US 20130255667A1

(19) United States

(12) Patent Application Publication

(10) Pub. No.: US 2013/0255667 A1

(43) Pub. Date: Oct. 3, 2013

MA et al.

(54) SOLID PARTICLE THERMAL ENERGY STORAGE DESIGN FOR A FLUIDIZED-BED CONCENTRATING SOLAR POWER PLANT

(71) Applicant: **ALLIANCE FOR SUSTAINABLE ENERGY, LLC**, Golden, CO (US)

(72) Inventors: **Zhiwen MA**, Golden, CO (US); **Ruichong ZHANG**, Golden, CO (US)

(73) Assignee: **COLORADO SCHOOL OF MINES**, Golden, CO (US)

(21) Appl. No.: **13/855,092**

(22) Filed: **Apr. 2, 2013**

Related U.S. Application Data

(60) Provisional application No. 61/715,747, filed on Oct. 18, 2012, provisional application No. 61/619,317, filed on Apr. 2, 2012, provisional application No. 61/715,751, filed on Oct. 18, 2012, provisional application No. 61/715,755, filed on Oct. 18, 2012.

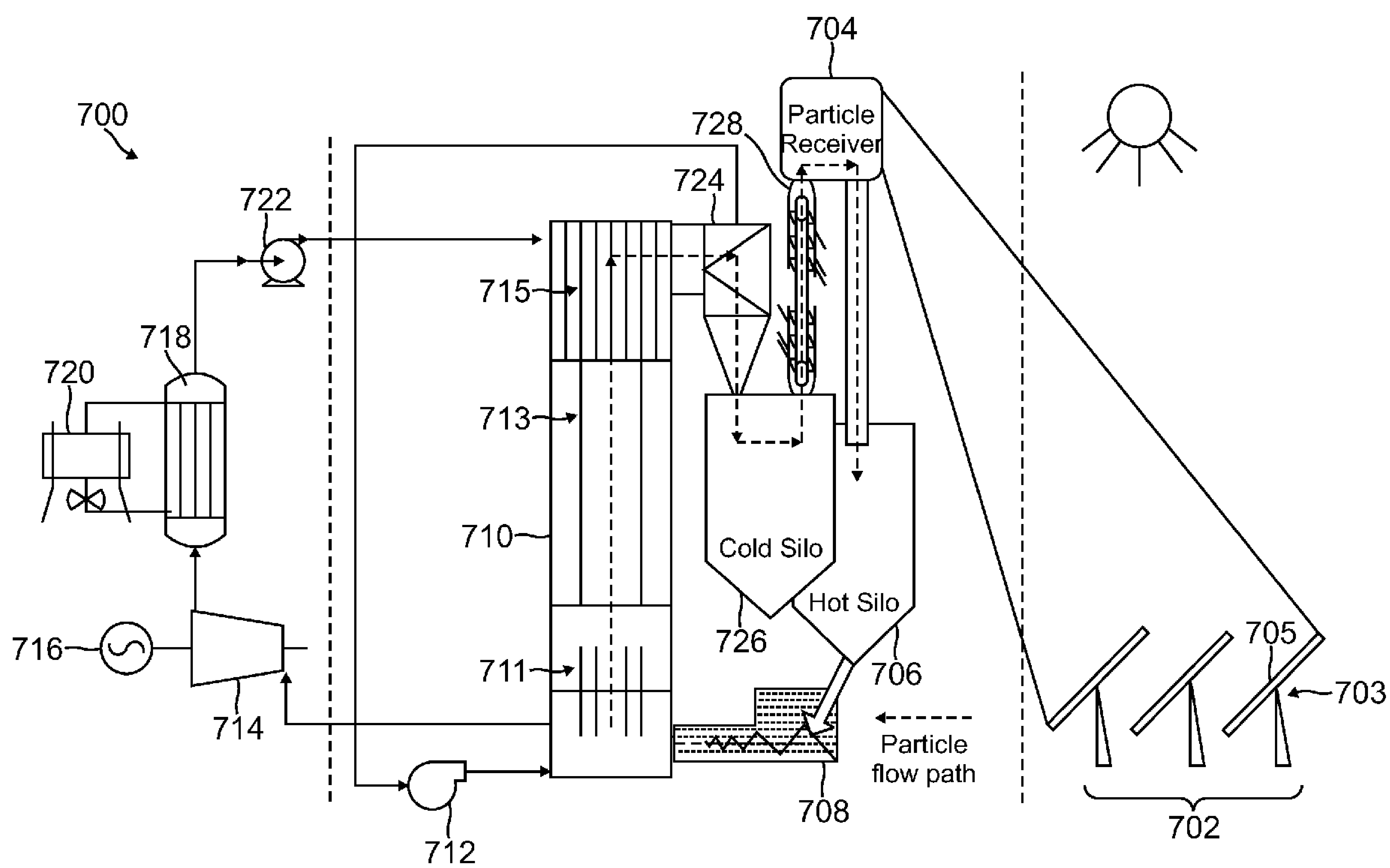
Publication Classification

(51) **Int. Cl.**
F24J 2/46 (2006.01)
F24J 2/34 (2006.01)

(52) **U.S. Cl.**
CPC . ***F24J 2/4649*** (2013.01); ***F24J 2/34*** (2013.01)
USPC **126/617**; 165/104.18

(57) **ABSTRACT**

A fluidized-bed concentrating solar power plant comprises a particle receiver configured to contain solid state particles, wherein the particle receiver heats the solid state particles by transferring thermal energy from sunlight to the solid state particles. The plant also comprises a first silo configured to receive and store heated solid state particles from the particle receiver; a heat exchanger configured to receive the heated solid state particles from the first silo and generate a fluidized mixture comprising the heated solid state particles suspended in a gas; and a second silo configured to feed cooled solid state particles to the particle receiver, the cooled solid state particle extracted from the fluidized mixture. The first silo and the second silo each comprise a foundation comprising a base supported by a plurality of micropile units. Each micropile unit comprises a plurality of micropile columns coupled to a support block which supports the base.



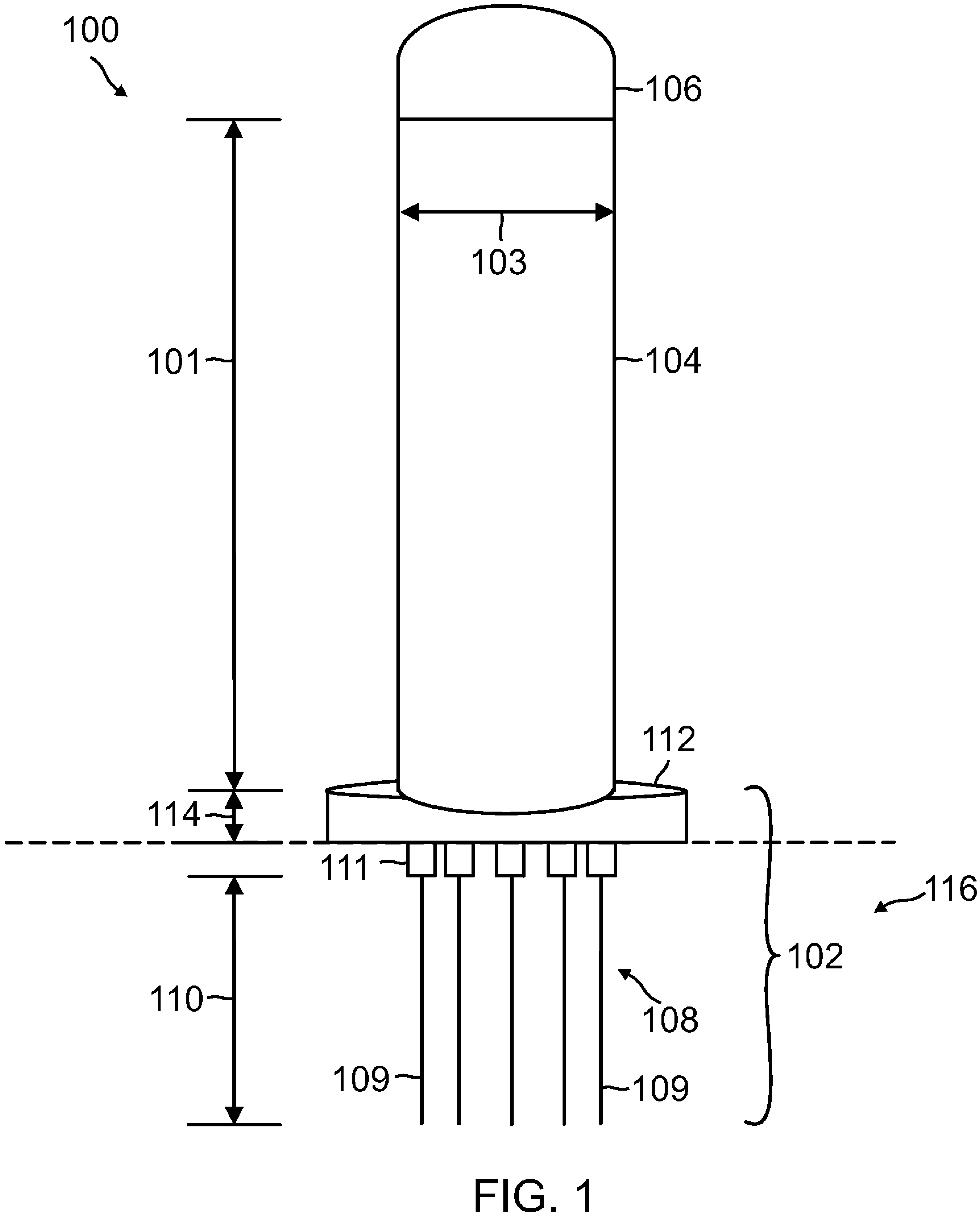


FIG. 1

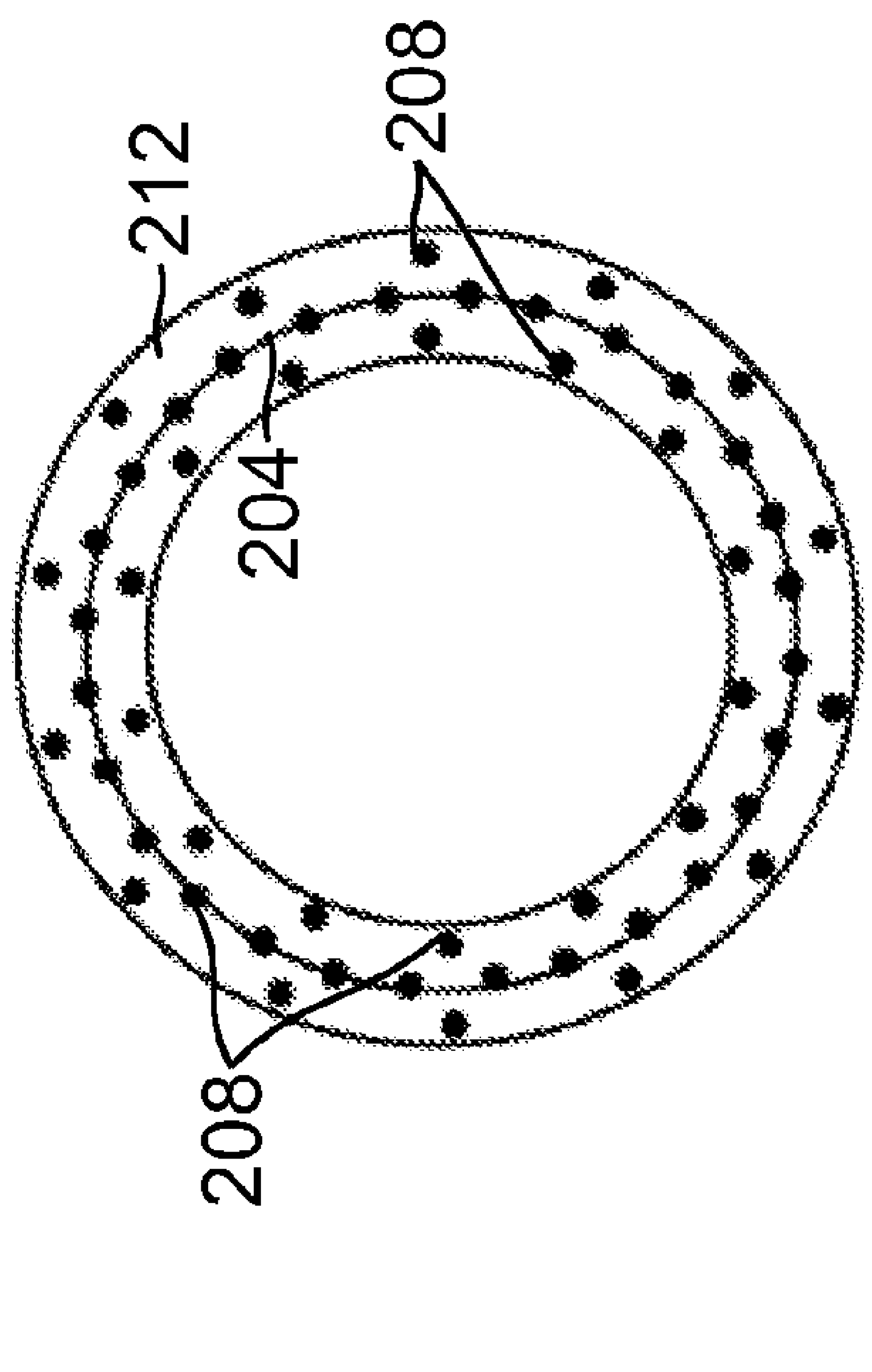


FIG. 2A

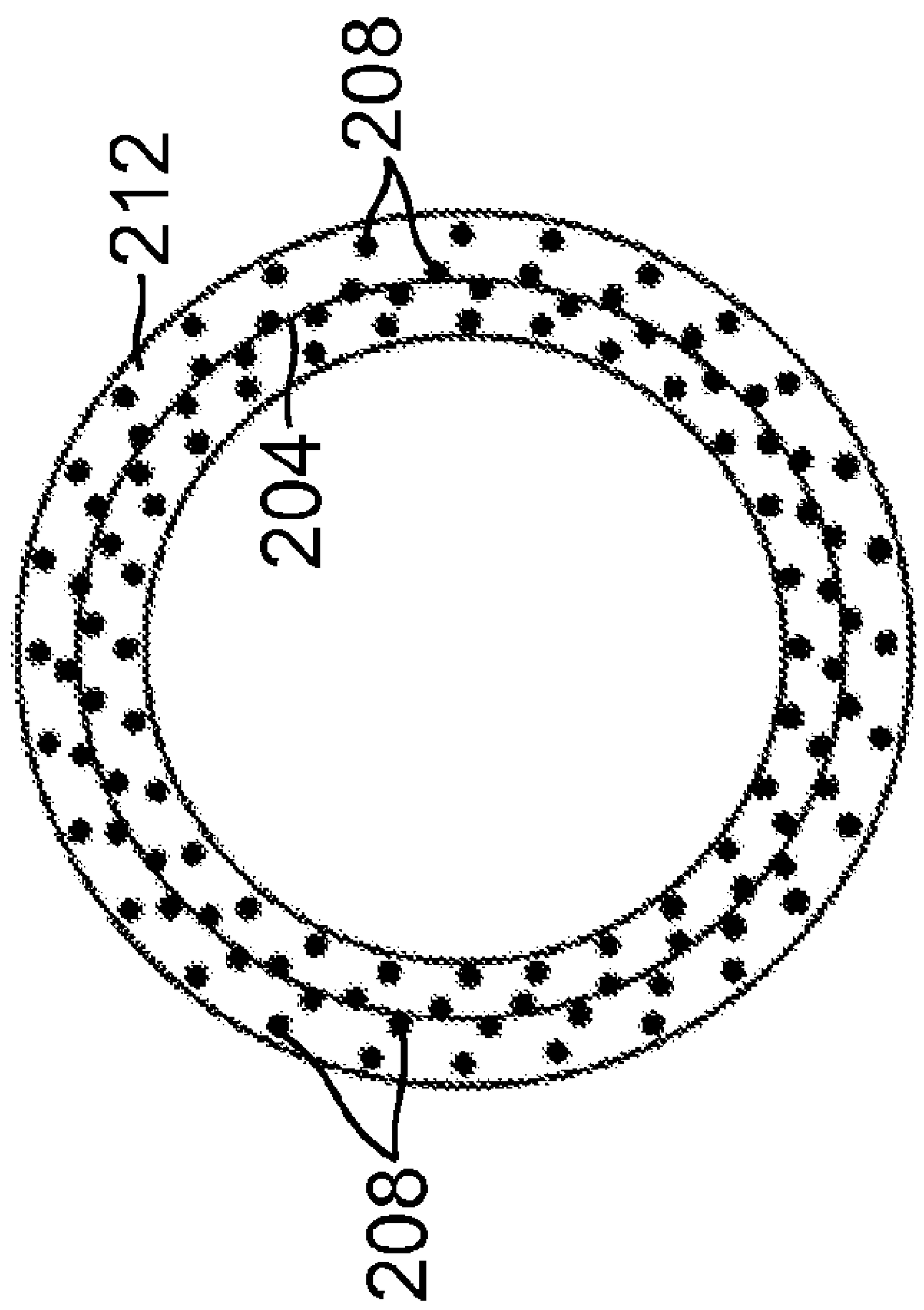


FIG. 2B

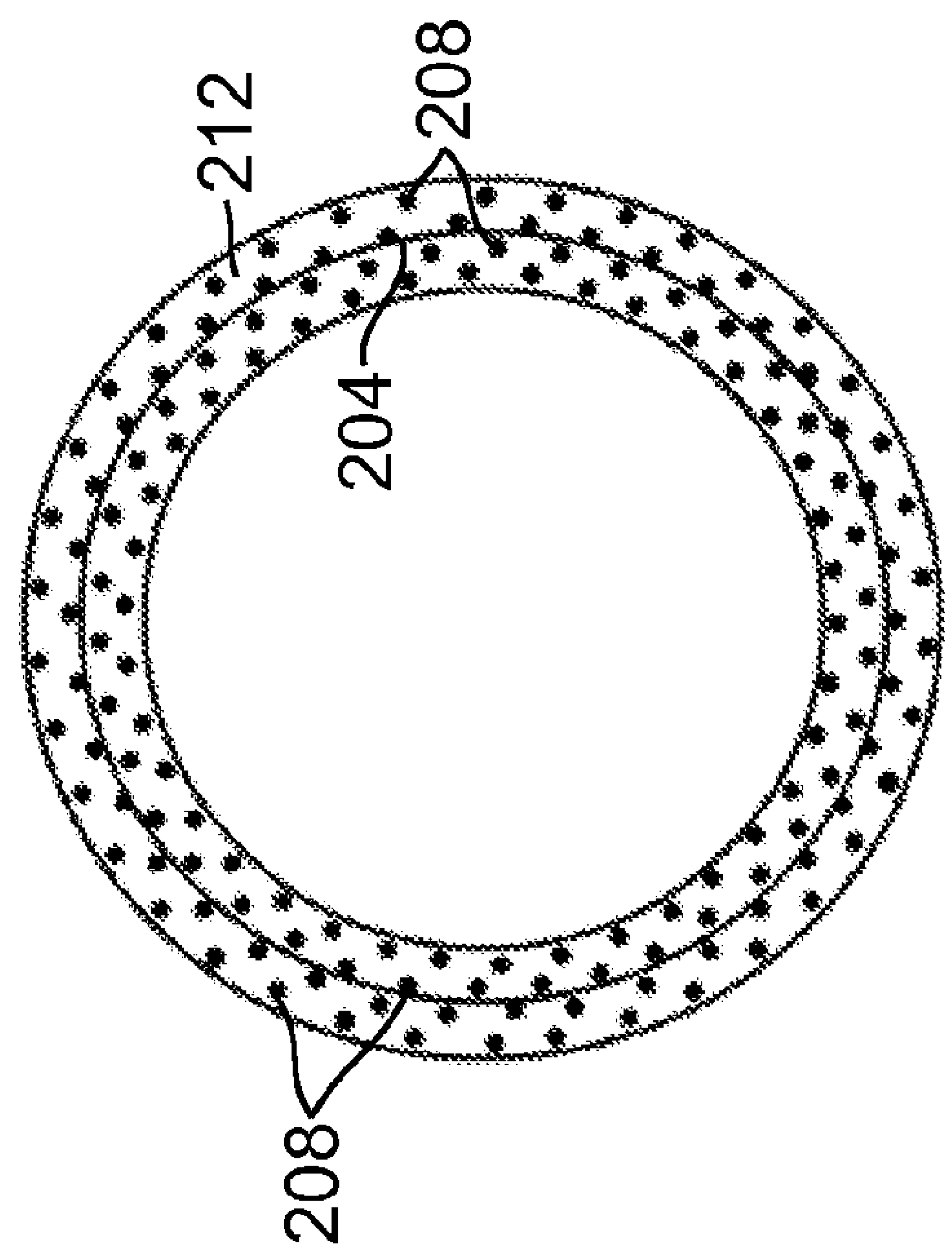


FIG. 2C

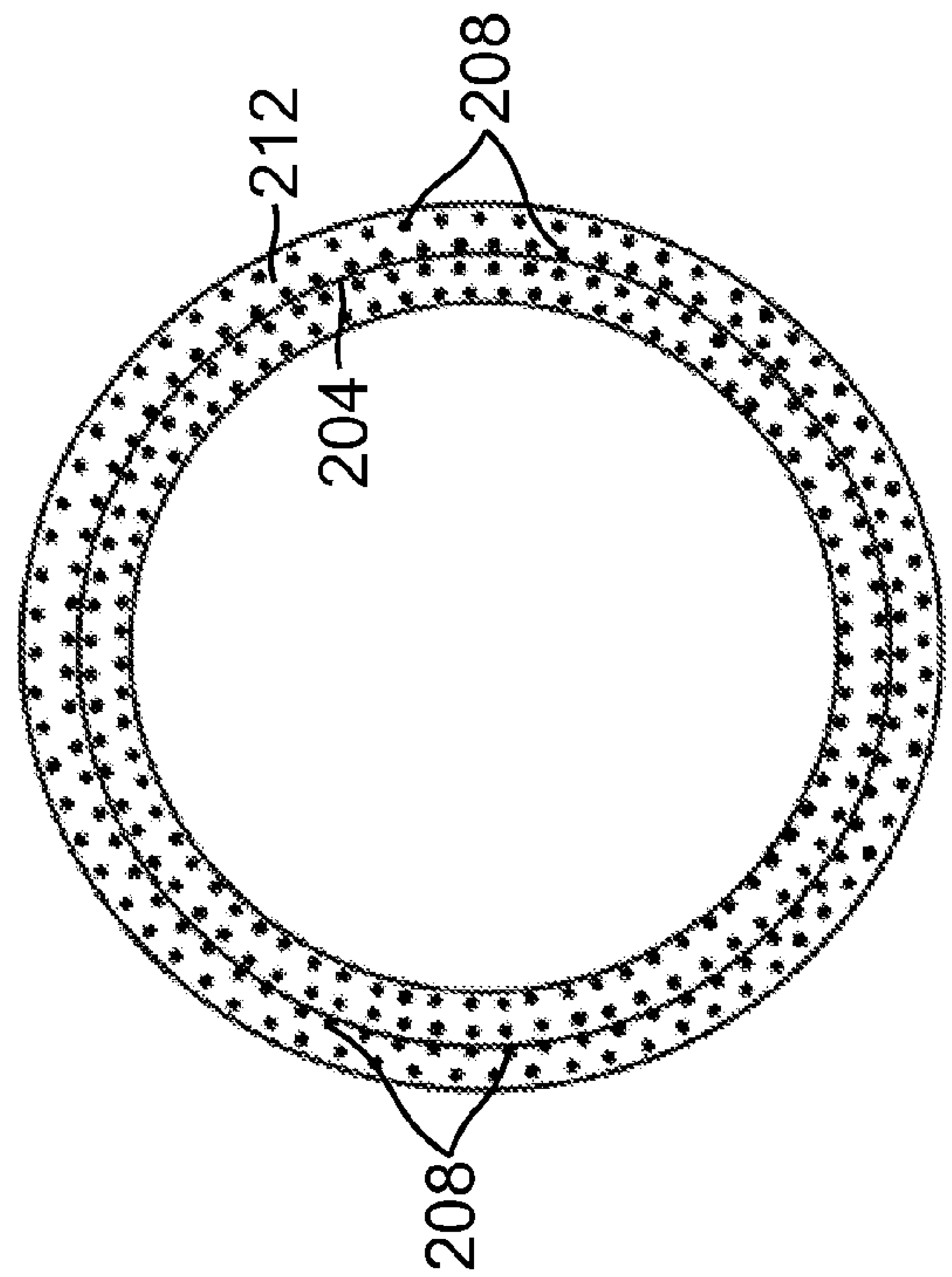


FIG. 2D

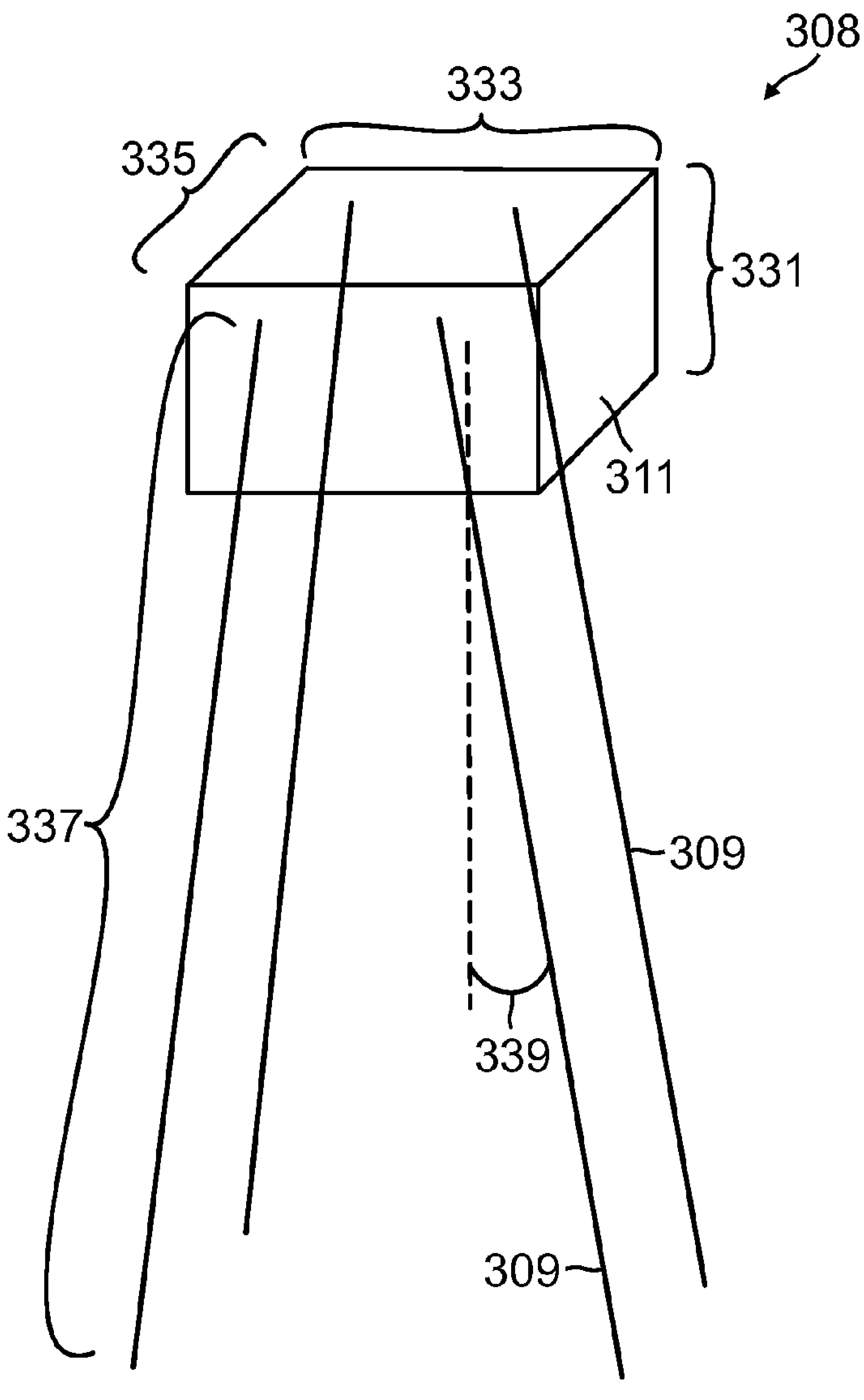


FIG. 3

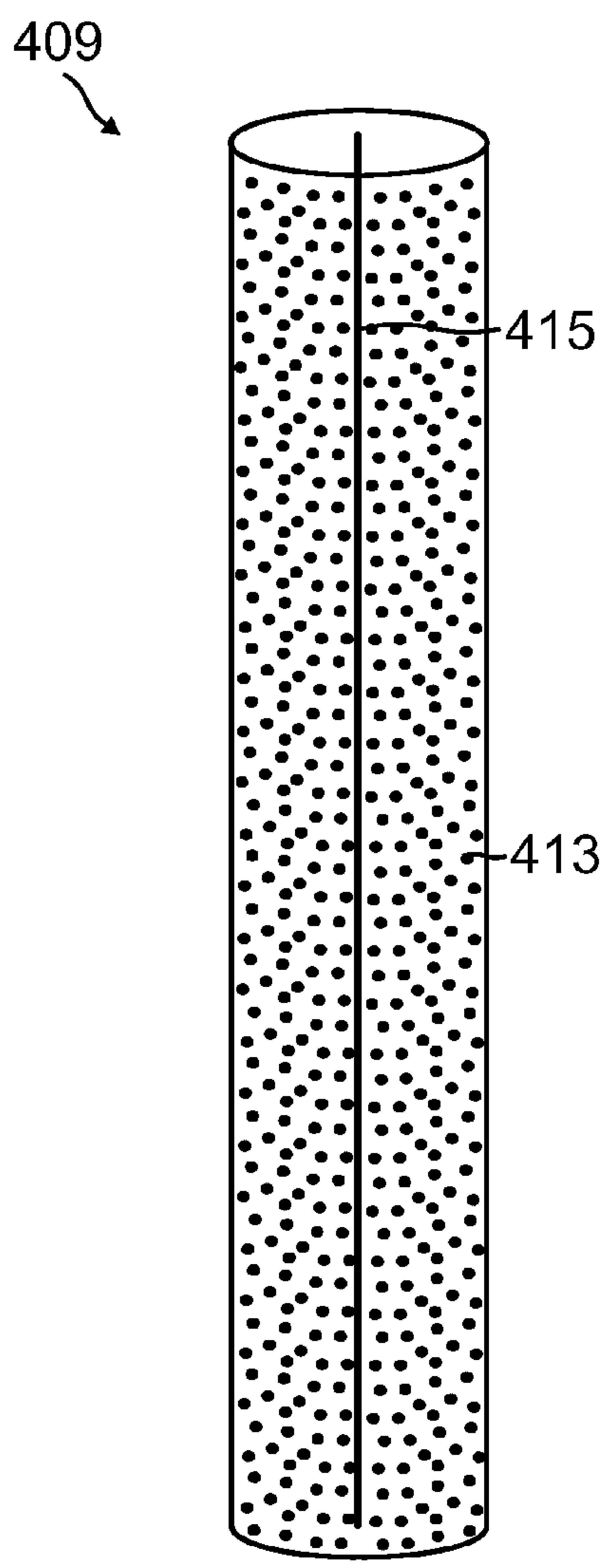


FIG. 4

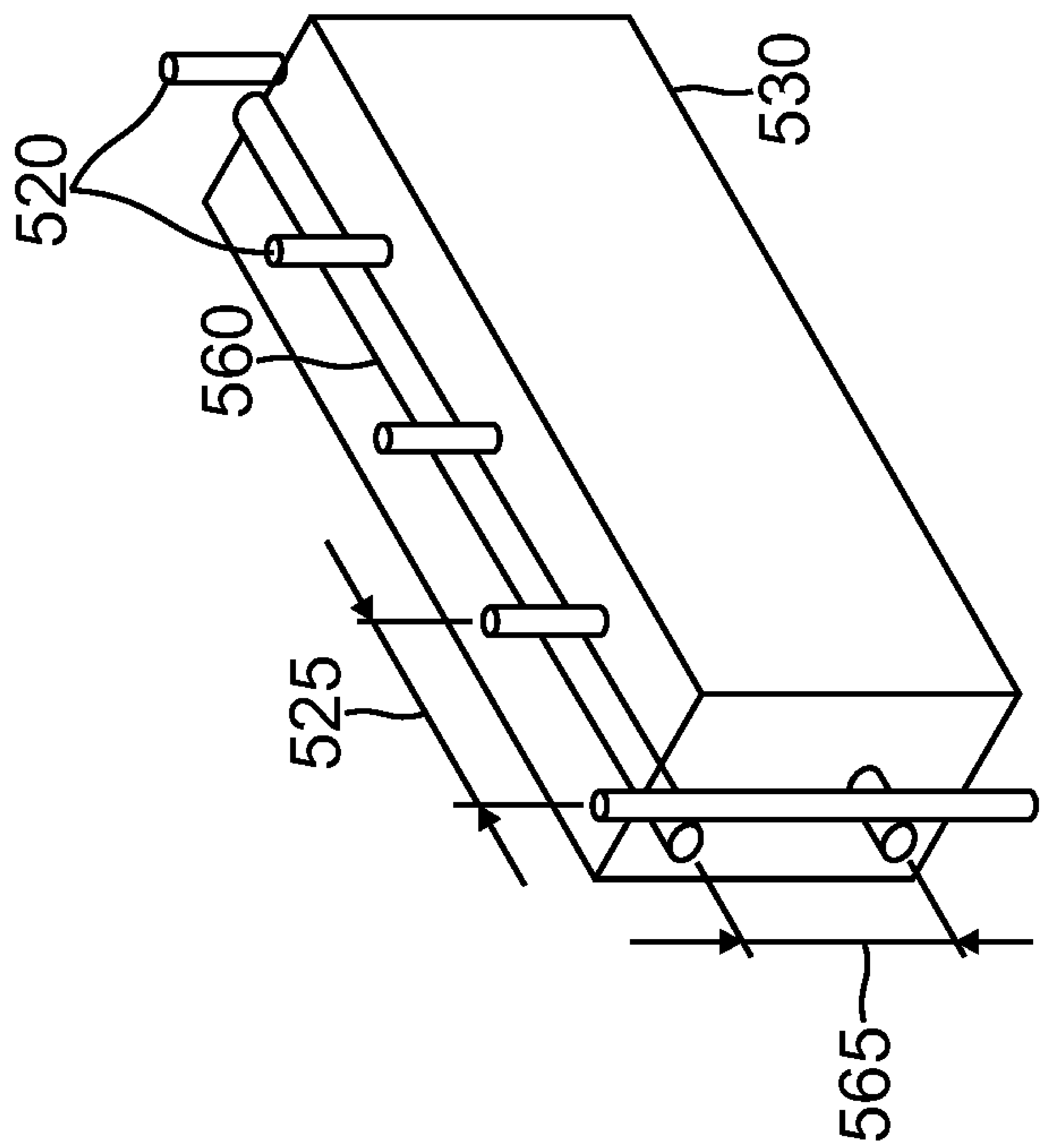


FIG. 5B

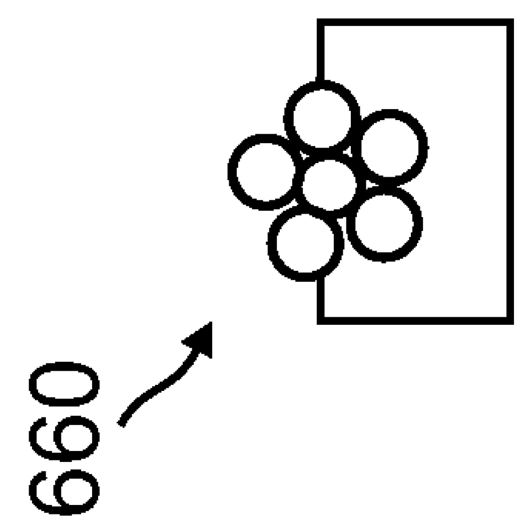


FIG. 6

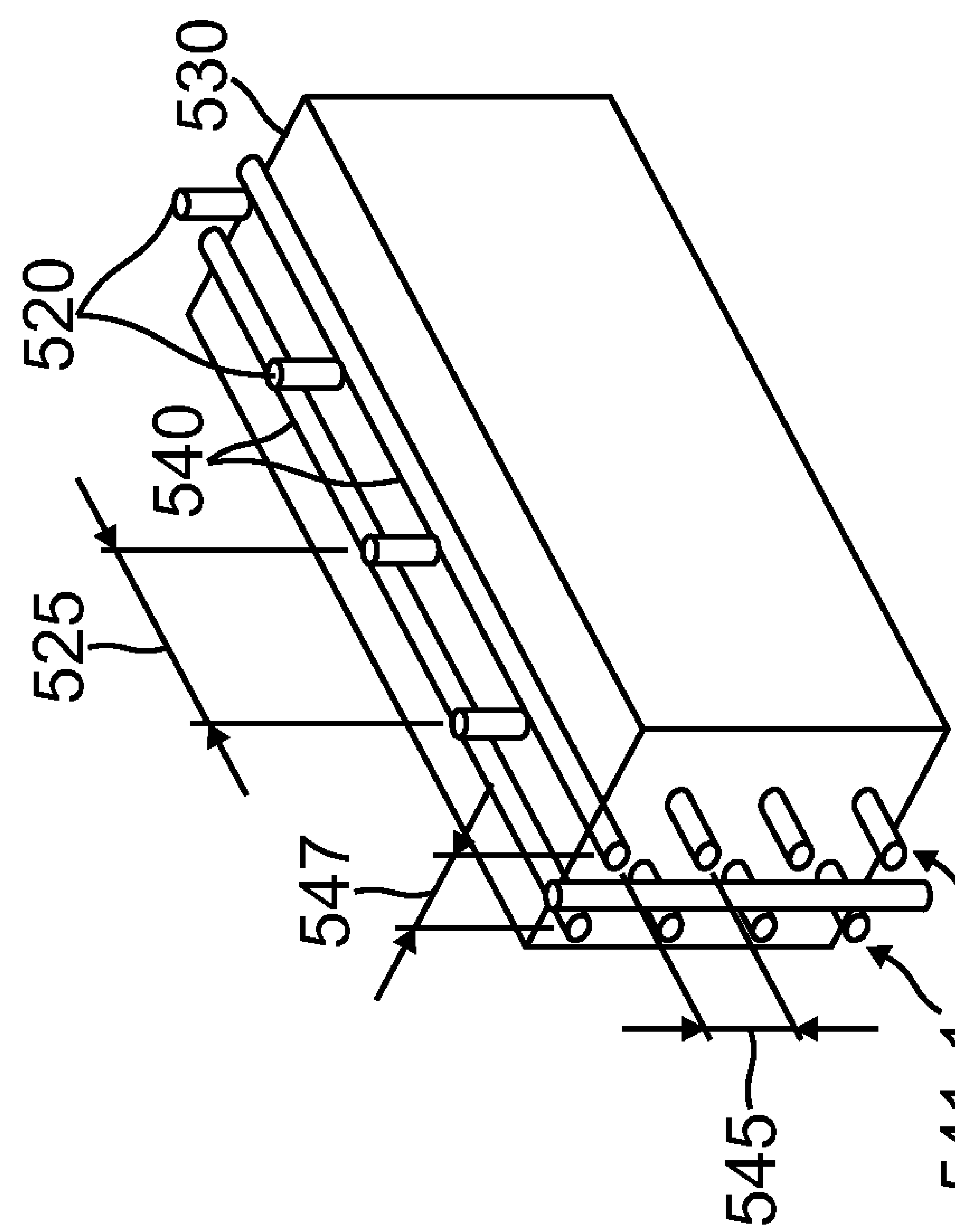


FIG. 5A

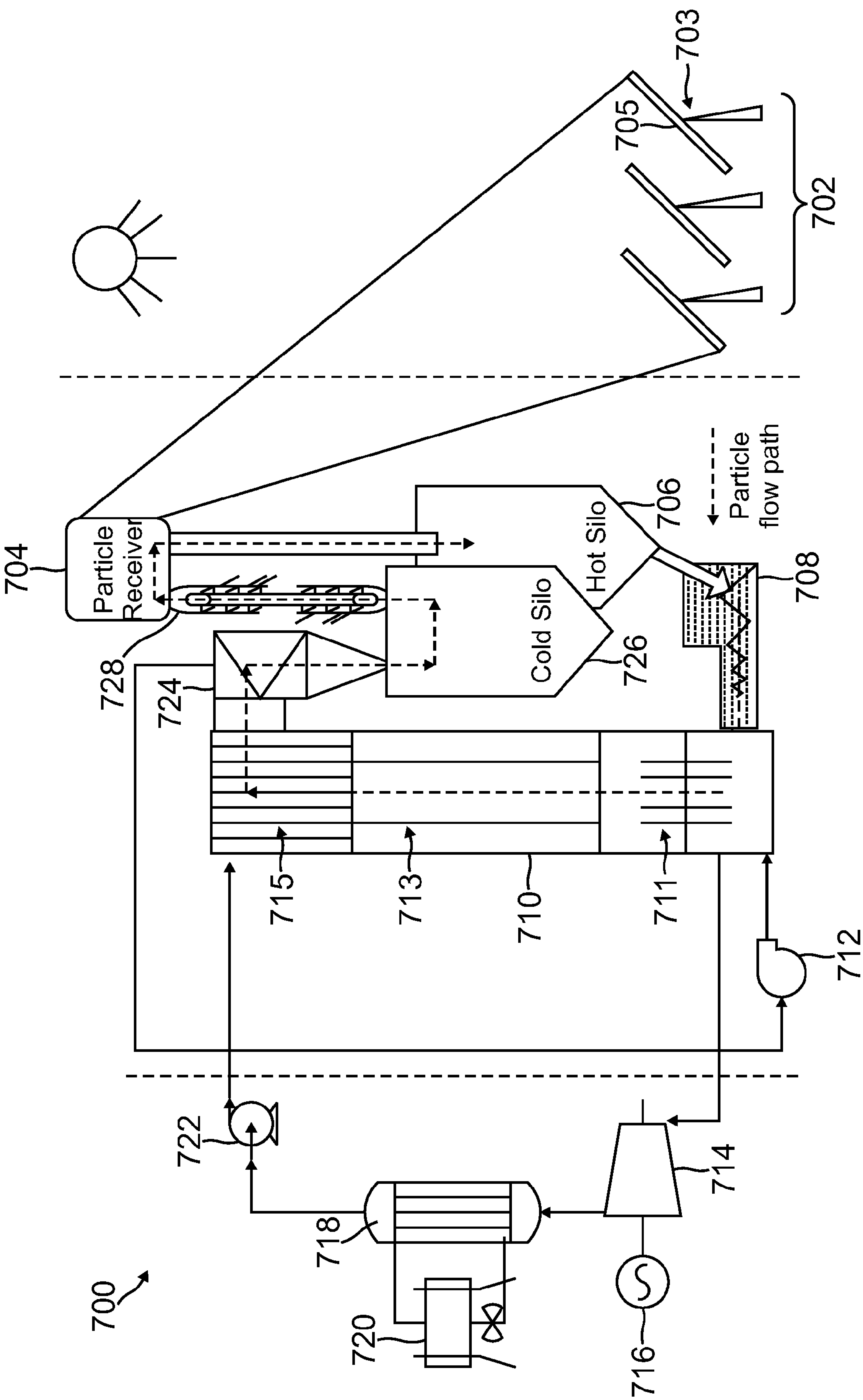

703
705
702
704
Particle Receiver
706
Hot Silo
Particle flow path
708
Cold Silo
726
728
724
715
713
710
711
712
722
714
718
700
720
716

FIG. 7

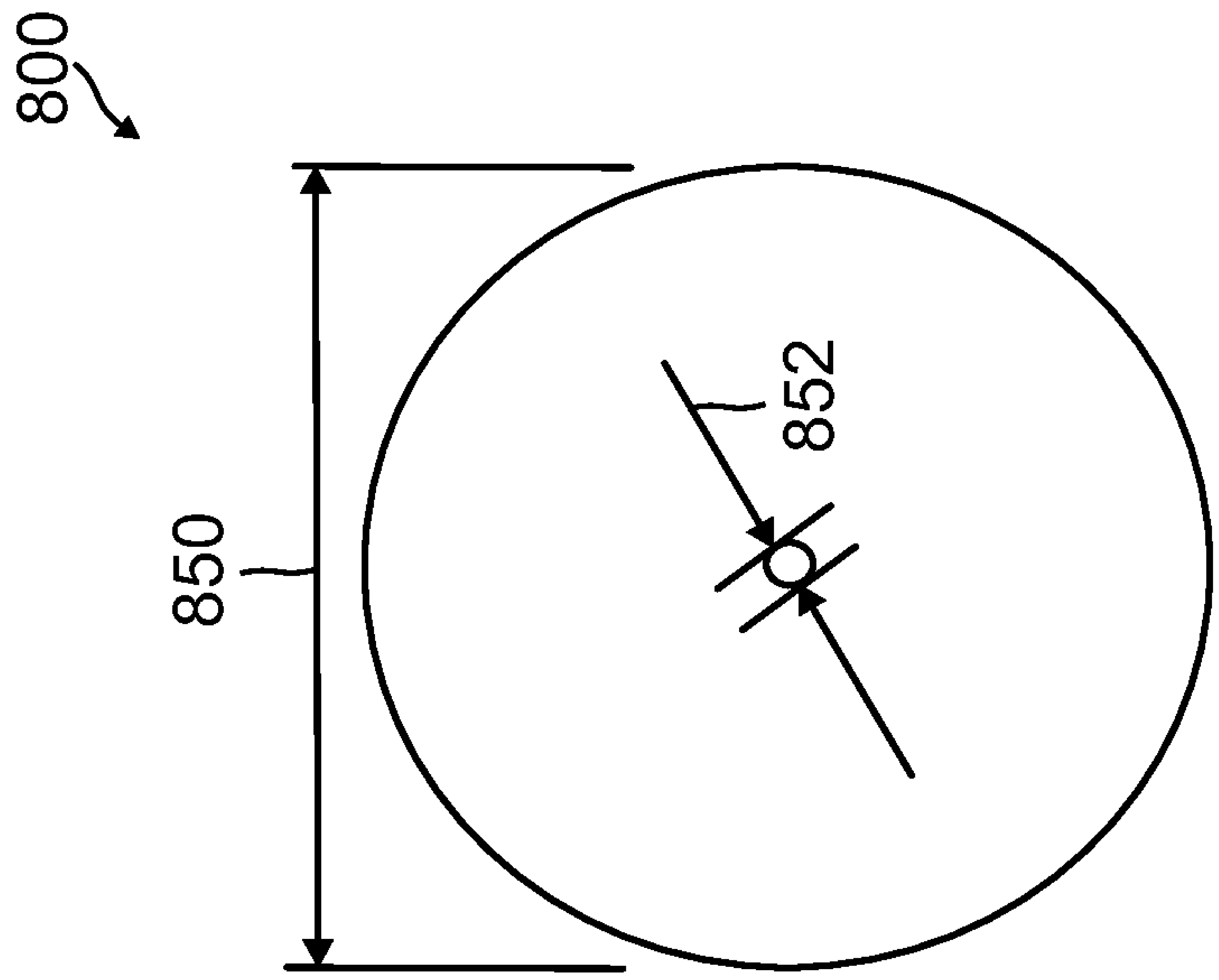


FIG. 8B

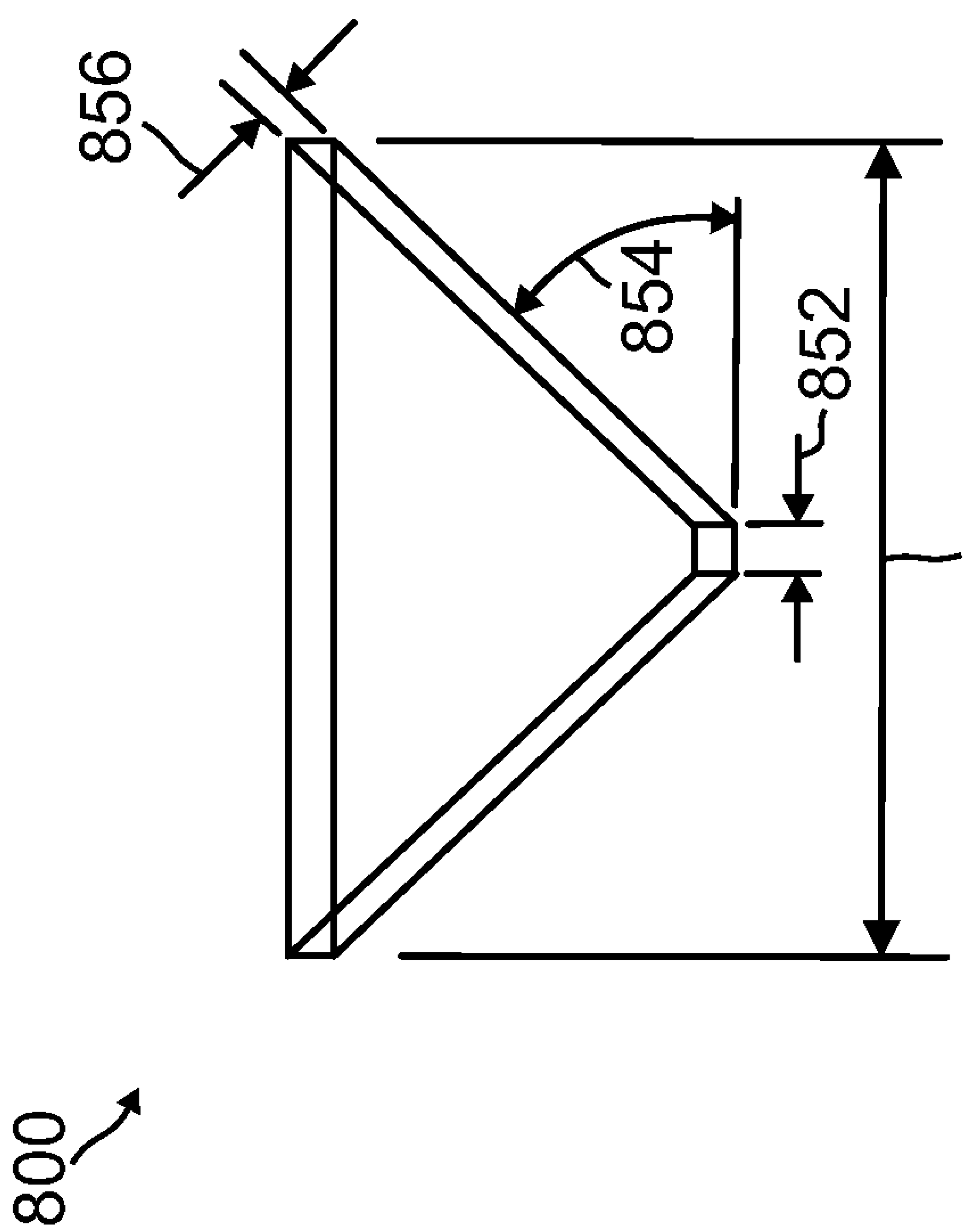


FIG. 8A

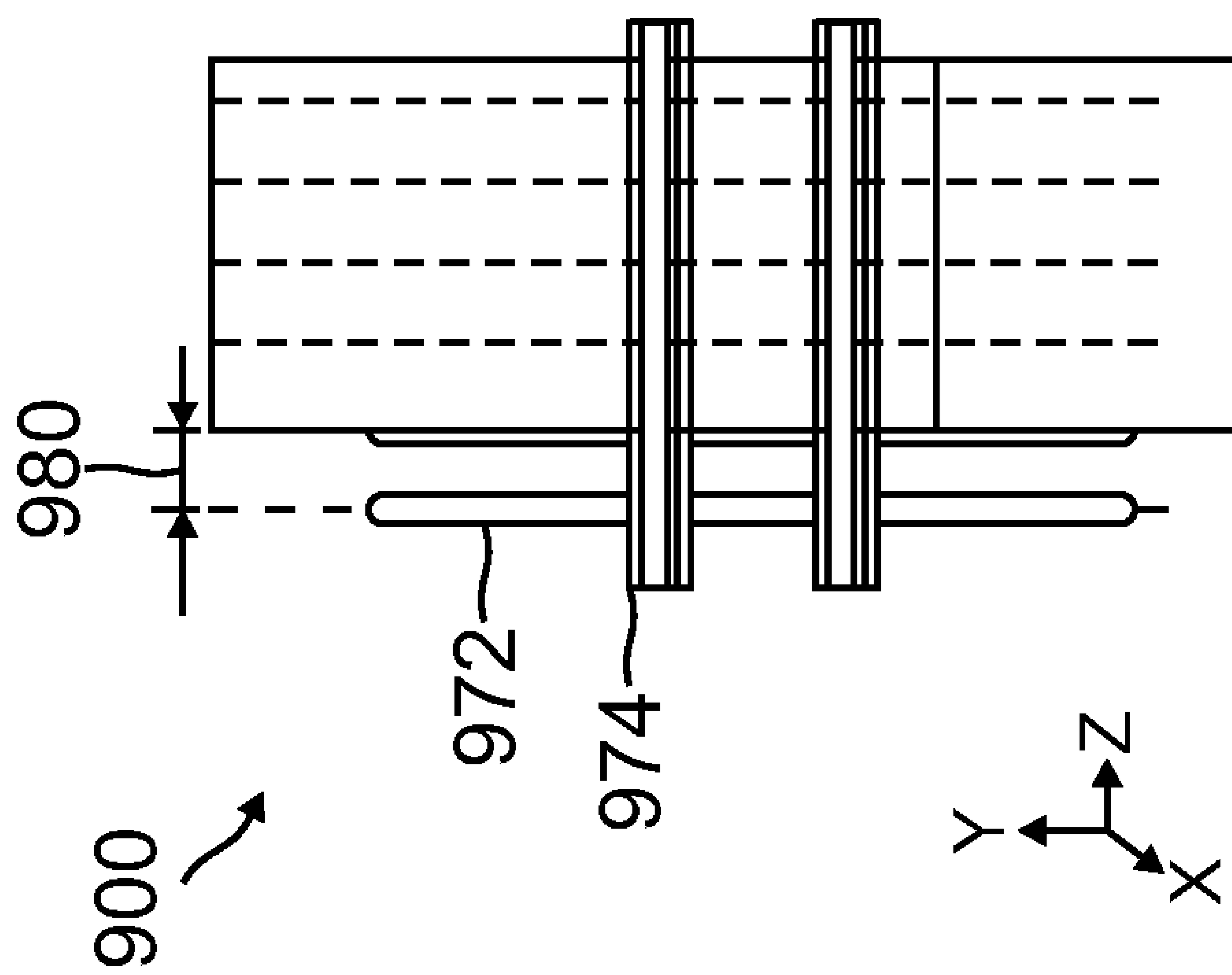


FIG. 9B

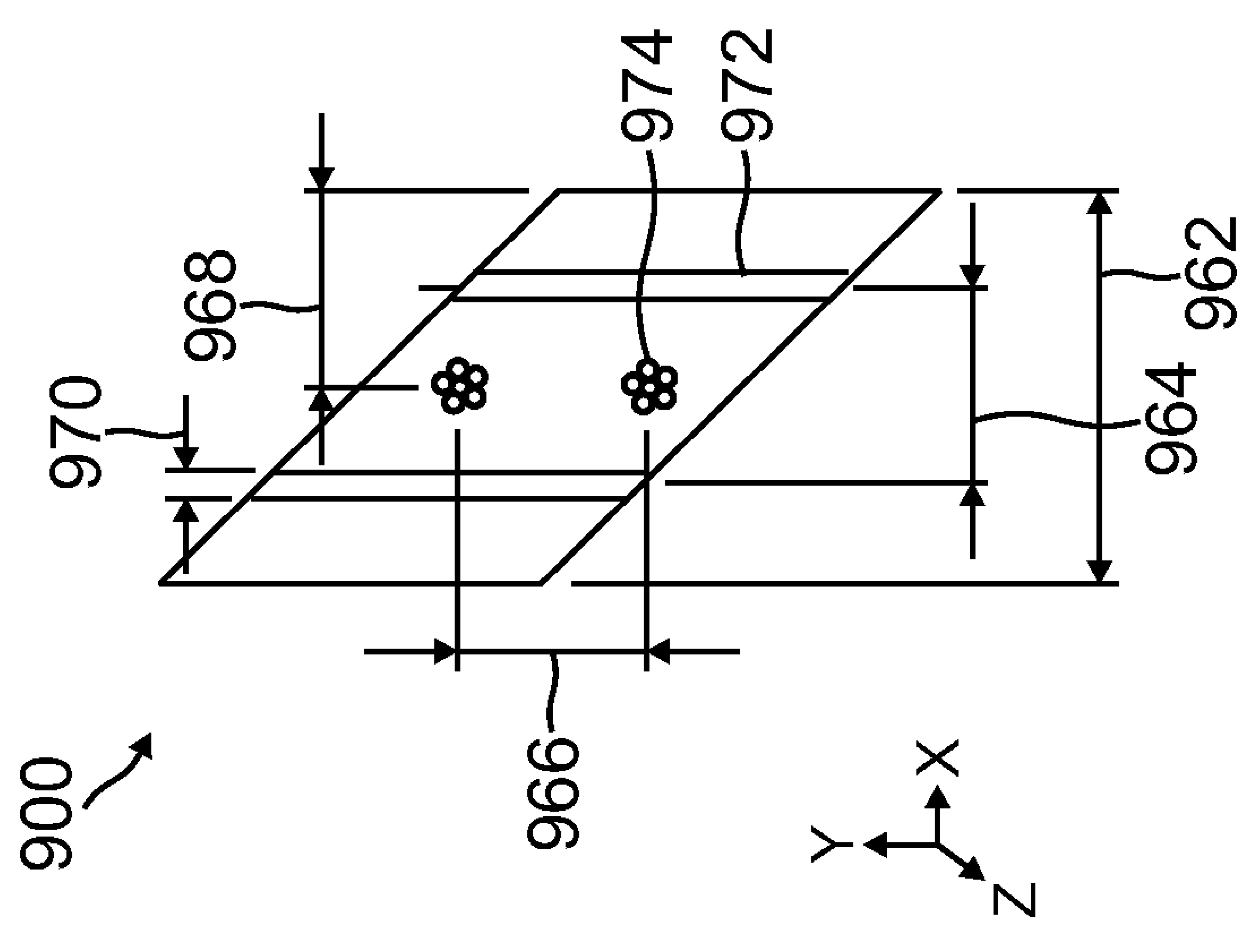


FIG. 9A

SOLID PARTICLE THERMAL ENERGY STORAGE DESIGN FOR A FLUIDIZED-BED CONCENTRATING SOLAR POWER PLANT

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to and the benefit of:

[0002] U.S. Provisional Application No. 61/715,747 entitled "Solid Particle Thermal Energy Storage Design For A Fluidized-Bed Concentrating Solar Power Plant" and filed on Oct. 18, 2012, (Applicant Docket No. NREL PROV/12-73) , which is incorporated herein by reference in its entirety;

[0003] U.S. Provisional Application No. 61/619,317 entitled "Gas-Solid Two-Phase Heat Transfer Material CSP Systems and Methods" and filed on Apr. 2, 2012, (Applicant Docket No. NREL PROV/11-92) which is incorporated herein by reference in its entirety;

[0004] U.S. Provisional Application No. 61/715,751 entitled "Fluidized-Bed Heat Exchanger Designs for Different Power Cycle in Power Tower Concentrating Solar Power Plant with Particle Receiver and Solid Thermal Energy Storage", filed on Oct. 18, 2012, (Applicant Docket NREL PROV/12-74), which is incorporated herein by reference in its entirety; and

[0005] U.S. Provisional Application No. 61/715,755, entitled "Enclosed Particle Receiver Design for a Fluidized Bed in Power Tower Concentrating Solar Power Plant", filed on Oct. 18, 2012, (Applicant Docket NREL PROV/13-05), which is incorporated herein by reference in its entirety.

[0006] Attorney Docket No. NREL 12-73 1

CONTRACTUAL ORIGIN

[0007] The United States Government has rights in this invention under Contract No. DE-AC36-08G028308 between the United States Department of Energy and the Alliance for Sustainable Energy, LLC, the Manager and Operator of the National Renewable Energy Laboratory.

BACKGROUND

[0008] Concentrating Solar power (CSP) systems utilize solar energy to drive a thermal power cycle for the generation of electricity. CSP technologies include parabolic trough, linear Fresnel, central receiver or "power tower," and dish/engine systems. Considerable interest in CSP has been driven by renewable energy portfolio standards applicable to energy providers in the southwestern United States and renewable energy feed-in tariffs in Spain. CSP systems are typically deployed as large, centralized power plants to take advantage of economies of scale. A key advantage of certain CSP systems, in particular parabolic troughs and power towers, is the ability to incorporate thermal energy storage. Thermal energy storage is often less expensive and more efficient than electric storage and allows CSP plants to increase capacity factor and dispatch power as needed—for example, to cover evening or other demand peaks. Improved plant structural designs are needed, however, to support improvements in CSP systems utilizing thermal energy storage.

[0009] The foregoing examples of the related art and limitations related therewith are intended to be illustrative and not exclusive. Other limitations of the related art will become apparent to those of skill in the art upon a reading of the specification and a study of the drawings.

DRAWINGS

[0010] Exemplary embodiments are illustrated in referenced figures of the drawings. It is intended that the embodiments and figures disclosed herein are to be considered illustrative rather than limiting.

[0011] FIG. **1** is a diagram of one embodiment of an exemplary storage silo.

[0012] FIGS. **2**A-**2**D depict exemplary layouts of micropile units within a foundation base.

[0013] FIG. **3** depicts one embodiment of an exemplary micropile unit.

[0014] FIG. **4** depicts one embodiment of an exemplary micropile column.

[0015] FIGS. **5**A-**5**B depict embodiments of exemplary reinforced concrete.

[0016] FIG. **6** is a cross-section view of an exemplary post-tension strand bundle.

[0017] FIG. **7** is a block diagram of one embodiment of an exemplary concentrating solar power plant.

[0018] FIG. **8**A is a cross-section view of an exemplary coned bottom for a silo.

[0019] FIG. **8**B is a top view of the exemplary coned bottom in FIG. **8**A.

[0020] FIGS. **9**A and **9**B are cross-section views of exemplary reinforced concrete for a coned bottom of a silo.

DETAILED DESCRIPTION

[0021] In the following detailed description, reference is made to the accompanying drawings that form a part hereof, and in which is shown by way of illustration specific illustrative embodiments. However, it is to be understood that other embodiments may be utilized. The following detailed description is, therefore, not to be taken in a limiting sense.

[0022] FIG. **1** is a diagram of one exemplary embodiment of a storage silo **100** for storage of solid particles (e.g., sand or ash) used in a fluidized-bed concentrating solar power plant, such as the power plant described below with respect to FIG. **7**. Silo **100** is configured to meet the demands of storing solid particles for use in a fluidized-bed concentrating solar power plant. For example, the storage silo **100** is configured to store thousands of tons of sand up to a temperature range of approximately 800°-900° C. Additionally, the storage silo **100** is configured to accommodate different types of environmental conditions such as, but not limited to, high wind loads, seismic activity, and/or varying soil conditions. Additionally, in some embodiments, the silo **100** is made of concrete with a refractory liner for heat resistance and insulation using materials known to one of skill in the art.

[0023] The exemplary storage silo **100** in FIG. **1** is comprised of a foundation **102** and a hollow cylinder **104**. The cylinder **104** has a height **101** and a diameter **103** which define a volume for storing the solid particles. The environment of the volume defined by the cylinder **104** is inert with only hot air in this example. For instance, there are no combustion gases in this example.

[0024] In the examples described herein, the diameter **103** is measured from the center of the wall of the cylinder **104**. For example, in this embodiment, the cylinder **104** is comprised of a wall having a thickness of approximately 12 inches. The diameter **103** is, therefore, measured from a point six inches deep into the wall of the cylinder **104** in this example. However, it is to be understood that other thicknesses of the wall can be used in other embodiments and that the diameter can be measured from an inner surface or exterior surface of the wall of the cylinder **104**. Table 1 provides exemplary values for the height, diameter, and corresponding storage capacity of solid particles. It is to be understood that the values in Table 1 are provided by way of example only and that other dimensions can be used in other embodiments. For example, in some embodiments, a height-to-diameter ratio of approximately 3:1 is used in determining the dimensions of the silo.

TABLE 1

DIAMETER	HEIGHT	CAPACITY
45 ft	130 ft	6,250 tons
50 ft	148 ft	12,500 tons
55 ft	165 ft	17,000 tons
65 ft	230 ft	34,000 tons

[0025] In this example, a cover or dome **106** is optionally located at one end of the cylinder **104** to enclose the volume defined by the cylinder **104** at the end of the cylinder **104**. The cover **106** is comprised of the same material as the cylinder **104**. For example, in this embodiment, the cover **106** and cylinder **104** are comprised of steel-reinforced concrete, as described in more detail below. The foundation **102** is located at the end of the cylinder **104** opposite from the cover **106**. The foundation **102** includes a plurality of micropile units **108**. Each micropile unit **108** includes a plurality of micropile columns **109** and a footing or block **111** surrounding one end of the respective micropile columns. The micropile columns **109** have a length **110** which extends into the ground or soil **116**. In this embodiment, the length **110** of the micropile units **108** is 50 feet. However, it is to be understood that the length **110** can be different in other embodiments. Additionally, all of the micropile units **108** do not, or may not have the same length in other embodiments. The micropile units **108** are used to anchor the foundation **102** and stabilize against seismic and surcharge loads from the earth as described in more detail below. The foundation **102** also includes a slab or base **112** having a thickness **114** placed on top of the footings **111**.

[0026] In some embodiments, the slab **112** is at least partially submerged in the soil **116**. In addition, the thickness **114**, in some embodiments, is 18 inches. However, other thickness can be used in other embodiments. The base **112** is concentric with the cylinder **104**. As measured from the center of the base **112**, the base **112** has the same wall-center to wall-center diameter as the cylinder **104** in this example. However, the base **112** may have a wider outside diameter than the cylinder **104**, as shown in this example. The micropile units **108** are formed in a pattern and are located under the wall of the cylinder **104**. For example, FIGS. **2**A-**2**D depict a top view of exemplary layouts of micropile units.

[0027] FIG. **2**A depicts an exemplary layout of micropile units **208** for a cylinder having a diameter of 45 feet. The circle **204** depicts the location of the cylinder **104** on the base **212** above the pattern of micropile units **208**. As shown in FIGS. **2**A-**2**D, the cylinder **104** is concentric with the slab **212** and therefore is located at approximately the center of the slab **212**. As mentioned above, the slab **212** may, however, have an outside diameter that is wider than the cylinder **104**'s outside diameter. FIG. **2**B depicts an exemplary layout of micropile units **208** for a cylinder having a diameter of 50 feet, as shown by circle **204**. FIG. **2**C depicts an exemplary layout of micropile units **208** for a cylinder having a diameter of 55 feet, as shown by circle **204**. FIG. **2**D depicts an exemplary layout of micropile units **208** for a cylinder having a diameter of 65 feet, as shown by the circle **204**.

[0028] As can be seen, each exemplary layout includes a plurality of rows of micropile units **208**. The number of rows and the number of micropile units **208** in each row depends on the maximum load or weight to be supported by the corresponding silo. Hence, as the diameter of the corresponding silo and foundation base **212** increases, the maximum load to be supported also increases. Hence, the number of micropile units **208** is also increased accordingly.

[0029] For example, in FIG. **2**A there are 3 rows of micropile units **208**, whereas in FIG. **2**D there are 4 rows of mircopile units **208**. Similarly, the total number of micropile units **208** increases with increasing diameter of foundation base **212**. In some embodiments, each of the micropile units **208** is located at least 2 feet from another micropile unit **208**. Separating each micropile unit **208** by at least 2 feet helps the micropile units **208** resist surcharges produced by loading the silo. Table 2 below provides exemplary values for the number of micropile units **208** to be used based on the diameter of the foundation base **212** and corresponding silo. It is to be understood that the number of micropile units in Table 2 are provided by way of example only.

TABLE 2

Number of Micropile units	Diameter
55	45 feet
102	50 feet
136	55 feet
264	65 feet

[0030] FIG. **3** depicts an exemplary embodiment of a micropile unit **308**. Micropile unit **308** can be used for each of the plurality of micropile units **108** in FIGS. **1** and **2**. Micropile unit **308** includes a plurality of micropile columns **309** and a support block **311** which encases or surrounds one end of the micropile columns **309**. The support block **311** can be comprised of concrete and has a height **331**, a width **333**, and a depth **335**. In one embodiment, the height **331** is approximately 4 feet, the width **333** is approximately 8 feet, and the depth **335** is approximately 8 feet. In this example, four micropile columns **309** are used to form micropile unit **308**. However, it is to be understood that more or fewer than four micropile columns **309** can be used in other embodiments. For example, in one alternative embodiment, a fifth micropile column is placed in the center of the other four micropile columns. In addition, the micropile columns **309** are placed relative to one another so that they resist loads from all directions. For example, as shown in the example of FIG. **3**, each micropile column **309** is placed near a corner of the concrete block **311**. However, other arrangements of the micropile columns **309** can be used in other embodiments. Each micropile column **309**, in this example, is placed at a non-zero angle **339** relative to a plane perpendicular to the bottom of the block **311**. In this example, the angle **339** is 10 degrees. However, other angles greater or less than 10 degrees can be used in other embodiments.

[0031] An exemplary micropile column **409** is depicted in FIG. **4**. As shown in FIG. **4**, each micropile column is comprised of a column of grout **413** having a steel reinforcing bar **415** placed within the grout **413**. For example, a column can be dug in the soil. The steel reinforcing bar **415** is placed in the column and then the grout **413** is placed into the column under pressure. In particular, in this example, the grout **413** is compressed into the column under 5,000 pounds per square inch (psi), and the steel reinforcing bar **415** is a #20, 150 Grade steel bar. In other embodiments, other grout pressures and reinforcing bar materials may be used. A plurality of centralizers can be used to assure that the bar **415** is centrally placed in the column in some embodiments. For example, in some embodiments, centralizers can be placed at 10 foot centers along each bar **415**. Each micropile column **409**, in this example, is 50 feet long and has a diameter of 12 inches. In addition, in some embodiments, more than one steel reinforcing bar **415** is used in each column **409**. For example, in one embodiment, a plurality of bars **415** can be evenly distributed in a column **409** having a diameter of 12 inches with a distance between any two bars in the range of approximately 2.8 inches to approximately 4 inches. Furthermore, in some embodiments, each individual column **409** includes a steel plate at the top of the column **409**. The plate extends the tributary area of the respective column **409**. As the tributary area increases, the capacity for the respective column **409** to resist direct loading becomes more effective.

[0032] FIGS. **5**A and **5**B depict exemplary embodiments of reinforced concrete which can be used in implementing the wall of a silo such as silo **100**. For example, the reinforced concrete described in FIG. **5**A or **5**B can be implemented in the cylinder **104** and cover **106**. In both FIG. **5**A and FIG. **5**B, vertical steel reinforcing bars (rebar) **520** are used for vertical reinforcement of the concrete **530**. As used herein, the term 'vertical' refers to a direction that is parallel with the axis of the silo's hollow cylinder. Similarly, the term 'horizontal' refers to a direction that is perpendicular with the axis of the silo's hollow cylinder.

[0033] In some embodiments, #**10** rebar having a diameter of 1.25 inches is used. However, in other embodiments, vertical rebar **520** having other sizes are used. In the examples shown in FIGS. **5**A and **5**B, the vertical reinforcing bars **520** have an approximately uniform horizontal separation distance **525** throughout the silo wall. In some embodiments, the separation distance **525** is selected from the range of approximately 6 inches to approximately 12 inches. However, it is to be understood that other values of the separation distance **525** can be used in other embodiments.

[0034] In FIG. **5**A, horizontal reinforcing bars **540** are also placed horizontally and used for periphery reinforcement of the concrete **530**. In particular, as shown in FIG. **5**A, two columns **541-1** and **541-2** of horizontal reinforcing bars **540** are used. A first column **541-1** is located on a first side of each of the vertical reinforcing bars **520** and a second column **541-2** is located on a second side of each of the vertical reinforcing bars **520**. The horizontal reinforcing bars **540** in each column are separated vertically by a vertical separation distance **545**. In addition, the columns **541-1** and **541-2** of horizontal reinforcing bars **540** are separated horizontally from one another by a horizontal separation distance **547**. In some embodiments, the vertical separation distance **545** is approximately 6 inches. Additionally, in some embodiments, the horizontal separation distance **547** is approximately 5 inches. However, it is to be understood that other values for vertical separation distance **545** and horizontal separation distance **547** can be used in other embodiments. In addition, the vertical separation distance **545** can increase from a first value near the bottom of the silo to a second value near the top of the silo, in some embodiments.

[0035] In FIG. **5**B, post-tension strand bundles **560** are used as the horizontal reinforcement in lieu of horizontal reinforcing bars **540**. The post-tension strand bundles **560** extend in a direction approximately perpendicular to the vertical steel reinforcing bars **520**. Each post-tension strand bundle **560** is a bundle of a plurality of steel strands that is located in a corresponding hole in the concrete **530** and tightened by pulling on both ends of the bundle **560**. For example, in one embodiment, after the concrete **530** is cured, the strand bundles **560** are tensioned to 270 kilopounds per square inch (ksi). FIG. **6** is a cross-section view of an exemplary post-tension strand bundle **660**. As shown in FIG. **6**, the exemplary strand bundle **660** includes six strands. Each strand, in some embodiments, has a diameter of 0.75 inches. However, it is to be understood that each strand can have a different diameter in other embodiments. In addition, the number of strands in each strand bundle **560** is dependent on the size of the corresponding silo. The size of the silo is represented in Table 3 by the amount of solid particles which can be stored therein. For example, Table 3 lists exemplary silo sizes and an exemplary corresponding number of strands used in each strand bundle **560**. However, the silo size can also be measured in terms of the diameter of the silo, as discussed above with respect to Table 1. Table 3 also includes an exemplary total number of strand bundles based on the silo size.

TABLE 3

SILO SIZE	NUMBER OF STRANDS
6,250 tons	5
12,500 tons	6
17,000 tons	7
34,000 tons	12

[0036] As shown in Table 3, as the size of the corresponding silo increases, the number of strands, per ton of material, in each strand bundle decreases. For example, the number of strands in each bundle **560** for a silo size of 6,250 tons is 5. If the same number of strands, per ton of material, in each strand bundle **560** was used for a silo size of 12,500 tons, then each strand bundle **560** would have 10 strands. However, as shown in the exemplary Table 3, the number of strands, per ton of material, in each strand bundle **560** is 6 for a silo size of 12,500 tons. Thus, the cost for horizontal reinforcement per ton of material contained decreases as the silo size increases. As a result, the cost of a post-tension strand horizontally reinforced silo may be up to 10% lower than the cost of a steel-rebar horizontally reinforced silo due to savings on the material.

[0037] Each strand bundle **560** is separated vertically from other strand bundles **560** by a vertical separation distance **565**. In some embodiments, the vertical separation distance **565** is uniform throughout the silo. However, in other embodiments, the vertical separation distance **565** varies as a function of height. That is, the vertical separation distance **565** has an initial value at the end of the silo cylinder near the foundation and a second final value at the opposite end of the silo cylinder. For example, in some such embodiments, the vertical separation distance **565** between two strand bundles **560** near the cover of the silo is greater than the vertical separation distance **565** in the middle of the silo which, in turn, is greater than the vertical separation distance **565** near the foundation of the silo. In other words, the vertical separation distance **565** for a given strand bundle **560** increases as the respective height of the given strand bundle **560** increases. The vertical separation distance **565** can increase with height in some embodiments because the load due to the stored solid particles decreases with height. In some embodiments, the initial vertical separation distance **565** at the foundation of the silo is approximately 12 inches and increases with height. For example, in one embodiment, the separation distance **565** between strand bundles **560** is 12 inches near the bottom of the silo and changes proportionally to 20 inches near the top.

[0038] The silo structure described above can be implemented in a concentrating solar power plant, such as the exemplary power plant **700** shown in FIG. **7**. The exemplary system **700** includes an array **702** of heliostats **703**. Each heliostat **703** includes a mirror **705** which reflects light from the sun toward a receiver **704**. In addition, each heliostat **703** is configured to turn its respective mirror **705** to compensate for the apparent motion of the sun in the sky due to the rotation of the earth. In this way, each respective mirror **705** continues to reflect sunlight toward the receiver **704** as the position of the sun in the sky changes.

[0039] The combined sunlight reflected from the plurality of heliostats **703** in the array **702** provides temperatures of approximately 500-1000° C. at the receiver **704**. The receiver **704** is configured to transfer the solar heat from the combined sunlight to a heat transport material adapted to store thermal energy such as molten salts or other particles. The heated particles are passed from the receiver **704** to a hot silo **706**. The hot silo **706** is implemented using a silo construction as described above with respect to FIGS. **1-6**. In some embodiments, the hot silo **706** has a cone bottom as shown and described below with respect to FIG. **8**A-**9**B. A cone bottom helps enable the hot silo **706** to dispense the stored particles using gravity flow.

[0040] Heated particles from the hot silo **706** are delivered via a conveyor **708** to a heat exchanger **710** as needed. In this embodiment, the heat exchanger **710** is implemented as a fluidized-bed heat exchanger having three stages. In particular, the heat exchanger **710** includes a super heater **711**, an evaporator **713**, and a preheater/economizer **715**. However, it is to be understood that other types and configurations of heat exchangers can be implemented in other embodiments.

[0041] A pump **712** compresses gas and delivers the compressed gas to the heat exchanger **710** where the pressure of the compressed gas suspends the heated particles in the gas. The fluidized mixture of compressed gas and heated particles is moved through the stages of the heat exchanger **710** to transfer heat from the heated particles to a working fluid, such as but not limited to water or ammonia. It is to be understood that, in other embodiments, other working fluids can be used. For example, other working fluids include, but are not limited to, hydrocarbons (e.g., butane, propane, propylene, etc.) and liquid fluorocarbons (e.g., tetrafluoroethane).

[0042] The transfer of heat to the working fluid vaporizes the working fluid. The vaporized working fluid is passed to a vapor turbine **714**. The pressure of the vapor turns the vapor turbine **714**, which is coupled to and drives the generator **716** to produce electricity. The vaporized working fluid is then expelled from the vapor turbine **714** and condensed again in condenser **718**. In particular, the remaining heat from the vaporized working fluid is transferred to a cooler **720** coupled to the condenser **718**. The removal of heat from the vaporized working fluid causes the working fluid to condense to a liquid state. A pump **722** is then used to move the working fluid back into the heat exchanger **710** where it is vaporized by the transfer of heat from the heated particles occurring in the heat exchanger **710**.

[0043] After the particles pass through the heat exchanger **710**, the resulting fluidized mixture is then passed to a cyclone **724** (also referred to as a particle separator). In the cyclone **724**, the solid state particles are separated from the gas particles. The solid particles are then stored in a cold silo **726** for later use. The cold silo **726** is also constructed using the silo structures discussed above with respect to FIGS. **1-6**. In some embodiments, the cold silo **726** has a flat bottom as opposed to a coned bottom. An elevator or conveyer **728** then moves the solid particles as needed from the cold silo **726** to the receiver **704** where the solid particles are again heated.

[0044] FIG. **8**A depicts a cross-section side view of one example of a coned bottom **800** for a silo, such as silo **100**. FIG. **8**B depicts a top view of the exemplary coned bottom **800**. As shown in FIGS. **8**A and **8**B, the coned bottom **800** has a first diameter **850** at a first end and a second diameter **852** at a second end. In addition, the walls of the coned bottom **800** have a width **856** and are formed at an angle **854** to a horizontal plane parallel with the bottom of the coned bottom **800**. In this example, the first diameter **850** is 50 feet and the second diameter **852** is 3 feet. In addition, in this example, the angle **854** is 45 degrees and the width **856** is 2 feet. However, it is to be understood that other diameters and angles can be used in other embodiments. The height of the coned bottom **800** is dependent on the values for the first diameter **850**, the second diameter **852**, and the angle **854**.

[0045] FIG. **9**A is a cross-section view of a segment of an exemplary reinforced concrete wall **900** for a coned bottom of a silo. As shown in FIG. **9**A, in this example, the wall **900** has a thickness **962** and includes a plurality of vertical reinforcement bars **972**. Each vertical bar **972** has a diameter **970**. In some embodiments, the vertical reinforcement bars **972** are implemented using #10 bars. Thus, the diameter **970** is 1.25 inches in such embodiments, as discussed above. The wall **900** also has embedded within it a plurality of post-tensioned strand bundles **974** in the horizontal direction. In some embodiments, the post-tensioned strand bundles **974** are tensioned to 270 ksi. The vertical bars **972** are evenly displaced in the wall **900** and separated from one another by a distance **964**. In some embodiments, the distance **964** is 1 foot. The strand bundles **974** are located at a distance **968** such that they are placed approximately in the center of the wall **900** in this example. For example, in some embodiments, the thickness **962** is 2 feet and the distance **968** is 1 foot. The strand bundles **974** are also separated from one another by a distance **966**. In some embodiments, the distance **966** is 1 foot.

[0046] FIG. **9**B is a cross-section view of the segment of the exemplary reinforced concrete wall **900**. The view in FIG. **9**B has been rotated from the view of FIG. **9**A as indicated by the change in the coordinate axes shown with the respective figure. As shown in FIG. **9**B, rows of vertical bars **972** are evenly spaced throughout the wall **900** by a distance **980**. In some embodiments, the distance **980** is 4 inches. For purposes of explanation, FIG. **9**B depicts one of the vertical bars **972** without the surrounding concrete. However, it is to be understood that each of the vertical bars **972** is embedded within the wall **900**.

[0047] While a number of exemplary aspects and embodiments have been discussed above, those of skill in the art will recognize certain modifications, permutations, additions and sub combinations thereof. It is therefore intended that the following appended claims and claims hereafter introduced are interpreted to include all such modifications, permutations, additions and sub-combinations as are within their true spirit and scope.

What is claimed is:

1. A fluidized-bed concentrating solar power plant comprising:

a particle receiver configured to contain solid state particles, wherein the particle receiver heats the solid state particles by transferring thermal energy from sunlight to the solid state particles;

a first silo configured to receive and store heated solid state particles from the particle receiver;

a heat exchanger configured to receive the heated solid state particles from the first silo and generate a fluidized mixture comprising the heated solid state particles suspended in a gas;

a second silo configured to feed cooled solid state particles to the particle receiver, the cooled solid state particle extracted from the fluidized mixture;

wherein the first silo and the second silo each comprise:

a foundation comprising a base supported by a plurality of micropile units, wherein each micropile unit comprises a plurality of micropile columns coupled to a support block, wherein the base is supported by the support block of each of the plurality of micropile units and each of the plurality of micropile columns extending into the ground under the foundation.

2. The fluidized-bed concentrating solar power plant of claim **1**, wherein each of the plurality of micropile columns is comprised of a steel reinforcing bar encased within pressurized grout.

3. The fluidized-bed concentrating solar power plant of claim **1**, wherein the first silo and the second silo each further comprise:

a hollow cylinder having a height, a width, and a diameter, the height and the diameter defining a volume for storage of solid particles; and

wherein the foundation is located at a first end of the hollow cylinder, the foundation comprising the base having a height, a width, and a diameter;

wherein the base is concentric with the hollow cylinder, and the width of the base being greater than or equal to the width of the cylinder.

4. The fluidized-bed concentrating solar power plant of claim **3**, wherein at least one of the first silo or the second silo further comprises a cover located at a second end of the hollow cylinder and configured to enclose the second end of the hollow cylinder.

5. The fluidized-bed concentrating solar power plant of claim **3**, wherein the hollow cylinder is comprised of steel-reinforced concrete, the steel-reinforced concrete comprising:

a plurality of vertical steel reinforcing bars, the plurality of vertical steel reinforcing bars separated from one another by a first separation distance, the first separation distance being selected from a range of approximately 6 inches to approximately 12 inches; and

two columns of horizontal steel reinforcing bars, a first column of the two columns located on a first side of each of the plurality of vertical steel reinforcing bars and a second column of the two columns located on a second side of each of the plurality of vertical steel reinforcing bars;

wherein the first column is separated from the second column by approximately 5 inches;

wherein the horizontal steel reinforcing bars in the first column are separated from one another by approximately 6 inches; and

wherein the horizontal steel reinforcing bars in the second column are separated from one another by approximately 6 inches.

6. The fluidized-bed concentrating solar power plant of claim **3**, wherein the hollow cylinder is comprised of steel-reinforced concrete, the steel-reinforced concrete comprising:

a plurality of vertical steel reinforcing bars, the plurality of vertical steel reinforcing bars separated from one another by a first separation distance, the first separation distance being selected from a range of approximately 6 inches to approximately 12 inches; and

a plurality of post-tension strand bundles separated vertically from one another by a vertical separation distance, the plurality of post-tension strand bundles extending in a direction approximately perpendicular to the plurality of vertical steel reinforcing bars;

wherein each of the post-tension strand bundles comprises a plurality of strands;

wherein the number of strands in each of the post-tension strand bundles is dependent on a size of the hollow cylinder.

7. The fluidized-bed concentrating solar power plant of claim **6**, wherein the vertical separation distance has an initial value near the first end of the hollow cylinder and increases as a function of height to a final value near a second end of the hollow cylinder.

8. The fluidized-bed concentrating solar power plant of claim **7**, wherein the initial value of the vertical separation distance is 12 inches and the final value is 20 inches.

9. The fluidized-bed concentrating solar power plant of claim **6**, wherein the number of strands, per ton of material, in each strand bundle decreases as a function of the size of the hollow cylinder.

10. The fluidized-bed concentrating solar power plant of claim **1**, wherein the first silo is configured with a coned bottom and the second silo is configured with a flat bottom.

11. The fluidized-bed concentrating solar power plant of claim **1**, wherein each of the micropile columns extends into the ground at a non-zero angle to a plane that is perpendicular to a bottom surface of the concrete block.

12. The fluidized-bed concentrating solar power plant of claim **1**, wherein the micropile units are separated from one another by at least 2 feet.

13. A silo structure for a fluidized-bed concentrating solar power plant, the silo structure comprising:

a hollow cylinder having a height, a width, and a diameter, the height and the diameter defining a volume for storage of solid particles used for transferring heat in the fluidized-bed concentrating solar power plant; and

a foundation located at a first end of the hollow cylinder, the foundation comprising a base and a plurality of micropile units, the base having a height, a width, and a wall-centered diameter;

wherein the base is concentric with the cylinder and the width of the base being greater than or equal to the width of the cylinder;

wherein each micropile unit comprises a plurality of micropile columns and a support block coupled to each of the plurality of micropile columns, each of the plurality of micropile columns extending into the ground under the foundation;

wherein the base is supported by the support block of each of the plurality of micropile units and the first end of the hollow cylinder is supported by the base.

14. The silo structure of claim **13**, wherein each micropile column

is comprised of a steel reinforcing bar surrounded by pressurized grout.

15. The silo structure of claim **13**, further comprising a coned bottom at the first end of the hollow cylinder.

16. The silo structure of claim **13**, wherein each of the micropile columns extends into the ground at a non-zero angle to a plane that is perpendicular to a bottom surface of the concrete block.

17. The silo structure of claim **13**, wherein the micropile units are separated from one another by at least 2 feet.

18. The silo structure of claim **13**, wherein the hollow cylinder is comprised of steel- reinforced concrete, the steel-reinforced concrete comprising:

a plurality of vertical steel reinforcing bars, the plurality of vertical steel reinforcing bars separated from one another by a first separation distance, the first separation distance being selected from a range of approximately 6 inches to approximately 12 inches; and

two columns of horizontal steel reinforcing bars, a first column of the two columns located on a first side of each of the plurality of vertical steel reinforcing bars and a second column of the two columns located on a second side of each of the plurality of vertical steel reinforcing bars;

wherein the first column is separated from the second column by approximately 5 inches;

wherein the horizontal steel reinforcing bars in the first column are separated from one another by approximately 6 inches; and

wherein the horizontal steel reinforcing bars in the second column are separated from one another by approximately 6 inches.

19. The silo structure of claim **13**, wherein the hollow cylinder is comprised of steel-reinforced concrete, the steel-reinforced concrete comprising:

a plurality of vertical steel reinforcing bars, the plurality of vertical steel reinforcing bars separated from one another by a first separation distance, the first separation distance being selected from a range of approximately 6 inches to approximately 12 inches; and

a plurality of post-tension strand bundles separated vertically from one another by a vertical separation distance, the plurality of post-tension strand bundles extending in a direction approximately perpendicular to the plurality of vertical steel reinforcing bars;

wherein each of the post-tension strand bundles comprises a plurality of strands;

wherein the number of strands in each of the post-tension strand bundles is dependent on the diameter of the hollow cylinder.

20. The silo structure of claim **19**, wherein the vertical separation distance has an initial value near the first end of the hollow cylinder and increases as function of height to a final value near a second end of the hollow cylinder.

* * * * *