US 20120234311A1

(19) United States
(12) Patent Application Publication
(10) Pub. No.: US 2012/0234311 A1
(43) Pub. Date: Sep. 20, 2012
Johnson et al.

(54) MULTI-TUBE SOLAR THERMAL RECEIVER

(75) Inventors: **Peter L. Johnson**, Mountain View, CA (US); **Robert J. Hanson**, Palo Alto, CA (US); **William M. Conlon**, Palo Alto, CA (US)

(73) Assignee: **AREVA Solar, Inc.**, Mountain View, CA (US)

(21) Appl. No.: **13/499,658**

(22) PCT Filed: **Oct. 6, 2010**

(86) PCT No.: **PCT/US2010/051690**

§ 371 (c)(1), (2), (4) Date: **May 21, 2012**

Related U.S. Application Data

(60) Provisional application No. 61/249,562, filed on Oct. 7, 2009, provisional application No. 61/303,615, filed on Feb. 11, 2010.

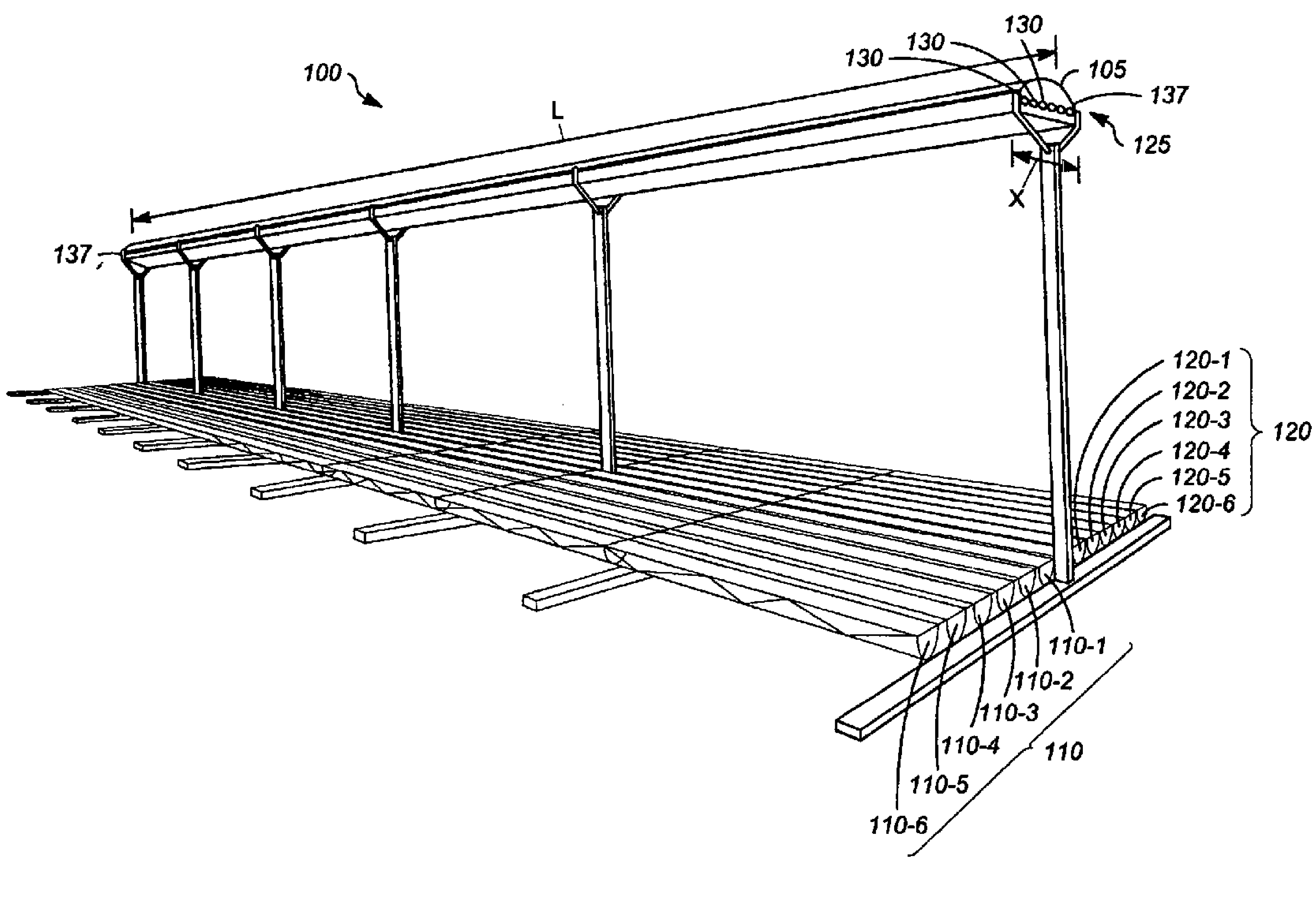
Publication Classification

(51) **Int. Cl.**
F24J 2/40 (2006.01)
F24J 2/00 (2006.01)

(52) **U.S. Cl.** **126/600**; 126/714

(57) **ABSTRACT**

Systems, methods, and apparatus by which solar energy may be collected as heat are disclosed. Some systems include an elevated solar receiver comprising multiple tubes arranged lengthwise in the receiver in a side-by-side parallel configuration across a transverse dimension of the receiver. The receiver comprises an inlet section configured to receive a heat transfer fluid into the tubing arrangement and an outlet section configured to output heated heat transfer fluid from the tubing arrangement. The multiple tubes of the tubing arrangement define together a flowing circuit between the inlet section and the outlet section from the outer tube or tubes to the inner tube or tubes. The solar energy collector system further includes an instrumentation and control system for controlling the orientation of at least one orientable reflector to provide in operation a concentrated illuminated area comprising a peaked profile across the transverse dimension of the receiver.



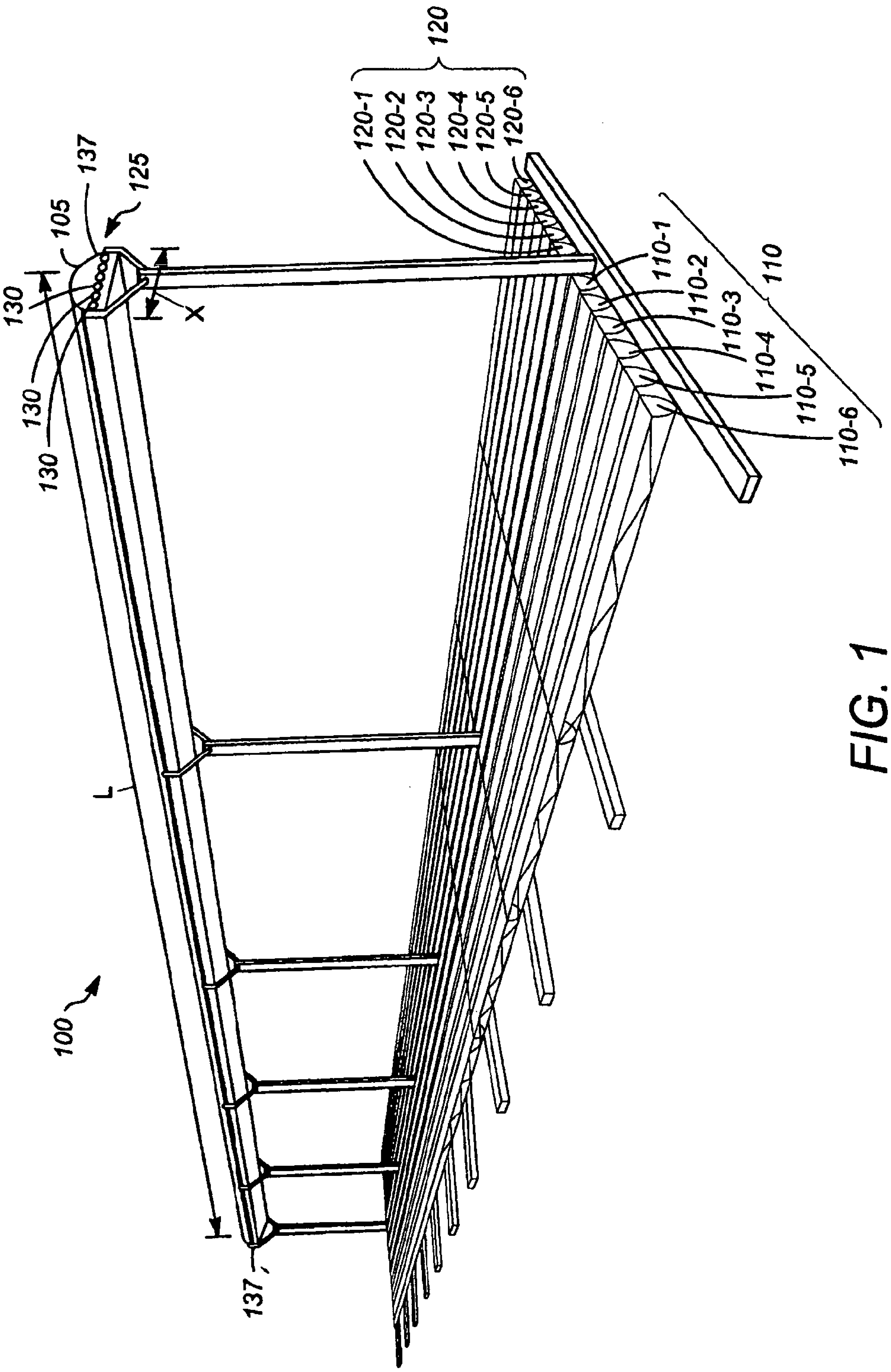

120
120-1
120-2
120-3
120-4
120-5
120-6
137
125
105
130
130
130
130
X
110-1
110-2
110-3
110-4
110-5
110-6
110
L
100
137

FIG. 1

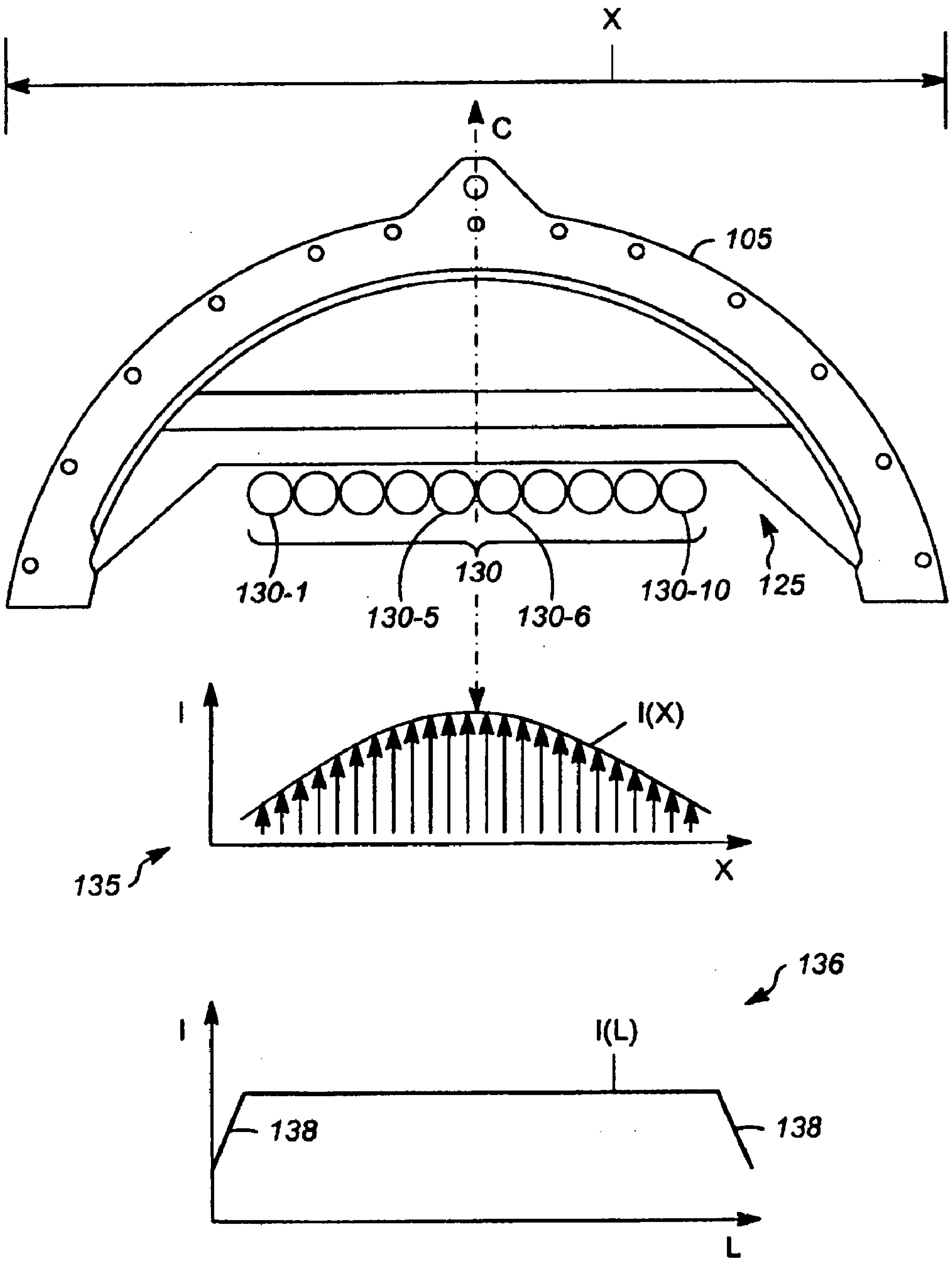


FIG. 2

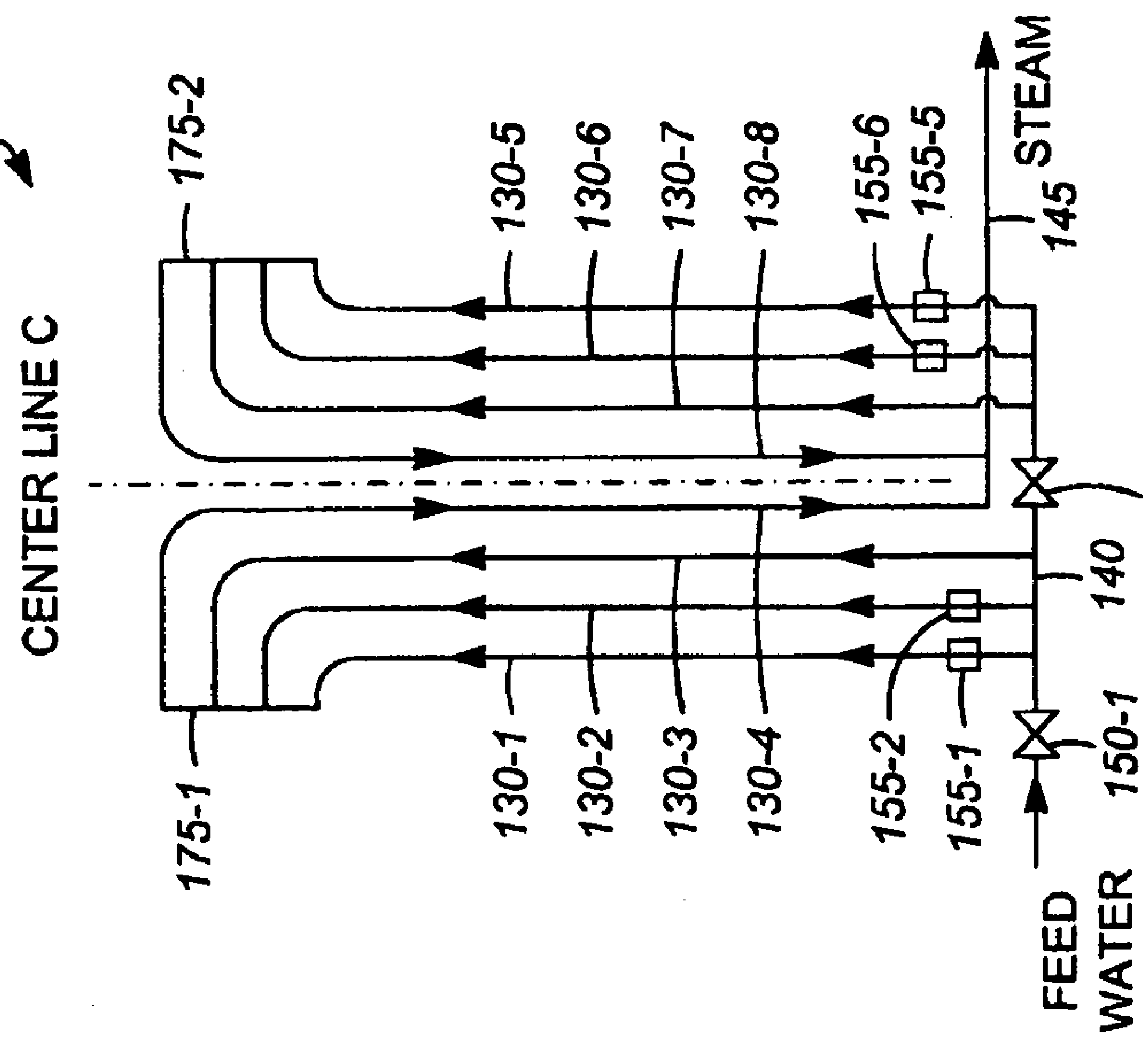

230
CENTER LINE C
175-1
175-2
130-1
130-2
130-3
130-4
130-5
130-6
130-7
130-8
155-1
155-2
155-5
155-6
150-1
150-2
140
145
FEED WATER
STEAM

FIG. 3

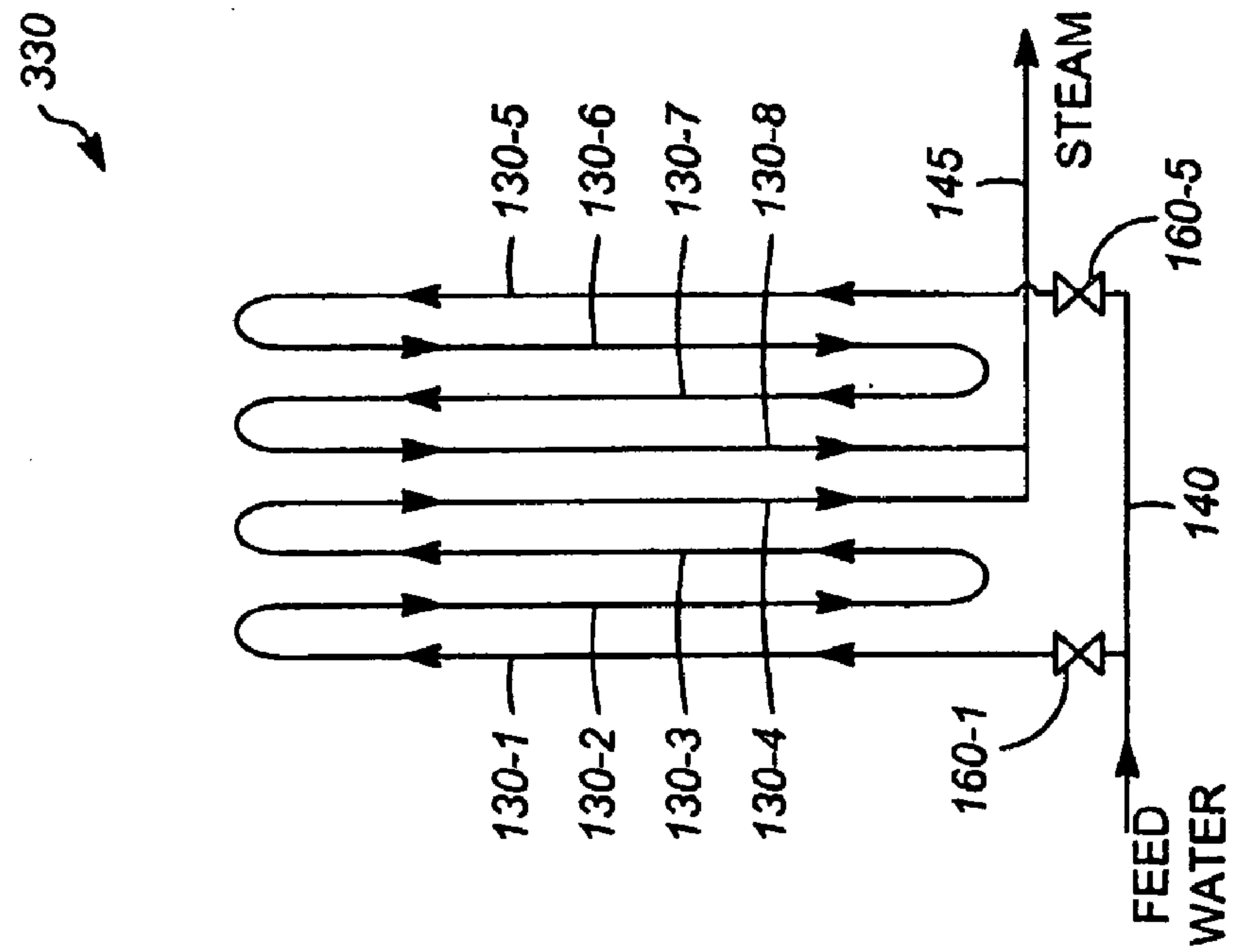

330
130-1
130-2
130-3
130-4
130-5
130-6
130-7
130-8
160-1
160-5
140
145
FEED WATER
STEAM

FIG. 4

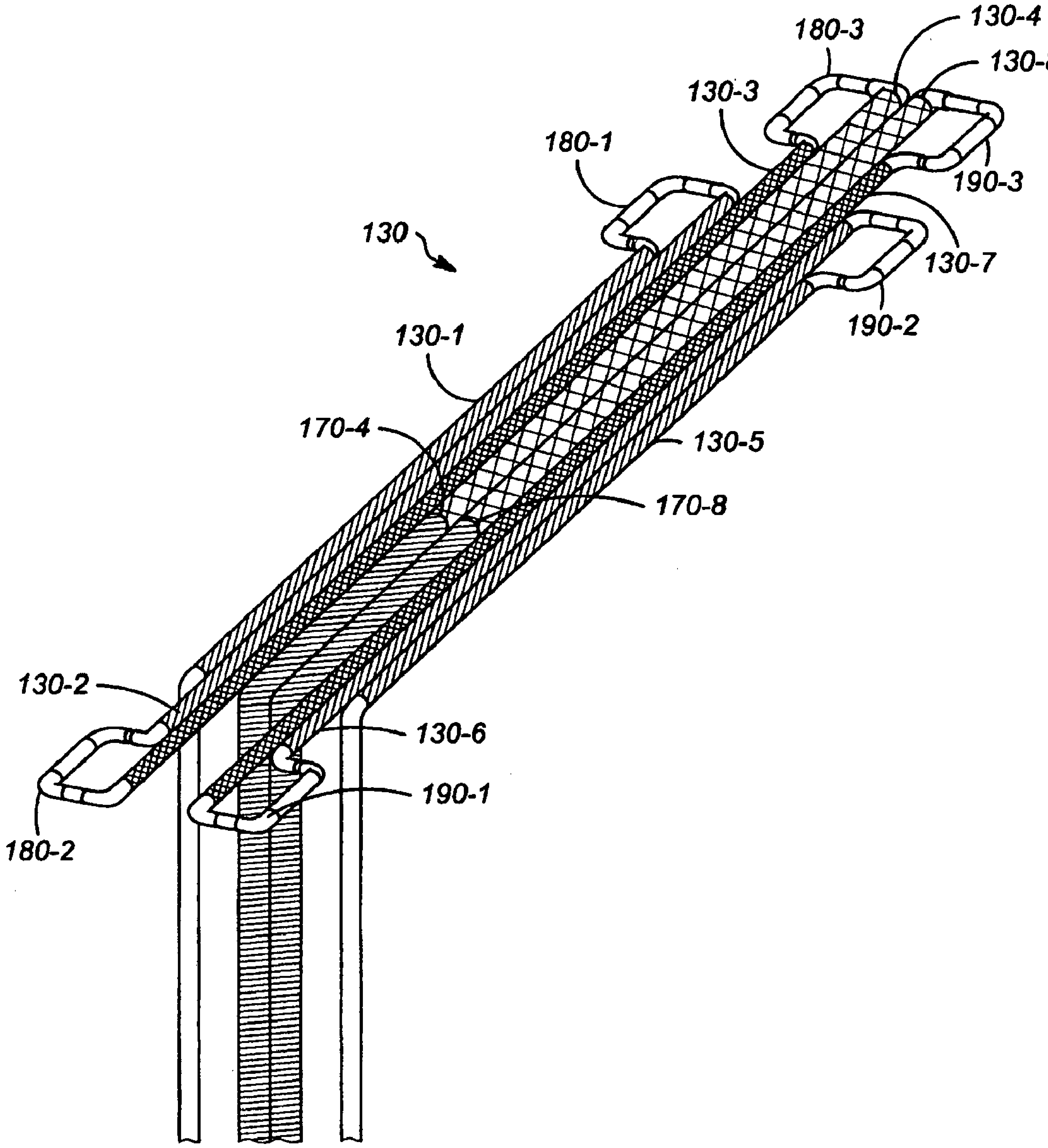

180-3
130-4
130-8
130-3
180-1
190-3
130
130-7
190-2
130-1
170-4
130-5
170-8
130-2
130-6
190-1
180-2

FIG. 5A

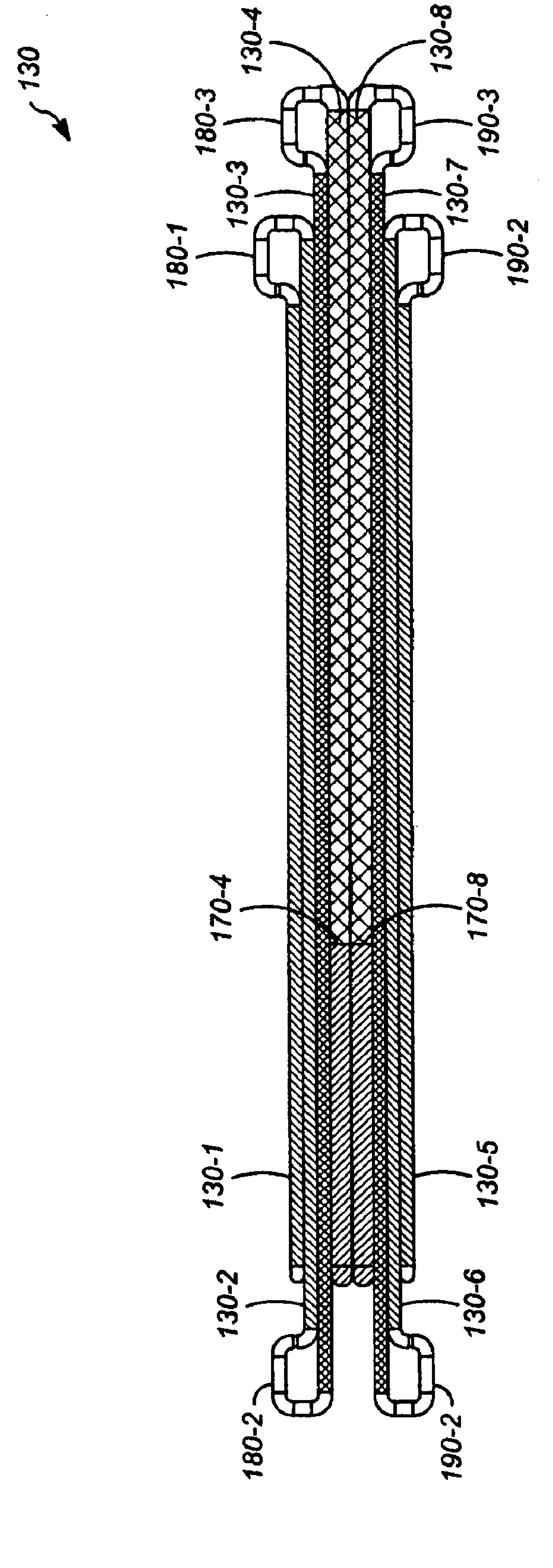

130
130-4
130-8
180-3
190-3
130-3
130-7
180-1
190-2
170-4
170-8
130-1
130-5
130-2
130-6
180-2
190-2

FIG. 5B

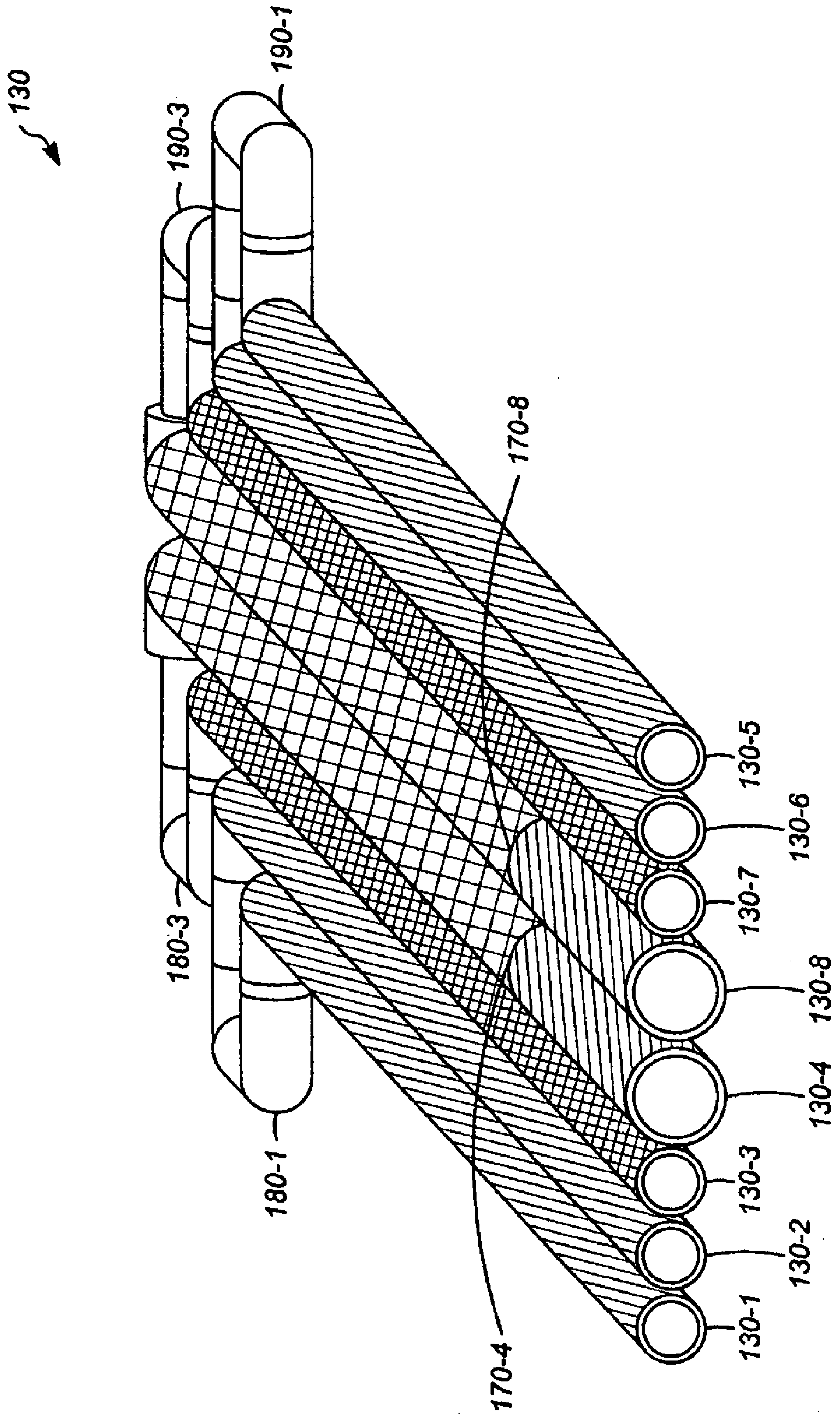

130
190-3
190-1
170-8
180-3
180-1
170-4
130-5
130-6
130-7
130-8
130-4
130-3
130-2
130-1

FIG. 5C

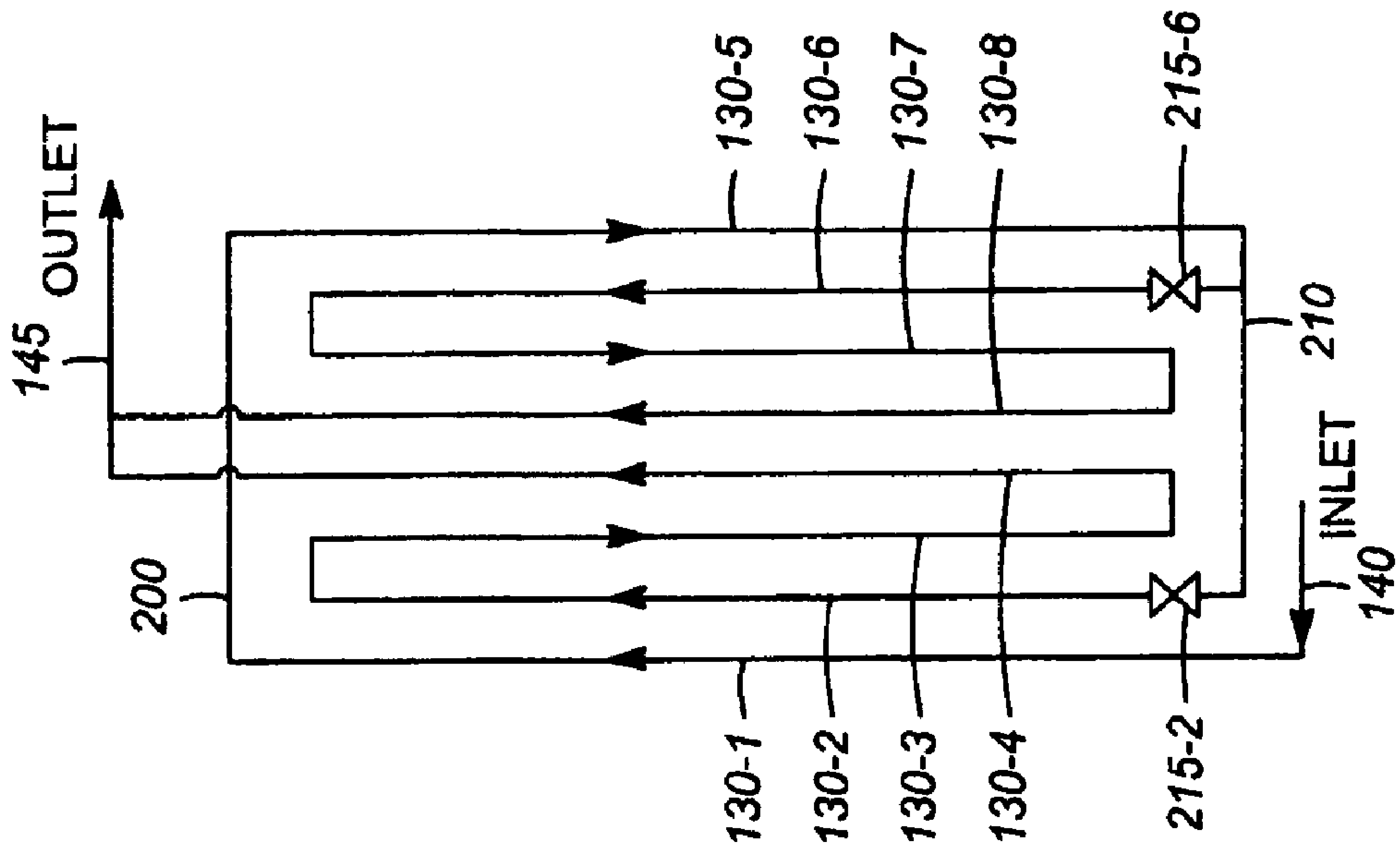

145
OUTLET
130-5
130-6
130-7
130-8
215-6
210
INLET
140
200
130-1
130-2
130-3
130-4
215-2

FIG. 7

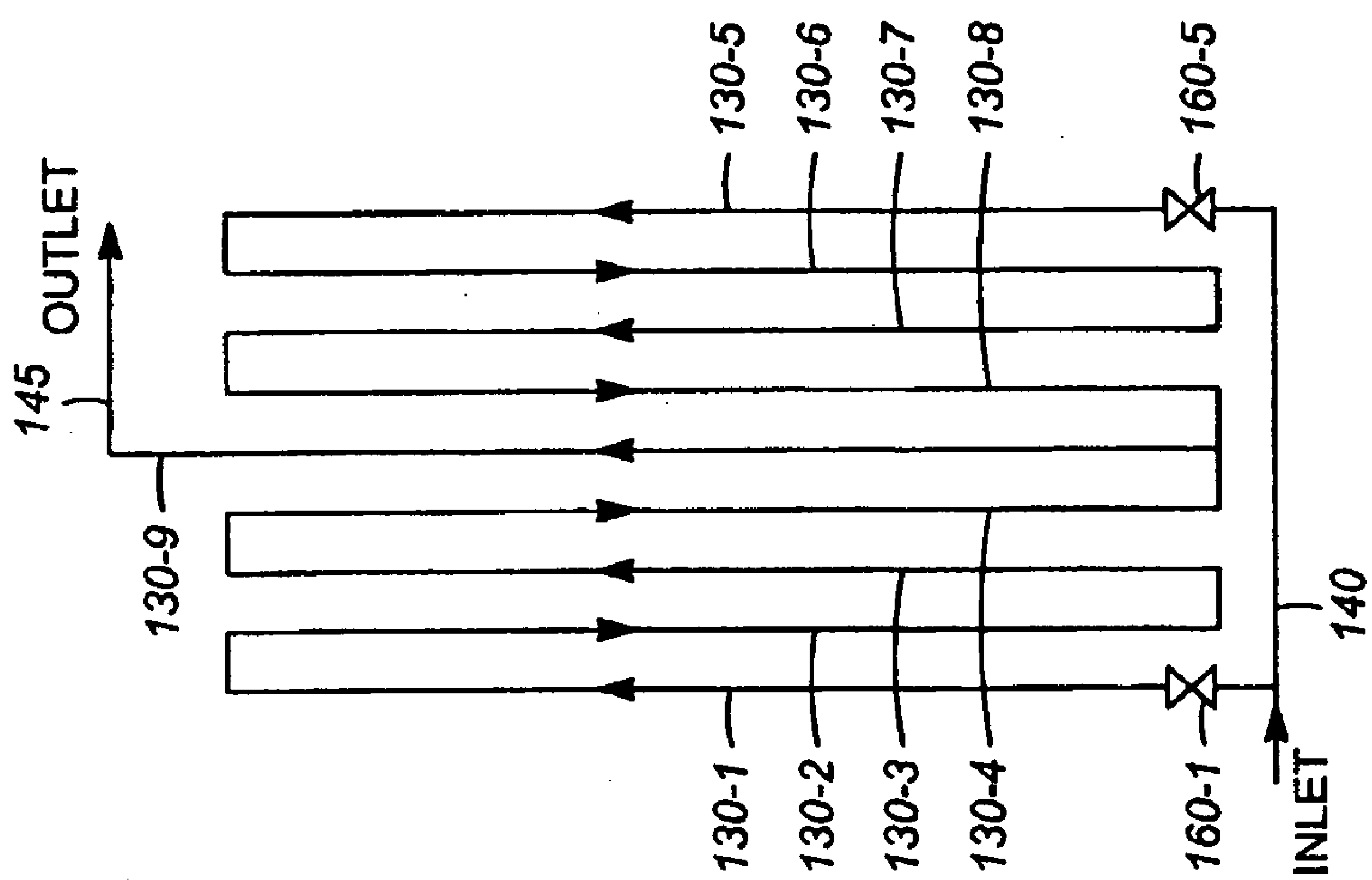

145
OUTLET
130-5
130-6
130-7
130-8
160-5
130-9
140
130-1
130-2
130-3
130-4
160-1
INLET

FIG. 6

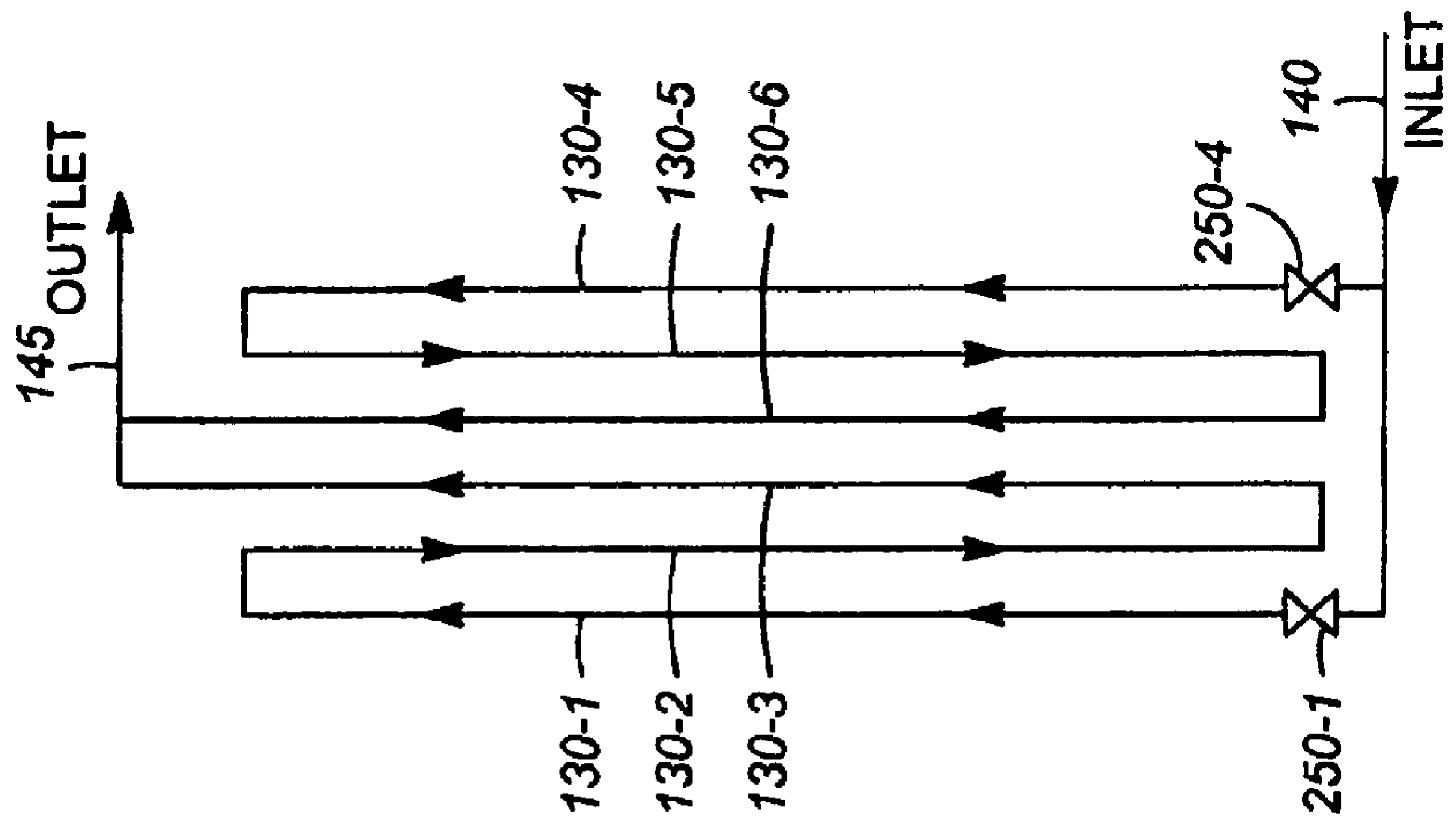

OUTLET
145
130-4
130-5
130-6
130-1
130-2
130-3
250-4
250-1
140
INLET

FIG. 9

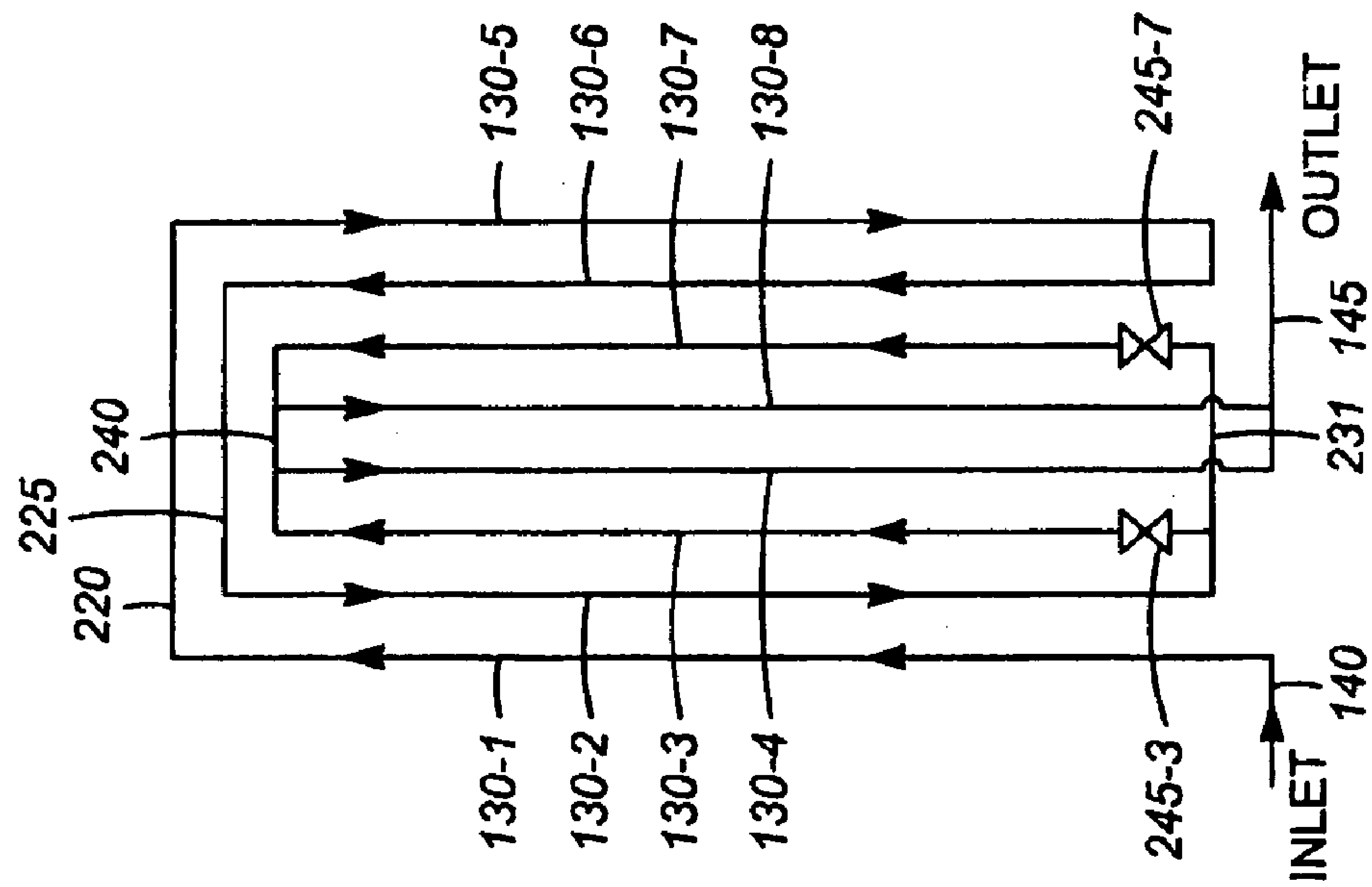

225
240
220
130-5
130-6
130-7
130-8
130-1
130-2
130-3
130-4
245-7
245-3
OUTLET
145
231
140
INLET

FIG. 8

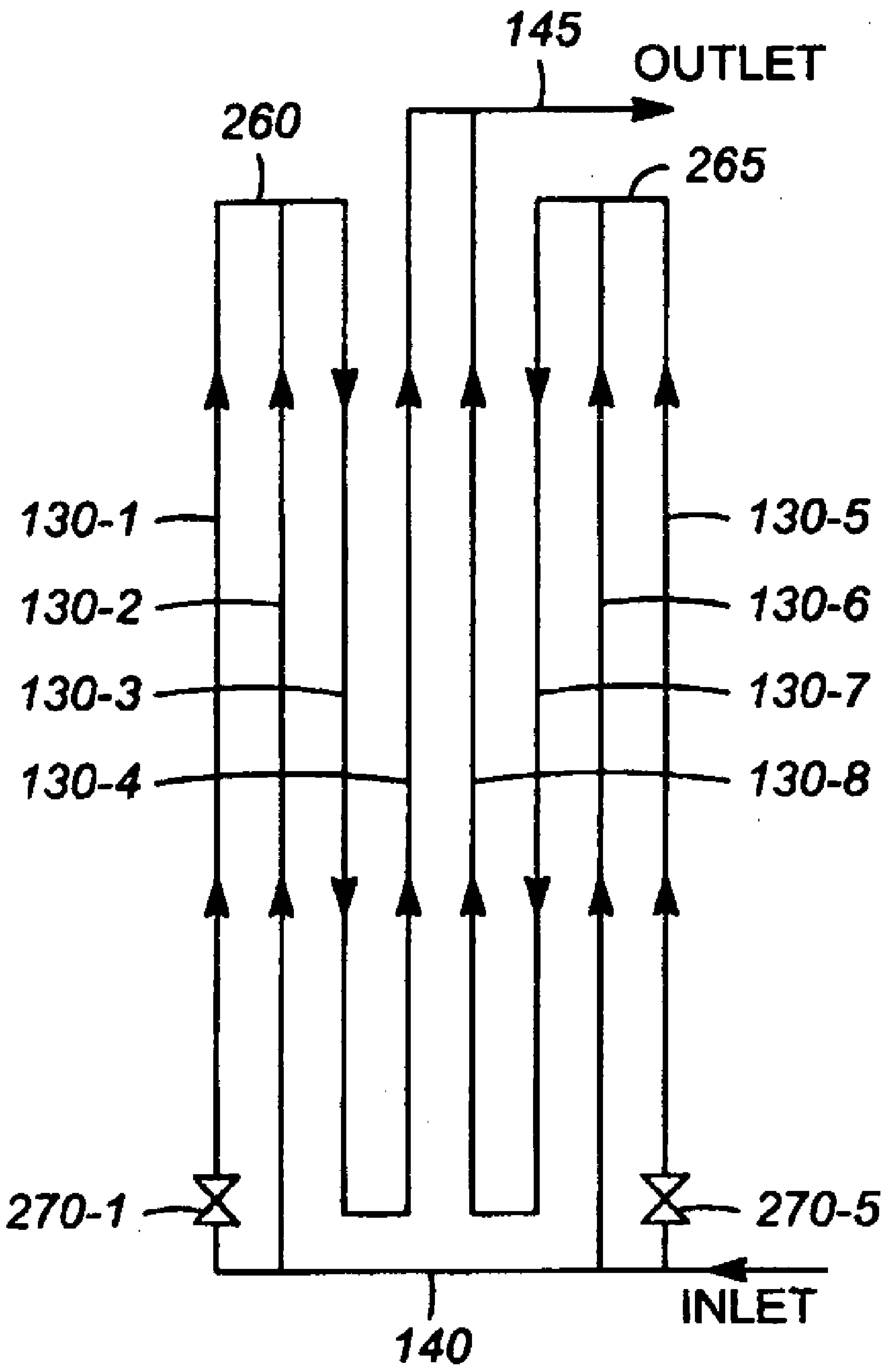

145
OUTLET
260
265
130-1
130-2
130-3
130-4
130-5
130-6
130-7
130-8
270-1
270-5
INLET
140

FIG. 10

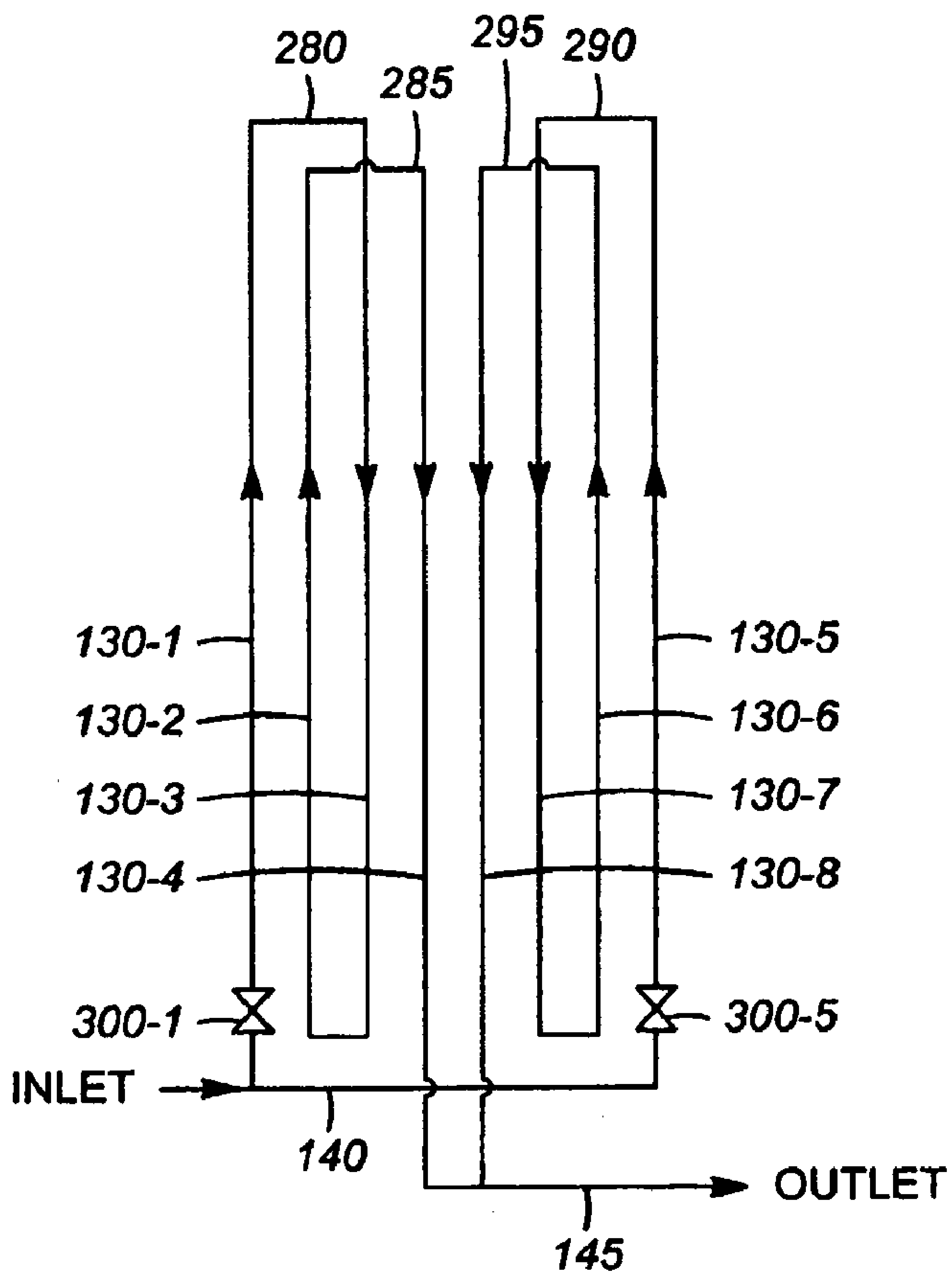


FIG. 11A

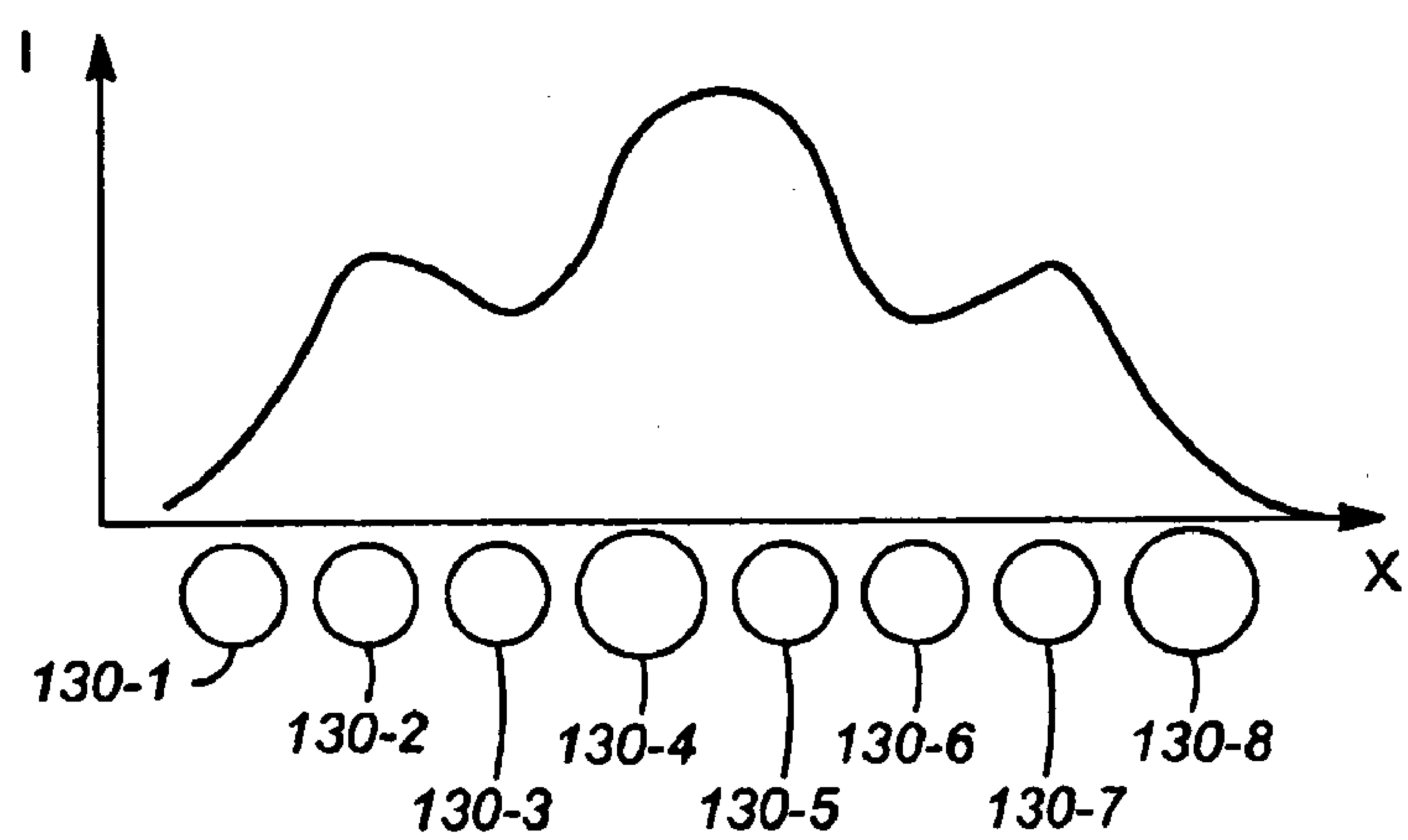


FIG. 11B

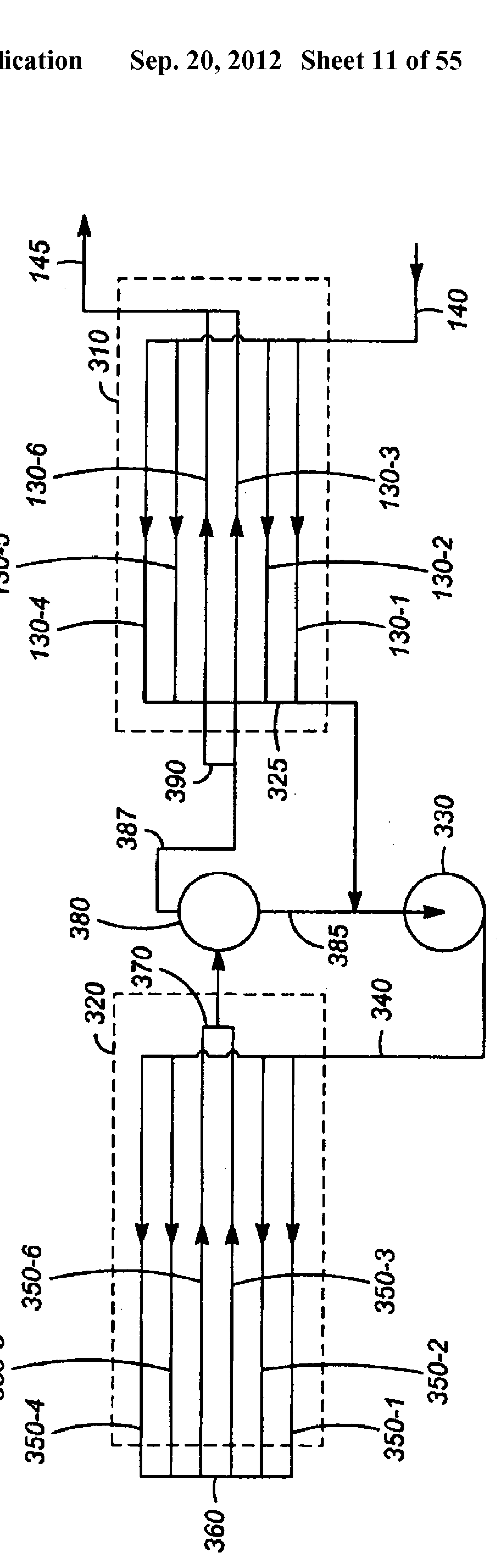

145
140
310
130-6
130-3
130-5
130-2
130-4
130-1
390
325
387
330
380
385
370
320
340
350-6
350-3
350-5
350-2
350-4
350-1
360

FIG. 12

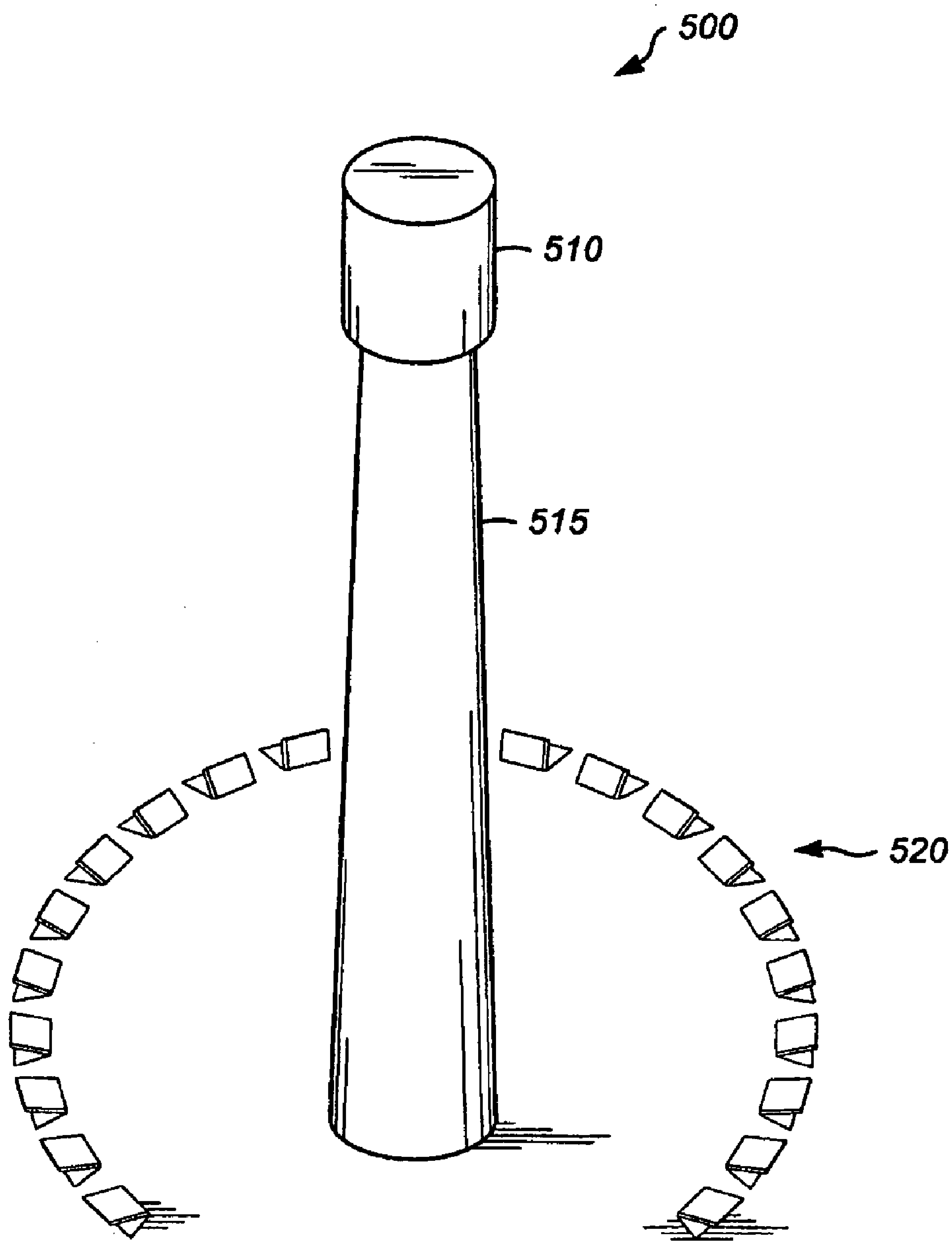


FIG. 13

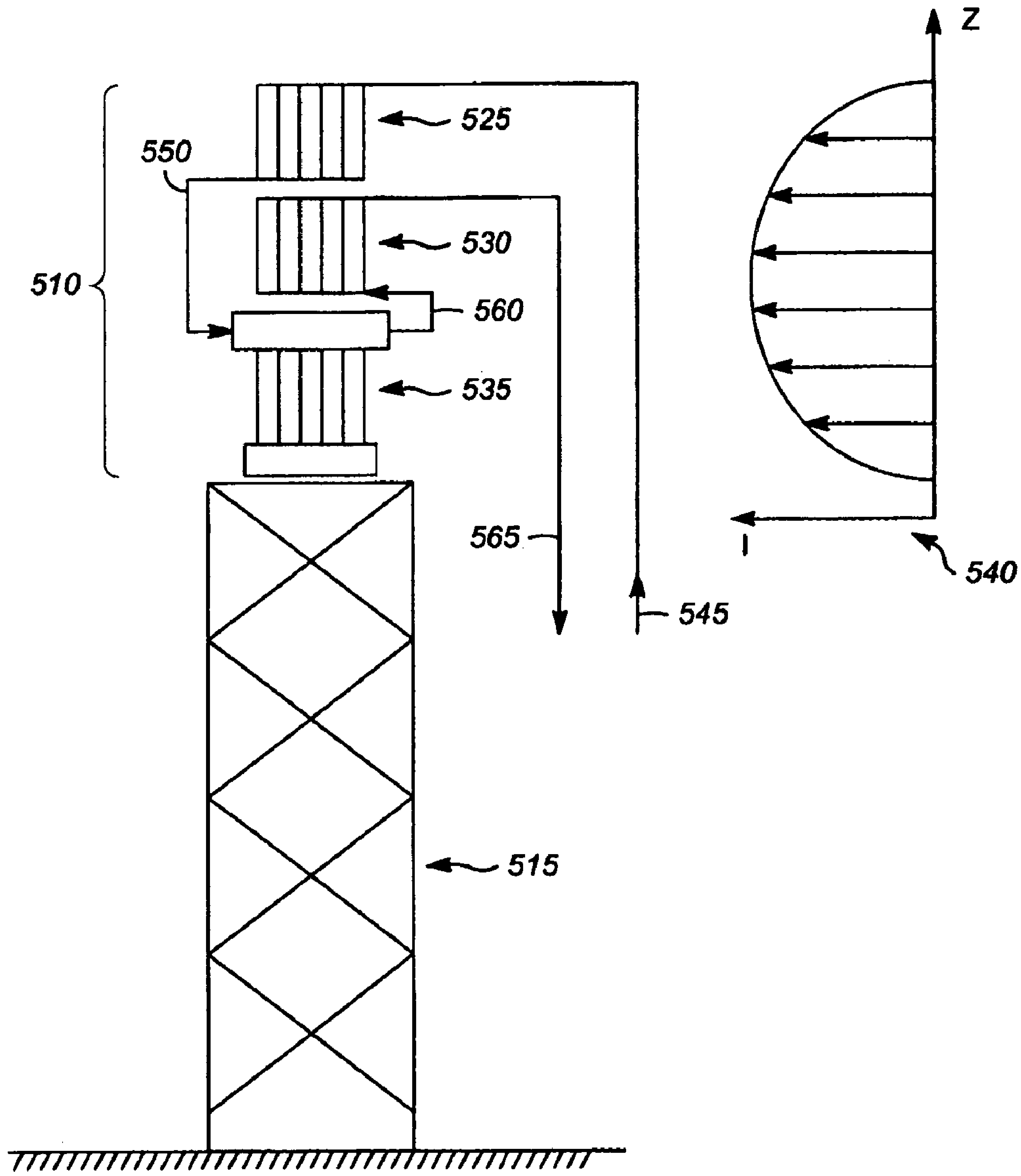


FIG. 14

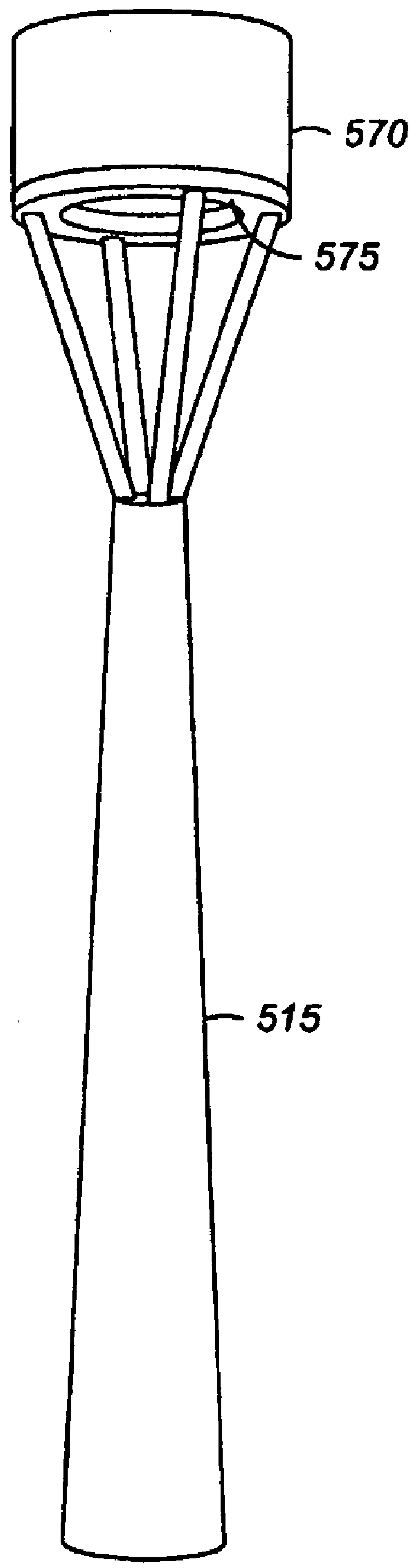


FIG. 15

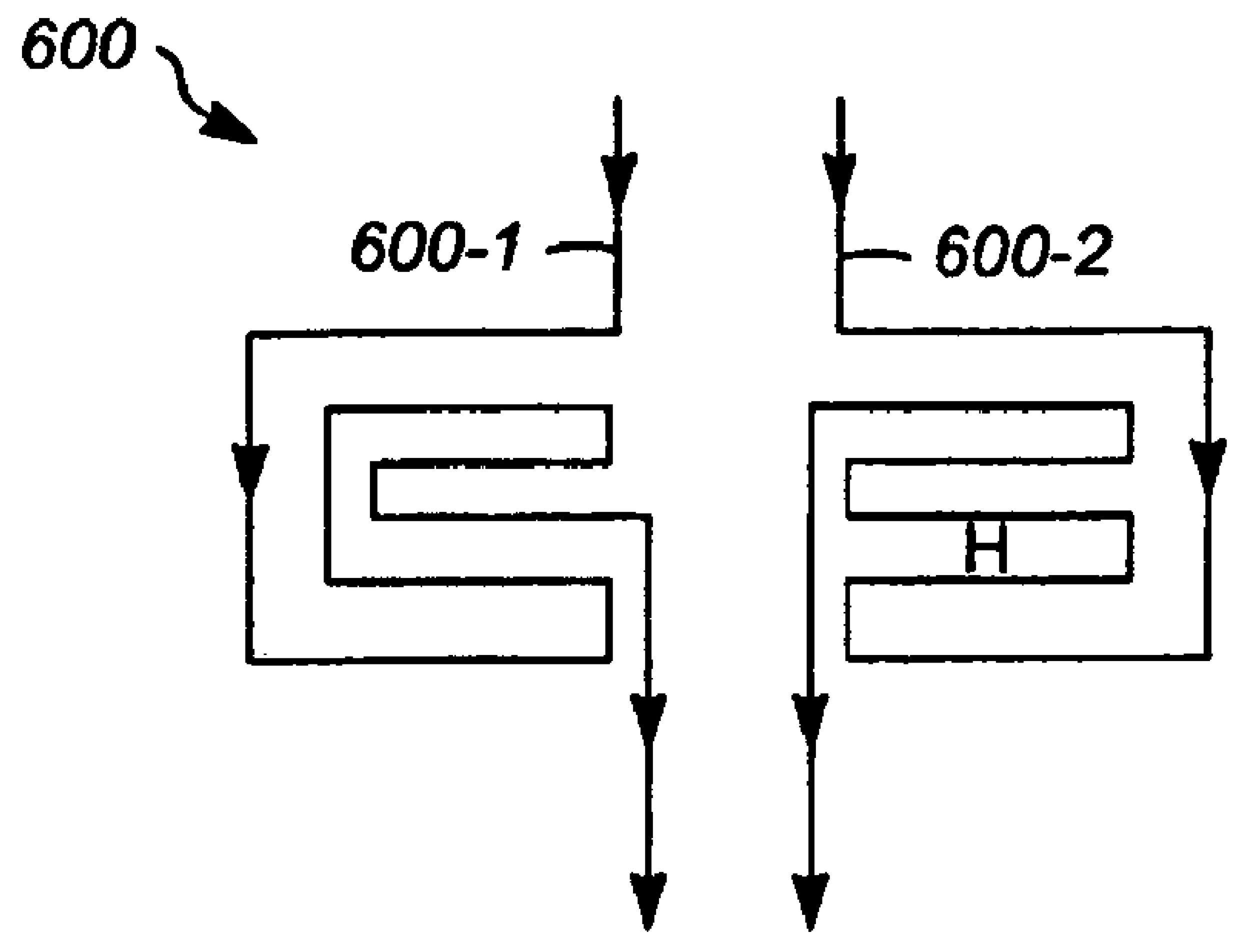


FIG. 16A

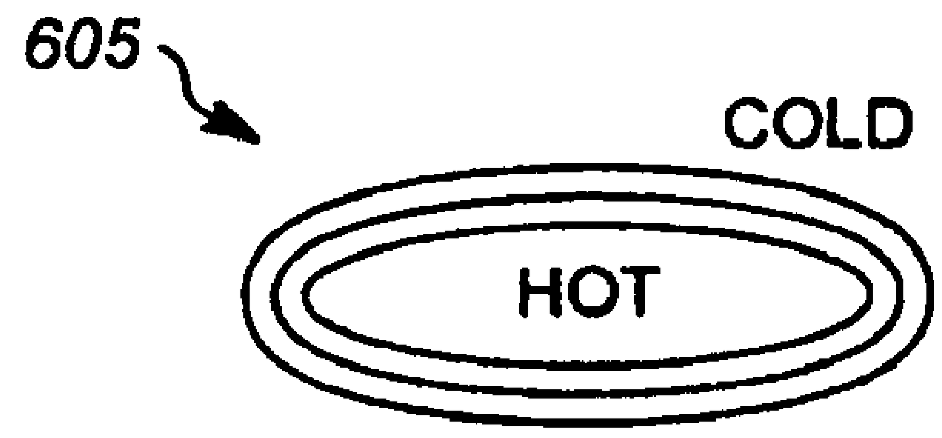


FIG. 16B

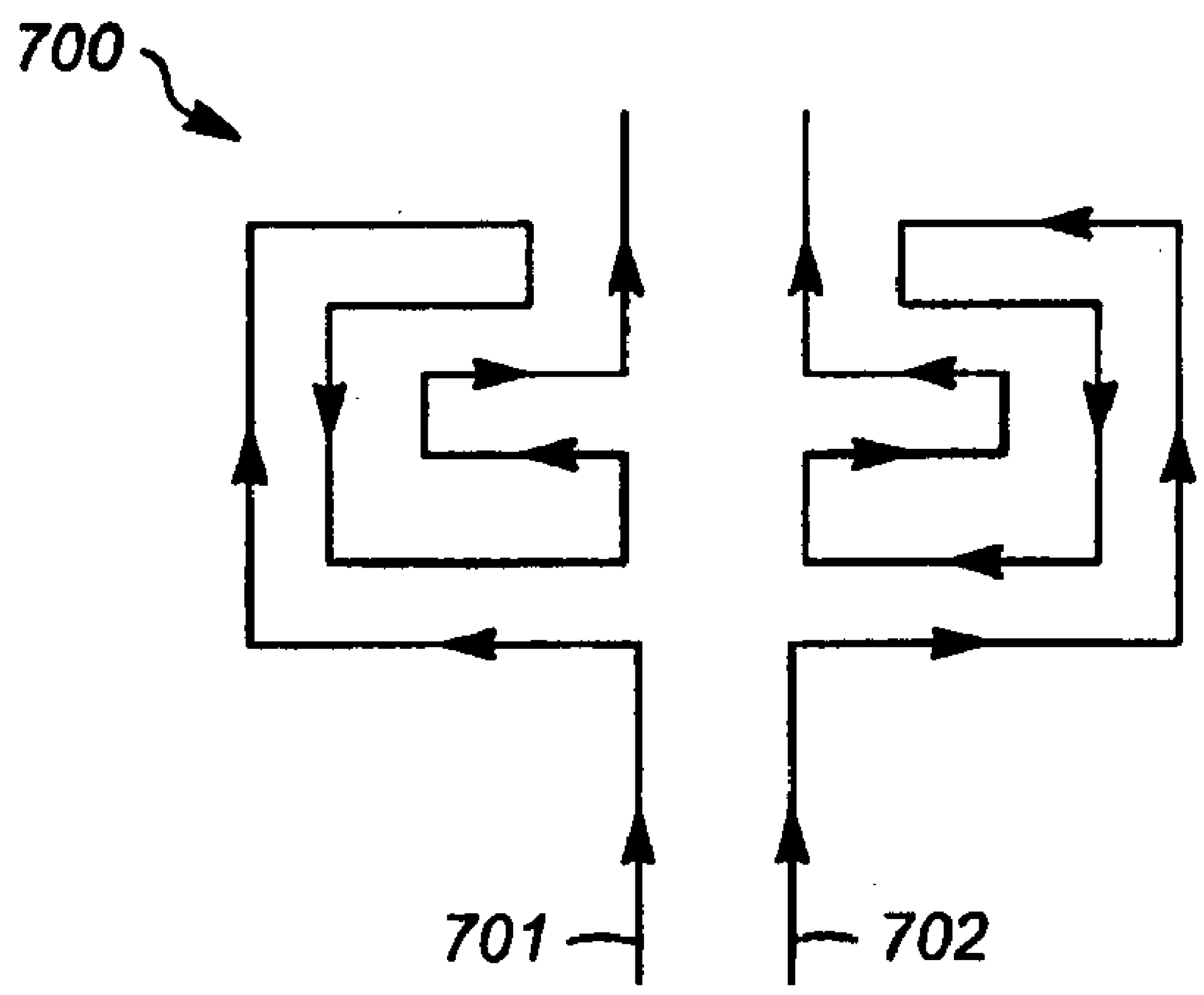


FIG. 17A

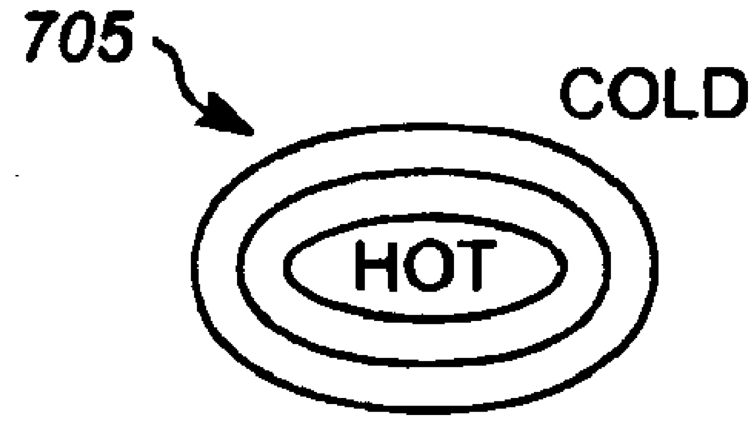


FIG. 17B

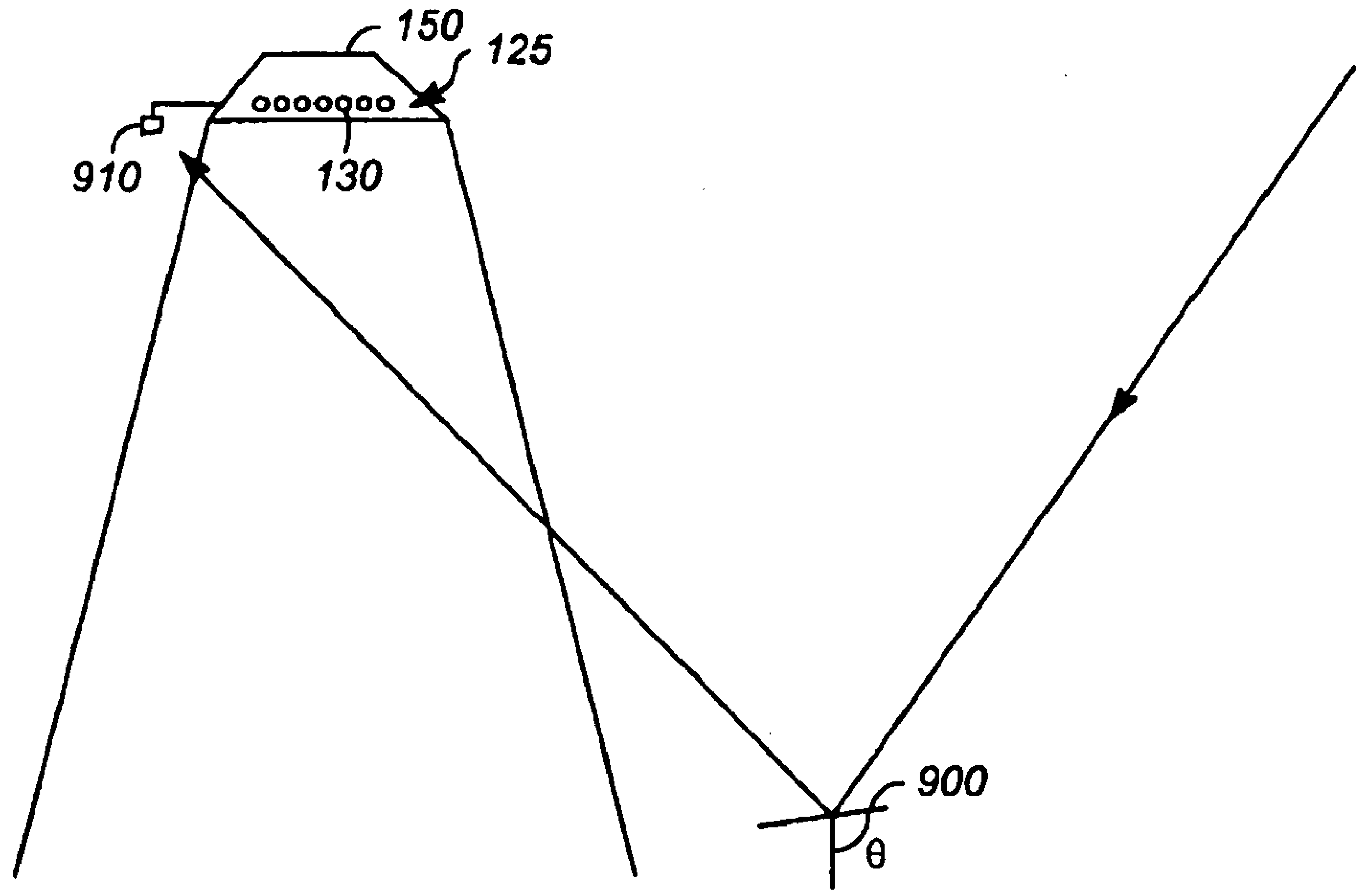


FIG. 18A

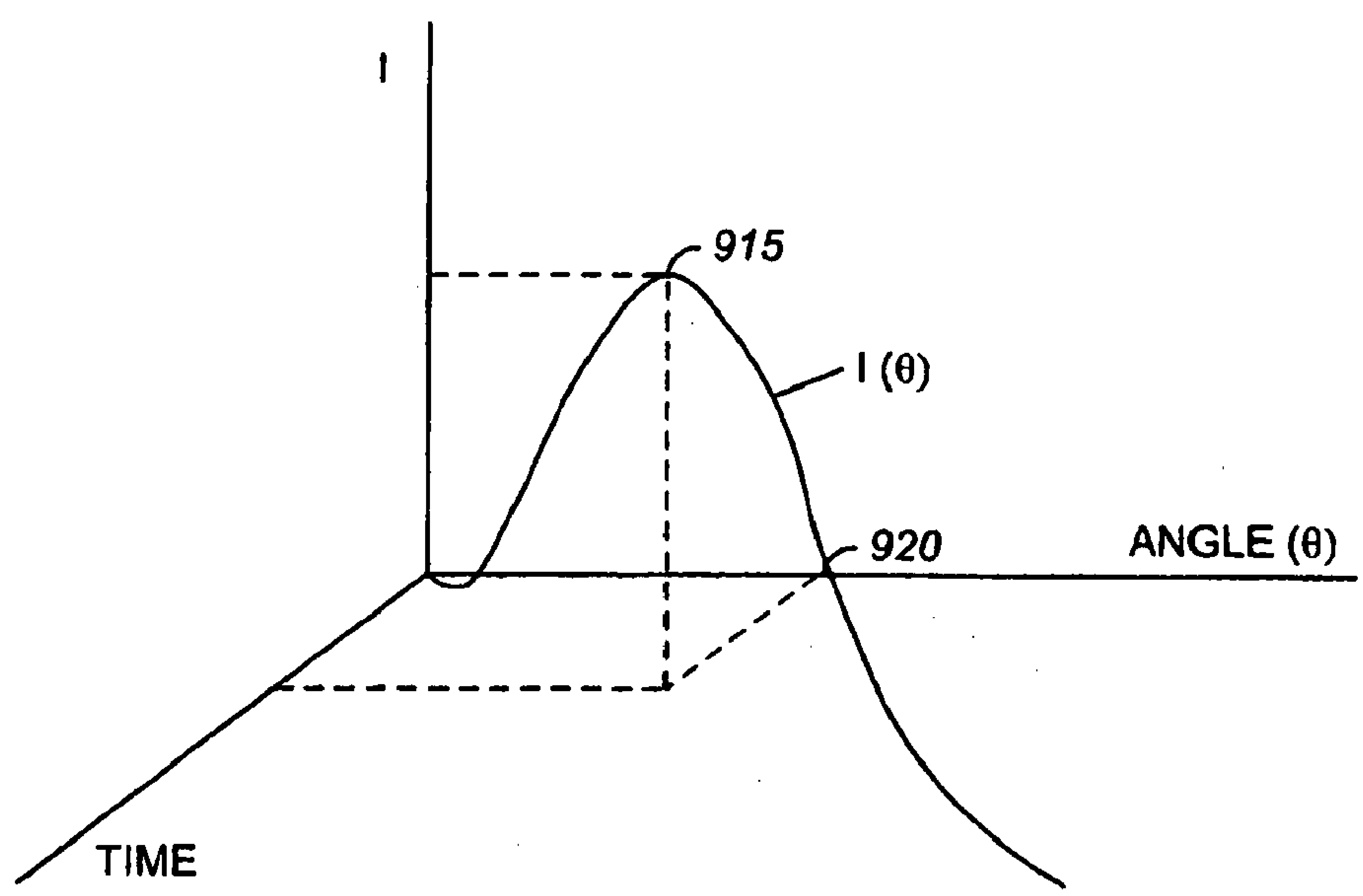


FIG. 18B

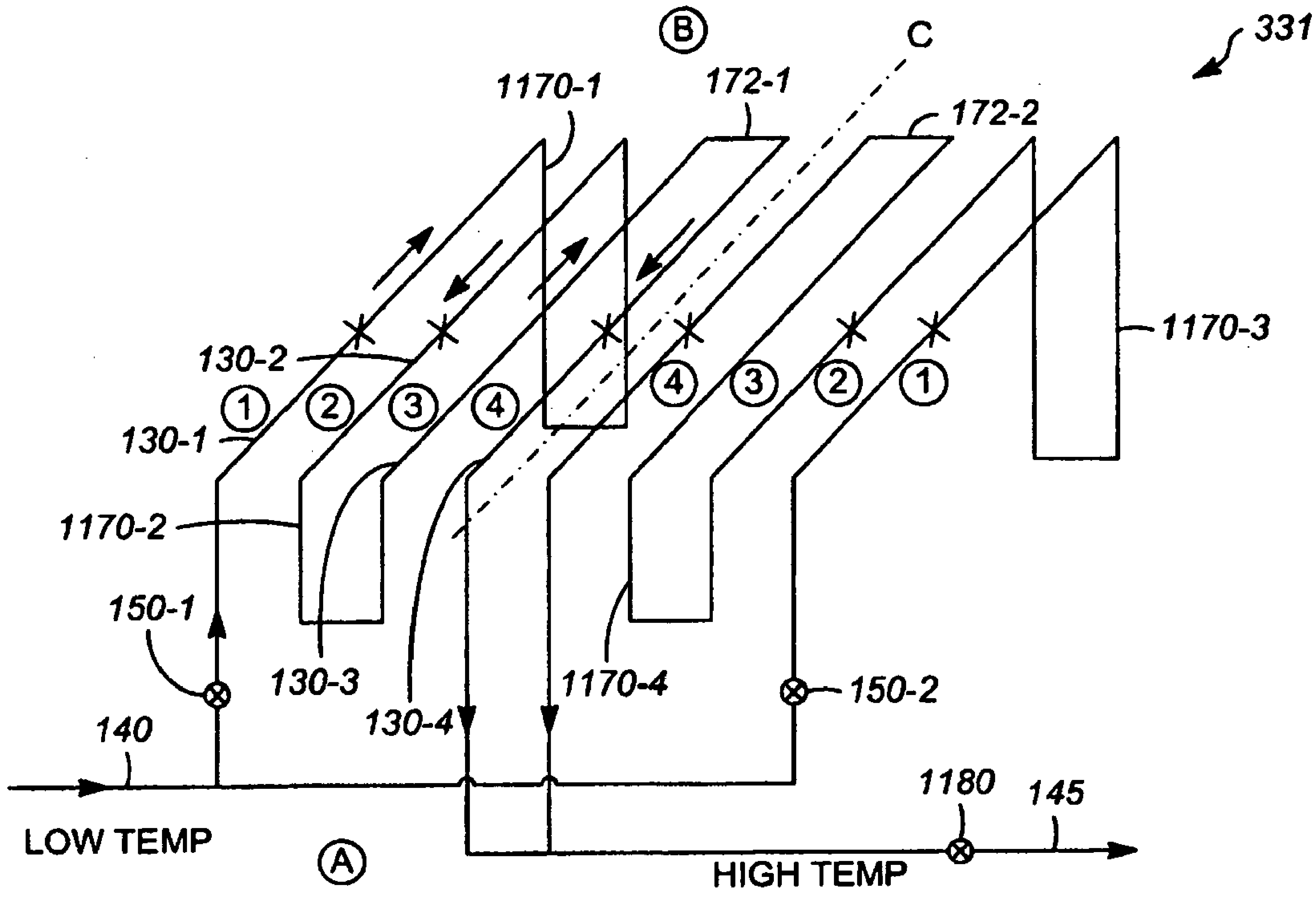


FIG. 19A

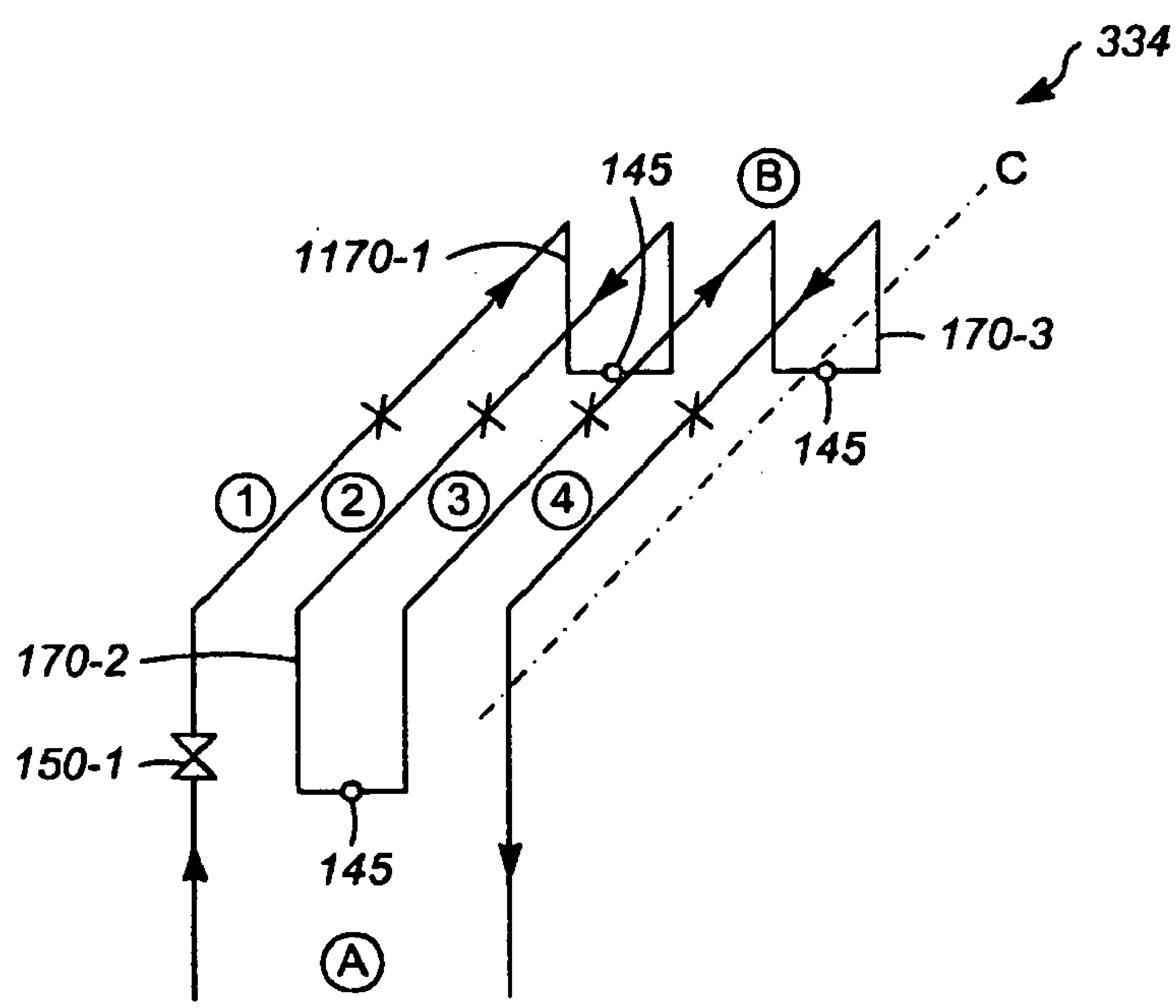


FIG. 19B

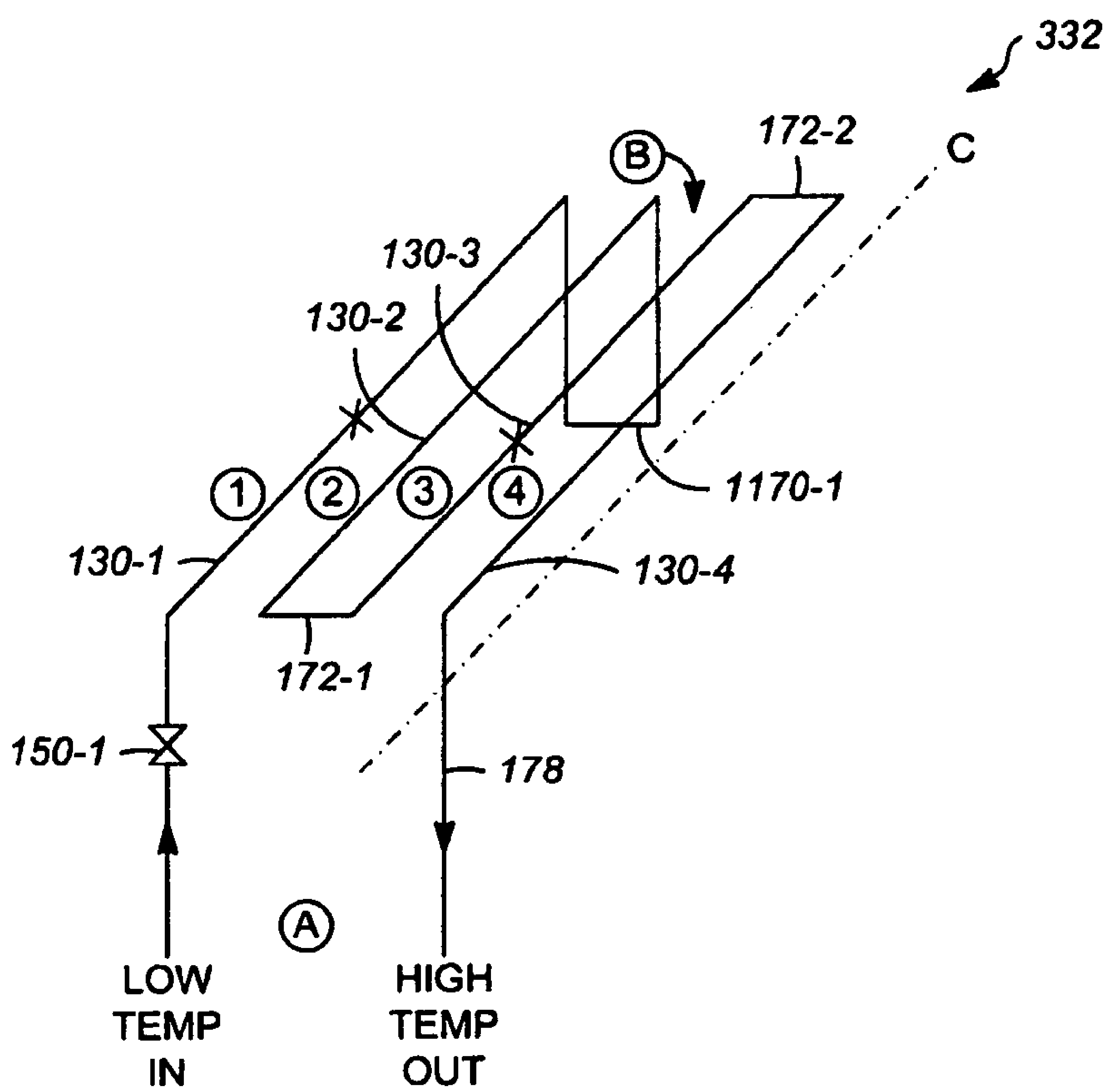


FIG. 20A

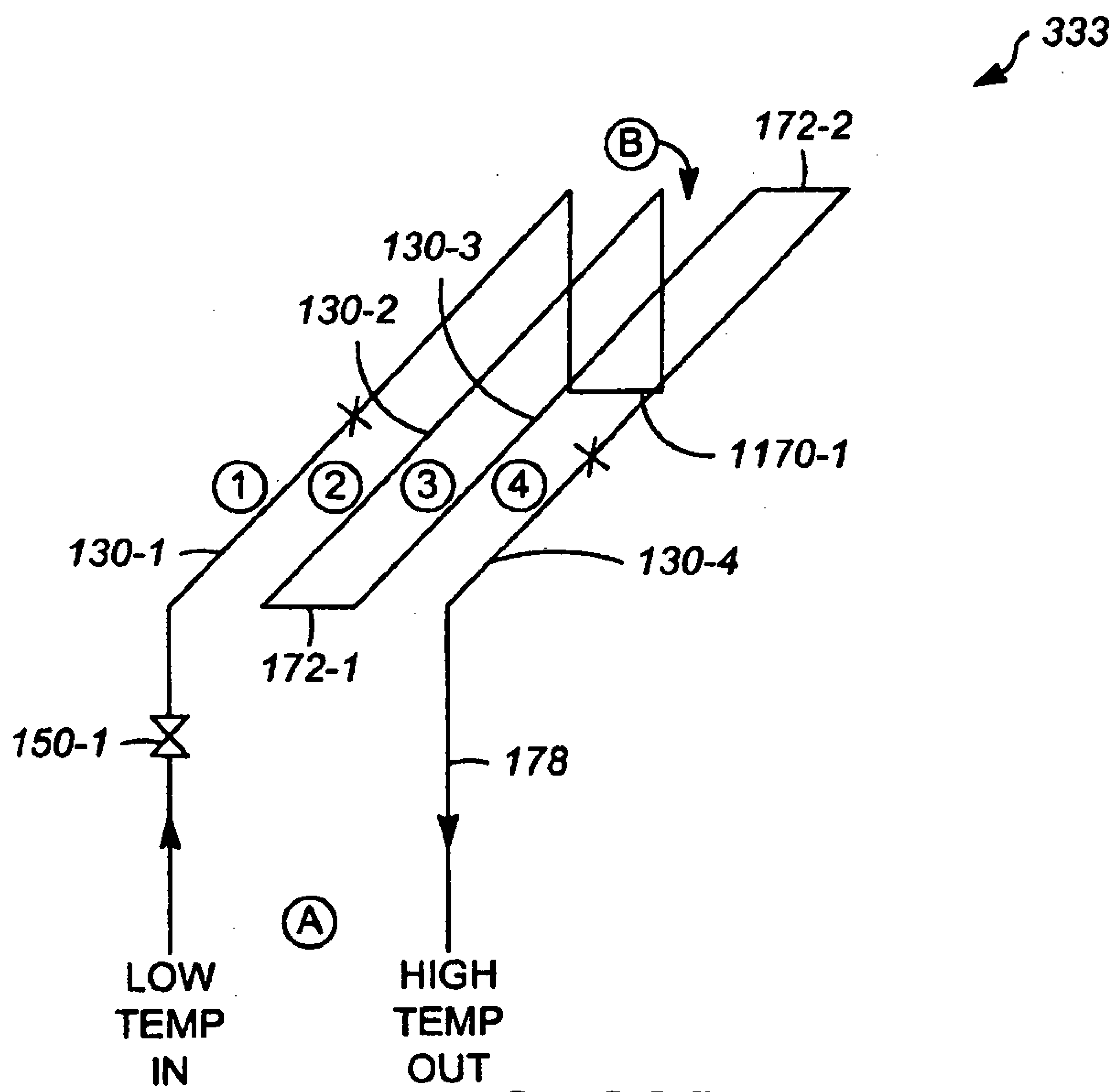


FIG. 20B

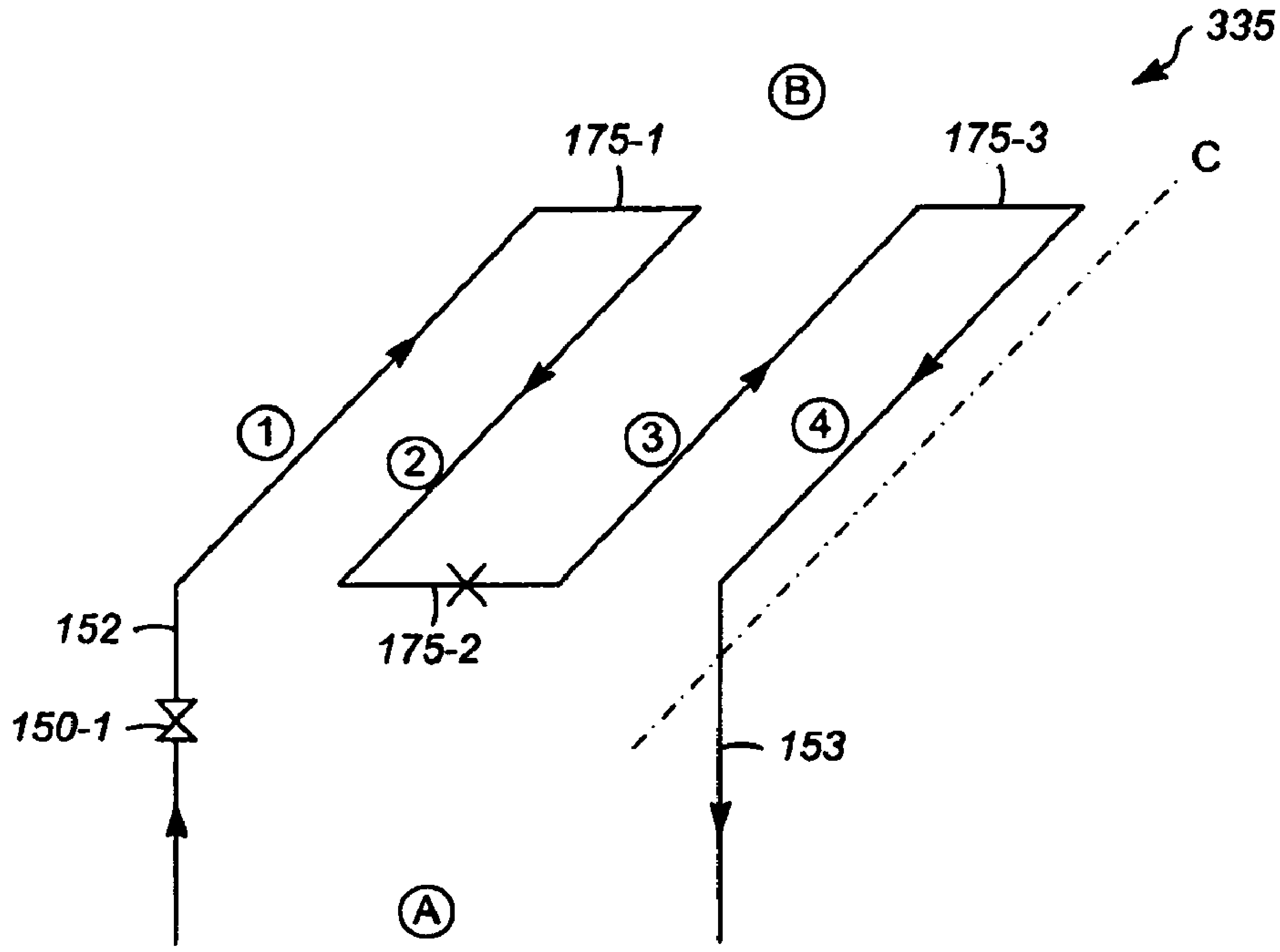


FIG. 21A

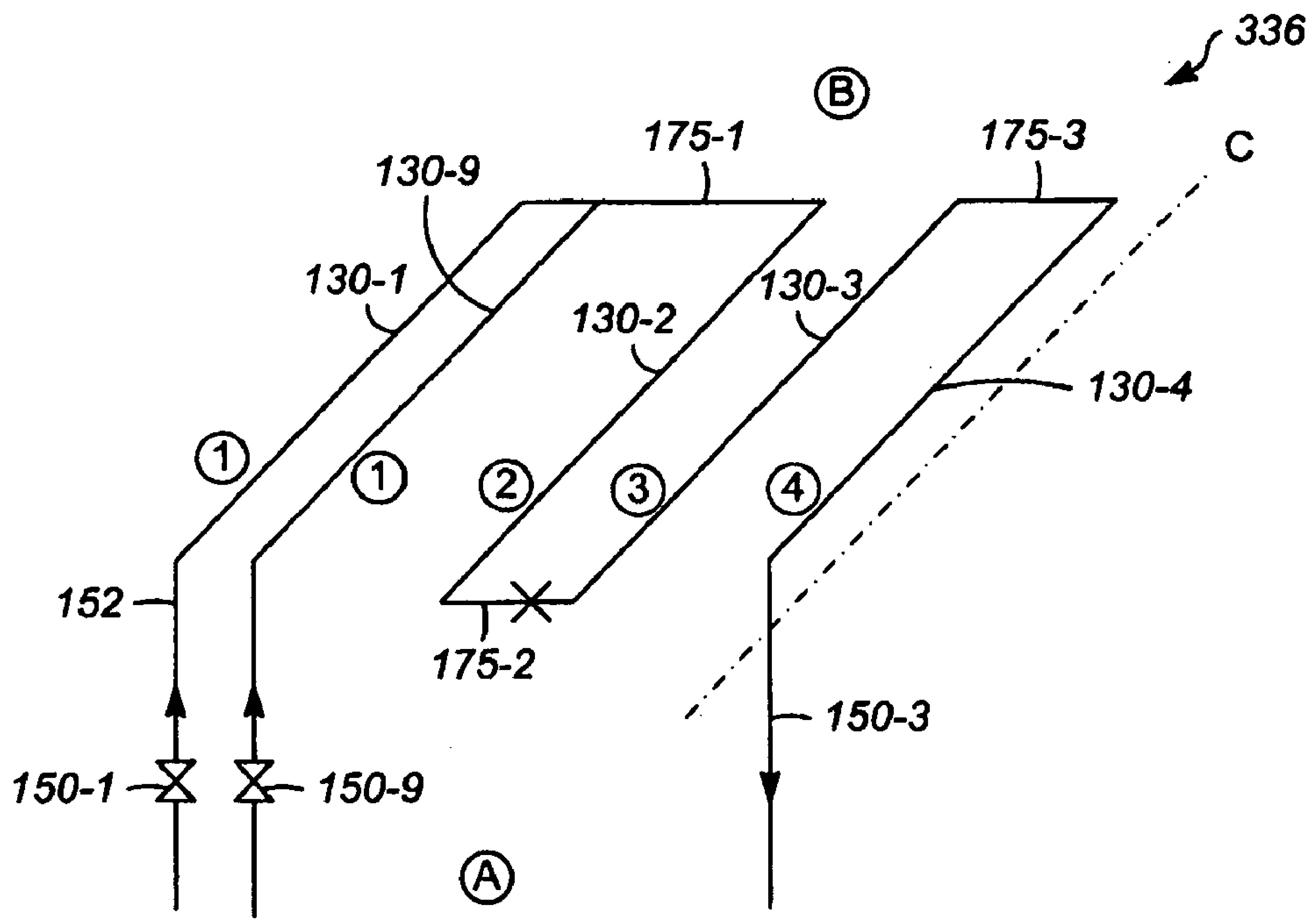


FIG. 21B

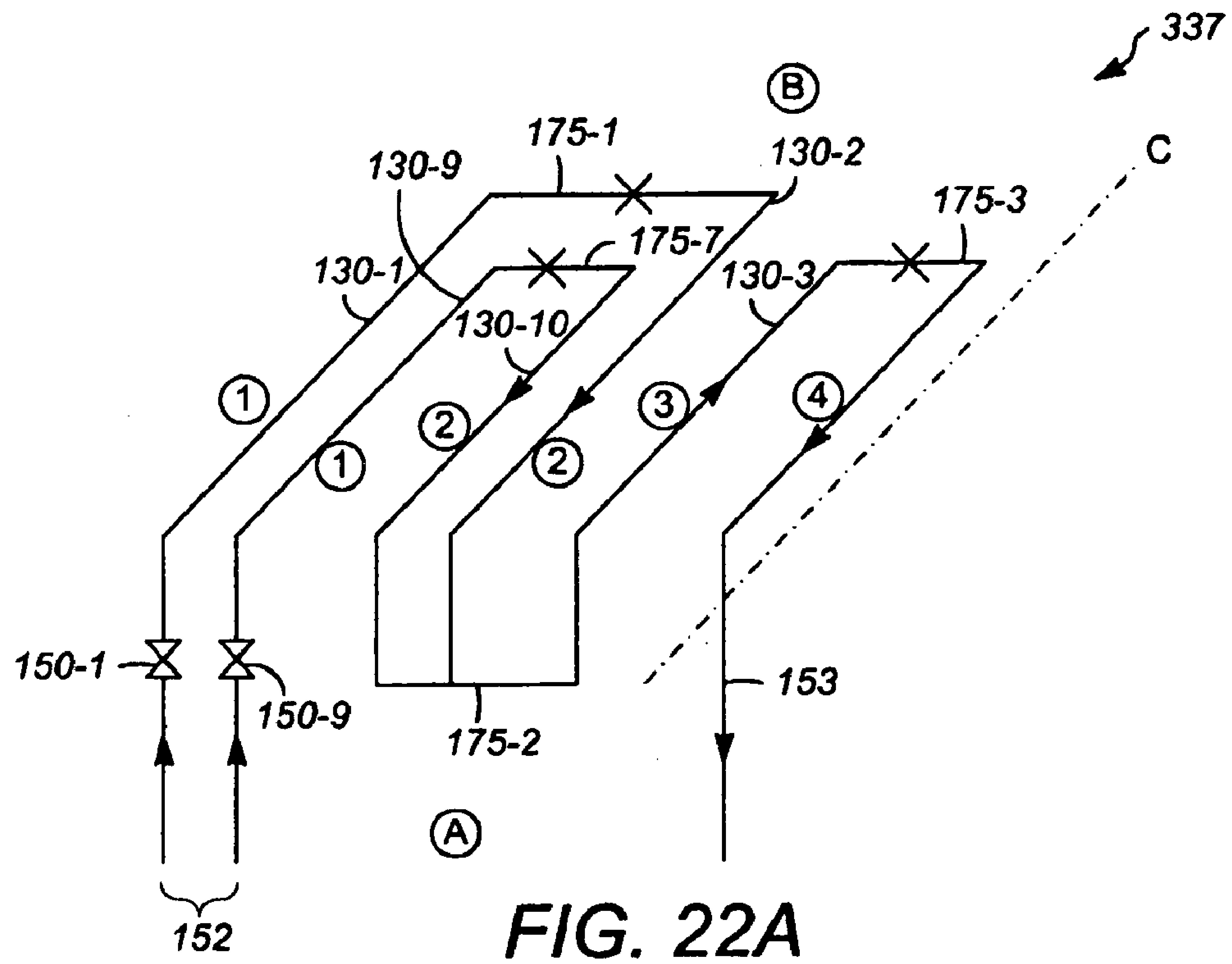


FIG. 22A

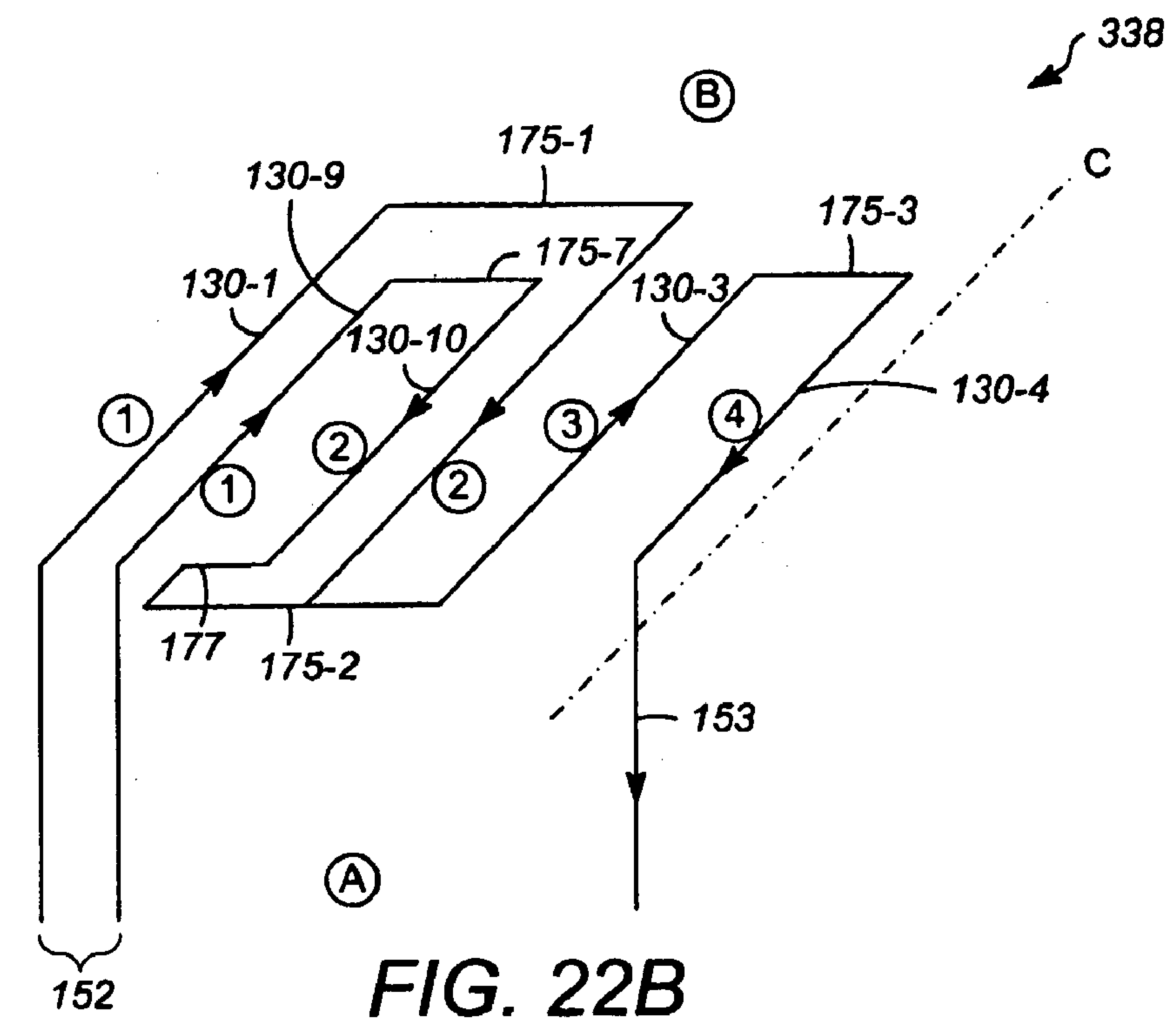


FIG. 22B

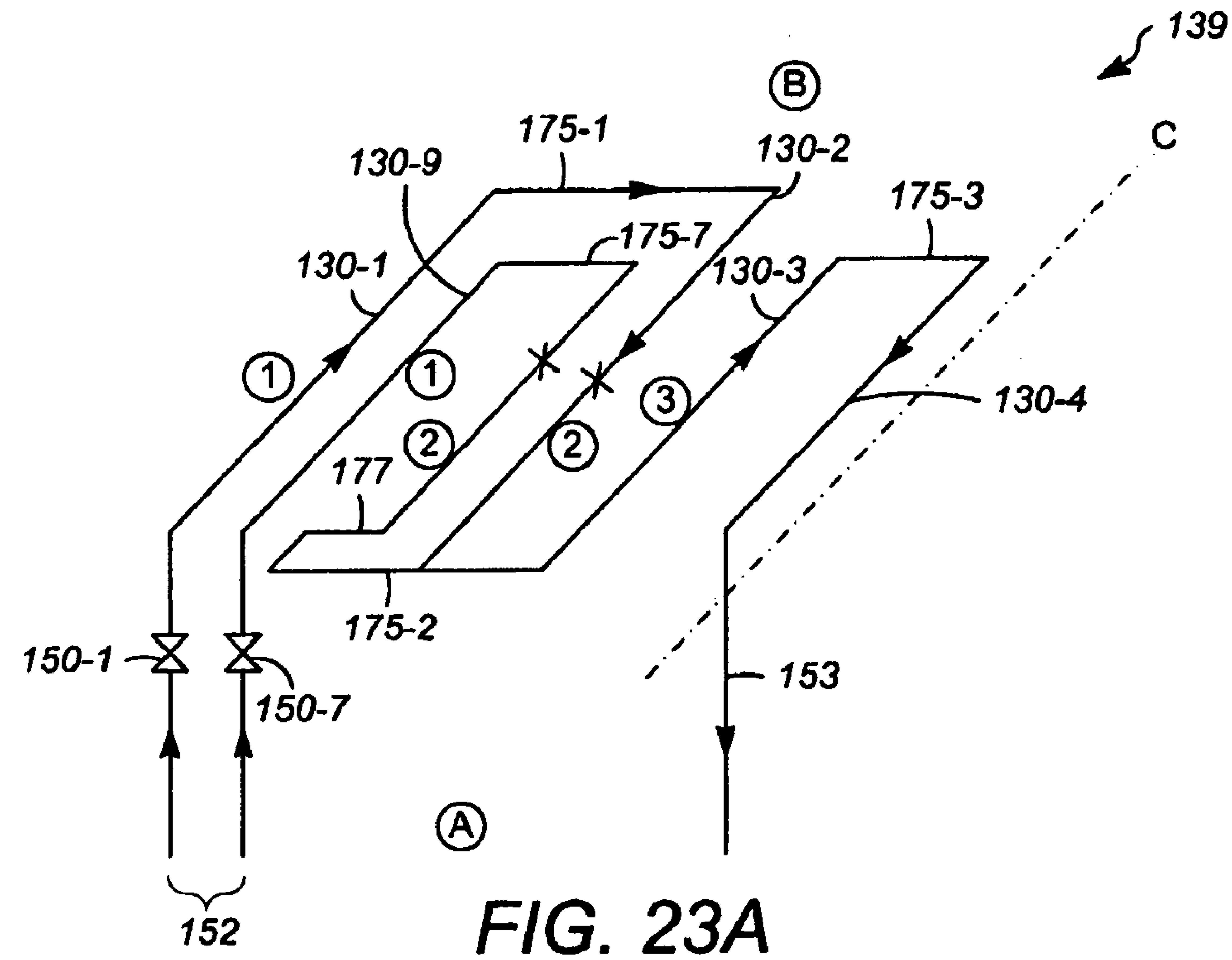


FIG. 23A

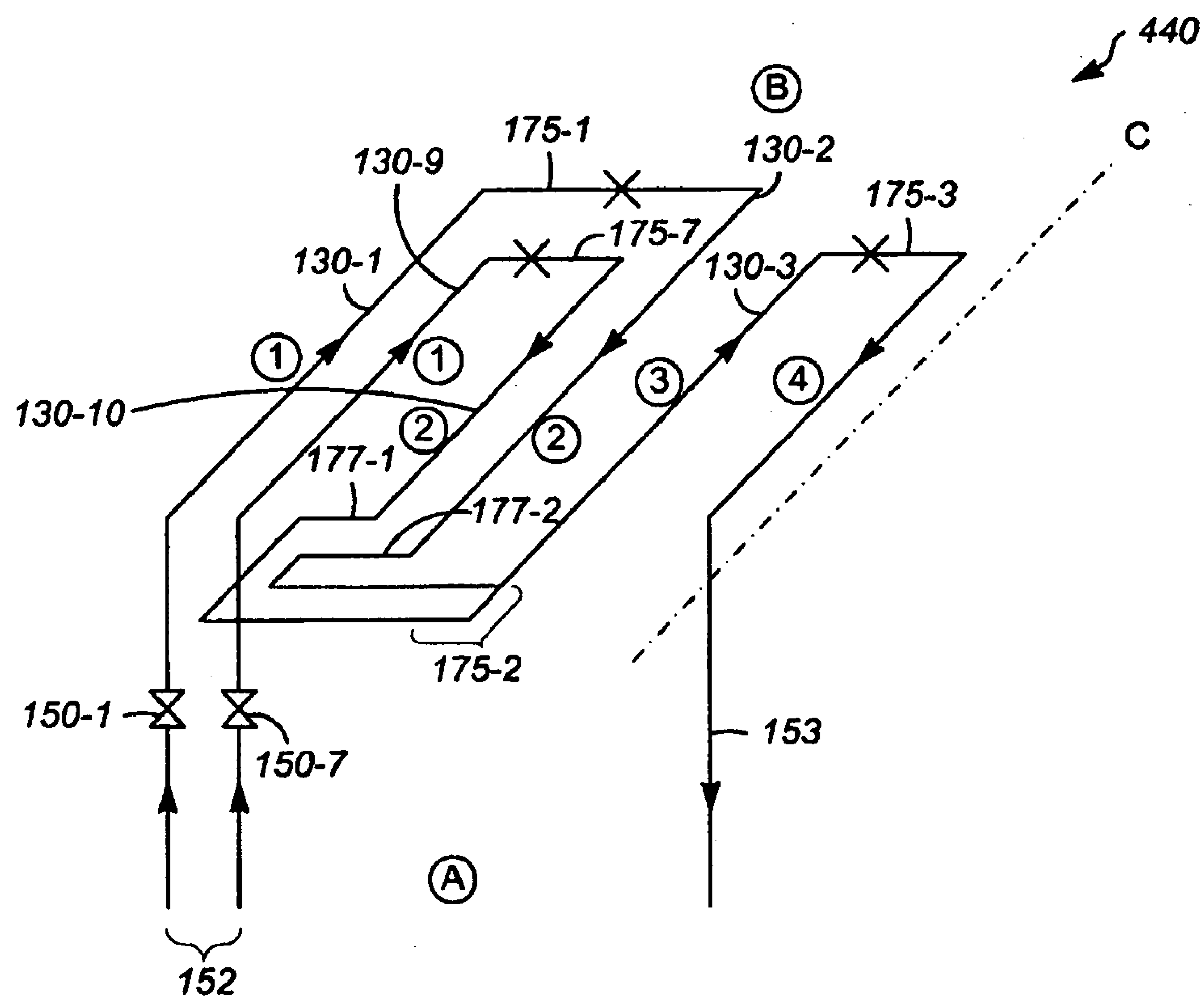
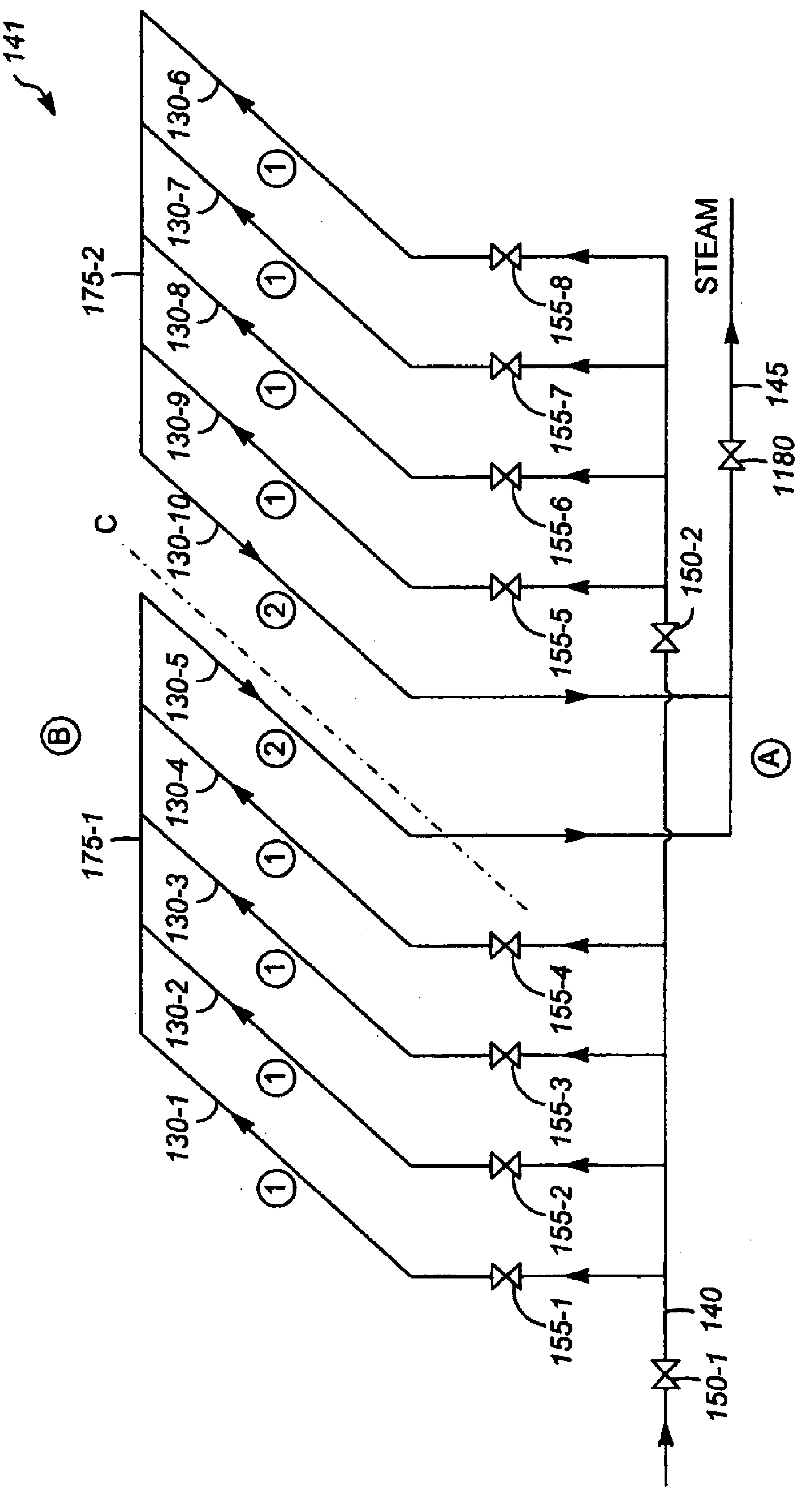


FIG. 23B



141
175-2
175-1
130-1
130-2
130-3
130-4
130-5
130-6
130-7
130-8
130-9
130-10
C
B
A
STEAM
145
1180
150-1
150-2
140
155-1
155-2
155-3
155-4
155-5
155-6
155-7
155-8
1
2

FIG. 24

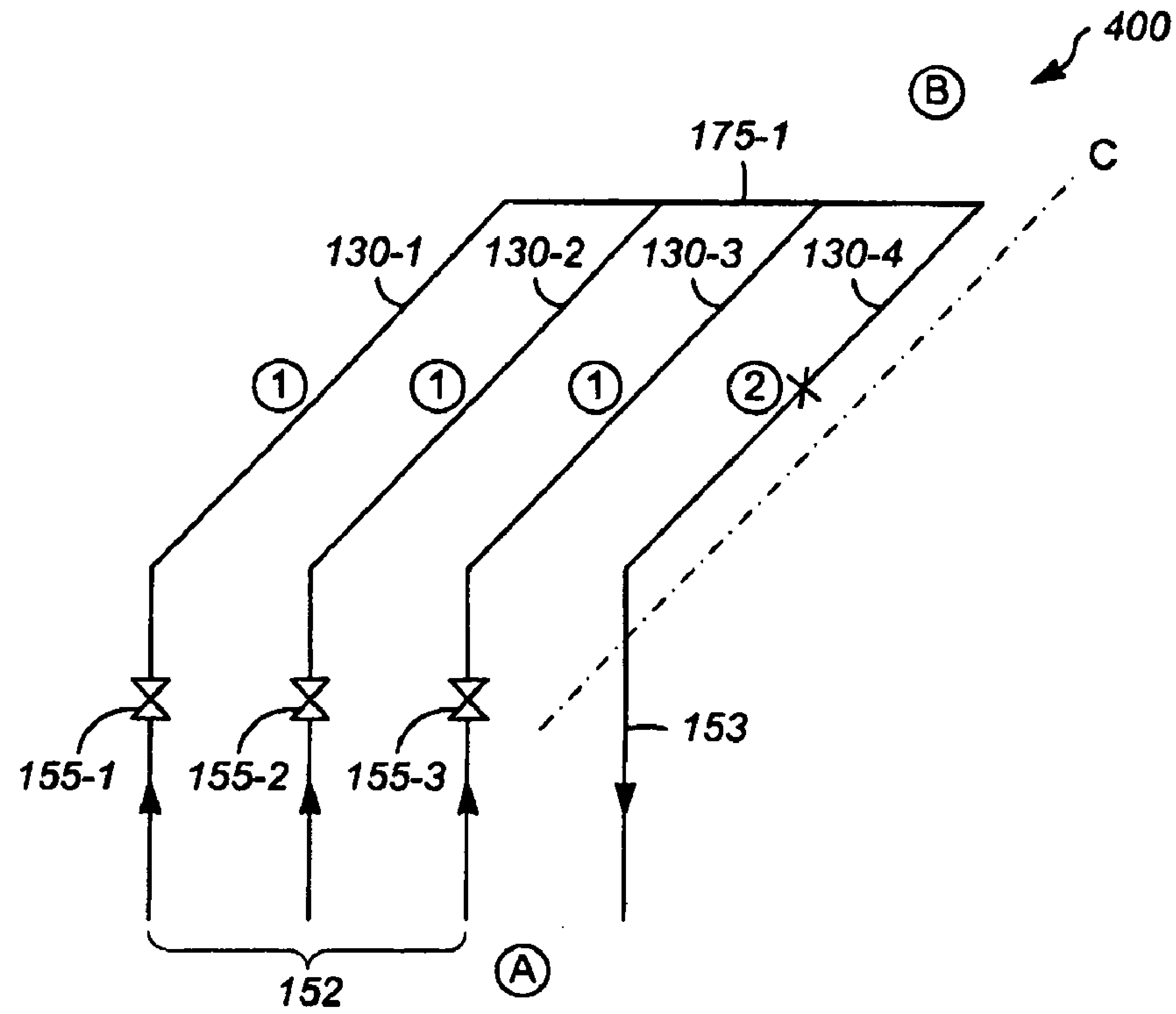


FIG. 25A

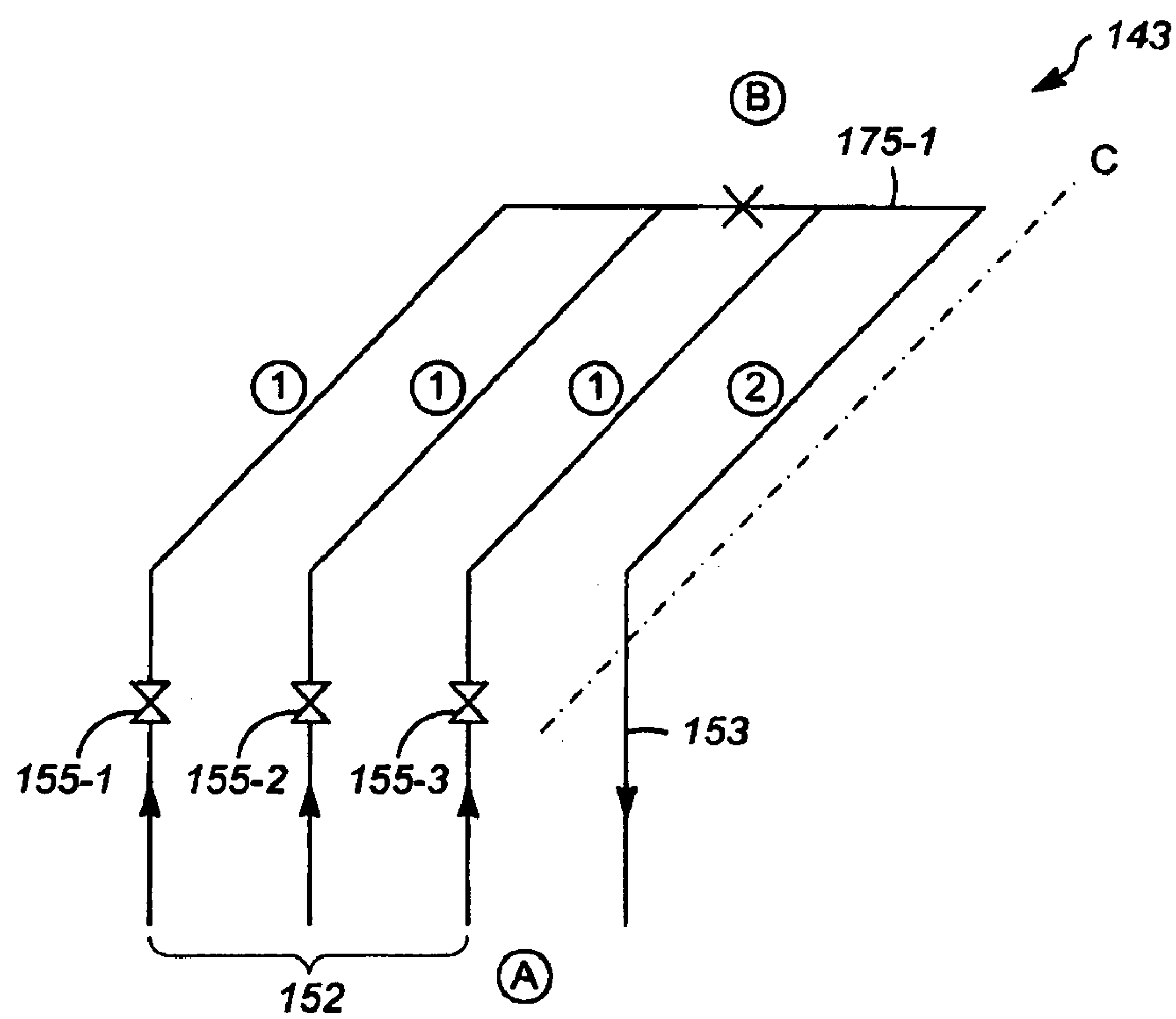


FIG. 25B

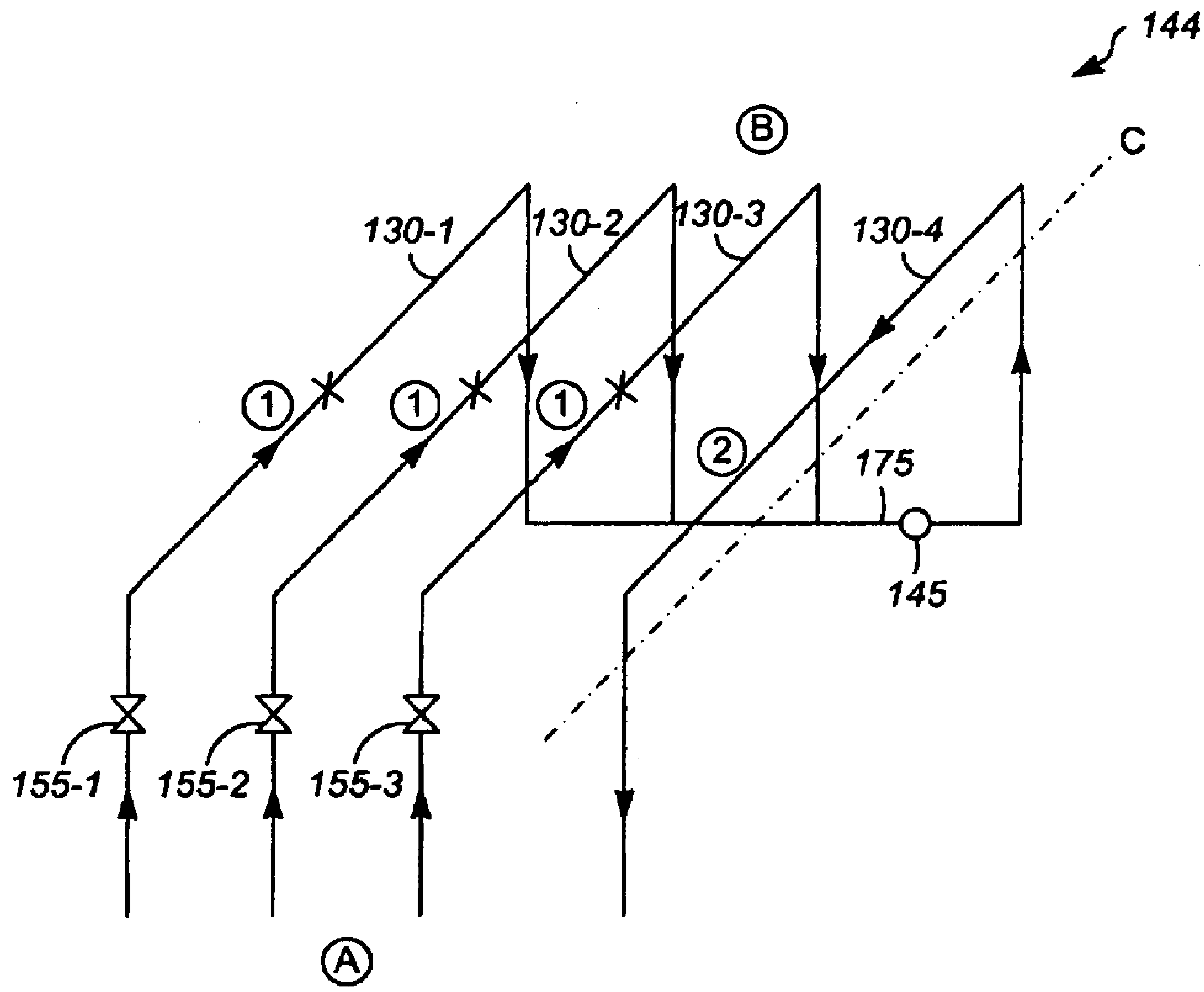
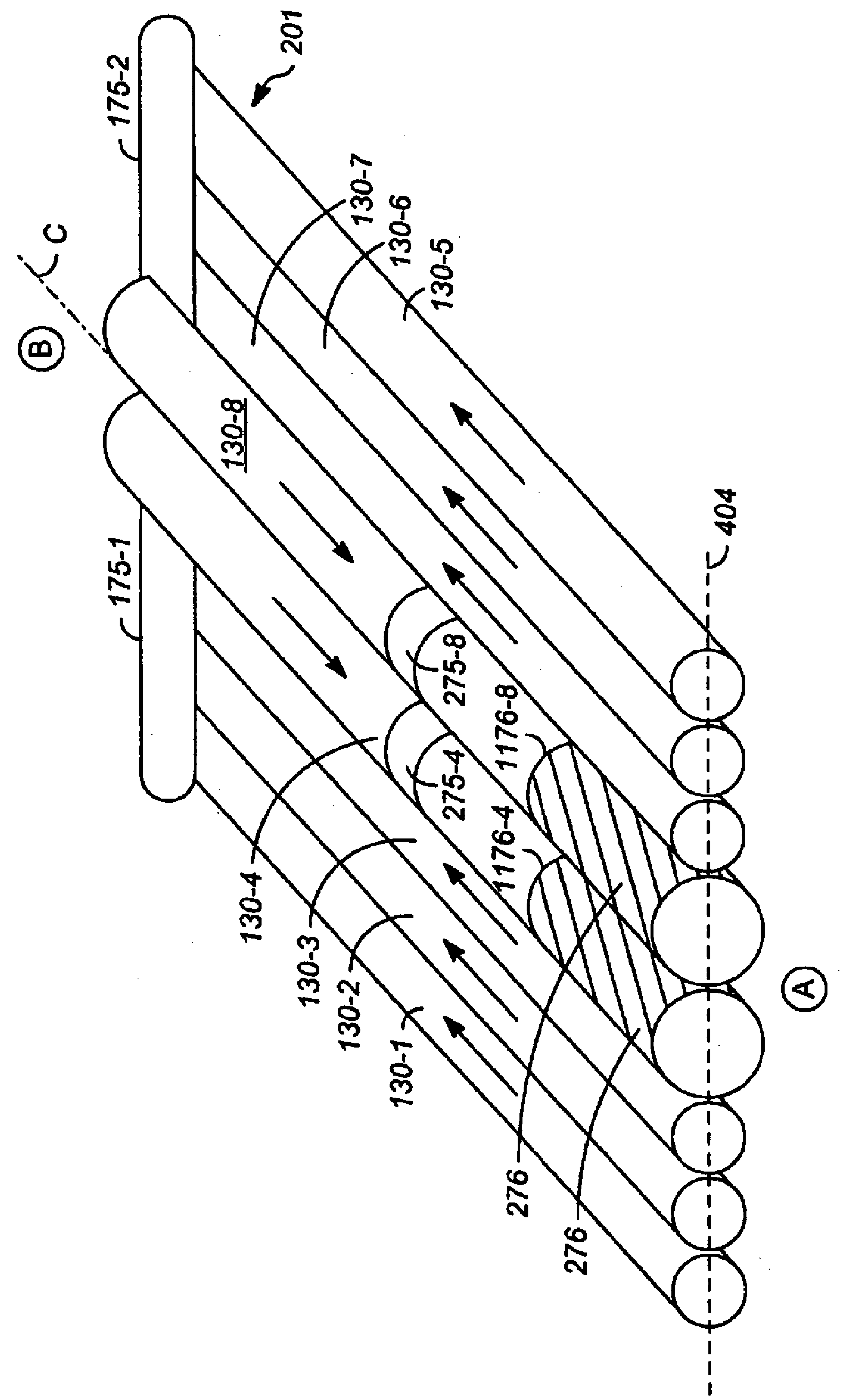


FIG. 25C



201
175-2
175-1
C
B
A
130-8
130-7
130-6
130-5
130-4
130-3
130-2
130-1
404
275-8
275-4
1176-8
1176-4
276
276

FIG. 26A

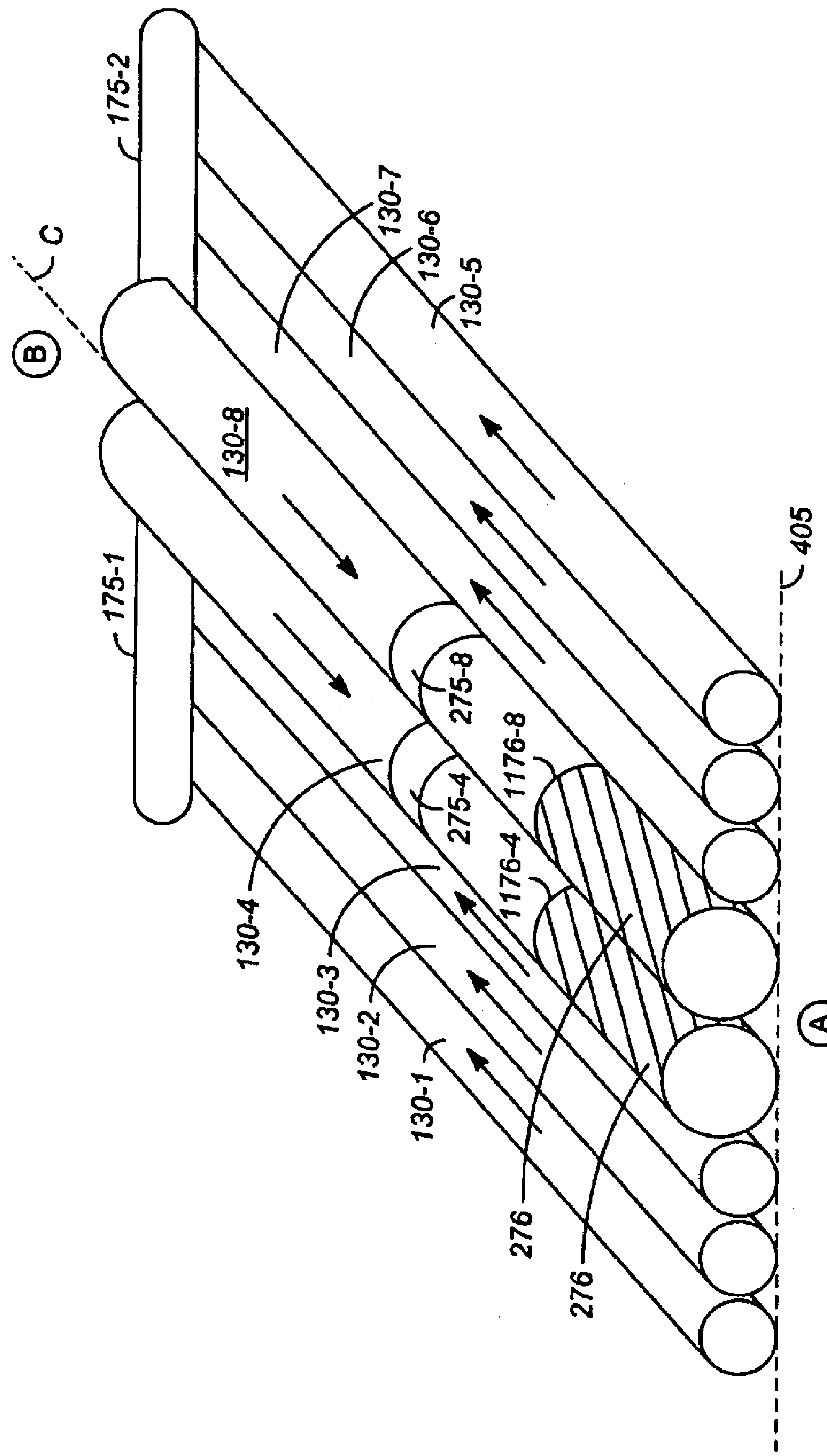

175-2
C
B
175-1
130-8
130-7
130-6
130-5
405
275-8
275-4
1176-8
1176-4
130-4
130-3
130-2
130-1
276
276
A

FIG. 26B

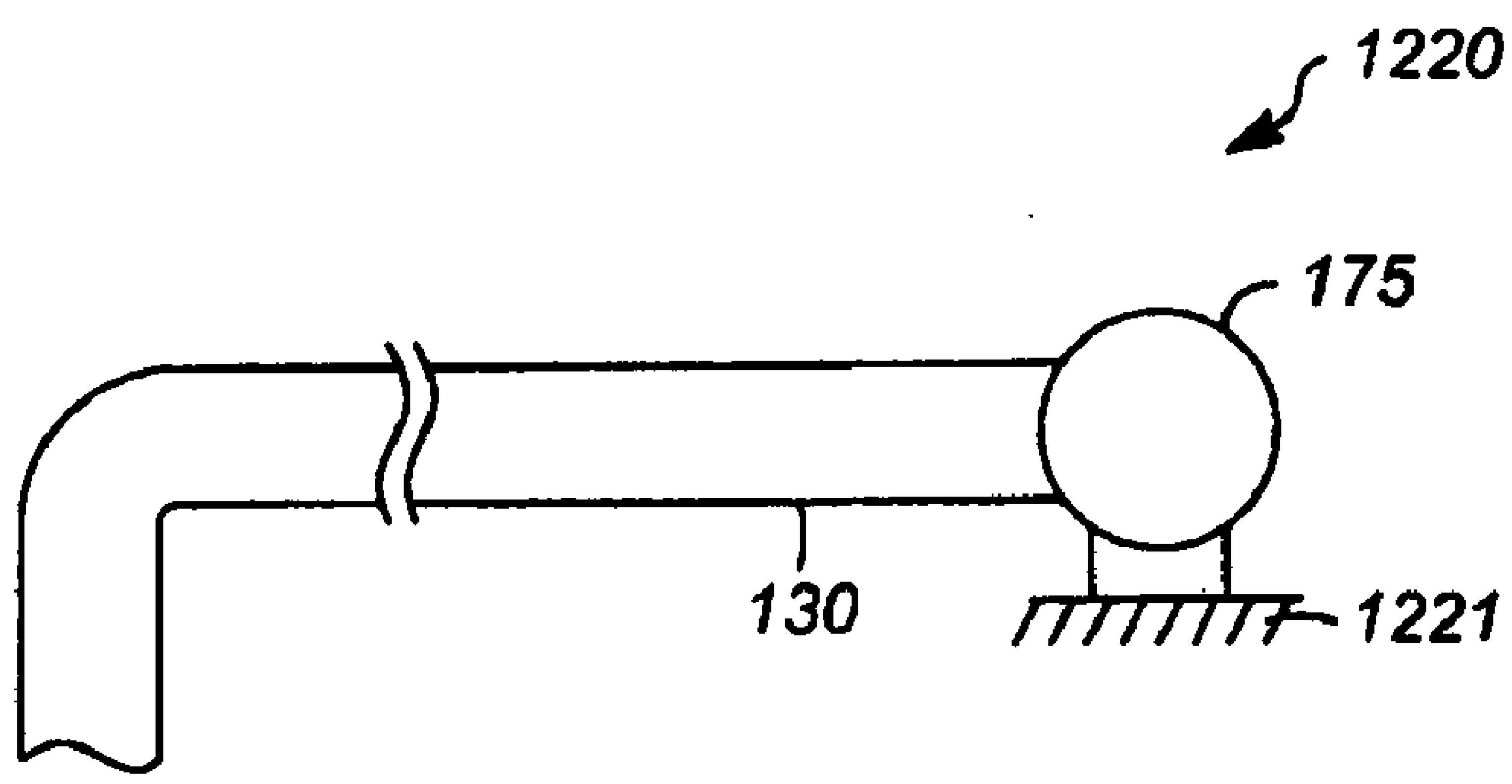


FIG. 27A

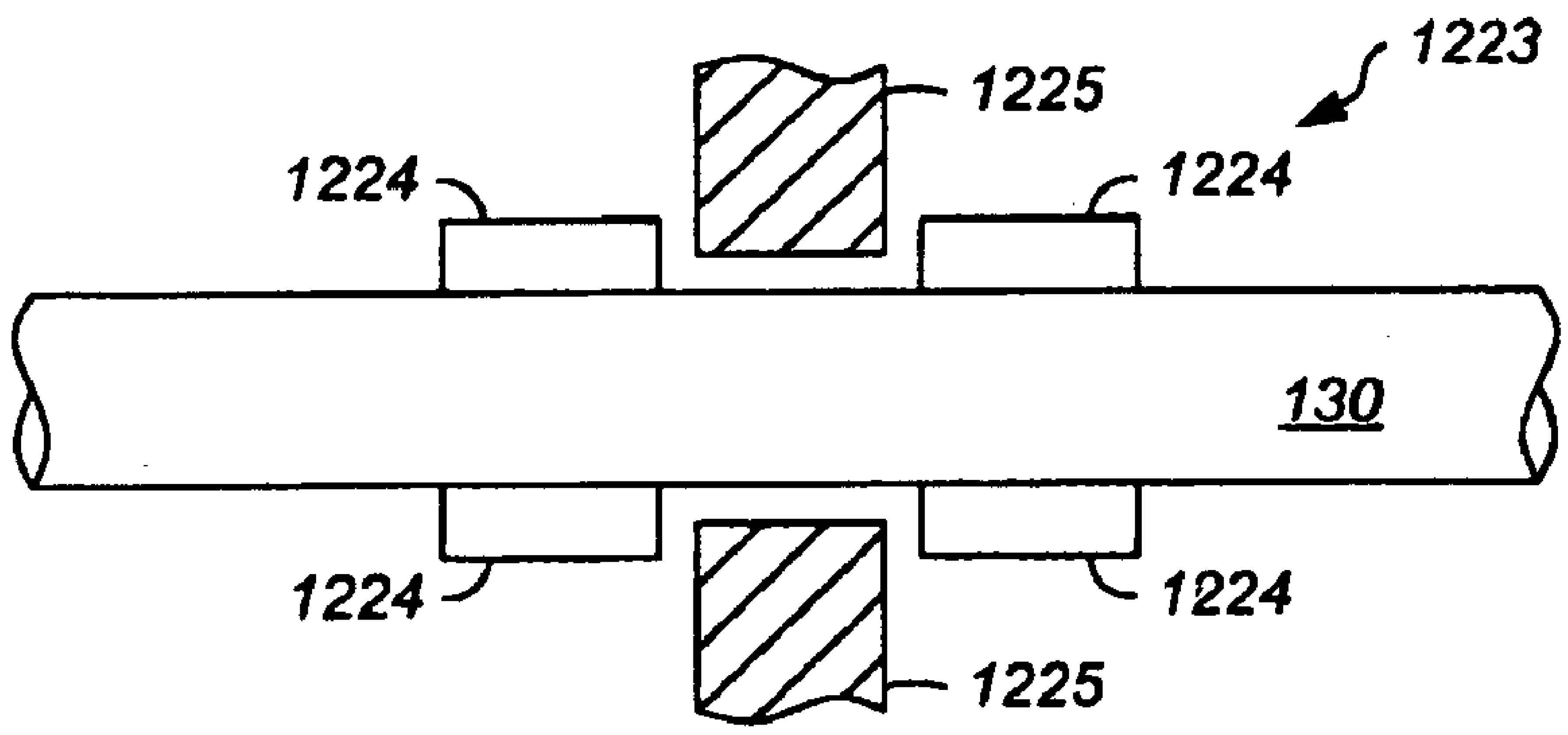


FIG. 27B

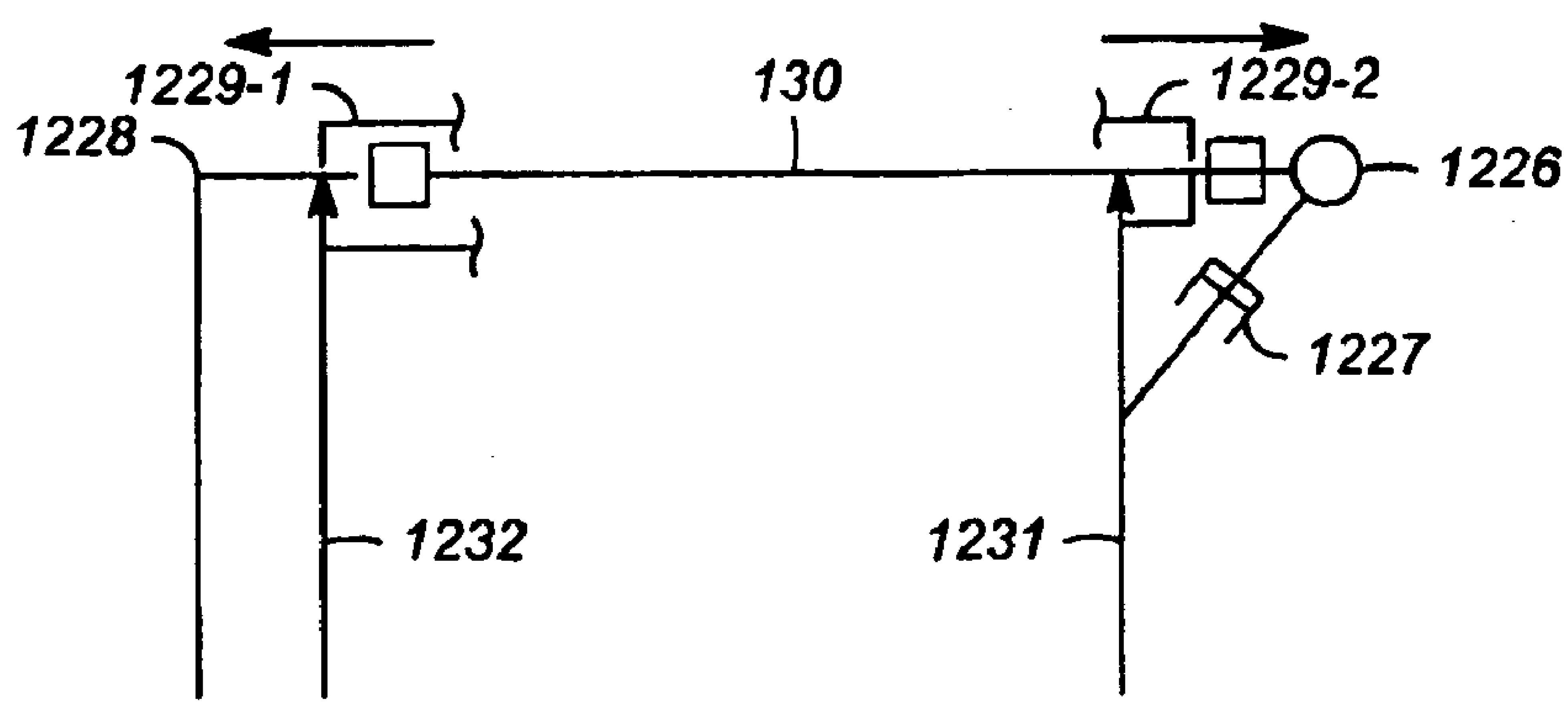


FIG. 28

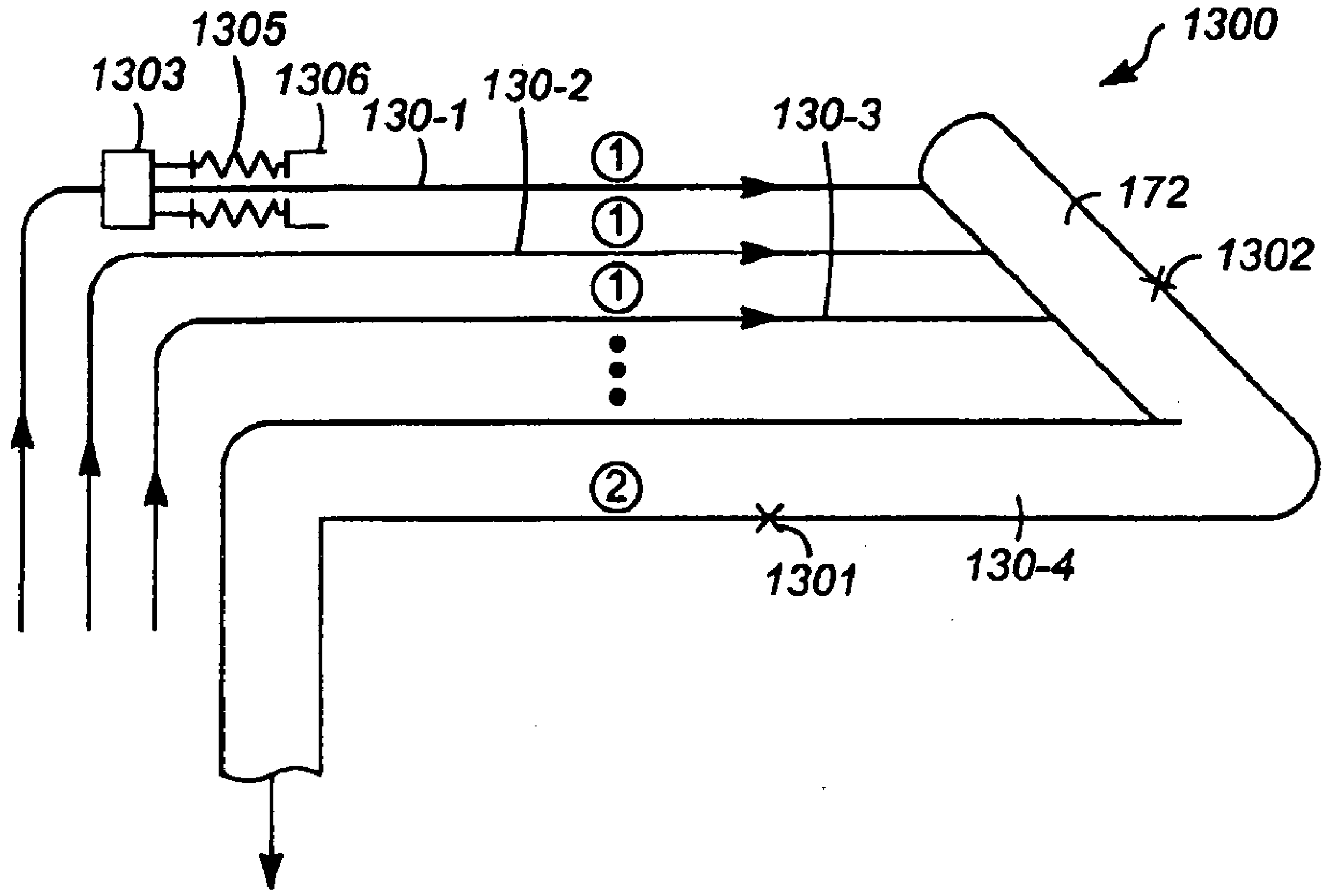

1300
1305
1303
1306
130-1
130-2
130-3
172
1302
①
①
①
②
1301
130-4

FIG. 29

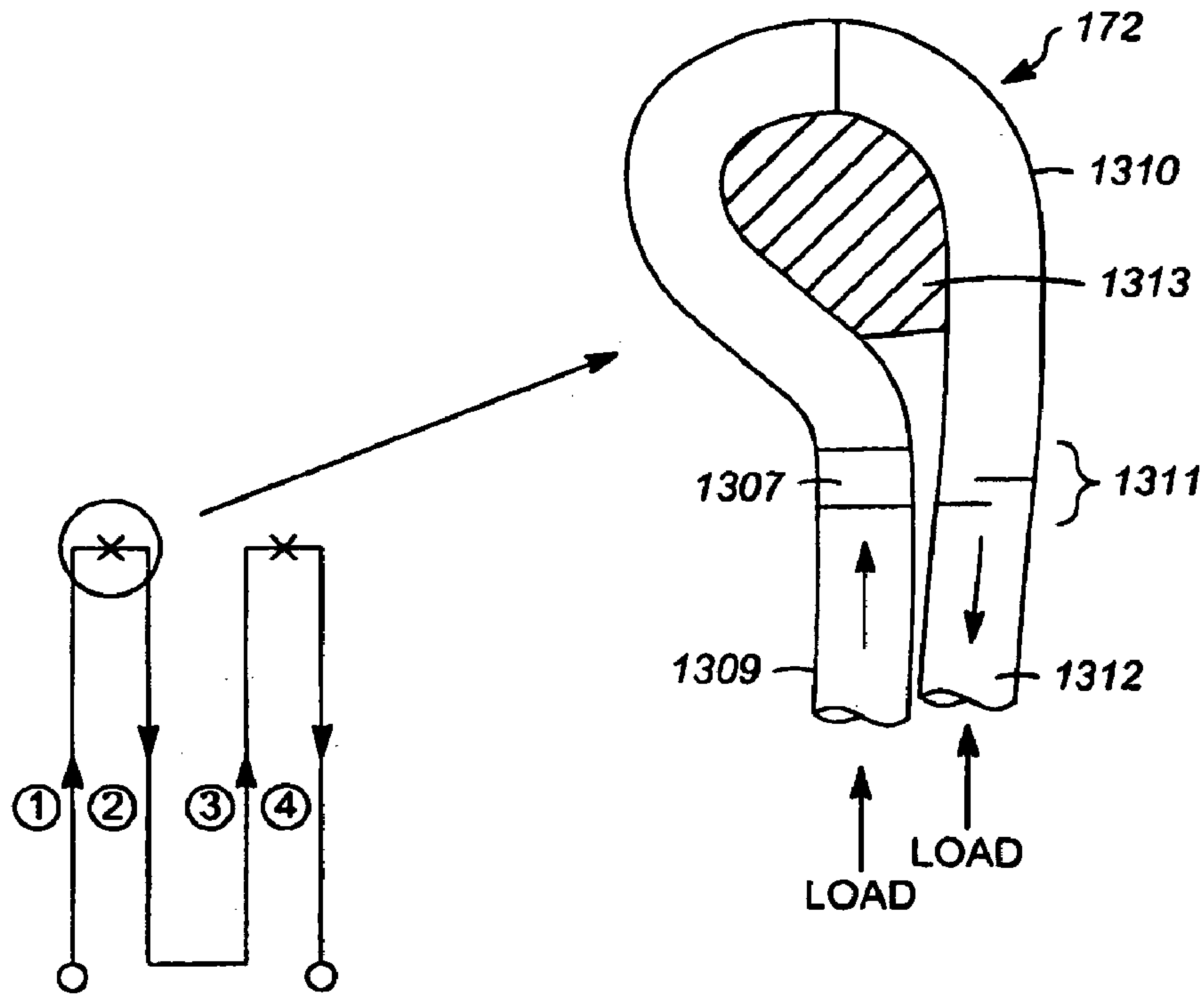

172
1310
1313
1307
1311
1309
1312
LOAD
LOAD
①
②
③
④

FIG. 30

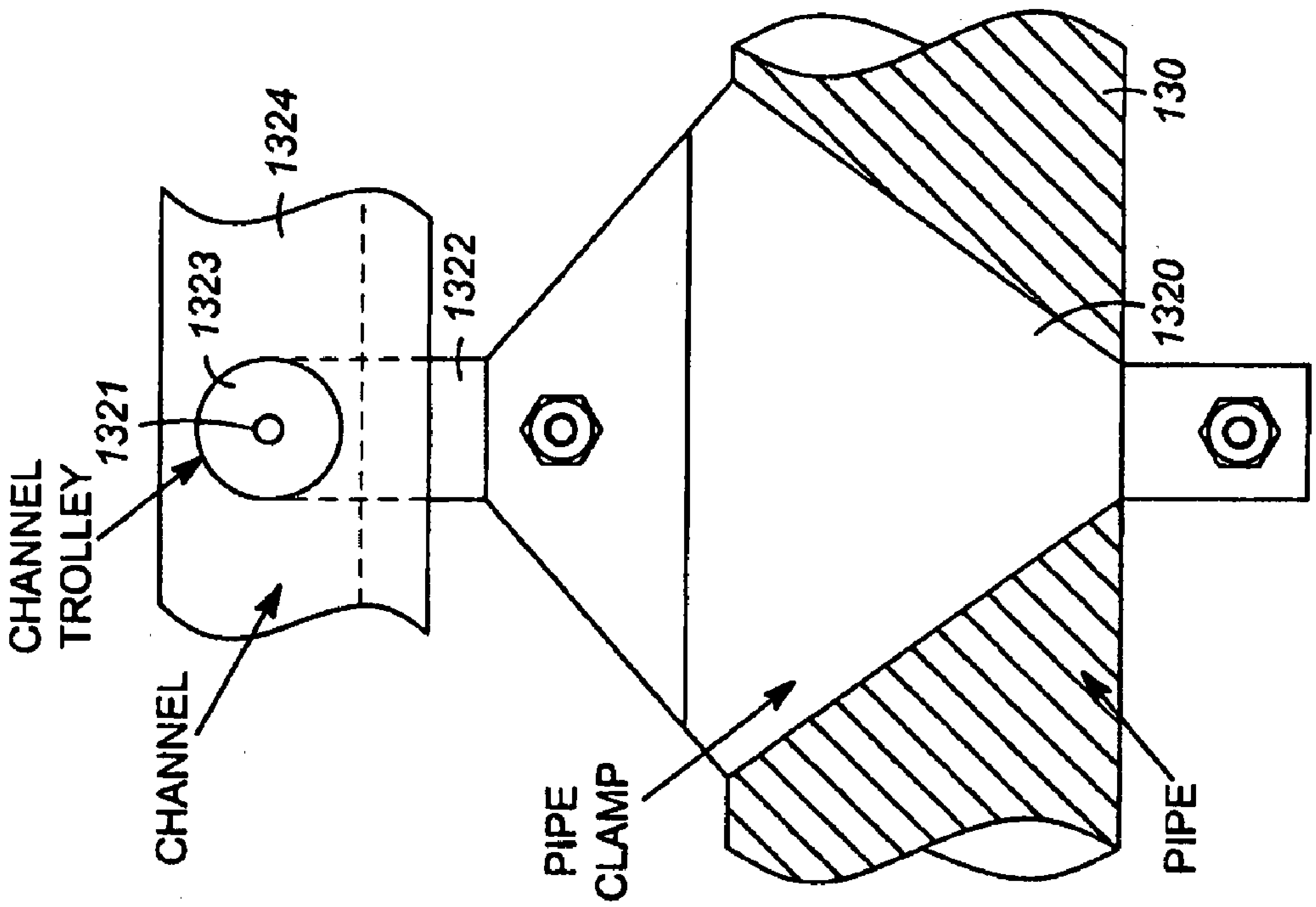


FIG. 31B

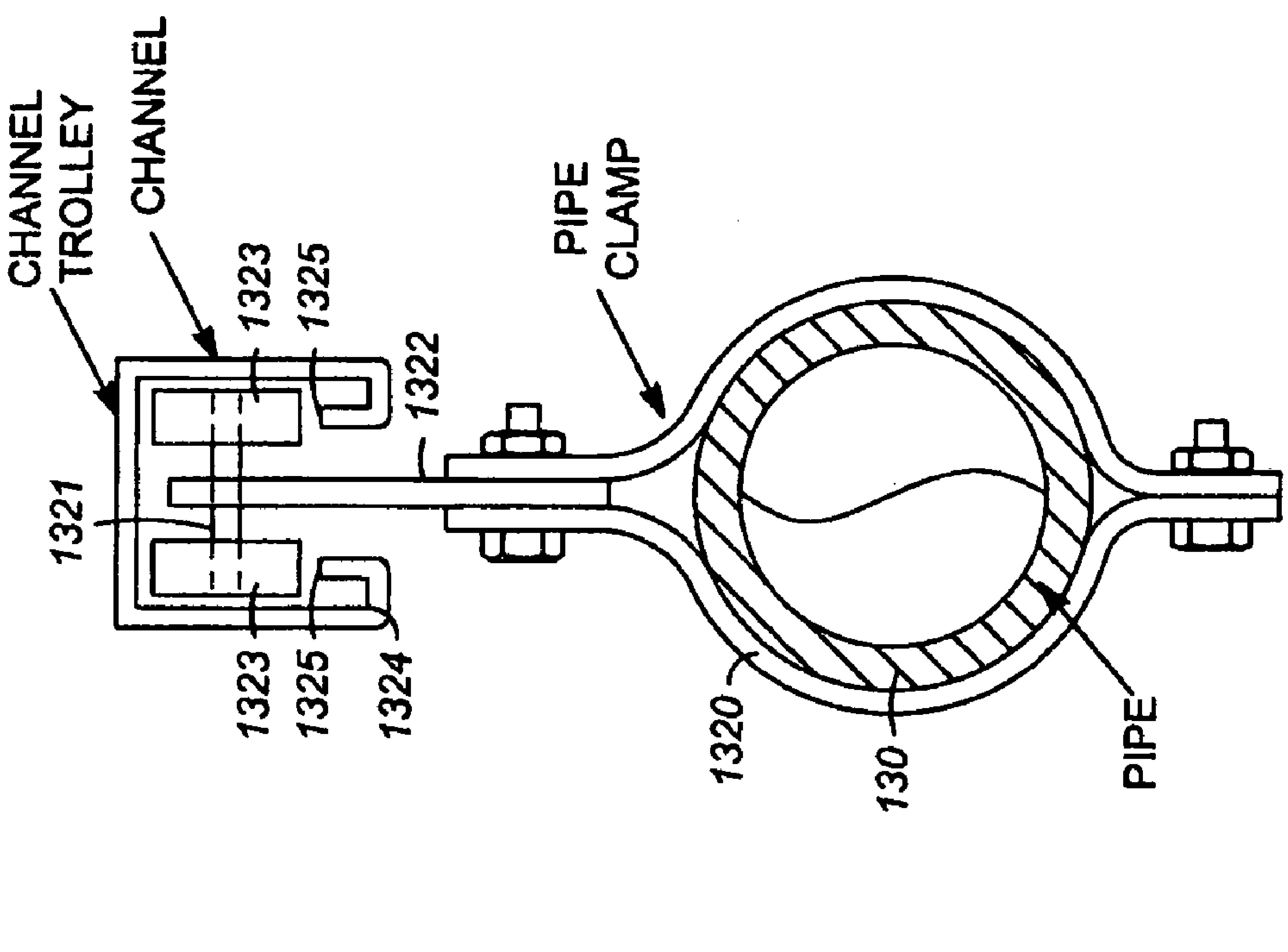


FIG. 31A

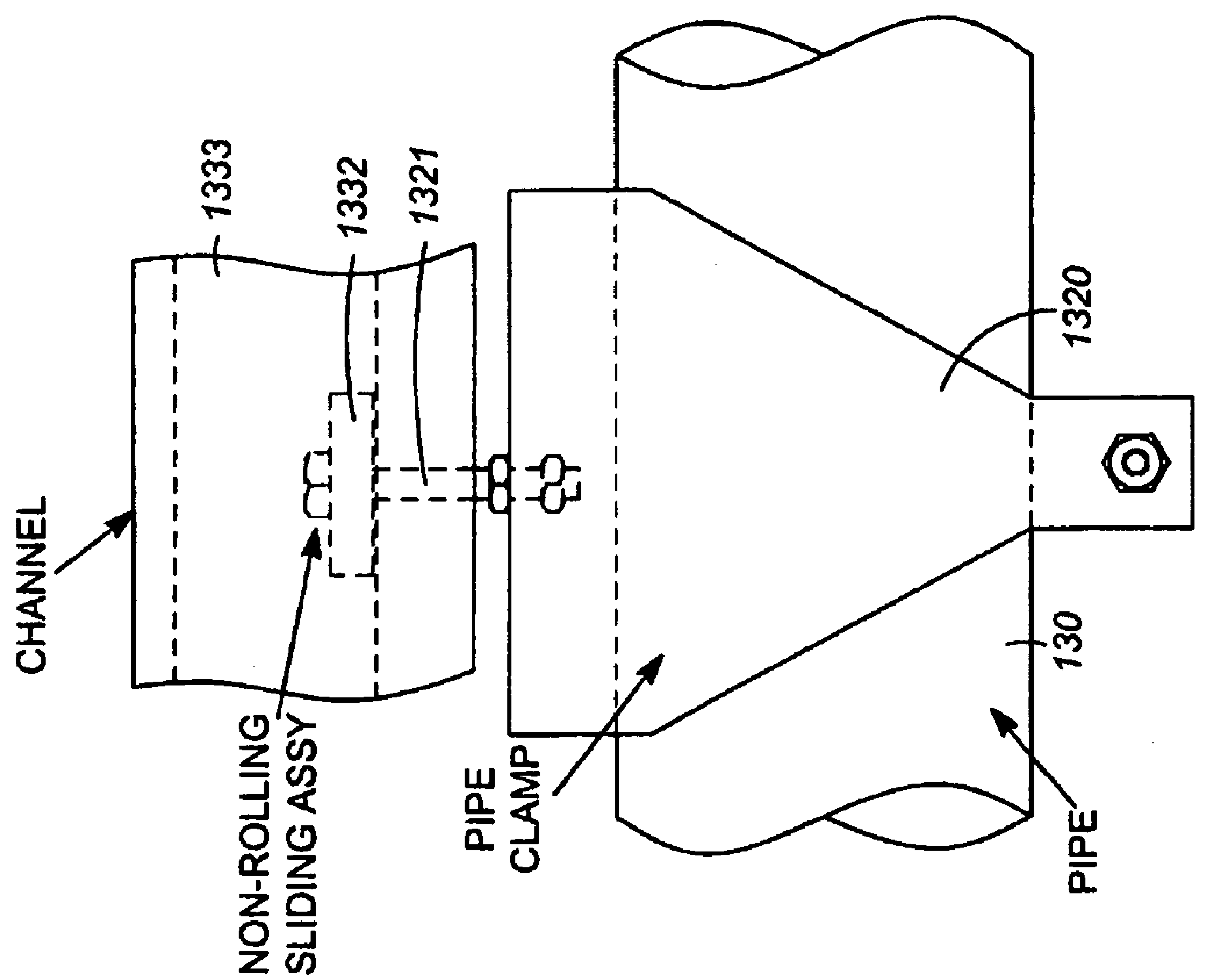


FIG. 32B

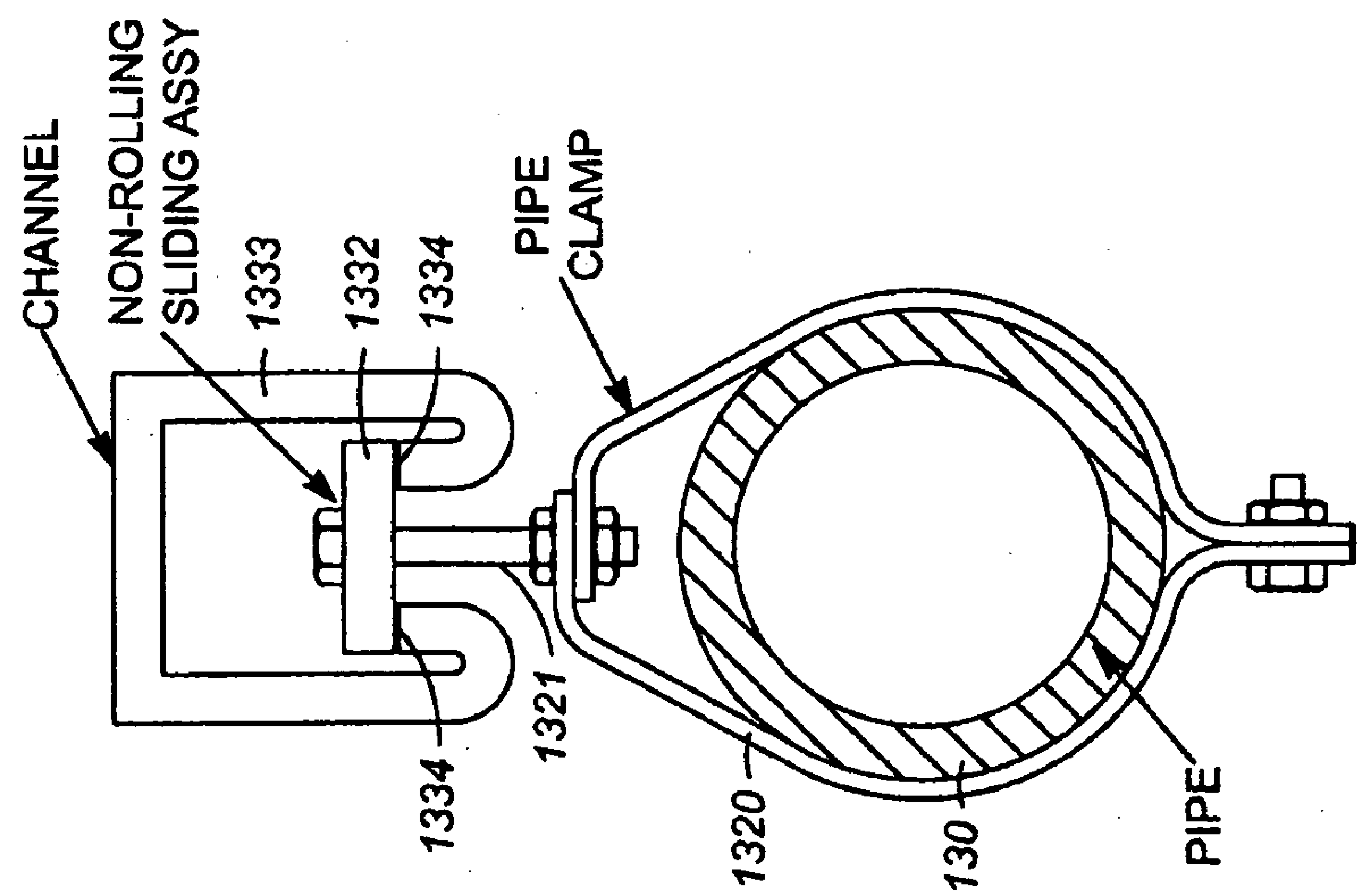


FIG. 32A

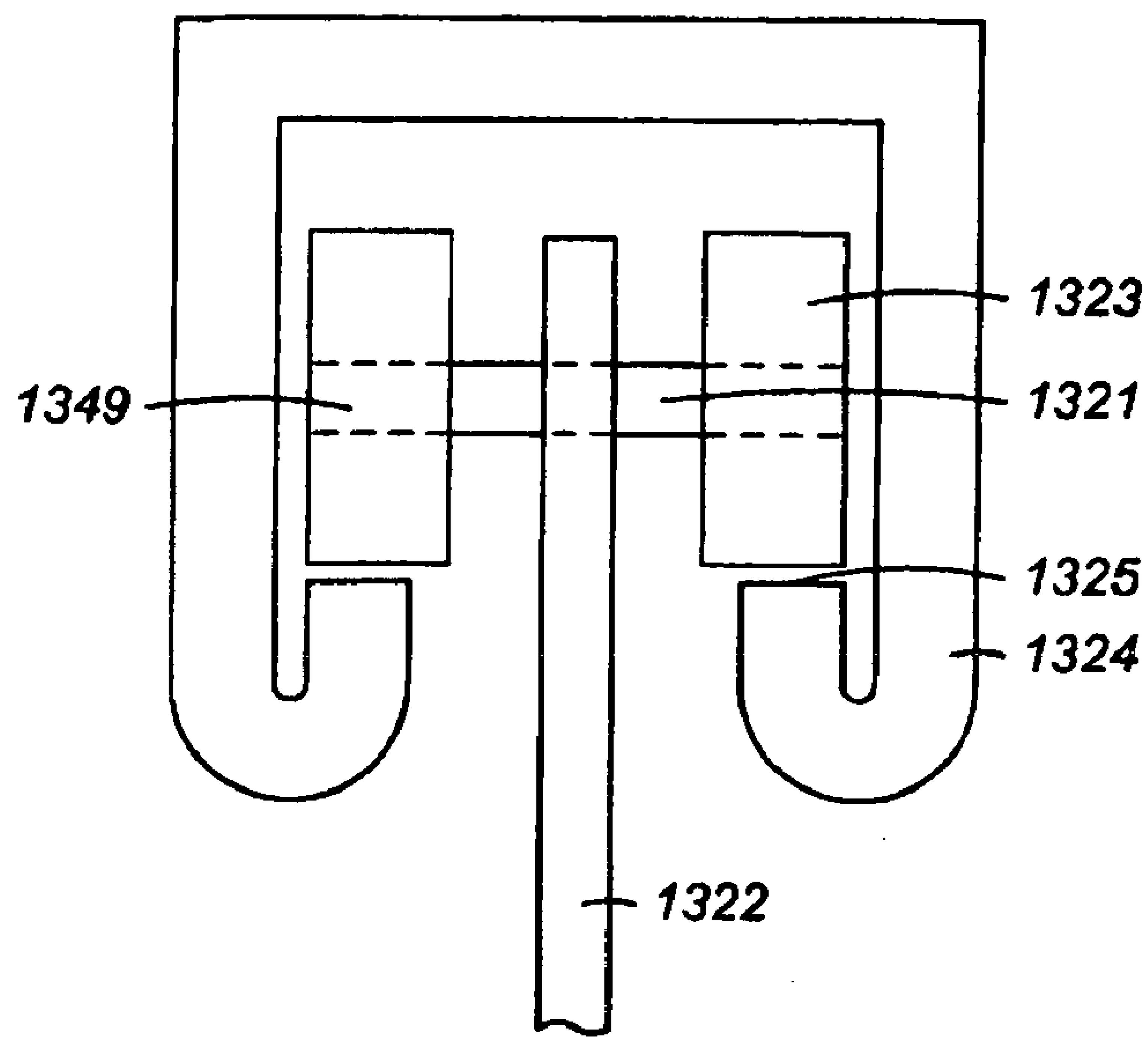


FIG. 33A

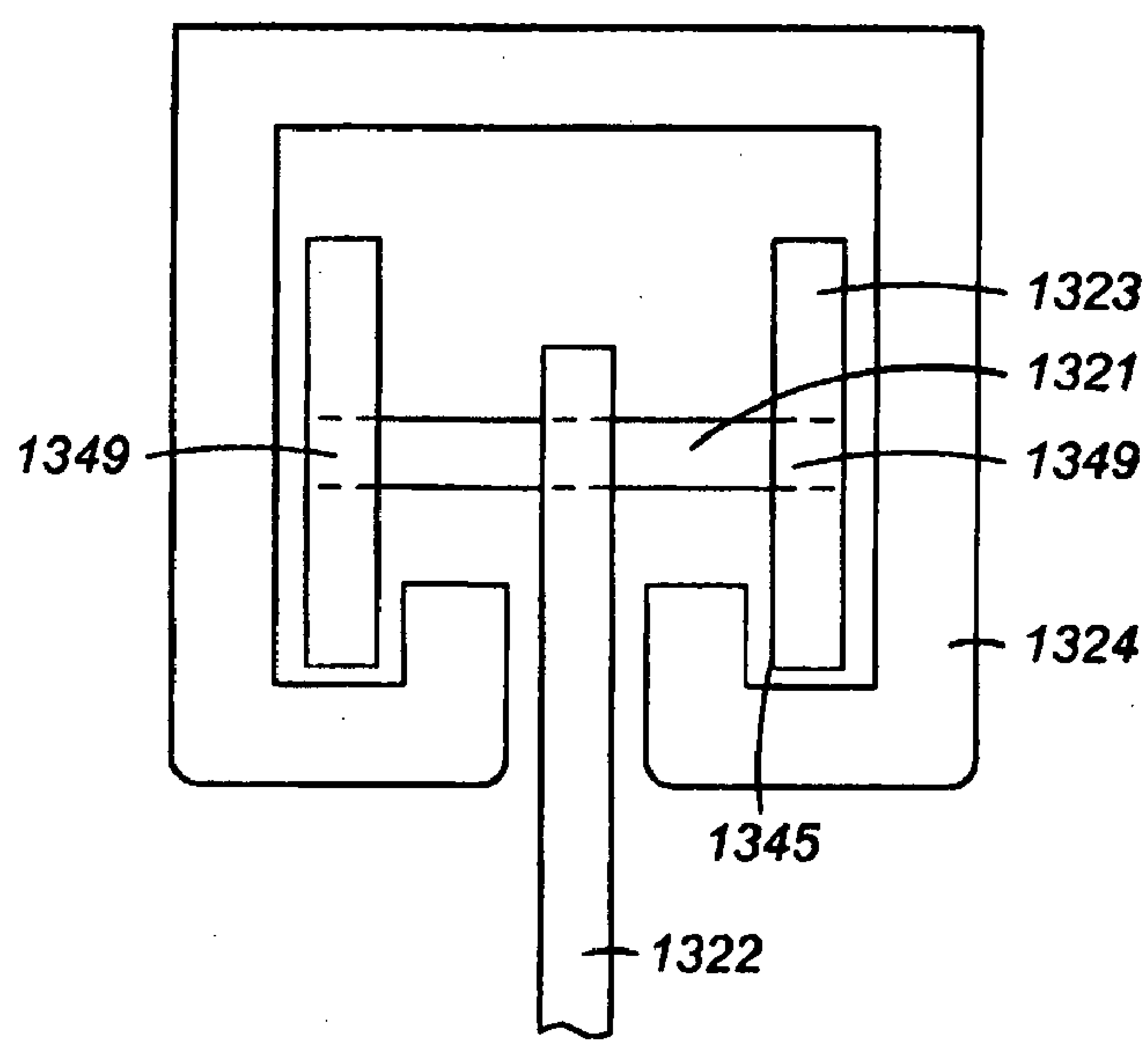


FIG. 33B

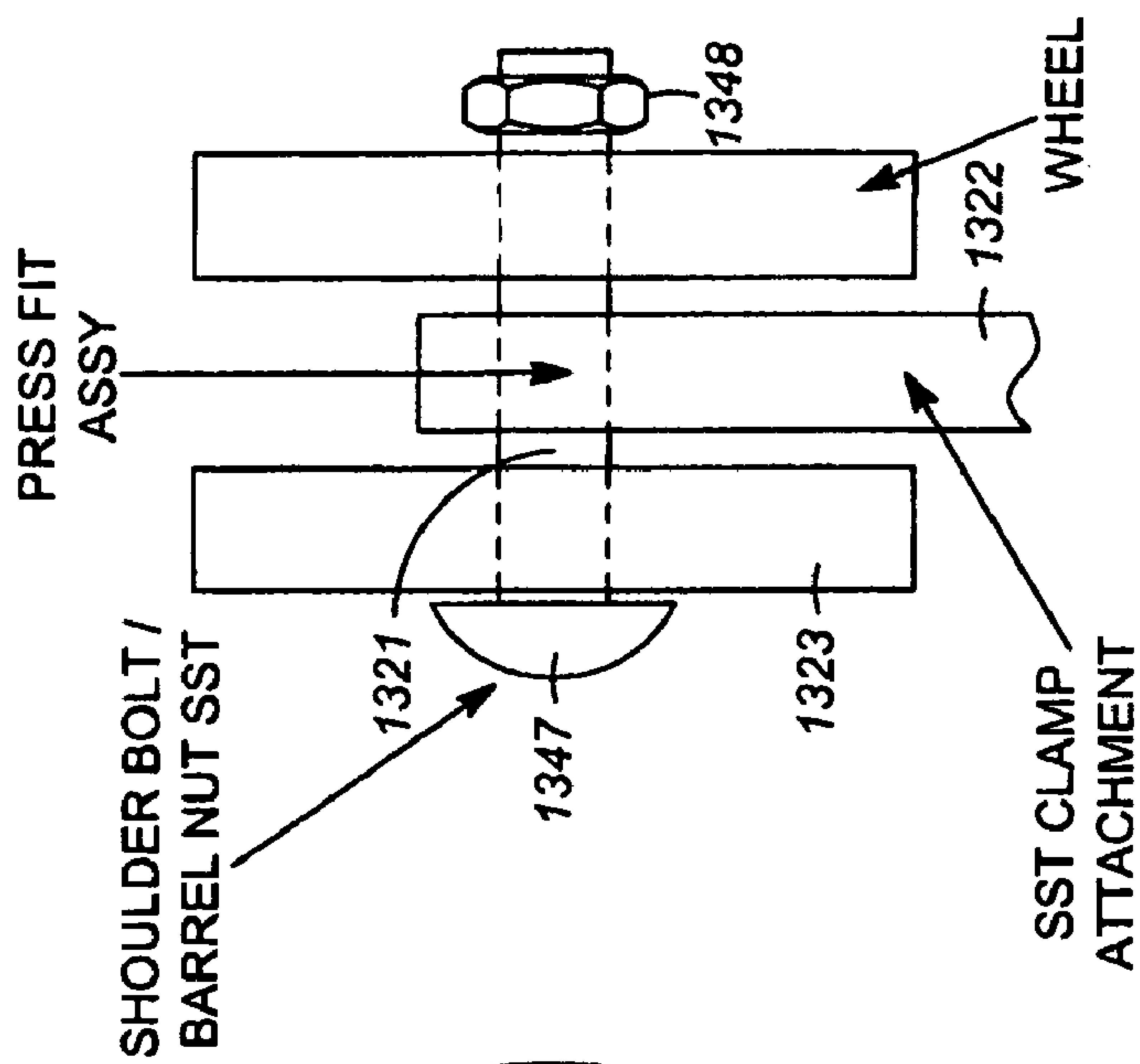


FIG. 33E

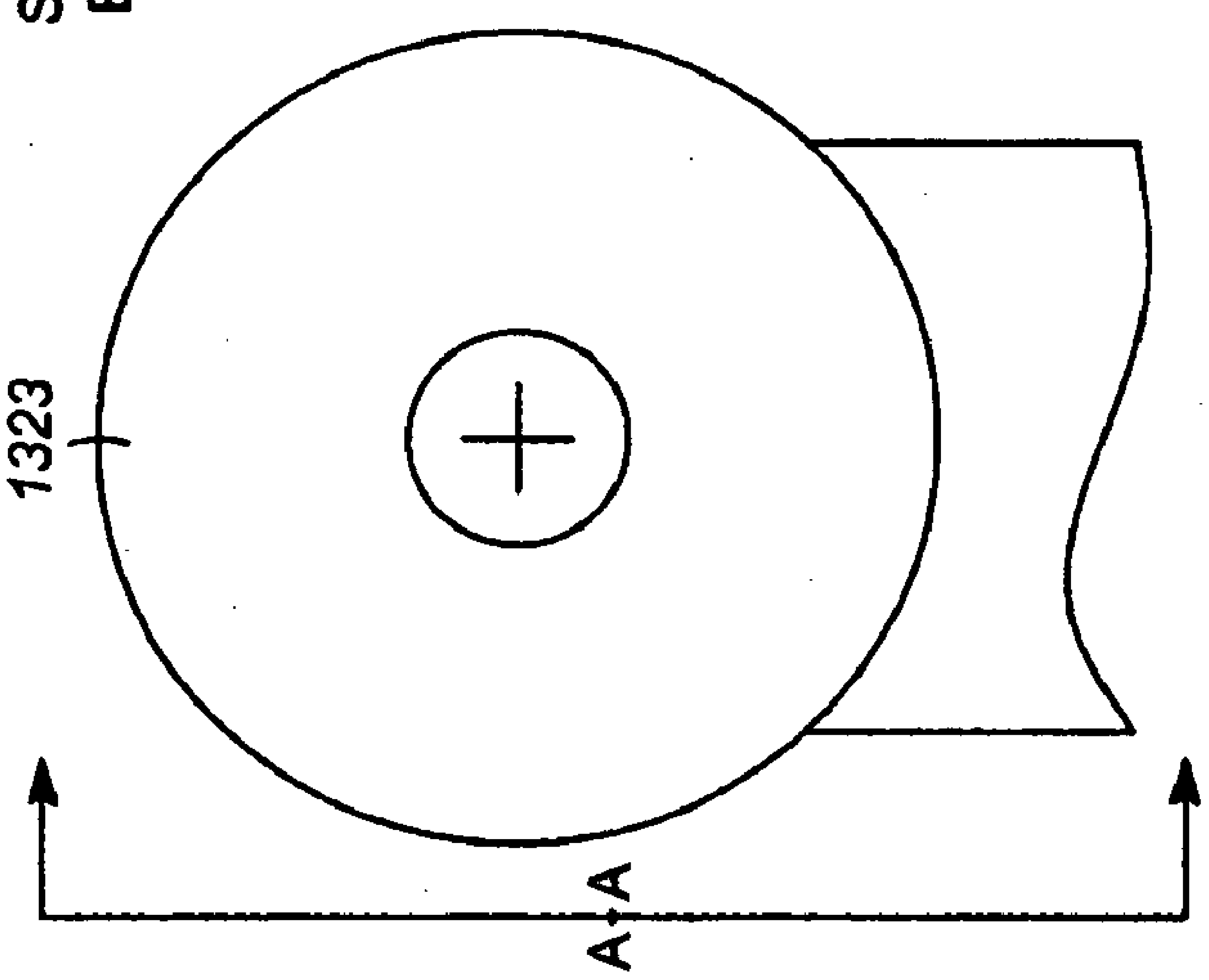


FIG. 33D

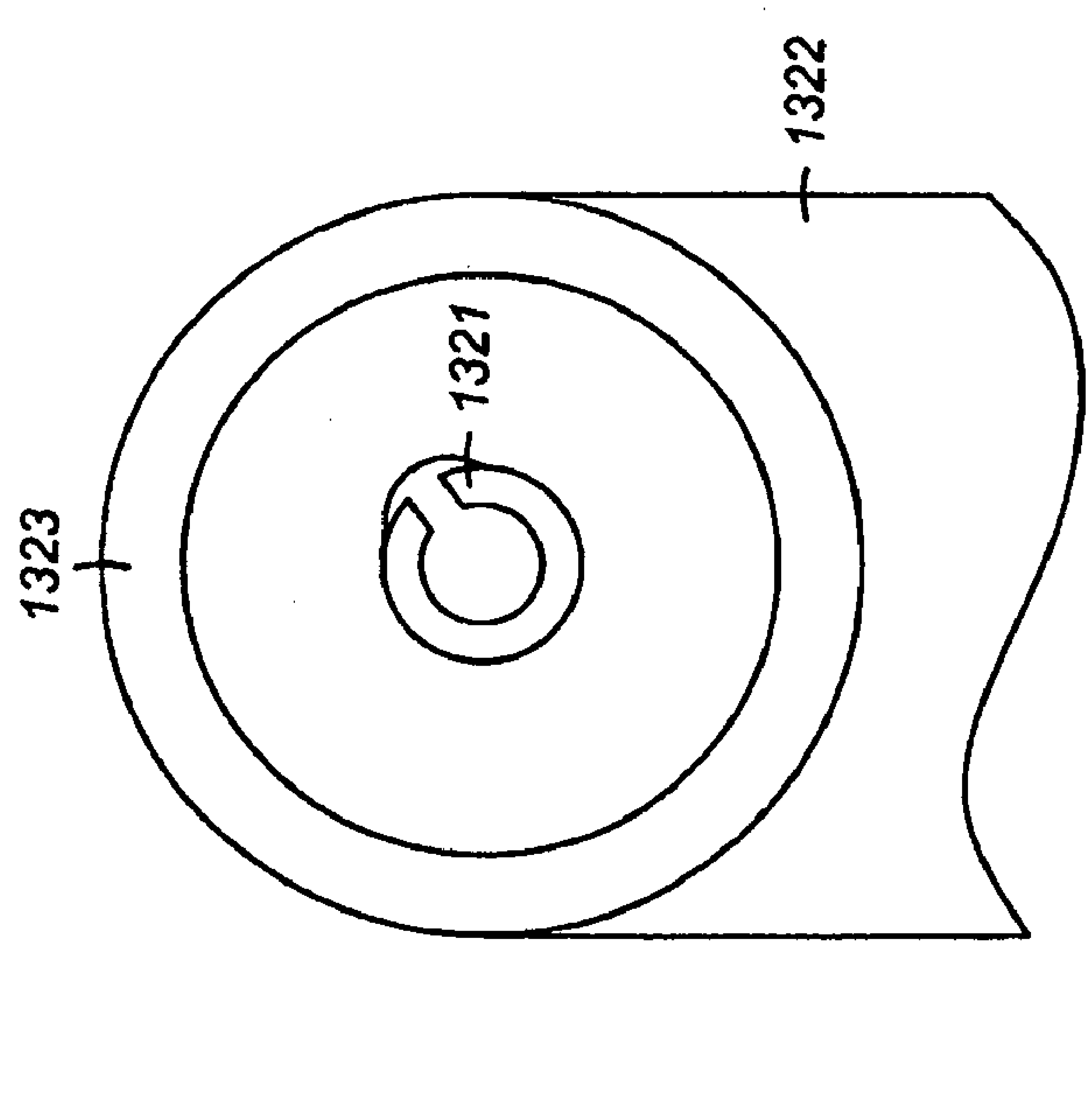
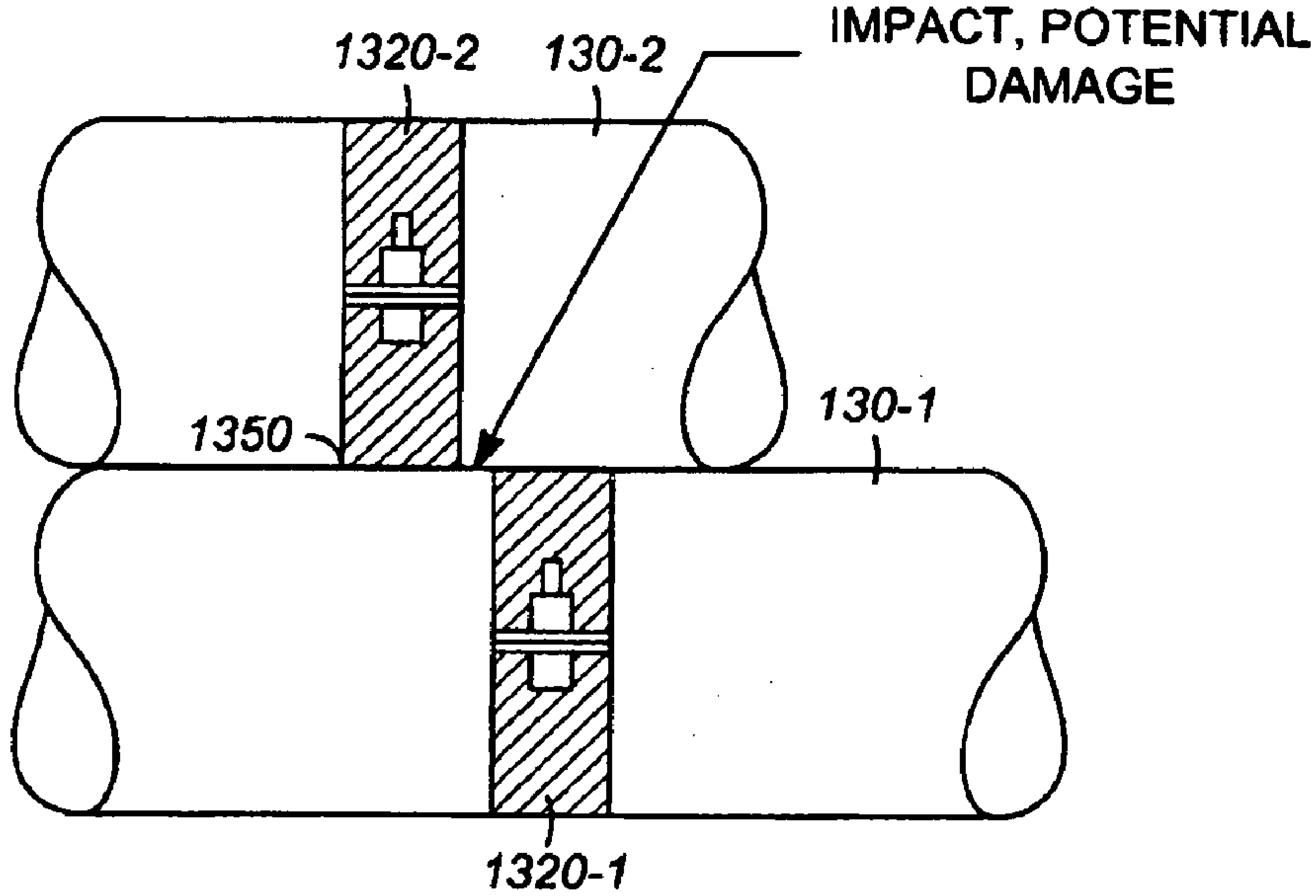
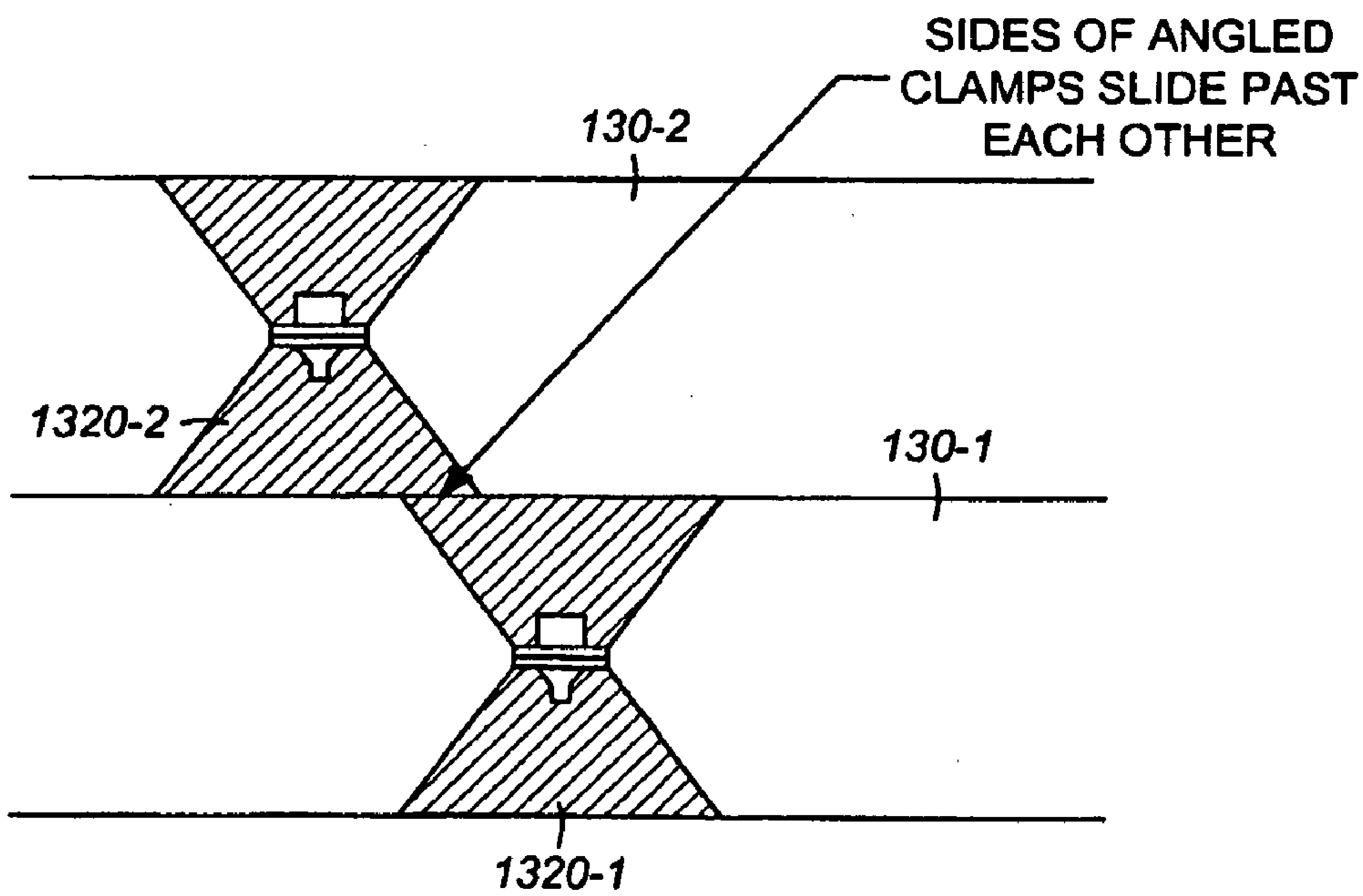


FIG. 33C



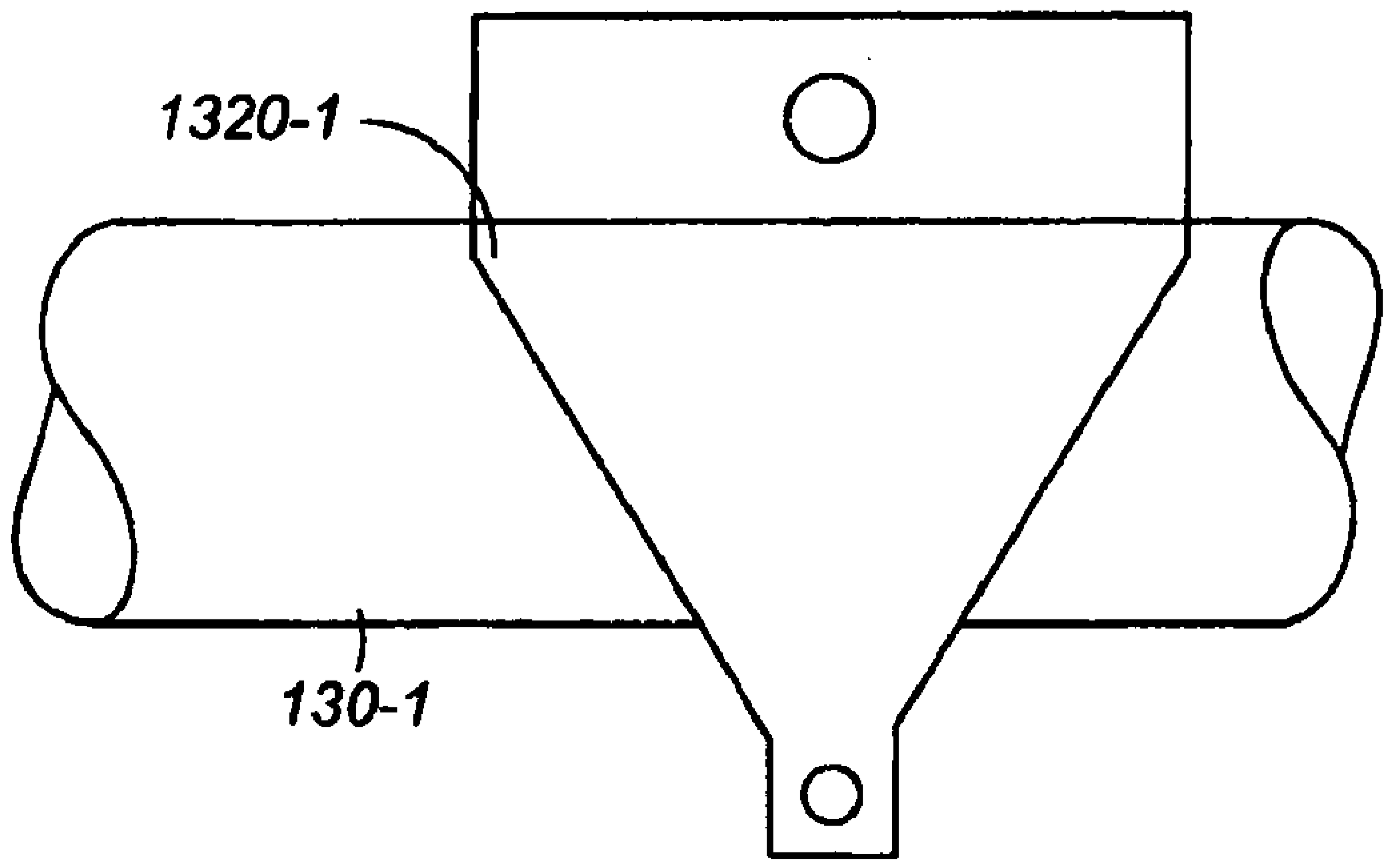
BOTTOM VIEW, HANGING PIPE CLAMPS

FIG. 34A



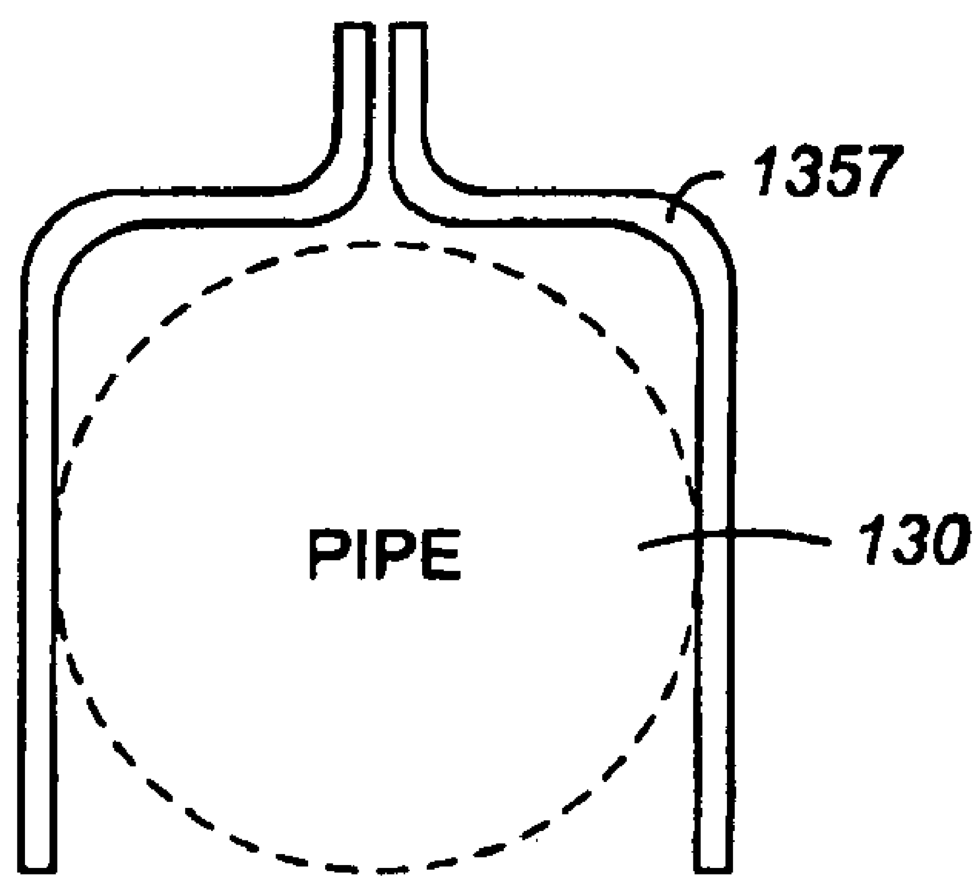
BOTTOM VIEW, ANGLED PIPE CLAMPS

FIG. 34B



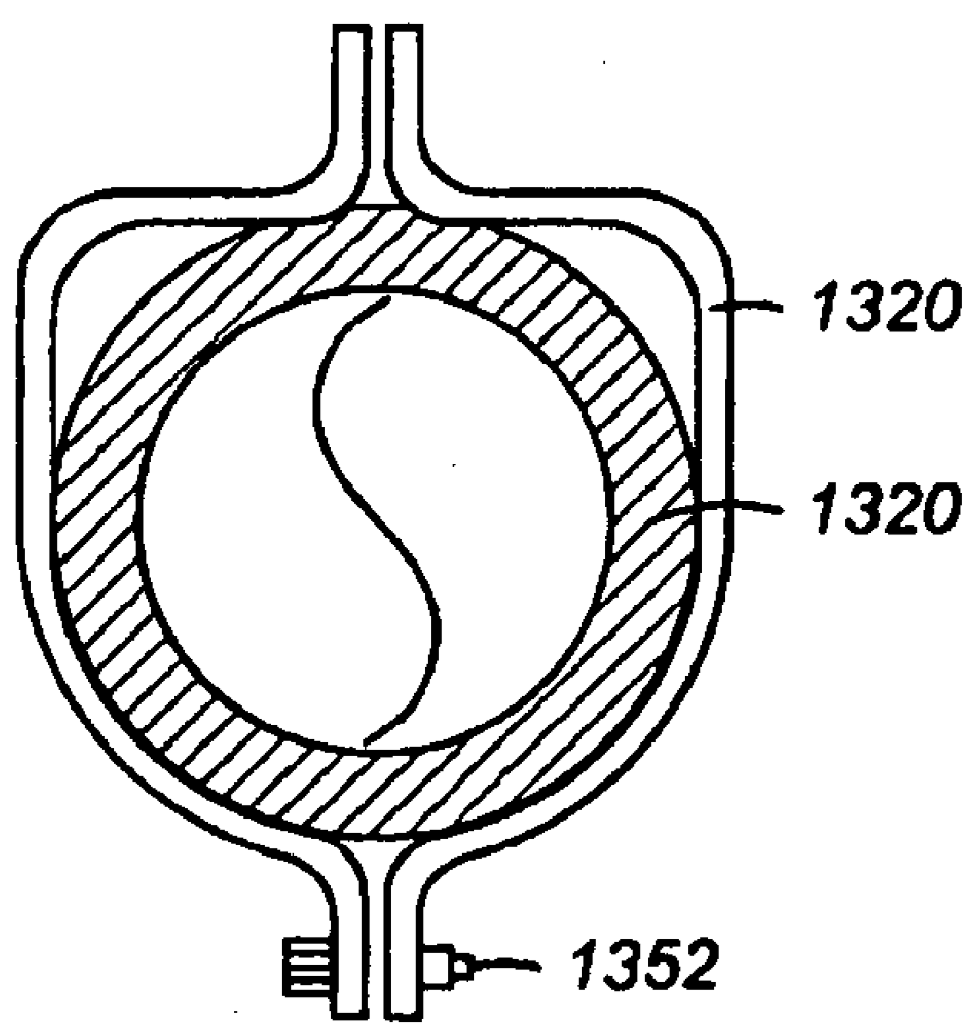
ANGLE CLAMP SIDE VIEW

FIG. 34C



ANGLE CLAMP FRONT VIEW
PRIOR TO INSTALLATION ON TUBE

FIG. 34D



ANGLE CLAMP FRONT VIEW,
AFTER TIGHTENING ONTO TUBE

FIG. 34E

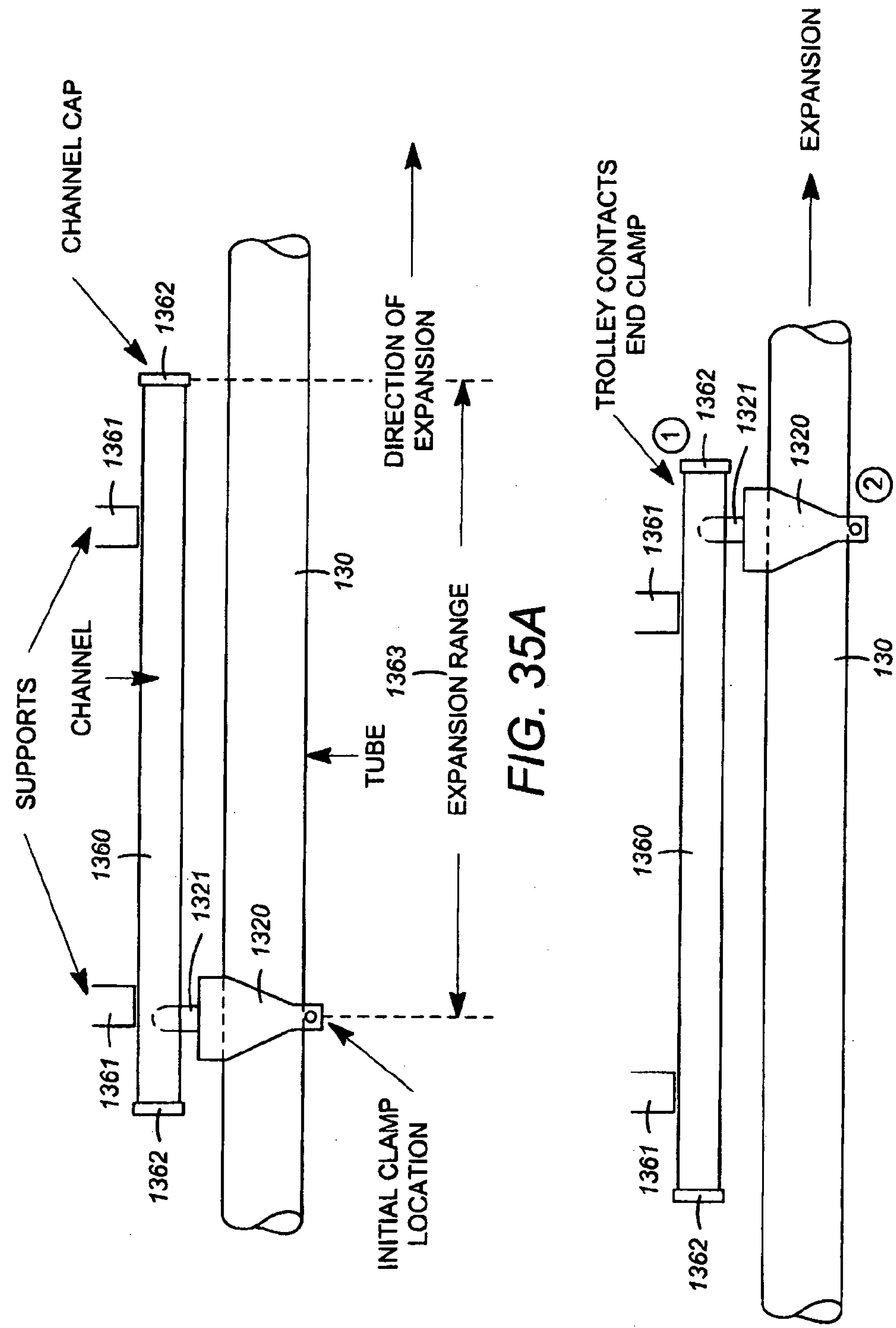
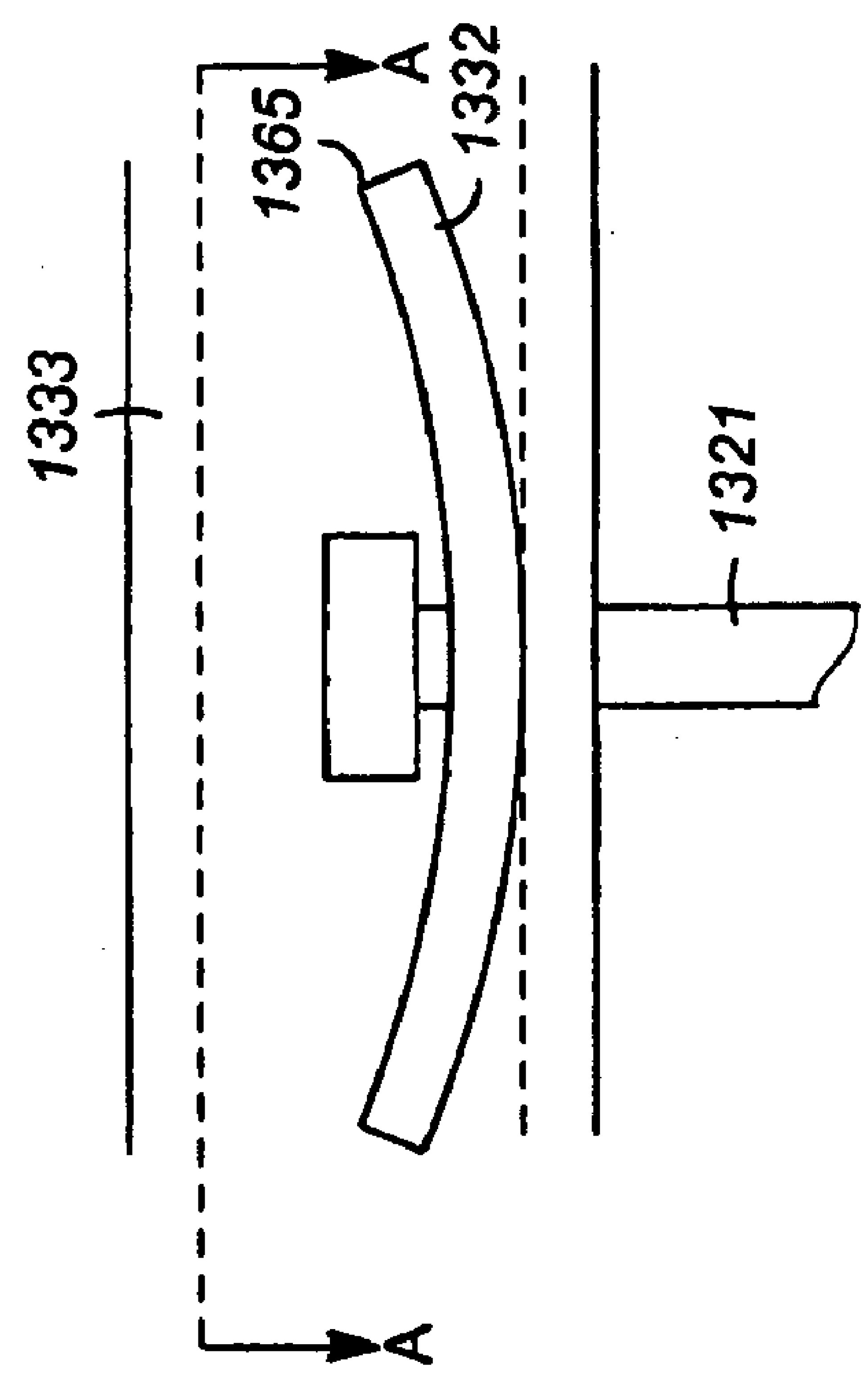


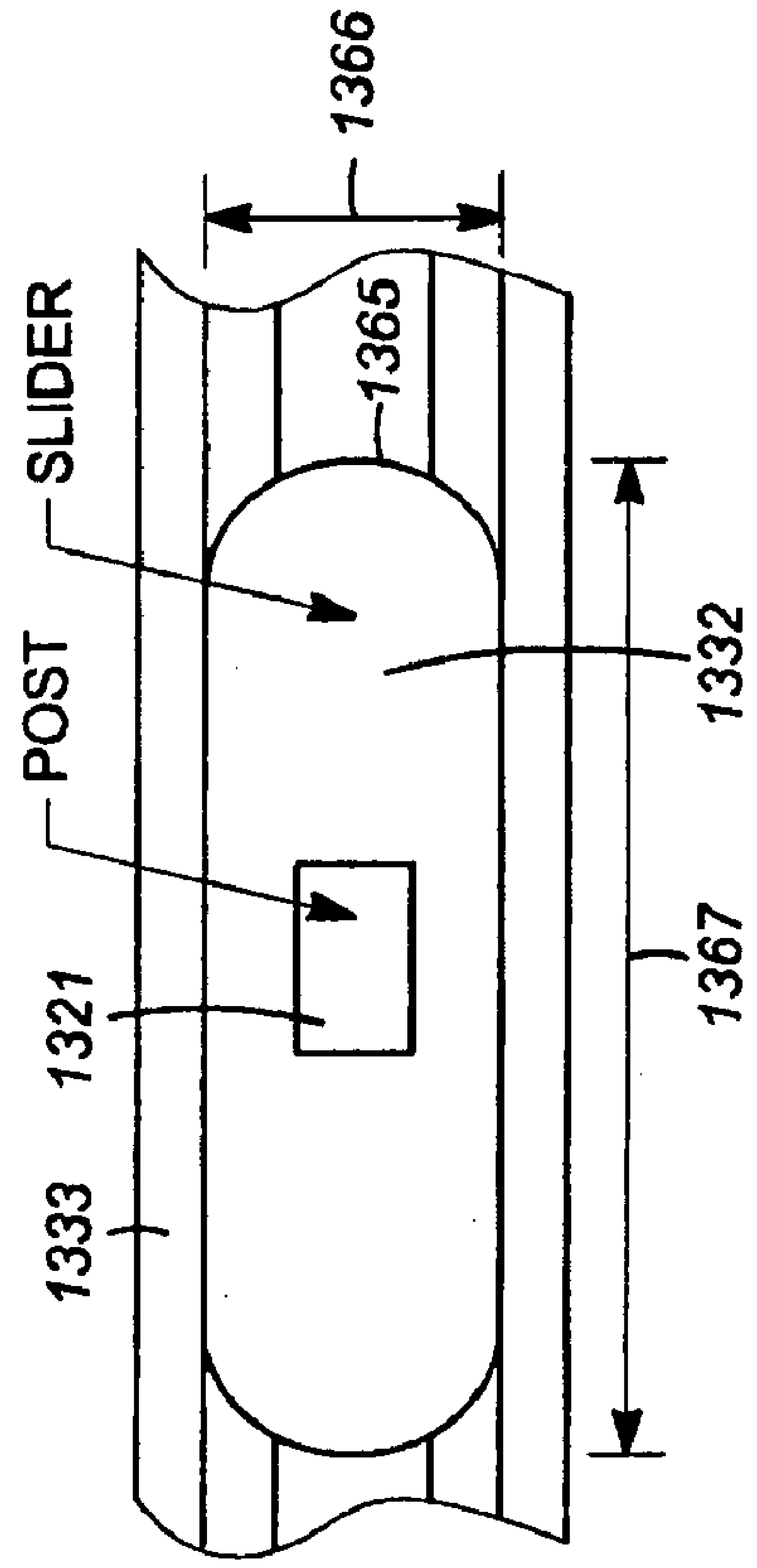
FIG. 35A

FIG. 35B



SECTION VIEW

FIG. 36A



TOP VIEW A-A

FIG. 36B

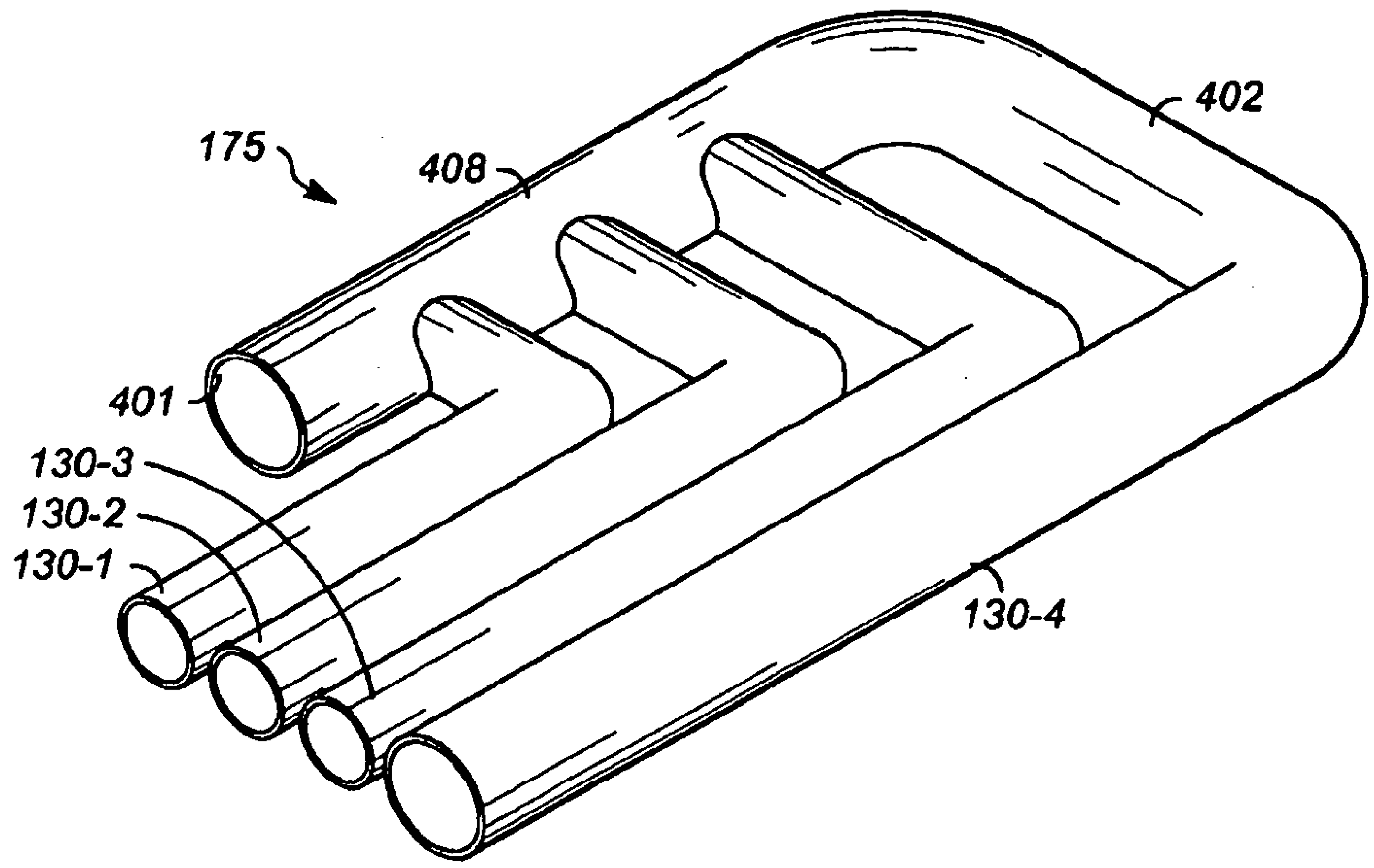


FIG. 37A

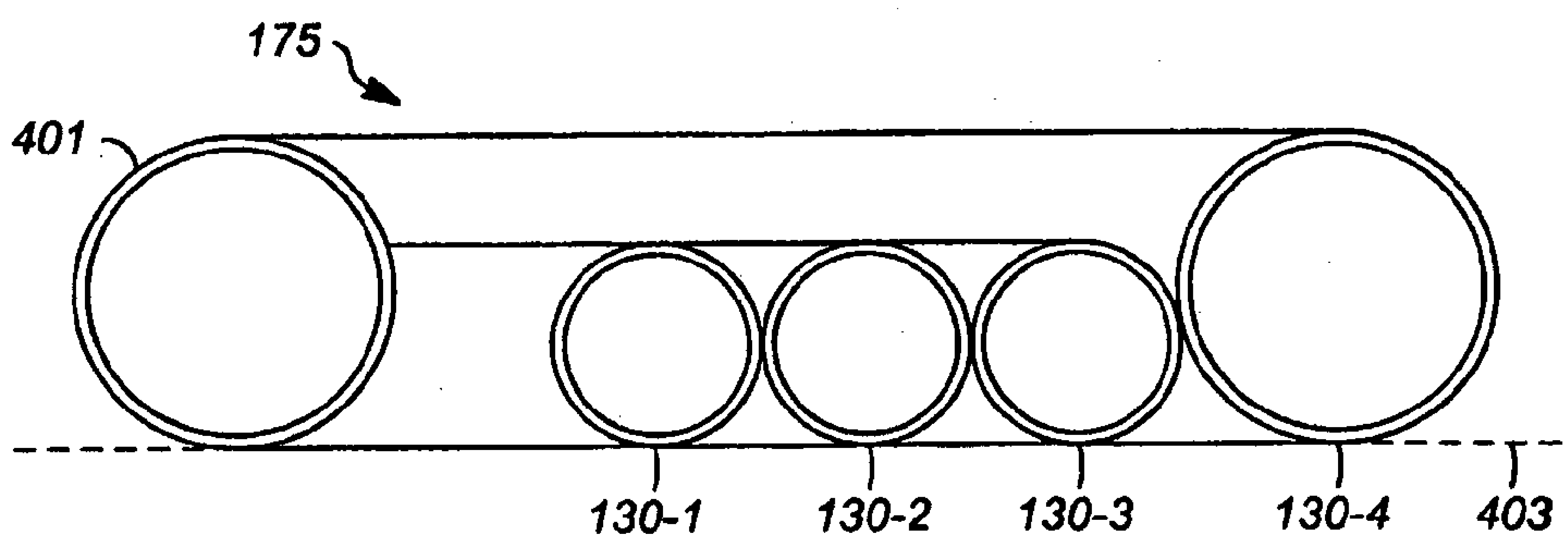


FIG. 37B

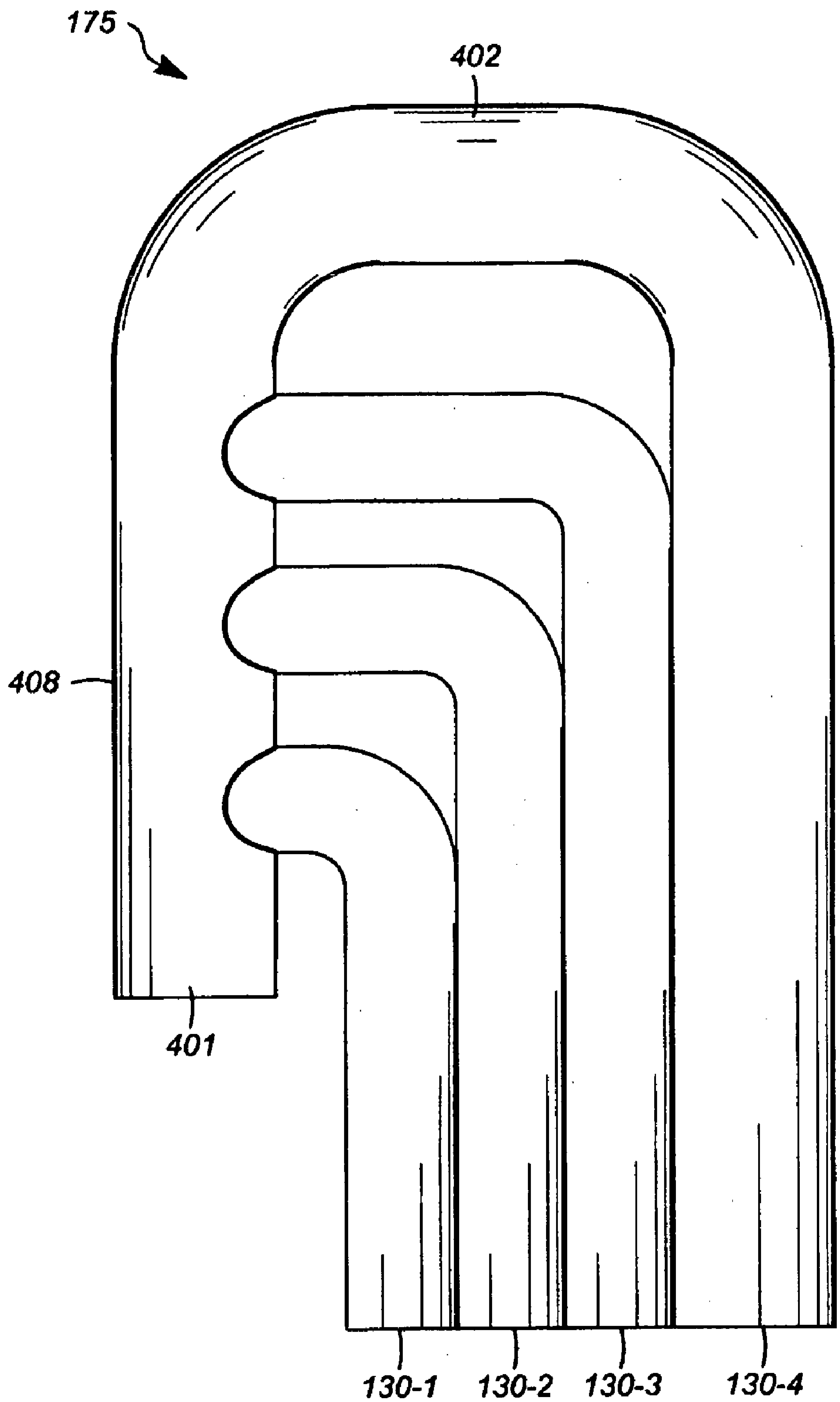


FIG. 37C

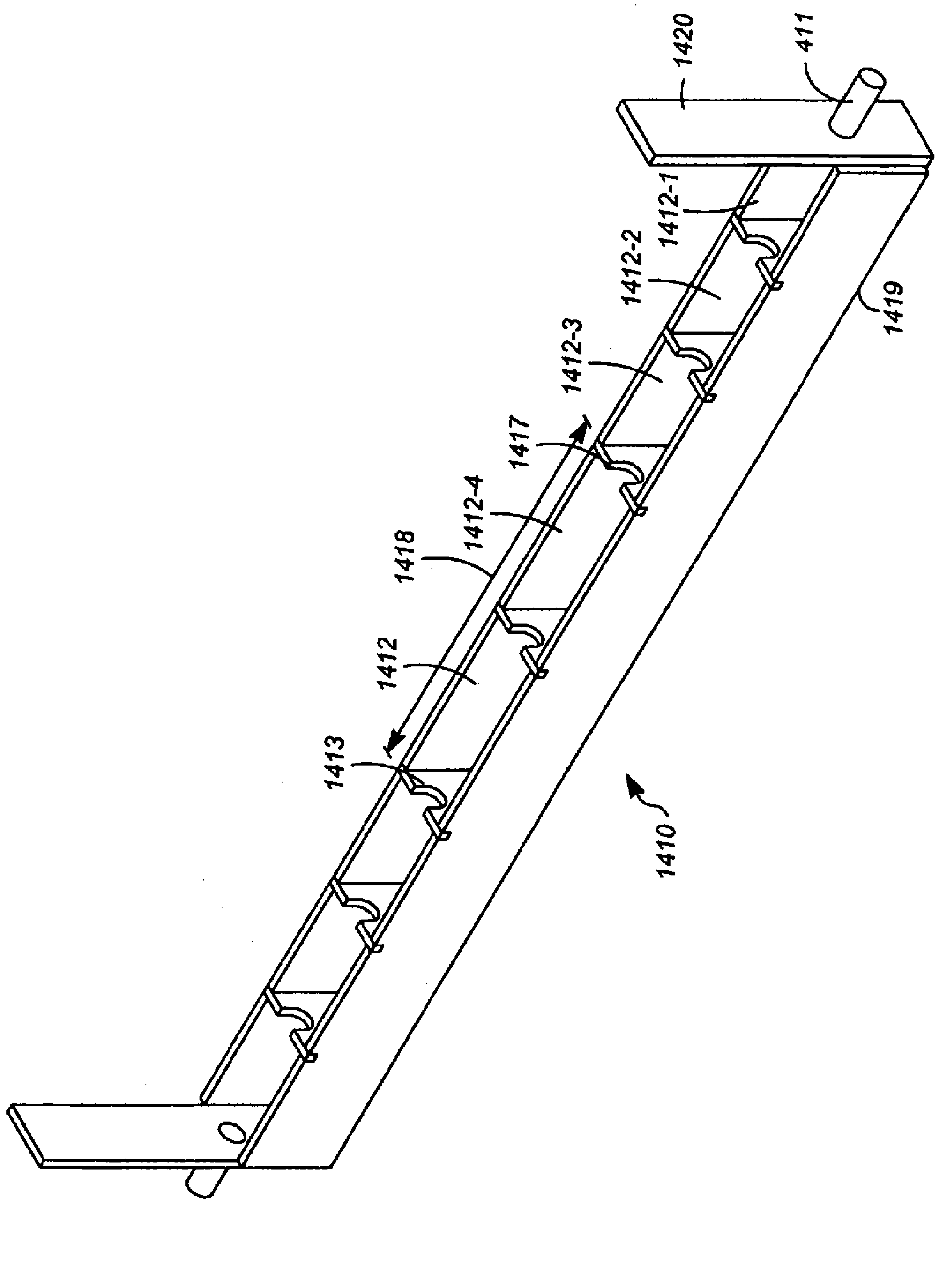

1420
411
1412-1
1412-2
1419
1412-3
1417
1412-4
1418
1412
1413
1410

FIG. 38A

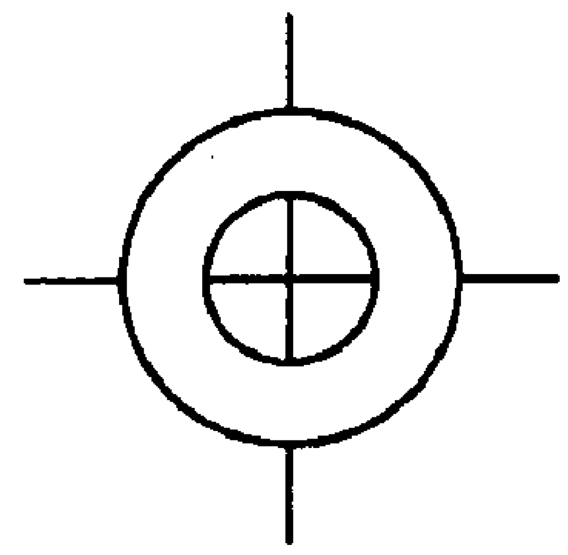


FIG. 38BB

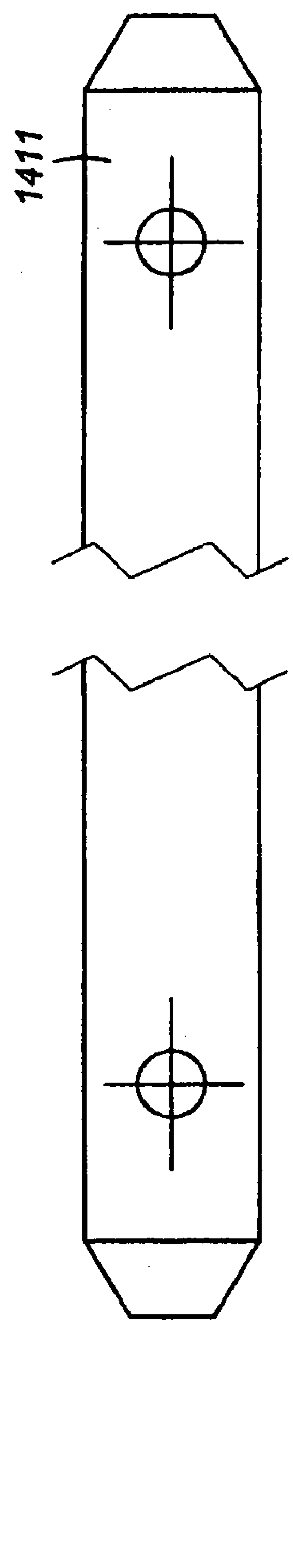


FIG. 38BA

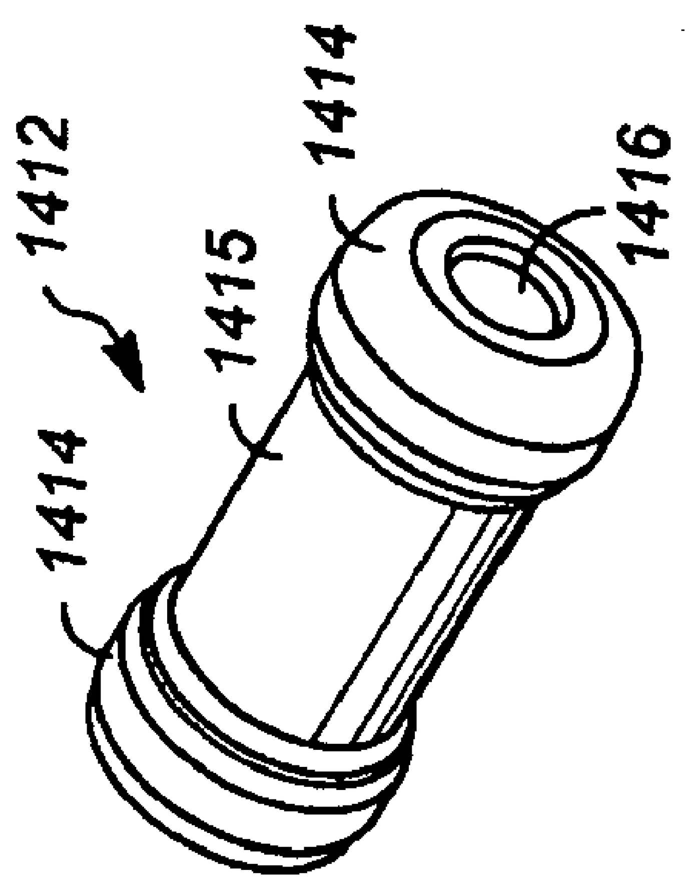


FIG. 38CC

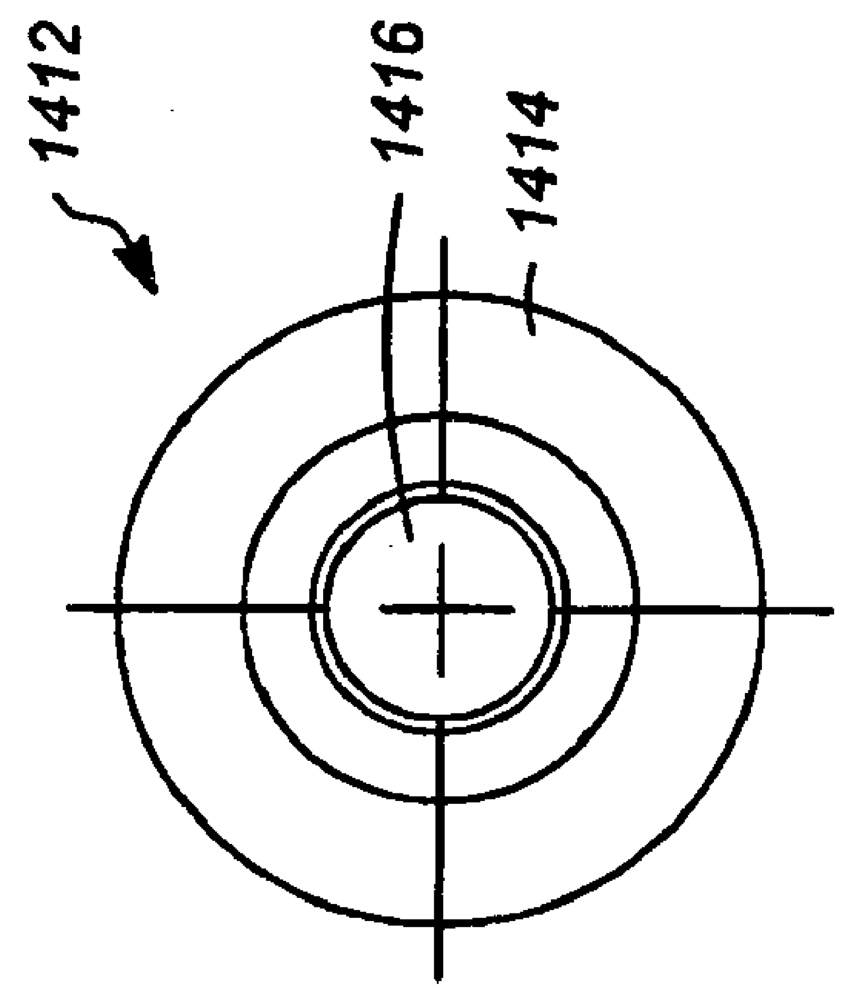


FIG. 38CB

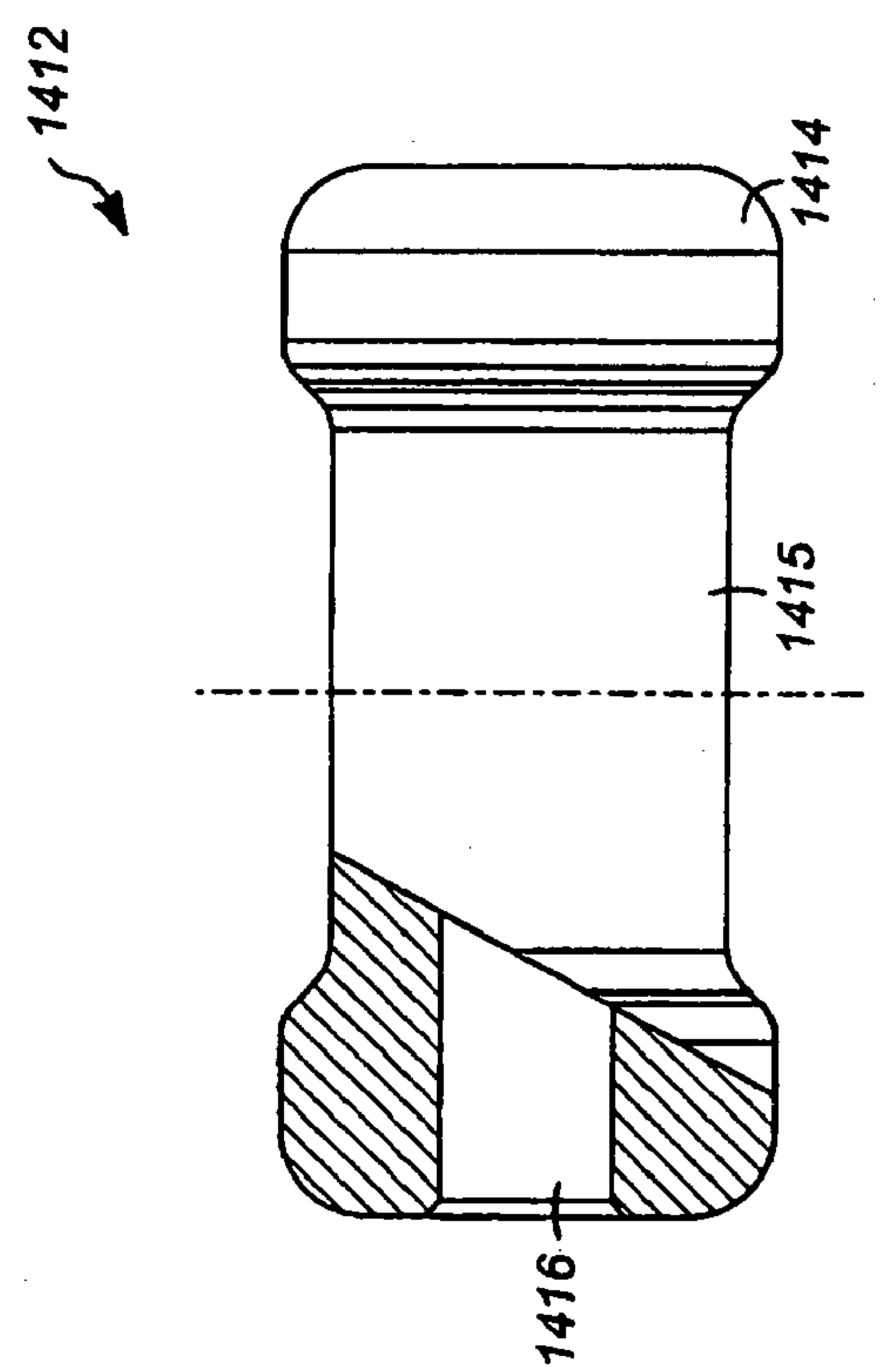


FIG. 38CA

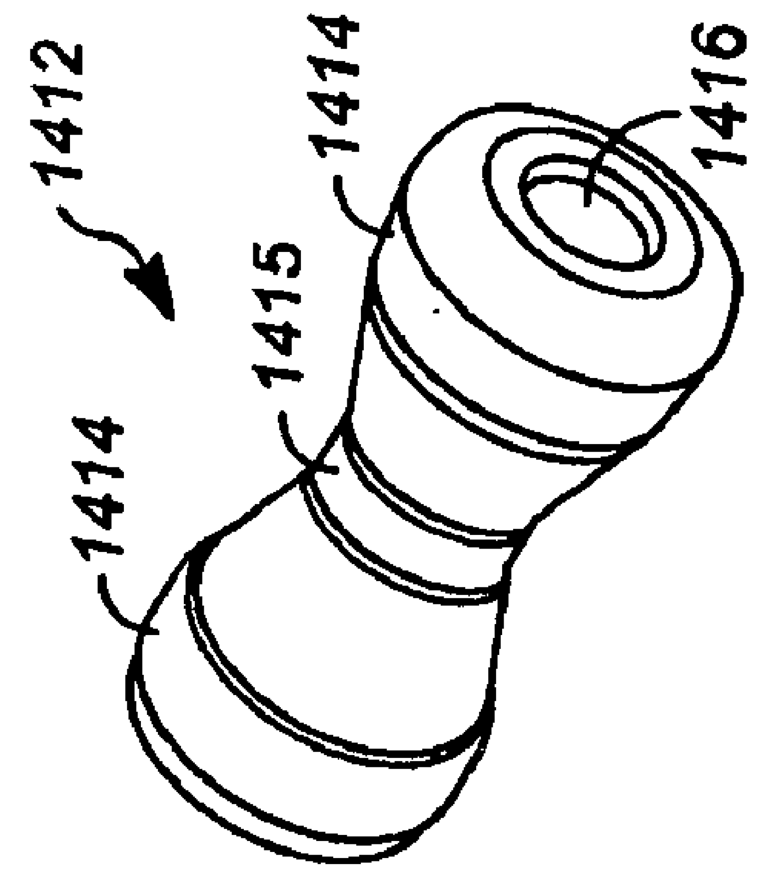


FIG. 38DC

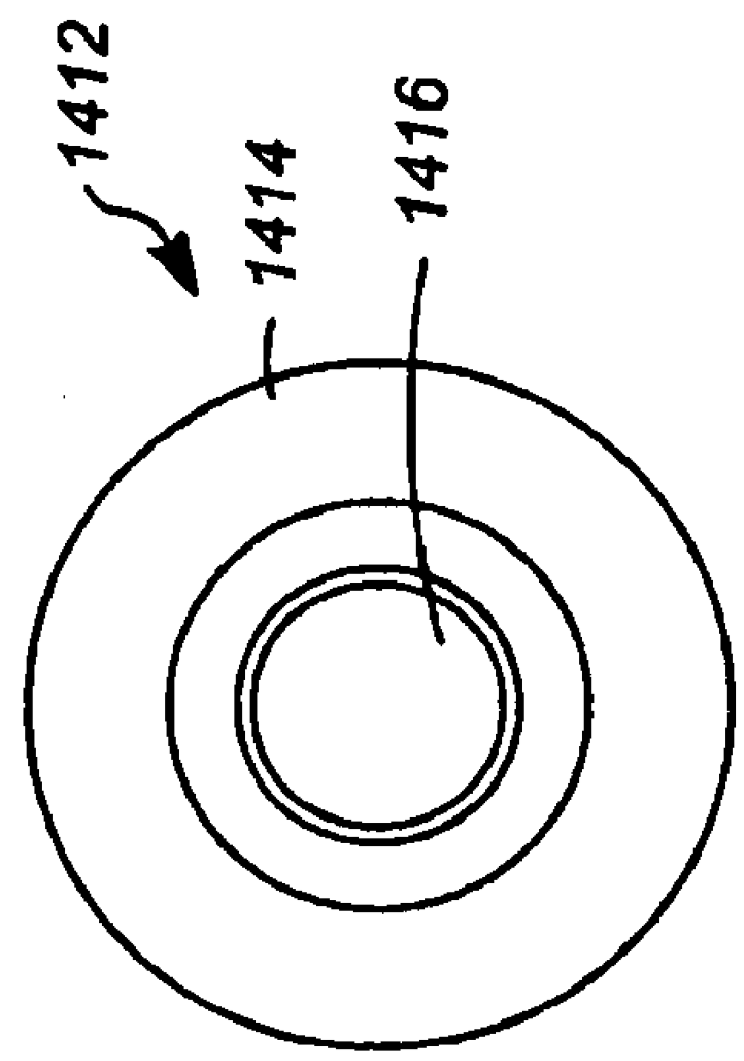


FIG. 38DB

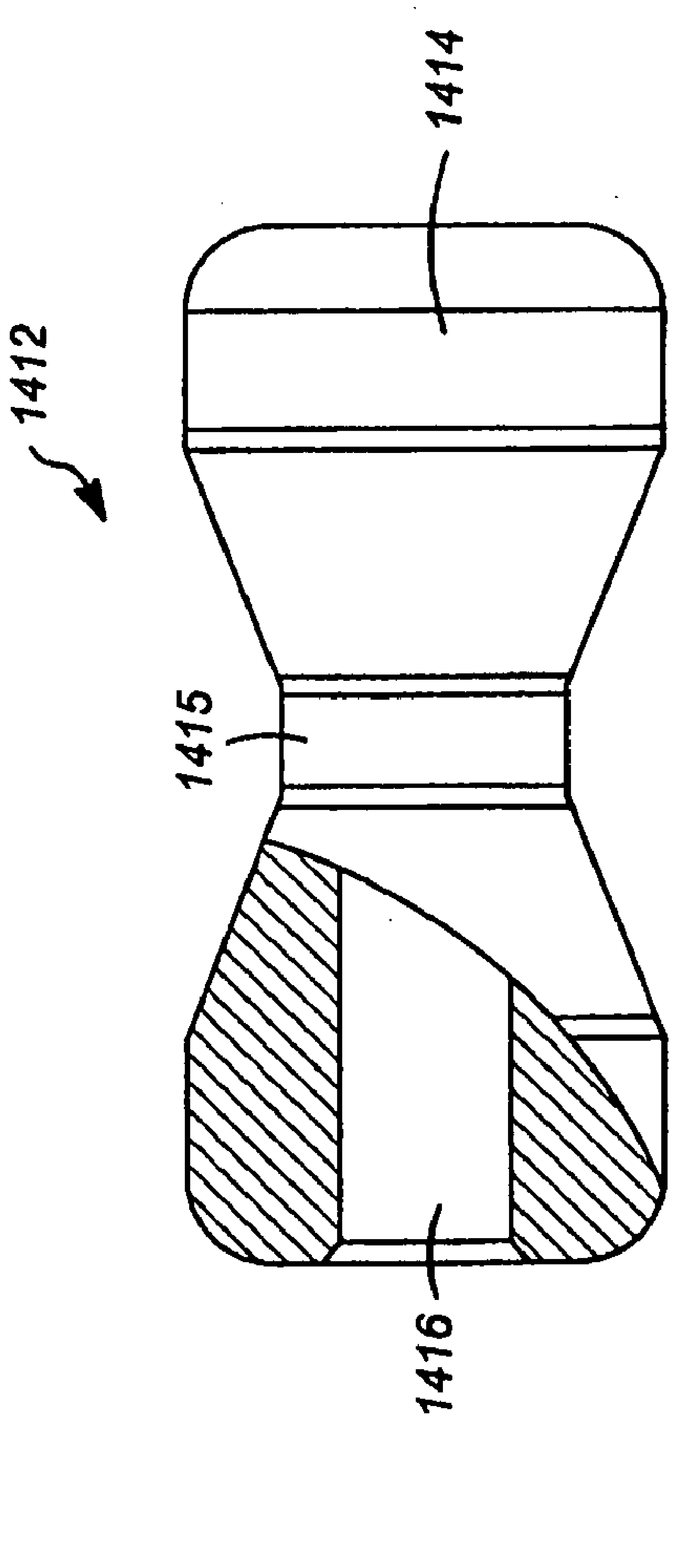


FIG. 38DA

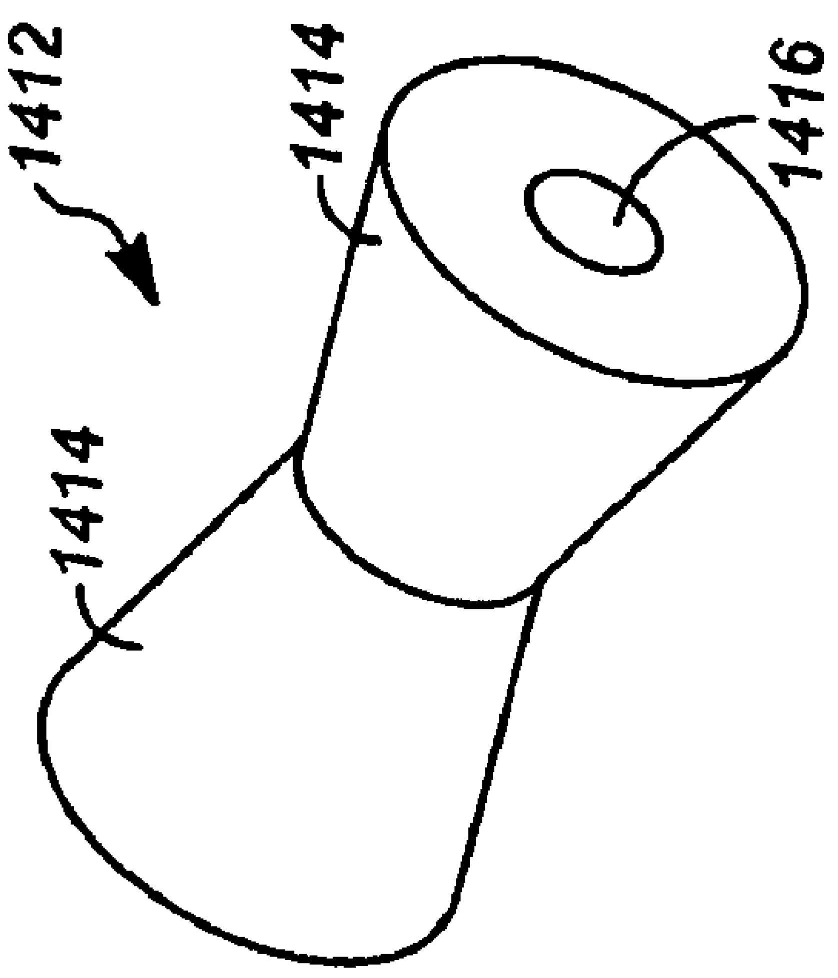


FIG. 38EC

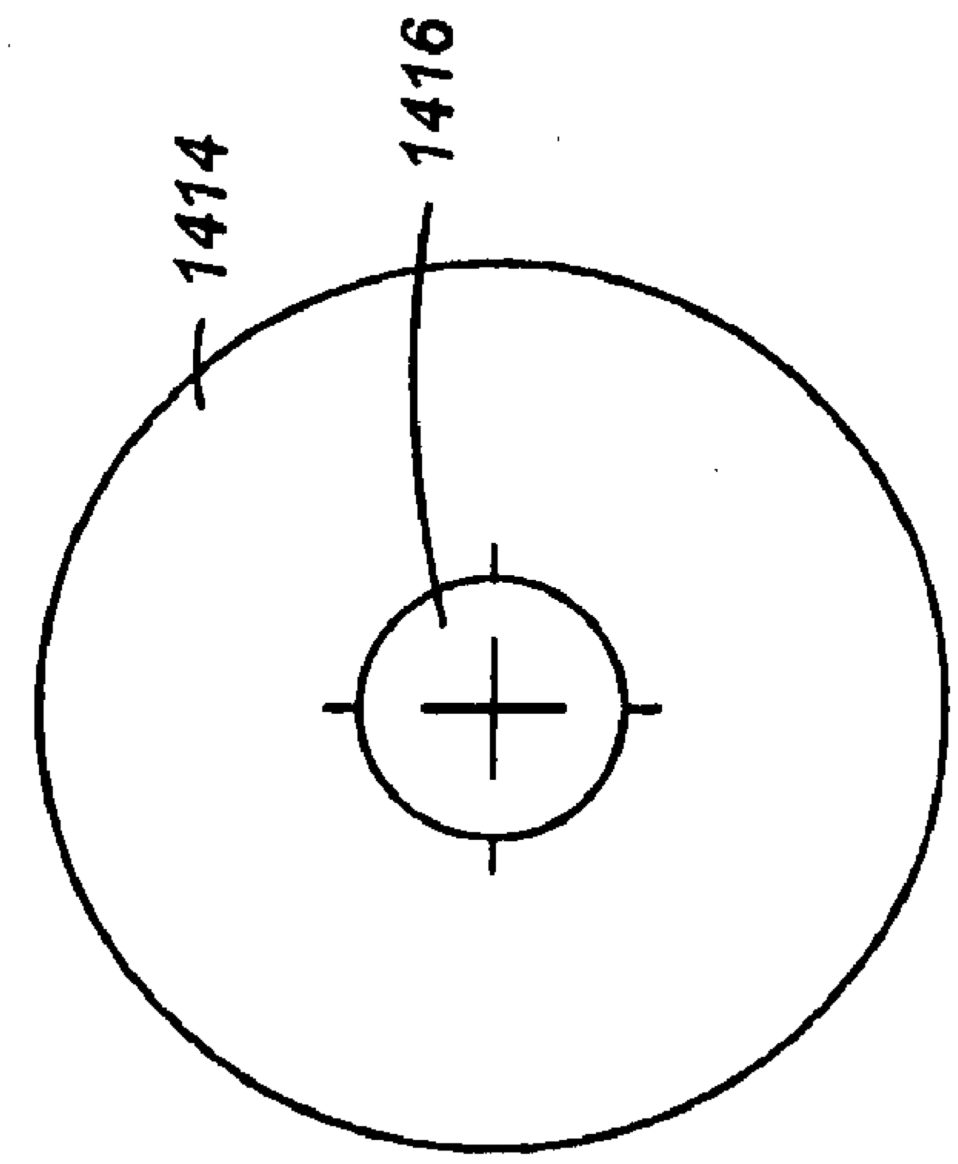


FIG. 38EB

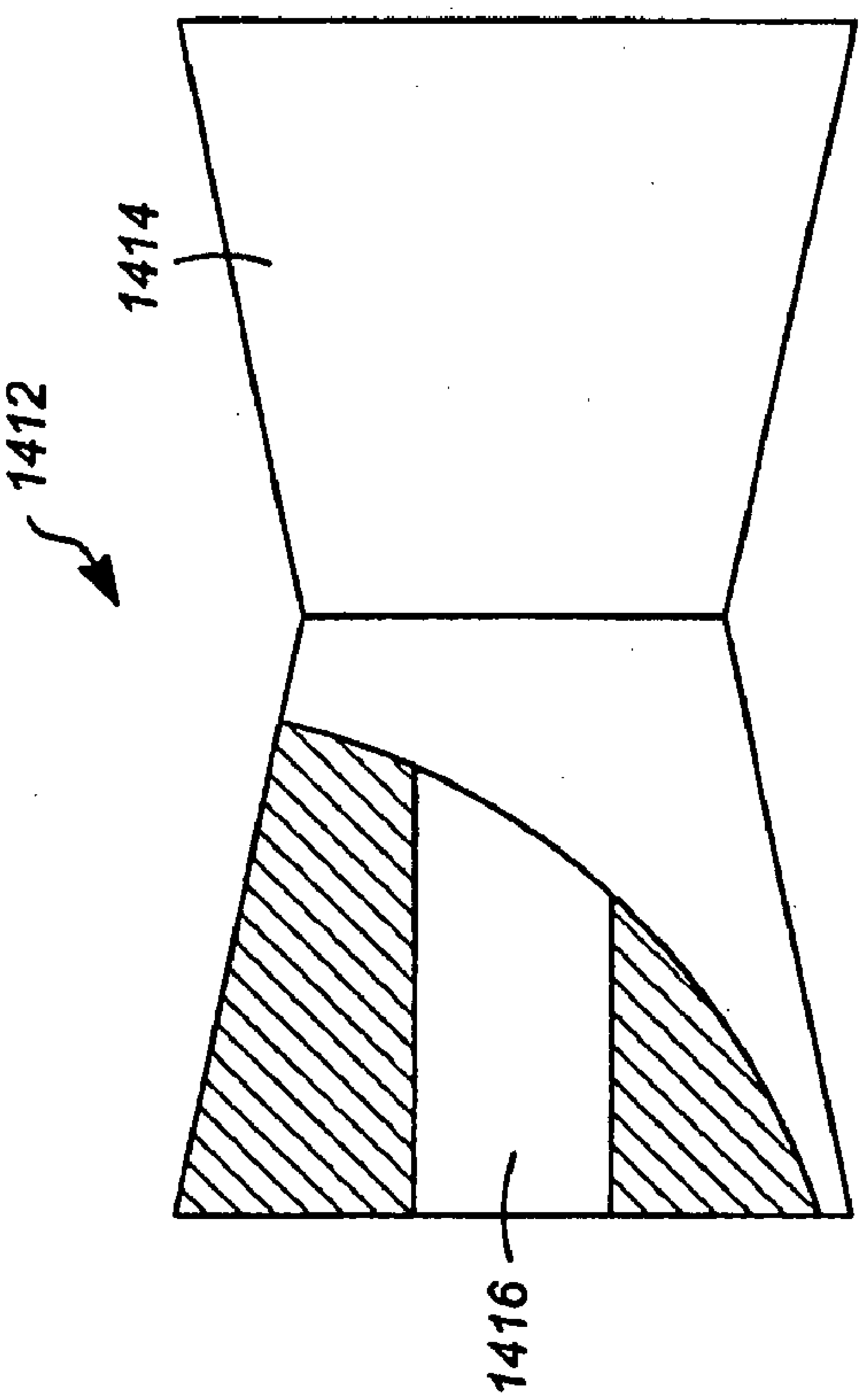


FIG. 38EA

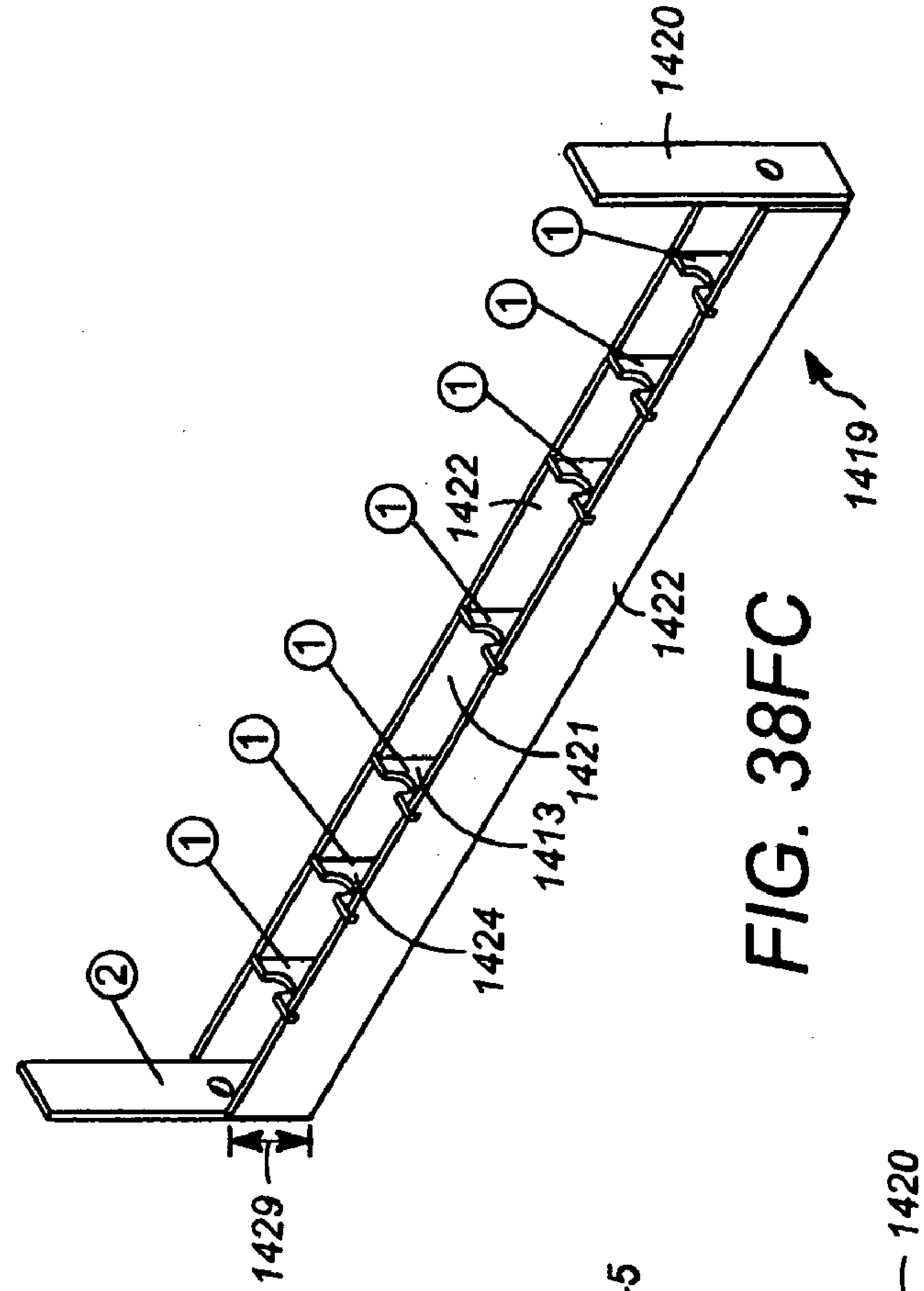


FIG. 38FC

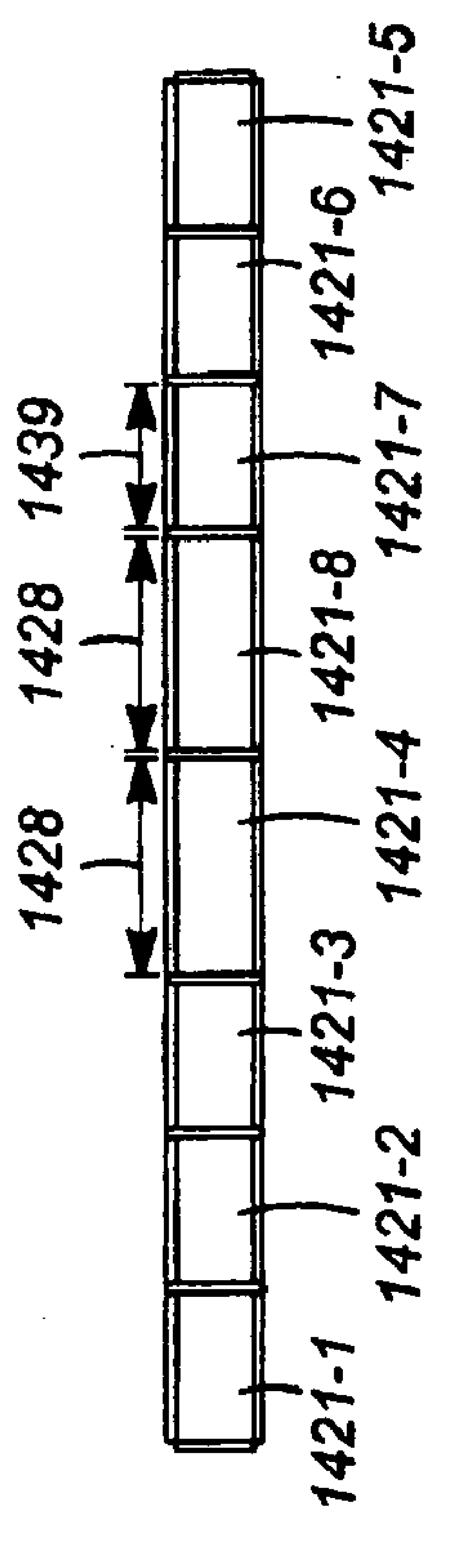


FIG. 38FA

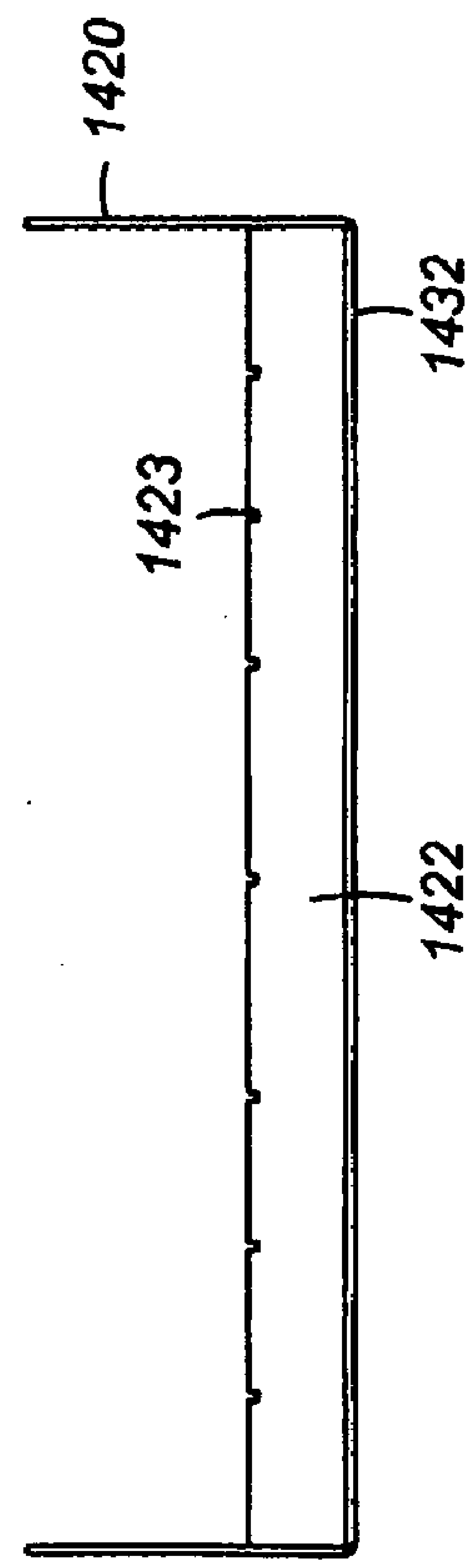


FIG. 38FB

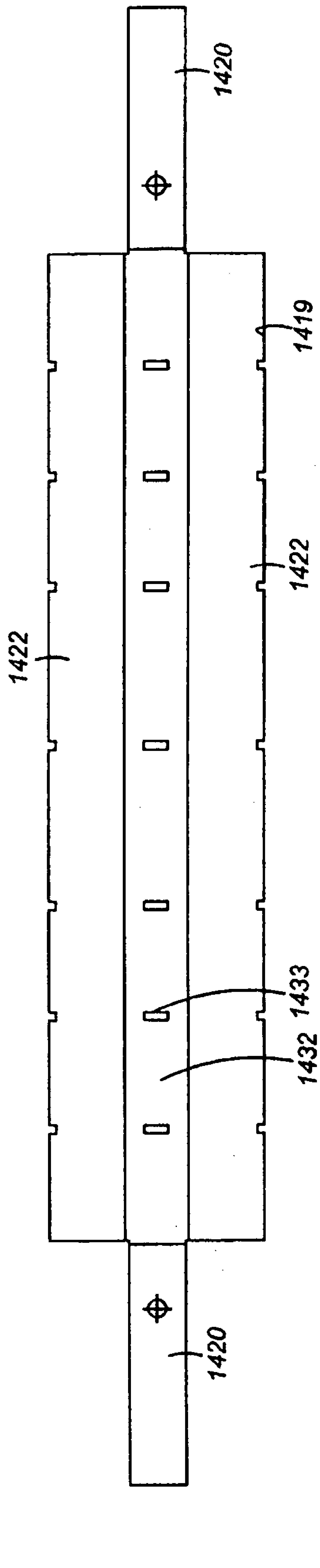


FIG. 38G

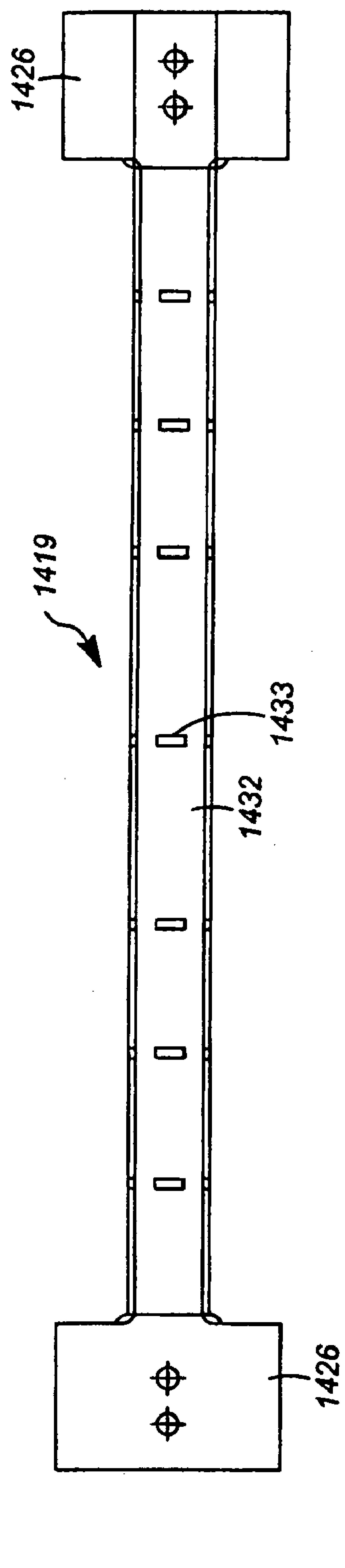


FIG. 38HA

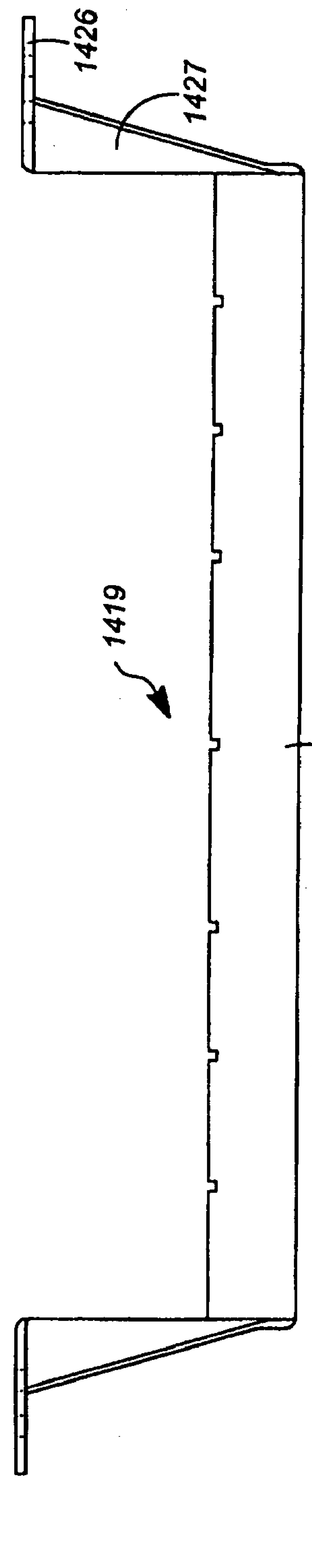


FIG. 38HB

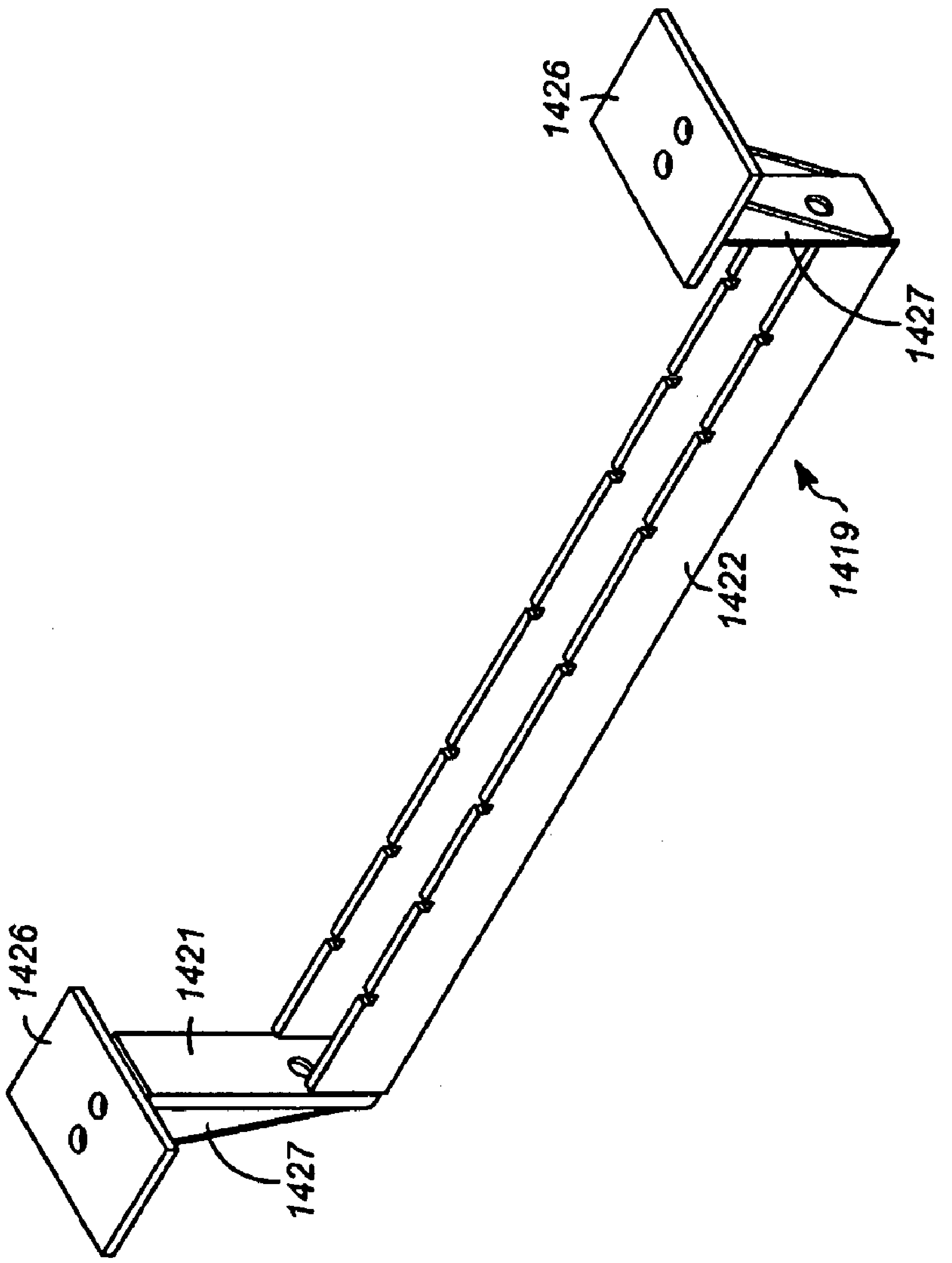


FIG. 38HD

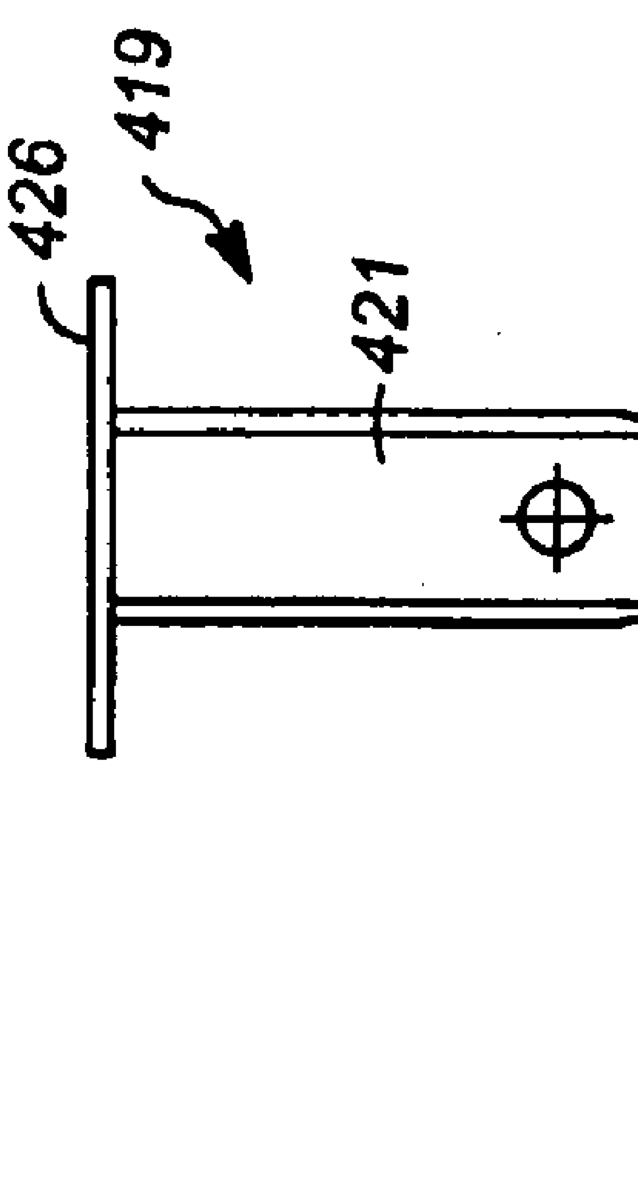


FIG. 38HC

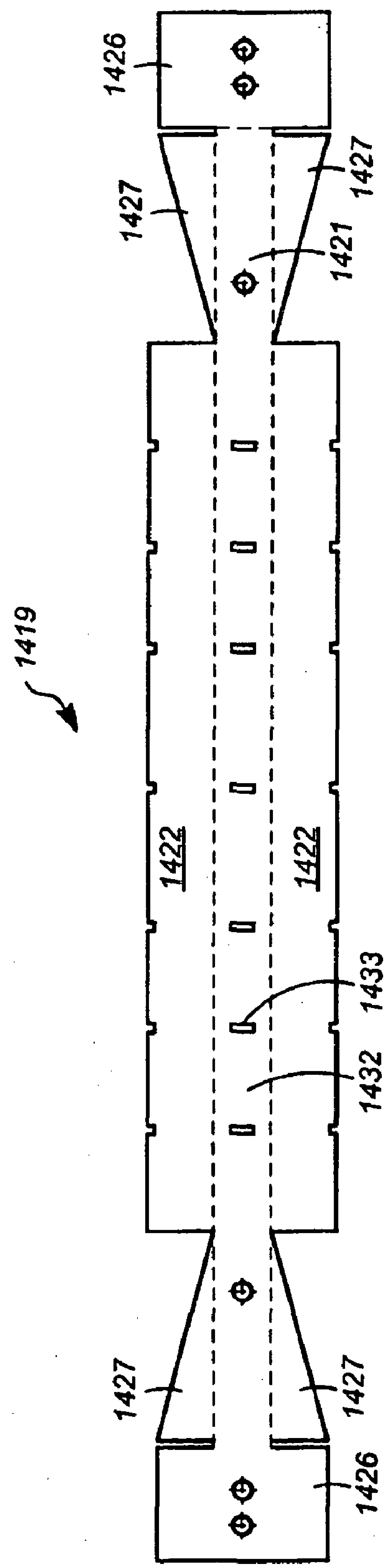


FIG. 38I

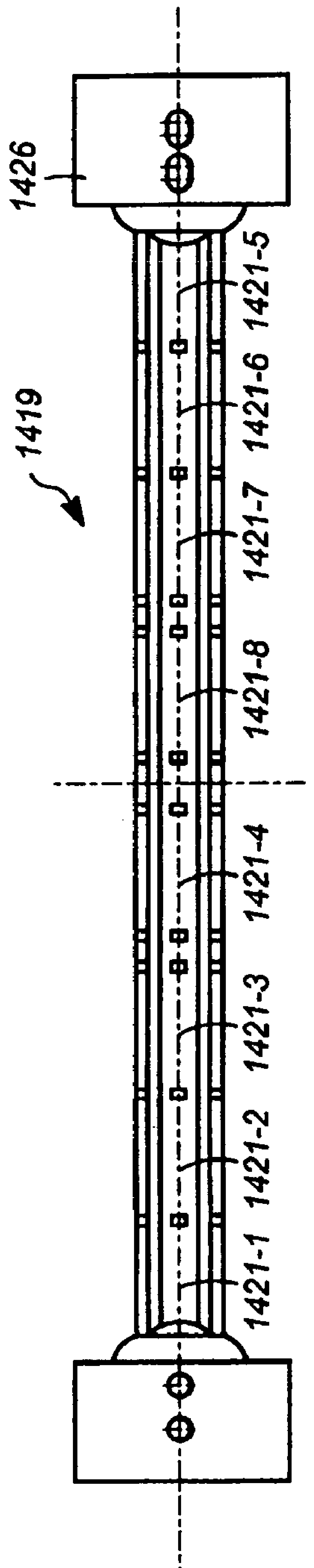


FIG. 38JA

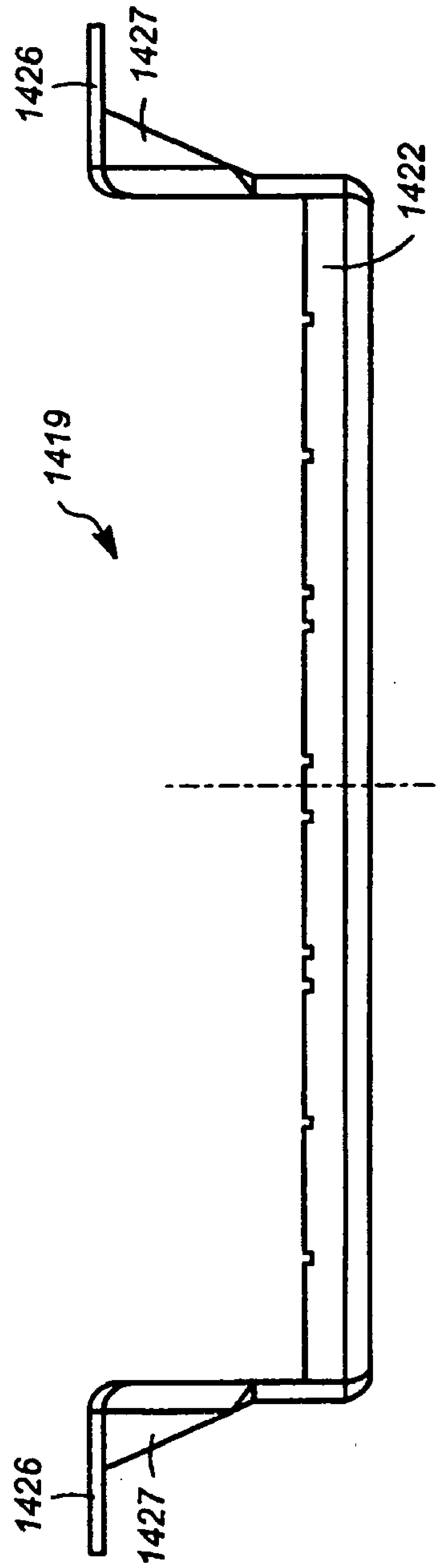


FIG. 38JB

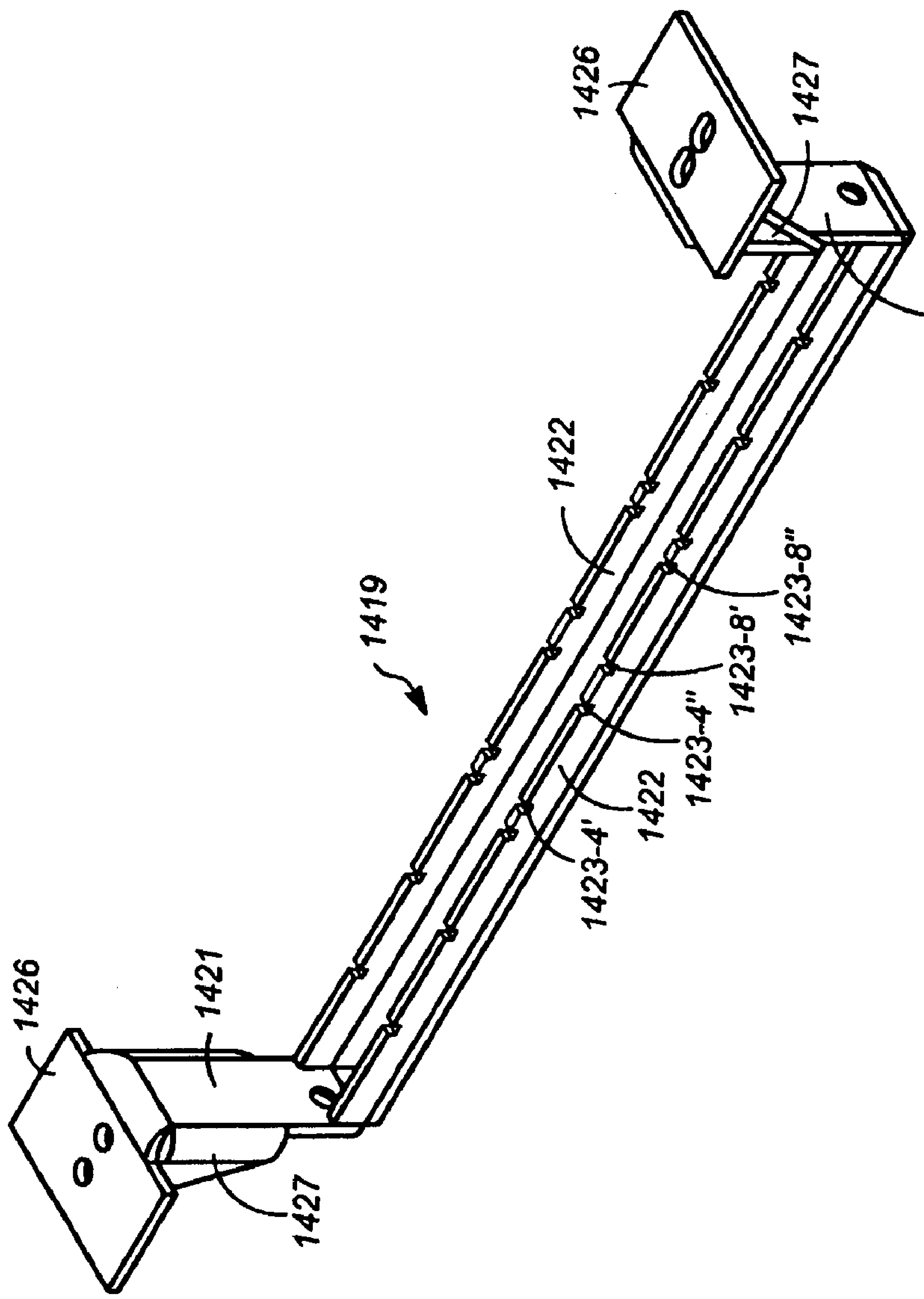


FIG. 38JD

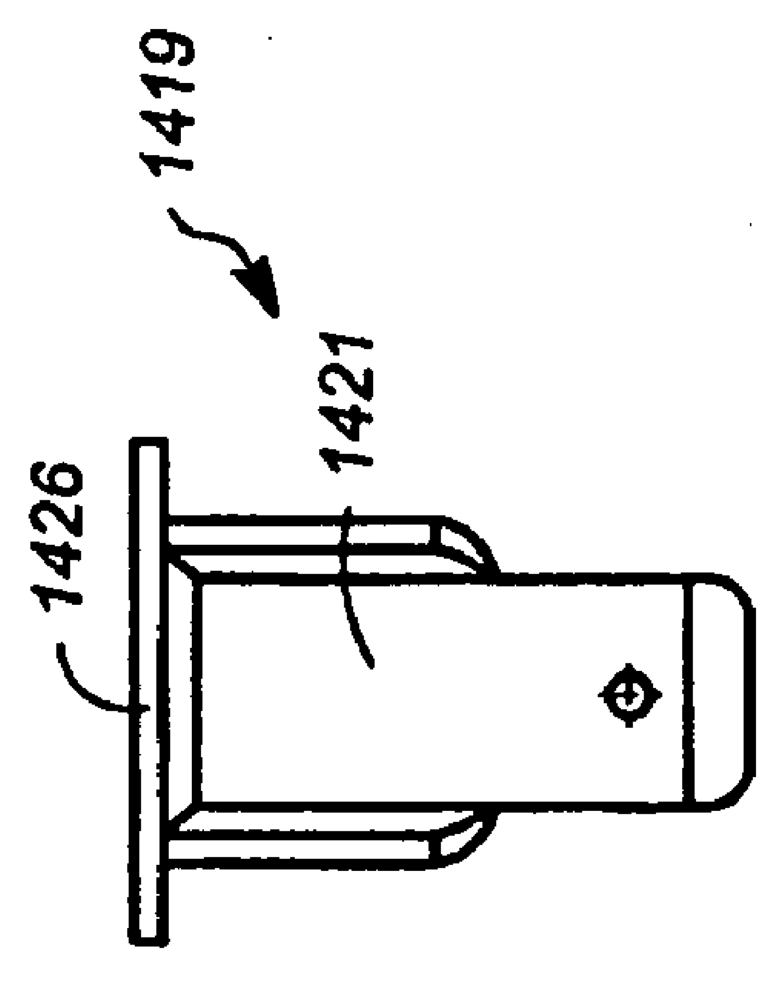


FIG. 38JC

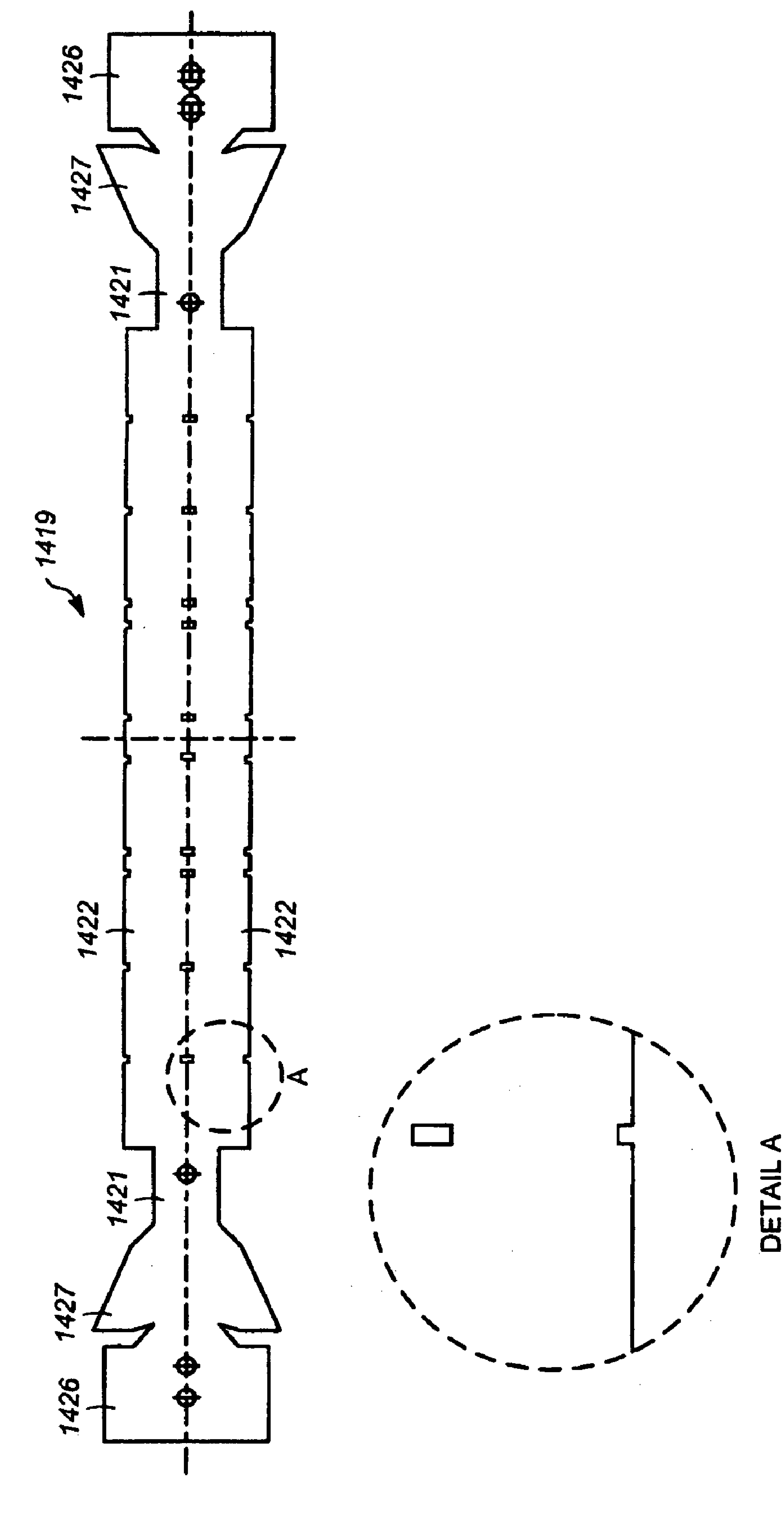


FIG. 38K

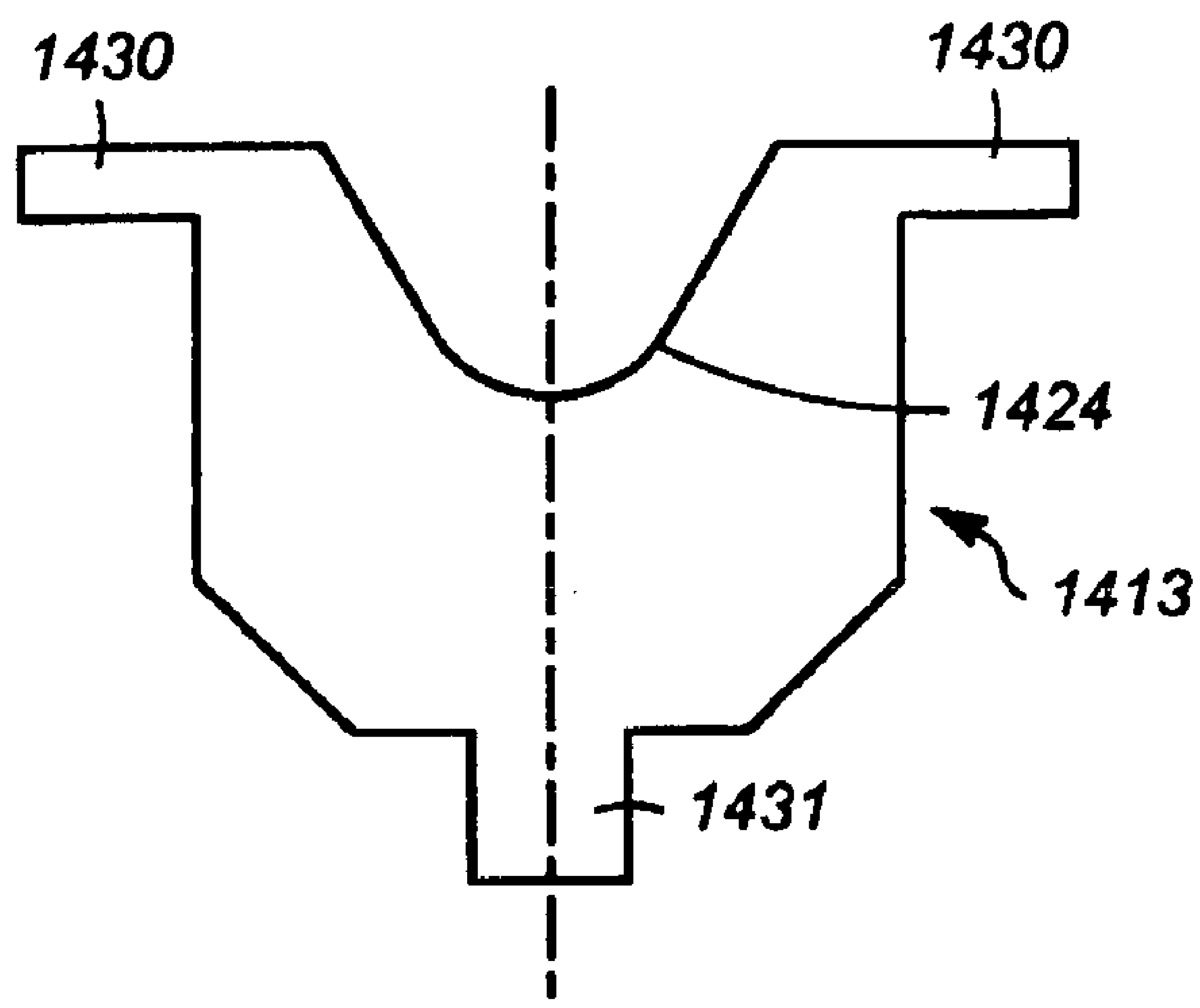


FIG. 38LA

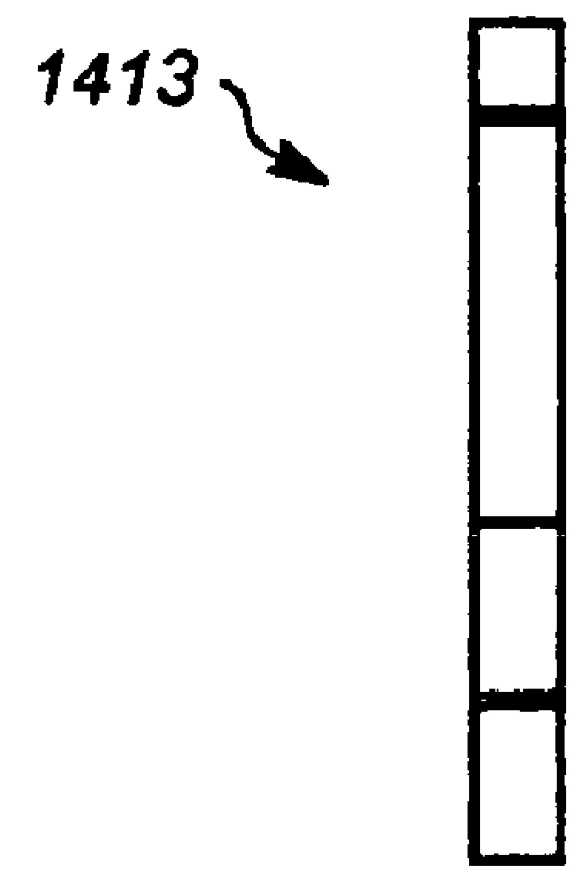


FIG. 38LB

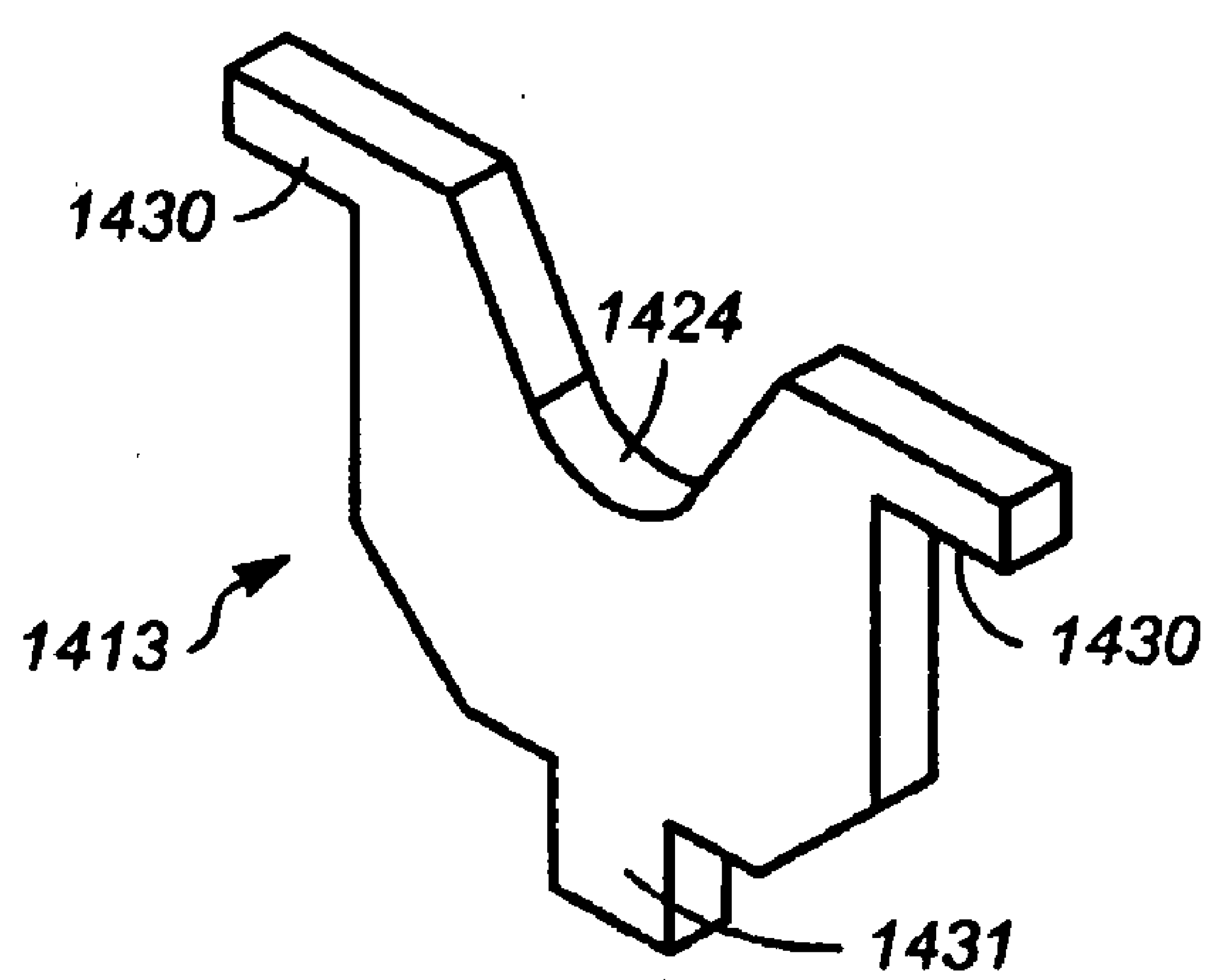


FIG. 38LC

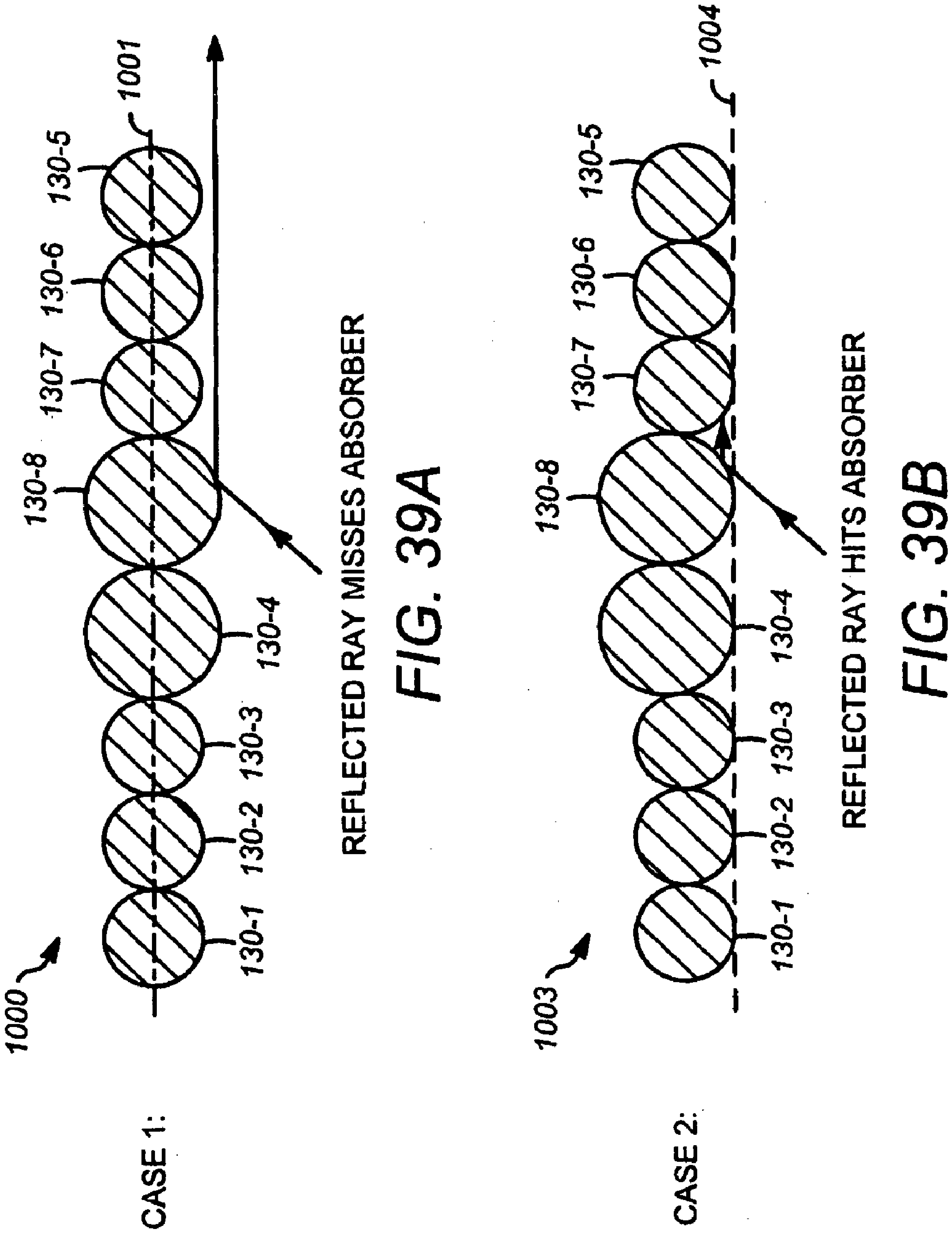


FIG. 39A

FIG. 39B

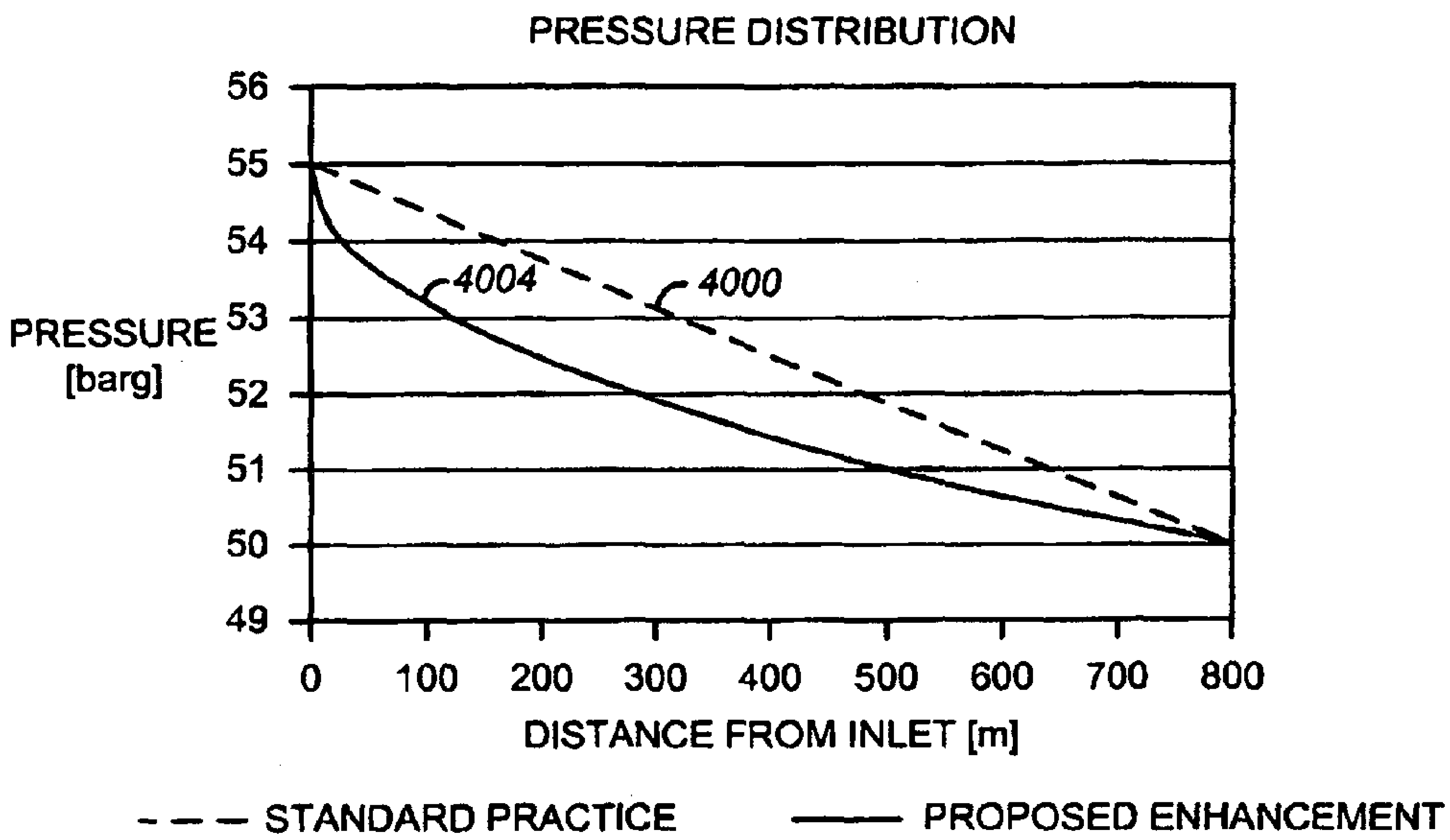


FIG. 40A

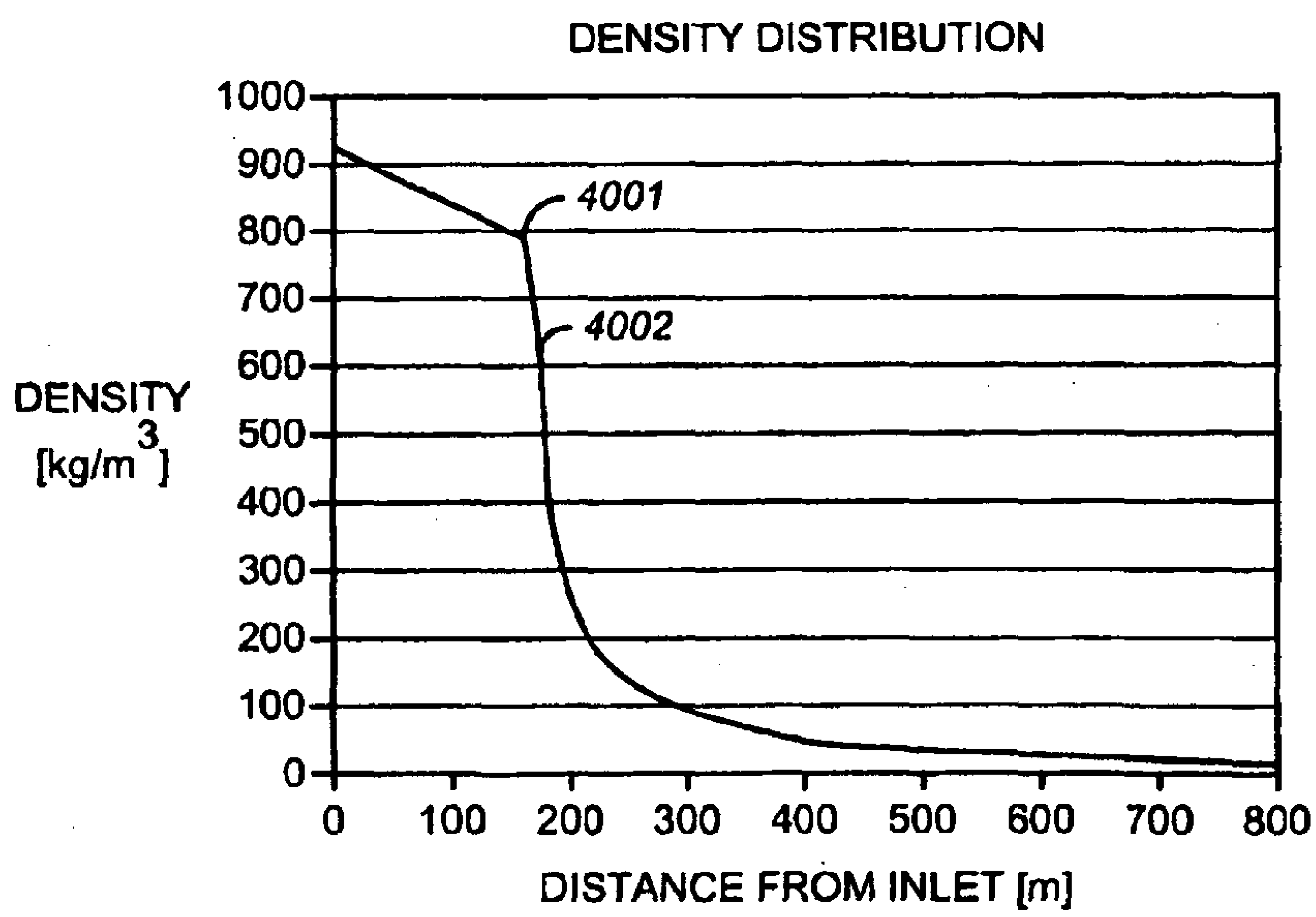


FIG. 40B

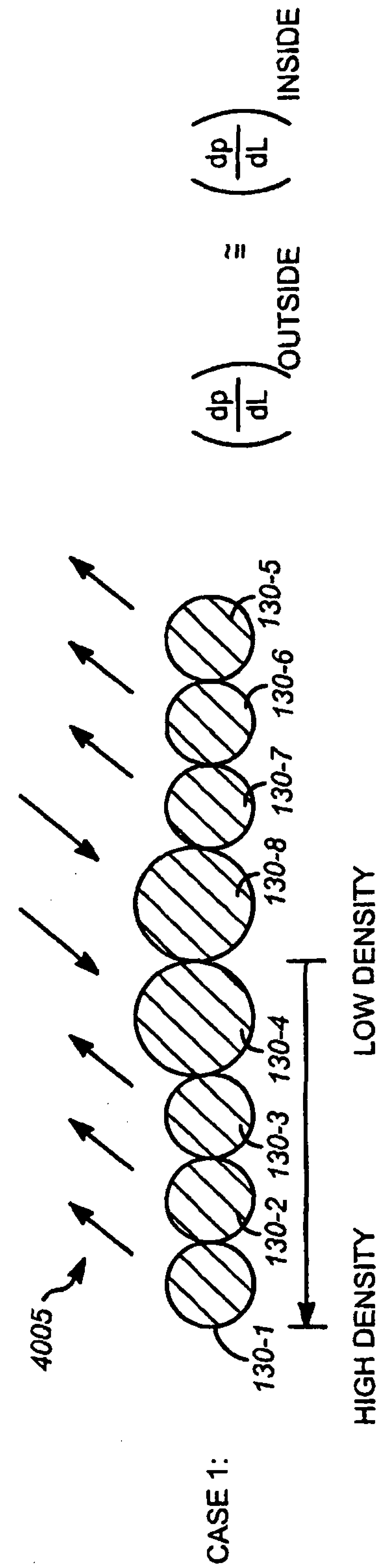


FIG. 40C

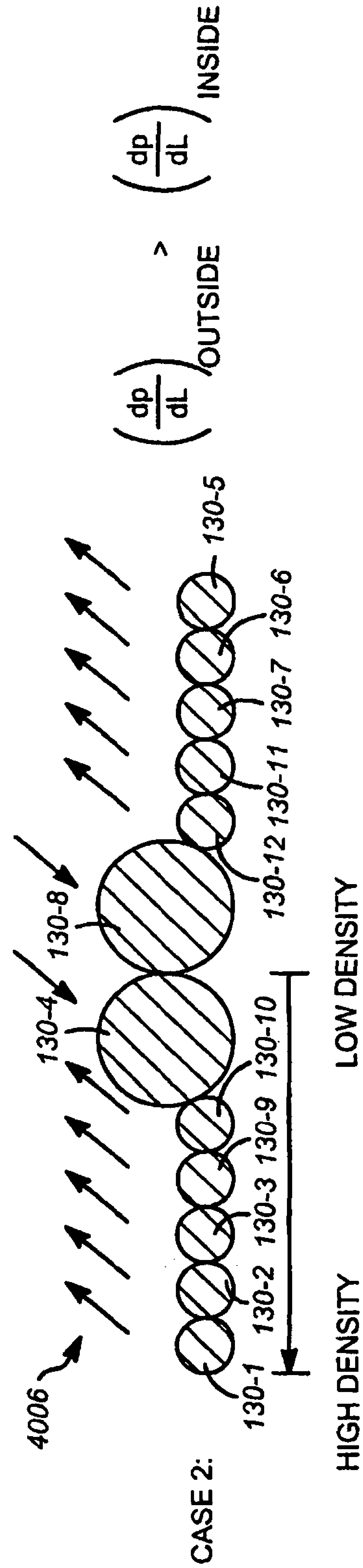


FIG. 40D

MULTI-TUBE SOLAR THERMAL RECEIVER

RELATED APPLICATIONS

[0001] This application claims the benefit of priority from U.S. provisional patent application entitled "Multi-Tube Solar Thermal Receiver", application Ser. No. 61/249,562, inventors Peter L. Johnson, Robert J. Hanson, and William M. Conlon, filed on Oct. 7, 2009, and U.S. provisional patent application entitled "Multi-Tube Solar Thermal Receiver", application Ser. No. 61/303,615, inventors Peter L. Johnson, Robert J. Hanson, and William M. Conlon, filed on Feb. 11, 2010, each of which is hereby incorporated by reference in its entirety for all purposes as if put forth in full below.

BACKGROUND

[0002] 1. Field

[0003] This application relates generally to the collection of solar energy, and more specifically to the collection of solar energy for the purpose of generating thermal energy or steam.

[0004] 2. Related Art

[0005] Additional sources of energy are needed to continue to supply an ever-increasing population and energy demand world-wide. Solar energy is readily available in certain geographic areas and can be used to generate electricity or provide heat for industrial and residential use. While solar energy may be converted directly to electricity with photovoltaic devices, for example, as an alternative solar energy may be collected as heat and converted to useful work. Solar energy collected as heat may be used, for example, to generate steam for use in electrical power generation or for other industrial processes.

SUMMARY

[0006] Systems, methods, and apparatus by which solar energy may be collected as heat are disclosed herein.

[0007] In a first aspect, solar energy collectors systems, such as linear Fresnel reflector solar arrays, are described herein. In some variations, the solar energy collector system comprises an elevated solar receiver comprising a tubing arrangement comprising multiple tubes arranged lengthwise in the receiver in a side-by-side parallel configuration across a transverse dimension of the receiver, wherein the multiple tubes comprise an inner tube or tubes, a first outer tube or tubes on one side of the inner tube or tubes, and a second outer tube or tubes on an opposite side of the inner tube or tubes from the first outer tube or tubes. The solar energy collector system further comprises at least one orientable reflector operable to direct incident solar radiation to form a concentrated illuminated area on the tubing arrangement. The solar energy collector system further comprises an instrumentation and control system for controlling the orientation of the at least one orientable reflector to provide in operation a concentrated illuminated area comprising a peaked profile across the transverse dimension of the receiver. The receiver comprises an inlet section configured to receive a heat transfer fluid into the tubing arrangement and an outlet section configured to output heated heat transfer fluid from the tubing arrangement. The multiple tubes of the tubing arrangement define together a flowing circuit between the inlet section and the outlet section from the outer tube or tubes to the inner tube or tubes.

[0008] In some variations, the tubing arrangement is configured such that the concentrated illuminated area distributes heat flux to the heat transfer fluid within the tubing arrangement such that, in operation, the density of the fluid within a tube of the tubing arrangement is inversely related to the heat flux delivered to that tube.

[0009] In those instances in which the solar energy collector system comprises a linear Fresnel reflector solar array, the receiver comprises an elevated linear receiver, the orientable reflector is contained within a reflector row that is aligned parallel to the receiver and focuses incident radiation on the receiver, and the concentrated illuminated area comprises a line focus.

[0010] In some variations, the tubing arrangement may or may not be symmetrical with respect to a longitudinal center line of the receiver.

[0011] In some variations, the system may include a flow control device on the flowing circuit to control mass flow of heat transfer fluid into the tubing arrangement.

[0012] In some variations, the tubing arrangement comprises one or more thermal expansion sections that accommodates thermal expansion of the tubing arrangement. In one example, at least one thermal expansion section extends in a plane defined by the multiple parallel tubes. In another example, at least one thermal expansion section extends out of a plane defined by the multiple parallel tubes. In yet another example, the thermal expansion section comprises a suspension mechanism having at least one clamp holding one of the tubes of the tubing arrangement, the suspension mechanism coupled to sliding or rolling means, said sliding or rolling means being supported by a track interconnected with the receiver structure and defining a path parallel to the tube length for said sliding or rolling means.

[0013] In some variations of the systems, heat transfer fluid enters the tubing arrangement through a first inlet section to enter a first outer tube or tubes to flow in a first direction to reach a turnaround header that redirects heat transfer fluid to enter a first inner tube to flow in a second flow direction counter-parallel to the first flow direction to reach a first outlet section, and the concentrated illuminated area provides greater heat flux to the first inner tube than to the first outer tube or tubes. In some variations, the first inner tube has a larger inner diameter than that of the first outer tube. A flow control device can be used on the first inlet to control mass flow of heat transfer fluid into the tubing arrangement.

[0014] In some variations, the heat transfer fluid enters the tubing arrangement through a second inlet section to flow in the first flow direction in a second outer tube or tubes to reach a second turnaround header that redirects the heat transfer fluid to enter a second inner tube and flow in the second flow direction to reach a second outlet section.

[0015] In some variations, the heat transfer fluid enters the tubing arrangement through a second inlet section to flow in the first flow direction in a second outer tube or tubes to reach a second turnaround header that redirects heat transfer fluid to enter the first inner tube and flow in the second flow direction to reach the first outlet section.

[0016] In some variations, the tubing arrangement comprises a plurality of tubes connected in parallel with the first outer tube or tubes, and heat transfer fluid flows in the first direction through the plurality of tubes to reach the turnaround header.

[0017] In some variations, the tubing arrangement comprises a plurality of tubes connected in parallel with the first inner tube, and heat transfer fluid flows in the second direction through the plurality of tubes to reach the first outlet section.

[0018] A tubing arrangement used in some of the solar energy collector systems can comprise a serpentine path between the first outer tube and the first inner tube such that heat transfer fluid flow path intersects the concentrated illuminated area more than twice.

[0019] In a second aspect, methods for collecting solar energy are provided herein. In this aspect, the methods comprise flowing a heat transfer fluid into a tubing arrangement of an elevated solar receiver through an inlet section, wherein the tubing arrangement comprises multiple tubes arranged lengthwise in the receiver in a side-by-side parallel configuration across a transverse dimension of the receiver, the multiple tubes comprising an inner tube or tubes, a first outer tube or tubes on one side of the inner tube or tubes, and a second outer tube or tubes on an opposite side of the inner tube or tubes from the first outer tube or tubes. The methods further comprise concentrating solar radiation onto the elevated solar receiver to form a concentrated illuminated area comprising a peaked profile across a transverse dimension of the receiver, wherein the receiver comprises an inlet section configured to receive the heat transfer fluid into the tubing arrangement and an outlet section configured to output heated heat transfer fluid from the tubing arrangement, and wherein the multiple tubes of the tubing arrangement defining together a flowing circuit between the inlet section and the outlet section from the outer tube or tubes to the inner tube or tubes.

[0020] In some variations, the tubing arrangement is configured such that the concentrated illuminated area distributes heat flux to the heat transfer fluid within the tubing arrangement such that, in operation, the density of the fluid within a tube of the tubing arrangement is inversely related to the heat flux delivered to that tube.

[0021] In some variations, the methods further comprise controlling mass flow of the heat transfer fluid into the tubing arrangement using a flow control device.

[0022] In some variations, the tubing arrangement comprises one or more thermal expansion sections that accommodates thermal expansion of the tubing arrangement. In one example, at least one thermal expansion section extends in a plane defined by the multiple parallel tubes. In another example, at least one thermal expansion section extends out of a plane defined by the multiple parallel tubes. In yet another example, the thermal expansion section comprises a suspension mechanism having at least one clamp holding one of the tubes of the tubing arrangement, the suspension mechanism coupled to sliding or rolling means, said sliding or rolling means being supported by a track interconnected with the receiver structure and defining a path parallel to the tube length for said sliding or rolling means.

[0023] In some variations, the methods further comprise flowing the heat transfer fluid into the tubing arrangement through the first inlet section to enter the first outer tube or tubes to flow in a first direction to reach a turnaround header that redirects heat transfer fluid to enter the first inner tube to flow in a second flow direction counter-parallel to the first flow direction to reach the first outlet section and the concentrated illuminated area provides greater heat flux to the first inner tube than to the first outer tube or tubes.

[0024] In some variations, the first inner tube has an inner diameter greater than that of the first outer tube.

[0025] These and other embodiments, features, and advantages will become more apparent to those skilled in the art when taken with reference to the following detailed description in conjunction with the accompanying drawings that are first briefly described.

BRIEF DESCRIPTION OF THE DRAWINGS

[0026] FIG. **1** shows a perspective view of an example linear Fresnel solar energy collector comprising a multi-tube solar thermal receiver.

[0027] FIG. **2** shows a cross-section of an example multi-tube solar thermal receiver and a plot of an example concentrated solar radiation distribution across the section.

[0028] FIG. **3** shows an example two-pass fluid flow pattern in a multi-tube solar thermal receiver.

[0029] FIG. **4** shows an example four-pass fluid flow pattern in a multi-tube solar thermal receiver.

[0030] FIGS. **5**A-**5**C show, respectively, perspective, plan view, and perspective illustrations of an example multi-tube solar thermal receiver that may support the flow pattern shown in FIG. **4**.

[0031] FIG. **6** shows an example five-pass fluid flow pattern in a multi-tube solar thermal receiver.

[0032] FIG. **7** shows another example five-pass fluid flow pattern in a multi-tube solar thermal receiver.

[0033] FIG. **8** shows an example six-pass fluid flow pattern in a multi-tube solar thermal receiver.

[0034] FIG. **9** shows an example three-pass fluid flow pattern in a multi-tube solar thermal receiver.

[0035] FIG. **10** shows another example three-pass fluid flow pattern in a multi-tube solar thermal receiver.

[0036] FIGS. **11**A and **11**B show, respectively, another example four-pass fluid flow pattern in a multi-tube solar thermal receiver and a plot of an example concentrated solar radiation distribution with which the flow pattern of FIG. **11**A may be used.

[0037] FIG. **12** shows an example fluid flow pattern through two fluidly coupled multi-tube solar thermal receivers.

[0038] FIG. **13** shows a schematic illustration of an example of a central receiver solar energy collector comprising a solar thermal receiver on a tower and an array of heliostats each angularly adjustable about two axes to direct solar radiation to the solar thermal receiver.

[0039] FIG. **14** shows schematic illustration of an example solar thermal receiver that may be used in the solar energy collection system of FIG. **13**.

[0040] FIG. **15** shows a schematic illustration of another example solar thermal receiver that may be used in the solar energy collection system of FIG. **13**.

[0041] FIGS. **16**A and **16**B show, respectively, another example fluid flow pattern and an example concentrated solar radiation distribution with which the fluid flow pattern of FIG. **16**A may be used.

[0042] FIGS. **17**A and **17**B show, respectively, another example fluid flow pattern and an example concentrated solar radiation distribution with which the fluid flow pattern of FIG. **17**A may be used.

[0043] FIGS. **18**A and **18**B show, respectively, an arrangement of a sensor and a mirror with respect to a solar thermal receiver, and a plot of a signal generated by the sensor for use in a method for calibrating control of the mirror orientation.

[0044] FIGS. **19**A-**19**B illustrate additional examples of tubing arrangements with a four pass flow pattern.

[0045] FIGS. **20**A-**20**B illustrate additional examples of tubing arrangements with a four pass flow pattern.

[0046] FIGS. **21**A-**21**B illustrate additional examples of tubing arrangements with a four pass flow pattern.

[0047] FIGS. **22**A-**22**B illustrate additional examples of tubing arrangements with a four pass flow pattern.

[0048] FIGS. **23**A-**23**B illustrate additional examples of tubing arrangements with a four pass flow pattern.

[0049] FIG. **24** illustrates an additional example of a tubing arrangement with a two pass flow pattern.

[0050] FIGS. **25**A-**25**C illustrate additional examples of tubing arrangements with a two pass flow pattern.

[0051] FIGS. **26**A-**26**B show perspective illustrations of example multi-tube solar thermal receiver that may support the flow pattern shown in FIG. **3**, FIG. **24**, or FIG. **25**A-**25**C.

[0052] FIGS. **27**A-**27**B show examples of tube anchors.

[0053] FIG. **28** shows an example of a tubing arrangement in which certain frequencies of movement are damped.

[0054] FIG. **29** shows an example of a tubing arrangement including a tube anchor coupled to a spring.

[0055] FIG. **30** shows an example of a turnaround loop that can be used in a tubing arrangement.

[0056] FIG. **31** illustrates an example of a suspension mechanism that accommodates thermal expansion of a tube.

[0057] FIG. **32** illustrates another example of a suspension mechanism that accommodates thermal expansion of a tube.

[0058] FIGS. **33**A-**33**E illustrate variations of suspension mechanisms that accommodate thermal expansion of a tube.

[0059] FIGS. **34**A-**34**E illustrate variations of tube clamps that can be used with suspension mechanisms, e.g. as illustrated in FIGS. **31**, **32**, and **33**A-**33**E.

[0060] FIGS. **35**A-**35**B show examples of a tube clamped to a suspension mechanism to accommodate thermal expansion.

[0061] FIGS. **36**A-**36**B illustrate variations of suspension mechanisms that accommodate thermal expansion of a tube.

[0062] FIGS. **37**A-**37**C illustrate one variation of a turnaround header, e.g. that can be used with a two pass tubing arrangement as illustrated in FIG. **3**, **24**, or **25**A-**25**C.

[0063] FIGS. **38**A-**38**L illustrate variations of support assemblies that support tubes from below and accommodate thermal expansion.

[0064] FIGS. **39**A-**39**B illustrate variations in which tubes in a tubing arrangement have different diameters.

[0065] FIGS. **40**A-**40**D illustrate variations in which pressure drops nonlinearly from a tube inlet to a far end of a receiver.

DETAILED DESCRIPTION

[0066] The following detailed description should be read with reference to the drawings, in which identical reference numbers refer to like elements throughout the different figures. The drawings, which are not necessarily to scale, depict selective embodiments and are not intended to limit the scope of the various embodiments. The detailed description illustrates by way of example, not by way of limitation, the principles of the present technology. This description will clearly enable one skilled in the art to make and use the various embodiments, and describes several embodiments, adaptations, variations, alternatives and uses of the present technology, including what is presently believed to be the best mode of carrying out the present technology.

[0067] As used in this specification and the appended claims, the singular forms "a," "an," and "the" include plural referents unless the context clearly indicates otherwise. Also, the term "parallel" is intended to mean "substantially parallel" and to encompass minor deviations from parallel geometries rather than to require that parallel rows of reflectors, or parallel tubes, for example, or any other parallel arrangements described herein be exactly parallel.

[0068] Disclosed herein are systems, methods, and apparatus by which solar energy may be collected as thermal energy. Solar radiation is directed to a solar energy absorber or receiver that includes one or more tubes containing a heat transfer fluid. Solar radiation absorbed by a tube is transferred to the heat transfer fluid contained within that tube.

[0069] Some of the systems, methods and apparatus described here relate to solar receivers comprising tubing arrangements that comprise multiple absorber tubes. In certain examples, the tubing arrangements can comprise thermal expansion sections or mechanisms that allow for thermal expansion of at least one of the multiple tubes, or some or all of the multiple tubes during operation. In some circumstances, the tubing arrangements allow for differential thermal expansion of certain tubes in a tubing arrangement relative to other tubes in that tubing arrangement. For example, a tubing arrangement can be configured to allow for differential thermal expansion between neighboring tubes, or between a centermost tube or tubes and an outer tube.

[0070] In some examples, a tubing arrangement can be coordinated with an illumination pattern or scheme of concentrated solar radiation on the absorber tubes to enhance an efficiency, output, and/or other performance metric of the solar receiver. Some of the systems, methods, and apparatus described here relate to potentially advantageous tubing arrangements (and therefore heat transfer fluid flow paths) through a solar energy absorber illuminated by concentrated solar radiation and/or to potentially advantageous arrangements of heat absorbing processes (e.g. heat absorbed as sensible heat or as latent heat) in a solar energy absorber illuminated by such concentrated solar radiation. Examples of such arrangements are given below primarily in the context of specific example solar energy concentration systems, including linear Fresnel reflector solar energy collectors and point or spot focus tower—heliostat solar energy concentration systems. It should be understood, however, that any suitable systems, methods, and apparatus for concentrating solar radiation known to one of ordinary skill in the art or later developed may be used in combination with improved solar energy receivers described here.

[0071] In some variations, one or more tubes in a solar receiver described here may be configured so that heat transfer fluid makes multiple passes through the receiver. When heat transfer fluid makes a "pass" or "loop" through a receiver, heat transfer fluid flows in a tubing arrangement through the receiver so as to intersect or pass through a portion of the tubing arrangement that is illuminated by a concentrated region of solar radiation, and to thereby be heated by solar radiation absorbed by the tubes in that region. In a multiple pass scenario, heat transfer fluid intersects or passes through a portion of the tubing arrangement that is illuminated by the concentrated region of solar radiation more than once. Thus, in two-pass configuration, heat transfer fluid flows through a first portion of the tubing arrangement so as to be heated by the concentrated solar energy incident on and absorbed by the absorbing tubes in a first pass, and subsequently at least some of the once-heated fluid is redirected so as to pass through a second portion of the tubing arrangement be heated again by concentrated solar energy incident on and absorbed by solar absorber tubes in a second pass. Note that in some examples, the heat flux experienced by the heat transfer fluid may be different (e.g. lower) in a first pass than in a subsequent pass, e.g. the solar radiation may be concentrated so that a higher intensity is incident on that portion of the tubing arrangement in which the heat transfer fluid is experiencing a second, third, fourth, or even higher multiple pass through the receiver.

[0072] In some cases, a multiple pass configuration may include one or more out and back loops, in which heat transfer fluid travels in a first direction along a length of the receiver to be heated by concentrated solar energy, and then is redirected in a second direction (e.g. a direction that is generally anti-parallel to the first direction) to be heated again by concentrated solar energy. In a receiver having a multiple pass configuration, redirection of the fluid can occur at any suitable position in the receiver, e.g. at an inlet end of a receiver, or at a far end of a receiver that is opposite the inlet end, or at any point in between the receiver inlet and its far end. In cases where there are more than two passes through a receiver, redirection of the fluid occurs at more than one position, e.g. at both the inlet and a far end of the receiver. There may be an even or an odd number of passes in a multi-pass configuration. If the number of passes is even, the fluid may enter and exit the receiver from the same end. If the number of passes is odd, the fluid may enter at an inlet end and exit at an opposed far end. The length of each pass may or may not be the same in a single receiver, e.g. one pass may extend along a full length of the receiver and another pass may extend along only a portion of the length of the receiver. In some cases, the fluid may enter and/or exit the receiver at a position that is between an inlet end and its opposite far end, e.g. about midway between the inlet and the opposed far end. In some multi-pass configurations, there may be multiple tubes connected in parallel flowing in a single direction, and the multiple parallel-connected tubes may be directed into fewer (e.g. one) or into additional tubes upon redirection. In some multi-pass configurations, a tubing arrangement may comprise multiple tubes connected in series so that the flow path crosses and re-crosses the region of concentrated solar radiation, e.g. in a serpentine arrangement.

[0073] Any suitable mechanism in the tubing arrangement can be used to cause the fluid to be redirected, e.g. a tube may include a bend, a tube or tubes may be fed into a turnaround header, and/or one or more tubes may be fed into a tube junction (such as a U-shaped junction, an L-shaped junction, or a T-shaped junction).

[0074] In some solar energy collection systems, the concentrated solar radiation incident on the receiver may have a nonuniform optical (e.g. intensity and/or power) profile along one or more dimensions of the receiver. For example, for a line focus system (e.g. a linear Fresnel system) the intensity of the solar radiation may be relatively uniform along the direction of the line focus, but may be nonuniform (e.g. a peaked distribution such as a Gaussian) in a direction transverse to the direction of the line focus. For a point-focus system, the intensity of the solar radiation may vary across the cross-section of the point focus (e.g. have a peaked distribution such as a Gaussian intensity profile in which the peak is located near a center of the point focus, and the intensity decreases in a direction radially outward from the center of the point focus). Depending on the focusing characteristics and arrangement and alignment of reflectors used to focus solar radiation on the receiver, and the distance between the reflectors and the receiver, other types optical profiles may be present along one or more dimensions of the receiver, e.g. an optical profile having multiple peaks or non-Gaussian peaked distributions. For example, a multi-peaked distribution may be formed at a receiver by off-setting focused beams from multiple reflectors, e.g. off-setting a linear focused beam at the receiver from one reflector row relative to a linear focused beam at the receiver from another reflector row.

[0075] Some receivers may be configured so that flow of heat transfer fluid within one or more tubes in the receiver is arranged to take advantage of a nonuniform illumination on the receiver. It may be advantageous to use absorber tube routing within a receiver to position low temperature regions of the tubes (such as where relatively cold heat transfer fluid has entered the receiver) to be illuminated by relatively low intensity portions of the solar radiation distribution, and to position regions of the tubes requiring higher heat flux (such as to initiate boiling or to achieve superheat) so as to be illuminated by relatively high intensity portions of the solar radiation distribution.

[0076] The tubing in a receiver can be configured to accommodate thermal expansion of the multiple absorber tubes and/or differential thermal expansion among the tubes. Further, the tubing in the receiver can be configured to allow control of the heat transfer fluid within the tubes, e.g. to allow control mass flow of heat transfer fluid into various sections of a tubing manifold in a receiver. For example, it may be advantageous to route tubing within a receiver so that one or more tubes undergoes multiple passes through a receiver illuminated with a nonuniform solar radiation distribution. The first pass (or the first passes, such as the first 2, 3, or 4 passes) may be positioned so as to illuminated with the relatively low intensity portion of the solar radiation distribution (e.g. to undergo sensible heating, such as to heat water without inducing boiling), and a subsequent pass (or subsequent passes) may be positioned so as to be illuminated with the relatively high intensity portion of the solar radiation distribution (e.g. to undergo latent heating, such as to boil water). A portion of a tube or a group of tubes that requires the highest heat flux (e.g. such as to superheat steam) may be positioned so as to be illuminated with a relatively higher or peak intensity portion of the solar radiation distribution. Such configurations may improve overall capacity, efficiency, output, reliability, steam quality, production of superheated steam, and/or other performance parameter of a solar energy collector.

[0077] In designing a solar absorber, it may be desired to decrease the combined length of conveyance members (tubes, downcomers, linkages, etc.) that, in operation, function primarily transport fluid relative to the combined length of conveyance members that are absorbing energy. Lowering the ratio of nonabsorbing conveyance members to absorbing conveyance members can result in more efficient material usage and lower capital costs for solar arrays. For example, a ratio of the length of non-absorbing conveyance to absorbing conveyance may be less than about 1, 0.8, 0.6, 0.4, 0.3, 0.2, 0.18, 0.16, 0.14, 0.12, 0.1, 0.08, 0.06, 0.04, 0.02, or 0.01. In some variations, the ration of the non-absorbing tubing length to the absorbing tubing length is about 0.02, 0.04, 0.06, 0.08, 0.10, or 0.12. In one variation, the length of the non-absorbing tubing is about 50 feet, and the length of the absorbing tubing is about 1280 feet.

[0078] All conveyance members, including thin-walled vessels or pressure-bearing tubes (e.g. steel tubes such as carbon steel tubes) require anchors or constraints for stabilization in the event of seismic activity. Seismic stabilization may be especially important for an elevated receiver, such as an elevated linear receiver as used in a linear Fresnel reflector array, or a tower. In elevated linear receivers, very long tubes having significant mass should be constrained so as to prevent high stress and damage in the event of seismic activity, but still allow expansion of one or more tubes and/or differential thermal expansion between two or more tubes. Anchors (which may or may not be fixed point anchors), motion-dampening devices such as snubbers, other types of tube support hardware, or any combination thereof, can be used for seismic stabilization.

[0079] Tubes (e.g. in an elevated receiver) can be anchored in any suitable way, e.g. to comply with local construction or seismic codes, to accommodate a geographic location, for ease of installation, for ease of maintenance, repair or retrofit, or any combination thereof. In certain variations, one or more tubes within a receiver may be anchored at an intermediate position so that expansion can occur outwardly in two opposing directions from that intermediate anchor position. For example, if the intermediate anchor is positioned on a tube approximately midway between an inlet end and a far end of a receiver, the net expansion of the tube section extending from that anchor position is decreased by approximately 50% relative to a configuration in which the same length of the tube is anchored at an inlet or a far end.

[0080] Tubes can be constructed of any suitable material. Selection of a tube may be influenced or controlled by local codes (e.g. boiler codes in the case that water/steam is used as a heat transfer fluid) and/or local or national standards organizations, such as ASME. In some cases, all tubing in a receiver is constructed of essentially the same or similar material, e.g. carbon steel. In other variations, tubing used in one section of a receiver may be of a different construction and/or composition in another section of a receiver. For example, one grade of carbon steel tubing may be used in those portions of the receiver reaching only relatively low temperatures in operation, whereas a higher grade of carbon steel tubing or a different alloy tubing rated for higher temperature use may be used in only that section of tubing reaching the highest temperatures. Analogous adjustments in tubing material selection can be made to accommodate pressures reached during use, or heat transfer fluid.

[0081] As stated above, a tubing configuration in a solar thermal receiver as described herein may include one or more features to accommodate thermal expansion of one or more of the tubes during operation of the receiver, and in particular, net expansion of each tube and/or differential thermal expansion between different tubes within the same receiver. For a solar thermal receiver, it may be desirable to reduce or minimize the length of tubing that does not absorb light relative to the length of tubing that does absorb light. Doing so can increase the efficiency of the system, and may reduce overall costs. In solar thermal absorbers, increased optical efficiency can be achieved by a longer continuous length of absorber to reduce effects due to absorber ends and sun position, and increased overall efficiency and lowered cost may be achieved by increasing the ratio of absorbing tube length to non-absorbing tube length. A receiver, and continuous lengths of tubing within that receiver may be as long as practicable, with the length limited by geographical constraints, by the pressure drop along the length of the pump, or by pumping power necessary to force heat transfer fluid through that length of the absorber. Dividing a long tube into sections may result in increased requirements such as down corners and the like, and control mechanisms to coordinate flow between multiple sections. Longer absorbing tubes result in increased tubing expansion upon heating. Described herein are expansion mechanisms that can, for example, be used in linear receivers having lengths of about 600, 800, 1000, 1200, 1400, 1600, 1800 or 2000 feet. Thermal expansion relief mechanisms or sections may be provided at any position in a tubing arrangement and along a receiver, e.g. at the inlet end of a receiver, at the far end of a receiver opposite the inlet end, or at one or more intermediate positions between an inlet and a far end of the receiver, or at more than one position in a tubing arrangement, e.g. at the inlet end and the far end, at the inlet and an intermediate position, or at the far end and an intermediate position. In some cases, e.g. to reduce mechanical complexity, to reduce shading central to the energy field, and/or to reduce the length of non-absorbing tubing in a system, it is desired to provide thermal expansion relief at the inlet and/or at the far end of the receiver.

[0082] Any suitable mechanism for tube expansion at an end of a receiver may be utilized. In some cases, thermal expansion joints, loops, or constructions utilizing solid welded construction is preferable. In other variations, non-welded joints such as ball joints, or flexible tubing or hosing may be utilized to accommodate thermal expansion. Tubing expansion can be designed to account for the thermal expansion coefficient of the material of the tubing at the expected use temperatures, e.g. for suitable grade of steel (such as carbon steel) at temperatures of about 200° C. to about 500° C. Additional factors may be accounted for in the design of thermal expansion, e.g. transients, start-up and cool down conditions, and operator error. Such additional margin of error may be about 0.02% to about 0.2% of the length of the tube may be used, e.g. about 0.2%, 0.15%, 0.1%, 0.08%, 0.05%, or 0.02%. For example, for a 1200 foot long tubing arrangement, design for +/−about 6 inches, about 12 inches, or about 18 inches beyond target expansion of one or more tubes or differential expansion between two or more tubes.

[0083] When using a heat transfer fluid such as water that can undergo a phase transition during use, it is desired to prevent or reduce the occurrence of slug flow or similar or related phenomena that can result in damage to tubes, supports, and/or destabilization of control systems. To manage phase slip within a solar absorber comprising multiple tubes, expansion joints that reduce the potential of slug formation can be used. The expansion joints can allow for thermal expansion of one or more tubes, or differential thermal expansion between two or more tubes.

[0084] In solar absorbers that include multiple tubes and have multiple pass flow paths, the number of tubes, the diameters of tubes, and/or the number of flow path loops in the absorber can be selected to improve efficiency of a solar array, e.g. a linear Fresnel reflector array comprising an elevated, multi-tube receiver. The amount of energy that is stored in the fluid that is resident in the array (receiver and any conveyance members) is an important parameter in determining efficiency and performance, e.g. in evaluating thermal losses, losses during nonoperation such as overnight, start-up losses, and shut down losses. In some variations, it is desired to reduce the amount of energy that is lost during nonoperation, and increase the amount of energy that is delivered to a host (turbine, process, etc.), e.g. on a net energy basis) during operation. In this way, performance of a system can be evaluated over both operating and nonoperating periods, rather than only during operation. In some variations, e.g. to increase efficiency of a solar thermal absorber while operating in steady state, the number and/or diameters of tubes can be selected to increase flow volume to account for increasing specific volume of the heat transfer fluid as heating progresses.

[0085] When two phase flow (e.g. water and steam) is present within two or more parallel paths in a multi-tube solar absorber, mass flow into each of the parallel paths can be controlled so that an uneven split between the multiple paths does not result, e.g. due to nonuniform heat flux and/or a nonuniform pressure drop. Such unbalanced flow between multiple parallel paths can result in runaway flow conditions, which can, in turn, lead to tube dry out or damage. Thus, in some multi-pass tubing arrangements, it may be desired to combine the flow of multiple outbound tubes into a single turnaround header, and then direct the combined flow from the tubes into a single return tube for a subsequent pass.

[0086] Any of the multi-tube solar absorbers described herein or variants thereof can be designed with one of or any combination of the following features: i) thermal expansion sections that allow for expansion of one or more tubes and/or differential thermal expansion between two or more tubes; ii) one or more mechanisms that allows for thermal expansion or differential thermal expansion of tubes while reducing or preventing wear, even long term wear, on tube surfaces; iii) a system of controlling or mitigating slug formation at turnaround points between passes; iv) one or more mechanisms that allows for expansion or thermal expansion of tubes yet limits tube expansion so that tubes are not in high stress configurations or positions; and/or v) anchoring (e.g. which may or may not be fixed anchors) to one or more structures to resist seismic motion and/or damage.

[0087] Flow control devices can be used within a tubing arrangement to maintain a balanced heat transfer fluid volume within the solar absorber, and to prevent overheating any portion of the solar absorber, e.g. during standard operation, warm up, or transients due to cloud cover and the like. When flow occurs through a downstream loop of multiple parallel tubes that are fed by multiple tubes in an upstream loop that is fewer than the number of tubes in the downstream loop and a flow control device is not present at the entrance to each of the tubes in the downstream loop, pressure drop down the length of the tubes in the downstream loop may differ based on differences in the mass flow and fluid density within each tube, owing to varying heat flux on the tubes. For example, a tube that receives lower heat flux but equal mass flow compared to parallel path tubes within the same loop will have less heat transfer and thus higher density, assuming phase change takes place with heat transfer, than the parallel path tubes within the same loop. The higher fluid density with equivalent mass flow into the tube is likely to result in lower average fluid velocity and thus lower pressure drop. Such differences in pressure drop can create an imbalance where more flow from the upstream loop is channeled down the tube with a lower pressure drop, which may have been caused by relatively lower heat flux incident on that tube. This, in turn, may lower the average fluid density in that tube even more, continuing to lower pressure drop and decreasing the added enthalpy in that tube. The tube within the downstream loop that receives higher heat flux and thus has decreased density has a higher pressure drop, which dampens flow into it, further increasing the added enthalpy to the fluid in it, decreasing density more. This could lead to a runaway condition where one tube would fill with water and the other would dry out with superheated steam because flow would eventually stop. Such flow imbalance can be avoided or reduced by inserting a flow control device (such as a control valve or orifice plate) on the inlet for each tube to either actively control the flow split or to dampen the effects of the pressure drop along the tube on flow split. If the tubing arrangement is such that one or more upstream tubes is branched into multiple downstream tubes, flow control devices can be used between the upstream tubes and the downstream tubes to control flow into the downstream tubes and reduce or prevent flow imbalance. In some cases, a flow control device placed at the inlet of a tube in the upstream loop can be used to control flow in the downstream loop without an additional flow control device placed between the upstream loop and the downstream loop, e.g. where a flow control device placed on the inlet of each of multiple tubes in an upstream loop channeled into the same number or fewer tubes in a downstream loop so that the number of parallel flow paths in the upstream loop is greater than or equal to the number of parallel flow paths in any downstream loop, in particular where multiple tubes in the upstream loop are channeled into a single tube in a downstream loop.

[0088] Referring now to FIG. **1**, in one variation a linear Fresnel reflector solar energy collector system **100** comprises reflector fields **110** and **120** positioned on opposite sides of an elevated linear extending solar thermal receiver **105**. Reflector fields **110** and **120** comprise, respectively, reflector rows **110-1** through **110-6** and **120-1** through **120-6**. Other configurations are contemplated in which there are more than or fewer than 6 reflector rows on opposite sides of the receiver **105**. For example, there may be 3, 4, 5, 6, 7, 8, 9, or 10 reflector rows on each side of the receiver. In some cases, there may be a different number of reflector rows on opposite sides of the receiver. The number of reflector rows need not be even. For example, there may be a reflector row positioned directly under the receiver and an even number of reflector rows on opposite sides of the receiver. The angular orientation of the reflectors may be adjusted around their long axes to track the sun's apparent motion during the day to reflect solar radiation to solar thermal receiver **105**. Examples of reflectors and drives for use in linear Fresnel systems are provided in U.S. patent application Ser. No. 10/563,170 entitled "Carrier and Drive Arrangement for a Solar Energy Reflector System," U.S. patent application Ser. No. 10/563,171 entitled "Carrier for a Solar Energy Reflector Element," and U.S. patent application Ser. No. 12/012,821 entitled "Linear Fresnel Solar Arrays and Drives Therefor," each of which is incorporated herein by reference in its entirety.

[0089] One of ordinary skill in the art will understand that linear Fresnel collectors are known in the art, and that features of the support structures and the general arrangement of the reflectors with respect to the linear Fresnel solar energy collector in FIG. **1** are intended as schematic illustrations representing numerous configurations known in the art. Suitable linear Fresnel systems may include, but are not limited to, those disclosed in U.S. patent application Ser. No. 10/597,966 titled "Multi-Tube Solar collector Structure," filed Aug. 14, 2006, U.S. patent application Ser. No. 12/012,821 titled "Linear Fresnel Solar Arrays and Drives Therefor," filed Feb. 5, 2008, U.S. patent application Ser. No. 12/012,829 titled "Linear Fresnel Solar Arrays and Receivers Therefor," filed Feb. 5, 2008, and U.S. patent application Ser. No. 12/012,920 titled "Linear Fresnel Solar Arrays and Components Therefor," filed Feb. 5, 2008, each of which is incorporated by reference herein in its entirety.

[0090] Referring again to FIG. **1**, solar thermal receiver **105** includes a solar thermal absorber tubing arrangement **125** comprising a plurality of parallel tubes **130** arranged in a side-by-side manner. A heat absorbing fluid (e.g. water) passed through tubes **130** may be heated by solar radiation concentrated onto thermal absorber **125**. In some variations, solar thermal receiver **105** may have an inverted trough type structure as described, for example, in the patent applications referred to above (e.g. U.S. patent application Ser. No. 10/597,966 entitled "Multi-Tube Solar Collector Structure," filed Aug. 14, 2006, U.S. patent application Ser. No. 12/012, 829 entitled "Linear Fresnel Solar Arrays and Receivers Therefor," filed Feb. 5, 2008). Solar thermal receiver **105** may further comprise, in some variations, reflective surfaces which reflect light incident on them from minor fields **110** and/or **120** to tubes **130**.

[0091] As described above, the intensity of solar radiation along one or more directions of a receiver may be nonuniform. For a line focus system, the solar radiation intensity may be relatively uniform in the receiver along a length of the receiver parallel to the linear direction of the line focus system, but nonuniform across a transverse width of the receiver orthogonal to the receiver length.

[0092] Referring now to FIGS. **1** and **2**, plot **135** shows an example in which concentrated solar radiation intensity ("I") exhibits a nonlinear profile I(X) along a width (direction "X") transverse (perpendicular) to the long axis (length "L") of solar thermal receiver **105**. In FIG. **2**, solar thermal receiver **105** is shown in cross section along its width (the X direction). In the illustrated example, the transverse solar radiation intensity distribution I(X), and consequently the distribution of the heat flux into the solar arsborber tubing arrangement **125** comprising tubes **130**, is peaked. As shown by plot **136**, the longitudinal solar radiation intensity I(L) along length L is substantially constant, except for possible end effects **138** corresponding to ends **137** of the receiver.

[0093] Although the particular variation illustrated in FIG. **2** shows a solar radiation profile I(X) having a single central peak, other types of nonlinear solar radiation profiles are contemplated. The shape of the profiles I(X) and/or I(L) can be adjusted by the reflector fields used to concentrate solar radiation at the receiver. For example, the focal length of the reflectors, the distance between the reflectors and the receiver, the relative alignment of the focused beams from multiple reflectors (e.g. relative alignment of linearly focused beams from multiple reflector rows, where the focus from one reflector row may be aligned with or offset with the focus from another reflector row), and/or the spatial packing of the reflectors can be used to adjust the shape of the profile I(X) and/or I(L). Further, the alignment of the profile I(X) relative to the receiver (and therefore a tube arrangement in the receiver) can be adjusted by positioning the reflectors, e.g. so that a peak of the profile I(X) is aligned with a centerline "C" of the receiver that bisects the transverse dimension X of the receiver and extends along the receiver length L. In other variations, a peak of the profile I(X) may be offset with respect to the centerline C of the receiver.

[0094] The optical profile on a receiver (e.g. I(X) across a transverse width of a multi-tube linear Fresnel receiver) may be sharply peaked, gradually peaked, or multi-peaked, or may vary monotonically across the width. The optical profile may be positioned symmetrically relative to the geometry of the receiver (e.g. so that a centerline of the optical profile is aligned with a transverse center of the receiver), or asymmetrically relative to the geometry of the receiver. The optical profile and the degree of solar concentration along the optical profile may be tuned or varied to adjust performance of a solar energy collector system, e.g. using the focal length of the reflectors, the distance between the reflectors and the receiver, the packing of reflectors, the alignment of reflectors, and/or the relative positioning of the light reflected from the reflector rows (e.g. the concentrated beam from each reflector row may be aligned on the same linear focus, or a concentrated beam from one reflector row may form a linear focus that is displaced relative to the linear focus from another reflector row.) In some variations, incident solar radiation is concentrated by a factor of about 2, about 3, about 4, or about 5, or about 6 (e.g. about 2, about 3, about 4, about 5, or about 6 suns) at the wing regions of the distribution (which may be aligned to be incident on the outer-most tubes and concentrated by a factor of about 20, about 30, about 40, about 50, about 60, or about 70 (e.g. about 20, about 30, about 40, about 50, about 60, or about 70 suns) at the peak of the profile, which may be aligned so as to be incident on the center-most tube or tubes of a tubing arrangement. As described above, the solar radiation intensity distribution along the long axis of solar thermal receiver **105** (i.e., the longitudinal solar radiation intensity distribution) may be, for example, substantially constant.

[0095] The heat flux into the tubing arrangement is greater at a peak of the profile I(X). For a receiver in a linear Fresnel receiver having parallel side-by-side tubes such as illustrated in FIG. **1** and FIG. **2**, if a peak of the profile I(X) is aligned with the centerline of the receiver, the heat flux is thus greater at the center-most tube or tubes than at the two outer-most tubes (in the example of the FIG. **2**, the heat flux at tubes **130-5** and **130-6** may be greater than at the tube farthest to the right **130-10** and the tube farthest to the left **130-1**).

[0096] A variety of solar radiation intensity distributions that are nonuniform across the transverse dimension (width) of the receiver are contemplated. The solar radiation intensity distributions may be nonuniform in shape and/or in the absolute or relative magnitudes of solar concentration. For example, in other variations the transverse solar radiation intensity distribution may include multiple peaks (e.g., FIG. **11**B below). Also, although the transverse solar radiation intensity distribution I(X) shown in FIG. **2** is substantially symmetric and centered on tubes **130**, in other variations the transverse solar radiation intensity distribution may be asymmetric and/or off-center of tubes **130**. In some variations, the ratio of the solar radiation intensity distribution at a center-line of tubes **130** parallel to the long axis of tubes **130** to the solar radiation intensity distribution at a center-line of an outermost one of tubes **130** is about 3:1 to about 20:1, about 3:1 to about 15:1, about 3:1 to about 10:1 or about 3:1 to about 5:1. In the example of FIG. **2**, the centerline C is located between and running parallel to the fifth and sixth tubes.

[0097] Note also that the heat flux experienced by the heat transfer tube is affected by the solar asbsorptivity and emission characteristics of the tubing itself. A solar selective coating that increases solar absorptivity and reduces emission at a desired operating temperature range can be used on all or a portion of a tubing arrangement. In some cases, different solar selective coatings can be applied to different portions of the tubing arrangement, e.g. a first solar selective coating that is suitable for use at lower temperatures may be applied to those tubes whose temperature increase is limited during use, and a second solar selective coating that is suitable for use at higher temperatures may be applied to those tubes that reach higher temperatures in use (e.g. centrally located tubes).

[0098] Note that although FIG. **2** shows ten tubes **130**, the methods, systems, and apparatus disclosed herein may use either more or fewer than ten tubes as suitable. For any tubing arrangement described herein, some or all of the illustrated tubes **130** may each represent groups of parallel tubes rather than individual tubes. As used herein, a plane defined by a side-by-side arrangement of tubes may be a plane defined by a center of the tubes, a tangent of a lower surface of the tubes, or a tangent of an upper surface of the tubes. Also, although tubes **130** are shown as lying in a plane, in other variations parallel tubes **130** may be arranged side-by-side in a nonplanar arrangement, e.g. to form a convex or a concave arc, or in two or more parallel or intersecting planes. Two such intersecting planes may form, for example a V-shape or chevron, or an inverted V-shape or chevron, relative to ground. In some cases a nonplanar arrangement may result from one or more tubes having a different exterior diameter than other tubes or one or more tubes positioned so as to be out of a plane defined by other tubes. Although the tubes **130** shown in FIG. **2** are illustrated to have substantially identical inner and outer diameters, in other variations (some of which are described below), one or more tubes may have a larger outer and/or inner diameter than other tubes in the same tubing arrangement. For example, a center-most tube or tubes may have a larger outer and inner diameter than an outer tube positioned at or near an outer side of a tubing arrangement. Referring now to FIG. **39**A, a tubing arrangement **1000** is illustrated in which the centers of tubes **130** define a plane **1001**, but the lower surfaces of the tubes **130** are not in the same plane because the centermost tubes **130-4** and **130-8** have a large diameter than outer tubes **130-1**, **130-2**, **130-3**, **130-5**, **130-6**, and **130-7**. FIG. **39**B illustrates a tubing arrangement **1003** in which the lower surfaces of the tubes **130** define a plane **1004**. Tubing arrangements such as those illustrated in FIGS. **39**A-**39**B can be selected based on the relative diameters of the tubes, the focusing of the reflectors on the tubing arrangements, and the positioning of any secondary reflector that may be present. For example, if no secondary reflector is present, it may be advantageous in certain circumstances to select a tubing arrangement such as that illustrated in FIG. **39**B, e.g. so that the larger diameter tubes do not effectively block light from reaching the smaller diameter neighboring tubes as illustrated in FIG. **39**A.

[0099] Referring now to FIG. **3**, a tubing arrangement **230** comprises tubes **130-1** through **130-8** in a solar absorber that are interconnected to provide the two-pass fluid flow paths shown. Heat transfer fluid (e.g. feedwater) from an inlet header flows in an outbound direction toward a far end of a receiver in one or more outbound paths (e.g. multiple parallel outbound paths) to make a first pass through a concentrated solar radiation profile (not shown) and then the flow from the one or more outbound paths is redirected (e.g. via a turnaround header) into one or more return paths to make a second pass through the concentrated solar radiation profile. In this particular example, one half of the tubing arrangement includes an outbound flow that comprises three parallel paths, and a return flow that comprises a single path in a direction anti-parallel to the outbound direction (counterflow). However, other variations are contemplated, in which any desired number of outbound parallel paths can be redirected into any desired number of return paths e.g. 1, 2, 4, 5, or 6 parallel outbound paths redirected into a single counterflow return path, or 1, 2, 3, 4, 5, or 6 parallel outbound paths redirected into 2 parallel counterflow return paths, or 1, 2, 3, 4, 5, or 6 parallel outbound paths redirected into 3 parallel counterflow return paths, or 1, 2, 3, 4, 5, or 6 parallel outbound paths redirected into 4 parallel counterflow return paths, or 1, 2, 3, 4, 5, or 6 parallel outbound paths redirected into 5 parallel counterflow return paths, or 1, 2, 3, 4, 5, or 6 parallel outbound paths redirected into 6 parallel counterflow return paths. Note that the above-referenced numbers of flow paths are intended to refer to an entire tubing arrangement in a receiver, or in half a tubing arrangement in a receiver, e.g. that is reflected in a mirror image relative to the receiver's centerline. As discussed in more detail below, some variations in tubing arrangements may include only branching or redirection from multiple parallel path tubes into the same number or fewer tubes (e.g. from multiple tubes into a single tube to avoid a scenario in which unbalanced branching into multiple tubes may lead to unstable or runaway operation). In some cases, one or more flow control devices can be included at a redirection or branching point, e.g. to allow balancing of flow between multiple branches in a tubing arrangement.

[0100] Referring again to FIG. **3**, heat transfer fluid (e.g. feedwater) is directed from inlet header **140** into three parallel outbound paths (outer-most tube **130-1** and its neighbors **130-2** and **130-3**) on one side of center line C of the receiver (not shown), and into three additional parallel outbound paths through outer-most tube **130-5** and its neighbors **130-6** and **130-7**. The fluid in tubes **130-1**, **130-2**, and **130-3** is combined at the end of those tubes (e.g. in turnaround header **175-1** as shown) to be redirected to flow through tube **130-4** in a return path counter-parallel to that through tubes **130-1**, **130-2**, and **130-3**. Similarly, the fluid in tubes **130-5**, **130-6**, and **130-7** is combined at the end of these tubes in turnaround header **175-2** to flow through tube **130-8** in a return path counter-parallel to that through tubes **130-5**, **130-6**, and **130-7**. Fluid from tubes **130-4** and **130-8** is then combined in outlet header **145**. In other variations, tubes **130-4** and **130-8** may be replaced with a single tube carrying the return flow of all of tubes **130-1**, **130-2**, **130-3**, **130-5**, **130-6**, and **130-7**. In yet other variations, some or all of the illustrated tubes **130** may each represent groups of parallel-connected tubes rather than individual tubes.

[0101] FIG. **3** shows an (imaginary) centerline C marked as a dashed line parallel to and located in the transverse center of tubes **130** in tubing arrangement **230**, about which flow paths through tubes **130-1-130-4** are symmetric to flow paths through tubes **130-5-130-8**. Flow paths similarly symmetric about a center line are exhibited, for example, below in FIGS. **4**, and FIGS. **5**A-**5**C, **6**, **9**, **10**, **11**, **12**, **16**A, **17**A, though the center lines of the respective tubing arrangements, solar absorbers or tubes are not expressly shown in those figures. Flow paths that are asymmetric with respect to a center line of the receiver may also be used in some variations, as illustrated for example in FIG. **7** and FIG. **8** below.

[0102] As described above, the tubing in a receiver may be arranged to correspond with a nonuniform transverse solar radiation intensity distribution. Referring still to FIG. **3**, in some variations the fluid flowing through tubes **130** is water and/or steam, and the tubes are illuminated with solar radiation having a nonuniform transverse intensity distribution with an intensity peak aligned with the centerline C, e.g.

shaped similarly to that illustrated in FIG. **2**. In such variations, the wings and shoulders of the intensity distribution may be incident on outermost tubes **130-1** and **130-5**, and on neighboring tubes **130-2**, **130-3** and **130-6**, **130-7**, respectively. Thus, the heat flux distribution into tubes **130-1**, **130-2**, **130-3**, **130-5**, **130-6**, and **130-7** for the outbound first pass may be relatively low so as to increase its temperature without inducing boiling. The peak intensity is incident on the centermost tubes **130-4** and **130-8** so that the corresponding heat flux in the second pass return path through centermost tubes **130-4** and **130-8** is greater than on the outermost tubes, so that the liquid water may be further heated to boil it to produce steam, and the steam may be further heated to produce superheated steam. Saturated or superheated steam may then exit tubes **130** through outlet header **145**. In such variations, the enthalpy of the fluid in tubes **130-1**, **130-2**, **130-3**, **130-5**, **130-6**, and **130-7** is initially approximately the same, and is then increased as the fluid absorbs heat during its first passage down the length of the tubes and further increased during its second pass return through tubes **130-4** and **130-8**.

[0103] Note that in the example just described and in the examples below, associations of particular heat absorption processes (heating liquid water, boiling water, superheating steam) with particular regions of a solar absorber and/or particular tubes among tubes **130** in a solar absorber are intended to refer to steady state operation of the solar absorber. Such associations may not necessarily hold during transient conditions, such as, for example, at start-up, at shutdown, and when clouds interrupt or diminish the solar flux.

[0104] Superheated steam generated in this variation, and in the other variations described below in this detailed description, may have, for example, a temperature of about 300° C. to about 450° C. and a pressure of about 70 bar to about 130 bar, or a temperature of about 370° C. to about 450° C. and a pressure of about 100 bar to about 130 bar. In some variations the superheated steam has a temperature of about 450° C. and a pressure of about 130 bar.

[0105] In any of the examples described herein, mass flow rates into a tube may be controlled with one or more flow control devices (e.g. valves and/or flow controlling orifices), and flow out of a tube and pressure may be controlled with one or more flow control devices (e.g. valves or flow controlling orifices). A flow controlling orifice may be a device that restricts flow (e.g. by having a reduced inner diameter) and/or modifies flow, e.g. to reduce turbulence, bubbles, rotational flow, or the like. A flow control device may be active (e.g. a valve that can be adjusted) or passive (a fixed diameter orifice or a valve that is fixed). In some cases, a valve may be used to determine a desired orifice size or during setup of a system, and subsequently the valve may be replaced by the orifice. In the case where a tubing arrangement comprises multiple parallel outbound tubes and/or multiple parallel return tubes, a single flow control device may be used to control mass flow rates into the multiple parallel tubes, and/or a single flow control device may be used to control flow out of multiple parallel return tubes. In other variations, a separate flow control device (e.g. a valve or an orifice) can be used on each outbound tube and/or on each return tube. In some cases, more than one flow control device may be used in combination, e.g. a flow controlling orifice may be used in series with a valve. As described above, in tubing arrangements in which multiple tubes in an upstream loop is branched into multiple tubes in a down stream loop, a flow control device can be used between the upstream loop and the downstream loop (e.g. at a turnaround region) to reduce or prevent flow imbalance from developing in the downstream loop. In some cases, a flow control device on a tube in an upstream loop (e.g. at an inlet to an upstream loop) can be used to control flow in a downstream loop, e.g. where that tube is channeled into a single tube so that the potential for flow imbalance to develop is reduced. Valves may be selected to modulate control of medium to low flow rates at system pressures up to about 5000 psig. Any suitable valve may be used, e.g. a standard globe control valve sized for ½", ¾", or 1" sizes such as any one of the family of RESEARCH CONTROL® Valve available from BadgerMeter, Inc. Tulsa, Okla. In some variations, a 1" size RESEARCH CONTROL® Valve is used.

[0106] In the example of FIG. **3**, fluid (e.g., water, steam, and superheated steam) flow rates through tubes **130** may be controlled, for example, with flow control devices (e.g. valves and/or orifices) **150-1** and **150-2**. Flow rates through tubes **130** may be controlled with these flow control devices, for example, to provide a desired steam quality (e.g., quality of saturated steam, or temperature and/or pressure of superheated steam) in outlet header **145**. Relative fluid flow rates through the parallel flow paths provided by tubes **130-1**, **130-2**, and **130-3** may be governed by optional flow control devices (which may be orifices) **155-1** and **155-2**. Device **155-1** if an orifice can have a diameter smaller than that of orifice **155-2**, in some variations, providing a slower flow rate through tube **130-1** than through tube **130-2**. Although not shown in FIG. **3**, an optional flow control device may govern flow through parallel tube **130-3**, which may provide a faster flow through tube **130-3** than through tube **130-2** or tube **130-1**. Similarly, relative fluid flow rates through the parallel flow paths provided by tubes **130-5**, **130-6**, and **130-7** may be governed by optional flow control devices (e.g. orifices) **155-5** and **155-6**, and optionally a flow control device on tube **130-7** (not shown). Device **155-5**, if an orifice, has a diameter smaller than that of device **155-6**, in some variations, providing a slower flow rate through tube **130-5** than through tube **130-6**. A flow control device on tube **130-7**, if used, may provide a faster flow through tube **130-7** than through tube **130-5** or tube **130-6**.

[0107] It should be understood that additional tubing arrangements are contemplated in which the heat transfer fluid makes more than two passes through a region of concentrated solar radiation, e.g. three, four, five, or six passes. An example of a tubing arrangement in which heat transfer fluid makes four passes through a region of concentrated solar radiation is illustrated in FIG. **4**. There, tubing arrangement **330** comprises tubes **130** that are interconnected in such a way so as to accomplish four-pass fluid flow paths. Fluid from inlet header **140** flows in parallel paths through outer-most tubes **130-1** and **130-5**. Fluid from tube **130-1** then follows a serpentine path through tubes **130-2**, **130-3**, and **130-4** alternately counter-parallel and parallel to that through tube **130-1**. Similarly, fluid from tube **130-5** follows a serpentine path through tubes **130-6**, **130-7**, and **130-8** alternately counter-parallel and parallel to that through tube **130-5**. Fluid from tubes **130-4** and **130-8** (e.g. saturated steam or superheated steam) is then combined in outlet header **145**. In other variations, tubes **130-4** and **130-8** may be replaced with a single tube carrying the return flow from tubes **130-3** and **130-7**. In yet other variations, some or all of the illustrated tubes **130** may each represent groups of parallel tubes rather than individual tubes.

[0108] Referring still to FIG. **4**, in some variations the fluid flowing through tubes **130** is water. In some cases, the tubes are illuminated with solar radiation having a nonlinear transverse intensity distribution, e.g. shaped similarly to that illustrated in FIG. **2**. In such variations, the heat flux distribution into tubes **130** may heat liquid water flowing through tubes **130** to increase its temperature under relatively low heat flux (compared to the peak heat flux provided by the concentrated solar radiation) in outer ones of tubes **130** (e.g. **130-1**, **130-2**, **130-5**, **130-6**), then boil the liquid water to generate steam under relatively higher heat flux in tubes nearer to the center of tubes **130** (e.g., **130-3**, **130-4**, **130-7**, **130-8**), then (optionally) superheat the steam, at a comparable or yet higher heat flux in the center-most tube or tubes of tubes **130** (e.g., **130-4**, **130-8**). Saturated or superheated steam may then exit tubes **130** through outlet header **145**. In such variations, the enthalpy of the fluid in tubes **130-1** and **130-5** is initially approximately the same, and is then increased as the fluid absorbs heat during its passage through the tubes.

[0109] In the example of FIG. **4**, fluid (e.g., water, steam, and superheated steam) flow rates through tubes **130** may be controlled, for example, with flow control devices **160-1** and **160-5**. Flow rates through tubes **130** may be controlled with these valves or orifices, for example, to provide a desired steam quality (e.g., quality of saturated steam, temperature and/or temperature/pressure of superheated steam) in outlet header **145**.

[0110] FIGS. **5**A-**5**C show an example arrangement of tubes **130** supporting the flow paths shown in FIG. **4**. These figures show an example distribution of fluid heat absorption processes in tubes **130** for a variation in which the heat absorbing fluid is water. Three regions shown with diagonal lines, crosshatching, and solid shading, respectively, illustrate sections in which water is heated to increase its temperature (economizer sections), saturated water is boiled to generate steam (boiler or evaporator sections), and steam is superheated (superheating sections). A first economizer section includes tubes **130-1** and **130-2**, a first boiler section includes tube **130-3** and a portion of tube **130-4**, and a first superheating section includes the remainder of tube **130-4**. A boundary between the first boiler section and the first superheating section occurs in tube **130-4** at location **170-4**. A second economizer section includes tubes **130-5** and **130-6**, a second boiler section includes tube **130-7** and a portion of tube **130-8**, and a second superheating section includes the remainder of tube **130-8**. A boundary between the second boiler section and the first superheating section occurs in tube **130-8** at location **170-8**.

[0111] In some variations of any of the fluid flow path arrangements disclosed herein, temperature measurements may be made on either side of the boiler/superheating boundaries (e.g., boundaries **170-4** and **170-8** in FIGS. **5**A-**5**C and boundaries **1176-4** and **1176-8** in FIGS. **26**A-**26**B) to aid in controlling fluid flow rates through tubes **130**. For example, if a temperature measurement on what is expected or intended to be a superheating side of a boiler/superheat boundary has a value corresponding to liquid water, the flow rate through the tubes in which that boundary occurs may be decreased. Alternatively, if a temperature measurement on what is expected to be a boiler side of a superheating/boiler boundary corresponds to superheated steam, the flow rate through the tubes in which that boundary occurs may be increased. Additionally or alternatively, fluid flow may be controlled using any suitable temperature and/or pressure measurements made elsewhere among tubes **130**. In some cases, a temperature in the economizing region of a tubing arrangement can be used as a feedback control variable for a control scheme. In some cases, a length of a tube can be used as a feedback control variable for a control scheme. In some variations, an attemperating spray can be used to adjust a temperature in a tube. An attemperating spray can be used alone or in combination with controlling mass flow of heat transfer fluid through a tube to achieve a desired output (quality and/or flow rate) of steam, or to control production of superheated steam (e.g. flow rate and temperature and/or pressure of superheated steam). Such additional or alternative control schemes may include or be similar to, but are not limited to, those disclosed in U.S. Patent Application Ser. No. 61/216,253, titled “Systems and Methods for Producing Steam Using Solar Radiation,” filed May 15, 2009, incorporated herein by reference in its entirety and/or those disclosed in U.S. Patent Application Ser. No. 61/216,878, also titled “Systems and Methods for Producing Steam Using Solar Radiation,” filed May 22, 2009, incorporated herein by reference in its entirety.

[0112] In some variations, fluid flow through tubes **130** is controlled by one, or at least one, flow control device (e.g. valve or orifice) for each (e.g., saturated steam or superheated steam) tube through which fluid exits tubes **130**. In some variations, all parallel flow paths in which water may boil (e.g., the three tubes on either side of tubes **130** in FIG. **3**) have their relative flow rates controlled by one or more flow control mechanism such as, for example, orifices or valves. In some variations in which superheated steam is generated, the temperature of the superheated steam is measured at the outlet of any tube through which the superheated steam exits tubes **130**. The measured temperature may be used, for example, to provide feedback for control valves controlling fluid flow through the superheating steam tube or tubes.

[0113] Fluid flow control schemes identical to or substantially similar to those so far disclosed in this specification (including use of valves, orifices, and temperature and pressure measurements) may also be used, in some variations, to control examples of fluid flow through tubes in solar absorbers described below in this detailed description.

[0114] In some variations in which the fluid flow path or paths make two passes (i.e., outbound and return) along tubes **130**, such as the example shown in FIG. **3**, a solar thermal receiver supporting such a flow path or paths may be inclined (e.g., the solar thermal receiver may be located on sloping ground) with tubes **130** oriented so that water in tubes **130** flows downhill and steam in tubes **130** flows uphill.

[0115] Referring now to FIG. **6**, in another variation, tubes **130** in a solar absorber are interconnected to provide the five-pass fluid flow paths shown. Fluid from inlet header **140** flows in parallel paths through outer-most tubes **130-1** and **130-5**. Fluid from tube **130-1** then follows a serpentine path through tubes **130-2**, **130-3**, and **130-4** alternately counter-parallel and parallel to that through tube **130-1**. Similarly, fluid from tube **130-5** follows a serpentine path through tubes **130-6**, **130-7**, and **130-8** alternately counter-parallel and parallel to that through tube **130-5**. Fluid from tubes **130-4** and **130-8** is then combined in tube **130-9**, which runs counter-parallel to tubes **130-4** and **130-8** to connect to outlet header **145**. In other variations, some or all of the illustrated tubes **130** may each represent groups of parallel tubes rather than individual tubes.

[0116] Referring still to FIG. 6, in some variations the fluid flowing through tubes **130** is water, and the tubes are illuminated with solar radiation having an intensity distribution shaped similarly to that of FIG. **2**. In such variations, the heat flux distribution into tubes **130** may heat liquid water flowing through tubes **130** to increase its temperature under relatively low heat flux (compared to the peak heat flux provided by the concentrated solar radiation) in outer ones of tubes **130** (e.g., **130-1**, **130-2**, **130-5**, **130-6**), then boil the liquid water to generate steam under relatively higher heat flux in tubes nearer to the center of tubes **130** (e.g., **130-3**, **130-4**, **130-7**, **130-8**), then (optionally) superheat the steam at a comparable or yet higher heat flux in the center-most tube or tubes of tubes **130** (e.g., **130-9**). Saturated or superheated steam may then exit tubes **130** through outlet header **145**. In such variations, the enthalpy of the fluid in tubes **130-1** and **130-5** is initially approximately the same, and is then increased as the fluid absorbs heat during its passage through the tubes.

[0117] In the example of FIG. **6**, fluid (e.g., water, steam, and superheated steam) flow rates through tubes **130** may be controlled, for example, with flow control devices (e.g. valves or orifices) **160-1** and **160-5**. Flow rates through tubes **130** may be controlled with these flow control devices, for example, to provide a desired steam quality (e.g., quality of saturated steam, temperature and/or pressure of superheated steam) in outlet header **145**.

[0118] In another variation, tubes **130** in a solar absorber are interconnected to provide the four-pass flow paths shown in FIG. **7**. Fluid from inlet header **140** flows through tube **130-1** to header **200**, through header **200** across to tube **130-5**, then through tube **130-5** (counter-parallel to the path through tube **130-1**) to header **210**. Fluid from header **210** flows in parallel paths through tubes **130-2** and **130-6** (parallel to the path through tube **130-1**). Fluid from tube **130-2** then follows a serpentine path through tubes **130-3** and **130-4** alternately counter-parallel and then parallel to that through **130-2**. Similarly, fluid from tube **130-6** follows a serpentine path through tubes **130-7** and **130-8** alternately counter-parallel to and then parallel to that through tube **130-6**. Fluid from tubes **130-4** and **130-8** is then combined in outlet header **145**. In other variations, tubes **130-4** and **130-8** may be replaced with a single tube carrying the flow from tubes **130-3** and **130-7** to outlet header **145**. In yet other variations, some or all of the illustrated tubes **130** may each represent groups of parallel tubes rather than individual tubes.

[0119] Referring still to FIG. **7**, in some variations the fluid flowing through tubes **130** is water, and the tubes are illuminated with solar radiation having an intensity distribution shaped similarly to that of FIG. **2**. In such variations, the heat flux distribution into tubes **130** may heat liquid water flowing through tubes **130** to increase its temperature under relatively low heat flux (compared to the peak heat flux provided by the concentrated solar radiation) in outer ones of tubes **130** (e.g., **130-1**, **130-2**, **130-5**, **130-6**), then boil the liquid water to generate steam under relatively higher heat flux in tubes nearer to the center of tubes **130** (e.g., **130-3**, **130-4**, **130-7**, **130-8**), then (optionally) superheat the steam at a comparable or yet higher heat flux in the center-most tube or tubes of tubes **130** (e.g., **130-4**, **130-8**). Saturated or superheated steam may then exit tubes **130** through outlet header **145**.

[0120] In the example of FIG. **7**, fluid (e.g., water, steam, and superheated steam) flow rates through tubes **130** may be controlled, for example, with valves or fixed diameter orifices **215-2** and **215-6**. Flow rates through tubes **130** may be controlled with these valves or orifices, for example, to provide a desired steam quality (e.g., quality of saturated steam, temperature and/or pressure of superheated steam) in outlet header **145**.

[0121] In another variation, tubes **130** in a solar absorber are interconnected to provide the four-pass flow paths shown in FIG. **8**. Fluid from inlet header **140** flows through tube **130-1** to header **220**, then through header **220** across to and through tube **130-5** counter-parallel to the path through tube **130-1**. Fluid from tube **130-5** then flows through tube **130-6** (counter-parallel to its path through tube **130-5**) to header **225**, then through header **225** across to and through tube **130-2** (counter-parallel to the path through **130-1**) to header **231**. Fluid from header **231** then flows in parallel paths through tube **130-3** and tube **130-7**, parallel to the path through tube **130-1**, to header **240**. Fluid from header **240** then flows in parallel paths through tube **130-4** and **130-8** (counter-parallel to the path through tube **130-1**) and is then combined in outlet header **145**. In other variations, tubes **130-4** and **130-8** may be replaced with a single tube carrying the flow from header **240** to outlet header **145**. In yet other variations, some or all of the illustrated tubes **130** may each represent groups of parallel tubes rather than individual tubes.

[0122] Referring still to FIG. **8**, in some variations the fluid flowing through tubes **130** is water, and the tubes are illuminated with solar radiation having an intensity distribution shaped similarly to that of FIG. **2**. In such variations, the heat flux distribution into tubes **130** may heat liquid water flowing through tubes **130** to increase its temperature under relatively low heat flux (compared to the peak heat flux provided by the concentrated solar radiation) in outer ones of tubes **130** (e.g., **130-1**, **130-2**, **130-5**, **130-6**), then boil the liquid water to generate steam under relatively higher heat flux in tubes nearer to the center of tubes **130** (e.g., **130-3**, **130-4**, **130-7**, **130-8**), then (optionally) superheat the steam at a comparable or yet higher heat flux in the center-most tube or tubes of tubes **130** (e.g., **130-4**, **130-8**). Saturated or superheated steam may then exit tubes **130** through outlet header **145**.

[0123] In the example of FIG. **8**, fluid (e.g., water, steam, and superheated steam) flow rates through tubes **130** may be controlled, for example, with valves or fixed diameter orifices **245-3** and **245-7**. Flow rates through tubes **130** may be controlled with these valves or orifices, for example, to provide a desired steam quality (e.g., quality of saturated steam, temperature and/or pressure of superheated steam) in outlet header **145**.

[0124] Referring now to FIG. **9**, in another variation tubes **130** are interconnected to provide the three-pass flow paths shown. Fluid from inlet header **140** flows in parallel paths through outer-most tubes **130-1** and **130-4**. Fluid from tube **130-1** then follows a serpentine path through tubes **130-2** and **130-3**, alternately counter-parallel and parallel to that through tube **130-1**. Similarly, fluid from tube **130-4** follows a serpentine path through tubes **130-5** and **130-6**, alternately counter-parallel and parallel to that through tube **130-4**. Fluid from tubes **130-3** and **130-6** is then combined in outlet header **145**. In other variations, tubes **130-3** and **130-6** may be replaced with a single tube carrying the return flow from tubes **130-2** and **130-5**. In yet other variations, some or all of the illustrated tubes **130** may each represent groups of parallel tubes rather than individual tubes.

[0125] Referring still to FIG. **9**, in some variations the fluid flowing through tubes **130** is water, and the tubes are illuminated with solar radiation having an intensity distribution shaped similarly to that of FIG. **2**. In such variations, the heat flux distribution into tubes **130** may heat liquid water flowing through tubes **130** to increase its temperature under relatively low heat flux (compared to the peak heat flux provided by the concentrated solar radiation) in outer ones of tubes **130** (e.g., **130-1**, **130-2**, **130-4**, **130-5**), then boil the liquid water to generate steam under relatively higher heat flux in tubes nearer to the center of tubes **130** (e.g., **130-2**, **130-3**, **130-5**, **130-6**), then (optionally) superheat the steam at a comparable or yet higher heat flux in the center-most tube or tubes of tubes **130** (e.g., **130-3**, **130-6**). Saturated or superheated steam may then exit tubes **130** through outlet header **145**. In such variations, the enthalpy of the fluid in tubes **130-1** and **130-4** is initially approximately the same, and is then increased as the fluid absorbs heat during its passage through the tubes.

[0126] In the example of FIG. **9**, fluid (e.g., water, steam, and superheated steam) flow rates through tubes **130** may be controlled, for example, with valves **250-1** and **250-4**. Flow rates through tubes **130** may be controlled with these valves or orifices, for example, to provide a desired steam quality (e.g., quality of saturated steam, temperature and/or pressure of superheated steam) in outlet header **145**.

[0127] Referring now to FIG. **10**, in another variation tubes **130** are interconnected to provide a three pass flow paths as shown. Fluid from inlet header **140** flows in parallel paths through tubes **130-1** and **130-2** to header **260**, and through tubes **130-5** and **130-6** to header **265**. Fluid from header **260** then follows a serpentine path through tubes **130-3** and **130-4**, alternately counter-parallel and parallel to the path through tube **130-1**. Similarly, fluid from header **265** follows a serpentine path through tubes **130-7** and **130-8**, alternately counter-parallel and parallel to the path through tube **130-5**. Fluid from tubes **130-4** and **130-8** is then combined in outlet header **145**. In other variations, tubes **130-4** and **130-8** may be replaced with a single tube carrying the return flow from tubes **130-3** and **130-7**. In yet other variations, some or all of the illustrated tubes **130** may each represent groups of parallel tubes rather than individual tubes.

[0128] Referring still to FIG. **10**, in some variations the fluid flowing through tubes **130** is water, and the tubes are illuminated with solar radiation having an intensity distribution shaped similarly to that of FIG. **2**. In such variations, the heat flux distribution into tubes **130** may heat liquid water flowing through tubes **130** to increase its temperature under relatively low heat flux (compared to the peak heat flux provided by the concentrated solar radiation) in outer ones of tubes **130** (e.g., **130-1**, **130-2**, **130-5**, **130-6**), then boil the liquid water to generate steam under relatively higher heat flux in tubes nearer to the center of tubes **130** (e.g., **130-3**, **130-4**, **130-7**, **130-8**), then (optionally) superheat the steam at comparable or relatively higher heat flux in the center-most tube or tubes of tubes **130** (e.g., **130-4**, **130-8**). Saturated or superheated steam may then exit tubes **130** through outlet header **145**.

[0129] In the example of FIG. **10**, fluid (e.g., water, steam, and superheated steam) flow rates through tubes **130** may be controlled, for example, with valves or fixed diameter orifices **270-1** and **270-5**. Flow rates through tubes **130** may be controlled with these valves or orifices, for example, to provide a desired steam quality (e.g., quality of saturated steam, temperature and/or pressure of superheated steam) in outlet header **145**.

[0130] In another variation, FIG. **11**A shows tubes **130** interconnected to support fluid flow paths that may match fluid heat absorption processes to, for example, the multi-peaked concentrated solar radiation intensity distribution ("I") shown in FIG. **11**B. Fluid from inlet header **140** flows in parallel paths through outer-most tubes **130-1** and **130-5** to, respectively, headers **280** and **290**. Fluid from tube **130-1** then flows through header **280** past tube **130-2** to tube **130-3**, then flows through tubes **130-3** and **130-2**, alternately counter-parallel and parallel to the path through tube **130-1**, to header **285**. Fluid from tube **130-2** then flows through header **285** past tube **130-3** to tube **130-4**, then through tube **130-4** counter-parallel to the path through tube **130-1** to outlet header **145**. Similarly, fluid from tube **130-5** flows through header **290** past tube **130-6** to tube **130-7**, then through tube **130-7** and **130-6**, alternately counter-parallel and parallel to the path through tube **130-5**, to header **295**. Fluid from tube **130-6** then flows through header **295** past tube **130-7** to tube **130-8**, then through tube **130-8** to outlet header **145**. In other variations, headers **285** and **295** may be replaced by a single header, and tubes **130-4** and **130-8** may be replaced with a single tube carrying the return flow from that header. In yet other variations, some or all of the illustrated tubes **130** may each represent groups of parallel tubes rather than individual tubes.

[0131] Referring still to FIG. **11**A, in some variations the fluid flowing through tubes **130** is water, and the tubes are illuminated with solar radiation having an intensity distribution shaped similarly to that of FIG. **2**. In such variations, the heat flux distribution into tubes **130** may heat liquid water flowing through tubes **130** to increase its temperature under relatively low heat flux compared to the peak heat flux provided by the concentrated solar radiation (e.g., in tubes **130-1**, **130-3**, **130-5**, and **130-7**), then boil the liquid water to generate steam under relatively higher heat flux (e.g., in tubes **130-2**, **130-4**, **130-6**, and **130-8**), then (optionally) superheat the steam at comparable or relatively higher heat flux in the center-most tube or tubes of tubes **130** (e.g., **130-4**, **130-8**). Saturated or superheated steam may then exit tubes **130** through outlet header **145**.

[0132] In the example of FIGS. **11**A and **11**B, fluid (e.g., water, steam, and superheated steam) flow rates through tubes **130** may be controlled, for example, with valves or fixed diameter orifices **300-1** and **300-5**. Flow rates through tubes **130** may be controlled with these valves or orifices, for example, to provide a desired steam quality (e.g., quality of saturated steam, temperature and/or pressure of superheated steam) in outlet header **145**.

[0133] Referring now to FIG. **12**, in one variation a solar energy collection system comprises a first solar thermal absorber **310**, comprising tubes **130-1-130-6** interconnected to provide the flow paths shown, and a second solar absorber **320** comprising tubes **350-1-350-6** interconnected to provide the flow paths shown. Fluid from inlet header **140** flows in parallel through peripheral (e.g., outer-most and next outer-most) tubes **130-1**, **130-2**, **130-4**, and **130-5** of absorber **310** to header **325**, from which it is pumped by pump **330** to header **340** of absorber **320**. Fluid from header **340** flows in parallel through peripheral (e.g., outer-most and next outer-most) tubes **350-1**, **350-2**, **350-4**, and **350-5** to header **360**. Fluid from header **360** than flows in parallel through center-most tubes **350-3** and **350-4** (counter-parallel to the flow through tube **350-1**) to header **370**. Fluid from header **370** flows to separator **380**, which separates the fluid into gas and liquid phases. The liquid phase flows through conduit **385** to pump **330**, which returns it to absorber **320**. The gas phase flows through conduit **387** to header **390**, and then through center-most tubes **130-3** and **130-6** of absorber **310**, counter-parallel to the flow through tube c**130-1**, to outlet header **145**. In some variations, tubes **350-3** and **350-6** may be combined into a single tube, tubes **130-3** and **130-6** may be combined into a single tube, and/or some or all of tubes **130-1-130-6** and **350-1-350-6** may each represent groups of parallel tubes rather than individual tubes.

[0134] Referring still to FIG. **12**, in some variations the fluid flowing through solar energy absorbers **310** and **320** is water and the tubes in each absorber are illuminated with solar radiation having intensity distributions shaped similarly to that of FIG. **2**. In such variations, a relatively low heat flux (compared to the peak heat flux provided by the concentrated solar radiation) into tubes **130-1**, **130-2**, **130-4**, and **130-5** may heat liquid water to increase its temperature. A comparable relatively low (or relatively higher) heat flux into tubes **350-1**, **350-2**, **350-4**, and **350-5** may further heat the liquid water to increase its temperature and/or begin to boil it. A relatively higher heat flux into tubes **350-3** and **350-6** may begin and/or continue to boil the liquid water. A comparable or relatively yet higher heat flux into tubes **130-3** and **130-6** may further heat steam from separator **380** to superheat that steam.

[0135] As described above, the tubing arrangements may comprise one or more thermal expansion sections (e.g. loops, joints, flexible tube sections, or other suitable mechanism) to accommodate net and differential thermal expansion of multiple tubes in a receiver. More than one type of thermal expansion mechanism may be used within a single receiver, and a particular thermal expansion section inserted between tubes may be selected based on the net and/or relative thermal expansion anticipated for those tubes, keeping in mind that certain tubes are likely to experience larger temperature swings than other tubes (e.g. those tubes illuminated by the peak of the solar radiation intensity distribution are likely to reach a higher ultimate temperature than those illuminated with only the wings or shoulders of the concentrated solar radiation distribution). Further, a tube can be anchored at a position intermediate (e.g. midway) between its inlet end and its opposing far end so that tube expands in two directions away from the anchor. In a tubing arrangement, not every tube need have an anchor, as a tube's motion may be sufficiently controlled or limited by neighboring tubes in the arrangement. As illustrated in several examples below, a tubing expansion section may be essentially in the same plane as the tubing arrangement, or may extend out of a plane defined by the tubing arrangement.

[0136] Tubes can be supported along their length at any suitable interval. It may be desired to position supports as far apart as practicable, e.g. to reduce costs and/or to reduce shading. Further, each span of tubing can be supported as necessary for the diameter of tube in that span. For example, if a first pass contains smaller diameter tubes and a second pass contains a larger diameter tube, then supports in the first pass can be positioned closer together than supports in the second pass. If, for example, the first pass comprises 4 parallel tubes having a 1.66" outer diameter, and the second pass consists of a single tube having a 3.5" outer diameter, the tubes in the first pass could be supported approximately every 8 feet, while the tube in the second pass could be supported at intervals at least as great as 16 feet. Supporting all tubes at the same interval, regardless of tube diameter, may be redundant for the larger diameter tubes and could result in higher costs for tube support components.

[0137] Referring again to FIGS. **5**A-**5**C, tubes **130** comprise thermal expansion joints (e.g., loops) **180-1**, **180-2**, **180-3**, **190-1**, **190-2**, and **190-3** to accommodate differential thermal expansion among the interconnected tubes. In some variations, expansion loops that are expected or intended to experience two-phase (e.g., water and steam) flow are arranged to lie in the plane of tubes **130** to prevent water slug flow from developing. As an example, expansion loops **180-3** and **190-3** are expected to experience such two phase flow and hence lie in the plane of tubes **130**. Expansion loops not expected to experience two-phase flow may lie outside of the plane of tubes **130** (e.g., in a drop down configuration). Though expansion loops **180-1**, **180-2**, **190-1**, and **190-2** are also shown in the plane of tubes **130** in the illustrated variation, these expansion loops are not expected to experience two-phase flow and hence might alternatively be arranged to lie outside of the plane of tubes **130**.

[0138] Referring still to FIGS. **5**A-**5**C, in some variations portions of thermal expansion sections **180-2** and **190-2** connecting, respectively, to tubes **130-3** and **130-7** are fixed in place with respect to the ground, and all or substantially all other portions of tubes **130** may move with respect to the ground to accommodate bulk and/or differential thermal expansion.

[0139] Referring now to FIG. **19**A, a tubing configuration following a flow pattern as illustrated in FIG. **4** is illustrated. The variation in FIG. **19**A comprises thermal expansion sections that comprise a vertically oriented loop. As used in this context, "vertically oriented" means having an orientation that includes vector component that is substantially perpendicular to ground, e.g. about 30°, about 45°, about 60°, or about 90° relative to ground. A vertically oriented loop may be used in a situation in which the heat transfer fluid is not expected to change phase during steady state operation. Heat transfer fluid (e.g. feedwater) flows into inlet header **140** and enters tube **130-1** through an optional first flow control device **150-1** and enters tube **130-5** through an optional second flow control device **150-2**. Tubes **130-1** and **130-5** are anchored at a position X that may be approximately midway between an inlet end (A) and an opposite far end (B) of the receiver (not shown). The fluid in tube **130-1** flows in direction **1** to reach a thermal expansion section **1170-1** where it is redirected towards the centerline of the tubing arrangement (indicated by dashed line C) and to flow in an opposite counterflow direction **2** in tube **130-2**. The thermal expansion section **1170-1** is vertically oriented so as to extend downward out of a plane defined by tubes **130**. Fluid in tube **130-2** reaches a second thermal expansion section **1170-2** in which it is redirected towards C and to flow in a direction **3** (parallel to direction **1**) in tube **130-3**. In this particular variation, the second expansion section **170-2** is also vertically oriented relative to the tubes **130**. Flow in tube **130-3** flows in direction **3** until it reaches a turnaround section **172-1**, where it is redirected towards C and to flow in direction **4** (parallel to direction **2**) through tube **130-4**, where it exits via outlet header **145** (e.g. as steam or superheated steam). An optional flow control device **1180** may be provided in outlet header **145** to control outflow and/or pressure within the tubing. By the time fluid reaches turnaround section **172-1**, the fluid has made **3** passes through the concentrated solar radiation, and may experience relatively high heat flux if the solar radiation profile is concentrated near the centerline C such that boiling has begun. Thus, it may be desirable for fluid to remain substantially in plane in the turnaround section **172-1** so as to reduce formation of phase slip or slug formation within the tube. Tube **130-3** may not include an anchor X and instead be supported by neighboring tubes **130-2** and **130-4**. At least a portion of tubing arrangement **331** is symmetrical with respect to centerline C, with tube **130-5** reflecting tube **130-1**, tube **130-6** reflecting tube **130-2**, tube **130-7** reflecting tube **130-3**, and tube **130-8** reflecting **130-4**, and expansion section **1170-3** reflecting expansion section **1170-1**, expansion section **1170-4** reflecting expansion section **1170-2**, and turnaround section **172-2** reflecting turnaround section **172-1**. Note that sections **172-1** and **172-2** can be configured so as to accommodate thermal expansion of and between tubes.

[0140] Another variation of a tubing arrangement is illustrated in FIG. **19**B. The example shown in FIG. **19**B shows a similar flow pattern as illustrated in FIG. **4** and FIG. **19**A. Here, only half the tubing arrangement **334** is shown, for ease of illustration. The tubing arrangement is symmetrical relative to centerline C. A vertical or other expansion section **1170** is used at each turnaround point. An optional flow control device **150-1** controls flow input to the outermost-tube **130-1**. In this particular example, each tube is anchored at a position X in between (e.g. midway) inlet end A and far end B of the receiver. The anchor positions on the different tubes may be at or near the same distance between end A and end B, or may be at different positions relative to end A and end B. Each of the expansion sections includes one or more flow control devices **145** that can be used to ensure homogeneous flow of any two phase fluid that may be present during stead state operations or during non-steady state operation, e.g. start up or transition conditions. Such flow control devices can operate to prevent or reduce the occurrence of slug flow and resulting potential damage to tubes and/or loss of control of system operation. Although the expansion sections **1170** are illustrated in this example as vertical expansion loops, they need not be. For example, section **1170-1** may be vertical and sections **1170-2** and **1170-3** may be horizontal, or sections **1170-1** and **1170-2** may be vertical and section **1170-3** may be horizontal. As described above, vertical expansion sections may be used at locations in a tubing arrangement in which no two phase flow is expected during steady state operation. However, the addition of flow control devices **145** may allow vertical expansion sections to be used even where two phase flow may occur during operation.

[0141] FIG. **20**A illustrates another example including a vertical expansion section in a region in which no phase change is expected during steady state operation. The flow path is similar to that shown in FIG. **4**. In this illustration, the tubing arrangement **332** is symmetrical with respect to a centerline C, but only one half of the symmetrical tubing arrangement is shown to simplify the illustration. Heat transfer fluid (e.g. water) is provided through an inlet header (not shown) to enter an outermost tube **130-1** through an optional flow control device **150-1**. The outermost tube **130-1** is anchored at an anchoring position X that is intermediate (e.g. midway) between the inlet end (A) and its opposite far end (B) of the receiver (not shown) such that the tube **130-1** can expand toward both A and B from anchor position X. Fluid flows in a direction **1** (from A toward B) through tube **130-1** until it reaches expansion section **1170-1**, where it is redirected toward the centerline C and to flow in direction **2** toward A (counterflow relative to direction **1**) in tube **130-2**. If the fluid is not expected to undergo phase transition in the expansion section **1170-1** during operation, a vertically oriented expansion section may be used, as illustrated. Fluid in tube **130-2** flows in direction **2** to reach turnaround section **172-1** where it is redirected toward the transverse center and to flow in tube **130-3** in a direction **3** toward B (parallel to direction **1**). Tube **130-3** can be anchored at a position X intermediate (e.g. midway) between inlet end A and far end B. Turnaround section **172-1** can be substantially in plane with the tubes **130** so as to reduce formation of slugs or phase slip in the event that the fluid has begun to boil. Fluid flows through tube **130-3** in direction **3** until it reaches another turnaround section **172-2**, in which it is redirected toward the transverse center C and to flow in direction **4** toward A (parallel to direction **2**), where it can exit the tubes as steam or superheated steam through an outlet header (not shown). Turnaround section **172-2** can be substantially in plane with the tubes **130** so as to reduce formation of slugs or phase slip. Tubes **130-2** and **130-4** may not include anchors in some variations. Instead, tube **130-2** can be supported by anchors on neighboring tubes **130-1** and **130-3**, and expansion of tube **130-2** can be accommodated by expansion sections **1170-1** and turnaround section **172-1**. Tube **130-4** can be supported by the anchor on tube **130-3** and expansion of tube **130-4** can be accommodated by turnaround section **172-2** and outlet section **178**. Another variation of a tubing arrangement is illustrated in FIG. **20**B. There, tubing arrangement **333** includes tube **130-1** is anchored as shown in FIG. **20**A, tube **130-4** is anchored at a position X between (e.g. midway) inlet end A and far end B, but tube **130-3** is not anchored. Note that in the examples shown in FIGS. **20**A-**20**B, the anchor positions X on different tubes can be aligned (e.g. at the same distance between end A and end B), or they may be at different positions relative to end A and end B. Anchoring positions may be selected for seismic purposes, so that a tube or tubes within a loop are sufficiently anchored against compressive and/or tensile forces from seismic motions. Thus, it may be advantageous to locate an anchor on a relatively large diameter tube to constrain motion of smaller diameter tubes in the loop if the larger diameter tube is better able to withstand compression, tension and/or to resist buckling. Note that turnaround sections **172** in FIGS. **20**A-**20**B can be configured to accommodate thermal expansion of and between tubes **130**.

[0142] Another tubing arrangement example **335** is illustrated in FIG. **21**A. The flow path in FIG. **21**A is similar to that shown in FIG. **4**. Half the tubing arrangement is illustrated, with the tubing arrangement **335** symmetrical with respect to center line C. In this variation, the turnaround sections **175** between tubes may or may not accommodate thermal expansion, and in some variations exhibit little or no ability to accommodate thermal expansion. The tubing arrangement may include only one anchor along the flow path between the inlet section **152** and the outlet section **153**, e.g. midway along that flow path at position X in the turnaround section **175-2** between tubes **130-2** and **130-3**. Thermal expansion may be accommodated in inlet sections **152** and **153**. For example, at least one of the inlet section or outlet section may comprise one or more bends that may expand, contract, and/or twist to accommodate tube length changes. One example f such a tube structure is one that comprises two or more bends, where at least two of two or more bends are not in the same plane as each other. For example, the two bends may be in planes that are approximately orthogonal to each other. Expansion of the tube may lead to torsional movement via expansion through the two bends that reduces stress on the tube and/or on any joints to the tubes. Illustrations of tubes having such bends to accommodate thermal expansion are provided in U.S. patent application Ser. No. 12/012,920, entitled "Linear Fresnel Solar Arrays and Components Therefor," which is incorporated herein by reference in its entirety.

[0143] Another variation is illustrated in FIG. **21**B, in which another tube **130-9** is placed in parallel with outermost tube **130-1**. Tube **130-1** may optionally include a flow control device **150-1**, and tube **130-9** may optionally include a flow control device **150-9**. Devices **150-1** and **150-9** may be independently controlled so as to allow balancing between tubes **130-1** and **130-9**. The tubes **130-1** and **130-9** feed into turnaround section **175-1**. Additional variations are contemplated in which more than one extra tubes (e.g. 2, 3, 4, or 5) are placed in parallel with tube **130-1** and fed into turnaround section **175-1**. Similar to the example illustrated in FIG. **21**A, the tubing arrangement **336** is anchored at only one position between the inlet section **152** and the outlet section **153**. Although the anchor position X is illustrated as located approximately midway along the tubing arrangement **336** between inlet **152** and outlet **153** in the turnaround section **175-2**, the anchor can be located along any one of the tubes **130**, or on another turnaround section **175**. The turnaround sections **175** may or may not accommodate thermal expansion, and in some variations exhibit little or no ability to accommodate thermal expansion. The thermal expansion may be accommodated in the inlet section **152** and in the outlet section **153**, e.g. as described in connection with FIG. **21**A.

[0144] As described above, combining flow from multiple tubes into a single turnaround header and expanding out into multiple tubes on the return path may lead to flow imbalance on the return path, especially in the case of two phase flow (e.g. when water is used as a heat transfer fluid), unless flow into the multiple parallel return tubes is controlled to guard against runaway conditions. For example, for a progression from 4 tubes in a first pass to 2 tubes in a return second pass, separate flow control devices (e.g. a valve, orifice plate or the like), can be placed on the inlets of the return tubes to allow for controlled balance of flow between the parallel paths. Alternatively or in addition, 2 of the 4 tubes in the first pass can be combined into a first return tube, and the other 2 of the 4 tubes in the first pass can be combined into a second return tube. For a progression from 3 parallel flow tubes in a first pass to 2 parallel flow tubes in a second pass, flow control devices can be used on each of the 2 return path tubes as described above. Alternatively or in addition, 2 of the 3 tubes in the first pass can be combined into one of the 2 tubes in the second return pass, and the remaining tube in the first pass can flow directly into the second of the 2 tubes in the second return pass. No intermediate flow control device is needed at a turnaround point as long as only one tube in a downstream pass is connected to any number of parallel tubes in an upstream pass, and instead flow through both the downstream and upstream passes can be controlled with flow control elements at the inlet to the downstream pass.

[0145] FIG. **22**A illustrates another example of a tubing arrangement **337**. The flow pattern is similar to that illustrated in FIG. **4**, in which there are four flow passes indicated by the encircled numbers in FIG. **22**A. Co-current flow through parallel tubes **130-1** and **130-9** in pass **1** travels from inlet end A toward far end B of the receiver. Optional flow control devices **150-1** and **150-9** can be used to control flow into tubes **130-1** and **130-9**, respectively. Co-current flow through parallel tubes **130-2** and **130-10** travels in pass **2** from far end B toward inlet end A. When parallel flow exists within a single pass with variable and/or unpredictable heat flux in steady state operation or during transients, it may not be possible to balance flow between the two parallel tubes, leading to a potential for pressure differences between the parallel tubes, which may result in unstable operation or runaway conditions, which, in turn, may result in dry out and possible damage of one or more tubes. The independently-controllable flow control devices **150-1** and **150-9** may be used to mitigate instability or runaway within the parallel tubes **130-1** and **130-9** and between the parallel tubes **130-2** and **130-10** if there is no mixing header used at the turnaround region. Thus, flow in tube **130-1** is redirected in turnaround section **175-1** into tube **130-2**, and flow in tube **130-9** is redirected in turnaround section **175-7** into tube **130-10**. In this particular example, the tubing arrangement is anchored (indicated by X) between pass **1** and pass **2** (e.g. in the turnaround sections **175-1** and **175-7**) and between pass **3** and pass **4** (e.g. in turnaround section **175-3**). Turnaround section **175-2** between pass **2** and pass **3** accommodates thermal expansion. Thermal expansion can optionally be accommodated in the inlet regions **152** and/or in outlet regions **153**, e.g. as described in connection with FIG. **21**A. Although turnaround section **175-2** is illustrated as one having a vertical drop, it may instead be a horizontal expansion section. If two phase flow occurs between passes **2** and **3**, one or more optional flow control devices (not shown) as described above may be used to ensure homogeneous flow or mitigate slug formation. Other variations are envisioned in which pass **3** and or pass **4** includes more than one parallel tube. In those situations, it is desired that no mixing headers are used at the turnaround regions, so that inlet flow control devices (e.g. **150-1** and **150-9**) can be used to control relative flow in the parallel tubes to avoid runaway conditions.

[0146] Another tube arrangement variation is illustrated in FIG. **22**B. The flow pattern in FIG. **22**B is similar to that illustrated in FIG. **4** and in FIG. **22**A. In the particular variation shown in FIG. **23**B, the tubing arrangement **338** comprises a turnaround section **175-2** that includes a horizontal expansion device **177** that does not substantially displace fluid in the vertical direction, thereby reducing the chance that slug flow behavior is induced in this expansion section. The tubing arrangement is anchored at a position X located between passes **3** and **4**. Tubing upstream of the anchor position can expand via outlet section **153**, and tubing downstream of the anchor position can expand via inlet section **152**, e.g. as described in connection with FIG. **21**A.

[0147] Another variation of a tubing arrangement **139** is illustrated in FIG. **23**A. The fluid flow pattern in FIG. **23**A is similar to that illustrated in FIG. **4** and in FIG. **22**B. Tubing in arrangement **139** is anchored in the second pass, e.g. each of tubes **130-10** and **130-2** are anchored at a position X that is intermediate (e.g. midway) between inlet end A and far end B of the receiver. The anchoring positions X may be the same or different on the tubes **130-2** and **130-10**, relative to inlet end A and far end B. Differential thermal expansion in tubes in pass **1** upstream relative to anchor positions X is accommodated in inlet section **152**, and differential thermal expansion in passes **3** and **4** downstream relative to anchor positions X is accommodated in outlet section **153**. Differential expansion between the tubes **130-2** and **130-10** is accommodated for in the expansion section **177**.

[0148] Still another variation of a tube arrangement **440** is illustrated in FIG. **23**B. The fluid flow pattern in FIG. **23**B is similar to that illustrated in FIG. **4** and FIG. **22**B. In this particular variation, tubing arrangement **440** comprises a turnaround section **175-2** that includes two expansion sections **177-1** and **177-2**. Tube **130-10** flows through expansion section **177-1** before joining with tube **130-3** for the third pass through the receiver, and tube **130-2** flows through another expansion section **177-2** before joining with tube **130-3** for the third pass. One or more of the expansion sections **177** may be, but need not be, horizontally oriented. In this particular variation, the tubing arrangement is anchored at position X between the third and fourth passes in turnaround section **175-3**, and at positions X in the turnaround sections **175-1** and **175-7**. Differential expansion in the first pass can be accommodated by the inlet section **152**, and differential expansion in the fourth pass can be accommodated by outlet section **153**. Differential expansion in the second and third passes can be accommodated by the expansion sections **177**.

[0149] Another variation of a tubing arrangement is illustrated in FIG. **24**. Tubing arrangement **141** is routed so that heat transfer fluid makes two passes through a receiver, similar to the flow pattern illustrated in FIG. **3**. One or both passes may include multiple parallel tubes. As illustrated, the tubing arrangement may be symmetrical relative to centerline C. In the example illustrated, the first pass includes a first set of parallel tubes **130-1**, **130-2**, **130-3**, **130-4**, and a second set of outbound parallel tubes **130-6**, **130-7**, **130-8**, **130-9** and **130-10**. Inlet (e.g. feedwater inlet) **140** is controlled into the first set of outbound parallel tubes by flow control device **150-1**. An optional flow control device **150-2** may separately control flow into the second set of outbound parallel tubes. Optionally, another flow control device **155** may be placed in series with flow control device **150-1** on one or more of the tubes **130-1** through **130-5** to individually control flow into that parallel outbound tube, and another flow control device **155** may be placed in series with flow control device **150-1** on one or more of the tubes **130-6** through **130-10** to individually control flow into that parallel outbound tube. As described earlier, the flow control devices **150** and **155** may be adjustable valves, or fixed diameter orifices. In some cases the flow control devices may be **150** may be adjustable valves and at least one of the flow control devices **155** (if present) may be fixed diameter orifices. Although this particular variation is illustrated with 4 parallel outbound tubes on each side of the centerline C, any number of parallel outbound tubes may be used in a two pass configuration, e.g. 2, 3, 4, 5, 6, 7, 8, 9, or 10.

[0150] Still referring to FIG. **24**, the outbound parallel tubes are redirected in a turnaround section **175-1** to make a second pass through the receiver in a counterflow direction. In this particular variation, the return path is represented by a single tube **130-5**. However, other variations are contemplated in which the return path includes multiple parallel tubes, up to an equivalent number of parallel tubes in the first pass. In the example illustrated in FIG. **24**, four outbound tubes are combined in turnaround header **175** and then directed into a single return path. In general, any configuration involving multiple outbound tubes feeding into a single return tube can be operated with a single flow control device **150**, so that individual tube flow control devices **155** are optional. If the configuration allows for multiple parallel outbound tubes feeding into multiple parallel return tubes, flow from the multiple parallel outbound tubes should not be mixed in a turnaround header and then split into multiple parallel return flows unless the turnaround header includes one or more flow control devices that allows balancing of flow between the multiple return lines to avoid runaway conditions from developing. In one variation, mixing in the turnaround header should be limited so that each of the parallel paths within the first pass feeds into a parallel return path within the second pass. Control of the parallel paths in the second pass can be accomplished via the same flow control device that controls the upstream path in the first pass. Thus, in the case of multiple parallel return paths in a two pass system, individual flow control devices **155** may be used to control flow in an outbound tube and its corresponding single return path. In general, if the ratio between the outbound tubes and return tubes is an integral number, a tubing arrangement can be configured that does not require a flow control device between the first and second passes.

[0151] Two pass tubing arrangements can have a variety of anchoring configurations. In the example illustrated in FIG. **25**A, a two pass tubing arrangement **400** includes 3 parallel outbound tubes **130-1**, **130-2** and **130-3** feeding into a turnaround section **175-1** and redirected into a single return tube **130-4**. The tubing arrangement **400** may, but need not be, symmetrical, e.g. so that centerline C provides a plane of symmetry between two halves of the tubing arrangement. The turnaround section **175-1** may or may not be configured to accommodate net or relative thermal expansion of the tubes. At least a portion of the differential expansion between tubes in the first pass and the second pass can be accommodated by the vertical inlet section **152**, e.g. as described in connection with FIG. **21**A. As described above, optional flow control devices **155** may be used to control flow into each of the tubes with outbound flow. Although not illustrated in FIG. **25**B, some variations may not have a flow control device to control flow into each outbound tube, and may instead have a flow control device on some of the outbound tubes (e.g. on the tubes that will receive lowest heat flux during operation), or a single flow control device on an inlet (e.g. feedwater inlet) to control flow into the set of parallel-connected tubes, or an inlet flow control device in series with a flow control device on any one of or multiple ones of the parallel-connected tubes. The tubing arrangement **400** includes a single anchor at position X on the single return tube **130-4**, where the anchor position X is located between (e.g. midway) the inlet end A and the far end B of the receiver. The position of X can be selected so that the expansion in tube **130-4** toward the far end B matches or exceeds the total expected expansion in the first pass. If the tubes in the first pass are on average colder than in the second pass and expand through a phase change in the second pass (e.g. due to a nonuniform solar radiation profile in which the relatively higher intensity intersects the return tube or tubes), then larger diameter tubes may be used in the second pass. The anchor position X on the larger return tube or tubes can be selected so that the expansion of the large tube matches or exceeds that of the total expansion of the smaller diameter tubes in the first pass, thereby keeping the smaller tubes in tension, reducing compression and resultant buckling in the smaller diameter tubes. At least some of the thermal expansion of tube **130-4** can be accommodated by outlet section **153**, e.g. as described in connection with FIG. **21**A.

[0152] In another variation of a two pass tubing arrangement **143** illustrated in FIG. **25**B, an anchor position X is located in a turnaround section **175-1**. Tubing arrangement **143** illustrated in FIG. **25**B differs from tubing arrangement **400** illustrated in FIG. **400** in the position of the anchor. In the variation illustrated in FIG. **25**B, thermal expansion is accommodated at the vertical inlet section **152** and the vertical outlet section **153**, e.g. as described in connection with FIG. **21**A.

[0153] In still another variation of a two pass tubing arrangement **144** illustrated in FIG. **25**C, an expansion section (e.g. vertical or horizontal) is used in the turnaround section **175**. As shown, a flow control device **145** can be used at the turnaround to prevent phase slip or slug formation if two phase fluid is formed before the second pass. The use of an expansion section in the turnaround section **175** allows each tube to be anchored between the inlet end A and the far end B (indicated by anchor positions X). Here, again, anchor positions need not be the same (relative to inlet end A and far end B) for different tubes. For example, depending on the diameter, temperature excursions, and construction of the various tubes **130** in the arrangement **144**, anchor positions X can be selected to coordinate relative expansion of the tubes **130**, e.g. so that smaller diameter tubes are shielded from compression forces that could lead to buckling.

[0154] An example of a tubing arrangement supporting a two pass flow path (e.g. as illustrated in FIGS. **3**, **24**, and **25**A-**25**C) is provided in FIGS. **26**A-**26**B. There, the tubing arrangement **201** comprises three outbound parallel tubes **130-1**, **130-2**, **130-3** that are fed in a first pass into a turnaround header **175-1**, in which flow is redirected into a counterparallel direction in a single return tube **130-4** in the second pass. The return tube **130-4** is arranged closest to the centerline C of the receiver, and the tubing arrangement **201** can be, but need not be, symmetrical with respect to the transverse centerline C. The fluid can undergo a phase change before or during the second pass, so that the diameter of the return tube **130-4** can be selected to be larger than that of the outbound tubes, e.g. the outbound tubes can have an inner or outer diameter of about 1.5", 1.66", 2.0", or 2.5", and the return tube can have an inner or outer diameter that is about 0.5", 1.0", or 1.5" larger than that of the outbound tubes. In some variations, 2" inner or outer diameter outbound tubes are used with a 3" inner or outer diameter return tube, and in some variations, 1.66" inner or outer diameter outbound tubes are used with a 3.5" inner or outer diameter return tube. FIG. **26**A illustrates a variation in which the center line of the multiple tubes forms a plane **404** so that lower surfaces of larger diameter tubes fall below the lower surfaces of smaller diameter tubes. FIG. **26**B illustrates a tubing arrangement variation **202** in which the lower surfaces of all tubes, regardless of diameter, form a plane **405**. Other variations are contemplated in which an upper surface of the multiple tubes forms a plane, or in which the tubes are in a nonplanar arrangement, e.g. arranged in a convex or concave form such as an upright or inverted chevron.

[0155] Any anchoring configuration described herein or otherwise discovered can be used with the tubing configuration illustrated in FIGS. **26**A-**26**B. Optionally, the tubing configuration illustrated in FIG. **26**A-**26**B can be anchored similarly to that illustrated in FIG. **25**A, in which only the return tubes **130-4** and **130-8** are anchored at position **275-4** and **275-8**, respectively, that are approximately intermediate (e.g. midway) between inlet end A and far end B of the receiver. Thus, differential expansion of outbound tubes upstream of the second pass can be accommodated by an inlet section (not shown), and expansion of the return tube downstream of the anchor can be accommodated by the vertical outlet section (not shown). For example, at least one of the inlet section or outlet section may comprise one or more bends that may expand, contract, and/or twist to accommodate tube length changes. One example f such a tube structure is one that comprises two or more bends, where at least two of two or more bends are not in the same plane as each other. For example, the two bends may be in planes that are approximately orthogonal to each other. Expansion of the tube may lead to torsional movement via expansion through the two bends that reduces stress on the tube and/or on any joints to the tubes. Illustrations of tubes having such bends to accommodate thermal expansion are provided in U.S. patent application Ser. No. 12/012,920, entitled "Linear Fresnel Solar Arrays and Components Therefor," which is incorporated herein by reference in its entirety.

[0156] The positioning of the anchor position can be selected so that expansion in the smaller diameter outbound tubes is less than or approximately equal to the expansion in the return tube upstream of the anchor position, so that the smaller diameter outbound tubes are kept primarily in tension, rather than in compression that could lead to buckling.

[0157] Still referring to FIGS. **26**A-**26**B, any suitable anchor mechanism may be used to anchor tubes (e.g. tubes **130-4** and **130-8**), e.g. welds or tube lugs as illustrated in FIGS. **27**A and **27**B. If water/steam is used as the heat transfer fluid, the heat flux distribution on the tubing arrangement can be such that economizing and possibly some boiling takes place in the parallel outbound tubes **130-1**, **130-2**, **130-3**, **130-5**, **130-6**, and **130-7**, and boiling and superheating takes place in centermost tubes **130-4** and **130-8**. Aligning a higher intensity portion of the concentrated solar radiation with the centermost tubes in which superheating will take place may improve steam output, steam quality, superheated steam production, plant efficiency, reliability of operation, or any combination thereof. Boundary positions **1176-4** and **1176-8** indicate a position at which superheated steam is formed during normal operation. As described above, temperature sensors positioned both upstream and downstream of boundaries **1176-4** and **1176-8** can be used as feedback to control mass flow of fluid into the outbound tubes and/or to control an optional attemperating spray. As illustrated by hatched regions **276**, all or an end portion of the centermost tubes where superheating is expected to take place can be i) composed of a different type of tube material than the balance of the tubing arrangement; ii) have a different solar selective coating applied; or iii) both i) and ii). For example, the hatched regions **276** may represent tubing formed from a higher temperature alloy (e.g. a low steel alloy such as T22), and/or tubing on which a solar selective coating suitable for use at higher temperatures is applied. In some instances, a transition in solar selective coating may occur at a different portion of the tubing arrangement than a transition in tubing material, e.g. depending on the relative temperature stabilities of the coating and the tubing arrangement. The hatched region may represent about 100%, 90%, 80%, 70%, 60%, 50%, 40%, 30%, 20%, or about 10% of the length of the receiver. For a line focus receiver having a length of about 1600 feet used in a linear Fresnel array, the hatched region may represent about 200, 400, 600, 800, 1000, 1200, 1400, or 1600 feet.

[0158] Any suitable turnaround header may be used with the tubing arrangements described herein. One example is shown in FIGS. **37**A-**37**C. This particular variation of turnaround header may be used in some instances with the tubing configuration illustrated in FIGS. **25**A and **26**. The turnaround header **175** comprises a section **408** into which outbound tubes **130-1**, **130-2**, and **130-3** are fed. Section **408** is terminated on one end by a cap **401**. As illustrated, cap **401** may be spaced apart from outer-most tube **130-1** by a length of section **408**. Weld spacings on the tubing arrangements can be determined by expected stress to be experienced by that portion of the tubing arrangement, and by pressure codes. Section **408** is connected to a curved section **402**, so that combined flow from the outbound tubes **130-1**, **130-2**, and **130-3** is redirected into return tube **130-4** to flow in a reverse direction to make a second pass through the receiver. The turnaround header **175** illustrated in FIGS. **37**A-**37**C is in a plane **403** defined by the tubes **130-1**, **130-2**, **130-3**, and **130-4**. Although the turnaround header illustrated in FIGS. **37**A-**37**B is shown with 3 outbound tubes and a single return tube, variations are contemplated in which there are 2, 4, 5, 6, 7, or 8 or more outbound tubes. Also, although the variation shown in FIGS. **37**A-**37**C illustrates a return tube having a larger internal diameter than the outbound tubes, other variations are contemplated in which the outbound tubes have approximately the same internal diameter as the return tube, or larger internal diameters than the return tube as described herein.

[0159] Any suitable anchoring devices, methods, or mechanisms may be used to anchor the pipes for seismic or other stability purposes. For example, in some variation a lug can be used at a turnaround location or turnaround header to stabilize a tubing arrangement, e.g. one or more loops. Lugs can be welded or otherwise fixed to structural members in a solar energy collector system. An example of a lug **1220** used to anchor a turnaround header **175** (connected to a tube **130**) to a structural member **1221** is illustrated in FIG. **27**A.

[0160] An example of tube lug that can be used along a tube to anchor that tube is illustrated in FIG. **27**B. There, lug **1223** comprises a collar portion **1224** that is coupled to the tube **130** and mates with an captive device or structure **1225** fixed to a structural member such that tube **130** cannot translate past the captive device or structure **1225** in either direction. The lug **1223** can be reversibly mounted to or welded to the captive device or structure **1225**.

[0161] In other variations, one or more snubbers or other motion dampening devices can be used as anchors in a tubing arrangement. Such snubbers or motion dampening devices can operate to damp out relatively high frequency vibrations movement (such as may occur during a seismic or other sudden or transient event) but still allow very low frequency movement such as may occur during thermal expansion of a tube during operation. One example of an anchoring system using a snubber is provided in FIG. **28**. This design includes an end at which expansion is limited, and once the tube has expanded to reach that end's limit, the tube expands in the opposite direction. In FIG. **28**, tube **130** has one end **1226** at which expansion is limited, e.g. by a snubber **1227**. The snubber **1227** limits the amount of thermal expansion of the tube **130** at the end **1226**. An anchor **1229-2** is attached to structure **1231**, and allows limited expansion of the tube **130**. An end **1228** opposite end **1226** can be anchored to structure **1232** with an anchor **1229-1** that allows limited movement of the tube. Anchors **1229-1** and **1229-2** can be any suitable anchor such as a tube lug as illustrated in FIG. **27**B. A tube lug if used as an anchor can be configured so that the tube does not slide past a captive device in either direction, or in some circumstances, in only one direction.

[0162] Another variation of anchoring a tubing arrangement is illustrated in FIG. **29**. There, tubing arrangement **1300** comprises outbound tubes **130-1**, **130-2**, and **130-3** that connect with turnaround header **172**. Turnaround header **172** reverses flow into the single return tube **130-4**, in which boiling and/or superheating may occur. In this particular variation, tube **130-4** is anchored to a structure by anchor **1301**. Turnaround header **172** is anchored by anchor **1302**. One or both of anchors **1301** and **1302** can be dampened anchors that damp out high frequency motions, e.g. by using a snubber as illustrated in FIG. **28**. If only one of anchors **1301** and **1302** is a damped anchor, the other of anchors **1301** and **1302** can be a lug or weld anchor. Tube lug **1303** to anchor tube **130-1** to structure **1304** is optional.

[0163] In some cases, a tube lug can be connected to a structure via a spring, which can be selected to limit expansion and/or to damp out certain frequencies of motion. An example is shown in FIG. **29**. There, tube lug **1303** is attached to tube **130-1**, e.g. by welding. Spring **1305** connects lug **1303** to structure **1306**. The extension of the spring, the stiffness of the spring, and/or the spring constant can be selected to limit expansion of the tube **130-1**, and/or to damp out motions having certain frequencies (e.g. vibrations having relatively high frequencies).

[0164] Examples of turnaround sections that can accommodate thermal expansion are illustrated in FIG. **30**. Such turnaround sections may for example be used in a tubing arrangement such as illustrated in FIG. **4**. The turnaround section **172** comprises a loop **1310** that may be formed of tubing sections, or may be a unitary piece. In some cases, an expansion loop as illustrated in FIG. **30** may comprise a forged unitary piece, or multiple forged piece welded or otherwise connected together. A transverse member or plate (indicated by hatched area **1313**) can be used to stabilize a turnaround section. Optionally, a flow control device **1307** can be positioned at or near an inlet end **1309** of the loop **1310**. The flow control device **1307** can be any suitable device, e.g. a screen, a device for controlling vortex flow, a device for controlling rotational flow, a device for reducing turbulent flow, a device for reducing bubble formation, an orifice, a baffle, or the like. Optionally, a flow control device **1311** can be positioned at or near an outlet end **1312** of the loop **1310**. The flow control device **1311** can be any suitable device, e.g. a valve, a fixed diameter orifice, a baffle, a screen, a filter, a device for controlling rotational flow, a device for controlling turbulent flow, a device for reducing bubble formation, or the like.

[0165] A tube can be supported in a tubing arrangement in any suitable manner that allows an appropriate amount of thermal expansion of that tube, and differential thermal expansion between multiple tubes. In some variations, one or more tubes in a tubing arrangement can be suspended from above, and the suspension mechanism allows the tube to expand along its length. Non-limiting examples of suitable suspension mechanisms include track and roller mechanisms, pulley-type mechanisms, bearings, and sliding mechanisms.

[0166] An example of a suspension mechanism for a tube is provided in FIG. **31**. There, tube **130** is held in a clamp **1320**. The clamp **1320** is coupled to an axle **1321** extending in a direction that is orthogonal to the tube length, e.g. via an optional linkage extension member **1322**. Rotatable members **1323** (e.g. wheels or rollers) rotate about or with axle **1321** to travel along track or channel **1324** which extends parallel to the tube **130**.

[0167] In suspension mechanisms that employ rotatable elements such as wheels or rollers, any suitable mechanism or configuration can be used to couple the rotatable elements to a track or channel along which the rotatable members roll. Some non-limiting examples are illustrated in FIGS. **33**A-**33**E. Referring first to FIG. **33**A, a tube (not shown) can be suspended (e.g. via linkage or extension member **1322**) from axle **1321** that defines an axis around which rotatable elements **1323** rotate. In this variation, the rotatable elements **1323** ride along edges **1325** of a channel **1324**, which extends parallel to the tube. When the tube expands or contracts, the rotatable elements travel along channel **1324**, thereby accommodating the expansion and contraction. Another variation is shown in FIG. **33**B. In this variation, the rotatable elements **1323** ride in a track or recess **1345** of channel **1324**. For the examples shown in FIG. **31**, **32**, **33**A-**33**E, **34**A-**34**E, **35**A-**35**B, or **36**A-**36**B, the channel material can be any suitable material, but in some variations the channel material is selected from the group consisting of carbon steel, plated carbon steel (e.g. N1-plated carbon steel), stainless steel (e.g. ferritic or austenitic stainless steel), or plated stainless steel. The joint **1349** between the rotatable members **1323** and axle **1321** can be any suitable rotatable joint, e.g. one that reduces or eliminates sticking or jamming. For example, as illustrated in FIG. **33**C, one or more bearings can be used in joint **1349**, e.g. ball bearings such as stainless steel bearings can be used. The rotatable members can in some circumstances be constructed so that the surface is non-galling, e.g. rotatable members such as wheels can have at least a surface that contacts the channel made from bronze, nickel, graphite, graphite bronze, cast iron, carbide, alumina or other ceramic. The extension or linkage member **1322** can be made from stainless steel. The axle **1321** that defines an axis around which rotatable members **1323** turn can be any suitable axle type, but as illustrated in FIGS. **33**D-**33**E, in some variations axle **1321** can be provided by a shoulder bolt **1347** and barrel nut **1348**, which can for example be made from stainless steel. The coupling between the axle **1321** and the linkage **1322** can be any suitable coupling, but in some variations, a press-fit assembly is used.

[0168] Another variation of a suspension mechanism for a tube that accommodates thermal expansion is illustrated in FIG. **32**. There, tube **130** is held in a clamp **1320**. The clamp **1320** is coupled to a non-rolling sliding assembly **1332**, e.g. via optional extension member or linkage **1321**. As the tube **130** expands and contracts, the sliding assembly **1332** slides along channel **1333**, e.g. on slidable surface **1334**. Non-limiting examples of sliding assemblies are illustrated in FIGS. **36**A-**36**B. As illustrated in FIG. **36**A, in some variations the sliding assembly **1332** can be curved, bent, or otherwise turned up at edges **1365** to avoid catching at the edges. As shown in FIG. **36**B, in some variations the sliding assembly **1332** can have rounded edges. Variations with rounded edges **1365** may or may not be curved, bent or otherwise turned up at edges **1365** as illustrated in FIG. **36**A. Referring again to FIG. **36**A, in some variations, a sliding assembly **1332** has a length **1367** that is longer than a transverse width **1366** of the channel **1333**, so as to prevent twisting within the channel.

[0169] Any suitable type of clamp can be used to secure a tube to a suspension mechanism, e.g. as illustrated in FIG. **31**, **32**, **33**A-**33**B, **35**A-**35**B, or **36**A-**36**B. It is desirable to position clamps on adjacent tubes so that there is no rubbing, colliding, jamming, other type of interference between adjacent tubes. As illustrated in FIG. **34**A, in some cases, a straight clamp **1320-1** having an abrupt jutting junction **1350** with its tube **130-1** may collide with a neighboring clamp **1320-2** on neighboring tube **1320-2** in the case of differential thermal expansion between the tubes **130-1** and **130-2**. One possible solution is to arrange clamps on neighboring tubes so that they slide past one another as opposed to abruptly colliding, e.g. by angling sides of the clamps and/or positioning the clamps on neighboring tubes so that i) clamps are spaced apart along the length of neighboring tubes and do not collide under normal expansions; ii) clamps are angled with respect to tubes so that abrupt collisions at edges are avoided; and/or iii) clamps are arranged to continuously overlap with neighboring clamps so that clamps slide past each other without having to slide past a neighboring clamps edge. One example of an arrangement for neighboring angled clamps is provided in FIGS. **34**B-**34**C. There, angled clamps **1320-1** and **1320-2** on tubes **130-1** and **130-2**, respectively, are each angled with respect to tubes **130-1** and **130-2** and can slide past each other. Clamps, (e.g. straight clamps as illustrated in FIG. **34**A or angled clamps as illustrated in FIG. **34**B-**34**C) can be mounted onto tubes in any suitable manner. For example, a partially formed or unformed clamp **1351** (for an angled or straight clamp) can be applied over a tube as illustrated in FIG. **34**D, and subsequently tightened around a tube. The tightened clamp can be secured by any suitable securing device **1352**, e.g. a bolt, clamp, weld, cotter pin, or the like. An example of a tube suspended from a suspension mechanism (e.g. as illustrated in FIG. **31**, **32**, **33**A-**33**E, or **34**A-**34**E) is shown in FIGS. **35**A-**35**B. The channel **1360** may for example be channel **1324** as illustrated in FIGS. **31**, **33**A-**33**B or channels **1333** as illustrated in FIG. **32**. The channel **1360** is supported by supports **1361**, which may be coupled to a solar receiver (not shown), a support for a solar receiver (not shown), or a separate support (not shown). As illustrated in FIG. **35**A, the clamps **1320** may be positioned along tube **130** so that during normal expansion range **1363** of a tube in operation under expected operating conditions the clamps **1320** do not contact end caps **1362**. On some occasions, e.g. during a power loss or upset condition, the tube temperature may exceed expected or design limits. As illustrated in FIG. **35**B, in some variations, a clamp can be designed to allow the tube to slide through the clamp without substantially damaging the clamp, tube, or structure of the suspension mechanism or receiver, e.g. damage is limited to less than the point of failure. Even in those configurations, repair or replacement of the clamp, tube, suspension mechanism (e.g. channel), or tube coating, may be desired or required after sliding of the tube through its tube clamp.

[0170] In some cases, a tube can be supported from below in a manner that allows thermal expansion of a tube or differential thermal expansion of multiple tubes. In some cases, rollers can be used to support tubes from below, e.g. as described in U.S. patent application Ser. No. 10/597,966 and in U.S. patent application Ser. No. 12/012,829, each of which is incorporated by reference herein in its entirety. Examples of support assemblies comprising an individual support roller for each tube in a tubing arrangement is illustrated in FIGS. **38**A-**38**L These support assemblies may for example be used to support tubes in a tubing arrangement such as illustrated in FIG. **25**A, **26**A-**26**B, or **5**A-**5**C. Referring first to FIG. **38**A, the support assembly **1410** comprises a shaft **1411** about which rollers **1412** rotate. The shaft is generally perpendicular to the tube length. A variation of a shaft **1411** is illustrated in FIG. **38**B. A divider **1413** may optionally be placed between two adjacent rollers **1412**. The rollers **1412** may, but need not be, tapered or profiled so as to accommodate the cylindrical shape of the tubes. Non-limiting examples of profiled rollers are illustrated in FIGS. **38**C-**38**E. In FIG. **38**C, the roller **1412** has a nonprofiled intermediate region **1415**, profiled end regions **1414**, and core **1416** through which shaft **1411** extends. FIG. **38**D illustrates a variation of a roller **1412** in which the nonprofiled intermediate region **1415** is shorter than that illustrated in FIG. **38**C. A variation of a roller **1412** having no nonprofiled intermediate region is illustrated in FIG. **38**E. Other variations of rollers are contemplated in which the roller has no profiled region, or in which a single roller can support more than one tube. The rollers in a support assembly and/or the spacing of rollers in a support assembly may be varied to accommodate differing tube diameters. For example, as illustrated in FIG. **38**A, outer rollers **1412-1**, **1412-2**, **1412-1**, **1412-5**, **1412-6**, and **1412-7** may support smaller diameter tubes, and inner rollers **1412-4** and **1412-8** may support larger diameter tubes, e.g. as illustrated in FIGS. **25**A, **26**A-**26**C, and **5**A-**5**C. To accommodate such larger diameter tubes, the inner rollers **1412-4** and **1412-8** may be larger, e.g. have a longer end-to-end dimension **1417**, and/or may have a larger center-to-center spacing **1418**. Rollers may have a surface composition so as to reduce damage to tube surfaces, especially if a tube surface is coating with a solar selective coating. Roller material may be selected based on amount of expansion anticipated, make-up of tube, weight of tube and/or temperature of tube in use. Rollers in a single support assembly may, but need not, have the same or similar compositions. In some variations, one or more rollers in a support assembly may be at least partially made from graphite bronze. In some instances, one or more rollers may have a cast iron or carbide coating.

[0171] Optionally, the rollers **1412** and shaft **1411** may be carried in a roller tray **1419**. Non-limiting variations of roller trays are illustrated in FIGS. **38**A, **38**F-**38**J. Referring first to FIG. **38**F, roller tray **1419** comprises sidewalls **1422** and endwalls **1420**. Dividers **1413** are supported between sidewalls **1422**, e.g. in notches **1423**. Dividers **1413** form pockets **1421** in the roller tray **1419**, where each pocket **1421** is associated with a single roller. Dividers in use can function to align individual rollers **1412** with the overall support assemblies, and to keep adjacent rollers from contacting each other. Shaft **1411** can be carried by recesses **1424** (e.g. curved recesses) that are formed in dividers **1413**. An example of a divider **1413** is illustrated in FIG. **38**L. There, divider **1413** comprises curved recess **1424** having a lower radius of curvature to accommodate a desired shaft **1411**. In this particular variation, the divider **1413** comprises side tabs **1430** for insertion into sidewall notches **1423**. Optionally, a divider **1413** can comprise a lower tab **1431** for insertion into a bottom notches **1433** of bottom surface **1432** of the roller tray **1419**. The dividers **1413** can be arranged along tray **1419** to define different size pockets **1421** to accommodate different size tubes. For a tubing arrangement such as that illustrated in FIG. **25**A, **26**A-**26**B, or **5**A-**5**C, center most pockets **1421-4** and **1421-8** for accommodating rollers for larger diameter tubes may have longer lengths **1428** than lengths **1439** of outer pockets **1421-1**, **1421-2**, **1421-3**, **1421-5**, **1421-6** and **1421-7** for accommodating rollers for smaller diameter tubes. As illustrated in FIG. **38**G, the variation of roller tray **1419** illustrated in FIG. **38**F may optionally be formed (e.g. stamped) from a single flat sheet (e.g. steel) that is bent and subsequently welded. Another variation of a roller tray **1419** is illustrated in FIG. **38**H-**38**I. In this variation, an optional mounting shelf **1426** is connected to each of endwalls **1421**. Extending between each mounting shelf **1426** and its corresponding endwall **1421** are one or two angle brackets **1427**. As illustrated in FIG. **38**I, the variation of **1419** illustrated in FIG. **38**H may be formed (e.g. stamped) from a single sheet (e.g. steel) and subsequently bent and welded into its final form. Although not illustrated in FIGS. **38**H-**38**I, dividers **1413** may be supported by notches **1423** to carry shaft **1411** and divide adjacent rollers **1412**. Note that the dimensions of the roller trays **1419** (e.g. as illustrated in FIGS. **38**F-**38**I) may be varied, e.g. a height **1429** of sidewall **1422** may be made smaller so as to provide a roller tray with a lower profile. One example of a low profile tray design is provided in FIGS. **38**J-**38**K. As illustrated in FIG. **38**K, the low profile tray design as illustrated in FIG. **38**J may be formed from a single sheet (e.g. by stamping) and subsequently bent and welded into its final form. In some variations, two dividers **1413** can be used between neighboring tubes, e.g. between a larger diameter tube (such as a 3", 3.5" or 4" diameter tube) and a neighboring tube. An example of such a variation is illustrated in FIG. **38**K. Although the dividers **1413** are not explicitly shown in FIG. **38**K, it is shown there that notch **1423-4'** and notch **1423-4"** are each used to carry a separate divider **1413** to define tube pocket **1423-4**, and notch **1423-8'** and notch **1423-8"** are each used to carry a separate divider **1413** to define tube pocket **1423-4**. Thus, tube pockets **1421-4** and **1421-8** have a pair of dividers separating them from neighboring pockets. Tube pockets **1421-1**, **1421-2**, **1421-5** and **1421-6** have only a single divider separating them from neighboring pockets. Tube pockets **1421-3** and **1421-7** have a single divider separating them from a neighboring pocket on one side and a pair of dividers separating them from a neighboring pocket on the other side.

[0172] In some variations, the diameters of the various tubes of tubes **130** (in examples described above or below herein) vary, with tubes intended to carry hotter fluid having a larger diameter. As an example, superheating tubes **130-4** and **130-8** in FIGS. **5**A-**5**C have larger diameters than the other tubes. As another example, second pass tubes **130-4** and **130-8** (which may contain saturated steam or superheated steam) in FIGS. **26**A-**26**B have larger diameters than the other tubes. In variations of either of these examples, tubes **130-4** and **130-8** have inner or outer diameters of about 4, about 3.5, about 3, about 2.5 or about 2 inches, and the other tubes have inner or outer diameters of about 2, about 1.5, or about 1 inches. For example, tubes **130-4** and **130-8** may have inner or outer diameters of about 3 inches or 3.5 inches and the other tubes may have inner or outer diameters of about 2 inches, 1.66 inches, 1.5 inches, or 1 inch. Such an increase in tube diameter may be selected, for example, to maintain a pressure drop from inlet header to outlet header less than about 10 bar during expected peak solar conditions. In some cases, tubes having three, four, five, six or more different diameters may be used within in a single tubing arrangement. For example, tubes in each successive pass may have increased diameter relative to a tube in a previous pass. Wall thicknesses of a tube can be selected based on composition of the tube, composition of the heat transfer fluid, operating temperatures and/or pressures of the tubes, stresses or strains experienced by the tubes during operation, safety or product guidelines, regulations or codes, such as boiler codes, or any combination thereof. The tube diameters may also be selected to minimize the amount of metal used and/or to minimize the volume of water that can exist, e.g. is stored during nonoperation (e.g. overnight) in tubes **130**. Tube diameters may also be selected to minimize fluid transit time through all, or portions, of tubes **130**, such as through evaporating and superheating portions, for example, in the case where fluid flow is faster through a smaller diameter tube which, in turn, can provide a faster response to control systems, e.g. a control system that uses temperature or another physical parameter of fluid in a tube or exiting from a tube as control input or feedback to a control system that controls mass flow rate of fluid into a tube or tubes.

[0173] In some variations of the tubing arrangements described herein, tubing arrangements having six boiler tubes or less, tubes **130** comprise tubes of up to two different inner or outer diameters. In some variations having seven to twelve boiler tubes, tubes **130** comprise tubes of up to three different inner or outer diameters. In some variations having twelve or more boiler tubes, tubes **130** comprise tubes of up to four different inner or outer diameters.

[0174] In some variations, the materials from which various tubes of tubes **130** (in examples described above or below herein) are formed may vary depending on the heat absorbing fluid process that occurs within them. For example, in some variations economizer and boiler tubes (or partial portions of tubes in which boiling may occur) may be formed from carbon steel and superheating tubes (or partial portions of tubes in which superheating is expected to occur) may be formed from T22 or similar low alloy steel. T22 or similar material may allow superheated steam temperatures up to about 900° F. or about 1000° F., in some variations. In some cases, tubes (or portions of tubes) experiencing lower temperatures in operation (e.g. economizing and boiler tubes) may be made from carbon steel and tubes (or portions of tubes) experiencing higher temperatures in operation (e.g. superheating tubes) may be made from stainless steel, e.g. non-austenitic stainless steel such as martensitic or ferritic stainless steel.

[0175] In some variations, solar selective coatings on various tubes of tubes **130** (in examples described above or below herein) may differ in composition depending on (e.g., the maximum temperature of) the heat absorbing process that occurs within in them. For example, a solar selective coating comprising an electrodeposited nickel tin alloy and a sol-gel overcoat such as are described in U.S. Pat. Nos. 6,632,542 and 6,783,653, each of which is incorporated by reference herein in its entirety, may be used as a solar selective coating on those tubes (or portions of tubes) that are expected to remain at temperatures of about 250° C., 300° C., or 350° C. or lower, and a solar selective coating designed for use at higher temperatures such as SOLKOTE™ (available from SOLEC-Solar Energy Corp., Ewing, N.J.) can be used on remaining tubes or portions of tubes.

[0176] For the multi-tube receivers described herein, a relatively large amount of thermal energy is stored in the heat transfer fluid (e.g. water) and in the metal of the tubes. This stored energy is lost overnight. The amount of stored energy in a multi-tube receiver can be reduced by selecting the number of tubes and their diameters in a solar receiver to make the density of the fluid inside the tubes inversely proportional to the heat flux incident on the tubes, and the pressure drop across a length of a tube proportional to the density in that tube. This can reduce the amount of stored energy in the receiver. As illustrated in FIG. **40**A, standard practice in a boiler is for pressure to decrease linearly along a length of a boiler tube, as indicated by line **4000**. However, the density of the fluid within a tube decreases linearly only until it undergoes a phase transition, indicated at position **4001** in curve **4002** in FIG. **40**B. The number and diameters of tubes in a receiver can be selected so that a nonlinear pressure drop along the tube length is achieved (e.g. as illustrated by curve **4004** in FIG. **40**A) so that the pressure drop in a tube is approximately proportional to the density in the tube (e.g. as illustrated by curve **4002** in FIG. **40**B). Referring now to FIG. **40**C, an example of a tubing arrangement **4005** is illustrated that has a two pass flow path, similar to those illustrated in FIGS. **3**, **24**, **25**A-**25**C, and **26**A-**26**B. Feedwater enters parallel-connected outbound tubes **130-1**, **130-2**, **130-3**, **130-5**, **130-6**, and **130-7** and is irradiated a first time by concentrated solar radiation, until it reaches turnaround headers in which the combined flow from tubes **130-1**, **130-2**, and **130-3** returns through tube **130-4** in a second pass through the concentrated radiation, and the combined flow from tubes **130-5**, **130-6**, and **130-7** returns through tube **130-8** in a second pass through the concentrated radiation to produce superheated steam. As illustrated, the density in the tubing arrangements decreases from the centermost tubes to the outermost tubes. The relative tubing diameters of the outermost and centermost tubes can be selected so that the pressure drop along the length of the outermost tubes **130-1**, **130-2**, **130-3**, **130-5**, **130-6** and **130-7** is roughly equivalent to the pressure drop along the length of the centermost tubes **130-4** and **130-8**. Referring now to FIG. **40**D, a tubing arrangement **4006** is shown that has 12 tubes in a two-pass configuration. The relative diameters of the outermost tubes **130-1**, **130-2**, **130-3**, **130-5**, **130-6**, **130-7**, **130-9**, **130-10**, **130-11** and **130-12** and the centermost tubes **130-4** and **130-8** are selected so that the pressure drop along the length of the outermost tubes is greater than the pressure drop along the length of the centermost tubes. This is accomplished by choosing the diameters of the outermost tubes to be substantially smaller than the diameters of the centermost tubes. The configuration shown in FIG. **40**D results in less subcooled water than the configuration illustrated in FIG. **40**C. The configuration shown in FIG. **40**D stores more energy in the superheat region of the tubing arrangement **4006** because of the greater thermal mass of the larger tubes **130-4** and **130-8**. However, the excess heat stored in the superheat region of the tubing arrangement can help stabilize the superheat performance, during normal operation and/or during transients. Please note that the number of tubes shown in FIGS. **40**C and **40**D is illustrative only, and any suitable number of tubes may be used to achieve similar results, e.g. tubing arrangements having fewer than 8 tubes or more than 12 tubes.

[0177] FIG. **13** shows an example of a solar energy collector system **500** comprising a solar thermal receiver **510** atop a tower **515**, and an array of heliostats that each may be oriented about two angular axes to track the sun's apparent daily motion to reflect solar radiation to receiver **510**. One of ordinary skill in the art will understand that such solar energy collection systems are known in the art, and that features of the tower, the general arrangement of the receiver and heliostats, and the number of heliostats shown in FIG. **13** are intended as schematic illustrations representing numerous configurations known in the art.

[0178] Referring now to FIG. **14**, in some variations a solar thermal receiver **510** comprises solar energy absorbers **525**, **530**, and **535** arranged vertically as shown. Plot **540** shows an example distribution of solar radiation ("I") concentrated by heliostats (not shown) along a vertical direction ("Z") onto receiver **510**. In the illustrated example, the solar radiation intensity distribution, and hence the heat flux distribution into receiver **510**, is greater at absorber **530** than at absorber **525** or absorber **535**. In some variations liquid water flows through a conduit **545** to absorber **525**, where its temperature increases as it is heated by concentrated solar radiation providing a relatively low heat flux (compared to the peak heat flux provided by the concentrated solar radiation). Liquid water heated in absorber **525** than flows through header **550** to absorber **535**, where it is further heated to generate steam, also by concentrated radiation providing a relatively low heat flux. Steam from absorber **525** then flows through header **560** to absorber **530**, where it is superheated by concentrated solar radiation providing a relatively higher heat flux than that at absorbers **525** and **535**. Superheated steam leaves receiver **510** through outlet header **565**.

[0179] FIG. **15** shows an example of a downward facing receiver **575** atop a tower **515**. Downward facing receiver **575** comprises a downward facing aperture **575** through which solar radiation may be concentrated by heliostats (such as those of FIG. **13**, for example) onto an absorber within receiver **575**.

[0180] Referring now to FIGS. **16**A and **16**B, in one variation a solar energy absorber **600** comprises tubes **600-1** and **600-2** supporting the flow paths shown. When illuminated with the solar radiation intensity distribution **605** shown in FIG. **16**B (an approximately elliptical distribution hotter in the center and colder at the periphery), fluid flowing through absorber **600** will flow initially through the periphery of the solar radiation distribution and then into the center of the solar radiation distribution. If the fluid is water, for example, the water may be initially liquid water that is heated to increase its temperature in the lower intensity portions of the solar radiation distribution, then boiled and heated to produce superheated steam in the central portions of the solar radiation distribution.

[0181] In the example of FIGS. **17**A and **17**B, a solar energy absorber **700** comprises tubes **700-1** and **700-2** supporting the flow paths shown. Similarly to the example of FIGS. **16**A and **16**B, when illuminated with the solar radiation intensity distribution **705** shown in FIG. **17** B, fluid flowing through absorber **70** will flow initially through the periphery of the solar radiation distribution and then into its center. If the fluid is water, it may be heated to increase its temperature, boiled, and further heated to produce superheated steam as described with respect to FIGS. **16**A and **16**B.

[0182] Referring once more to FIG. **1**, in operation of solar energy collection system **100** a control system (not shown) controls motors that rotate the reflectors of reflector fields **110** and **120** to rotate the reflectors about their long axes to track the sun during its apparent motion across the sky and thereby reflect solar radiation to solar absorber **125**. In some variations the control system maintains a table of the reflector orientation angles, or can calculate reflector orientation angles, that will reflect solar radiation from particular reflectors to particular locations (e.g., to solar absorber **125**) at a particular time of day (e.g., a particular time on a particular day in a particular year).

[0183] Referring next to FIGS. **18**A and **18**B, in one example method for calibrating such orientation angles (e.g., angle θ for reflector **900** in FIG. **18**A) utilizes a light sensor **910** located adjacent to solar absorber **125** in solar thermal receiver **150**. In one variation of the method, sensor **910** detects the intensity of light reflected to it as reflector **900** is rotated through a sufficient range of θ that its reflected light beam sweeps onto and past sensor **910**. FIG. **18**B shows a plot of the signal intensity I(θ) output by the sensor as a function of the orientation angle of reflector **900** and time. Next, the peak **915** of the sensor output (approximately corresponding to the center of the light beam reflected by the reflector) is identified, along with the corresponding time and reflector orientation angle. Next, the reflector orientation angle at which the control system would have oriented the reflector to reflect light to the sensor is determined (by, e.g., calculation or by looking it up in a table as described above). Next, the angle so determined is subtracted from the orientation angle corresponding to the peak sensor signal to provide a calibration angle. The calibration angle may then be used as a correction, added to the angle that the control system determines (e.g., calculates or looks up) for aiming reflected solar radiation to solar absorber **125**, to improve the accuracy with which such solar radiation is reflected to the receiver.

[0184] In one aspect, a method of collecting solar energy comprises flowing a fluid comprising steam through a plurality of parallel tubes arranged in a side-by-side configuration, and concentrating solar radiation onto a heat absorber comprising the plurality of tubes to provide a heat flux distribution into the tubes that heats the fluid in the tubes. At least one of the plurality of tubes superheats the steam. The tube that superheats the steam may be located, for example, at an overall maximum of the heat flux distribution. The steam may be generated elsewhere, and introduced into the solar absorber for superheating, or generated within the solar absorber.

[0185] The fluid may comprise liquid water, in which case at least a portion of the steam may be generated in the plurality of tubes by boiling at least a portion of the liquid water under a heat flux lower than that which superheats the steam. At least a portion of the liquid water boiled in the plurality of tubes to generate the steam may be preheated in the plurality of tubes to increase its temperature, prior to boiling, under a heat flux lower than that which boils it. In variations in which the steam is generated outside the solar absorber, at least a portion of the water from which that steam is generated may preheated in the plurality of tubes, under a heat flux lower than that which superheats the steam, to increase its temperature prior to being boiled outside the solar absorber.

[0186] In the methods just described, in some variations the plurality of tubes may be interconnected to provide two or more fluid flow paths that are symmetric with each other about a centerline of the plurality of tubes.

[0187] In one aspect, a method of collecting solar energy comprises flowing a fluid comprising liquid water, steam, or liquid water and steam through a plurality of parallel tubes arranged in a side-by side configuration and interconnected to provide two or more fluid flow paths that are symmetric with each other about a centerline of the plurality of tubes. The method further comprises concentrating solar radiation onto a heat absorber comprising the plurality of tubes to provide a heat flux distribution into the tubes that heats the fluid in the tubes.

[0188] In some variations of the methods of the first or second aspect, the method comprises concentrating the solar radiation onto the heat absorber such that the heat flux distribution into the tubes is greater at the center-most tube or tubes than at the outer-most tubes. A portion of the fluid is flowed in a first direction through a first outer-most tube on one side of the center-most tube or tubes to collect heat. Another portion of the fluid is flowed in the first direction through a second outer-most tube, on an opposite side of the center-most tube or tubes from the first outer-most tube, to collect heat. At least a portion of the fluid heated in the first and second outer-most tubes is flowed through the center-most tube or tubes in a direction opposite to the first direction to collect additional heat.

[0189] In other variations, the method also comprises concentrating the solar radiation onto the heat absorber such that the heat flux distribution into the tubes is greater at the center-most tube or tubes than at the outer-most tubes. In these variations, a portion of the fluid having a first enthalpy is flowed through a first outer most tube on one side of the center-most tube or tubes to collect heat and thereby increase its enthalpy. Another portion of the fluid having the first enthalpy or approximately the first enthalpy is flowed through a second outer most tube, on an opposite side of the center-most tube or tubes from the first outer-most tube, to collect heat and thereby increase its enthalpy. At least a portion of the fluid heated in the first and second outer-most tubes is flowed through the center-most tube or tubes to collect additional heat and thereby further increase its enthalpy.

[0190] In the method just described, flow in the outer-most tubes may be parallel or anti-parallel. If flow in the outer-most tubes is parallel, flow in the center-most tube or tubes may be parallel or anti-parallel to that in the outer-most tubes.

[0191] In other variations of the methods, the method also comprises concentrating the solar radiation onto the heat absorber such that the heat flux distribution into the tubes is greater at the center-most tube or tubes than at the outer-most tubes. In these variations, a first portion of the fluid comprising water, steam, or water and steam is flowed through a first outer-most tube on one side of the center-most tube or tubes to collect heat, another portion of the fluid comprising water, steam, or water and steam is flowed through a second outer-most tube, on an opposite side of the center-most tube or tubes form the first outer-most tube, to collect heat. Steam generated in the first and second outer-most tubes, or generated from water heated in the first and second outer-most tubes, is flowed through the center-most tube or tubes to collect additional heat and thereby produce superheated steam.

[0192] In the method just described, as well, flow in the outer-most tubes may be parallel or anti-parallel. If flow in the outer-most tubes is parallel, flow in the center-most tube or tubes may be parallel or anti-parallel to that in the outer-most tubes.

[0193] In one aspect, a method of collecting solar energy comprises concentrating solar radiation onto a heat absorber comprising a plurality of parallel tubes arranged in a side-by-side configuration to provide a heat flux distribution into the tubes greater at the center-most tube or tubes than at the outer-most tubes. A fluid is flowed in a first direction through a first outer-most tube on one side of the center-most tube or tubes to collect heat. A fluid is also flowed in the first direction through a second outer-most tube, on an opposite side of the center-most tube or tubes from the first outer-most tube, to collect heat. At least a portion of the fluid heated in the first and second outer-most tubes is flowed through the center-most tube or tubes in the direction opposite to the first direction to collect additional heat.

[0194] In one aspect, a method of collecting solar energy comprises concentrating solar radiation onto a heat absorber comprising a plurality of parallel tubes arranged in a side-by-side configuration to provide a heat flux distribution into the tubes greater at the center-most tube or tubes than at the outer-most tubes. A fluid having a first enthalpy is flowed through a first outer most tube on one side of the center-most tube or tubes to collect heat and thereby increase its enthalpy. A fluid having the first enthalpy or approximately the first enthalpy is flowed through a second outer most tube, on an opposite side of the center-most tube or tubes from the first outer-most tube, to collect heat and thereby increase its enthalpy. At least a portion of the fluid heated in the first and second outer-most tubes is flowed through the center-most tube or tubes to collect additional heat and thereby further increase its enthalpy. Flow in the outer-most tubes may be parallel or anti-parallel. If flow in the outer-most tubes is parallel, flow in the center-most tube or tubes may be parallel or anti-parallel to that in the outer-most tubes.

[0195] In one aspect, a method of collecting solar energy comprises concentrating solar radiation onto a heat absorber comprising a plurality of parallel tubes arranged in a side-by-side configuration to provide a heat flux distribution into the tubes greater at the center-most tube or tubes than at the outer-most tubes. Water, steam, or a mixture of water and steam is flowed through a first outer-most tube on one side of the center-most tube or tubes to collect heat. Water, steam, or a mixture of water and steam is flowed through a second outer-most tube, on an opposite side of the center-most tube or tubes form the first outer-most tube, to collect heat. Steam generated in the first and second outer-most tubes, or generated from water heated in the first and second outer-most tubes, is flowed through the center-most tube or tubes to collect additional heat and thereby produce superheated steam. Flow in the outer-most tubes may be parallel or anti-parallel. If flow in the outer-most tubes is parallel, flow in the center-most tube or tubes may be parallel or anti-parallel to that in the outer-most tubes.

[0196] In some variations of the methods, the plurality of tubes may be interconnected to provide two or more fluid flow paths that are symmetric with each other about a centerline of the plurality of tubes.

[0197] In one aspect, a method of collecting solar energy uses a first heat absorber comprising a first plurality of parallel tubes arranged in a side-by-side configuration and a second heat absorber comprising a second plurality of parallel tubes arranged in a side-by-side configuration, The method comprises concentrating solar radiation onto the first heat absorber to provide a heat flux distribution into the first plurality of tubes greater at the center-most tube or tubes than at the outer-most tubes of the first plurality of tubes, and concentrating solar radiation onto the second heat absorber to provide a heat flux distribution into the second plurality of tubes greater at the center-most tube or tubes than at the outermost tubes of the second plurality of tubes.

[0198] A fluid is flowed through the first heat absorber in a first direction through a first outer-most tube on one side of the center-most tube or tubes of the first plurality of tubes to collect heat. A fluid is flowed through the first heat absorber in the first direction through a second outer-most tube, on an opposite side of the center-most tube or tubes from the first outer-most tube, to collect heat.

[0199] At least a portion of fluid heated in the first or second outer-most tubes of the first heat absorber is flowed through the second heat absorber in a second direction through a first outer-most tube on one side of the center-most tube or tubes to collect additional heat. At least another portion of fluid heated in the first or second outer-most tubes of the first heat absorber is flowed through the second heat absorber in the second direction through a second outer-most tube, on an opposite side of the center-most tube or tubes from the first outer-most tube, to collect additional heat.

[0200] At least a portion of the fluid heated in the first and second outer-most tubes of the second heat absorber is flowed through the center-most tube or tubes of the second heat absorber in the direction opposite to the second direction to collect additional heat and then separated into a gas phase and a liquid phase. At least a portion of the gas phase is flowed through the center most tube or tubes of the first heat absorber in the direction opposite to the first direction to heat the gas phase and increase its temperature.

[0201] In the method just described, the first direction and the second direction may be parallel, anti-parallel, or intersecting. In some variations, the tubes of the first absorber may be interconnected to provide two or more fluid flow paths that are symmetric with each other about a centerline of the first plurality of tubes. Alternatively, or in addition, the tubes of the second absorber may be interconnected to provide two or more fluid flow paths that are symmetric with each other about a centerline of the second plurality of tubes.

[0202] In one aspect, a method of collecting solar energy uses first, second, and third solar energy absorbers arranged adjacent to each other in a vertical direction with the second absorber between the first and the third. The method comprises concentrating solar radiation onto the first, second, and third solar energy absorbers to provide a heat flux distribution in the vertical direction greater at the second absorber than at the first and third absorbers. Water is flowed through the first absorber to collect heat and increase its temperature. At least a portion of the water heated in the first absorber is flowed through the second absorber to collect heat and thereby generate steam. At least a portion of the steam generated in the second absorber is flowed through the third absorber to superheat the steam.

[0203] In the methods of the various aspects summarized above, solar radiation may be concentrated onto solar absorbers using, for example, linear Fresnel reflector systems in which the absorber extends linearly and is elevated above one or more linearly extending rows of reflectors arranged parallel to the absorber. The angular orientation of the reflectors about their long axes may be adjusted to track the sun's apparent motion during the day to reflect solar radiation to a linear focus along the absorber. As another example, solar radiation may be concentrated onto solar absorbers in the above methods using reflectors for which the angular orientation may be adjusted around two axes to track the sun's apparent motion during the day to direct solar radiation to a point or spot focus on the absorber, which is located atop a tower above the reflectors. Other methods of concentrating solar radiation onto absorbers may also be used in the above methods.

[0204] In the methods summarized above utilizing heat absorbers comprising tubes, solar radiation may be concentrated directly onto the tubes or, alternatively, onto an absorbing plate, surface, or other absorbing feature of the heat absorber located between the tubes and the incident solar radiation. In the latter cases, heat absorbed by the absorbing plate, surface, or other absorbing feature is transferred by conduction, for example, to the tubes to provide the heat flux distribution into the tubes.

[0205] Also, in the methods summarized above utilizing heat absorbers comprising tubes, the tubes in an absorber may be, for example, coplanar, arranged in two or more parallel or intersecting planes, or arranged as a bundle of parallel tubes. Fluid flowing in an absorber comprising parallel tubes may make, for example, two, three, four, five, six, or more than six passes along the length of the absorber parallel to the tubes.

[0206] Systems and apparatus supporting the methods and fluid flow patterns summarized above are also disclosed herein.

[0207] This disclosure is illustrative and not limiting. Further modifications will be apparent to one skilled in the art in light of this disclosure and are intended to fall within the scope of the appended claims. For instance, although the heat absorbing fluid is identified as water in variations described above, any suitable alternative heat absorbing fluids may also be used. Example alternative fluids may include, but are not limited to, oils, molten salts, gases (e.g., air, helium), and organic fluids (including organic fluids that may change phase from liquid to gas phase under the operating conditions of the solar absorber in which they are used). All publications and patent applications cited in the specification are incorporated herein by reference in their entirety as if each individual publication or patent application were specifically and individually put forth herein.

What is claimed is:

1. A solar energy collector system comprising:

an elevated solar receiver comprising a tubing arrangement comprising multiple tubes arranged lengthwise in the receiver in a side-by-side parallel configuration across a transverse dimension of the receiver, the multiple tubes comprising an inner tube or tubes, a first outer tube or tubes on one side of the inner tube or tubes, and a second outer tube or tubes on an opposite side of the inner tube or tubes from the first outer tube or tubes;

at least one orientable reflector operable to direct incident solar radiation to form a concentrated illuminated area on the tubing arrangement; and

an instrumentation and control system for controlling the orientation of the at least one orientable reflector to provide in operation a concentrated illuminated area comprising a peaked profile across the transverse dimension of the receiver, wherein:

the receiver comprises an inlet section configured to receive a heat transfer fluid into the tubing arrangement and an outlet section configured to output heated heat transfer fluid from the tubing arrangement; and

the multiple tubes of the tubing arrangement defining together a flowing circuit between the inlet section and the outlet section from the first and second outer tube or tubes to the inner tube or tubes.

2. The solar energy collector system of claim **1**, wherein the tubing arrangement is configured such that the concentrated illuminated area distributes heat flux to the heat transfer fluid within the tubing arrangement such that, in operation, the density of the fluid within a tube of the tubing arrangement is inversely related to the heat flux delivered to that tube.

3. The solar energy collector system of claim **1**, configured as a linear Fresnel solar energy collector system, wherein:

the receiver is an elevated linear receiver;

the at least one orientable reflector is contained within a reflector row that is aligned parallel to the receiver and focuses incident radiation on the receiver; and

the concentrated illuminated area comprises a line focus.

4. The solar energy collector system of claim **1**, wherein the tubing arrangement is symmetrical with respect to a longitudinal center line of the receiver.

5. The solar energy collector system according to claim **1**, further comprising a flow control device on the flowing circuit to control mass flow of heat transfer fluid into the tubing arrangement.

6. The solar energy collector system according to claim **1**, wherein the tubing arrangement comprises one or more thermal expansion sections that accommodates thermal expansion of the tubing arrangement.

7. The solar energy collector system of claim **6**, wherein at least one thermal expansion section extends in a plane defined by the multiple parallel tubes.

8. The solar energy collector system of claim **6**, wherein at least one thermal expansion section extends out of a plane defined by the multiple parallel tubes.

9. The solar energy collector system of claim **6**, wherein the thermal expansion section comprises a suspension mechanism having at least one clamp holding one of the tubes of the tubing arrangement, the suspension mechanism coupled to sliding or rolling means, said sliding or rolling means being supported by a track interconnected with the receiver structure and defining a path parallel to the tube length for said sliding or rolling means.

10. The solar energy collector system of claim **1**, wherein:

the inlet section comprises a first inlet section;

the outlet section comprises a first outlet section;

the inner tube or tubes comprises a first inner tube;

heat transfer fluid enters the tubing arrangement through the first inlet section to enter the first outer tube or tubes to flow in a first direction to reach a turnaround header that redirects heat transfer fluid to enter the first inner tube to flow in a second flow direction counter-parallel to the first flow direction to reach the first outlet section; and

the concentrated illuminated area provides greater heat flux to the first inner tube than to the first outer tube or tubes.

11. The solar energy collector system of claim **10**, wherein:

the inlet section further comprises a second inlet section;

the outlet section further comprises a second outlet section;

the inner tube or tubes further comprises a second inner tube; and

heat transfer fluid enters the tubing arrangement through the second inlet section to flow in the first flow direction in the second outer tube or tubes to reach a second turnaround header that redirects the heat transfer fluid to enter the second inner tube and flow in the second flow direction to reach the second outlet section.

12. The solar energy collector system of claim **10**, wherein:

the inlet section further comprises a second inlet section; and

the heat transfer fluid enters the tubing arrangement through the second inlet section to flow in the first flow direction in the second outer tube or tubes to reach a second turnaround header that redirects heat transfer fluid to enter the first inner tube and flow in the second flow direction to reach the first outlet section.

13. The solar energy collector system of claim **10**, wherein the first inner tube has an inner diameter greater than that of the first outer tube or tubes.

14. The solar energy collector system of claim **10**, wherein the tubing arrangement comprises a plurality of tubes connected in parallel with the first outer tube or tubes, and wherein the tubing arrangement is configured such that heat transfer fluid flows in the first direction through the plurality of tubes to reach the turnaround header.

15. The solar energy collector system of claim **10**, wherein the tubing arrangement comprises a plurality of tubes connected in parallel with the first inner tube, and wherein the tubing arrangement is configured such that heat transfer fluid flows in the second direction through the plurality of tubes to reach the first outlet section.

16. The solar energy collector system of claim **10**, wherein the tubing arrangement comprises a serpentine path between the first outer tube or tubes and the first inner tube such that heat transfer fluid flow path intersects the concentrated illuminated area more than twice.

17. A method of collecting solar energy, the method comprising:

flowing a heat transfer fluid into a tubing arrangement of an elevated solar receiver through an inlet section, wherein the tubing arrangement comprises multiple tubes arranged lengthwise in the receiver in a side-by-side parallel configuration across a transverse dimension of the receiver, the multiple tubes comprising an inner tube or tubes, a first outer tube or tubes on one side of the inner tube or tubes, and a second outer tube or tubes on an opposite side of the inner tube or tubes from the first outer tube or tubes; and

concentrating solar radiation onto the elevated solar receiver to form a concentrated illuminated area comprising a peaked profile across a transverse dimension of the receiver, wherein:

the receiver comprises an inlet section configured to receive the heat transfer fluid into the tubing arrangement and an outlet section configured to output heated heat transfer fluid from the tubing arrangement; and

the multiple tubes of the tubing arrangement defining together a flowing circuit between the inlet section and the outlet section from the outer tube or tubes to the inner tube or tubes.

18. The method of claim **17**, wherein the tubing arrangement is configured such that the concentrated illuminated area distributes heat flux to the heat transfer fluid within the tubing arrangement such that, in operation, the density of the fluid within a tube of the tubing arrangement is inversely related to the heat flux delivered to that tube.

19. The method of claim **17**, further comprising controlling mass flow of the heat transfer fluid into the tubing arrangement using a flow control device.

20. The method of claim **17**, wherein the tubing arrangement comprises one or more thermal expansion sections that accommodates thermal expansion of the tubing arrangement.

21. The method of claim **20**, wherein at least one thermal expansion section extends in a plane defined by the multiple parallel tubes.

22. The method of claim **20**, wherein at least one thermal expansion section extends out of a plane defined by the multiple parallel tubes.

23. The method of claim **20**, wherein the thermal expansion section comprises a suspension mechanism having at least one clamp holding one of the tubes of the tubing arrangement, the suspension mechanism coupled to sliding or rolling means, said sliding or rolling means being supported by a track interconnected with the receiver structure and defining a path parallel to the tube length for said sliding or rolling means.

24. The method of claim **17**, wherein:

the inlet section comprises a first inlet section;

the outlet section comprises a first outlet section;

the inner tube or tubes comprises a first inner tube;

flowing the heat transfer fluid into the tubing arrangement comprises flowing the heat transfer fluid into the tubing arrangement through the first inlet section to enter the first outer tube or tubes to flow in a first direction to reach a turnaround header that redirects heat transfer fluid to enter the first inner tube to flow in a second flow direction counter-parallel to the first flow direction to reach the first outlet section; and

the concentrated illuminated area provides greater heat flux to the first inner tube than to the first outer tube or tubes.

25. The method of claim **24**, wherein the first inner tube has an inner diameter greater than that of the first outer tube or tubes.

* * * * *