period of time that the ion beam is on a off may depend on factors such as the rotational speed of blades 102, the number of blades gaps 106, and the dimensions of the blades or gaps.

[0085] The isotopes ^{18}F and ^{13}N, which are utilized in PET scans, may be generated fro nuclear reactions inside each fusion portion using an arrangement as illustrated in Figs. 12 ; 14. These isotopes can be created from their parent isotopes, $^{18}0$ (for ^{18}F) and $^{16}0$ (for ^{13}N) proton bombardment. The source of the parent may be a fluid, such as water ($H_2{}^{18}0$ or $H_2{}^{1}$ that may flow through the isotope generation system via an external pumping system (not shown) and react with the high energy protons in the target chamber to create the desired daughter compound. For the production of ^{18}F or ^{13}N, water ($H_2{}^{18}0$ or $H_2{}^{16}0$, respectively} flowed through isotope generation system 63, and the high energy protons created from the aforementioned fusion reactions may penetrate tube 64 walls and impact the parent compoi and cause (ρ,α) reactions producing ^{18}F or ^{13}N. In a closed system, for example, the isotops water may then be circulated through the heat exchanger (not shown) to cool the fluid and t into the chemical filter (not shown), such as an ion exchange resin, to separate the isotope f

the fluid. The water mixture may then recirculate into target chamber (60 or 70), while the isotopes are stored in a filter, syringe, or by other suitable means known in the art until eno has been produced for imaging or other procedures.

[0086] While a tubular spiral has been described, there are many other geometries that be used to produce the same or other radionuclides. For example, isotope generation syster may suitably be parallel loops or flat panel with ribs. In another embodiment, a water jacki be attached to the vacuum chamber wall. For ^{18}F or ^{13}N creation, the spiral could be replac any number of thin walled geometries including thin windows, or could be replaced by a so substance that contained a high oxygen concentration, and would be removed and processes transmutation. Other isotopes can be generated by other means.

[0087] With reference to Figs. 1 and 3, the operation of the fusion portions will now be described. Before operation of one of the fusion portions, the respective target chamber 60 is suitably filled by first pre-fiowing the target gas, such as ^{3}He, through the ion source 20 \ the power off, allowing the gas to flow through the apparatus 10 and into the target chambe operation, a reactant gas such as $^{2}H_2$ enters the ion source 20 and is positively ionized by th field to form plasma 22. As plasma 22 inside vacuum chamber 25 expands toward ion inje 26, plasma 22 starts to be affected by the more negative potential in accelerator 30. This ca the positively charged ions to accelerate toward target chamber 60 or 70. Acceleration electrodes 32 of the stages (23 and 35) in ion source 20 collimate the ion beam or beams, gi each a nearly uniform ion beam profile across the first stage of accelerator 30. Alternativel first stage of accelerator 30 may enable pulsing or on/off switching of the ion beam, as desc above. As the beam continues to travel through accelerator 30, it picks up additional energ; each stage, reaching energies of up to 5 MeV, up to 1 MeV, suitably up to 500 keV, suitabl keV to 5 MeV, suitably 50 keV to 500 keV, and suitably 0 to 10 Amps, suitably 10 to 100 mAmps, by the time it reaches the last stage of the accelerator 30. This potential is supplie an external power source (not shown) capable of producing the desired voltage. Some neut gas from ion source 20 may also leak out into accelerator 30, but the pressure in acceleratoi will be kept to a minimum by differential pumping system 40 or synchronized high speed p 100 to prevent excessive pressure and system breakdown. The beam continues at high velc into differential pumping 40 where it passes through the relatively low pressure, short path

length stages with minimal interaction. From here it continues into target chamber 60 or 7(impacting the high density target gas that is suitably 0 to 100 torr, suitably 100 mtorr to 30 suitably 5 to 20 torr, slowing down and creating nuclear reactions. The emitted nuclear par may be about 0.3 MeV to about 30 MeV protons, suitably about 10 MeV to about 20 MeV protons, or about 0.1 MeV to about 30 MeV neutrons, suitably about 2 MeV to about 20 M neutrons.

[0088] In the embodiment of linear target chamber 70, the ion beam continues in an approximately straight line and impacts the high density target gas to create nuclear reactio until it stops.

[0089] In the embodiment of magnetic target chamber 60, the ion beam is bent into an approximately helical path, with the radius of the orbit (for deuterium ions, ^{2}H) given by th equation (2):

$$r = \frac{204 * \sqrt{E_i}}{B} \qquad \textbf{(2)}$$

where r is the orbital radius in cm, Ei is the ion energy in eV, and B is the magnetic field st in gauss. For the case of a 500 keV deuterium beam and a magnetic field strength of 7 k orbital radius is about 20.6 cm and suitably fits inside a 25 cm radius chamber. Whi neutralization can occur, the rate at which re-ionization occurs is much faster, and the p will spend the vast majority of its time as an ion.

[0090] Once trapped in this magnetic field, the ions orbit until the ion beam stops, achii a very long path length in a short chamber. Due to this increased path length relative to lin< target chamber 70, magnetic target chamber 60 can also operate at lower pressure. Magnet target chamber 60, thus, may be the more suitable configuration. A magnetic target chamb be smaller than a linear target chamber and still maintain a long path length, because the be may recirculate many times within the same space. The fusion products may be more concentrated in the smaller chamber. As explained, a magnetic target chamber may operate lower pressure than a linear chamber, easing the burden on the pumping system because th

longer path length may give the same total number of collisions with a lower pressure gas a with a short path length and a higher pressure gas of the linac chamber.

[0091] Due to the pressure gradient between accelerator 30 and target chamber 60 or 7(may flow out of the target chamber and into differential pumping system 40. Vacuum pum may remove this gas quickly, achieving a pressure reduction of approximately 10 to 100 tir greater. This "leaked" gas is then filtered and recycled via gas filtration system 50 and pun back into the target chamber, providing more efficient operation. Alternatively, high speed pump 100 may be oriented such that flow is in the direction back into the target chamber, preventing gas from flowing out of the target chamber.

[0092] While the invention described herein is directed to a hybrid reactor, it is possibli produce certain isotopes using the fusion portion alone. If this is desired, an isotope extrad system 90 as described herein is inserted into target chamber 60 or 70. This device allows high energy protons to interact with the parent nuclide of the desired isotope. For the case production or ^{13}N production, this target may be water-based (^{16}0 for ^{13}N, and ^{18}0 for ^{18}F) will flow through thin-walled tubing. The wall thickness is thin enough that the 14.7 MeV protons generated from the fusion reactions will pass through them without losing substanti energy, allowing them to transmute the parent isotope to the desired daughter isotope. The or ^{18}F rich water then is filtered and cooled via external system. Other isotopes, such as ^{124} (from ^{124}Te or others), ^{11}C (from ^{14}N or ^{11}B or others), ^{15}0 (from ^{15}N or others), and ^{63}Zn, n also be generated. In constructions that employ the fission portion to generate the desired isotopes, the isotope extraction system 90 can be omitted.

[0093] If the desired product is protons for some other purpose, target chamber 60 or 7(be connected to another apparatus to provide high energy protons to these applications. Fo: example, the a fusion portion may be used as an ion source for proton therapy, wherein a b of protons is accelerated and used to irradiate cancer cells.

[0094] If the desired product is neutrons, no hardware such as isotope extraction systen required, as the neutrons may penetrate the walls of the vacuum system with little attenuati For neutron production, the fuel in the injector is changed to either deuterium or tritium, wi target material changed to either tritium or deuterium, respectively. Neutron yields of up tc

about 10^{15} neutrons/sec or more may be generated. Additionally, getter trap 13 may be ren The parent isotope compound may be mounted around target chamber 60 or 70, and the rel neutrons may convert the parent isotope compound to the desired daughter isotope compou Alternatively, an isotope extraction system may still or additionally be used inside or proxi the target chamber. A moderator (not shown) that slows neutrons may be used to increase **1** efficiency of neutron interaction. Moderators in neutronics terms may be any material or materials that slow down neutrons. Suitable moderators may be made of materials with lov atomic mass that are unlikely to absorb thermal neutrons. For example, to generate Mo-99 a Mo-98 parent compound, a water moderator may be used. Mo-99 decays to Tc-99m, whi may be used for medical imaging procedures. Other isotopes, such as 1-131, Xe-133, In-1 1 1-125, may also be generated. When used as a neutron source, the fusion portion may inclu shielding such as concrete or a fluid such as water at least one foot thick to protect the oper from radiation. Alternatively, the neutron source may be stored underground to protect the operators from radiation. The manner of usage and operation of the invention in the neutro mode is the same as practiced in the above description.

[0095] The fusion rate of the beam impacting a thick target gas can be calculated. The incremental fusion rate for the ion beam impacting a thick target gas is given by the equatic

$$df\{E) = n_b * i\wedge * \sigma\{E) * dl \quad (3)$$

where *df(E)* is the fusion rate (reactions/sec) in the differential energy interval *dE*, n_b is the gas density (particles / m^3), I_{ion} is the ion current (A), *e* is the fundamental charge of 1.602^ ^{19} coulombs/particle, σ(E) is the energy dependent cross section (m^2) and *dl* is the increi path length at which the particle energy is *E*. Since the particle is slowing down once insi target, the particle is only at energy *E* over an infinitesimal path length.

[0096] To calculate the total fusion rate from a beam stopping in a gas, equation (2) is integrated over the entire particle path length from where its energy is at its maximum of *E*, where it stops as shown in equation (4):

$$F(E_i) = \int_0^{E_i} n_b * \frac{I_{ion}}{e} * \sigma(E) dl = \frac{n_b I_{ion}}{e} \int_0^{E_i} \sigma(E) dl \quad (4)$$

where *E(I¾)* is the total fusion rate for a beam of initial energy *Ei* stopping in the gas targi solve this equation, the incremental path length *dl* is solved for in terms of energy. relationship is determined by the stopping power of the gas, which is an experimi measured function, and can be fit by various types of functions. Since these fits and fits fusion cross section tend to be somewhat complicated, these integrals were solved numer Data for the stopping of deuterium in ^{3}He gas at 10 torr and 25°C was obtained fro computer program Stopping and Range of Ions in Matter (SRIM; James Ziegler, www.srii and is shown in FIG. 19.

[0097] An equation was used to predict intermediate values. A polynomial of order ten fit to the data shown in FIG. 19. The coefficients are shown in TABLE 1, and resultant fit the best-fit 10th order polynomial is shown in FIG. 20.

TABLE 1.

Order	Coefficient
10	-1.416621E-27
9	3.815365E-24
8	-4.444877E-21
7	2.932194E-18
6	-1.203915E-15
5	3.184518E-13
4	-5.434029E-1 1
3	5.847578E-09
2	-3.832260E-07
1	1.498854E-05
0	-8.529514E-05

[0098] As can be seen from these data, the fit was quite accurate over the energy range considered. This relationship allowed the incremental path length, *dl*, to be related to an incremental energy interval by the polynomial tabulated above. To numerically solve this, suitable to choose either a constant length step or a constant energy step, and calculate eifhe how much energy the particle has lost or how far it has gone in that step. Since the fusion i

equation (4) is in terms of *dl*, a constant length step was the method used. The recursive relationship for the particle energy *E* as it travels through the target is the equation (5):

$$E_{n+1} = E_n - S(E) * dl \quad (5)$$

where *n* is the current step («=0 is the initial step, and E_o is the initial particle energy), $E_{n+}i$ energy in the next incremental step, *S(E)* is the polynomial shown above that relates the p energy to the stopping power, and *dl* is the size of an incremental step. For the form incremental energy shown above, *E* is in keV and *dl* is in μη.

[0099] This formula yields a way to determine the particle energy as it moves through t plasma, and this is important because it facilitates evaluation of the fusion cross section at ε energy, and allows for the calculation of a fusion rate in any incremental step. The fusion r the numerical case for each step is given by the equation (6):

$$/\,„(E) = n_b * \frac{I_{ion}}{e} * \sigma(\mathrm{E}_\eta) * dl \quad (6)$$

[00100] To calculate the total fusion rate, this equation was summed over all values of *E* E=0 (or $n*dl$ = the range of the particle) as shown in equation (7):

$$F(E_o') = \sum_{n=0}^{n*dl=range} f„(E) \quad \mathbf{m}$$

[00101] This fusion rate is known as the "thick-target yield". To solve this, an initial en was determined and a small step size *dl* chosen. The fusion rate in the interval *dl* at full en was calculated. Then the energy for the next step was calculated, and the process repeated. goes on until the particle stops in the gas.

[00102] For the case of a singly ionized deuterium beam impacting a 10 torr helium-3 ga background at room temperature, at an energy of 500 keV and an intensity of 100 niA, the] rate was calculated to be approximately 2xl0 ^{13} fusions / second, generating the same numb

high energy protons (equivalent to 3 μA protons). This level is sufficient for the productioi medical isotopes, as is known by those of skill in the art. A plot showing the fusion rate foı 100 mA incident deuterium beam impacting a helium-3 target at 10 torr is shown in FIG. 2

[00103] The fusion portions as described herein may be used in a variety of different applications. According to one construction, the fusion portions are used as a proton sourcs transmutate materials including nuclear waste and fissile material. The fusion portions may be used to embed materials with protons to enhance physical properties. For example, the i portion may be used for the coloration of gemstones. The fusion portions also provide a ne source that may be used for neutron radiography. As a neutron source, the fusion portions ı be used to detect nuclear weapons. For example, as a neutron source the fusion portions mi used to detect special nuclear materials, which are materials that can be used to create nuck explosions, such as Pu, ^{233}U, and materials enriched with ^{233}U or ^{235}U. As a neutron source fusion portions may be used to detect underground features including but not limited to tun oil wells, and underground isotopic features by creating neutron pulses and measuring the reflection and/or refraction of neutrons from materials. The fusion portions may be used as neutron source in neutron activation analysis (NAA), which may determine the elemental composition of materials. For example, NAA may be used to detect trace elements in the picogram range. As a neutron source, the fusion portions may also be used to detect materi including but not limited to clandestine materials, explosives, drugs, and biological agents 1 determining the atomic composition of the material. The fusion portions may also be used driver for a sub-critical reactor.

[00104] The operation and use of the fusion portion 10, 11 is further exemplified by the following examples, which should not be construed by way of limiting the scope of the invention.

[00105] The fusion portions 10, 11 can be arranged in the magnetic configuration 10 to function as a neutron source. In this arrangement, initially, the system 10 will be clean and empty, containing a vacuum of 10^{-9} torr or lower, and the high speed pumps 17 will be up t speed (two stages with each stage being a turbomolecular pump). Approximately 25-30 sta cubic centimeters of gas (deuterium for producing neutrons) will be flowed into the target

chamber 60 to create the target gas. Once the target gas has been established, that is, once a specified volume of gas has been flowed into the system and the pressure in the target chamber 60 reaches approximately 0.5 torr, a valve will be opened which allows a flow of 0.5 to 1 sccm (standard cubic centimeters per minute) of deuterium from the target chamber 60 into the ion source 20. This gas will re-circulate rapidly through the system, producing approximately the following pressures: in the ion source 20 the pressure will be a few mtorr; in the accelerator the pressure will be around 20 μιοπ·; over the pumping stage nearest the accelerator, the pressure will be <20 μιοπ·; over the pumping stage nearest the target chamber, the pressure will be approximately 50 mtorr; and in the target chamber 60 the pressure will be approximately 0. After these conditions are established, the ion source 20 (using deuterium) will be excited by enabling the RF power supply (coupled to the RF antenna 24 by the RF matching circuit) to about 10-30 MHz. The power level will be increased from zero to about 500 W creating a deuterium plasma with a density on the order of 10^{11} particles / cm^3. The ion extraction voltage will be increased to provide the desired ion current (approximately 10 mA) and focusing. The accelerator voltage will then be increased to 300 kV, causing the ion beam to accelerate through the flow restrictions and into the target chamber 60. The target chamber 60 will be filled with a magnetic field of approximately 5000 gauss (or 0.5 tesla), which causes the ion beam to re-circulate. The ion beam will make approximately 10 revolutions before dropping to a negligible low energy.

[00106] While re-circulating, the ion beam will create nuclear reactions with the target gas producing 4 x 10^{10} and up to 9 x 10^{10} neutrons / sec for D. These neutrons will penetrate the target chamber 60, and be detected with appropriate nuclear instrumentation.

[00107] Neutral gas that leaks from the target chamber 60 into the differential pumping section 40 will pass through the high speed pumps 17, through a cold trap 13, 15, and back to the target chamber 60. The cold traps 13, 15 will remove heavier gasses that in time can contaminate the system due to very small leaks.

[00108] The fusion portions 11 can also be arranged in the linear configuration to function as a neutron source. In this arrangement, initially, the system will be clean and empty, containing a vacuum of 10^{-9} torr or lower and the high speed pumps 17 will be up to speed (three stages,

the two nearest that accelerator being turbomolecular pumps and the third being a different such as a roots blower). Approximately 1000 standard cubic centimeters of deuterium gas be flowed into the target chamber 70 to create the target gas. Once the target gas has been established, a valve will be opened which allows a flow of 0.5 to 1 seem (standard cubic centimeters per minute) from the target chamber 70 into the ion source 20. This gas will re circulate rapidly through the system, producing approximately the following pressures: in t source 20 the pressure will be a few mtorr; in the accelerator 30 the pressure will be around μιθrr; over the pumping stage nearest the accelerator, the pressure will be < 20 μιθrr; over t center pumping stage the pressure will be approximately 50 mtorr; over the pumping stage nearest the target chamber 70, the pressure will be approximately 500 mtorr; and in the targ chamber 70 the pressure will be approximately 20 torr.

[00109] After these conditions are established, the ion source 20 (using deuterium) will 1 excited by enabling the RF power supply (coupled to the RF antenna 24 by the RF matchin circuit) to about 10-30 MHz. The power level will be increased from zero to about 500 W creating a dense deuterium plasma with a density on the order of 10^{11} particles / cm^3. The i extraction voltage will be increased to provide the desired ion current (approximately 10 m and focusing. The accelerator voltage will then be increased to 300 kV, causing the ion bea accelerate through the flow restrictions and into the target chamber 70. The target chamber will be a linear vacuum chamber in which the beam will travel approximately 1 meter befoi dropping to a negligibly low energy.

[00110] While passing through the target gas, the beam will create nuclear reactions, producing 4 x 10^{10} and up to 9 x 10^{10} neutrons / sec. These protons will penetrate the targe chamber 70, and be detected with appropriate nuclear instrumentation.

[00111] Neutral gas that leaks from the target chamber 70 into the differential pumping section 40 will pass through the high speed pumps 17, through a cold trap 13, 15, and back the target chamber 70. The cold traps 13, 15 will remove heavier gasses that in time can contaminate the system due to very small leaks.

[00112] In another construction, the fusion portions 10 are arranged in the magnetic configuration and are operable as proton sources. In this construction, initially, the system

be clean and empty, containing a vacuum of 10^{-9} torr or lower, and the high speed pumps 1 be up to speed (two stages with each stage being a turbomolecular pump). Approximately 1 standard cubic centimeters of gas (an approximate 50/50 mixture of deuterium and helium- generate protons) will be flowed into the target chamber 60 to create the target gas. Once t target gas has been established, that is, once the specified volume of gas has been flowed in system and the pressure in the target chamber 60 reaches approximately 0.5 torr, a valve wi opened which allows a flow of 0.5 to 1 seem (standard cubic centimeters per minute) of deuterium from the target chamber 60 into the ion source 20. This gas will re-circulate rapi through the system, producing approximately the following pressures: in the ion source 20 pressure will be a few mtorr; in the accelerator 30 the pressure will be around 20 μiθrr; ove pumping stage nearest the accelerator 30, the pressure will be <20 μiθrr; over the pumping nearest the target chamber 60, the pressure will be approximately 50 mtorr; and in the targe chamber 60 the pressure will be approximately 0.5 torr. After these conditions are establisl the ion source 20 (using deuterium) will be excited by enabling the RF power supply (coup the RF antenna 24 by the RF matching circuit) to about 10-30 MHz. The power level will 1 increased from zero to about 500 W creating a dense deuterium plasma with a density on th order of 10^{11} particles / cm^3. The ion extraction voltage will be increased to provide the de: ion current (approximately 10 mA) and focusing. The accelerator voltage will then be incr to 300 kV, causing the ion beam to accelerate through the flow restrictions and into the targ chamber 60. The target chamber 60 will be filled with a magnetic field of approximately 5 gauss (or 0.5 tesla), which causes the ion beam to re-circulate. The ion beam will make approximately 10 revolutions before dropping to a negligibly low energy.

[00113] While re-circulating, the ion beam will create nuclear reactions with the target g producing 1×10^{11} and up to about 5×10^{11} protons / sec. These protons will penetrate the of the isotope extraction system, and be detected with appropriate nuclear instrumentation.

[00114] Neutral gas that leaks from the target chamber 60 into the differential pumping section 40 will pass through the high speed pumps 17, through a cold trap 13, 15, and back the target chamber 60. The cold traps 13, 15 will remove heavier gasses that in time can contaminate the system due to very small leaks.

[00115] In another construction, the fusion portions 11 are arranged in the linear configu and are operable as proton sources. In this construction, initially, the system will be clean i empty, containing a vacuum of 10^{-9} torr or lower and the high speed pumps 17 will be up tc speed (three stages, with the two nearest that accelerator being turbomolecular pumps and t third being a different pump such as a roots blower). Approximately 1000 standard cubic centimeters of about 50/50 mixture of deuterium and helium-3 gas will be flowed into the t chamber 70 to create the target gas. Once the target gas has been established, a valve will b opened which allows a flow of 0.5 to 1 seem (standard cubic centimeters per minute) from target chamber 70 into the ion source 20. This gas will re-circulate rapidly through the syst producing approximately the following pressures: in the ion source 20 the pressure will be ; mtorr; in the accelerator 30 the pressure will be around 20 μιθrr; over the pumping stage ne the accelerator 30, the pressure will be < 20 μίοπ·; over the center pumping stage the pressu will be approximately 50 mtorr; over the pumping stage nearest the target chamber 70, the pressure will be approximately 500 mtorr; and in the target chamber 70 the pressure will be approximately 20 torr.

[00116] After these conditions are established, the ion source 20 (using deuterium) will 1 excited by enabling the RF power supply (coupled to the RF antenna 24 by the RF matchin circuit) to about 10-30 MHz. The power level will be increased from zero to about 500 W creating a dense deuterium plasma with a density on the order of 10^{11} particles / cm^3. The i extraction voltage will be increased to provide the desired ion current (approximately 10 m and focusing. The accelerator voltage will then be increased to 300 kV, causing the ion bea accelerate through the flow restrictions and into the target chamber 70. The target chamber will be a linear vacuum chamber in which the beam will travel approximately 1 meter befoi dropping to a negligibly low energy.

[00117] While passing through the target gas, the beam will create nuclear reactions, producing 1×10^{11} and up to about 5×10^{11} protons / sec. These neutrons will penetrate the walls of the tubes of the isotope extraction system, and be detected with appropriate nuclea instrumentation.

[00118] Neutral gas that leaks from the target chamber 70 into the differential pumping section 40 will pass through the high speed pumps 17, through a cold trap 13, 15, and back the target chamber 70. The cold traps 13, 15 will remove heavier gasses that in time can contaminate the system due to very small leaks.

[00119] In another construction, the fusion portions 10, 11 are arranged in either the maj configuration or the linear configuration and are operated as neutron sources for isotope production. The system will be operated as discussed above with the magnetic target cham with the linear target chamber 70. A solid sample, such as solid foil of parent material Mo- will be placed proximal to the target chamber 60, 70. Neutrons created in the target chamb 70 will penetrate the walls of the target chamber 60, 70 and react with the Mo-98 parent ma to create Mo-99, which may decay to meta-stable Tn-99m. The Mo-99 will be detected usi suitable instrumentation and technology known in the art.

[00120] In still other constructions, the fusion portions 10, 11 are arranged as proton sou for the production of isotopes. In these construction, the fusion portion 10, 11 will be opera as described above with the magnetic target chamber 60 or with the linear target chamber 7 The system will include an isotope extraction system inside the target chamber 60, 70. Par material such as water comprising $H_2{}^{16}0$ will be flowed through the isotope extraction syst The protons generated in the target chamber will penetrate the walls of the isotope extractic system to react with the $^{16}0$ to produce ^{13}N. The ^{13}N product material will be extracted fro parent and other material using an ion exchange resin. The ^{13}N will be detected using suita instrumentation and technology known in the art.

[00121] In summary, each fusion portion 10, 11 provides, among other things, a compac energy proton or neutron source. The foregoing description is considered as illustrative on] the principles of the fusion portion 10, 11. Further, since numerous modifications and chan will readily occur to those skilled in the art, it is not desired to limit the fusion portion 10, 1 the exact construction and operation shown and described, and accordingly, all suitable modifications and equivalents may be resorted to as required or desired.

[00122] As illustrated in Figs. 22 and 23, the fission portions 400a, 400b of the hybrid re 5a, 5b are positioned adjacent the target chambers 60, 70 of a plurality of fusion portions 1(

The fusion portions 10, 11 are arranged such that a reaction space 405 is defined within the chambers 60, 70. Specifically, the ion trajectories within the target chambers 60, 70 do not the reaction space 405, and so materials to be irradiated can be placed within that volume. order to further increase the neutron flux, multiple fusion portions 10, 11 are stacked on top one another, with as many as ten sources being beneficial. As illustrated in Fig. 22, the hyt reactor 5a includes the fission portion 400a and fusion portions 10 in the magnetic arranger to produce a plurality of stacked target chambers 60 that are pancake shaped but in which tl beam flows along an annular path. Thus, the reaction space 405 within the annular path ca1 used for the placement of materials to be irradiated.

[00123] Fig. 23 illustrates a linear arrangement of the fusion portions 11 coupled to the fission portion 400b to define the hybrid reactor 5b. In this construction, the ion beams are directed along a plurality of substantially parallel, spaced-apart linear paths positioned with annular target chamber 70. The reaction space 405 (sometimes referred to as reaction chan within the annular target chamber 70 is suitable for the placement of materials to be irradiai Thus, as will become apparent, the fission portions 400a, 400b described with regard to Fig 29 could be employed with either the magnetic configuration or the linear configuration of fusion portions 10, 11.

[00124] With reference to Figs. 22 and 23 the fission portion 400a, 400b includes a substantially cylindrical activation column 410 (sometimes referred to as an activation cell) positioned within a tank 415 that contains a moderator/reflector material selected to reduce radiation that escapes from the fission portion 400a, 400b during operation. An attenuator be positioned proximate the activation cell and selected to maintain the fission reaction at a subcritical level, a reflector may be positioned proximate the target chamber and selected tc reflect neutrons toward the activation cell, and a moderator may substantially surround the activation cell, the attenuator, and the reflector. The activation column 410 is positioned w the target chamber 60, 70 where the fusion reactions occur. The target chamber 60, 70 is al m tall. A layer of beryllium 420 may surround the target chamber 60, 70. The moderating material is typically D_20 or H_20. In addition, a gas regeneration system 425 is positioned < of the tank 415. An aperture 430 in the center of the gas regeneration system 425 extends i the activation column 410 where a sub-critical assembly 435 including a LEU mixture and/

other parent material may be located. In preferred constructions, the aperture 430 has abou cm radius and is about 1 m long.

[00125] Each fusion portion 10, 11 is arranged to emit high energy neutrons from the tar chamber. The neutrons emitted by the fusion portions 10, 11 are emitted isotropically, and at high energy those that enter the activation column 410 pass through it with little interacti The target chamber is surrounded by 10-15 cm of beryllium 420, which multiplies the fast neutron flux by approximately a factor of two. The neutrons then pass into the moderator v they slow to thermal energy and reflect back into the activation cell 410.

[00126] It is estimated that the neutron production rate from this configuration is about 1 n/s (the estimated source strength for a single fusion portion 10, 11 operating at 500 kV anc mA is 10^{14} n/s and there are ten of these devices in the illustrated construction). The total volumetric flux in the activation cell 410 was calculated to be 2.35 * 10^{12} n / cm^2 / s with ai uncertainty of 0.0094 and the thermal flux (less than 0.1 eV) was 1.34 * 10^{12} n / cm^2 / s wit uncertainty of 0.0122. This neutron rate improves substantially with the presence of LEU ε be discussed.

[00127] As discussed with regard to Figs. 1 and 3, the fusion portion 10, 11 can be arran the magnetic arrangement or the linear arrangement. The real advantage of the magnetic arrangement of the fusion portions 10, 11 is that they allow for a long path length in a relati low pressure gas. To effectively use the linear configuration, the target gas must be cooled must be maintained at a higher pressure. One example of such a configuration would have several deuterium beam lines shooting axially into the target chamber 70 from above and b the device as illustrated in Fig. 23. While the target chambers 70 may need to operate at up torr for this to be successful, it may be a simpler and more efficient approach for the fusion portion 10, 11.

[00128] The primary simplification in the linear configuration is the elimination of the components needed to establish the magnetic field that guides the beam in the spiral or heli pattern. The lack of the components needed to create the field makes the device cheaper an magnets do not play a role in attenuating the neutron flux. However, in some constructions

magnetic field is employed to collimate the ion beam produced by the linear arrangement o fusion portions 11, as will be discussed.

[00129] In order to produce Mo-99 of high specific activity as an end product, it should 1 made from a material that is chemically different so that it can be easily separated. The mo common way to do this is by fission of ^{235}U through neutron bombardment. The fusion poi 10, 11 described previously create sufficient neutrons to produce a large amount of Mo-99 no additional reactivity, but if ^{235}U is already present in the device, it makes sense to put it : configuration that will provide neutron multiplication as well as providing a target for Mo-9 production. The neutrons made from fission can play an important role in increasing the sp activity of the Mo-99, and can increase the total Mo-99 output of the system. The multiplic factor, k_{eff} is related to the multiplication by equation $1/(1- k_{eff})$. This multiplication effect c result in an increase of the total yield and specific activity of the end product by as much as factor of 5-10. k_{eff} is a strong function of LEU density and moderator configuration.

[00130] Several subcritical configurations of subcritical assemblies 435 which consist of (20% enriched) targets combined with H_20 (or D_20) are possible. All of these configuratic are inserted into the previously described reaction chamber space 405. Some of the configurations considered include LEU foils, an aqueous solution of a uranium salt dissolvs water, encapsulated $U0_2$ powder and others. The aqueous solutions are highly desirable dvj excellent moderation of the neutrons, but provide challenges from a criticality perspective. order to ensure subcritical operation, the criticality constant, $\mathbf{k_{eff}}$ should be kept below 0.95. Further control features could easily be added to decrease k_{eff} if a critical condition were obtained. These control features include, but are not limited to control rods, injectable pois or pressure relief valves that would dump the moderator and drop the criticality.

[00131] Aqueous solutions of uranium offer tremendous benefits for downstream chemii processes. Furthermore, they are easy to cool, and provide an excellent combination of fue moderator. Initial studies were performed using a uranium nitrate solution-$U0_2(N0_3)_2$, but solutions could be considered such as uranium sulfate or others. In one construction, the sa concentration in the solution is about 66 g of salt per 100 g H_20. The solution is positionec within the activation cell 410 as illustrated in Figs. 24 and 25. In addition to the solution, tl

a smaller diameter cylinder 500 in the center of the activation cell 410 filled with pure wate This cylinder of water allows the value of $\mathbf{k_{eff}}$ to be reduced so that the device remains subcritical, while still allowing for a large volume of LEU solution to be used.

[00132] In the aqueous solution layout illustrated in Figs. 24 and 25, the central most cy] 500 contains pure water and is surrounded by an aqueous mixture of uranium nitrate that is contained between the tube and a cylindrical wall 505 that cooperate to define a substantial annular space 510. The target chamber 60, 70 is the next most outward layer and is also an The pure water, the aqueous mixture of uranium nitrate, and the target chamber 60, 70 are surrounded by the Be multiplier / reflector 420. The outermost layer 520 in this case is a la volume of D_20 contained within the tank 415. The D_20 acts as a moderator to reduce radii leakage from the fission portion 400a, 400b. Figs. 26-29 illustrate similar structural compo but contain different materials within some or all of the volumes as will be discussed with t particular figures.

[00133] A common method to irradiate uranium is to form it into either uranium dioxide pellets or encase a uranium dioxide powder in a container. These are inserted into a reactoi irradiated before removal and processing. While the $U0_2$ powders being used today utilize HEU, it is preferable to use LEU. In preferred constructions, a mixture of LEU and H_20 th provides $\mathbf{K_{eff}} < 0.95$ is employed.

[00134] Figs. 26 and 27 illustrate an activation column 410 that includes $U0_2$ in a homogeneous solution with D_20. The center cylinder 500 in this construction is filled with 525, as is the outermost layer 530 (only a portion of which is illustrated). The first annular 535 contains a solution of 18% LEU (20% enriched) and 82% D_20. The second annular la 540 is substantially evacuated, consistent with the fusion portion target chambers 60, 70. T center cylinder 500, the first annular space 535, and the second annular space 540 are surro by a layer of Be 420, which serves as a multiplier and neutron reflector.

[00135] In another construction, Mo-99 is extracted from uranium by chemical dissolutii LEU foils in a modified Cintichem process. In this process, thin foils containing uranium a placed in a high flux region of a nuclear reactor, irradiated for some time and then removed foils are dissolved in various solutions and processed through multiple chemical techniques

[00136] From a safety, non-proliferation, and health perspective, a desirable way to prod Mo-99 is by (η,γ) reactions with parent material Mo-98. This results in Mo-99 with no contamination from plutonium or other fission products. Production by this method also dc not require a constant feed of any form of uranium. The disadvantage lies in the difficulty separating Mo-99 from the parent Mo-98, which leads to low specific activities of Mo-99 ii generator. Furthermore, the cost of enriched Mo-98 is substantial if that is to be used. Still considerable progress has been made in developing new elution techniques to extract high Tc-99m from low specific activity Mo-99, and this may become a cost-effective option in t near future. To implement this type of production in the hybrid reactor 5a, 5b illustrated he a fixed subcritical assembly 435 of LEU can be used to increase the neutron flux (most like UO_2), but can be isolated from the parent Mo-98. The subcritical assembly 435 is still loca inside of the fusion portion 10, 11, and the Mo-99 activation column would be located with subcritical assembly 435.

[00137] In preferred constructions, Mo-98 occupies a total of 20% of the activation colu: 410 (by volume). As illustrated in Figs. 28 and 29, the centermost cylinder 500 contains a homogeneous mixture of 20% Mo-98 and H_2O. The first annular layer 555 includes a subc assembly 435 and is comprised of an 18% LEU (20% enriched) / D_2O mixture. The seconc annular layer 560 is substantially evacuated, consistent with the fusion portion target chaml 60, 70. The center cylinder 500, the first annular space 555, and the second annular space i are surrounded by the layer of Be 420, which serves as a multiplier and neutron reflector. T outermost layer 570 (only a portion of which is illustrated) contains water that reduces the amount of radiation that escapes from the fission portion 5a, 5b.

[00138] For the LEU cases, the production rate and specific activity of Mo-99 was deten by calculating 6% of the fission yield, with a fusion portion 10, 11 operating at 10^{15} n / s. i was calculated for various configurations as well. Table 1 summarizes the results of these calculations. In the case of production from Mo-98, an (η,γ) tally was used to determine th production rate of Mo-99. The following table illustrates the production rates for various e configurations in the hybrid reactor 5a, 5b.

Target Configuration	K_{eff}	Mo-99 yield / g U (or Mo-98) (Ci)	Total Mo-99 yield @ saturation (6 day kCi)
Aqueous $UO_2(NO_3)_2$	0.947	1.51	2.93
UO_2 powder	0.945	2.92	22
Natural Mo (w subcritical)	0.943	0.68	2.69
Mo-98 (w subcritical)	0.943	2.83	11.1
Natural Mo (w/o subcritical)	-	0.085	0.44
Mo-98 (w/o subcritical)	-	0.35	1.8

[00139] While the specific activity of Mo-99 generated is relatively constant for all of th subcritical cases, some configurations allow for a substantially higher total production rate. is because these configurations allow for considerably larger quantities of parent material. also worth noting that production of Mo-99 from Mo-98 is as good a method as production LEU when it comes to the total quantity of Mo-99 produced. Still, the LEU process tends t more favorable as it is easier to separate Mo-99 from fission products than it is to separate i from Mo-98, which allows for a high specific activity of Mo-99 to be available after separa

[00140] In constructions in which Mo-98 is used to produce Mo-99, the subcritical asser 435 can be removed altogether. However, if the subcritical assembly 435 is removed, the specific activity of the end product will be quite a bit lower. Still, there are some indicatior advanced generators might be able to make use of the low specific activity resulting from N irradiation. The specific activity produced by the hybrid reactor 5a, 5b without subcritical multiplication is high enough for some of these technologies. Furthermore, the total deman U.S. Mo-99 could still be met with several production facilities, which would allow for a f free process.

[00141] For example, in one construction of a fusion only reactor, the subcritical assemb 435 is omitted and Mo-98 is positioned within the activation column 410. To enhance the production of Mo-99, a more powerful ion beam produced by the linear arrangement of the fusion portion 11 is employed. It is preferred to operate the ion beams at a power level approximately ten times that required in the aforementioned constructions. To achieve this magnetic field is established to collimate the beam and inhibit the undesirable dispersion of beams. The field is arranged such that it is parallel to the beams and substantially surround accelerator 30 and the pumping system 40 but does not necessarily extend into the target

chamber 70. Using this arrangement provides the desired neutron flux without the multipli effect produced by the subcritical assembly 435. One advantage of this arrangement is that uranium is required to produce the desired isotopes.

[00142] Thus, the invention provides, among other things, a segmented activation cell 6(use in producing medical isotopes. The segmented activation cell may be used, for exampl with a hybrid reactor 5a, 5b. The constructions of the hybrid reactor 5a, 5b described abovi illustrated in the figures are presented by way of example only and are not intended as a limitation upon the concepts and principles of the invention.

CLAIMS

We claim:

1. A reactor operable to produce an isotope, the reactor comprising:

a region for containing a controlled nuclear fission reaction, the region segmented plurality of independent compartments, each of the compartments for containing a material in an aqueous solution that interacts with neutrons to produce the isotope via a *i* reaction.

2. The reactor of claim 1, wherein the region is segmented into *n* indepi compartments, and *n* is an integer greater than or equal to 2.

3. The reactor of any one of the above claims, wherein the *n* compartments are ra symmetrically disposed about a central axis.

4. The reactor of any one of the above claims, wherein the fission reaction is maintain subcritical level, and driven by a neutron source.

5. The reactor of claim 4, wherein the neutron source comprises an ion source opera produce an ion beam from a gas, and a target chamber for holding a target which interact the ion beam to produce neutrons.

6. The reactor of claim 4 or 5, wherein the ion source and the target chamber togei least partially define a fusion reactor.

7. The reactor of any one of the above claims, wherein the parent material con uranium.

8. The reactor of claim 7, wherein the parent material comprises low enriched U-235.

9. The reactor of any one of the above claims, wherein the isotope comprises Mo-99.

10. A reactor operable to produce an isotope, the reactor comprising:

a fusion portion including a target path disposed within a target chambe substantially encircles a space, the fusion portion operable to produce a neutron flux witl target chamber; and

a fission portion for containing a controlled nuclear fission reaction, the fission p segmented into a plurality of independent compartments and positioned within the spa containing a parent material in an aqueous solution that reacts with a portion of the neutro to produce the isotope during a fission reaction.

11. The reactor of claim 10, wherein the fission portion is divided into *n* compartmem *n* is an integer greater than or equal to 2.

12. The reactor of claim 11, wherein the *n* compartments are radially symmetrically dis about a central axis.

13. The reactor of any one of claims 10-12, wherein the parent material comprises uran:

14. The reactor of claim 13, wherein the parent material comprises low enriched U-235

15. The reactor of any one of the above claims, wherein the isotope comprises Mo-99.

16. A method of producing an isotope, the method comprising:

positioning a parent material in an aqueous solution within a region for contaii controlled nuclear reaction, the region segmented into a plurality of independent compartm

reacting, in at least one of the compartments over a time period *y*, neutrons wi parent material to produce the isotope; and

extracting the aqueous solution comprising the isotope from the compartment.

17. The method of claim 16, wherein the fission reaction is subcritical and driven neutron source produced by exciting a gas to produce an ion beam; accelerating the ion

passing the accelerated ion beam through a target path including a target gas, the target g the ions reacting through a fusion reaction to produce neutrons.

18. The method of claim 16 or 17, wherein the region is segmented into *n* indepi compartment, and *n* is an integer which is greater than or equal to 2 to 10, and *y* is about 1 about 2 weeks.

19. The method of any one of claims 16-18, wherein *y* is about 12 h to about 2 weeks.

20. The method of claim 18, wherein *n* is an integer from 3 to 8.

21. The method of any one of claims 16-20, wherein the parent material comprises uran

22. The reactor of claim 13, wherein the parent material comprises low enriched U-235

23. The reactor of any one of the above claims, wherein the isotope comprises Mo-99, 1-125, Xe-133, Cs-137, Co-60, or Sr-89.

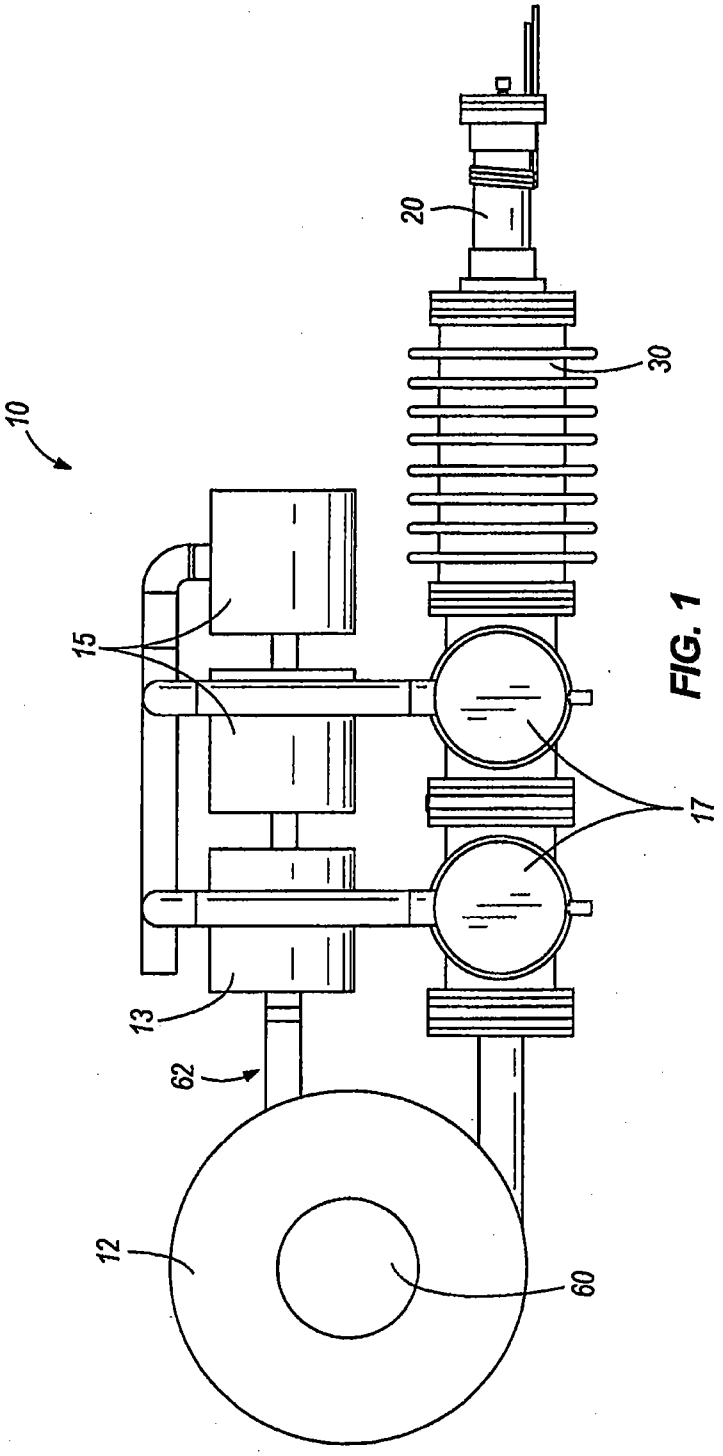


FIG. 1

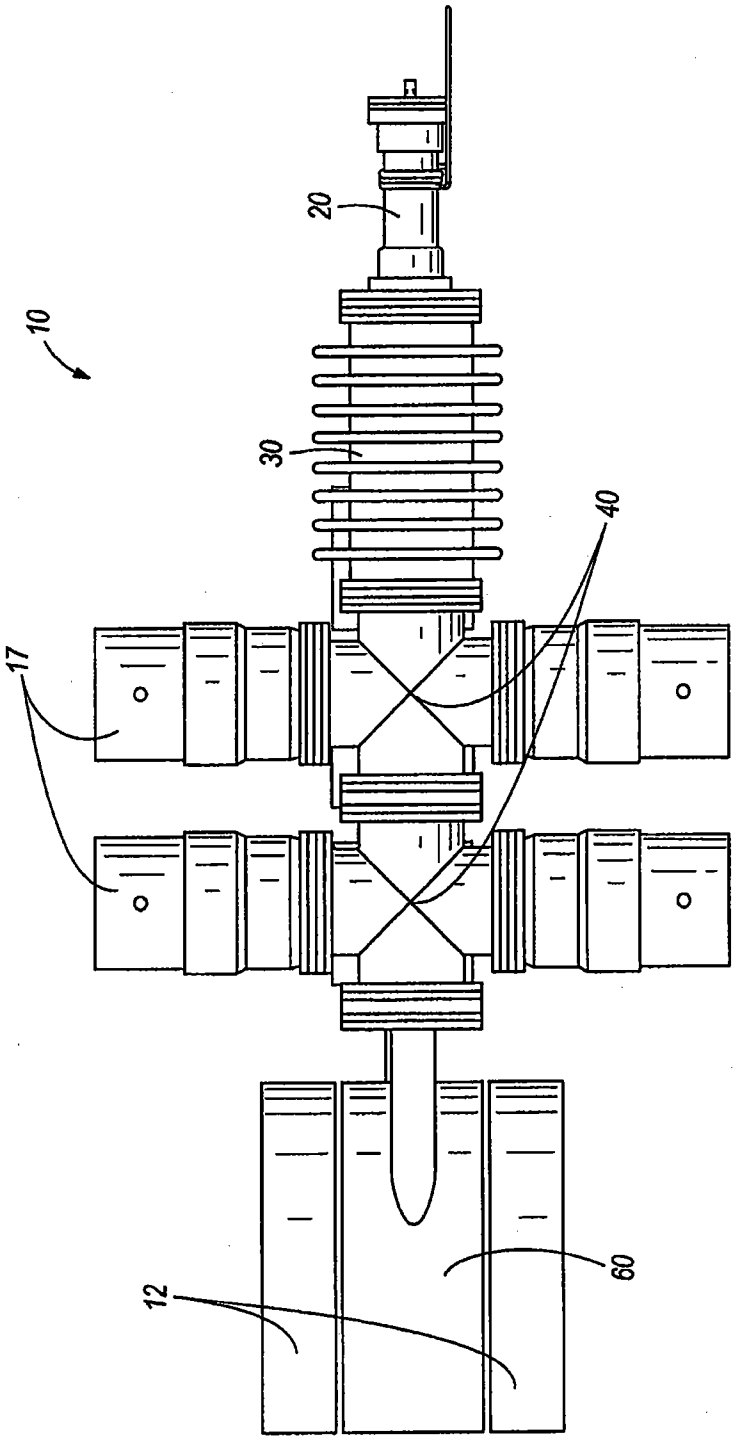


FIG. 2

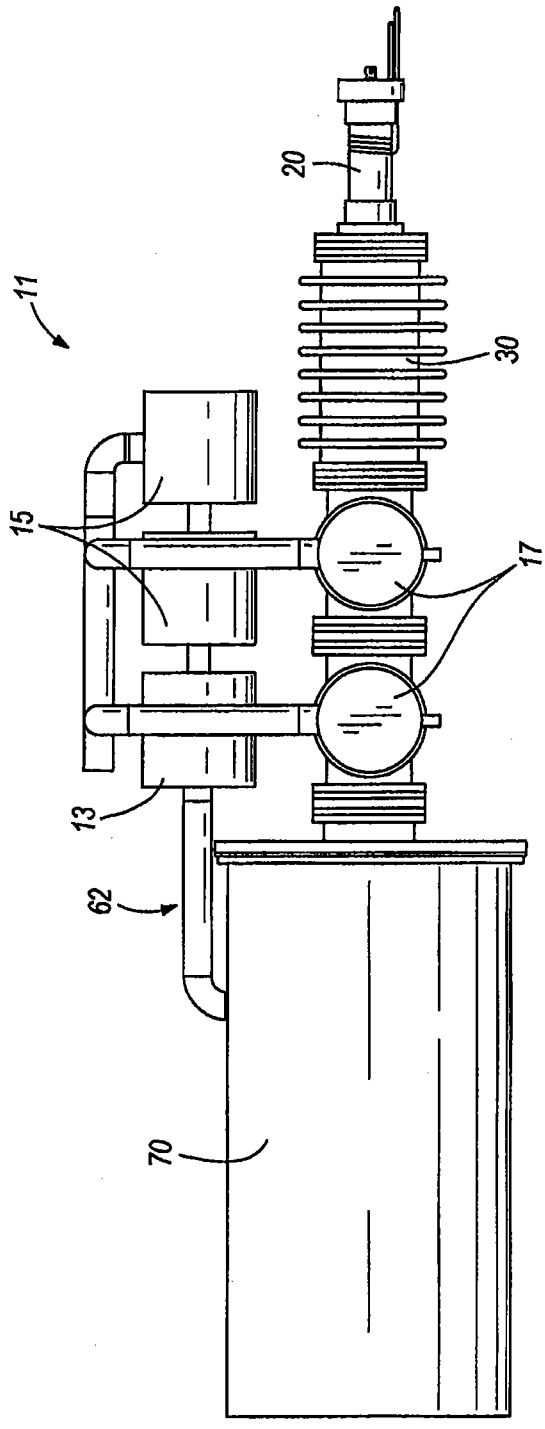


FIG. 3

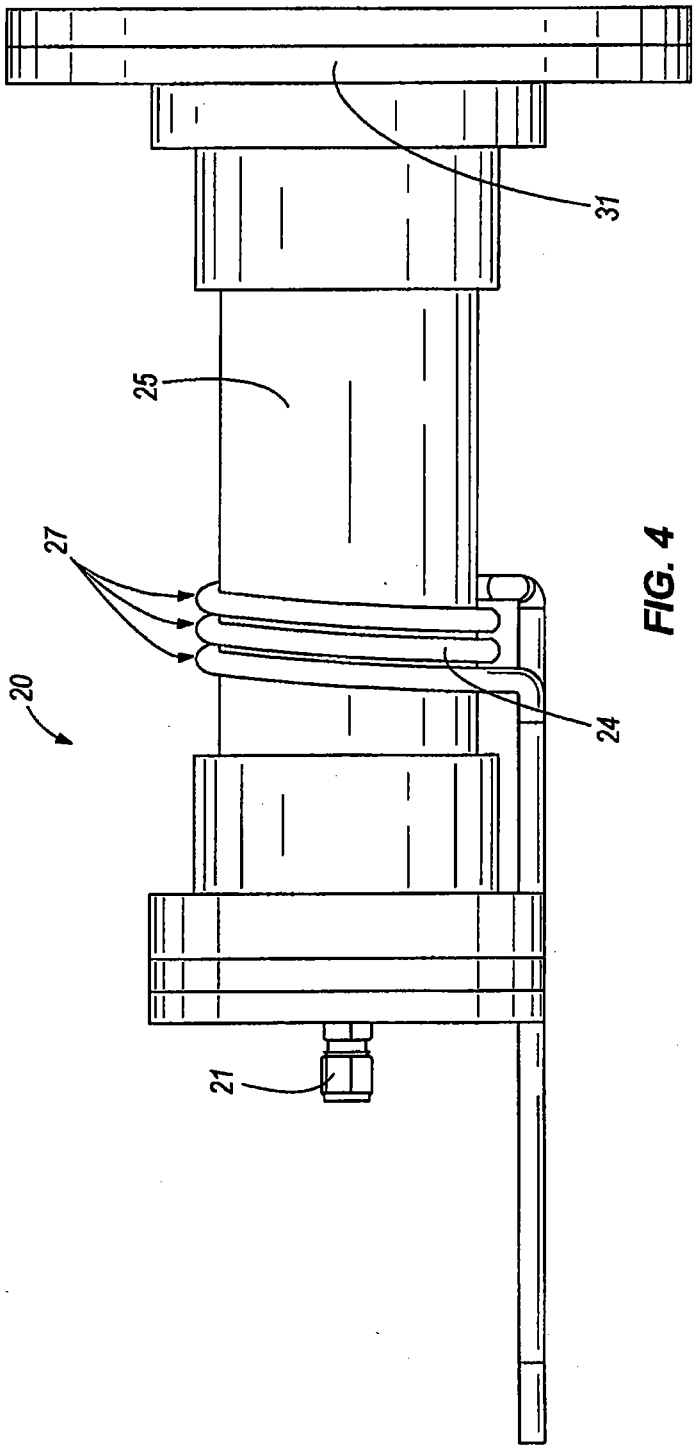


FIG. 4

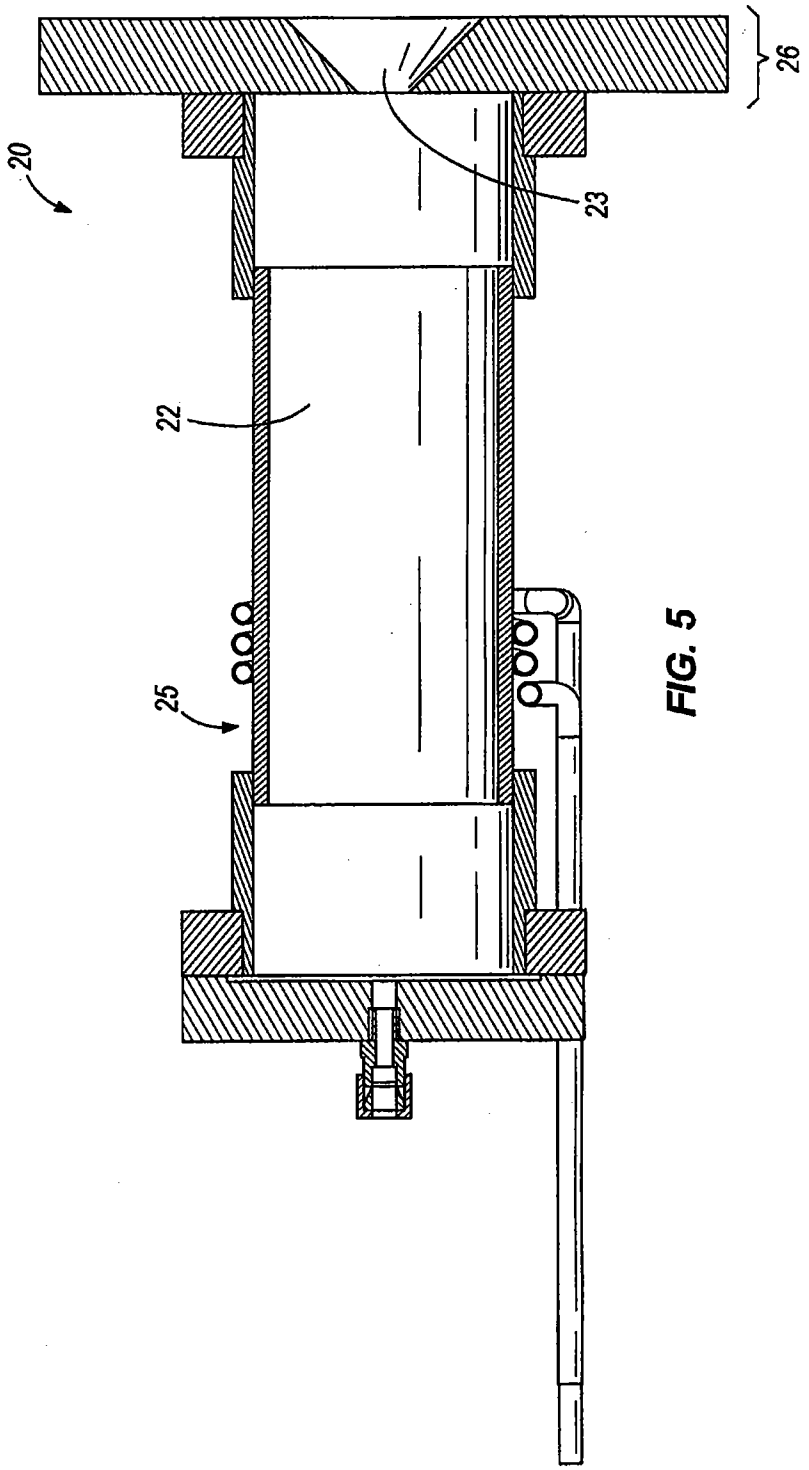


FIG. 5

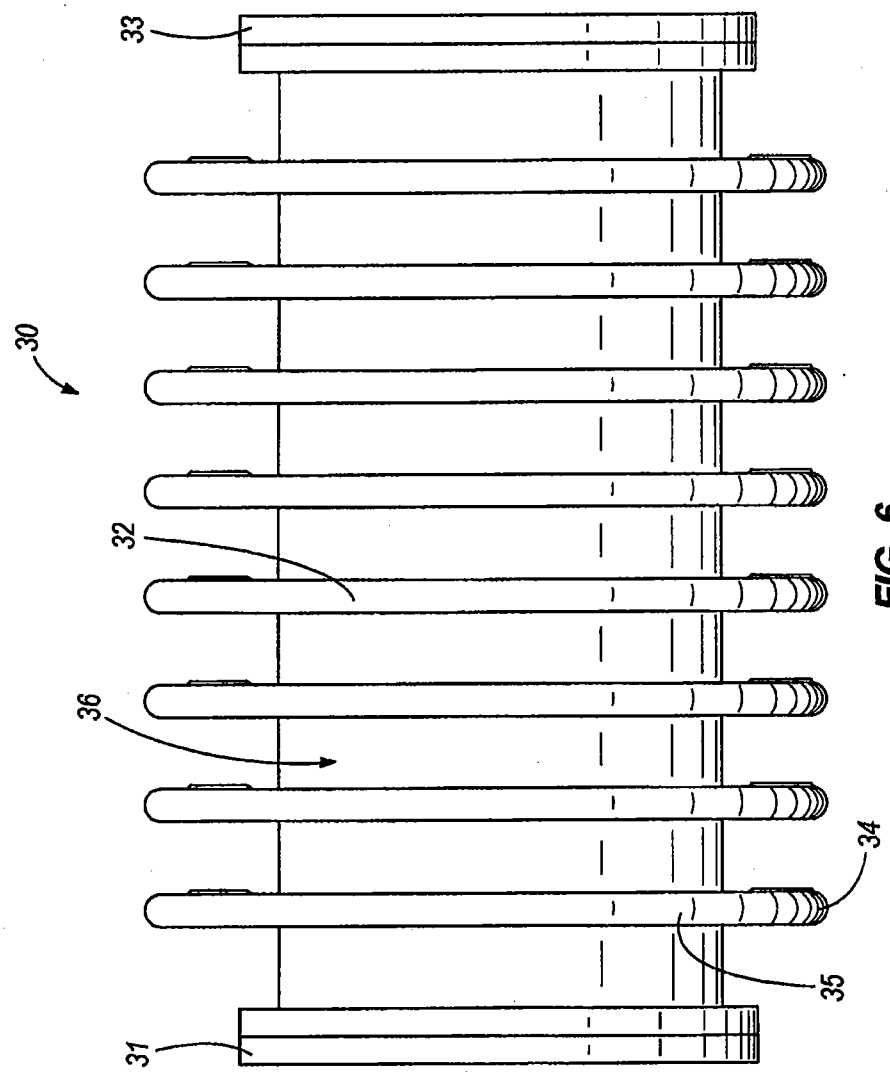


FIG. 6

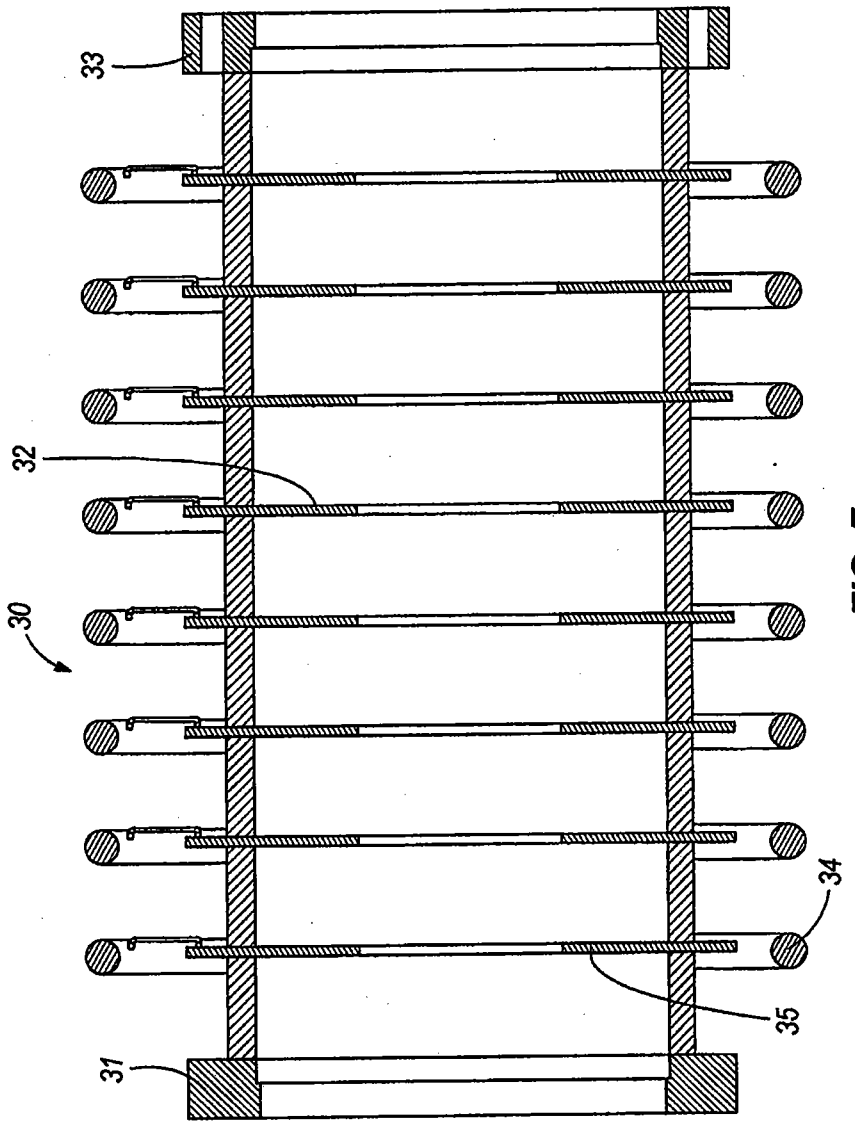


FIG. 7

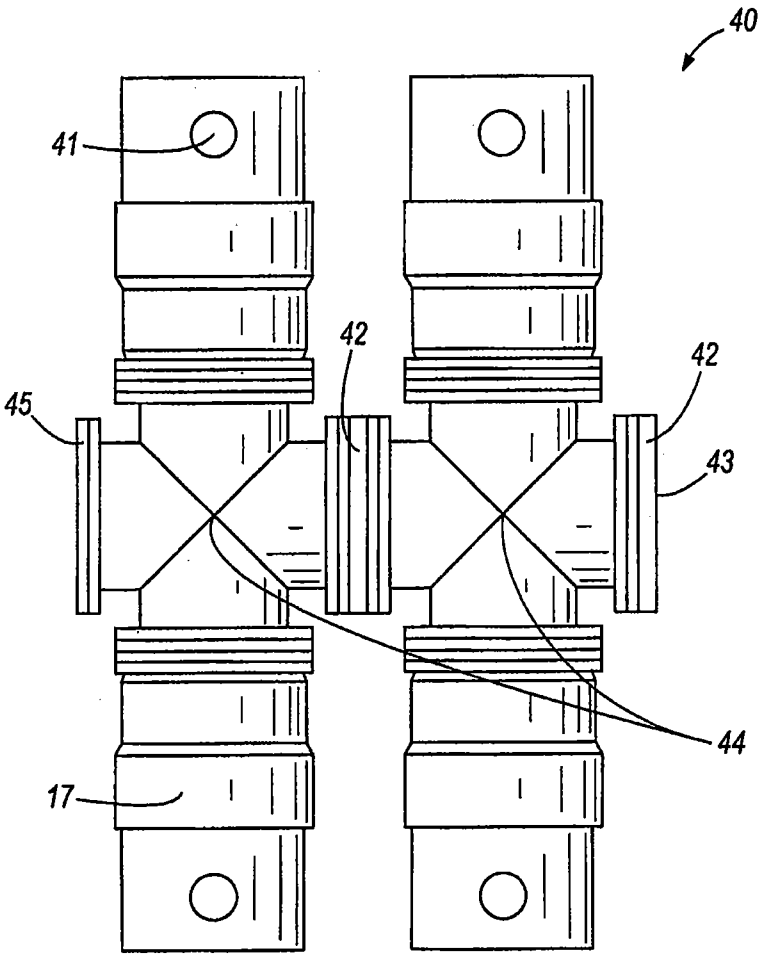


FIG. 8

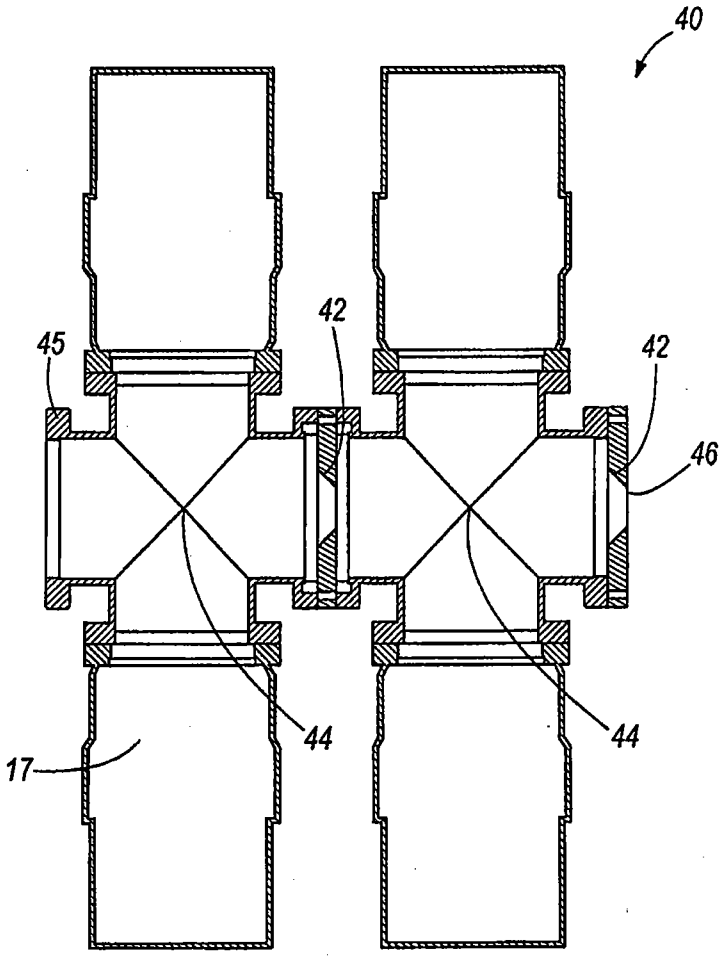


FIG. 9

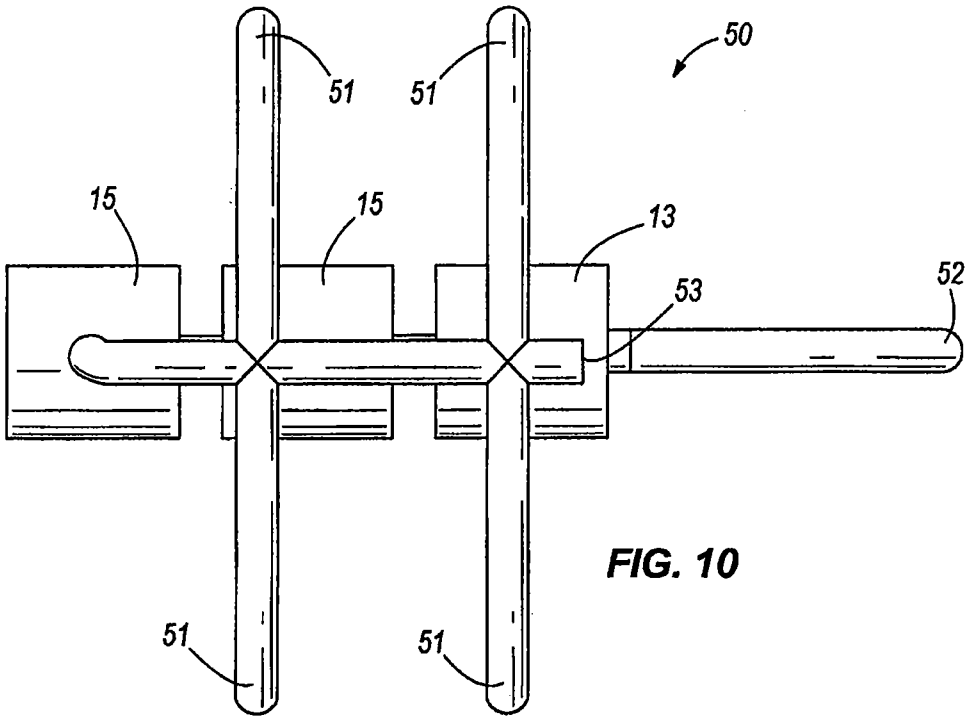


FIG. 10

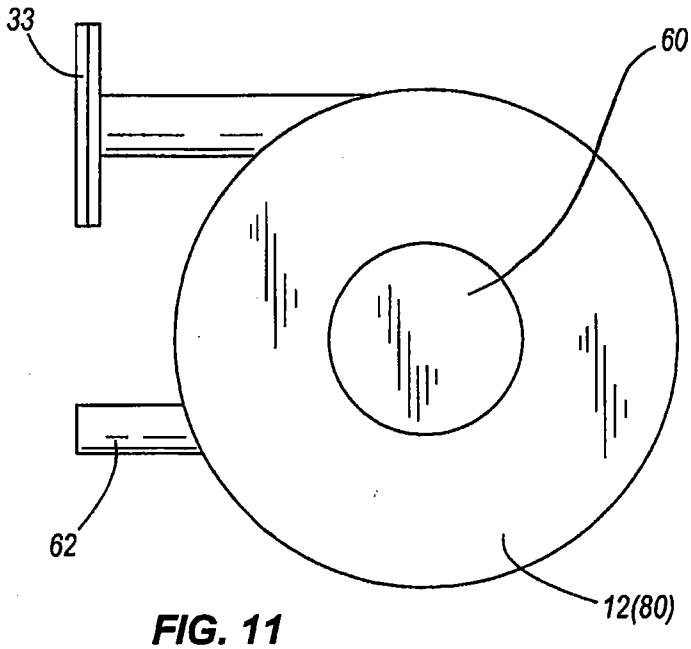


FIG. 11

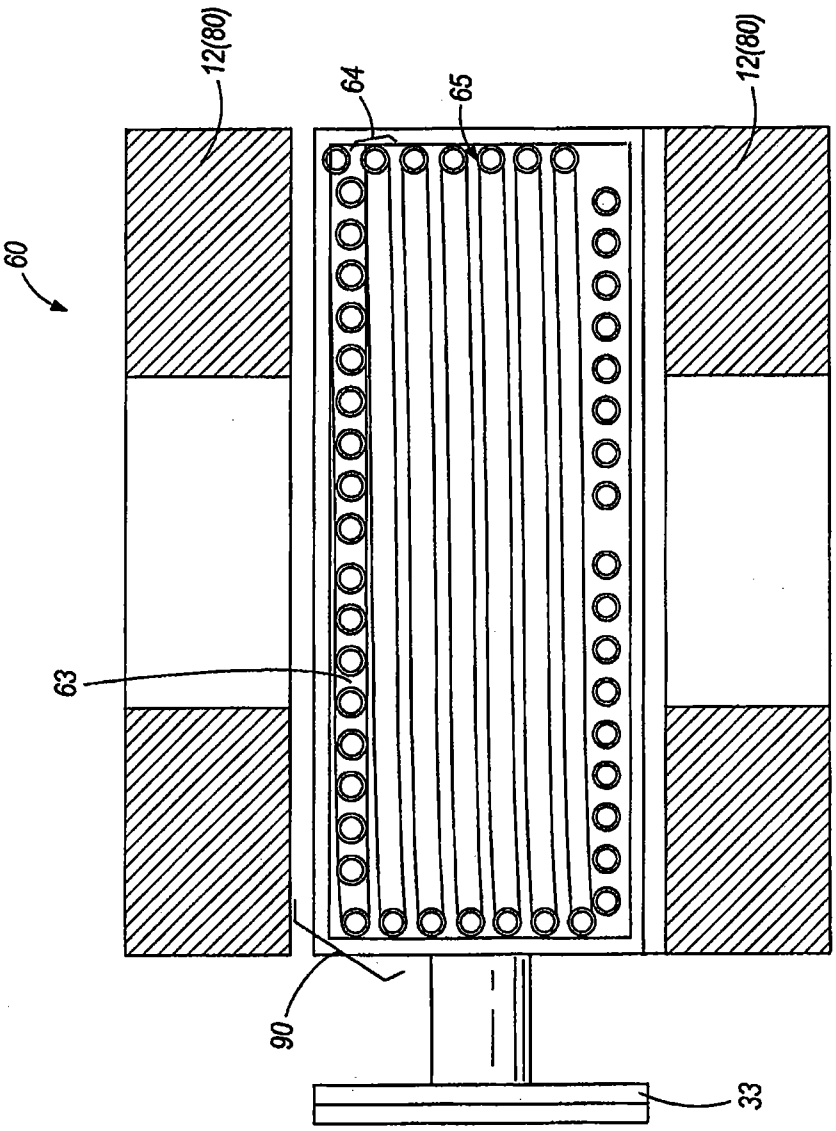


FIG. 12

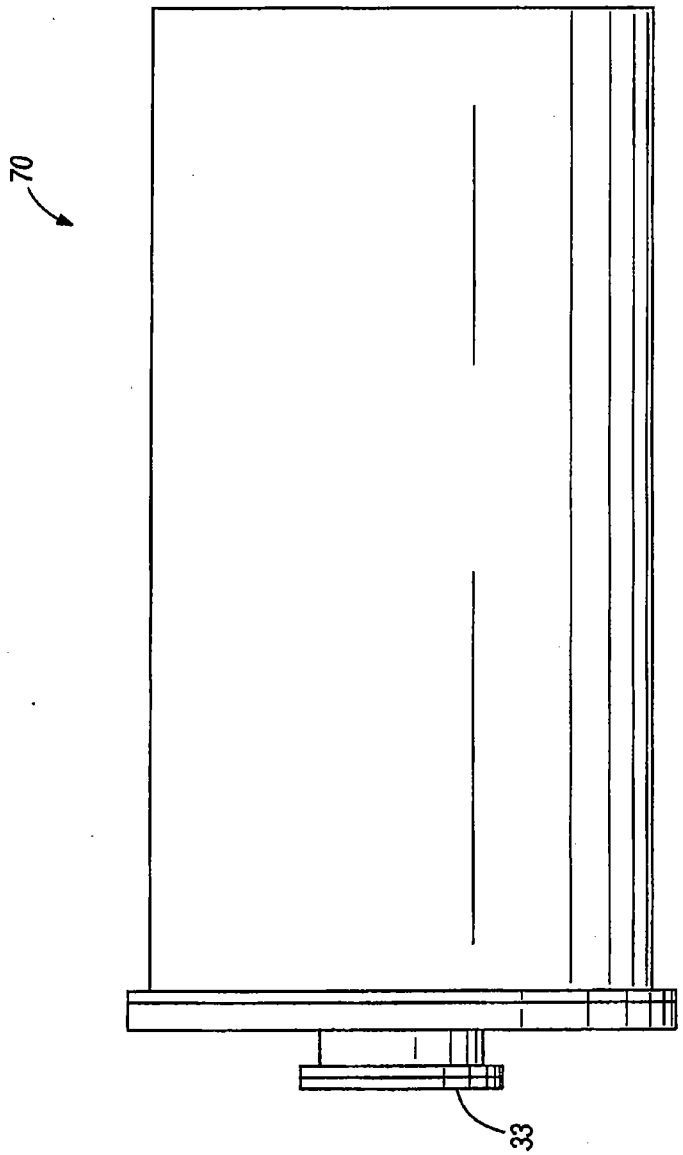


FIG. 13

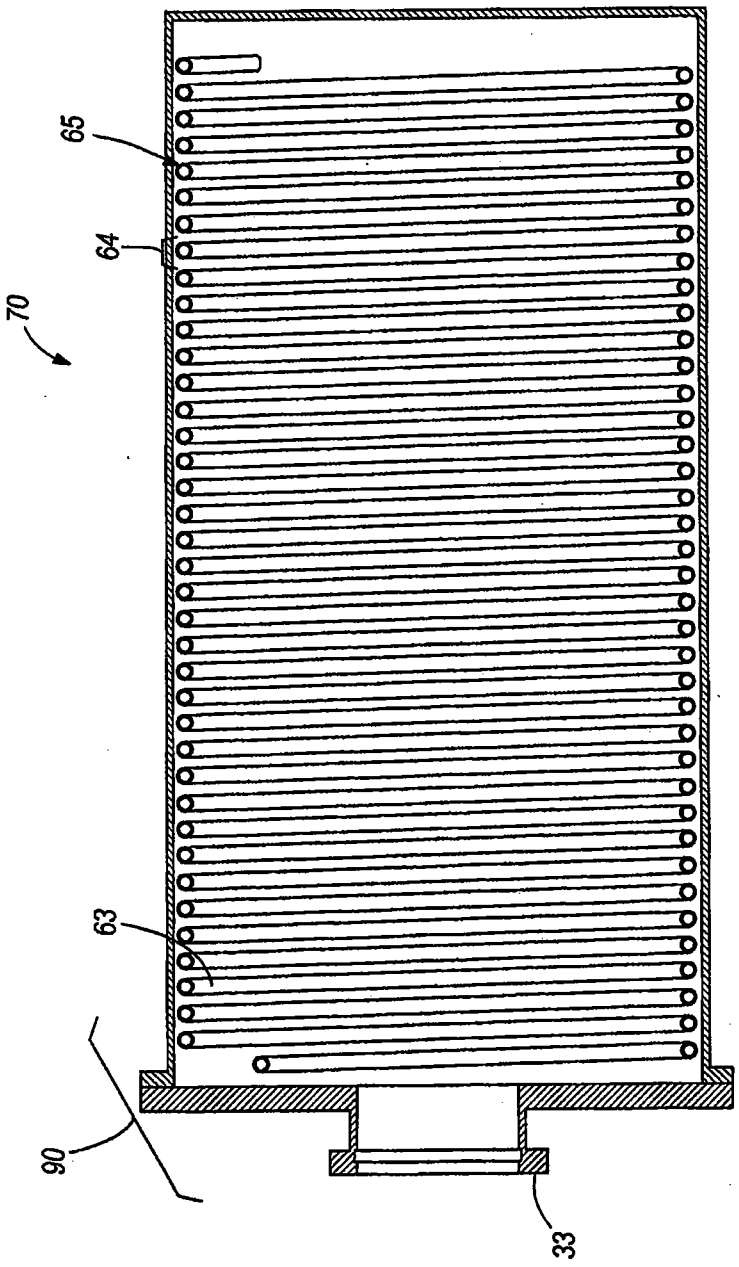


FIG. 14

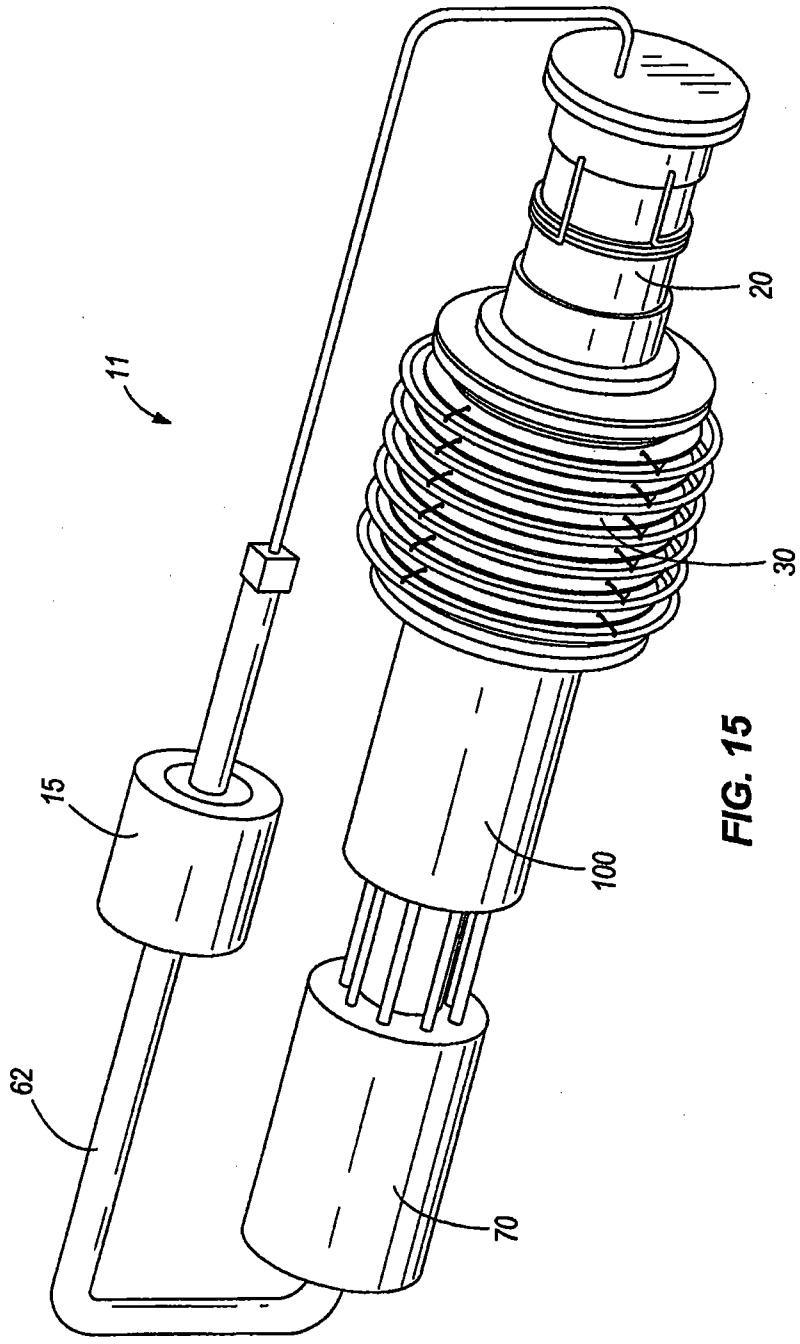


FIG. 15

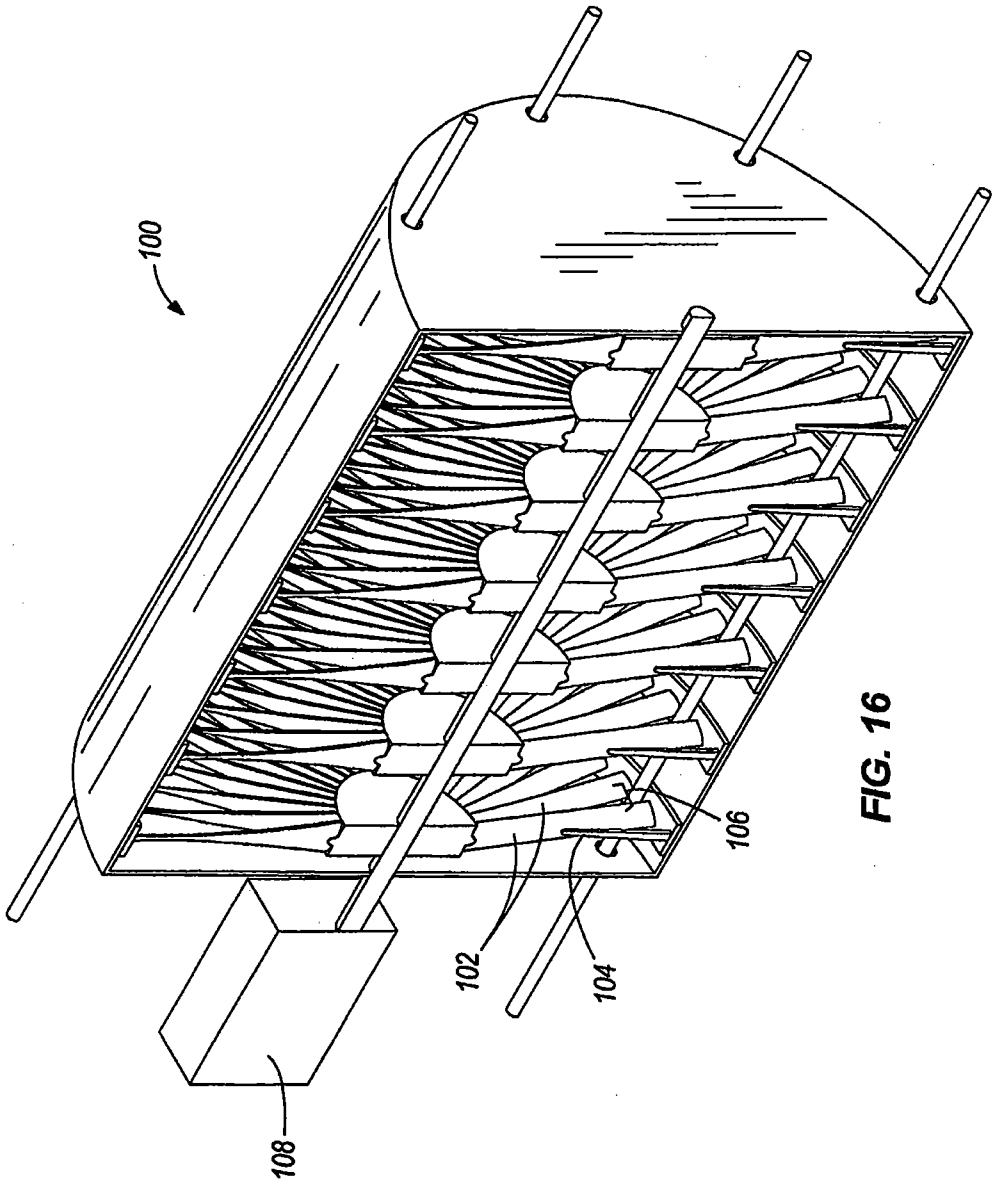


FIG. 16

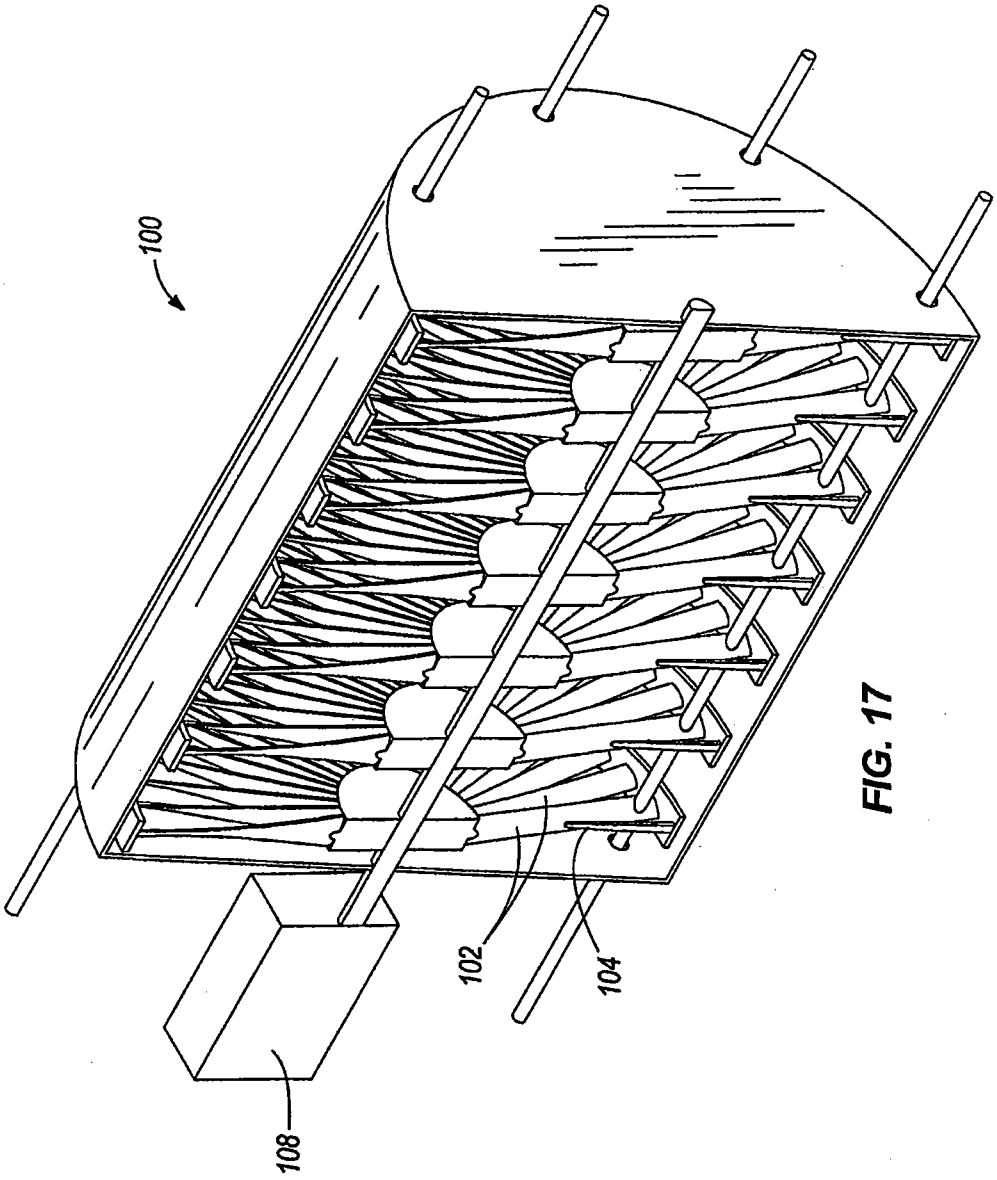


FIG. 17

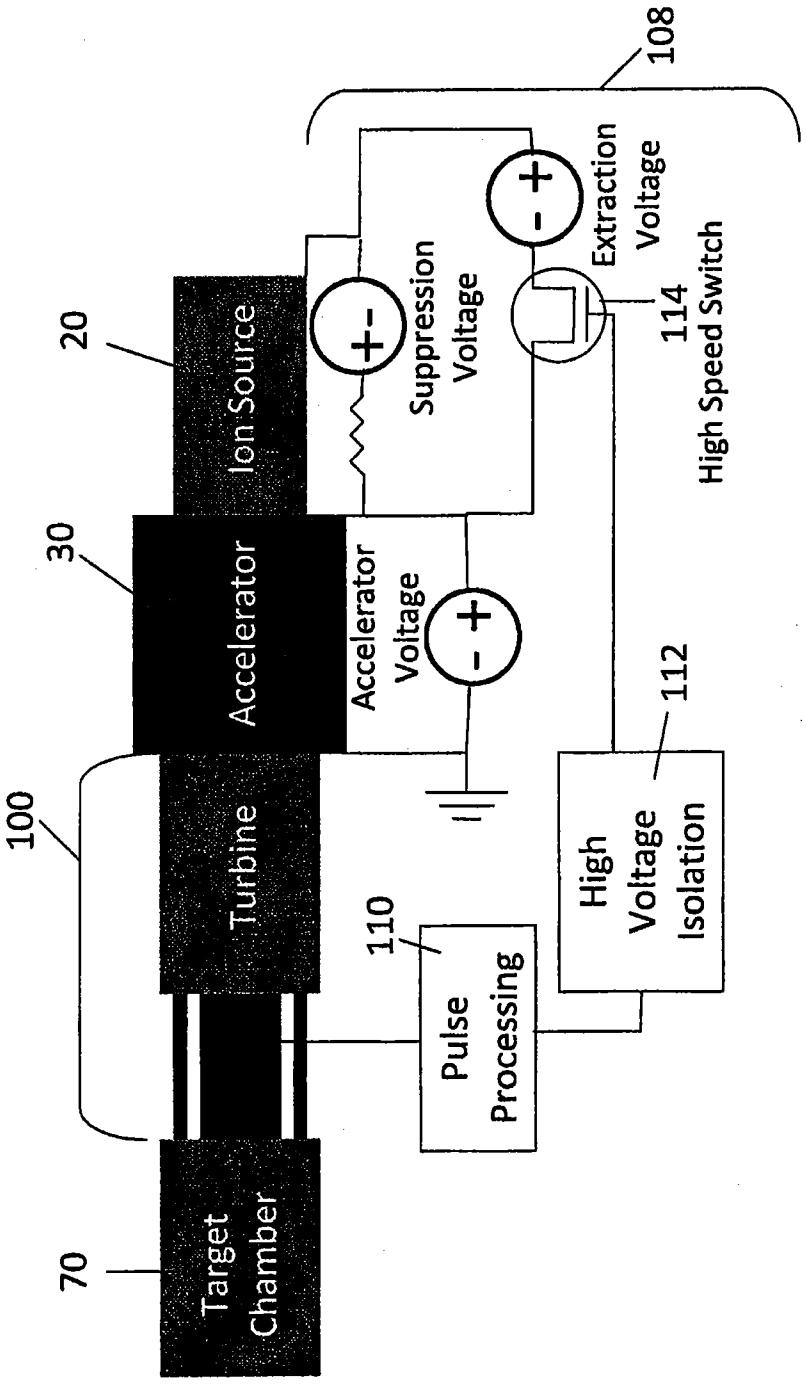

108
20
Ion Source
Suppression Voltage
Extraction Voltage
114
High Speed Switch
30
Accelerator
Accelerator Voltage
112
100
Turbine
110
Pulse Processing
High Voltage Isolation
70
Target Chamber

FIG. 18

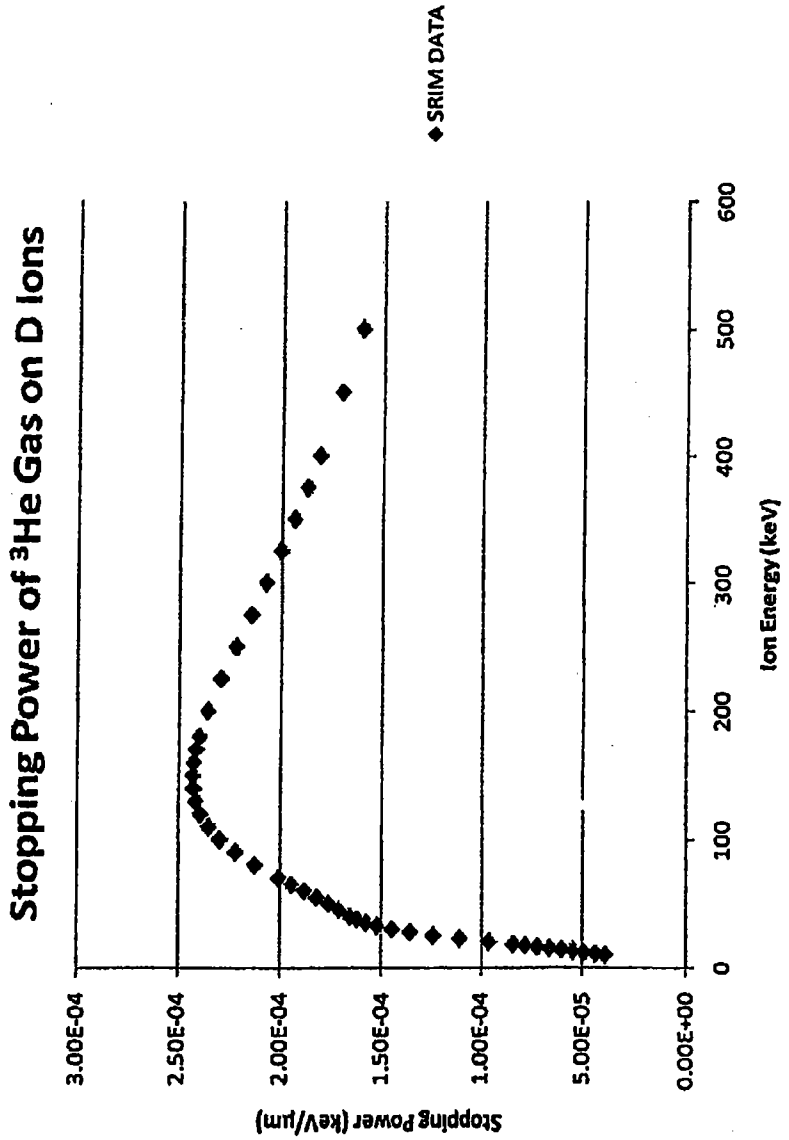

Stopping Power of ^{3}He Gas on D Ions
◆ SRIM DATA
Stopping Power (keV/µm)
3.00E-04
2.50E-04
2.00E-04
1.50E-04
1.00E-04
5.00E-05
0.00E+00
0
100
200
300
400
500
600
Ion Energy (keV)

FIG. 19

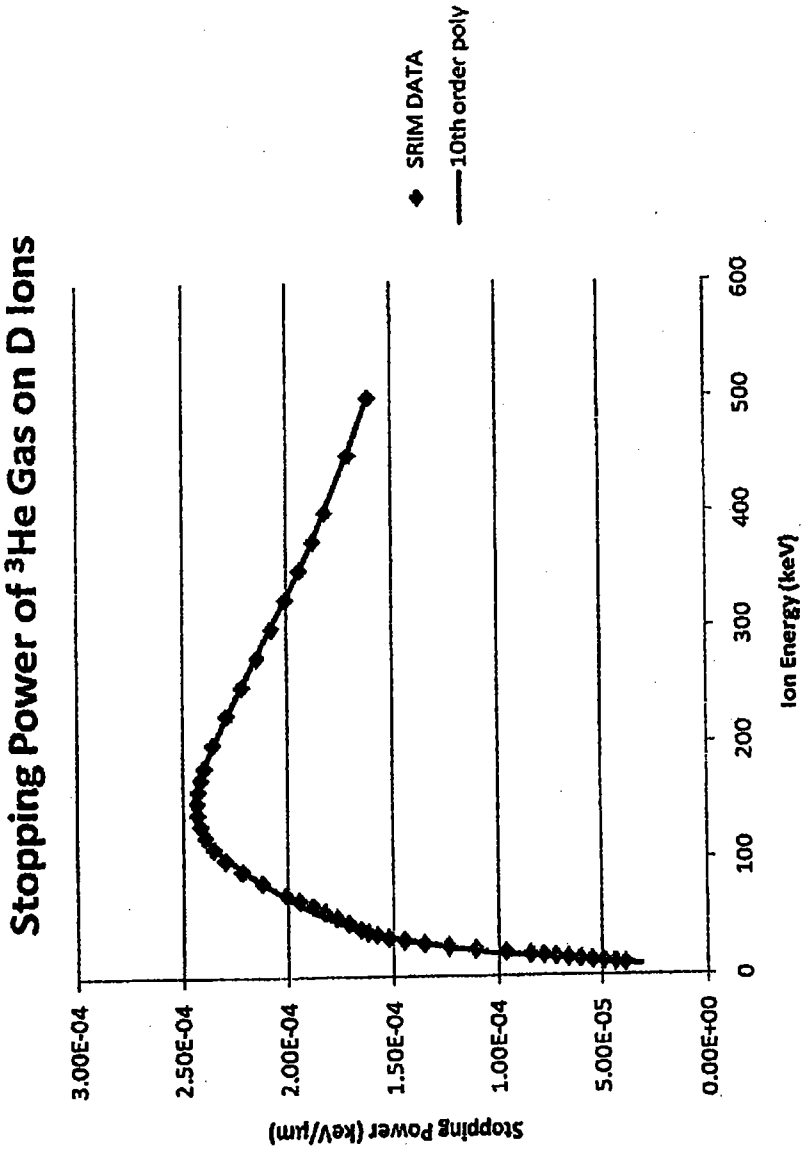

Stopping Power of 3He Gas on D Ions
SRIM DATA
10th order poly
Stopping Power (keV/μm)
3.00E-04
2.50E-04
2.00E-04
1.50E-04
1.00E-04
5.00E-05
0.00E+00
0
100
200
300
400
500
600
Ion Energy (keV)

FIG. 20

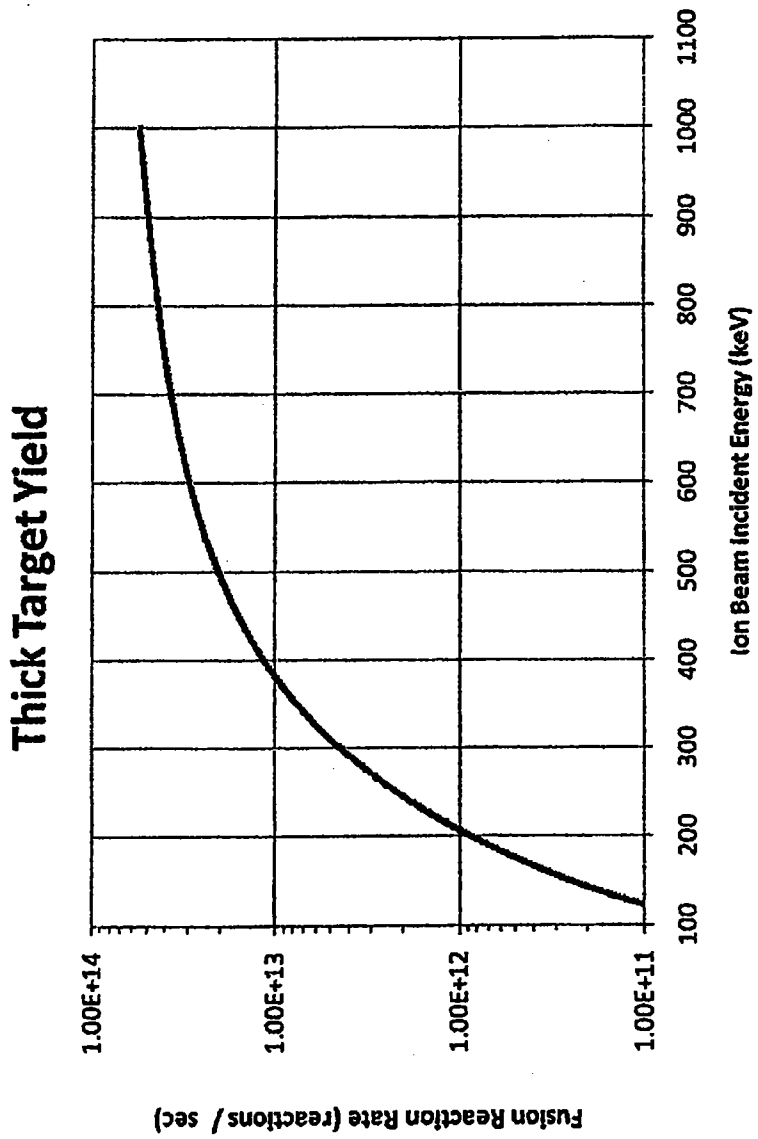

Thick Target Yield
Fusion Reaction Rate (reactions / sec)
1.00E+14
1.00E+13
1.00E+12
1.00E+11
100
200
300
400
500
600
700
800
900
1000
1100
Ion Beam Incident Energy (keV)

FIG. 21

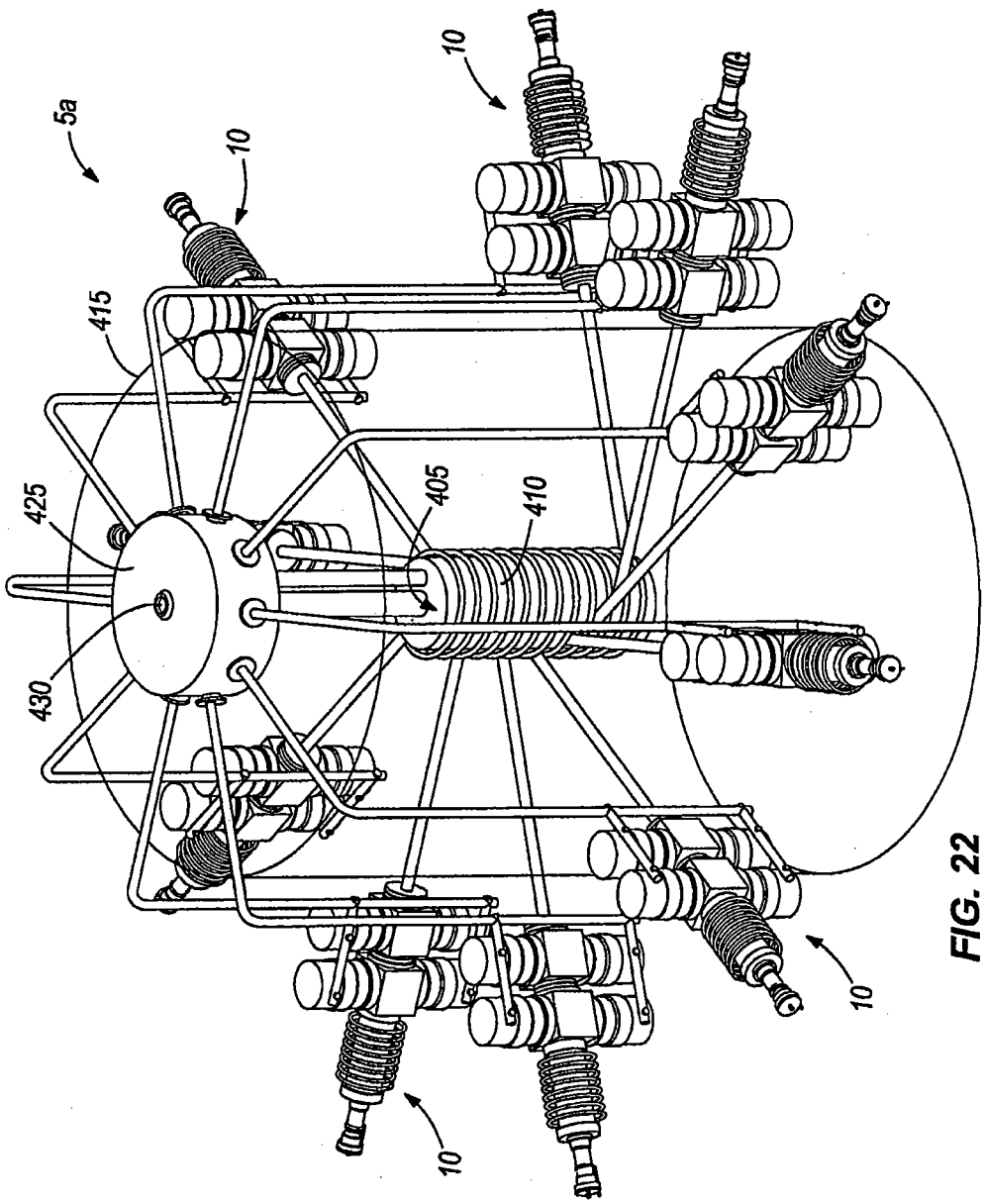


FIG. 22

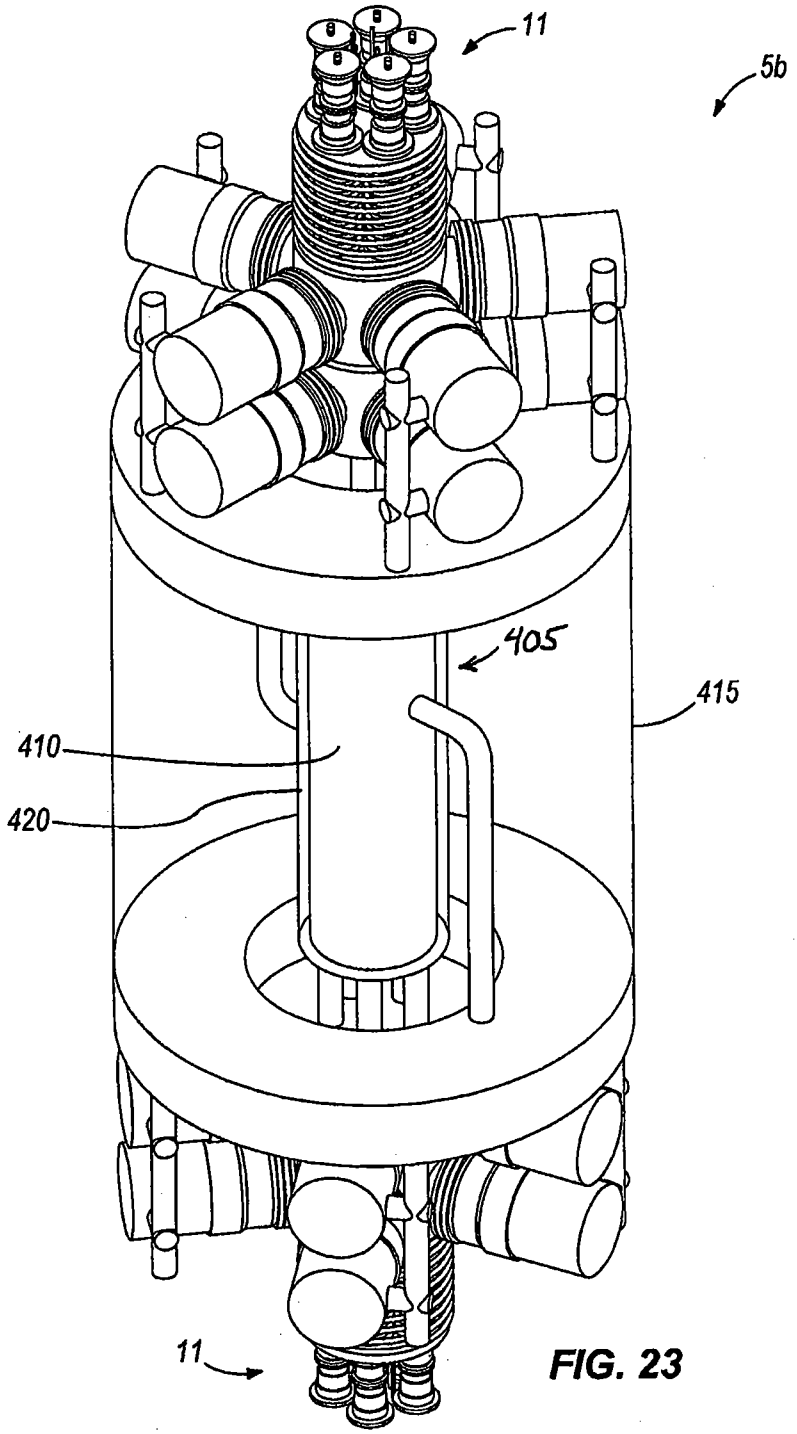


FIG. 23

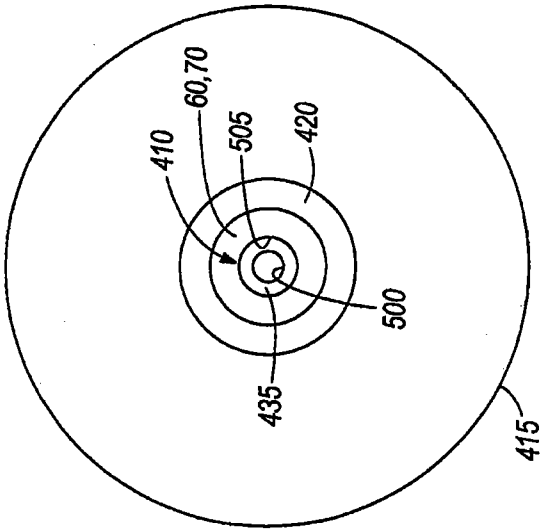

60,70
505
420
410
500
435
415

FIG. 25

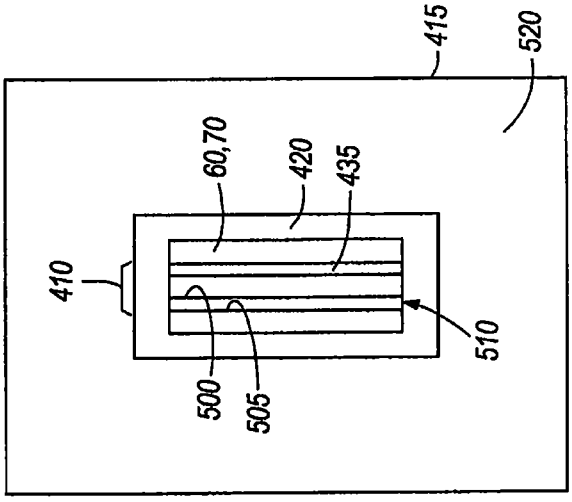

415
520
60,70
420
435
410
510
500
505

FIG. 24

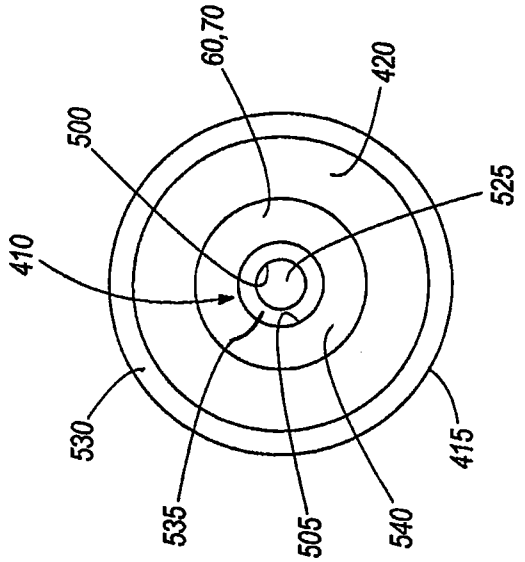

60,70
420
500
525
410
530
415
535
505
540

FIG. 27

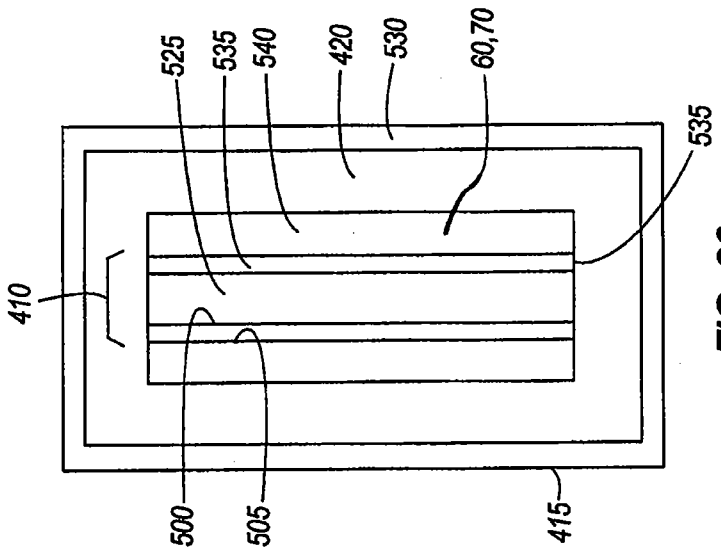

525
535
540
420
530
60,70
535
410
500
505
415

FIG. 26

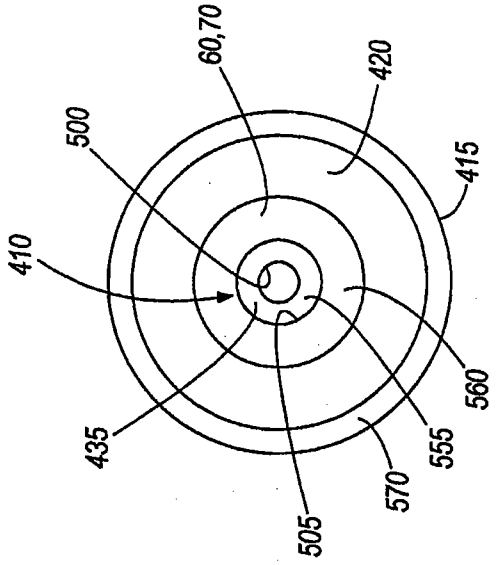

60,70
420
500
415
410
560
435
555
570
505

FIG. 29

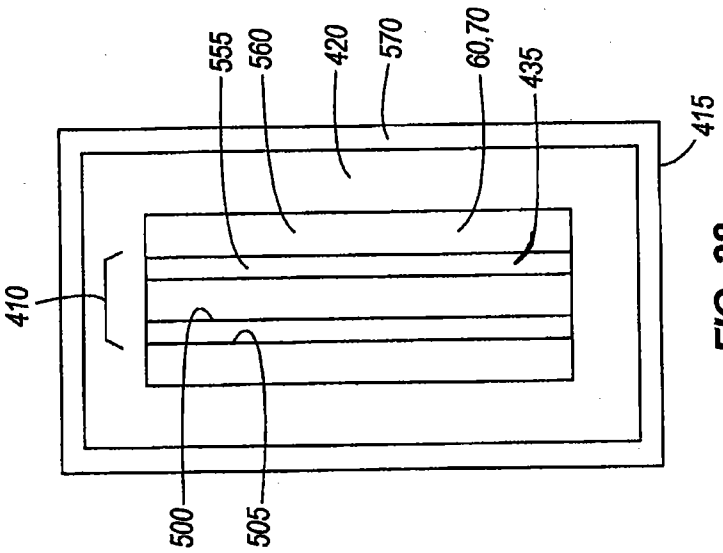

555
560
420
570
60,70
435
415
410
500
505

FIG. 28

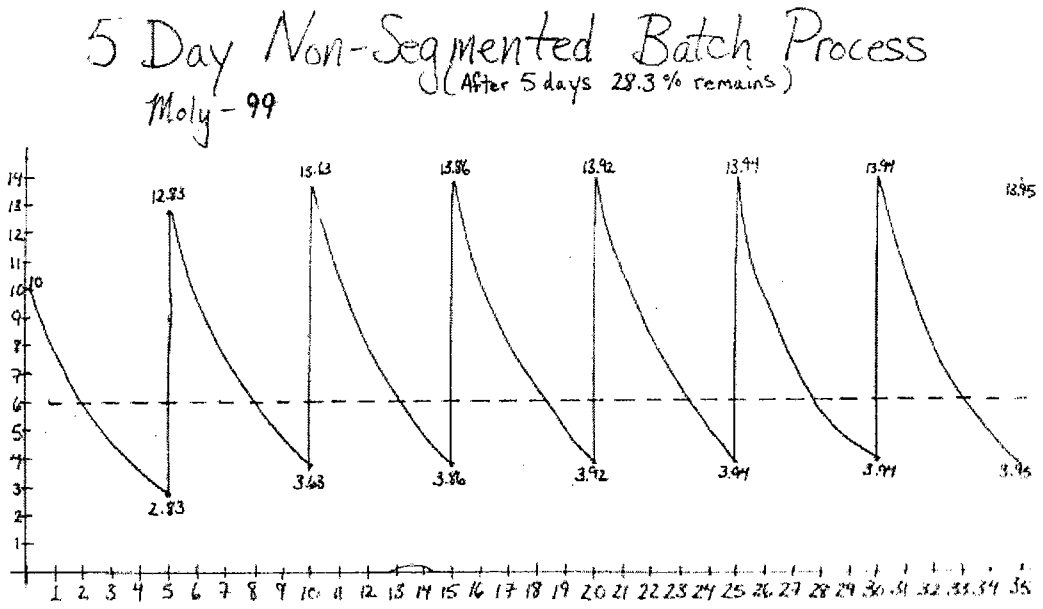

5 Day Non-Segmented Batch Process
(After 5 days 28.3% remains)
Moly-99
12.83
13.13
13.86
13.92
13.94
13.94
13.95
10
2.83
3.48
3.86
3.92
3.94
3.94
3.95

FIG. 30

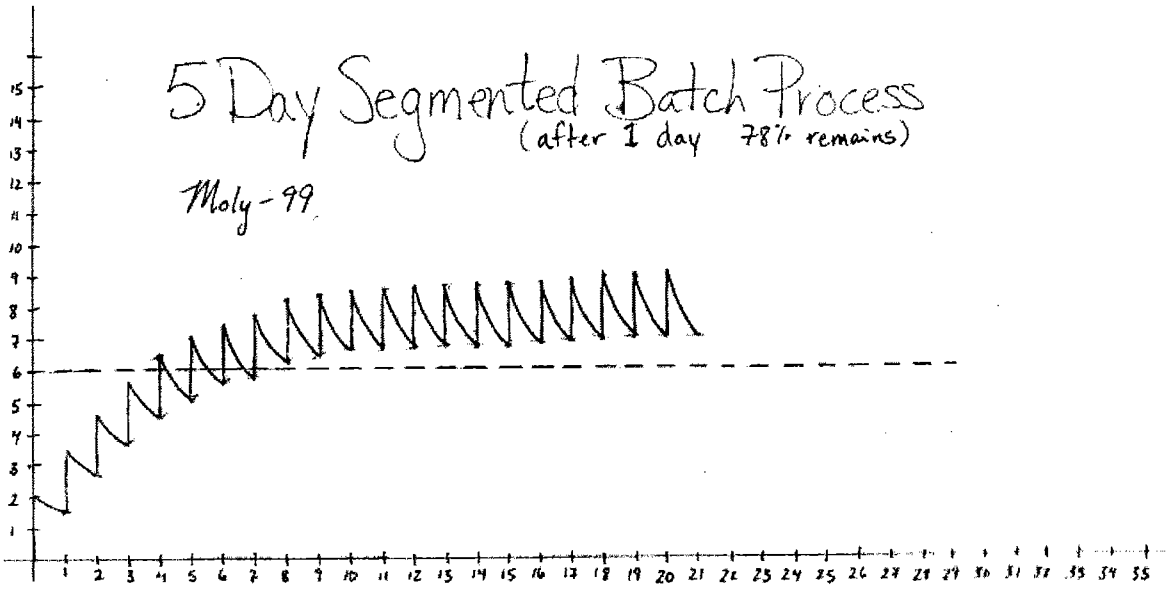

5 Day Segmented Batch Process
(after 1 day 78% remains)
Moly-99

FIG. 31

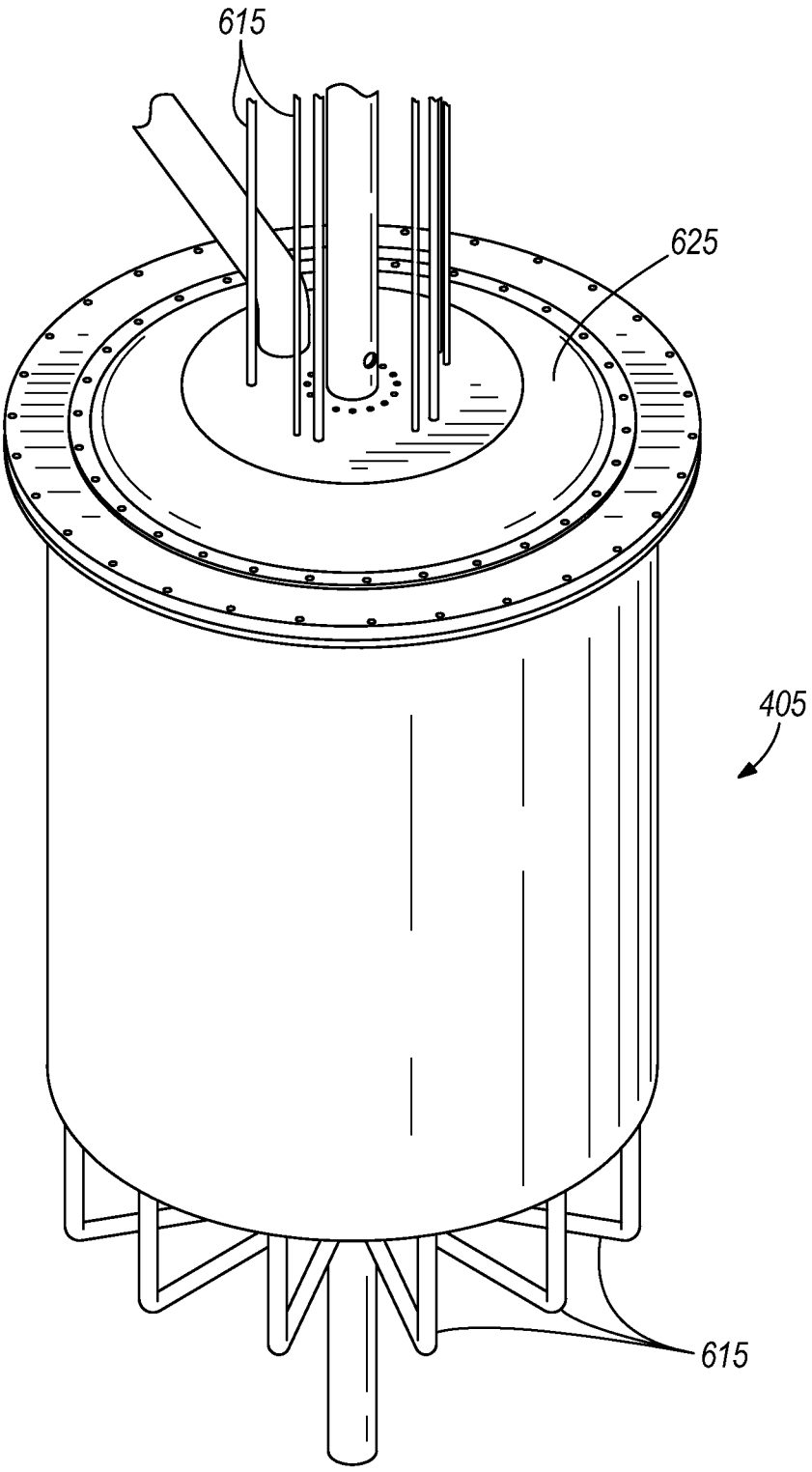
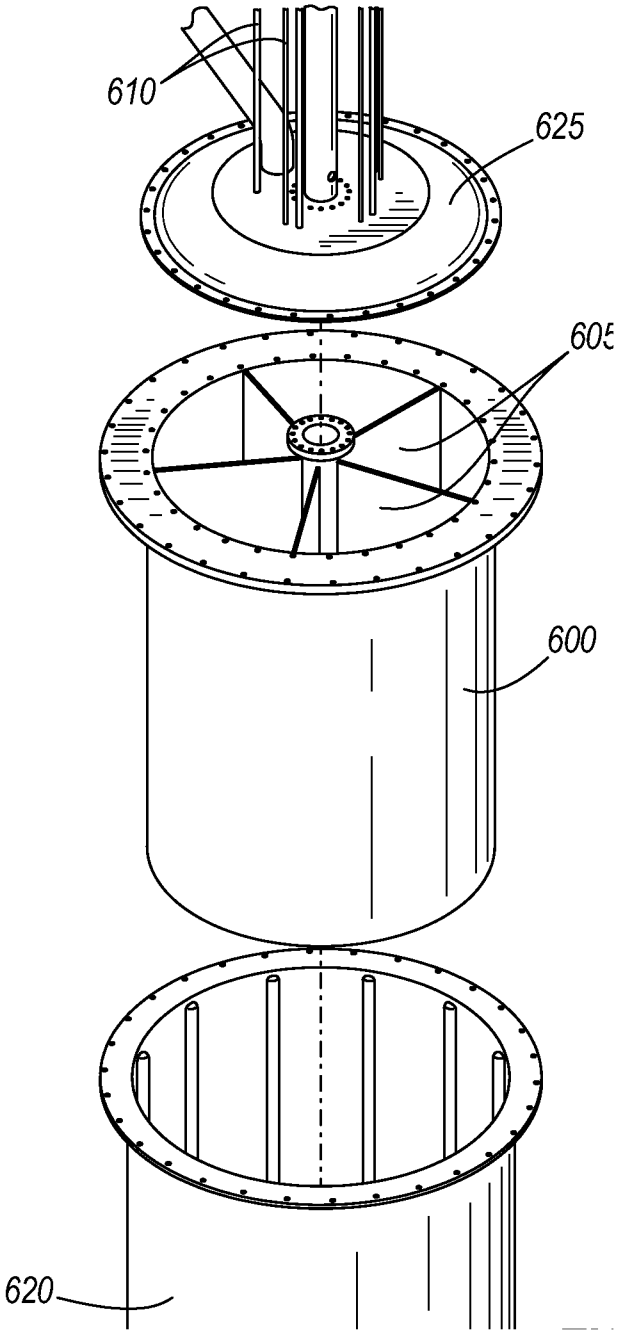


FIG. 32


610
625
605
600
620

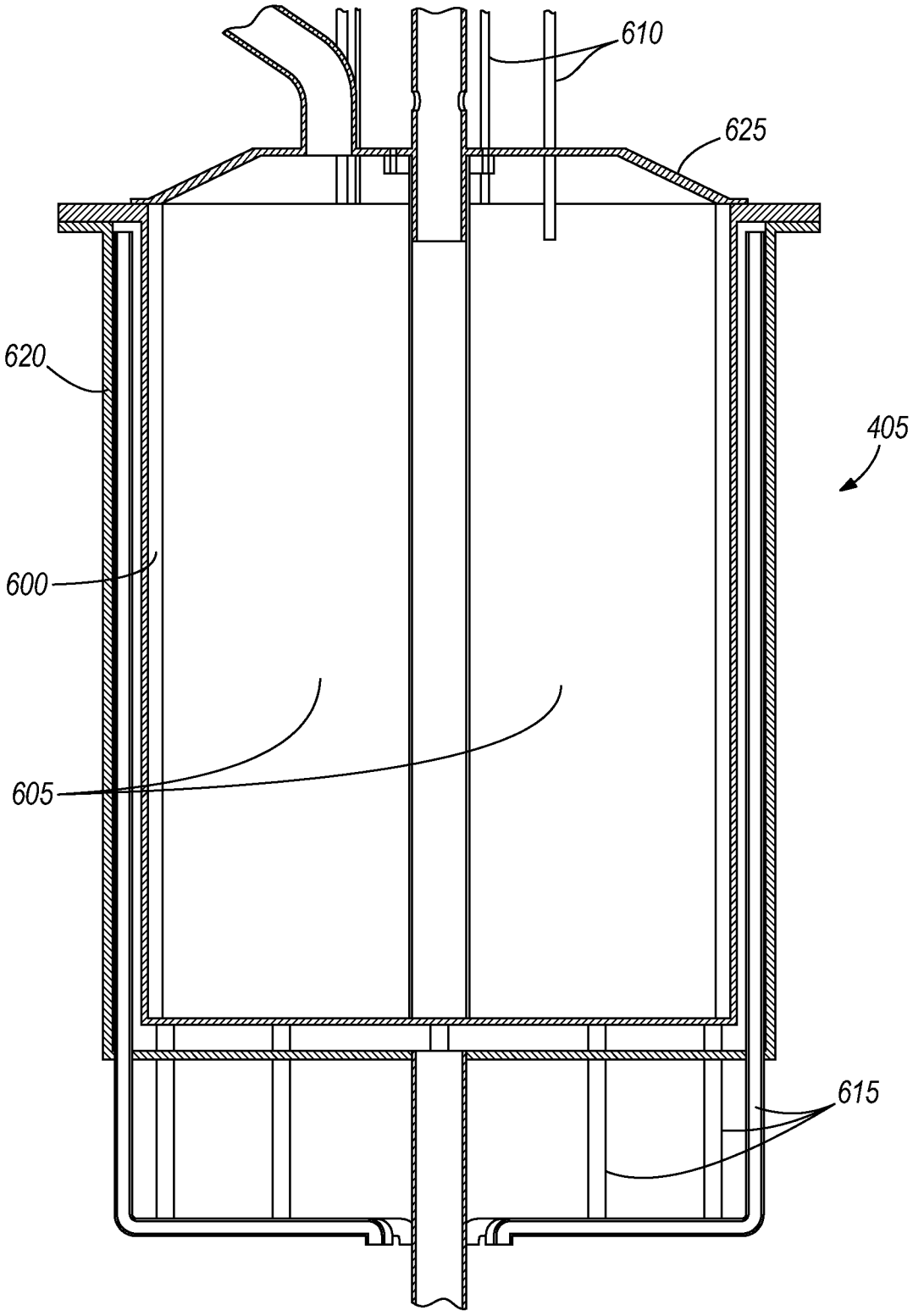


FIG. 34

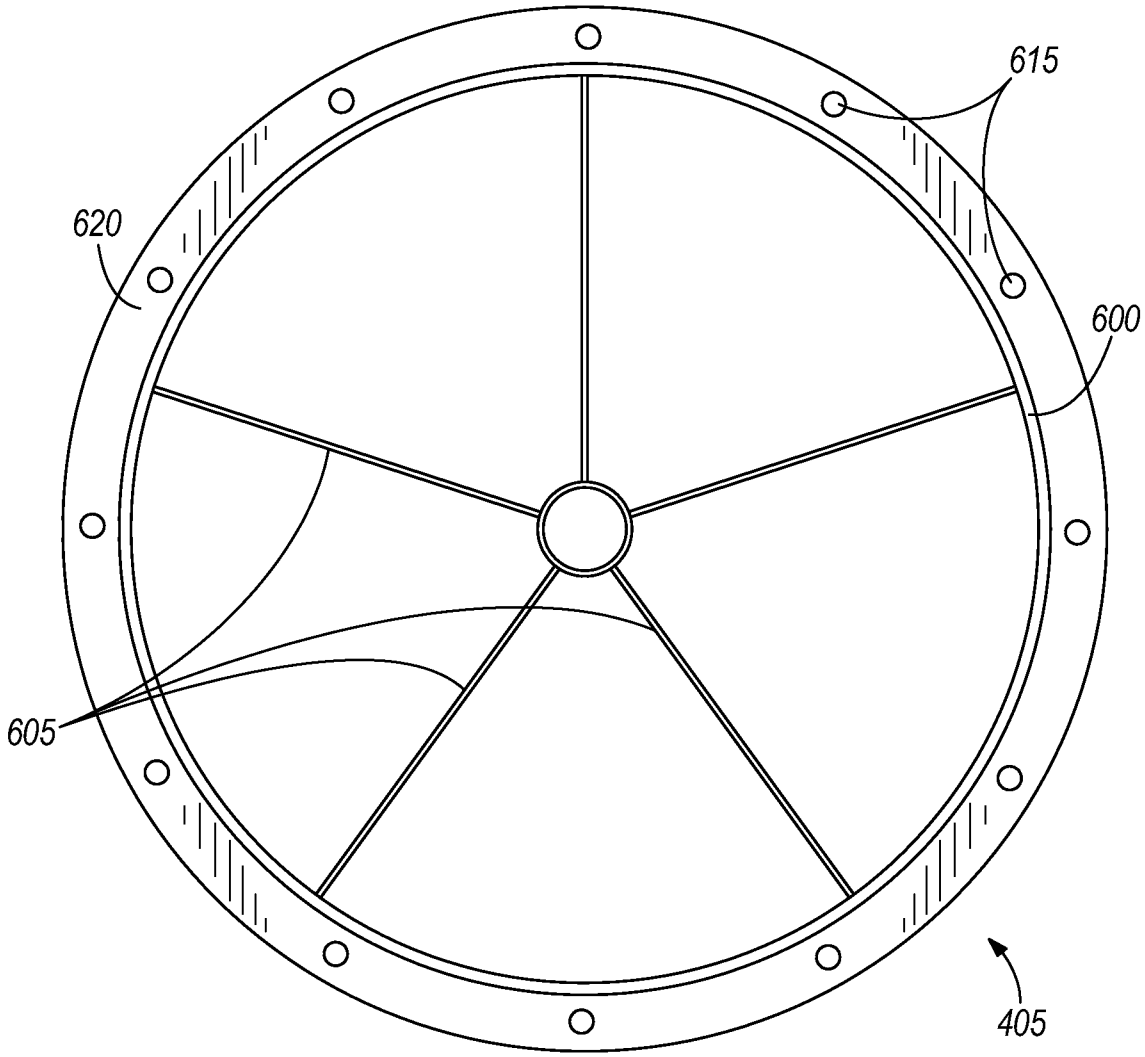


FIG. 35