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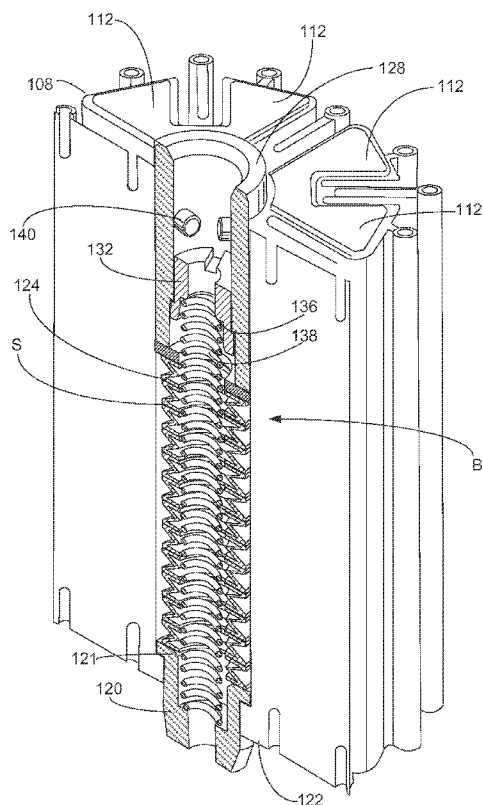
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[Continued on next page]

(54) Title: CONTROL ROD ASSEMBLY IMPACT LIMITER



(57) Abstract: A control rod assembly including at least one movable control rod including a neutron absorbing material, a control rod drive mechanism (CRDM) for controlling movement of the at least one control rod, and a coupling operatively connecting the at least one control rod and the CRDM. The coupling includes a terminal element engaged with a connecting rod of the CRDM and the at least one moveable control rod, and a kinetic energy absorbing element supported by the terminal element for absorbing kinetic energy during a SCRAM event, the kinetic energy absorbing element configured to act between the terminal element and an upper plate of an associated fuel assembly.



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CONTROL ROD ASSEMBLY IMPACT LIMITER

[0001] This application claims the benefit of U.S. Provisional Application No. 61/624,034 filed April 13, 2012. U.S. Provisional Application No. 61/624,034 filed April 15, 2012 is incorporated herein by reference in its entirety.

BACKGROUND

[0002] The following relates to the nuclear power reactor arts, nuclear reaction control apparatus arts, control rod assembly arts, and related arts.

[0003] In thermal nuclear power plants, a nuclear reactor core comprises a fissile material having size and composition selected to support a desired nuclear fission chain reaction. The core is disposed in a pressure vessel immersed in primary coolant water. It is further known to control or stop the reaction by inserting "control rods" comprising a neutron-absorbing material into guide tubes passing through the reactor core. When inserted, the control rods absorb neutrons so as to slow or stop the chain reaction.

[0004] The control rods are operated by control rod drive mechanisms (CRDMs). In so-called "regulating" control rods, the insertion of the control rods is continuously adjustable so as to provide continuously adjustable reaction rate control. In so-called "shutdown" control rods, the insertion is either fully in or fully out. During normal operation the shutdown rods are fully retracted from the reactor core; during a SCRAM, the shutdown rods are rapidly fully inserted so as to rapidly stop the chain reaction. Control rods can also be designed to perform both regulating and shutdown rod functions. In some such dual function control rods, the control rod is configured to be detachable from the CRDM in the event of a SCRAM, such that the detached control rod falls into the reactor core under the influence of gravity. In some systems, such as naval systems, a hydraulic pressure or other positive force (other than gravity) is also provided to drive the detached control rod into the core.

[0005] To complete the control system, a control rod/CRDM coupling is provided. A known coupling includes a connecting rod having a lower end at which a spider is

secured. The upper portion of the connecting rod operatively connects with the CRDM. In regulating rods, this connection includes a lead screw or other incremental adjustment element. Conventionally, the lead screw scrams with the connecting rod, spider, and control rods as a translating assembly (also known as the "control rod assembly"). In some known approaches, however, the lead screw may be retained in the CRDM such that only the connecting rod scrams. See, e.g. U.S. Pub. No. 2010-0316177 A1 published Dec. 16, 2010 which is incorporated herein by reference in its entirety, and U.S. Pub. No. 2011-0222640 A1 published Sept. 15, 2011 which is incorporated herein by reference in its entirety. To reduce cost and overall system complexity, a single CRDM is typically connected with a plurality of control rods via a spider. In this arrangement, all the control rods coupled with a single spider together as a translating control rod assembly (CRA). In practice a number of CRDM units are provided, each of which is coupled with a plurality of control rods via a spider, so as to provide some redundancy. The spider extends laterally away from the lower end of the connecting rod to provide a large "surface area" for attachment of multiple control rods.

[0006] The translating CRA (including the control rods, spider, connecting rod, and optionally also the lead screw) represents a substantial mass that falls under the force of gravity during a scram. It is advantageous for the translating CRA to have substantial mass in order to provide the driving force for the scram. In some designs, the translating CRA has a mass of a hundred pounds to a few hundred pounds, and may reach a terminal velocity of 10 feet per second or higher. Thus, consideration is given to the termination of the scram, that is, to the slowing and stopping of the downward falling of the translating assembly at the end of the scram event.

[0007] Prior to termination of the scram, the descending control rod tips engage dashpot tubes of narrowed inner diameter that produce a slowing force via a piston effect. Alternatively, a dashpot can be located in the CRDM which engages with the descending connecting rod or lead screw. Although such dashpots can provide some cushioning, the ultimate "stop" for the scram is impact of the descending spider onto the top of the fuel assembly (or onto a structural plate located above the fuel assembly). To cushion this final impact, it is known to employ one or more helical springs disposed in the connecting rod and/or spider. However, it is difficult to insert long springs into the translating CRA, and shorter springs do not provide large

energy absorption. As a consequence, a substantial portion of the kinetic energy of the translating CRA is ultimately absorbed by the impact of the spider onto the fuel assembly, which can lead to damage to these critical components.

BRIEF SUMMARY

[0008] In one aspect of the disclosure, a control rod assembly comprises at least one movable control rod including a neutron absorbing material, a connecting rod configured for connection to an associated control rod drive mechanism (CRDM) for controlling movement of the at least one control rod, and a coupling operatively connecting the at least one control rod and the connecting rod. The coupling includes a spider engaged with the connecting rod and the at least one moveable control rod, and a kinetic energy absorbing element supported by the spider for absorbing kinetic energy during a SCRAM event, the kinetic energy absorbing element configured to act between the spider and an associated impact surface.

[0009] The spider can include a casing having an upper surface and a lower surface, and the kinetic energy absorbing element can include a plunger mounted to the spider for reciprocating movement parallel to a SCRAM direction, and can further include at least one Belleville washer interposed between the casing and the plunger for biasing the plunger away from the top surface of the casing. The spider can be a heavy spider that is elongate in the SCRAM direction, and the at least one Belleville washer can be contained within the spider. The heavy spider can include a first portion comprising a first material having a first density and a second portion comprising a second material having a second density that is greater than the first density.

[0010] The connecting rod can be detachably engagable with the associated CRDM such that detachment of the spider causes a translating assembly including at least the connecting rod, the spider and the at least one control rod to fall toward a reactor core disposed in a lower region of the nuclear reactor pressure vessel, and whereby the kinetic energy absorbing element is configured to absorb at least some of the kinetic energy of the translating assembly during impact with the reactor core. The coupling can include a J-Lock coupling for connecting the spider with a lower end of the connecting rod, the J-Lock coupling can be supported in a central bore of the spider extending between the upper and lower surface of the casing, the J-Lock

coupling can include a spring, and the Belleville washer can be coaxially aligned with said spring of the J-Lock coupling. The spring of the J-Lock coupling and the Belleville washer can be axially coextensive along a portion of their respective lengths.

[0011] In another aspect of the disclosure, an apparatus comprises a spider connectable with a lower end of an associated connecting rod of an associated CRDM and with upper ends of a plurality of associated control rods, and a kinetic energy absorbing element including at least one Belleville washer supported by the terminal element for absorbing kinetic energy during a SCRAM event.

[0012] In another aspect of the disclosure, a control rod assembly comprises: a spider; a plurality of mutually parallel control rods connected with the spider, the control rods including neutron absorbing material; a connecting rod having an end connected with the spider and configured for detachable connection to an associated control rod drive mechanism (CRDM) wherein responsive to detachment of said connection to the associated CRDM the control rod assembly undergoes a scram event in which the control rod assembly descends under force of gravity; and a stack of Belleville washers disposed in at least one of the connecting rod and the spider, the stack of Belleville washers arranged to absorb kinetic energy of a descent terminating impact of the control rod assembly during a SCRAM event. In some such embodiments the stack of Belleville washers is disposed in a central bore of the spider.

[0013] In another aspect of the disclosure, an apparatus comprises: a spider configured to support a plurality of mutually parallel control rods; and a kinetic energy absorbing element disposed at least partially in a central bore of the spider and including a plunger arranged to stop descent of the spider during a SCRAM event with kinetic energy developed during the SCRAM event being absorbed by the kinetic energy absorbing element disposed in the central bore of the spider. In some embodiments the kinetic energy absorbing element further comprises a stack of Belleville washers disposed in a central bore of the spider. In some such embodiments the stack of Belleville washers does not extend outside of the central bore of the spider.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] The invention may take form in various components and arrangements of components, and in various process operations and arrangements of process operations. The drawings are only for purposes of illustrating preferred embodiments and are not to be construed as limiting the invention.

[0015] FIGURE 1 diagrammatically shows a perspective sectional view a lower portion of an illustrative nuclear reactor pressure vessel including an illustrative control rod assembly (CRA).

[0016] FIGURE 2 diagrammatically shows a perspective view of the illustrative CRA of FIGURE 1.

[0017] FIGURE 3 diagrammatically shows a perspective view of the control rod guide frame with the CRDM unit removed so as to reveal an upper end of a connecting rod of the CRA.

[0018] FIGURE 4 diagrammatically shows a perspective view the control rods and the connecting rod of the CRA of FIGURES 1-3, with components that would occlude the view of these components removed.

[0019] FIGURE 5 diagrammatically shows a perspective view of the terminal weighting element of the CRA of FIGURES 1-4.

[0020] FIGURE 6 diagrammatically shows a perspective sectional view of the terminal weighting element of FIGURE 5.

[0021] FIGURE 7 diagrammatically shows a top view of a casing of the terminal weighting element of FIGURES 5 and 6.

[0022] FIGURE 8 diagrammatically shows a top view of the casing of the terminal weighting element of FIGURES 5-7 located in the control rod guide frame of the CRA of FIGURES 1-3.

[0023] FIGURE 9 diagrammatically shows a perspective sectional view of the J-Lock female attachment assembly housed or disposed in the central passage of the terminal weighting element of FIGURES 5-7.

[0024] FIGURE 10 diagrammatically shows a perspective view of the assembly of the connecting rod, terminal weighting element, and control rods including an upper portion of the J-Lock coupling.

[0025] FIGURE 11 diagrammatically shows a perspective sectional view of the assembly of the connecting rod, terminal weighting element, and control rods including details of the J-Lock coupling in its locked configuration.

[0026] FIGURE 12 diagrammatically shows a perspective view of another exemplary CRA in accordance with the disclosure.

[0027] FIGURE 13 diagrammatically shows a perspective sectional view of the terminal element of FIGURE 12 having a kinetic energy absorbing element including a stack of Belleville washers.

[0028] FIGURES 14a-14f illustrate various Belleville washer stacks that can be utilized to achieve various spring constants and plunger stroke lengths.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0029] In existing control rod assemblies, a plurality of control rods connect with a lightweight, "spidery" spider having a minimal weight and surface area oriented broadside to the SCRAM direction. The spider is configured to provide a large "effective" area for attachment of control rods, but a small "actual" area contributing to hydraulic resistance during SCRAM. Both the spider and the connecting rod are stainless steel components so as to provide benefits such as strength and robustness, low cost, manufacturability, and compatibility with the reactor vessel environment.

[0030] Disclosed herein are control rod assemblies that include one or both of the following aspects: (i) replacement of the conventional lightweight spider with a "heavy" spider that serves as a terminal weighting element, and/or (ii) replacement of a substantial portion of the stainless steel of the spider and/or connecting rod with a denser material such as tungsten (optionally in a powdered or granulated form), molybdenum, tantalum, or so forth. The disclosed control rod assemblies are substantially heavier than conventional control rod assemblies of the same vertical dimensions, which advantageously enhances the speed and reliability of gravitationally-induced SCRAM.

[0031] In the case of control rod assemblies employing the disclosed heavy spider as a terminal weighting element, the increased weight provided by the heavy spider as compared with a conventional lightweight spider enables the heavy spider to

optionally have a larger actual surface area broadside to the SCRAM direction (for example, in order to provide the additional weight) as compared with the conventional spider. In addition, the heavier than conventional control rod assemblies disclosed herein also include a kinetic energy absorbing element for absorbing kinetic energy during a scram event. The kinetic energy absorbing elements disclosed herein act to limit the impact of the spider with the “stopping” surface or component, such as a top plate fitting of a fuel assembly. As disclosed herein, special spring elements/arrangements are used to accommodate the kinetic load. In one example, a stack of Belleville washers is used. It will be appreciated that aspects of the disclosure relating to the kinetic energy absorbing element are also applicable to control rod assemblies with conventional light-weight spiders. For example, the disclosed kinetic energy absorbing element is useful with a conventional control rod assembly that uses a lightweight spider but includes relatively long (and hence massive) control rods and/or a long connecting rod.

[0032] With reference to FIGURE 1, a relevant portion of an illustrative nuclear reactor pressure vessel **10** includes a reactor core **12** located proximate to a bottom of the pressure vessel **10**. The core **12** includes or contains radioactive material (not shown) such as, by way of illustrative example, enriched uranium oxide (that is, UO_2 processed to have an elevated $^{235}\text{U}/^{238}\text{U}$ ratio). A control rod drive mechanism (CRDM) unit **14** is diagrammatically illustrated. The illustrative CRDM **14** is an internal CRDM that is disposed within the pressure vessel **10**; alternatively, an external CRDM may be employed. FIGURE 1 shows the single illustrated CRDM unit **14** as an illustrative example; however, more generally there are typically multiple CRDM units each coupled with a different plurality of control rods (although these additional CRDM units are not shown in FIGURE 1, the pressure vessel **10** is drawn showing the space for such additional CRDM units).

[0033] Below the CRDM unit **14** is a control rod guide frame **16**, which in the perspective view of FIGURE 1 blocks from view the control rod/CRDM coupling assembly (i.e., the spider and connecting rod, both not shown in FIGURE 1). Extending below the guide frame **16** is a plurality of control rods **18**. FIGURE 1 shows the control rods **18** in their fully inserted position in which the control rods **18** are maximally inserted into the core **12**. In the fully inserted position, the spider is located at a lower location **20** within the control rod guide frame **16** (and, again,

hence not visible in FIGURE 1). In the illustrative embodiment of FIGURE 1, the CRDM unit **14** and the control rod guide frame **16** are spaced apart by a standoff **22** comprising a hollow tube having opposite ends coupled with the CRDM unit **14** and the guide frame **16**, respectively, and through which the connecting rod (not shown in FIGURE 1) passes.

[0034] FIGURE 1 shows only a lower portion of the illustrative pressure vessel **10**. In an operating nuclear reactor, an open upper end **24** of the illustration is connected with one or more upper pressure vessel portions that together with the illustrated lower portion of the pressure vessel **10** forms an enclosed pressure volume containing the reactor core **12**, the control rods **18**, the guide frame **16**, and the internal CRDM unit **14**. In an alternative embodiment, the CRDM unit is external, located above the reactor pressure vessel. In such embodiments, the external CRDM is connected with the control rods by a control rod/CRDM coupling assembly in which the connecting rod extends through a portal in the upper portion of the pressure vessel.

[0035] With reference to FIGURE 2, the control assembly including the CRDM unit **14**, the control rod guide frame **16**, the intervening standoff **22**, and the control rods **18** is illustrated isolated from the reactor pressure vessel. Again, the control rod/CRDM coupling assembly is hidden by the control rod guide frame **16** and the standoff **22** in the view of FIGURE 2.

[0036] With reference to FIGURE 3, the control rod guide frame **16** and the standoff **22** is again illustrated, but with the CRDM unit removed so as to reveal an upper end of a connecting rod **30** extending upwardly above the standoff **22**. If the CRDM unit has regulating rod functionality, then this illustrated upper end of the connecting rod **30** engages with the CRDM unit to enable the CRDM unit to raise or lower the control rod **30** and, hence, the attached control rods **18** (not shown in FIGURE 3). If the CRDM unit has shutdown rod functionality, then this illustrated upper end is detachable from the CRDM unit during SCRAM. In each of FIGURES 1-4, a SCRAM direction **S** is indicated, which is the downward direction of acceleration of the falling control rods in the event of a SCRAM.

[0037] With reference to FIGURE 4, the control rods **18** and the connecting rod **30** are shown without any of the occluding components (e.g., without the guide frame, standoff, or CRDM unit). In the view of FIGURE 4 an illustrative terminal weighting

element or "heavy" spider **32** is visible, which provides connection of the plurality of control rods **18** with the lower end of the connecting rod **30**. It will be noticed that, unlike a conventional spider, the heavy spider **32** has substantial elongation along the SCRAM direction **S**. The illustrated heavy spider **32** has the advantage of providing enhanced weight which facilitates rapid SCRAM; however, it is also contemplated to replace the illustrated terminal weighting element **32** with a conventional "spidery" spider.

[0038] With reference to FIGURES 5 and 6, a perspective view and a side-sectional perspective view, respectively, of the heavy spider **32** is shown. The heavy spider **32** includes a substantially hollow casing **40** having upper and lower ends that are sealed off by upper and lower casing cover plates (surfaces) **42**, **44**. Four upper casing cover plates **42** are illustrated in FIGURE 5 and two of the upper casing cover plates **42** are shown in the side-sectional perspective view of FIGURE 6. The tilt of the perspective view of FIGURE 5 occludes the lower cover plates from view, but two of the lower cover plates **44** are visible "on-edge" in the side-sectional view of FIGURE 6. The illustrative heavy spider **32** includes four lower casing cover plates **44** arranged analogously to the four upper casing cover plates **42** illustrated in FIGURE 5.

[0039] Further visualization of the illustrative heavy spider **32** is provided by FIGURE 7, which shows a top view of the hollow casing **40** with the cover plates omitted. As seen in FIGURE 7, the hollow casing **40** is cylindrical having a cylinder axis parallel with the SCRAM direction **S** and a uniform cross-section transverse to the cylinder axis. That cross-section is complex, and defines a central passage **50** and four cavities **52** spaced radially at 90° intervals around the central passage **50**. The cross-section of the hollow casing **40** also defines twenty-four small passages **54** (that is, small compared with the central passage **50**), of which only some of the twenty-four small passages **54** are expressly labeled in FIGURE 7.

[0040]

[0041] The four cavities **52** spaced radially at 90° intervals around the central passage **50** are next considered. The substantially hollow casing **40** and the upper and lower cover plates **42**, **44** are suitably made of stainless steel, although other materials are also contemplated. The upper and lower cover plates **42**, **44** seal the four cavities **52**. As shown in the side-sectional view of FIGURE 6, the four cavities

52 are filled with a filler **56** comprising a heavy material, where the term "heavy material" denotes a material that has a higher density than the stainless steel (or other material) that forms the hollow casing **40**. For example, the filler **56** may comprise a heavy material such as tungsten (optionally in a powdered or granulated form), depleted uranium, molybdenum, or tantalum, by way of some illustrative examples. By way of illustrative example, stainless steel has a density of about 7.5-8.1 grams/cubic centimeter, while tungsten has a density of about 19.2 grams/cubic centimeter and tantalum has a density of about 16.6 grams per cubic centimeter. In some preferred embodiments, the heavy material comprising the filler **56** has a density that is at least twice the density of the material comprising the casing **40**. In some preferred embodiments in which the casing **40** comprises stainless steel, the heavy material comprising the filler **56** preferably has a density that is at least 16.2 grams per cubic centimeter. (All quantitative densities specified herein are for room temperature.)

[0042] In some embodiments, the filler **56** does not contribute to the structural strength or rigidity of the heavy spider **32**. Accordingly, heavy material comprising the filler **56** can be selected without consideration of its mechanical properties. For the same reason, the filler **56** can be in the form of solid inserts sized and shaped to fit into the cavities **52**, or the filler **56** can be a powder, granulation, or other constitution. The cover plates **42**, **44** seal the cavities **52**, and so it is also contemplated for the heavy material comprising the filler **56** to be a material that is not compatible with the primary coolant flowing in the pressure vessel **10**. Alternatively, if the heavy material comprising the filler **56** is a material that is compatible with the primary coolant flowing in the pressure vessel **10**, then it is contemplated to omit the upper cover plates **42**, in which case the cavities **52** are not sealed. Indeed, if the filler **56** is a solid material securely held inside the cavities **52**, then it is contemplated to omit both the upper cover plates **42** and the lower cover plates **44**.

[0043] With continuing reference to FIGURES 5-7 and with further reference to FIGURE 8, the heavy spider **32** passes through the control rod guide frame **16** as the control rods **18** are raised or lowered by action of the CRDM unit **14**. The cylindrical configuration with constant cross-section over the length of the heavy spider **32** along the SCRAM direction **S** simplifies this design aspect. Moreover, the

control rod guide frame **16** should cam against each control rod **18** to provide the desired control rod guidance. Toward this end, the cross-section of the heavy spider **32** is designed with recesses **58** (some of which are labeled in FIGURE 7). As shown in FIGURE 8, into these recesses **58** fit mating extensions **60** of the control rod guide frame **16**. A gap **G** also indicated in FIGURE 8 provides a small tolerance between the outer surface of the heavy spider **32** and the proximate surface of the control rod guide frame **16**. The twenty-four partial circular openings of the guide frame **16** which encompass the twenty-four small passages **54** of the heavy spider **32** are sized to cam against the control rods **18**. For completeness, FIGURE 8 also shows the connecting rod **30** disposed inside the central passage **50** of the heavy spider **32**.

[0044] FIGURES 5-7 show that providing space for the four cavities **52** substantially increases the actual cross-sectional area of the heavy spider **32** (that is, the area arranged broadside to the SCRAM direction **S**), as compared with the actual cross-sectional area that could be achieved without these four cavities **52**. In some embodiments, the "fill factor" for the cross-section oriented broadside to the SCRAM direction **S** (including the area encompassed by the cover plates **42**, **44**) is at least 50%, and FIGURE 7 demonstrates that the fill factor is substantially greater than 50% for the illustrative terminal weighting element. Thus, the design of the heavy spider **32** is distinct from the "spidery" design of a typical spider, which is optimized to minimize the actual surface area broadside to the SCRAM direction **S** and generally has a fill factor of substantially less than 50% in order to reduce hydraulic resistance. In general, the SCRAM force achieved by the weight of the heavy spider **32** more than offsets the increased hydraulic resistance of the greater actual broadside surface area imposed by the four cavities **52**.

[0045] Additional weight to overcome the hydraulic resistance and enhance SCRAM speed is obtained by elongating the heavy spider **32** in the SCRAM direction **S** as compared with a conventional spider. Said another way, a ratio of a length of the heavy spider **32** in the SCRAM direction **S** versus the largest dimension oriented broadside to the SCRAM direction **S** is optionally equal to or greater than one, and is more preferably equal to or greater than 1.2. The illustrative heavy spider **32** is not a generally planar element as per a typical spider, but rather is a volumetric component that provides substantial terminal weight to the lower end of the connecting rod **30**.

[0046] Another advantage of the elongation of the heavy spider **32** in the SCRAM direction **S** is that it optionally allows for streamlining the heavy spider **32** in the SCRAM direction **S**. This variation is not illustrated; however, it is contemplated to modify the configuration of FIGURE 5 (by way of illustrative example) to have a narrower lower cross-section and a broader upper cross section, with a conical surface of increasing diameter running from the narrower lower cross-section to the broader upper cross section. The small passages **54** for securing the control rods would remain oriented precisely parallel with the SCRAM direction **S** (and, hence, would be shorter for control rods located at the outermost positions). Such streamlining represents a trade-off between hydraulic resistance (reduced by the streamlining) and weight reduction caused by the streamlining.

[0047] The illustrative heavy spider **32** provides a desired weight by a combination of the filler **56** comprising a heavy material (which increases the average density of the heavy spider **32** to a value greater than the average density of stainless steel) and the elongation of the heavy spider **32** (which increases the total volume of the heavy spider **32**).

[0048] In some embodiments, it is contemplated to omit the filler material entirely, and instead to rely entirely upon elongation to provide the desired weight. For example, the illustrated heavy spider **32** can be modified by omitting the four cavities **52** and the filler **56**. In this configuration the casing **40** can be replaced by a single solid stainless steel element having the same outer perimeter as the casing **40**, with the top and bottom of the single solid stainless steel element defining (or perhaps better stated, replacing) the upper and lower casing cover plates **42**, **44**.

[0049] Various embodiments of the disclosed heavy spiders use a stainless steel casing that does not compromise the primary function of providing a suitable structure for coupling the control rods to the lower end of the connecting rod. At the same time, the stainless steel casing leaves sufficient void or cavity volume to allow a filler comprising a heavy material to be inserted. Although stainless steel is referenced as a preferred material for the casing, it is to be understood that other materials having desired structural characteristics and reactor pressure vessel compatibility can also be used. The filler comprising heavy material is suitably tungsten, depleted uranium, or another suitably dense material.

[0050] With reference to FIGURES 9, 10, and 11, various attachment configurations can be used for securing the connecting rod **30** in the attachment passage **50** of the casing **40** of the heavy spider **32**. In an illustrative example of one such attachment configuration, the central passage **50** of the casing **40** houses a J-Lock female attachment assembly **70**, which is suitably coaxially disposed inside the central passage **50** of the casing **40**. FIGURE 9 illustrates a side sectional view of the J-Lock female attachment assembly **70**, while FIGURE 10 shows a side view of the connected assembly and FIGURE 11 shows a side sectional view of the connected assembly. With particular reference to FIGURE 9, the illustrative J-Lock female attachment assembly **70** includes a hub **72** which in the illustrative embodiment comprises a round cylinder coaxially welded or otherwise secured in the central passage **50** of the casing **40**. Alternatively, the hub may be integral with or defined by an inside surface of the central passage **50**. The hub **72** serves as an interface between the casing **40** and the J-Lock female attachment components, which include three J-Lock pins **74** (two of which visible in the sectional view of FIGURE 9) disposed inside of the hub **72**. These pins **74** provide the connection points for a J-Lock male attachment assembly **80** (see FIGURE 11) disposed at the lower end of the connecting rod **30**. A J-Lock plunger **76** and a J-Lock spring **84** keeps the J-Lock male attachment assembly **80** of the connecting rod **30** in place once it has been engaged with the heavy spider **32**. (Locked arrangement shown in FIGURE 11).

[0051] The illustrative J-Lock female attachment assembly **70** further includes a lower plunger **82**, an inner spring **78**, and a spring washer **86** which cooperate to absorb the impact of the lower translating assembly (that is, the translating combination of the control rods **18**, the heavy spider **32**, the connecting rod **30**, and optionally a lead screw (not shown)) during a SCRAM. As will be appreciated, the lower plunger **82** is mounted within the attachment passage (bore) **50** of the casing **40** of the heavy spider **32**, and protrudes from a bottom surface of the heavy spider **32** for engagement with another surface during a SCRAM event. The lower plunger **82** is supported for reciprocating movement within the attachment passage **50**, and biased downwardly by spring **78** and/or J-Lock spring **84**. Together, the plunger **82** and spring **78** and/or J-Lock spring **84** comprise a kinetic energy absorbing element supported by the heavy spider **32** for absorbing kinetic

energy during a SCRAM event. The kinetic energy absorbing element can be configured to act between the terminal element **32** and an upper plate of an associated fuel assembly, for example, as will be described in more detail below.

[0052] The illustrative J-Lock connection between the lower end of the connecting rod **30** and the heavy spider **32** is an example. More generally, substantially any type of connection, including another type of detachable connection or a permanently welded connection or an integral arrangement, is contemplated. The J-Lock arrangement has the advantage of enabling the connecting rod **30** to be detached from the heavy spider **32** (and, hence, from the control rods **18**) by a simple "push-and-twist" operation. This allows the connecting rod **30** to be moved separately from the remainder of the translating assembly (that is, the heavy spider **32** and the attached control rods **18**) during refueling of the nuclear reactor.

[0053] With reference to FIGURES 10 and 11, additional weight for the translating assembly is additionally or alternatively obtained by enhancing the density of the connecting rod **30**. Toward this end, the illustrative connecting rod **30** includes a hollow (or partially hollow) connecting rod tube **90** which (as seen in the sectional view of FIGURE 11) contains a filler region **92** adapted to accept a filler comprising a heavy material. Thus, the connecting rod tube **90** serves the structural purpose analogous to the casing **40** of the terminal weighting element **32**, while the filler comprising heavy material serves a weighting (or average density-enhancing) purpose analogous to the filler **56** of the terminal weighting element **32**.

[0054] In one suitable embodiment, the filler comprising heavy material is in the form of tungsten slugs each having a diameter substantially coinciding with an inner diameter of the connecting rod tube **90** and being stacked in the connecting rod tube **90**, with the number of stacked tungsten slugs being selected to achieve the desired weight. If the number of tungsten slugs is insufficient to fill the interior volume of the connecting rod tube **90** and it is desired to avoid movement of these slugs, then optionally the filler is prevented from shifting by a suitable biasing arrangement or by filling the remaining space within the interior volume of the connecting rod tube **90** with a light weight material such as stainless steel slugs. In the illustrative example of FIGURE 11, a biasing arrangement region **98** is employed, in which the interior volume of the connecting rod tube **90** is sealed off by upper and lower welded plugs **94**, **96**, and a biasing arrangement such as a compressed spring takes up any slack

along the SCRAM direction **S** that may be introduced by incomplete filling of the interior volume of the connecting rod tube **90** by the filler. Instead of tungsten, the heavy material comprising the filler may be depleted uranium, molybdenum, tantalum, or so forth, by way of some other illustrative examples. The filler may comprise one or more solid slugs or rods, a powder, a granulation, or so forth.

[0055] With continuing reference to FIGURES 10 and 11, the illustrative connecting rod **30** has an upper end that includes an annular groove **100** for securing with a latch of the CRDM unit **14** (latch not shown), and a magnet **102** for use in conjunction with a control rod position sensor (not shown). A suitable embodiment of the CRDM unit **14** including a motor/lead screw arrangement for continuous (regulating rod) adjustment and a separate latch for detaching the connecting rod **30** from the CRDM unit **14** (with the lead screw remaining operatively connected with the motor) is described in U.S. Pub. No. 2010-0316177 A1 published Dec. 16, 2010 which is incorporated herein by reference in its entirety and in U.S. Pub. No. 2011-0222640 A1 published Sept. 15, 2011 which is incorporated herein by reference in its entirety.

[0056] Alternatively, in other embodiments a lead screw (not shown) is secured with or integral with the connecting rod tube **90**, and the lead screw SCRAMs together with the connecting rod/terminal weighting element (or spider)/control rod (in other words, the lead screw forms part of the translating assembly during SCRAM). In some such alternative embodiments, the motor is suitably coupled with the lead screw by a separable ball nut that separates to release the lead screw and initiate SCRAM.

[0057] If the interior volume of the hollow connecting rod tube **90** is only partially filled by the filler, then stainless steel rods or some other light weight filler (not shown) may be inserted into the remaining interior volume to fill complete the filling.

[0058] The filler generally has a lower coefficient of thermal expansion than the stainless steel (or other material) of the hollow connecting rod tube **90**. The connecting rod **30** is assembled at room temperature, and then heated to its operating temperature. For a connecting rod having a length of, e.g. 250 centimeters or greater, the thermal expansion will result in the rod tube **90** increasing by an amount of order a few centimeters or more. The lower coefficient of thermal expansion of the filler results in a substantially lower length increase of the filler. The

spring in the biasing arrangement region **98** suitably compensates for this effect. Additionally, if the spring is located below the filler, then it can assist in dissipating the kinetic energy of the filler at the termination of the SCRAM drop.

[0059] Turning now to FIGURES 12 and 13, and initially to FIGURE 12, another exemplary control rod assembly is illustrated and identified generally by reference numeral **100**. As will be appreciated, a typical reactor core will have a plurality of control rod assemblies **100**. As shown in FIGURE 12, the illustrative control rod assembly **100** consists of an array of twenty-three or twenty-four rodlets **104** attached to a spider **108**, which may be a relatively massive tungsten-ballasted heavy spider as described herein and as illustrated in FIGURES 12 and 13, or alternatively may be a conventional lightweight spider. Each rodlet **104** contains neutron poisons sealed in cladding tubes (e.g., 304L stainless steel) via welded end plugs of the same material. Each control rod assembly **104** is associated with a fuel assembly **110** into which the control rodlets **104** are moved to control operation of the reactor.

[0060] In some core designs, the control rod assemblies in the standard control banks use full-length silver-indium-cadmium absorbers in twenty-three or twenty-four rodlets. The control rod assemblies in the shutdown banks have a row of fifteen or sixteen rodlets with B4C absorbers in the outboard positions surrounding eight inboard rodlets with standard silver-indium-cadmium absorbers. These are merely illustrative examples.

[0061] The array of rodlets **104** are mechanically fastened to the arms **112** of the spider **108** by threading extensions on the top end plugs into tapped receiving holes in the bottom of the spider arms **112** and then lock welding them to the spider **108** so they cannot back out. Tapered "nuts" are threaded into similar tapped receiving holes in the top surface of the spider arms to serve as lead-ins when the control rods **104** are withdrawn from the core upward through the reactor internals guide structure. The "nuts" are also lock-welded to the spider to prevent them from backing off during operation. A reduced-diameter section in the top end plugs allows the rodlets **104** to flex relative to the spider **108** as necessary to accommodate any misalignment between a fuel assembly **110** and the rod guide structure.

[0062] During operation of a reactor, the control rod assemblies **100** in the shutdown banks are typically fully withdrawn from the core, while the regulating

control rod assemblies may be partially inserted into the core and their axial position changed with time. When a SCRAM occurs, the connecting rods (not shown in FIGURE 12, but described above) are released and the control rod assemblies **104** fall into the core under gravity, reaching a terminal velocity of approximately 12 feet per second if they are fully withdrawn prior to the SCRAM. When a control rod assembly **104** is approximately 75% inserted into the corresponding fuel assembly **110** during a SCRAM, the tips of the rodlets **104** enter dashpot tubes (not shown) installed in the bottom of the control rod guide tubes of the fuel assembly **110**. These small dashpot tubes have a significantly smaller inside diameter than the larger control rod guide tubes, greatly reducing the radial clearance with the control rodlets **104**. This produces a piston effect as water is forced to flow through the resulting narrow annulus, slowing the falling control rod assemblies. However, the downward motion continues until eventually the spider **108** on the falling control rod assembly impacts the top of the fuel assembly **110**. An impact limiter, also referred to as a kinetic energy absorbing element, accommodates the remaining kinetic energy.

[0063] Turning to FIGURE 13, the kinetic energy absorbing element includes a cup-like spider plunger **120** that is preloaded against the bottom of the spider central bore **B** by two concentric spring features. Plunger **120** includes a radially outwardly extending flange **121** that is configured to engage a shoulder **122** of central bore **B** to limit further downward axial movement of the plunger **120** from the position shown in FIG. 13.

[0064] A relatively stronger, outer spring feature is comprised of a stack **S** of Belleville washers (also called Belleville springs) **124**, such as age-hardened Inconel-718 Belleville washers. The stack **S** of Belleville washers **124** provides the majority of the preload on the plunger **120**. The Belleville washer stack **S** reacts against a hub **128** which is welded into the top of the central bore **B** and contains a J-lock mechanism **132** that mates with a coupling mechanism on the bottom end of a connecting rod, (not shown). The relatively weaker inner spring **132** is a conventional helical compression spring made of, for example, age-hardened Inconel-718 wire, which reacts against a J-lock plunger **136**. The Belleville washer stack **S** and the coil spring **132** are coaxially aligned and are axially coextensive along at least a portion of their respective lengths resulting in a compact arrangement. When the connecting rod engages the spider **108**, the plunger **136** is depressed sufficiently to

enable the coupling mechanism of the connecting rod to pass under J-lock pins **140** in the hub **128** and rotate to the locked position (e.g., as described above).

[0065] During a scram, the kinetic energy absorbing element **120**, **S** acts between the spider **32** and an associated impact surface, such as an upper plate of an associated fuel assembly, or an upper core plate (not shown) spanning the space above the fuel assemblies making up the reactor core. The Belleville washer stack **S** provides a higher load capability in a more compact arrangement than can be achieved using a conventional helical compression spring. This allows the kinetic energy absorbing element to absorb more energy than would otherwise be possible given the limited volume available in the spider hub. This high energy capability particularly well-suited to applications where a massive tungsten ballasted spider, such as that set forth above, is used, and more generally is well-suited to applications in which the overall translating control rod assembly is heavy, e.g. due to the use of long control rods, a long connecting rod, a heavy spider, various combinations thereof, and so forth.

[0066] It will be appreciated that the amount of energy the impact limiter must absorb depends on the mass of the falling assembly and its velocity, which in turn depends on how far it falls and on the fluid resistance imparted by travel through the primary coolant. Everything else being equal, a longer control rod assembly will fall further from the fully withdrawn position, and impact the fuel assembly with greater energy. The capability of the kinetic energy absorbing element to absorb this energy can be adjusted by tailoring the Belleville washer stack **S**.

[0067] Turning to FIGURES 14a-14f, various Belleville washer stacks **S** suitably used as the stack **S** of FIGURE 13 are illustrated. The plunger stroke, stiffness, and maximum load capability of the kinetic energy absorbing element can be customized utilizing several different approaches. For example:

- Decreasing the number of Belleville washers in the stack **S** as illustrated in FIGURE 14a, without changing their geometry or material of construction, will result in a kinetic energy absorbing element having a shorter allowable plunger stroke and a higher stiffness with the same maximum load capability.
- Conversely, increasing the number of Belleville washers in the stack **S** as illustrated in FIGURE 14b, without changing their geometry or material of construction, will result in a kinetic energy absorbing element having a longer

allowable plunger stroke and a lower stiffness with the same maximum load capability.

- Using thicker Belleville washers in the stack **S** as illustrated in FIGURE 14c will result in a kinetic energy absorbing element having a shorter allowable plunger stroke, a higher stiffness, and a higher allowable load.
- Conversely, employing thinner Belleville washers in the stack **S** as illustrated in FIGURE 14d will yield a design with a longer allowable plunger stroke, a lower stiffness, and a lower allowable load.

[0068] It is also possible to tailor the kinetic energy absorbing element characteristics by changing the nesting arrangement of the Belleville washers. FIGURES 14a-14d all show a stacking arrangement in which the orientation of each Belleville washer is reversed relative to the Belleville washer above and below it. This alternating stacking arrangement maximizes the allowable stroke while minimizing the stiffness and allowable load of the kinetic energy absorbing element. If instead, the same Belleville washers are stacked in pairs as illustrated in FIGURE 14e, with the washers in each pair nested together in the same orientation and each pair of washers then oriented the reverse of the neighboring pair above and below, the allowable stroke of the kinetic energy absorbing element will be cut in half, the stiffness will be doubled, and the allowable load will be doubled.

[0069] If instead, the same Belleville washers are stacked in sets of three as illustrated in FIGURE 14f, with the washers in each set again nested together in the same orientation and each set of three washers then oriented the reverse of the neighboring set of three washers above and below, the allowable stroke of the kinetic energy absorbing element will be cut by two thirds, the stiffness will be tripled, and the allowable load will be tripled.

[0070] The same principle can be extended to Belleville washers arranged in sets of four, five, etc.; each increase in the number of washers nested together resulting in a proportional decrease in the allowable stroke of the kinetic energy absorbing element and proportional increases in the stiffness and allowable load.

[0071] Although the kinetic energy absorbing elements disclosed herein have been described in the context of weighted terminal elements or elongated terminal

elements (i.e., heavy spiders), it should be appreciated that aspects of the disclosure are applicable to conventional spider assemblies as well.

[0072] The preferred embodiments have been illustrated and described. Obviously, modifications and alterations will occur to others upon reading and understanding the preceding detailed description. It is intended that the invention be construed as including all such modifications and alterations insofar as they come within the scope of the appended claims or the equivalents thereof.

CLAIMS

We claim:

1. A control rod assembly comprising:
at least one movable control rod including a neutron absorbing material;
a connecting rod configured for connection to an associated control rod drive mechanism (CRDM) for controlling movement of the at least one control rod; and
a coupling operatively connecting the at least one control rod and the connecting rod;
wherein the coupling includes a spider engaged with the connecting rod and the at least one moveable control rod, and a kinetic energy absorbing element supported by the spider for absorbing kinetic energy during a SCRAM event, the kinetic energy absorbing element configured to act between the spider and an associated impact surface.
2. The control rod assembly set forth in claim 1, wherein the spider includes a casing having an upper surface and a lower surface, and wherein the kinetic energy absorbing element includes a plunger mounted to the spider for reciprocating movement parallel to a SCRAM direction, and further comprising at least one Belleville washer retained by the casing and engaging the plunger for biasing the plunger away from the top surface of the casing.
3. The control rod assembly as set forth in claim 1, wherein the spider is a heavy spider that is elongate in the SCRAM direction, and the at least one Belleville washer is contained within the spider.
4. The control rod assembly as set forth in claim 3, wherein the heavy spider includes
a first portion comprising a first material having a first density and a second portion comprising a second material having a second density that is greater than the first density.

5. The control rod assembly as set forth in claim 1, wherein the connecting rod is detachably engagable with the associated CRDM such that detachment of the connecting rod from the associated CRDM causes a SCRAM event in which a translating control rod assembly including at least the connecting rod, the spider, and the at least one control rod falls toward a reactor core disposed in a lower region of the nuclear reactor pressure vessel, and wherein the kinetic energy absorbing element is configured to absorb at least some of the kinetic energy of the translating control rod assembly during impact with the associated impact surface.
6. The control rod assembly as set forth in claim 2, wherein the coupling includes a J-Lock coupling connecting the spider with a lower end of the connecting rod, the J-Lock coupling supported in a central bore of the spider extending between the upper and lower surface of the casing, the J-Lock coupling including a spring, and wherein the at least one Belleville washer is coaxially aligned with said spring of the J-Lock coupling.
7. The assembly as set forth in claim 6, wherein the spring of the J-Lock coupling and the at least one Belleville washer is axially coextensive along a portion of their respective lengths.
8. An apparatus comprising:
a spider connectable with a lower end of an associated connecting rod of an associated CRDM and with upper ends of a plurality of associated control rods; and
a kinetic energy absorbing element including at least one Belleville washer supported by the spider for absorbing kinetic energy during a SCRAM event.
9. The control rod/control rod drive mechanism (CRDM) coupling as set forth in claim 8, wherein the spider includes a casing having an upper surface and a lower surface, and wherein the kinetic energy absorbing element includes a plunger mounted to the spider for reciprocating movement parallel to the SCRAM direction.

10. The apparatus as set forth in claim 9, wherein the plunger is supported in a bore of the spider, said bore opening to the lower surface of the casing, and wherein the Belleville washer is interposed between the plunger and the casing of the spider for biasing the plunger away from the top surface of the casing.

11. The apparatus as set forth in claim 8, wherein the spider includes a casing having a bore extending axially between an upper surface and a lower surface thereof, the spider further comprising a coupling portion supported in the bore, said coupling portion having an upper female coupling element configured to detachably lock with a male coupling portion disposed at the lower end of the associated connecting rod in order to connect the spider with the lower end of the associated connecting rod, and said coupling portion further including, at the lower end thereof, the kinetic energy absorbing element.

12. The apparatus as set forth in claim 11, wherein the kinetic energy absorbing element includes a plunger adapted for reciprocating movement within the bore.

13. The apparatus as set forth in claim 12, wherein the plunger is biased away from the upper surface of the casing by the least one Belleville washer interposed between the plunger and the female coupling member.

14. The apparatus as set forth in claim 13, wherein the female coupling includes a spring, and wherein said spring and the at least one Belleville washer are coaxially aligned.

15. The apparatus as set forth in claim 8, wherein the spider is a heavy spider having an elongation in a SCRAM direction that is at least as large as a largest dimension of the spider transverse to the SCRAM direction.

16. A control rod assembly comprising:
a spider;

a plurality of mutually parallel control rods connected with the spider, the control rods including neutron absorbing material;

a connecting rod having an end connected with the spider and configured for detachable connection to an associated control rod drive mechanism (CRDM) wherein responsive to detachment of said connection to the associated CRDM the control rod assembly undergoes a scram event in which the control rod assembly descends under force of gravity; and

a stack of Belleville washers disposed in at least one of the connecting rod and the spider, the stack of Belleville washers arranged to absorb kinetic energy of a descent-terminating impact of the control rod assembly during a SCRAM event.

17. The control rod assembly of claim 16 wherein the stack of Belleville washers is disposed in a central bore of the spider.

18. The control rod assembly of claim 17 wherein the spider is elongated along the descent direction by an elongation amount effective to accommodate the stack of Belleville washers inside the spider.

19. A control system comprising the control rod assembly of claim 16, and a CRDM coupled to the connecting rod.

20. An apparatus comprising:
a spider configured to support a plurality of mutually parallel control rods; and
a kinetic energy absorbing element disposed at least partially in a central bore of the spider and including a plunger arranged to stop descent of the spider during a SCRAM event with kinetic energy developed during the SCRAM event being absorbed by the kinetic energy absorbing element disposed in the central bore of the spider.

21. The apparatus of claim 20 wherein the kinetic energy absorbing element further comprises a stack of Belleville washers disposed in a central bore of the spider.

22. The apparatus of claim 21 wherein the stack of Belleville washers does not extend outside of the central bore of the spider.

23. The apparatus of claim 21 further comprising:
a plurality of mutually parallel control rods having ends connected with the spider and extending away from the spider in a first direction.

24. The apparatus of claim 23 further comprising:
a connecting rod having an end connected with the spider and extending away from the spider in a second direction opposite the first direction.

25. The apparatus of claim 24 further comprising:
a control rod drive mechanism (CRDM) detachably engaging the connecting rod wherein detachment of the connecting rod from the CRDM initiates a SCRAM event.

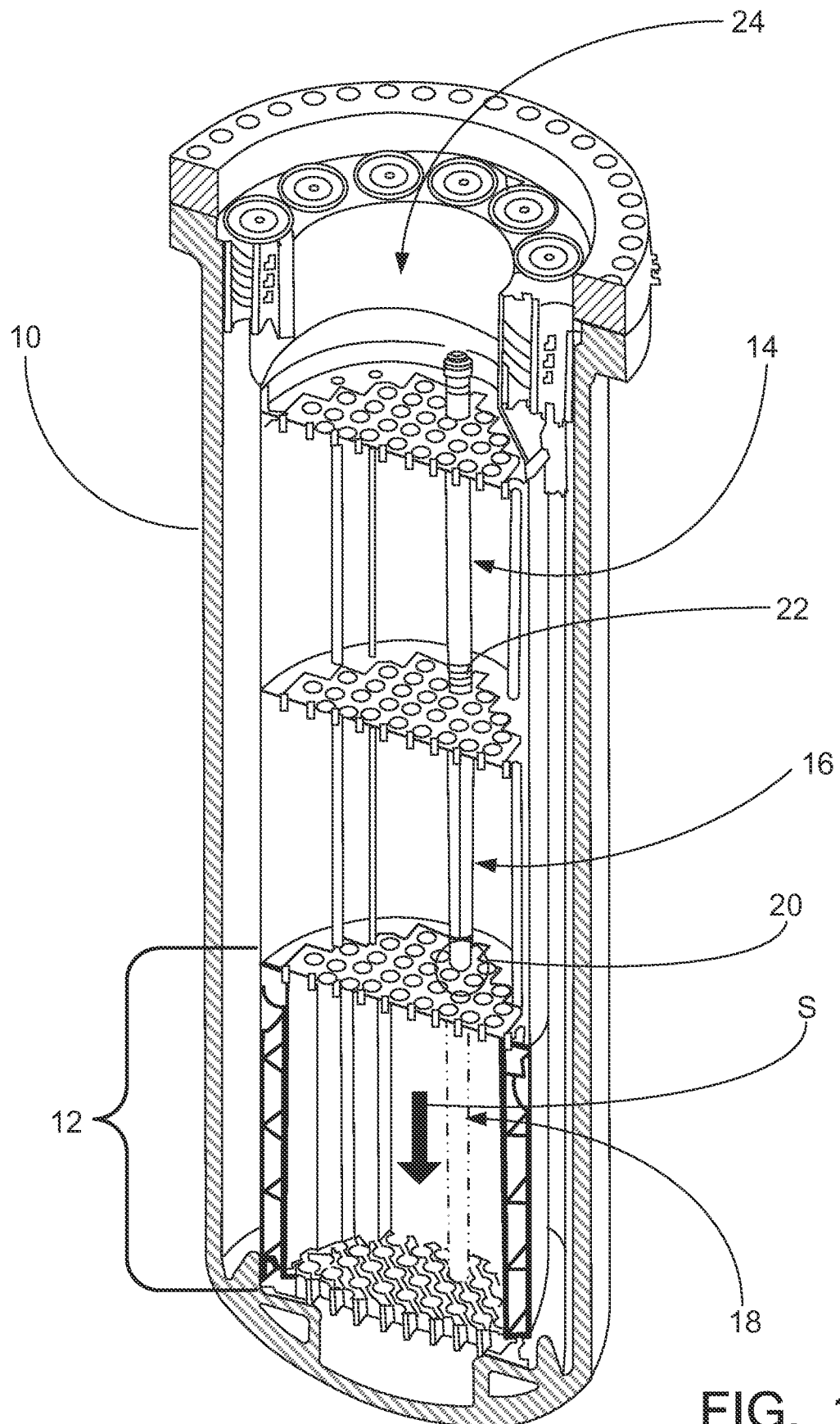


FIG. 1

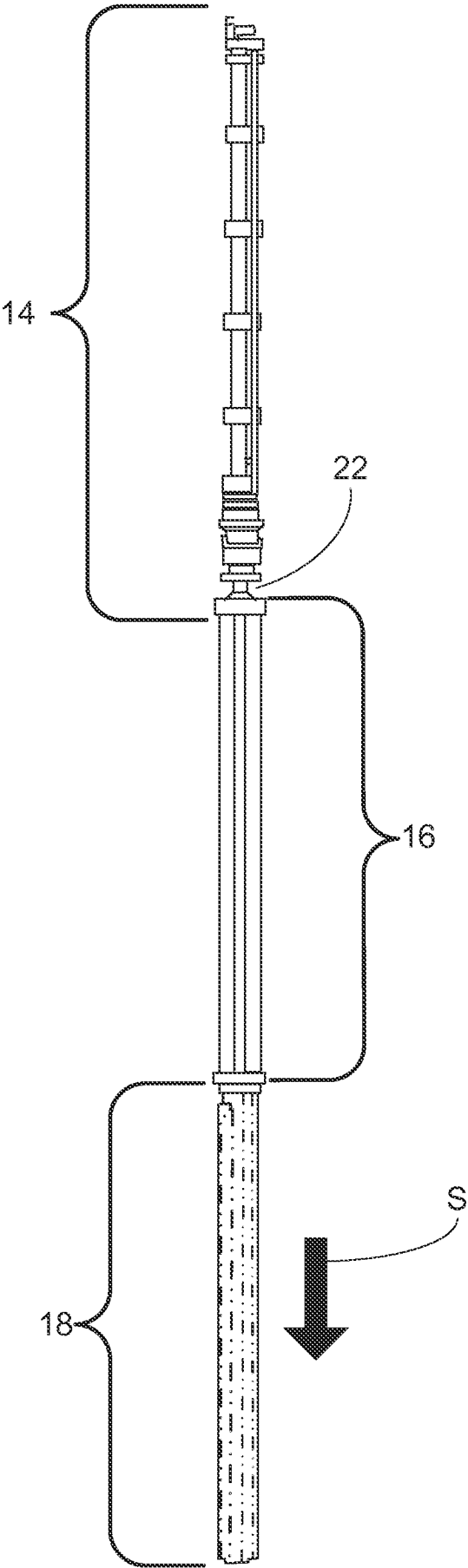
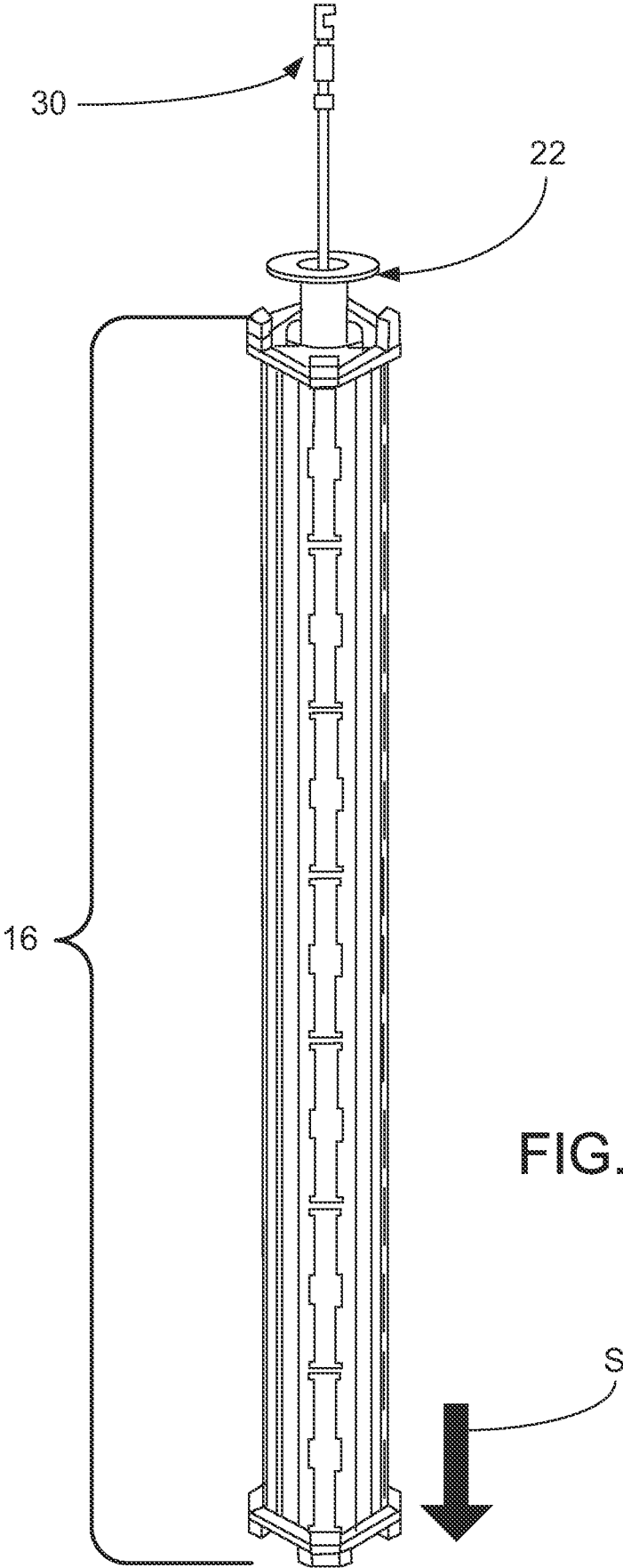


FIG. 2



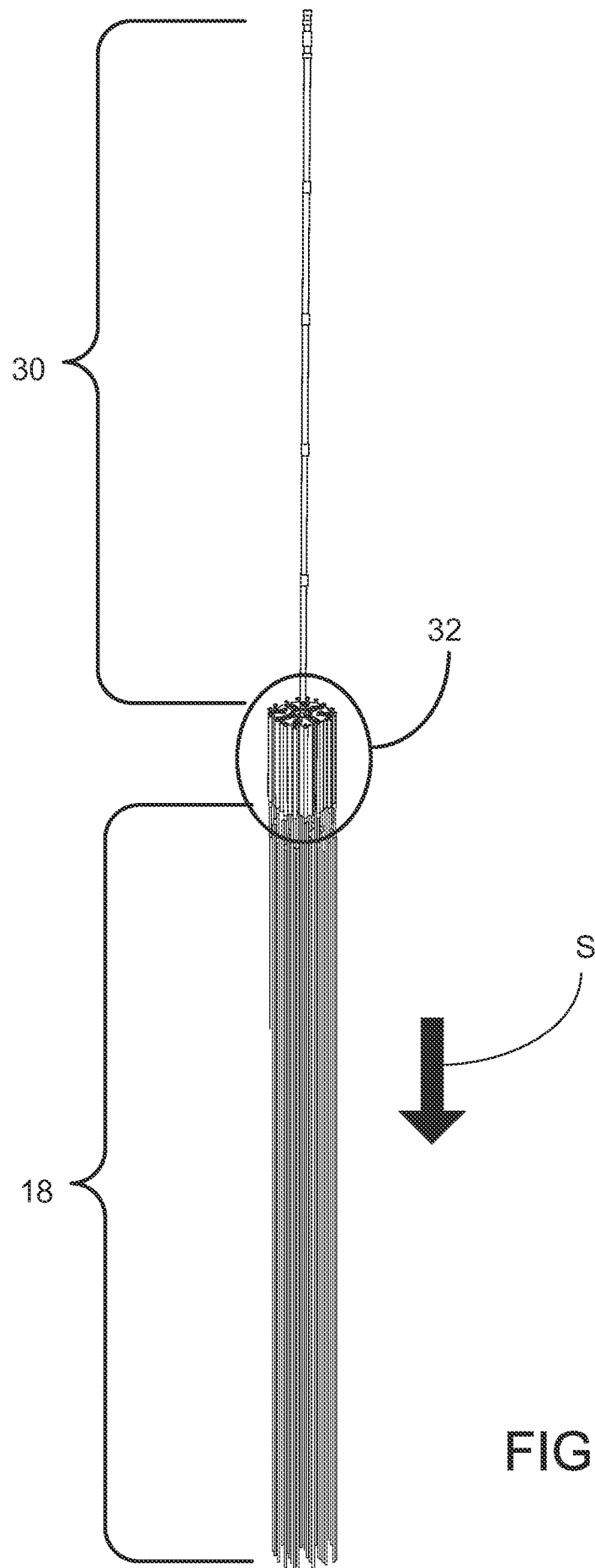


FIG. 4

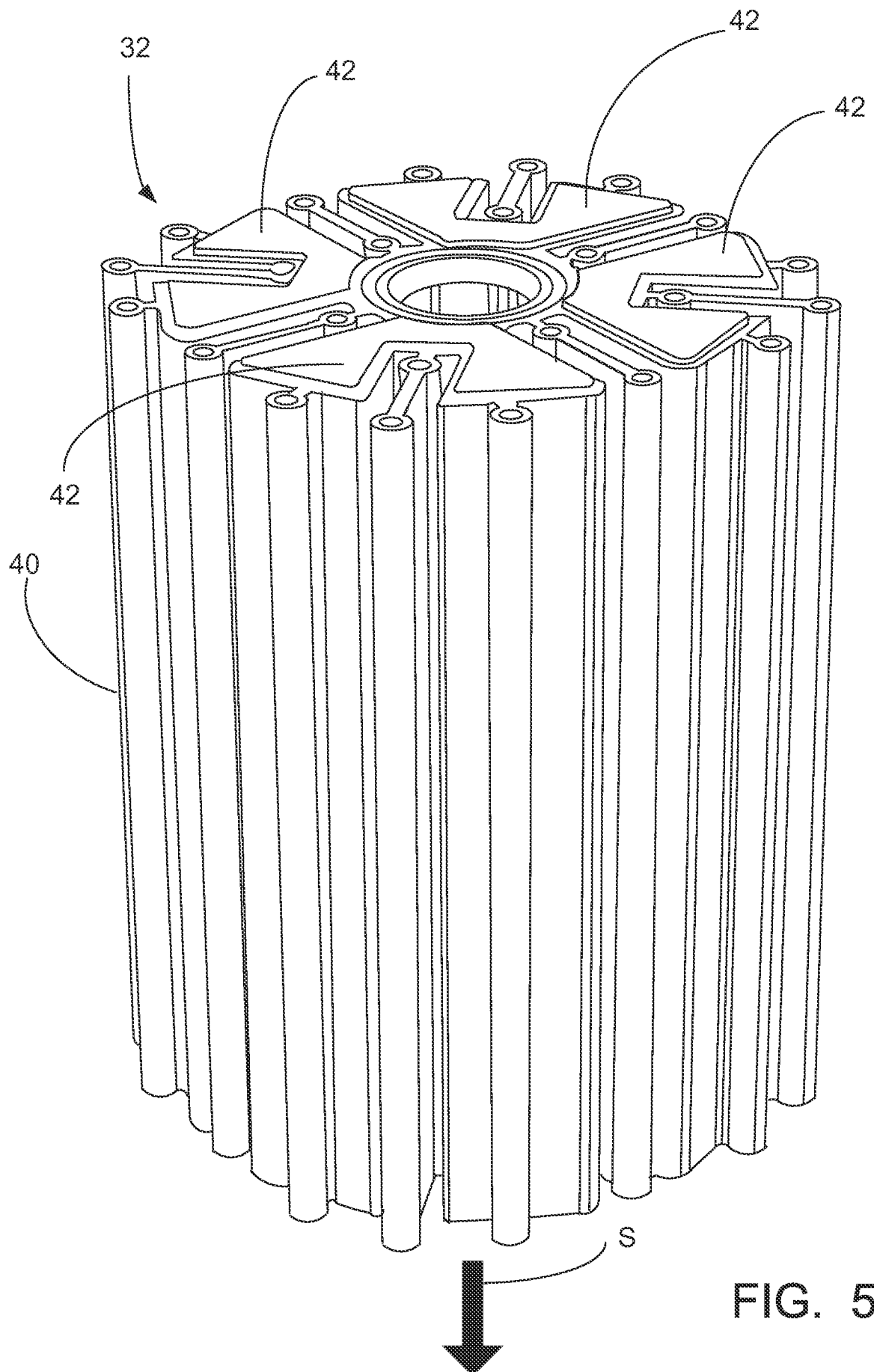


FIG. 5

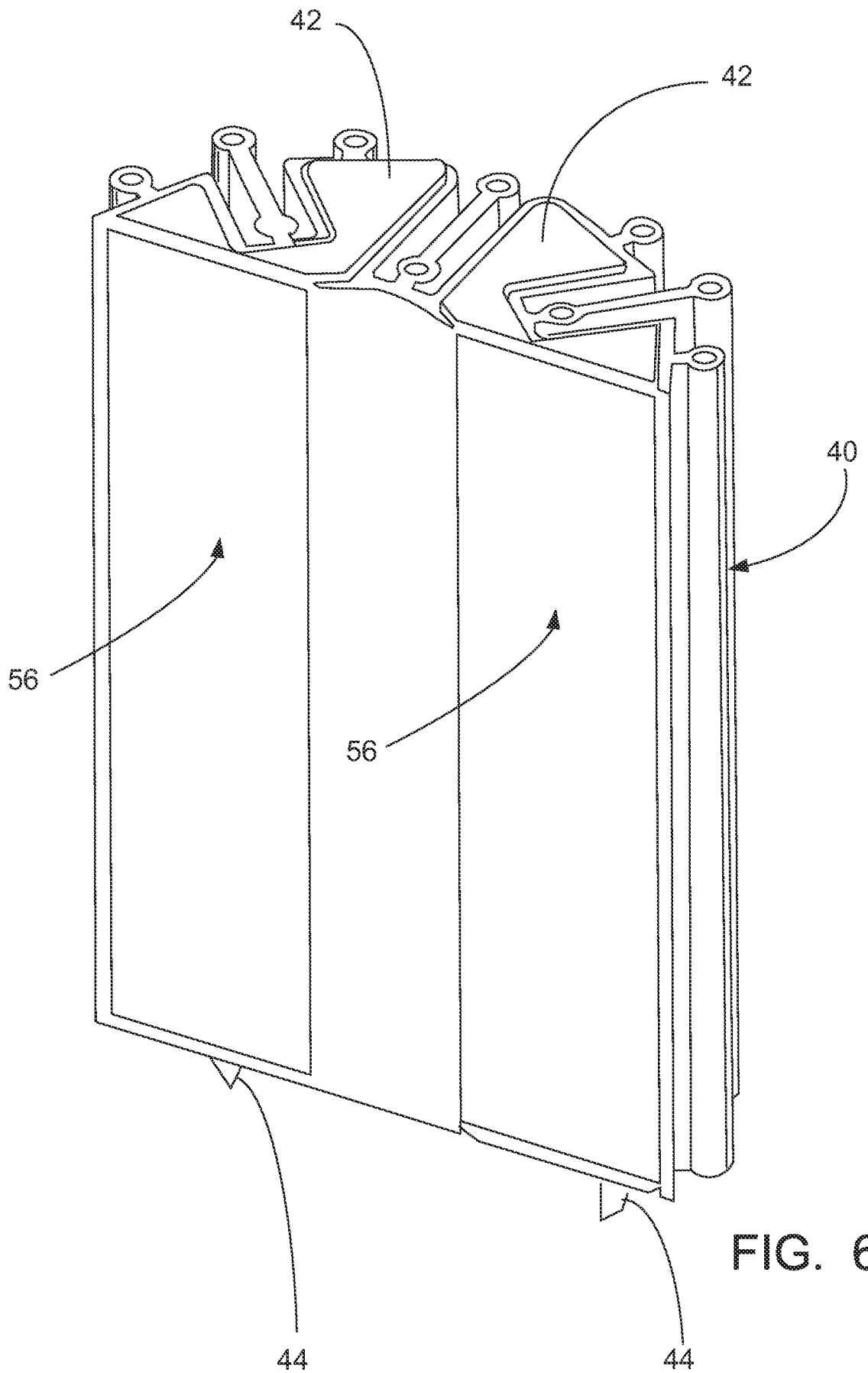


FIG. 6

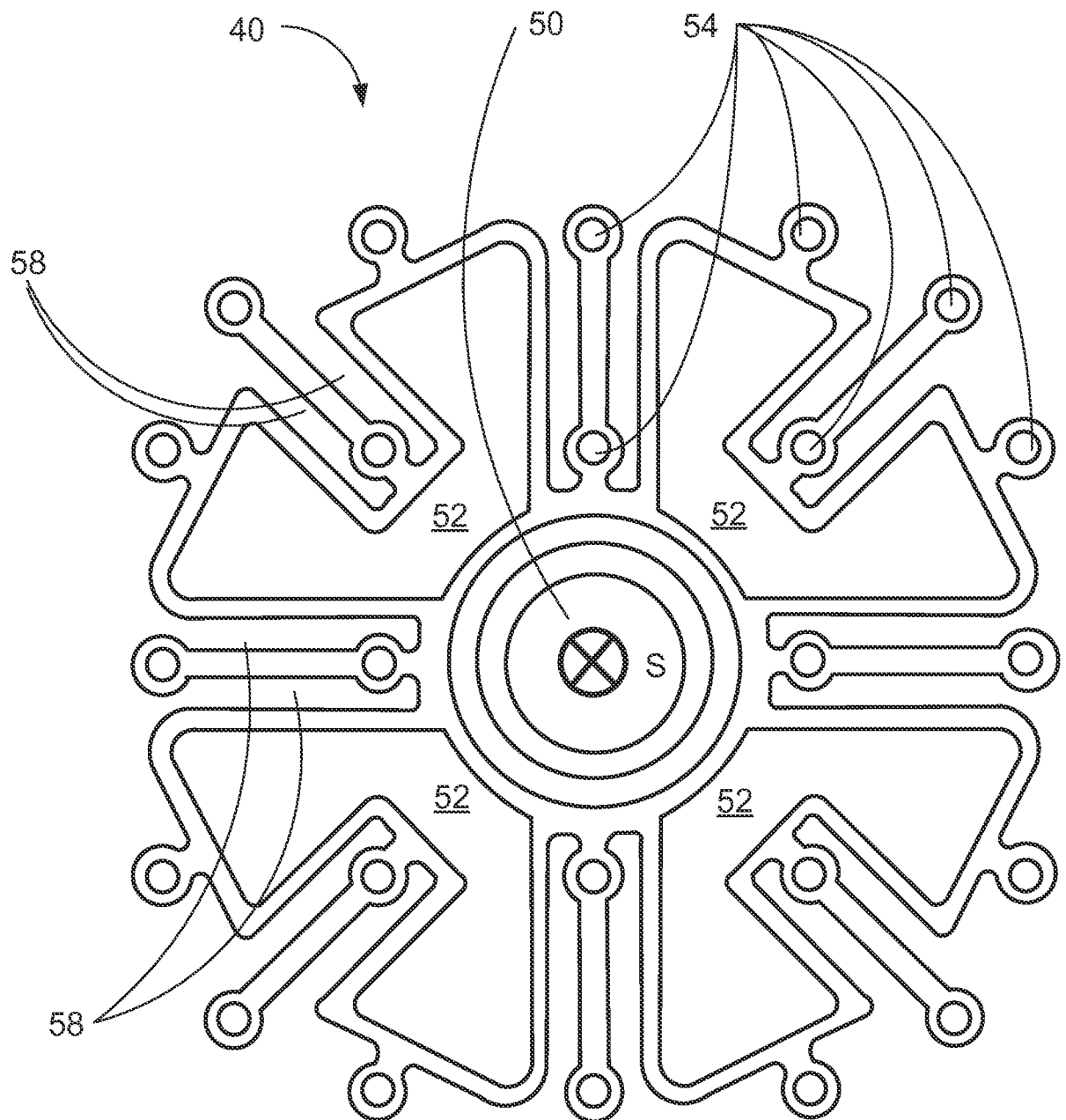


FIG. 7

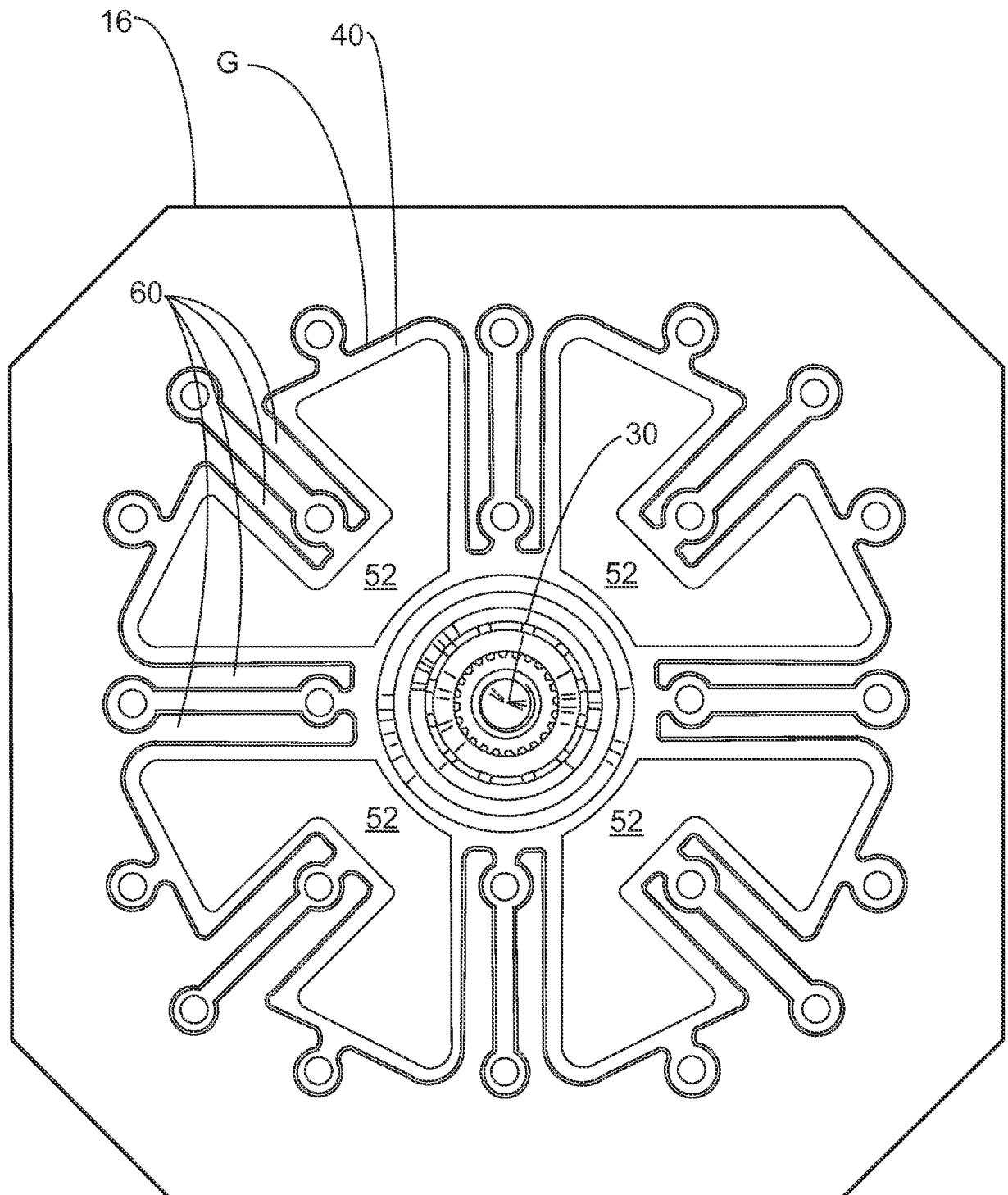
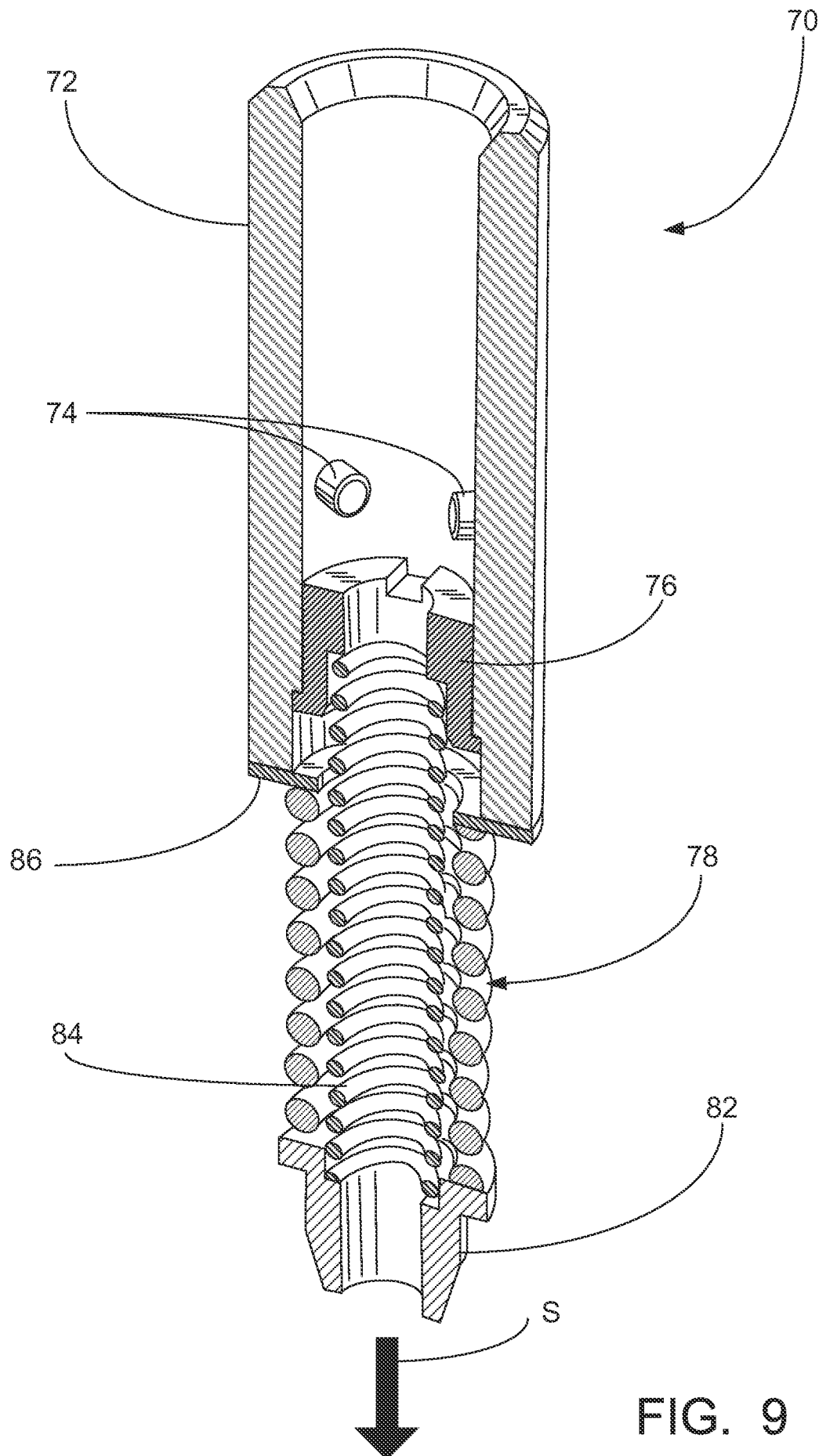


FIG. 8



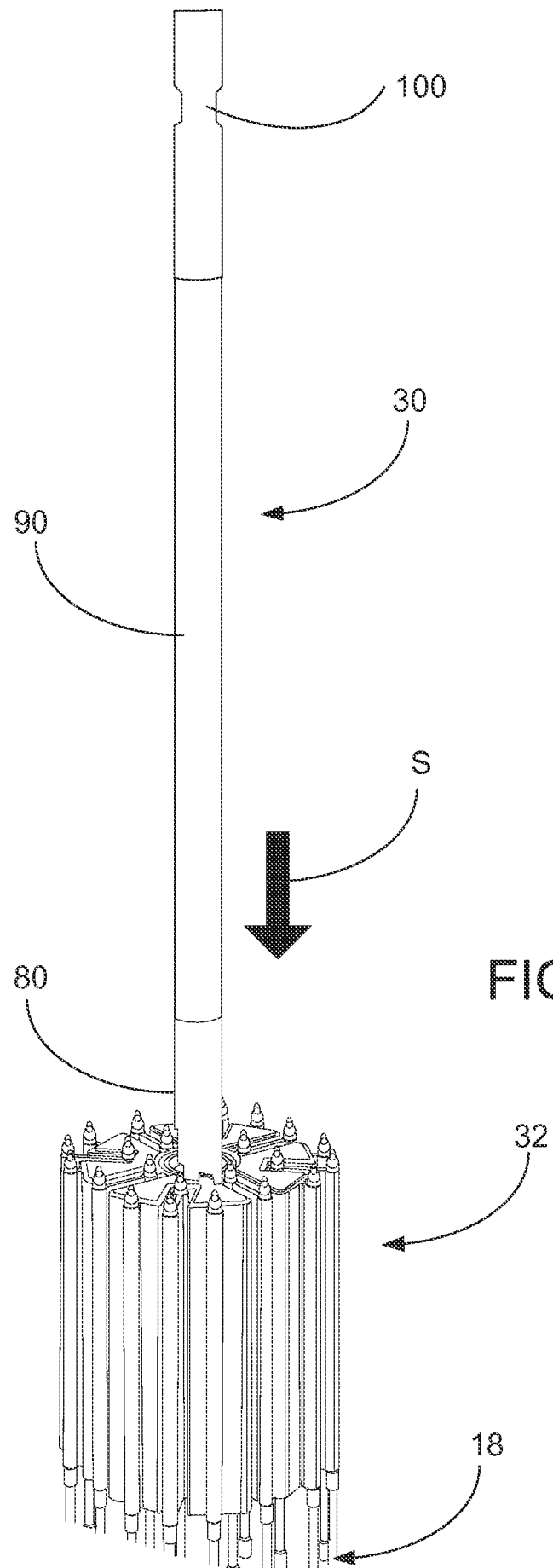
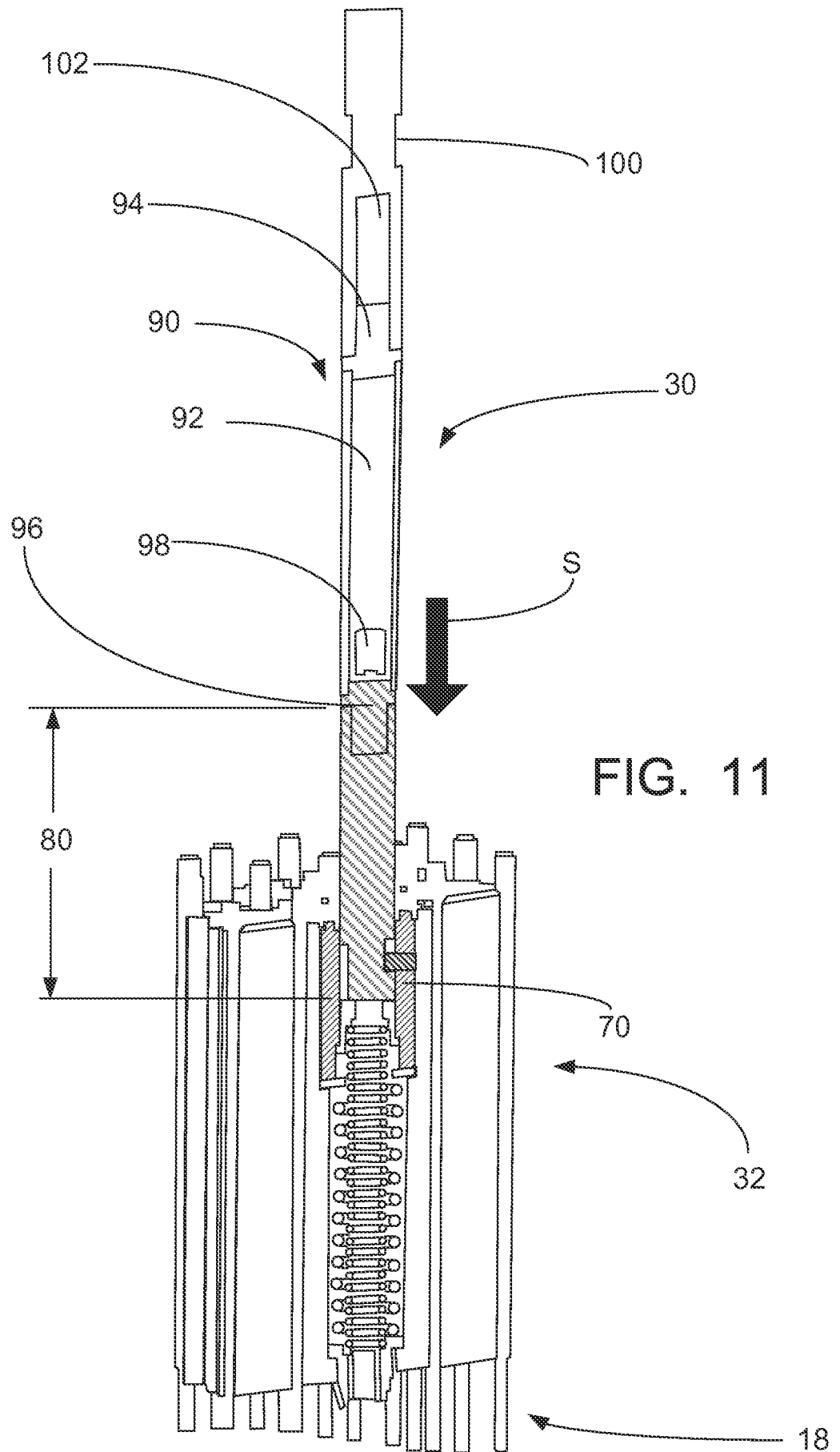
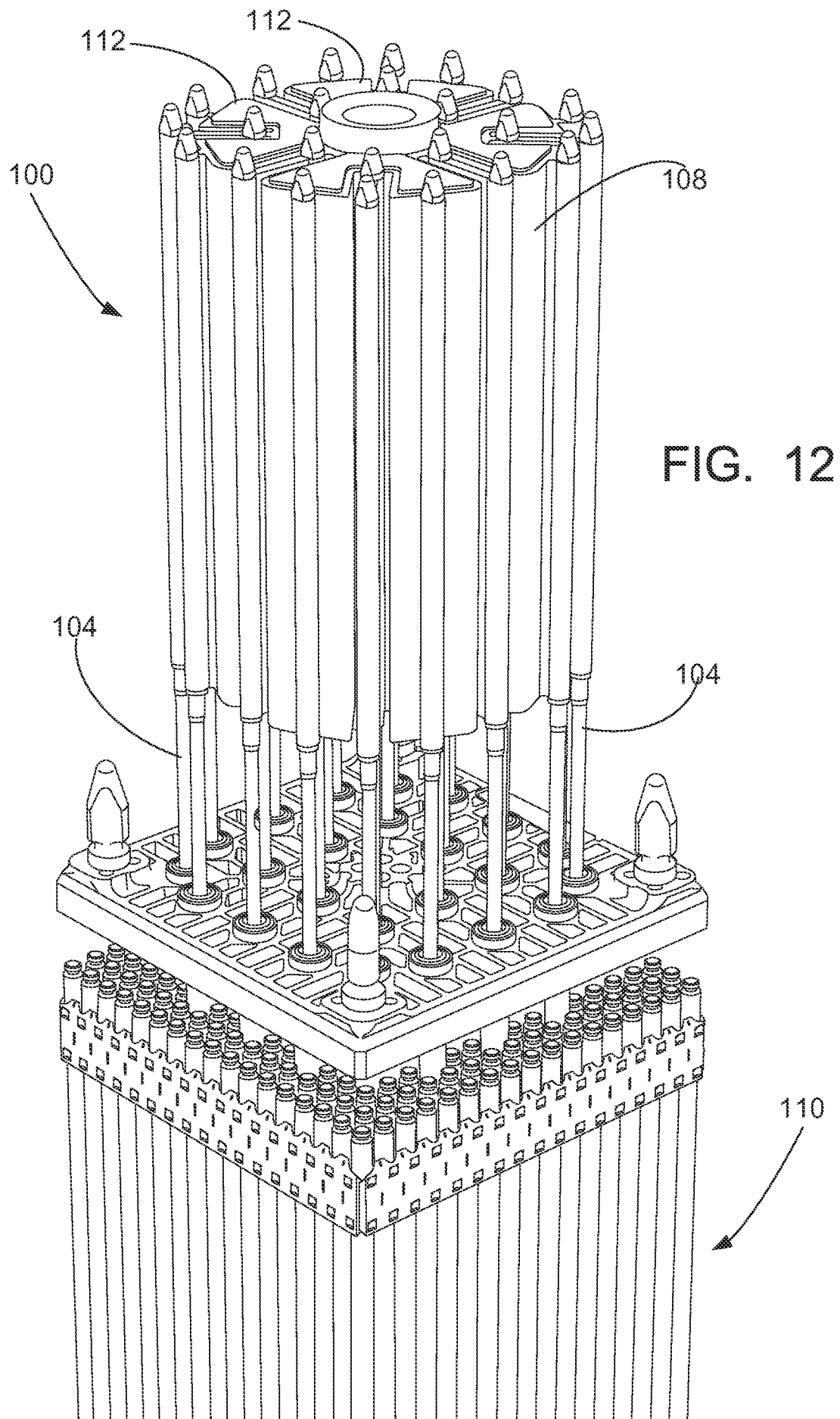


FIG. 10





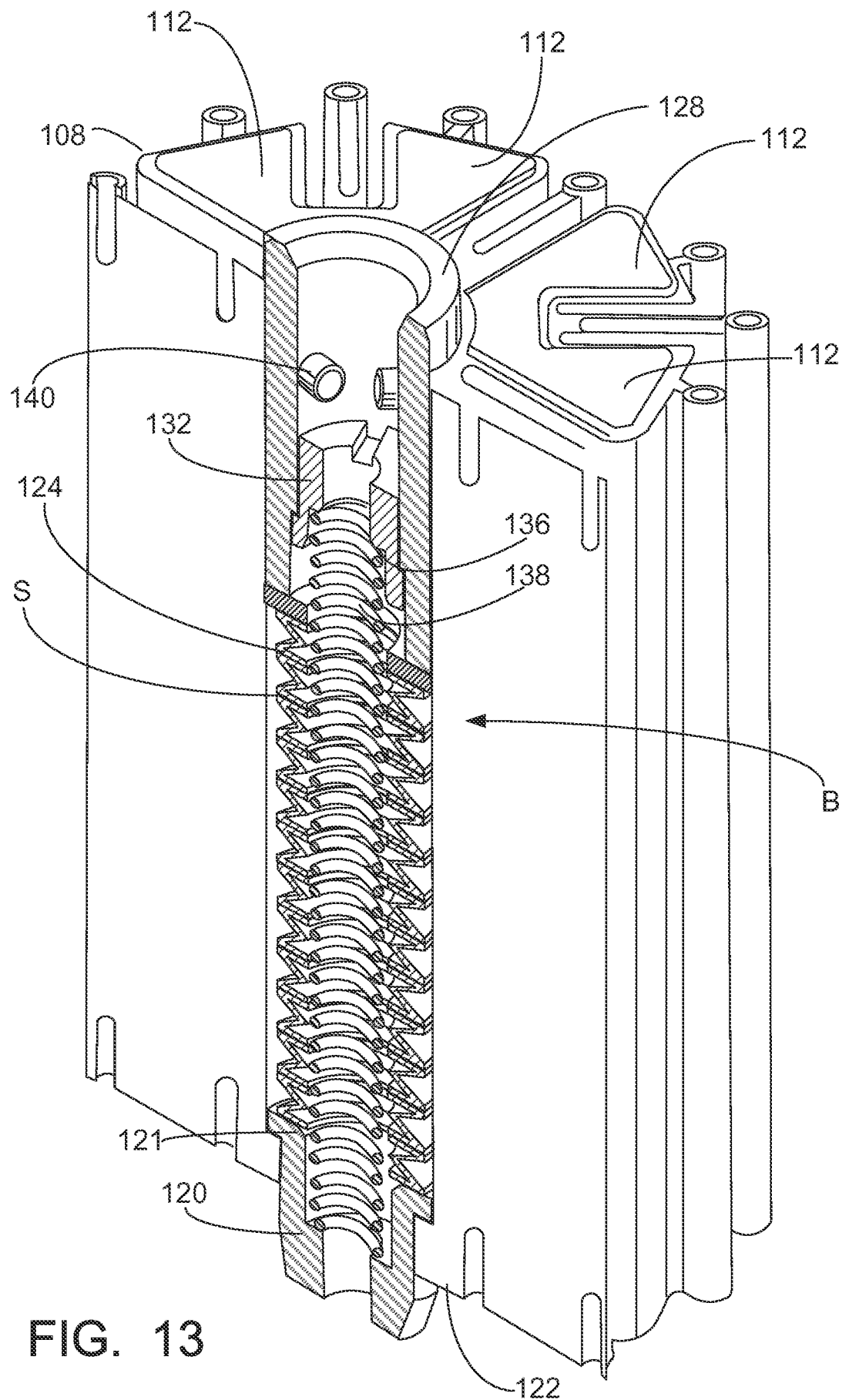


FIG. 13

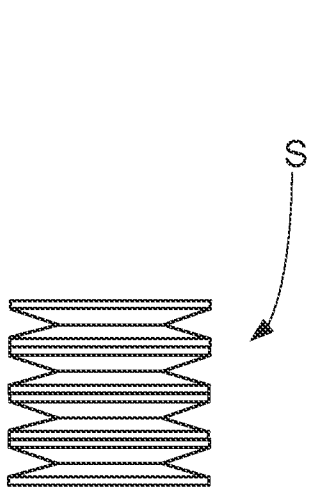


FIG. 14A

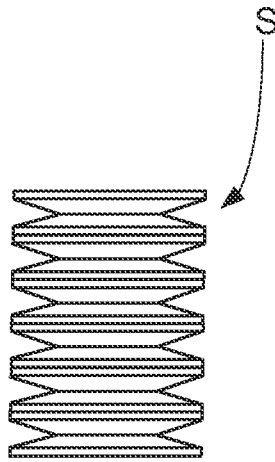


FIG. 14B

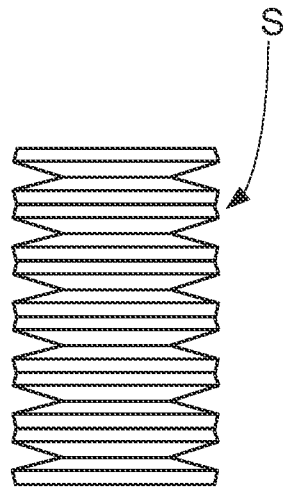


FIG. 14C

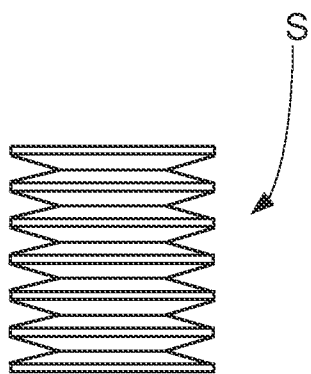


FIG. 14D

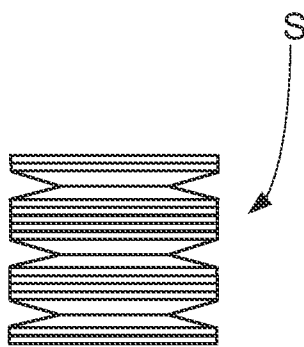


FIG. 14E

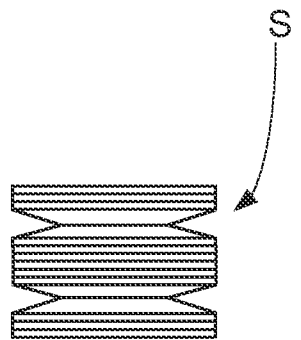


FIG. 14F