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(12) **United States Patent**
Parker et al.

(10) **Patent No.: US 12,392,562 B2**
(45) **Date of Patent: Aug. 19, 2025**

(54) **INDIRECT HEAT EXCHANGER PRESSURE VESSEL WITH CONTROLLED WRINKLE BENDS**

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(72) Inventors: **Daniel E. Parker**, Union Bridge, MD (US); **Advait Damle**, Columbia, MD (US); **Frank T. Morrison**, Crownsville, MD (US)

(73) Assignee: **Baltimore Aircoil Company, Inc.**, Jessup, MD (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 600 days.

(21) Appl. No.: **17/576,061**

(22) Filed: **Jan. 14, 2022**

(65) **Prior Publication Data**

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Related U.S. Application Data

(60) Provisional application No. 63/270,953, filed on Oct. 22, 2021, provisional application No. 63/138,655, filed on Jan. 18, 2021.

(51) **Int. Cl.**
F28D 1/047 (2006.01)
F28F 1/00 (2006.01)

(52) **U.S. Cl.**
CPC ***F28F 1/006*** (2013.01); ***F28D 1/0477*** (2013.01); *F28F 2225/04* (2013.01)

(58) **Field of Classification Search**
CPC F28D 1/0477; F28D 7/085; F28D 7/087; F28F 1/006; F28F 2225/04
See application file for complete search history.

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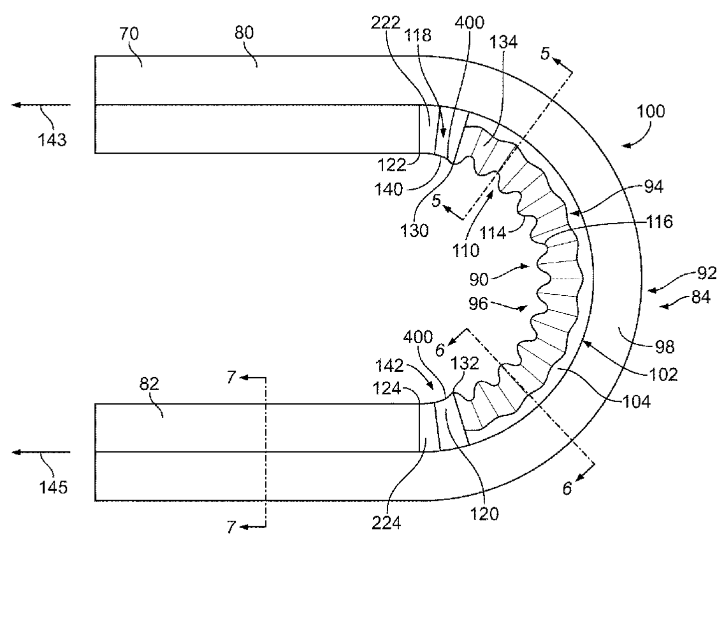
Primary Examiner — Eric S Ruppert
Assistant Examiner — Hans R Weiland
(74) *Attorney, Agent, or Firm* — Fitch, Even, Tabin & Flannery LLP

(57) **ABSTRACT**

In one aspect of the present disclosure, an indirect heat exchanger pressure vessel is provided that includes an inlet header to receive a pressurized working fluid, such as water, glycol, ammonia, and/or CO_2. The indirect heat exchanger pressure vessel includes an outlet header to collect the pressurized working fluid and a serpentine circuit tube connecting the inlet and outlet headers. The serpentine circuit tube permits the pressurized working fluid to flow from the inlet header to the outlet header. The serpentine circuit tube includes runs and a return bend connecting the runs. The return bend has a controlled wrinkled portion comprising alternating ridges and grooves. The alternating ridges and grooves strengthen the return bend and permit the indirect heat exchanger pressure vessel to facilitate working fluid heat transfer at a high internal operating pressure.

50 Claims, 38 Drawing Sheets



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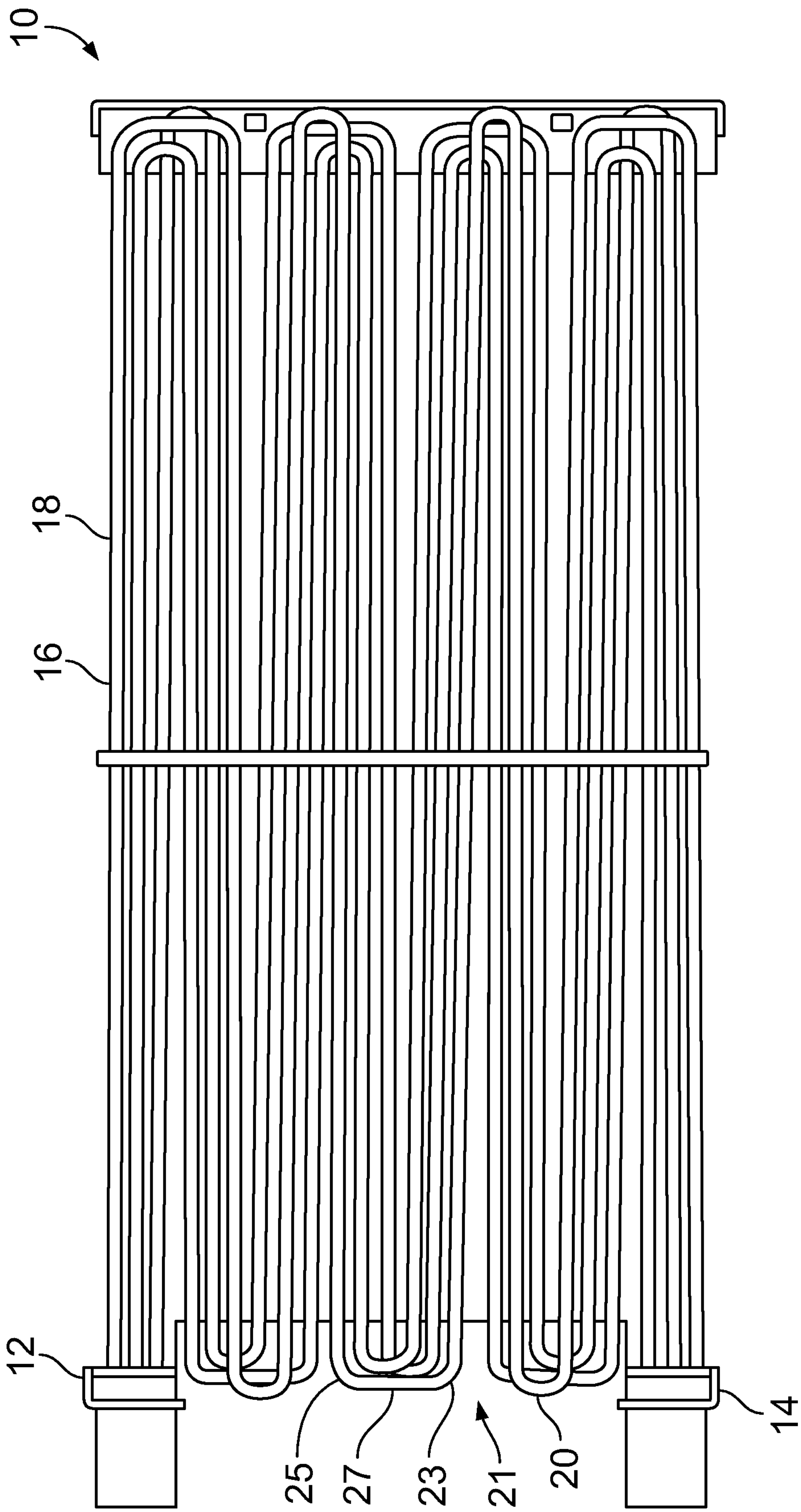
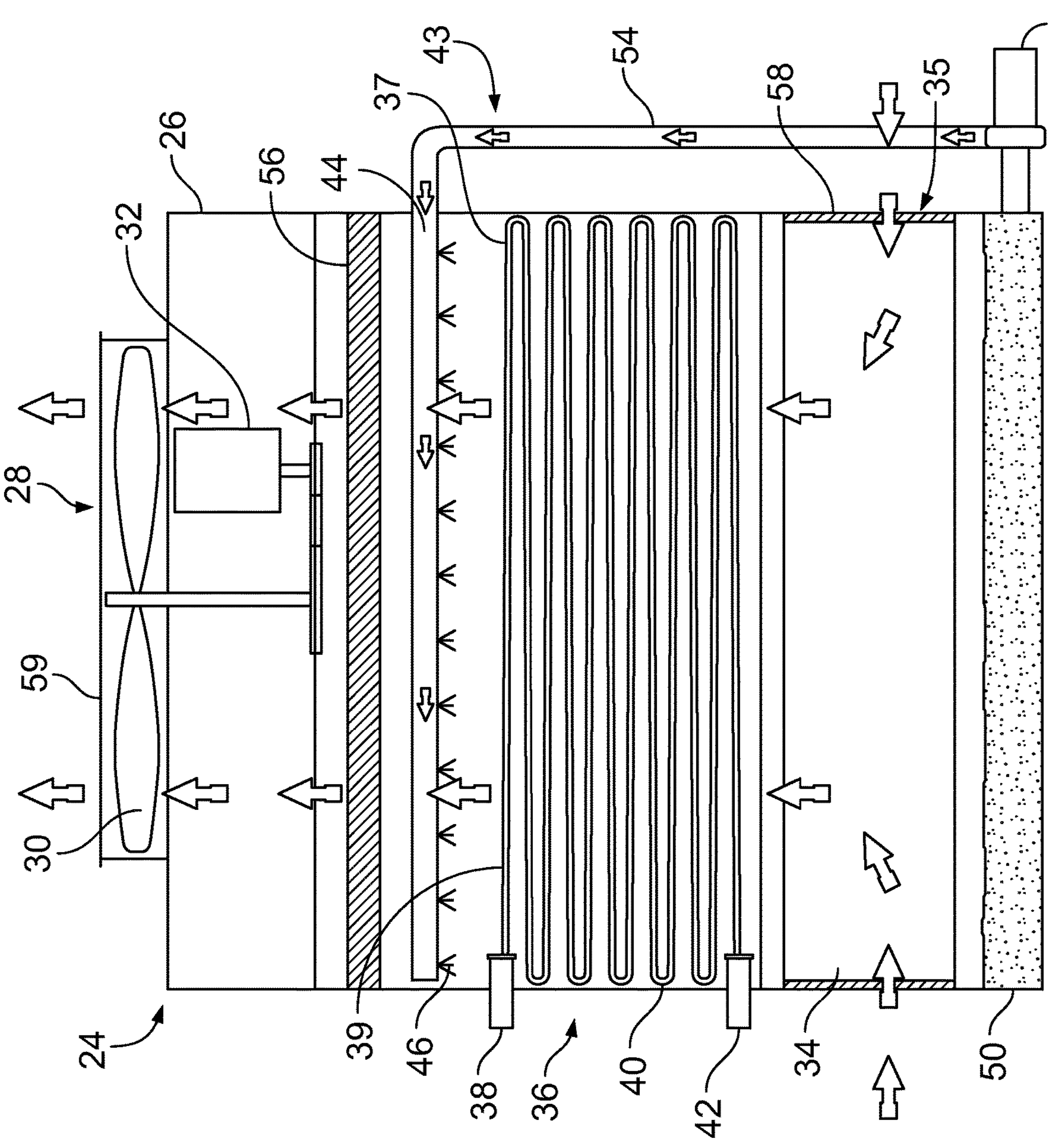


FIG. 1



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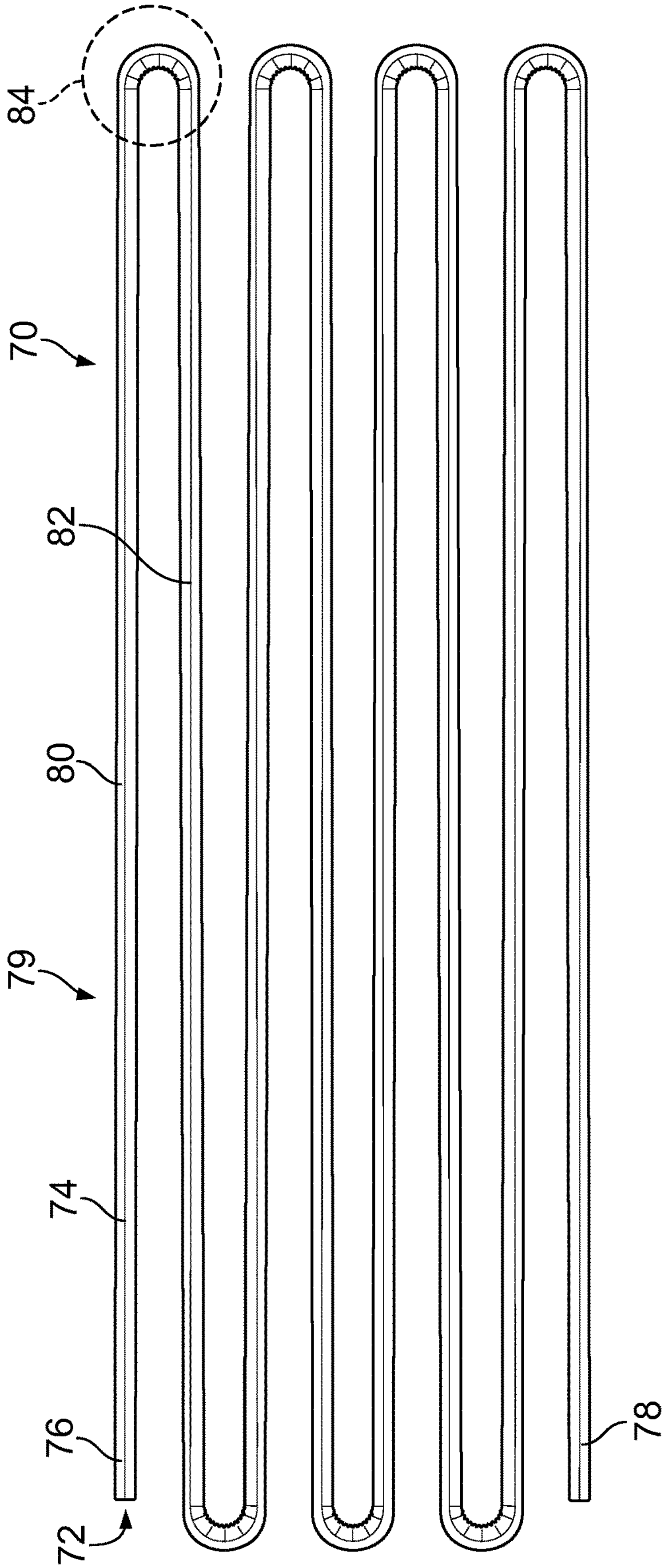

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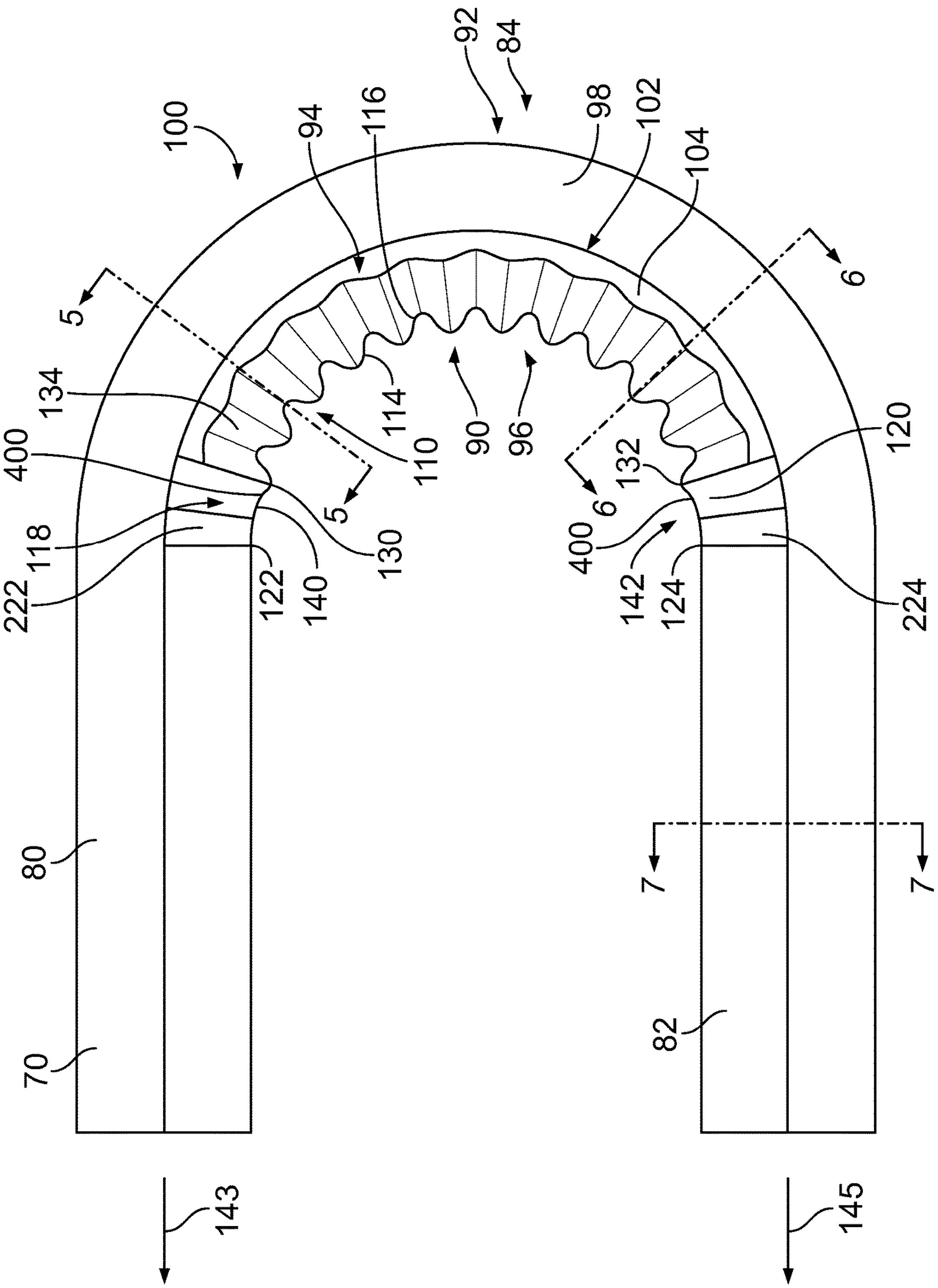
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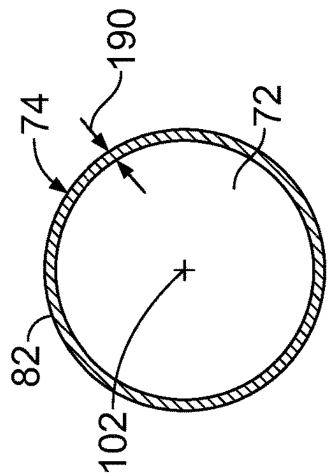
FIG. 4



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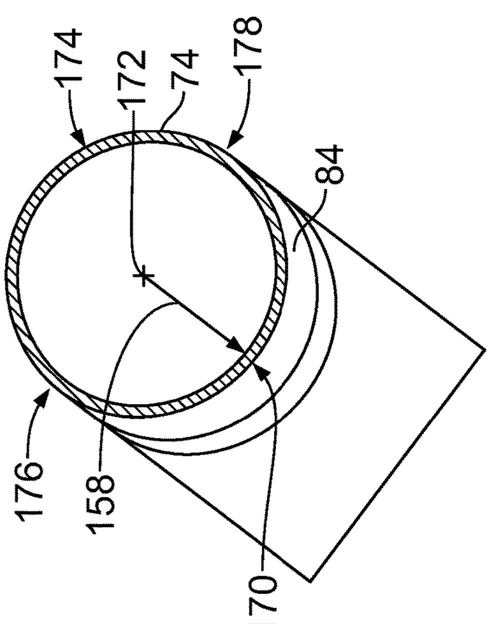

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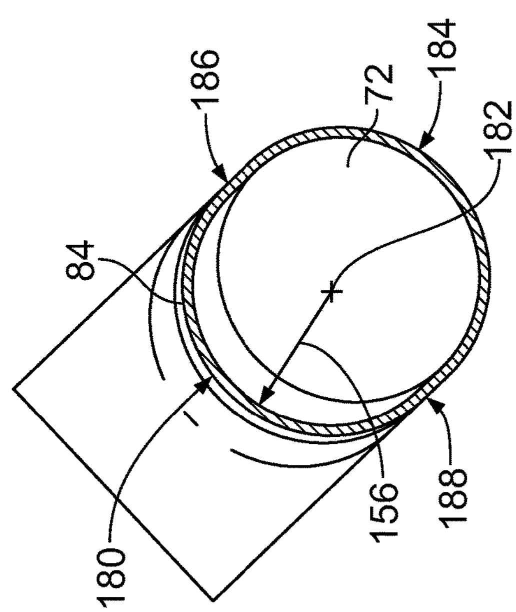

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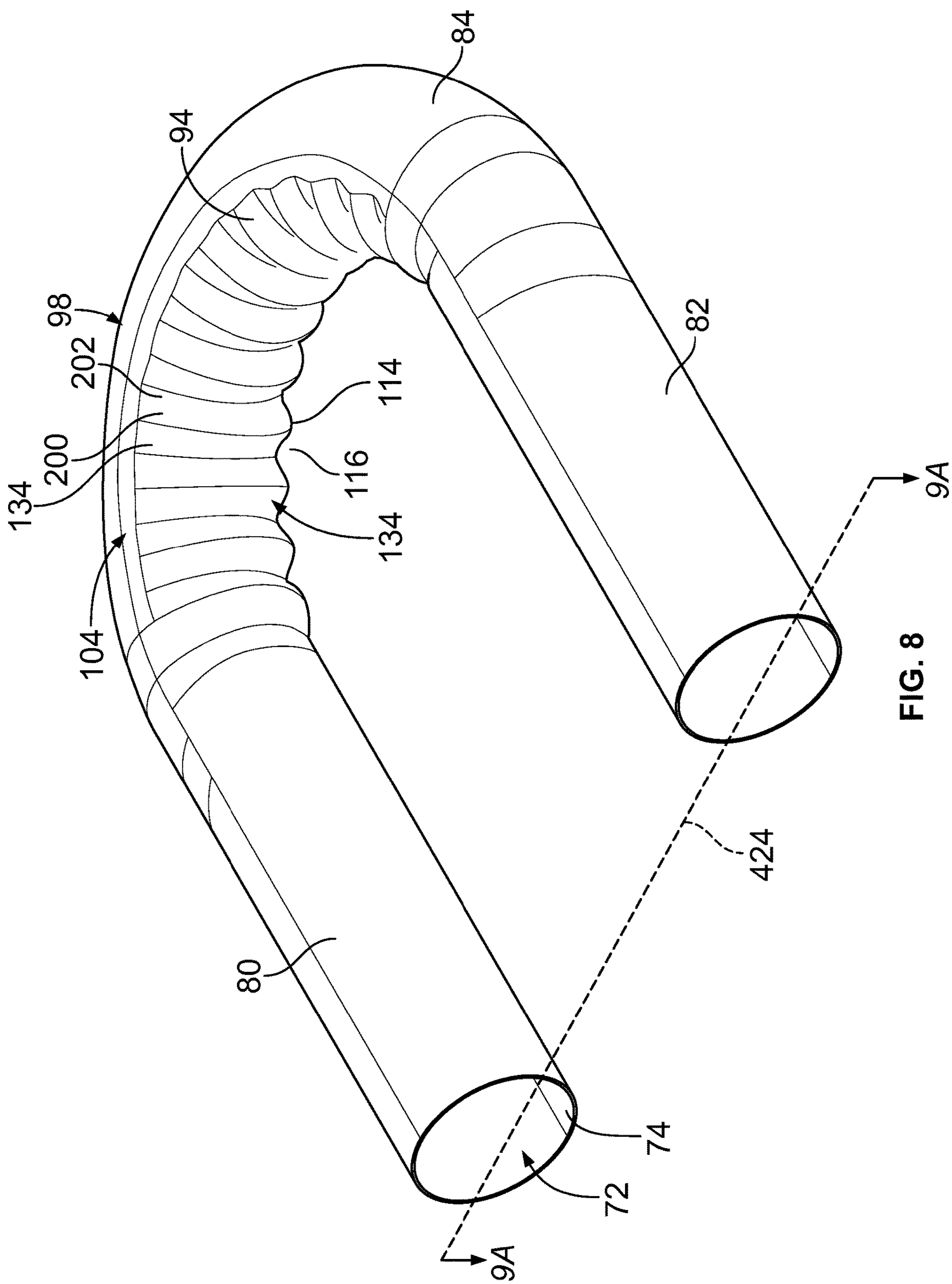

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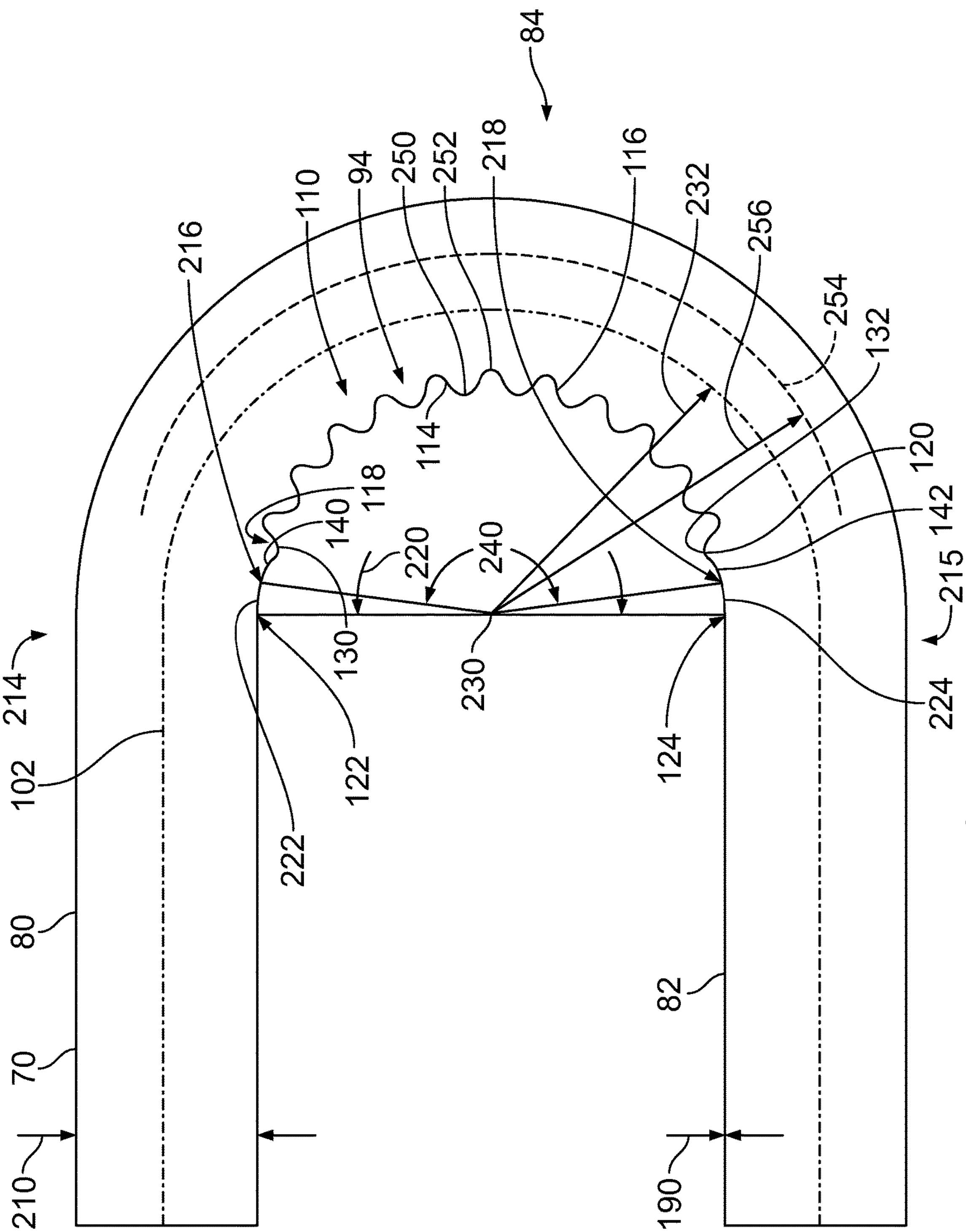
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FIG. 9A

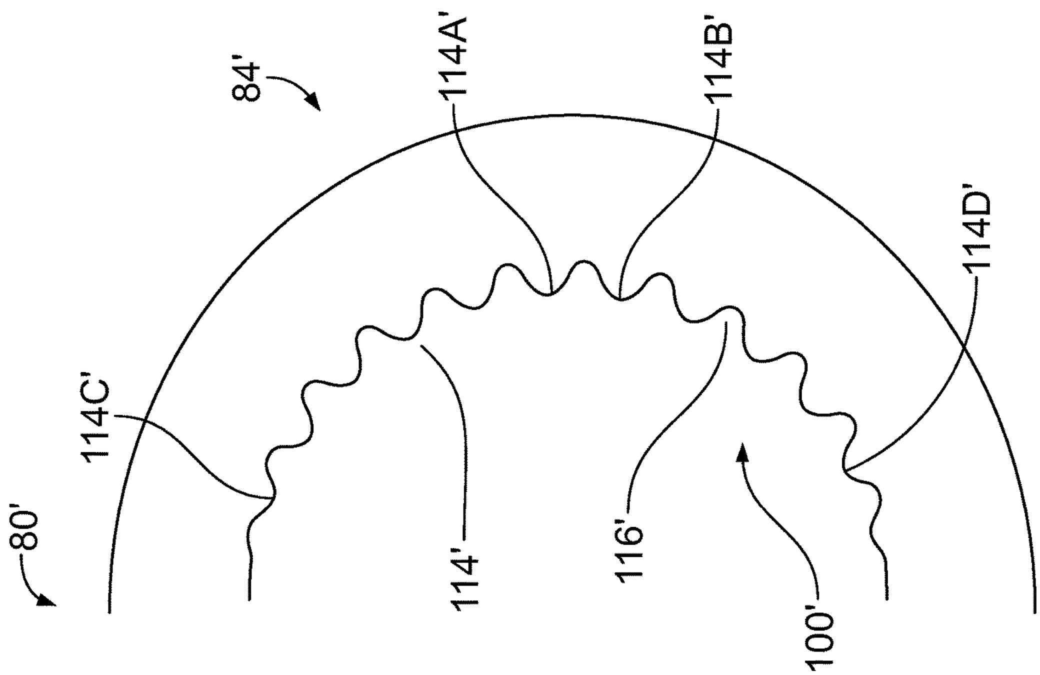

FIG. 9B

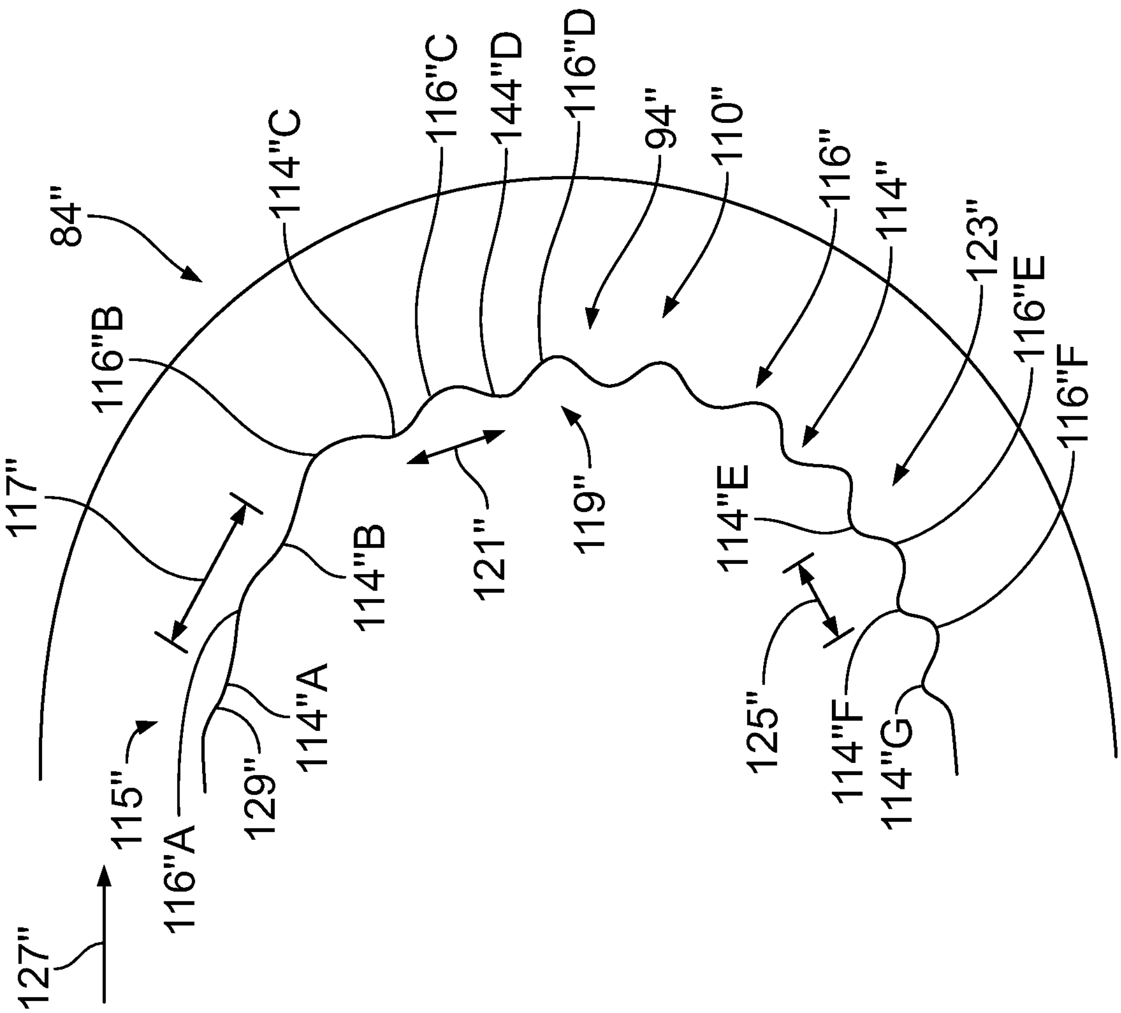
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FIG. 9C

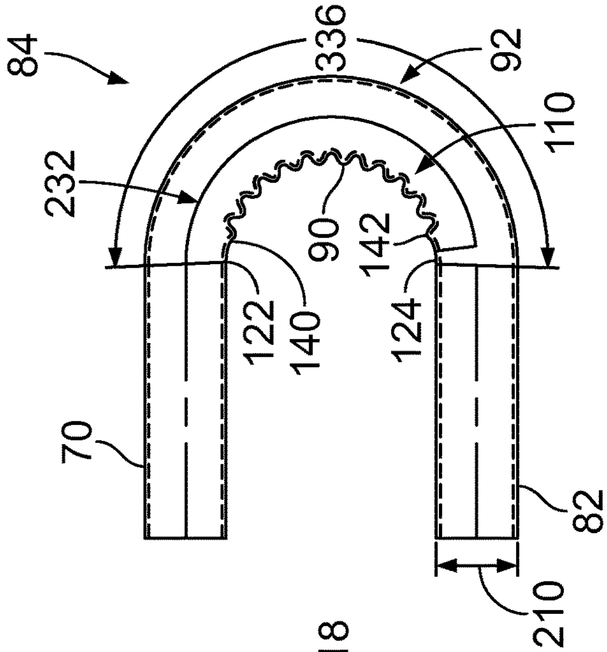


FIG. 12

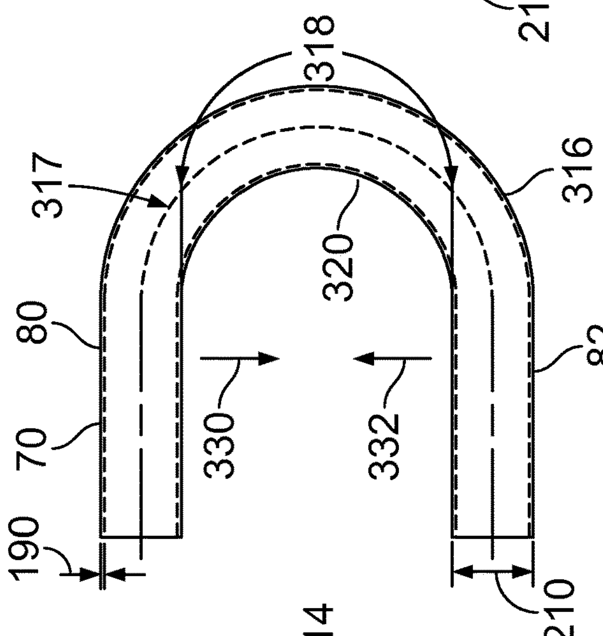


FIG. 11

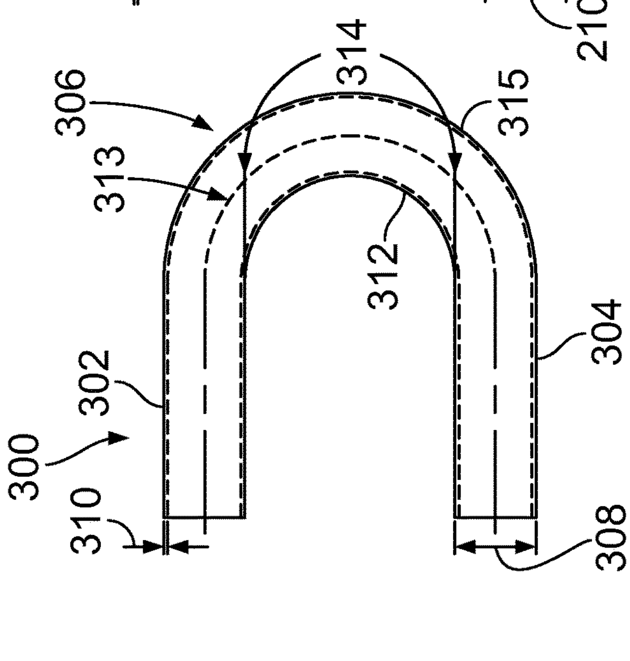


FIG. 10

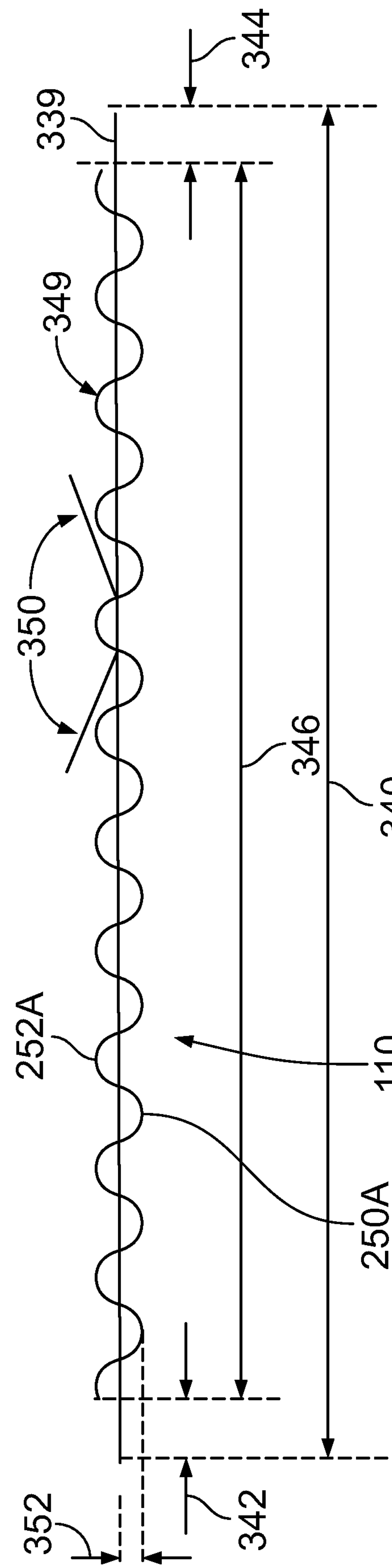
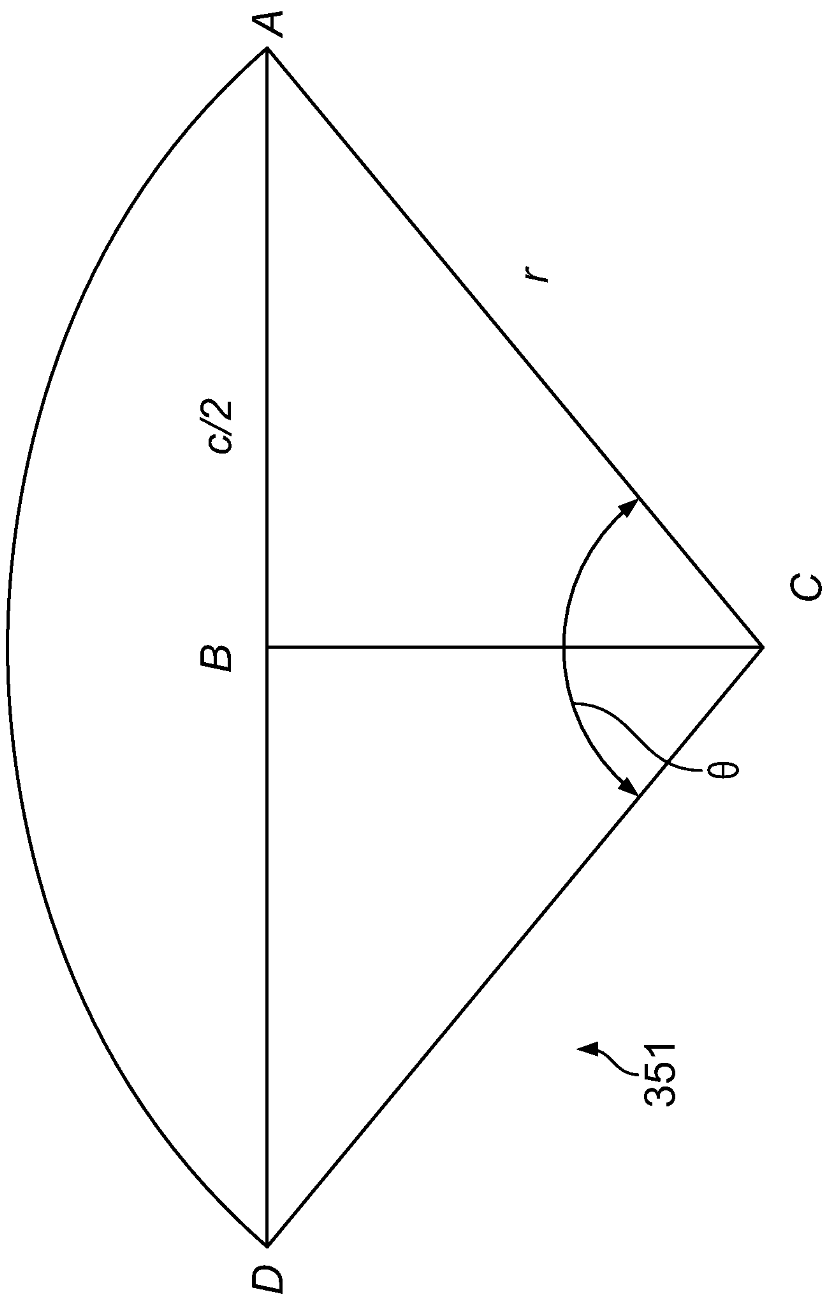


FIG. 13A



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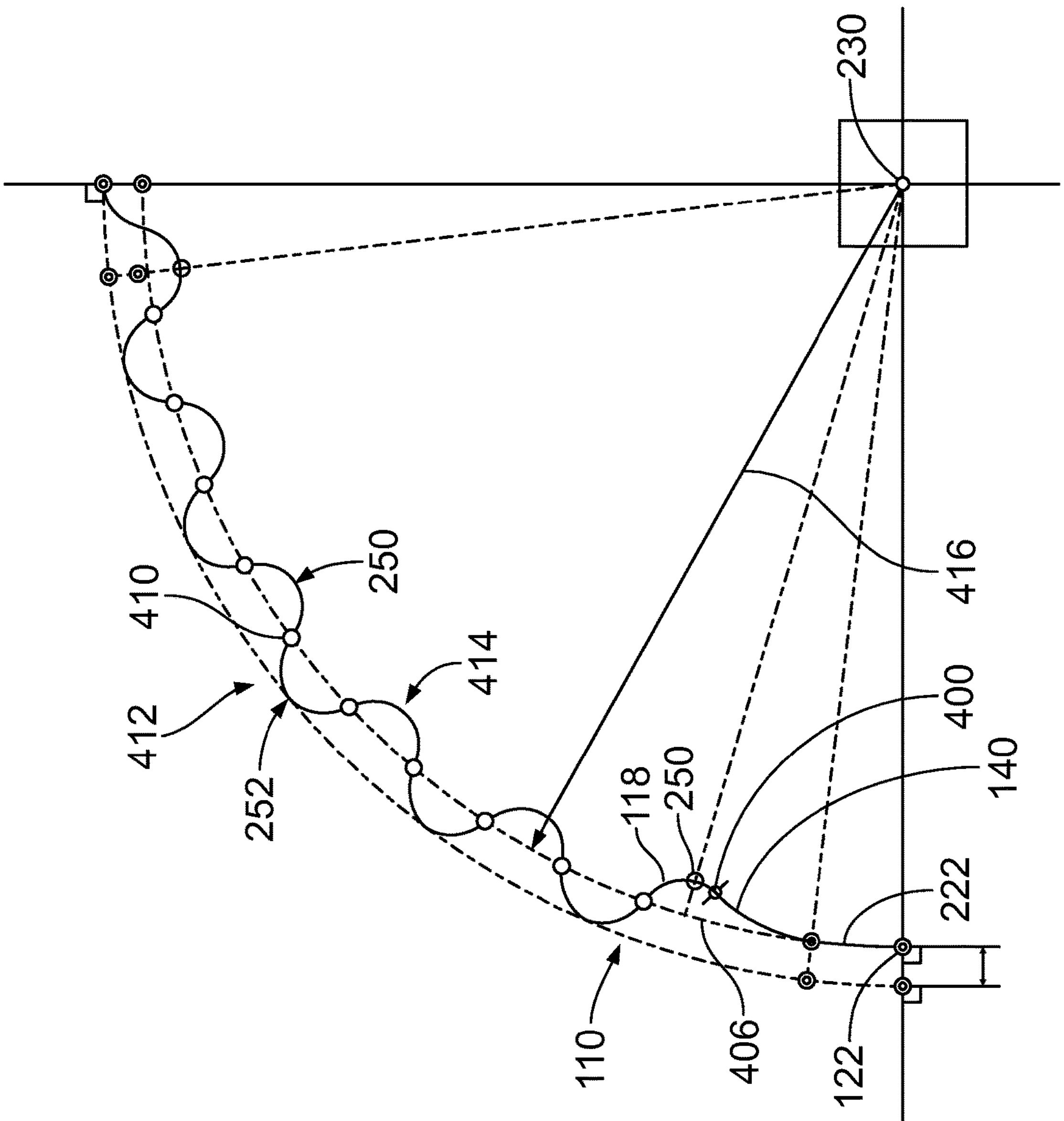
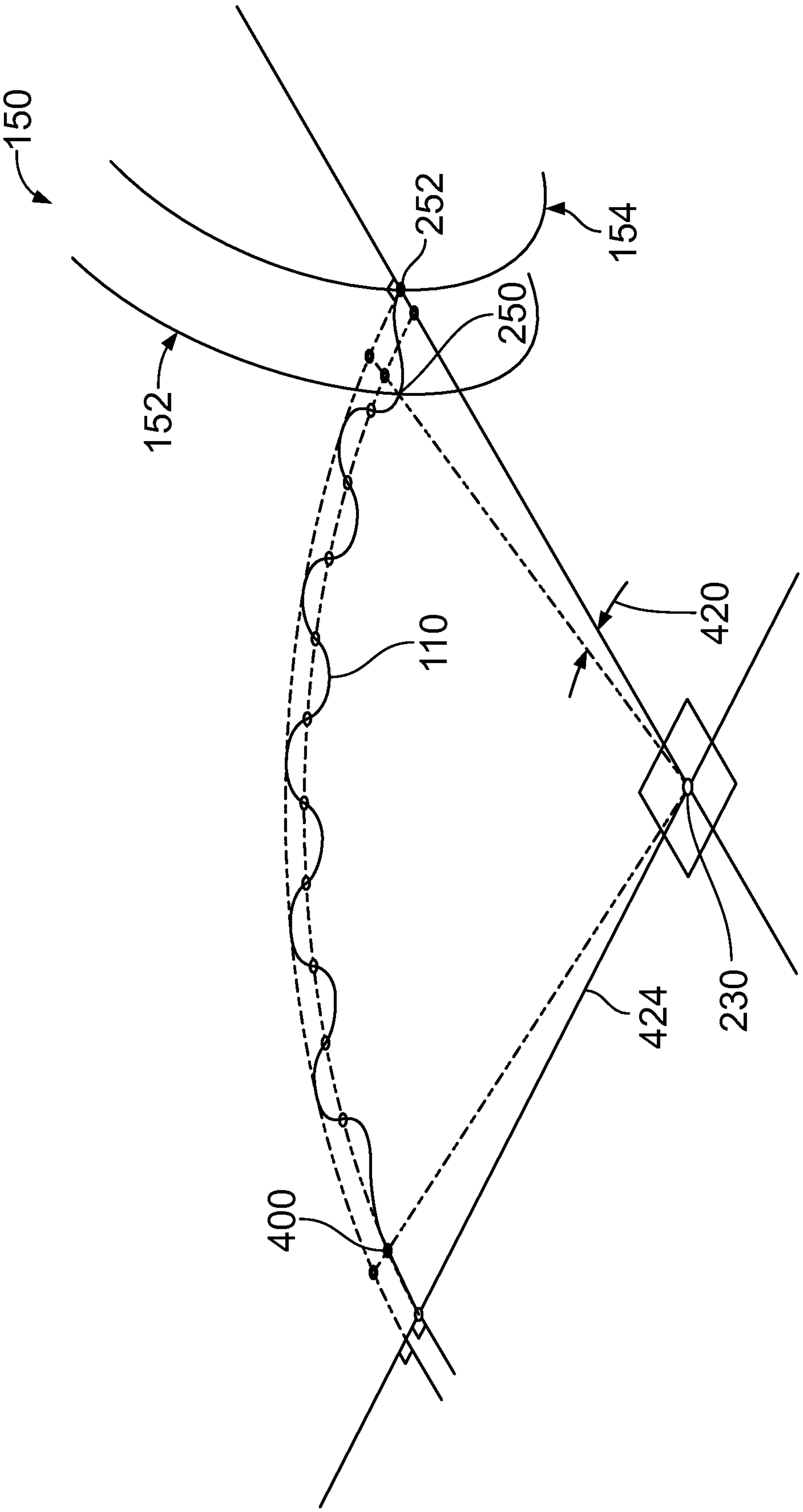


FIG. 14



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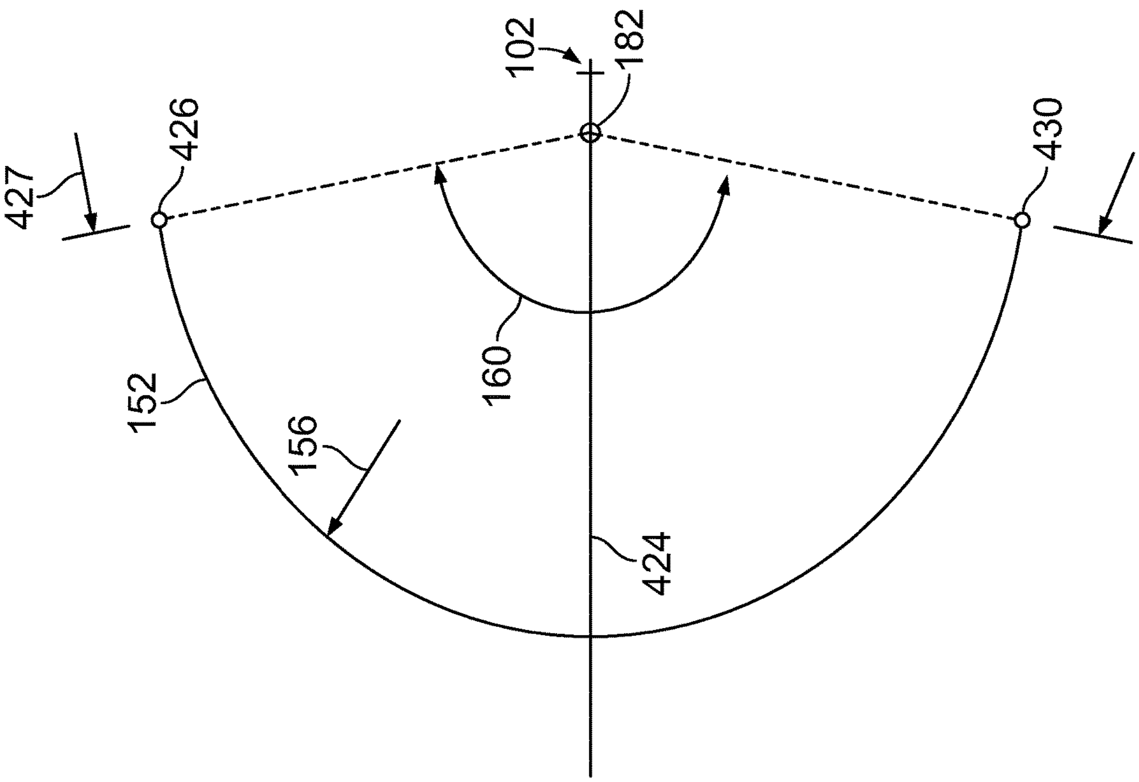

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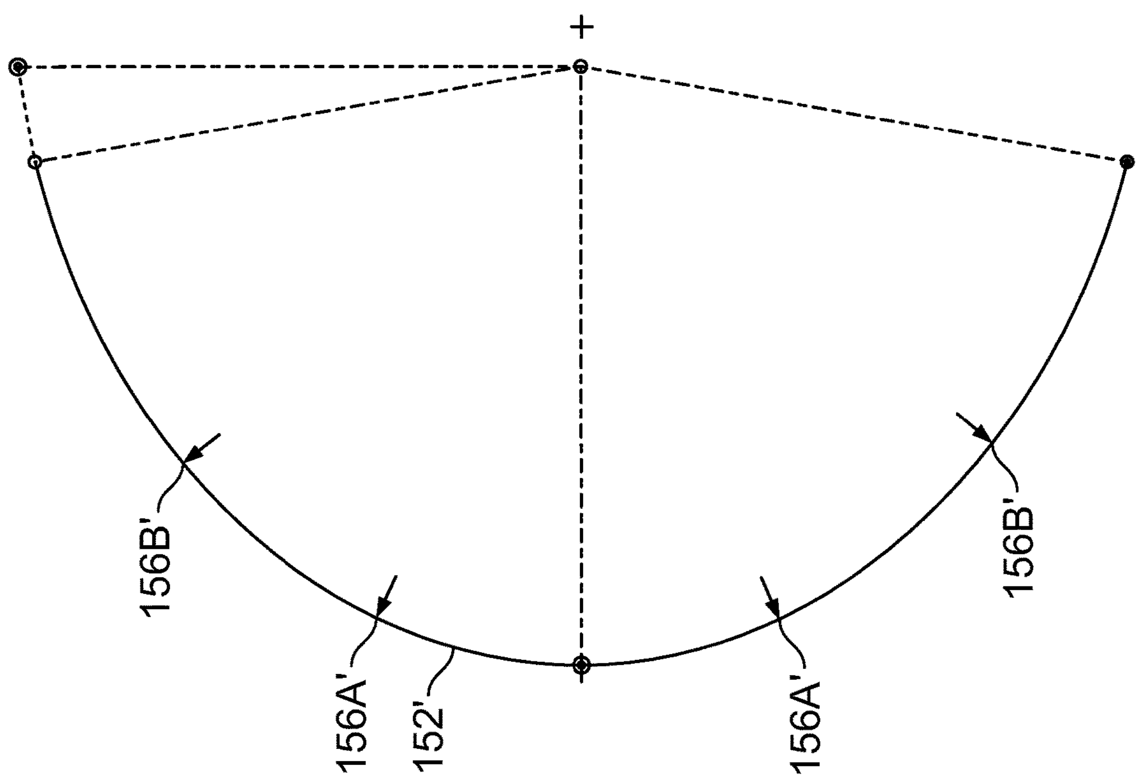

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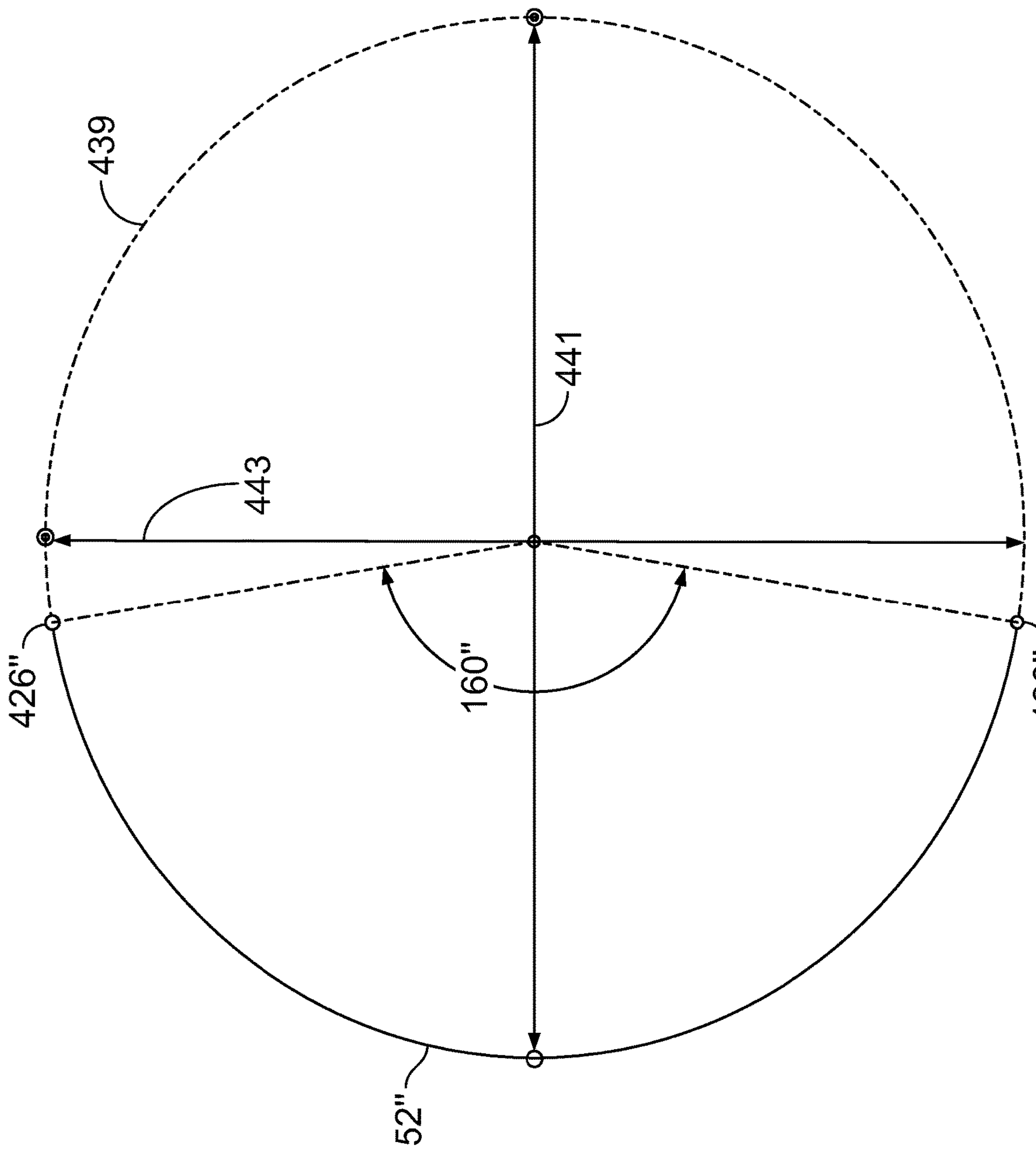

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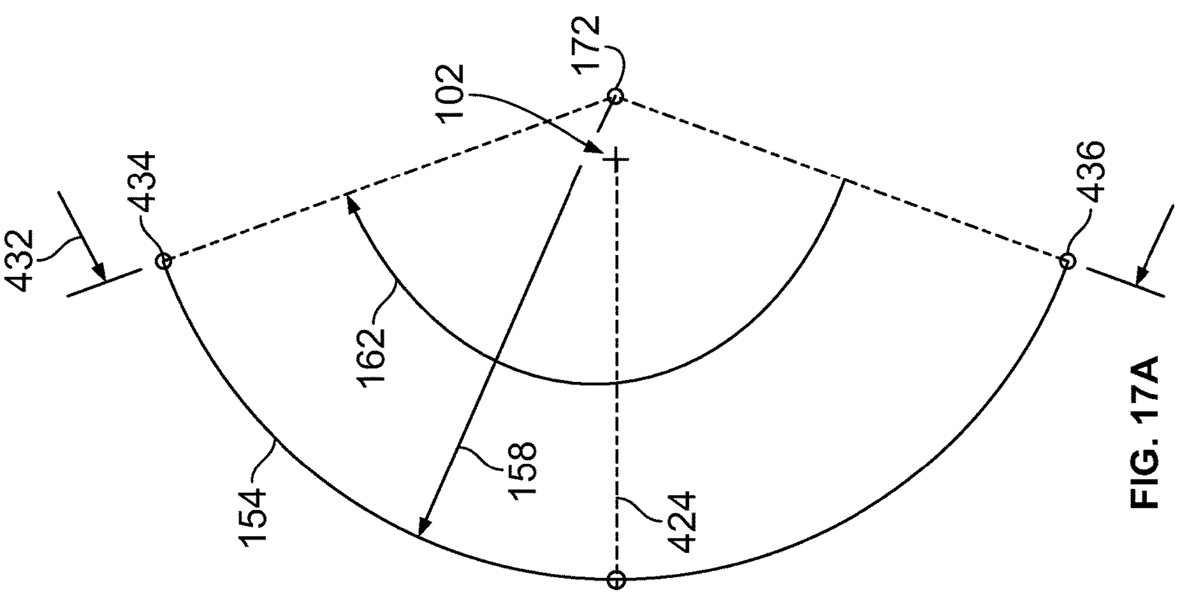

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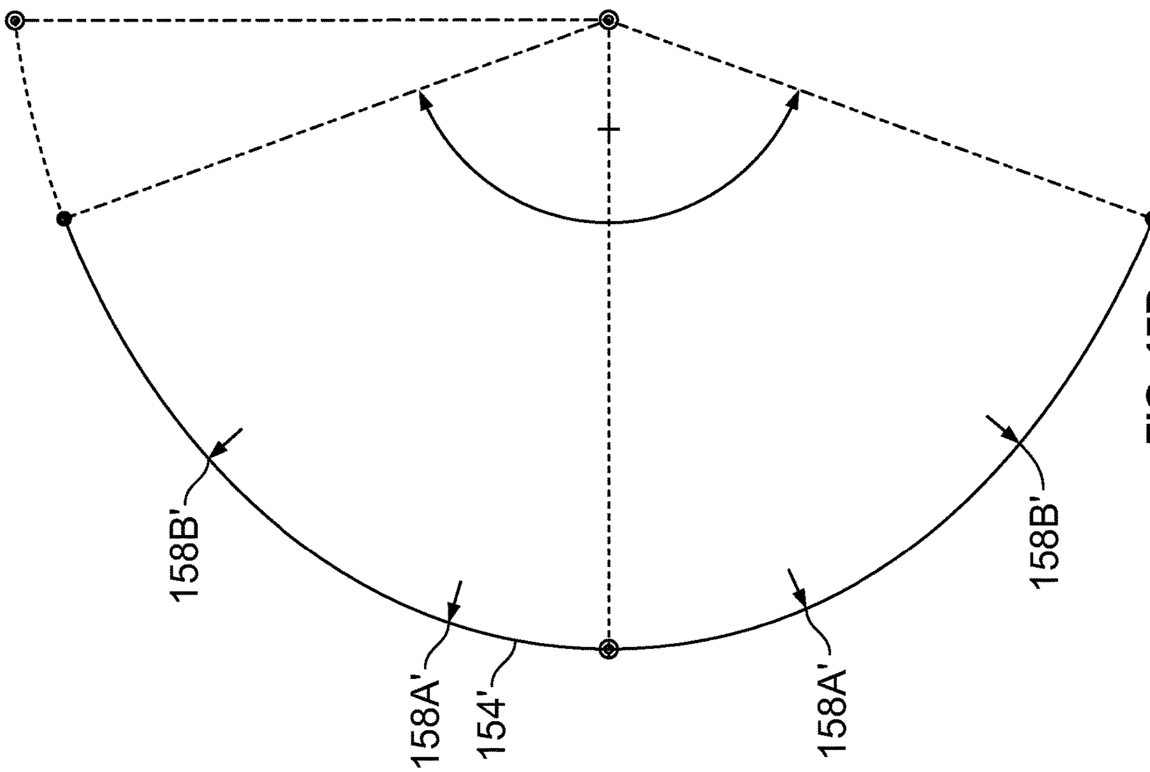

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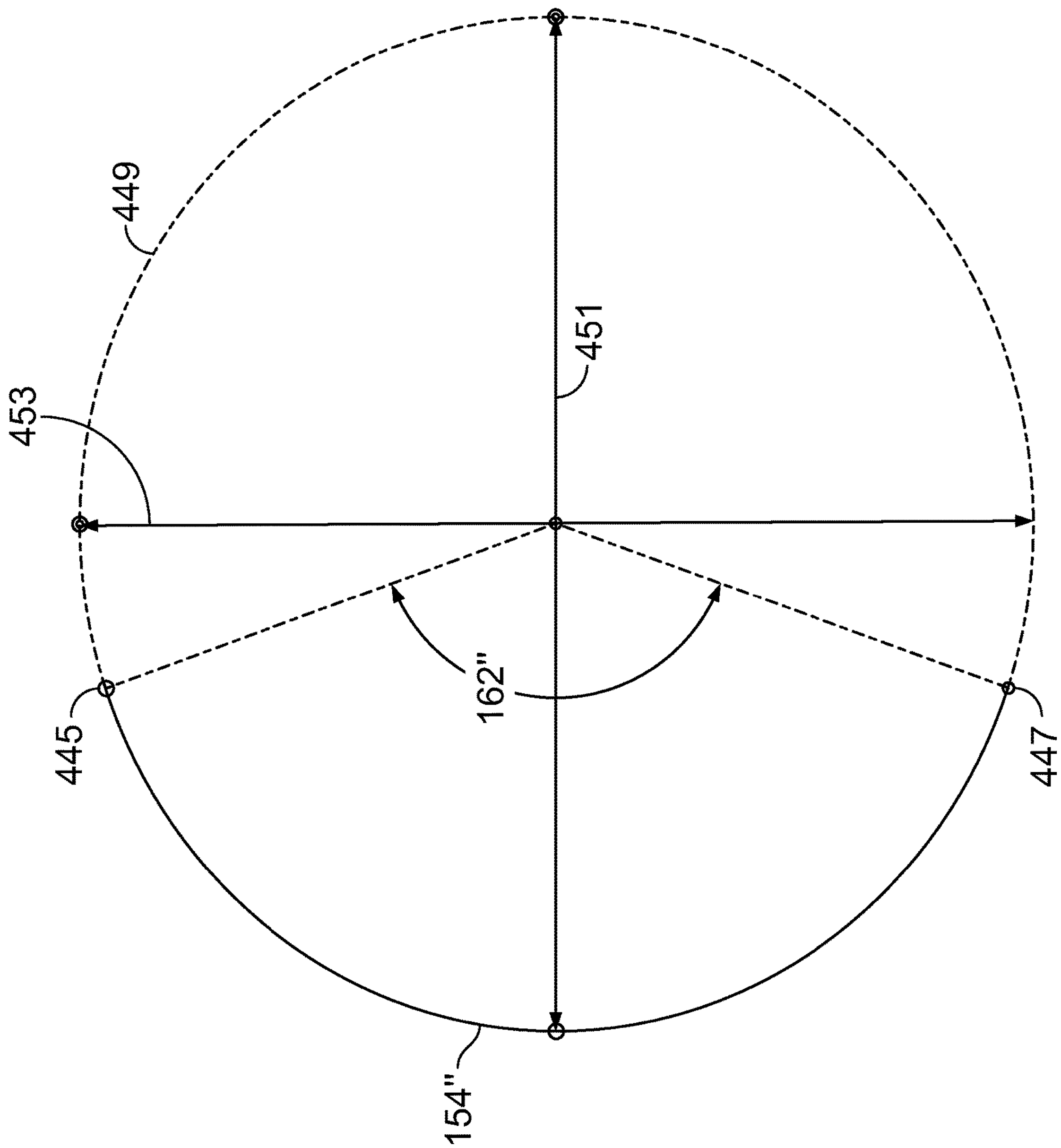

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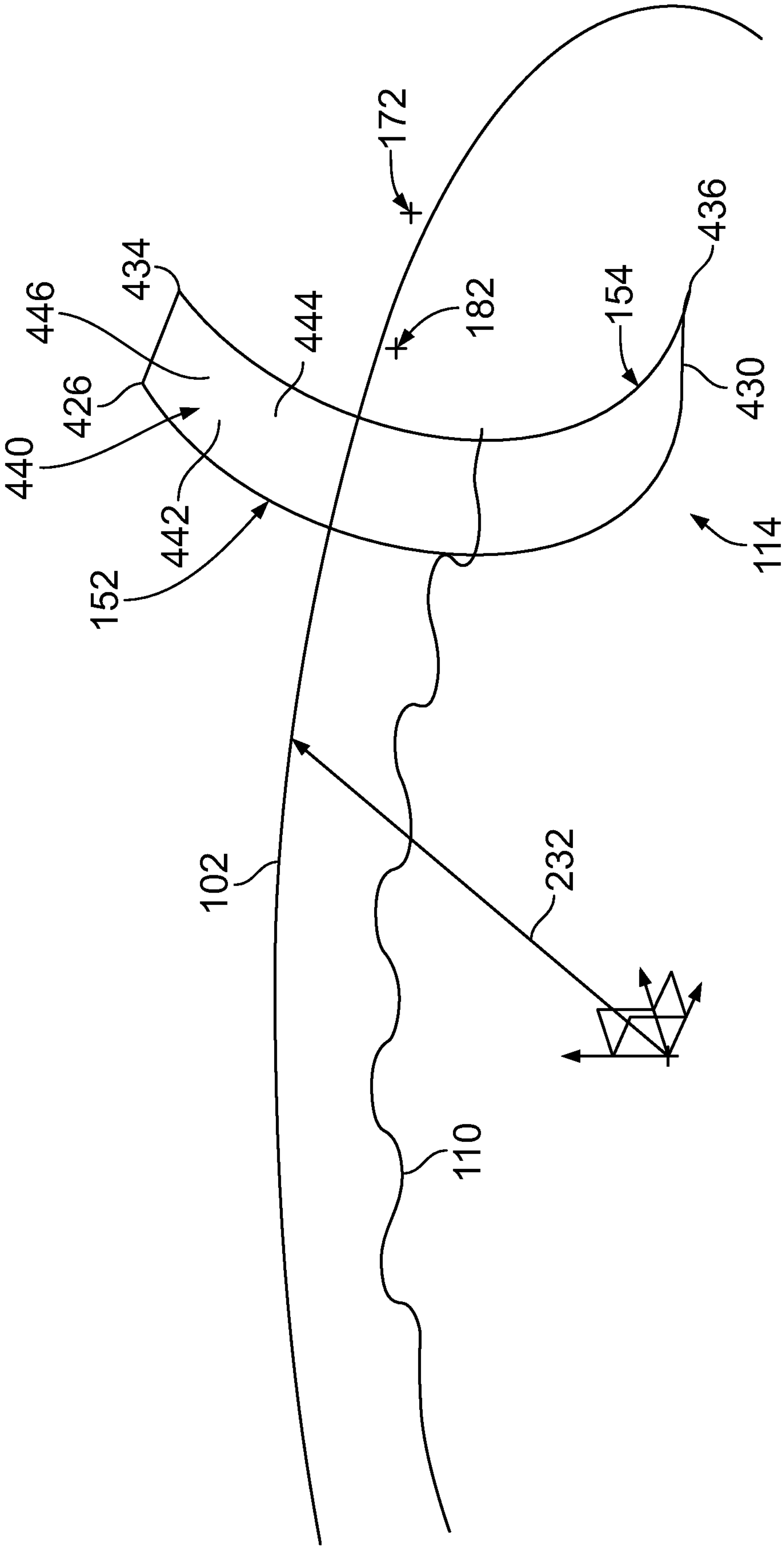

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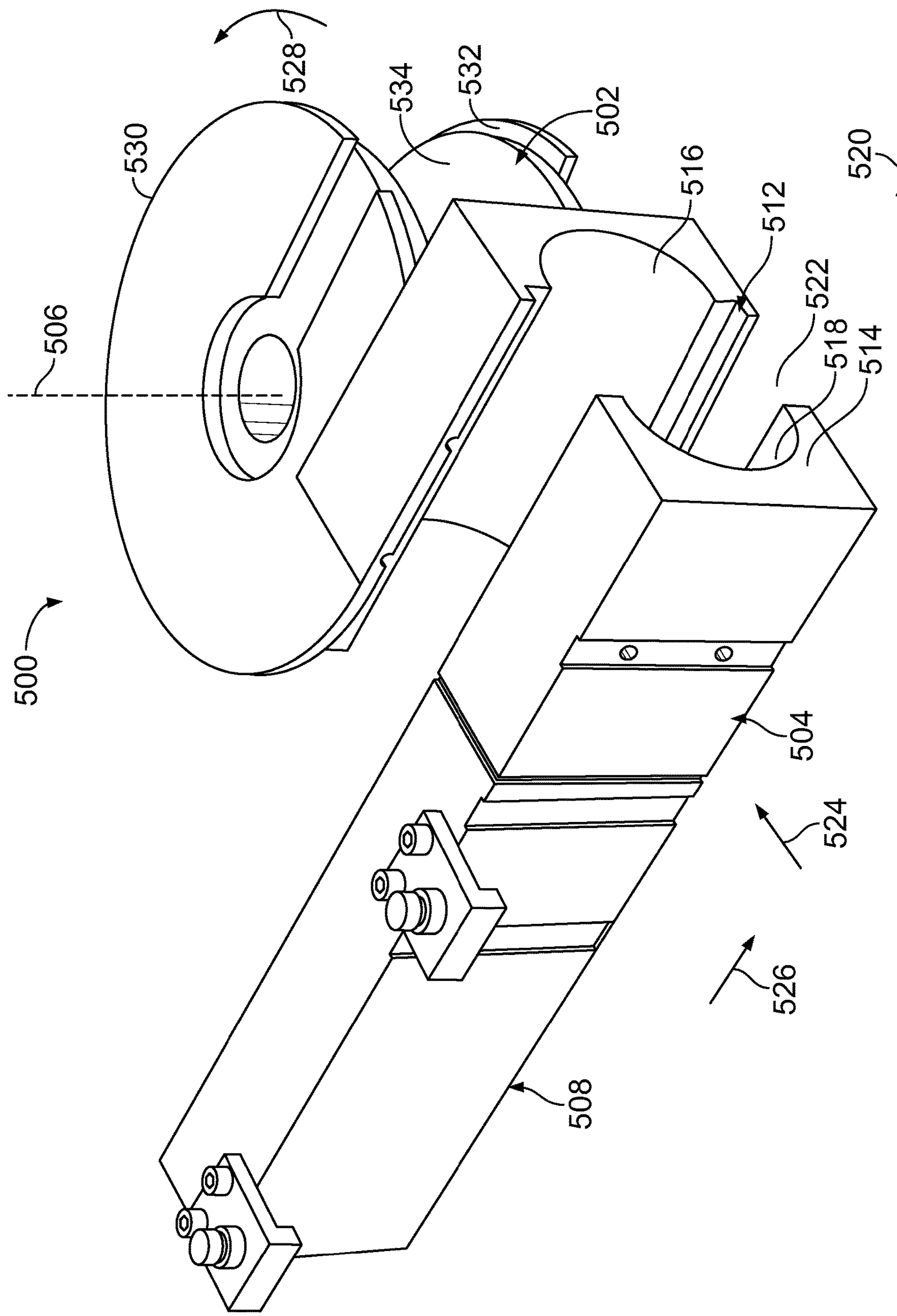
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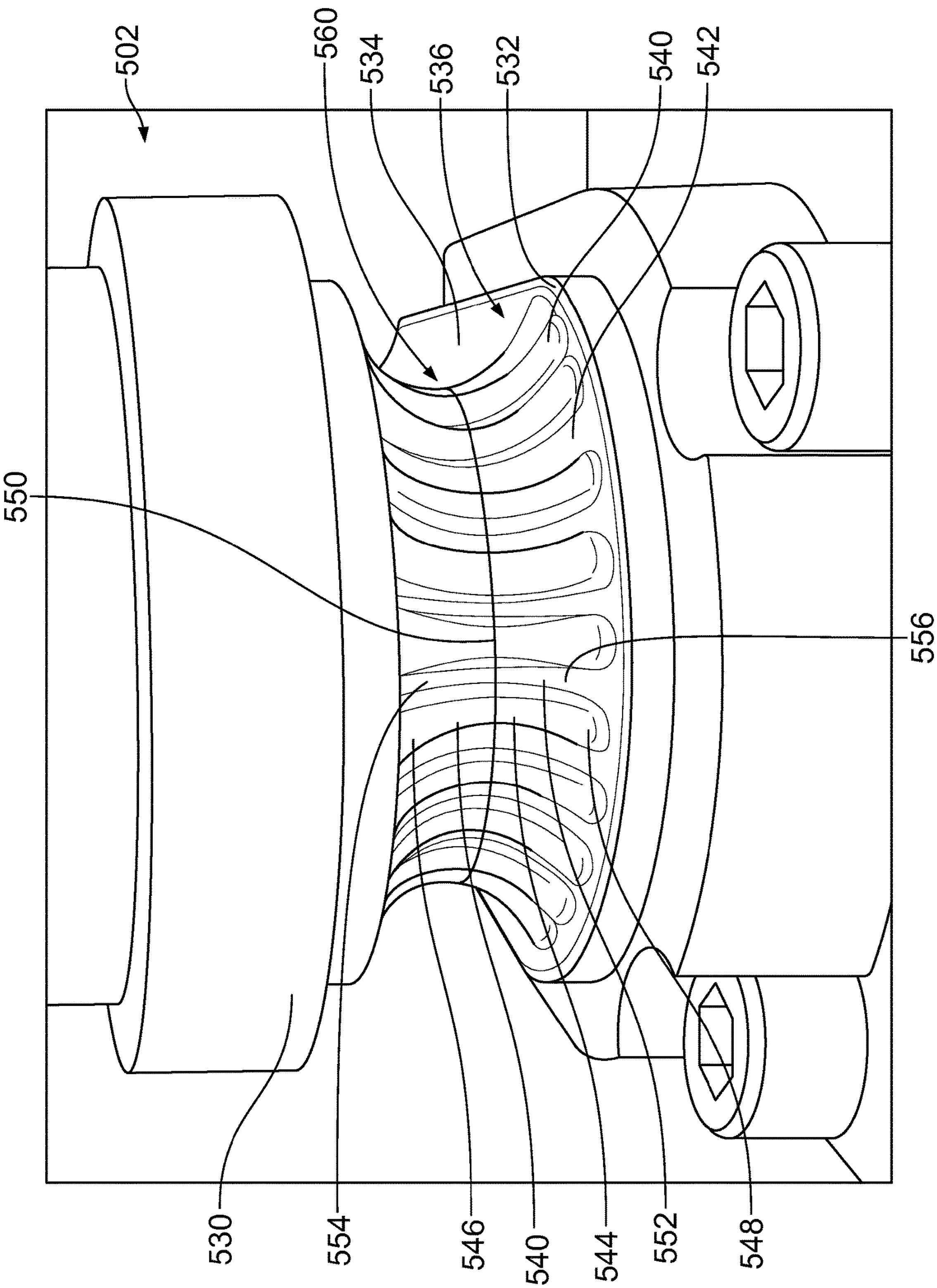
FIG. 19



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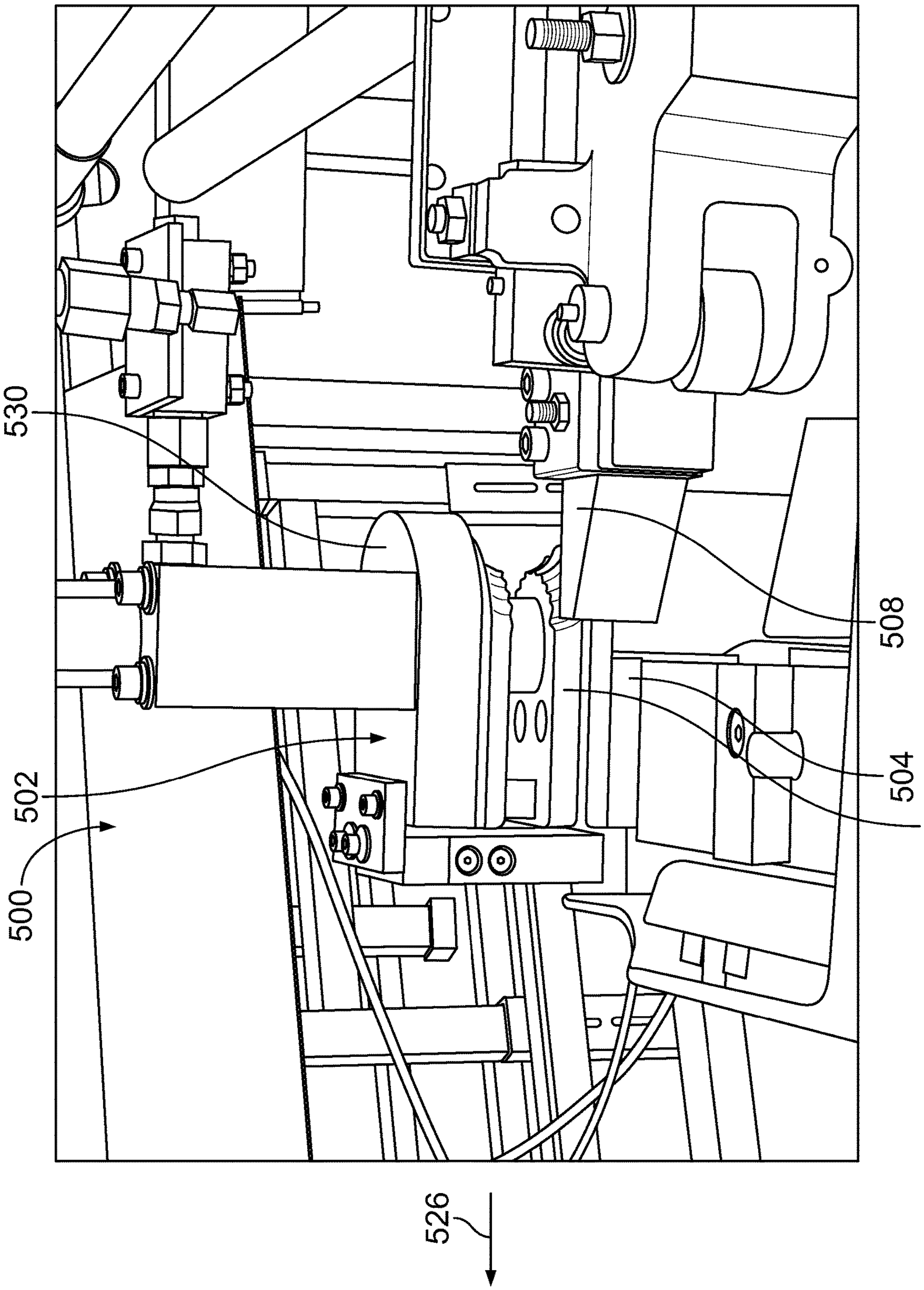

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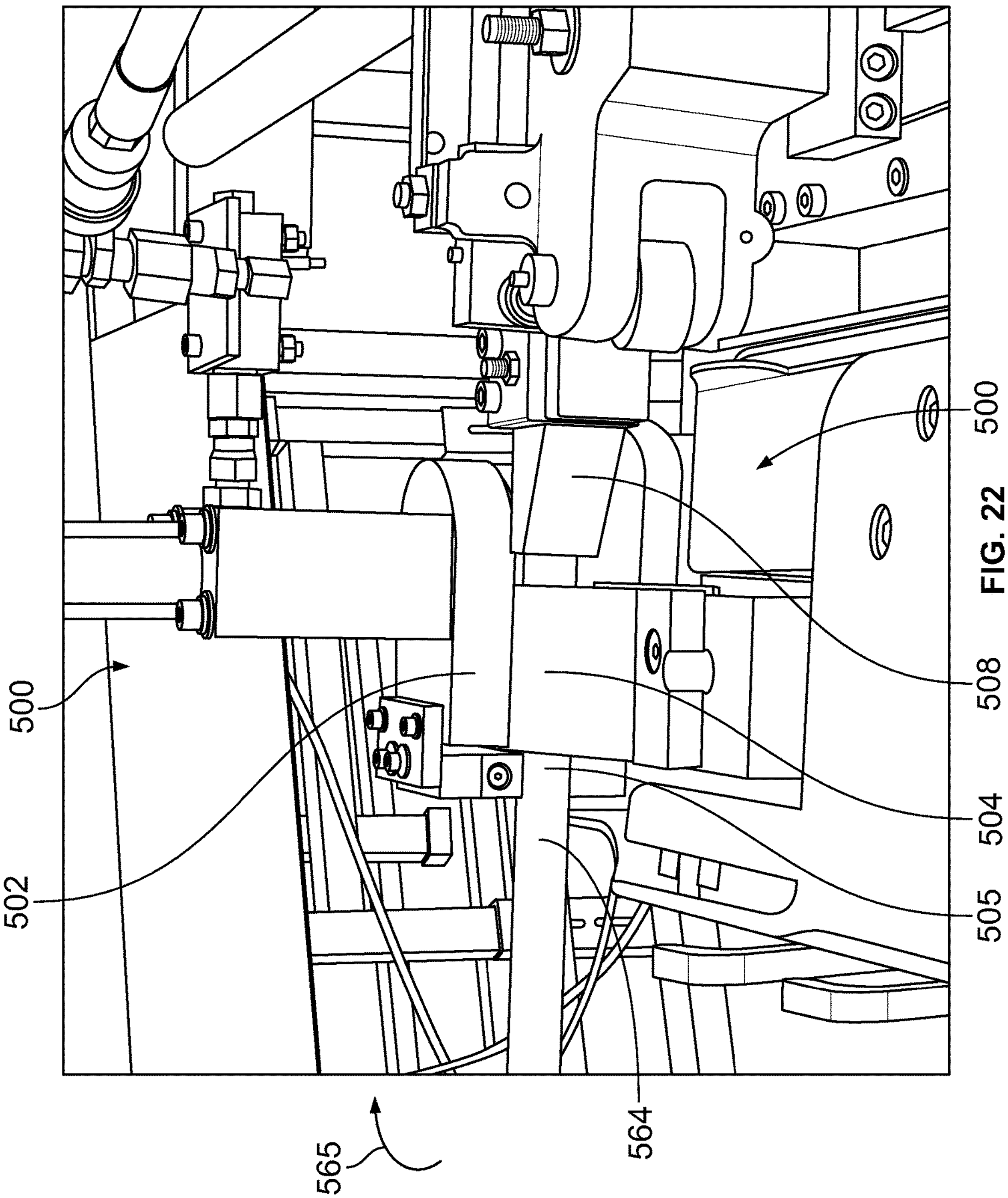
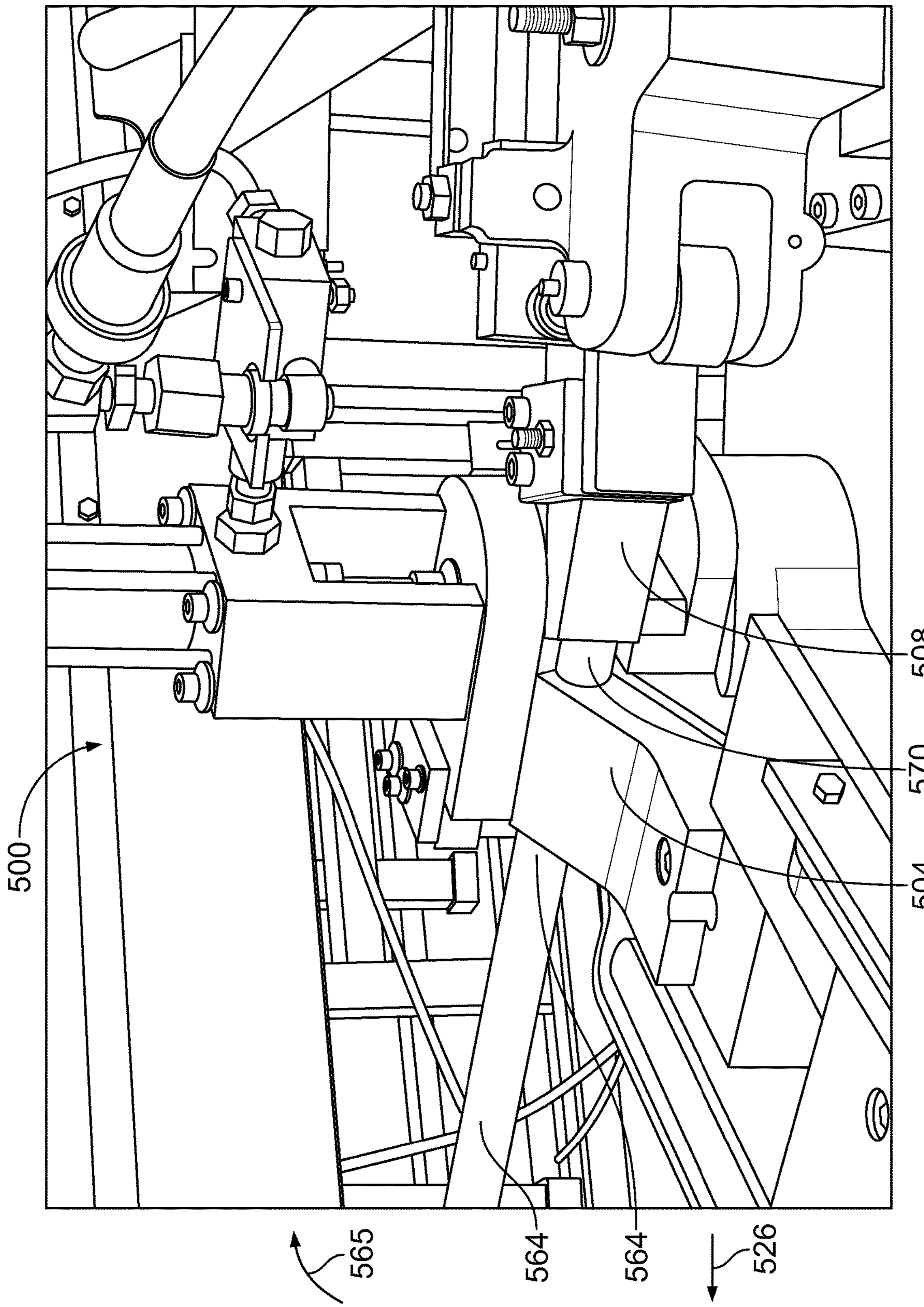


FIG. 22



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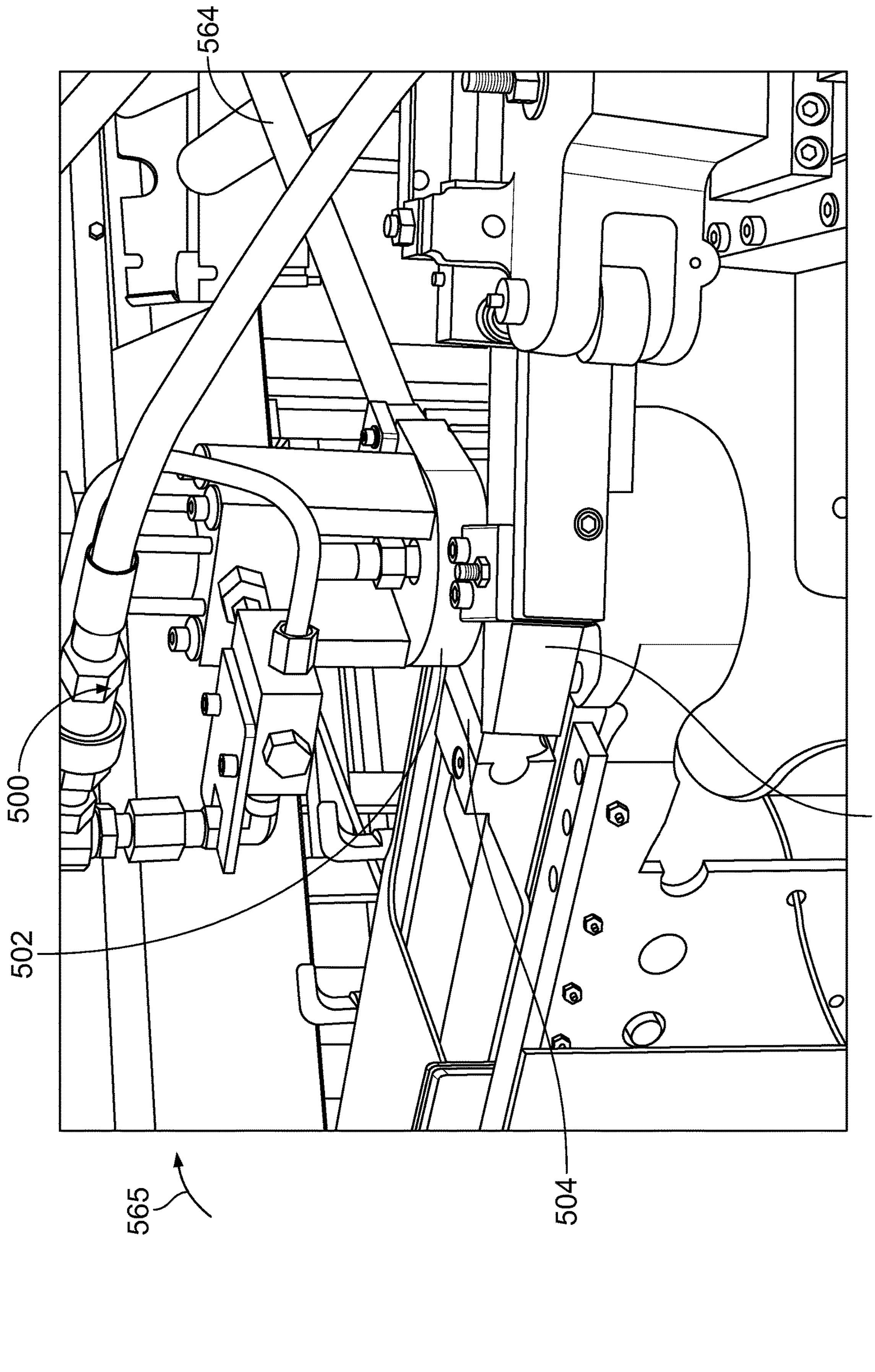

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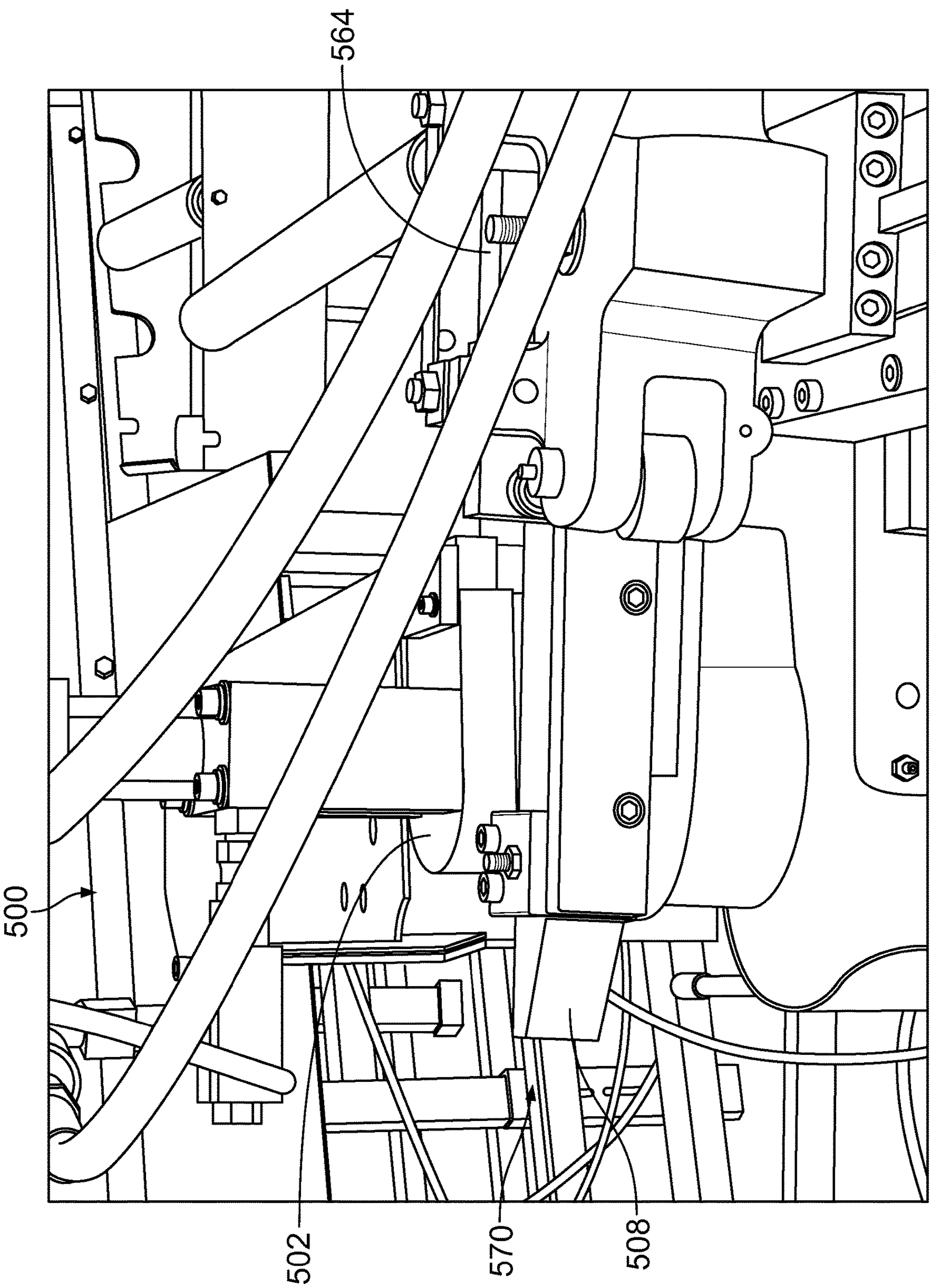

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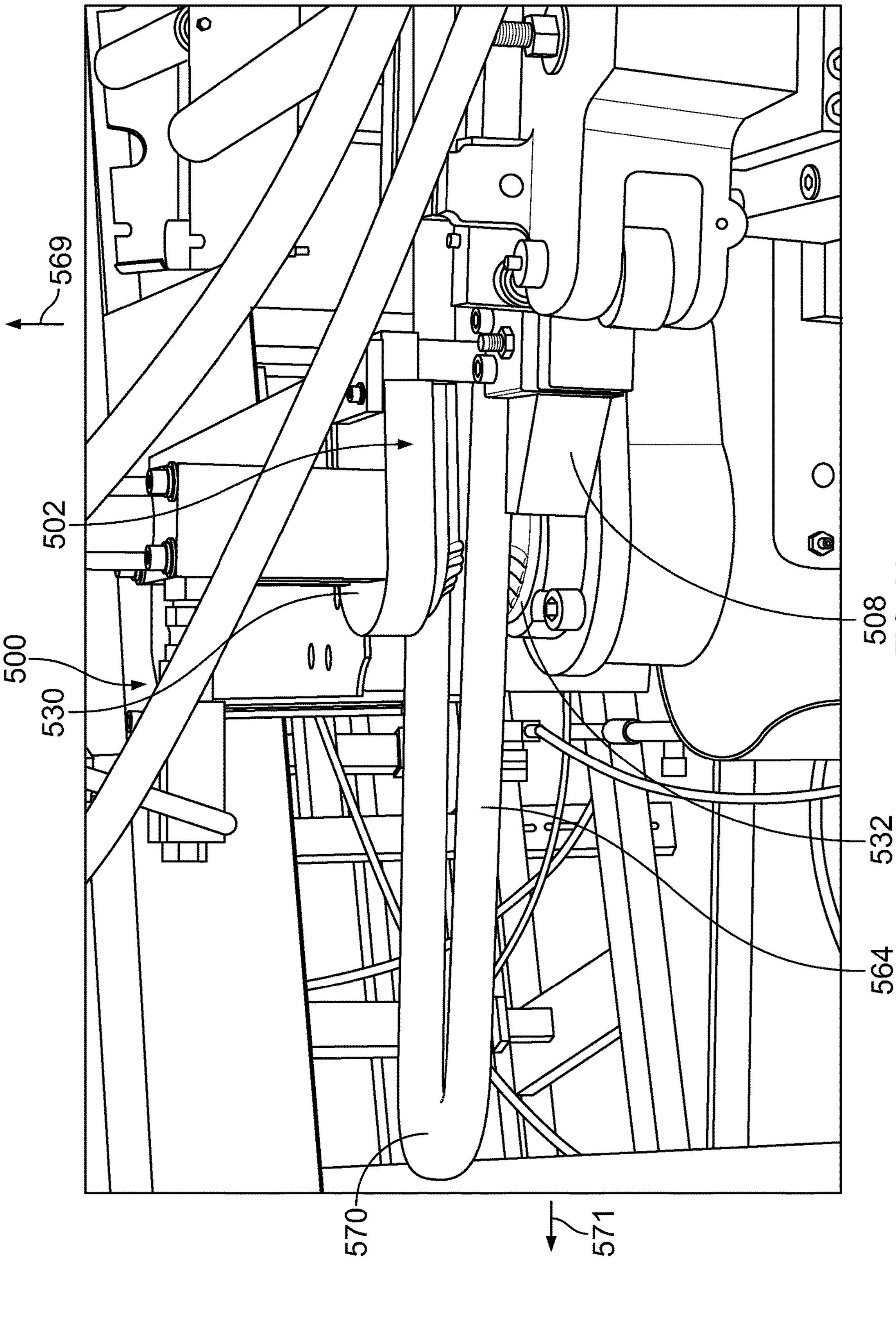

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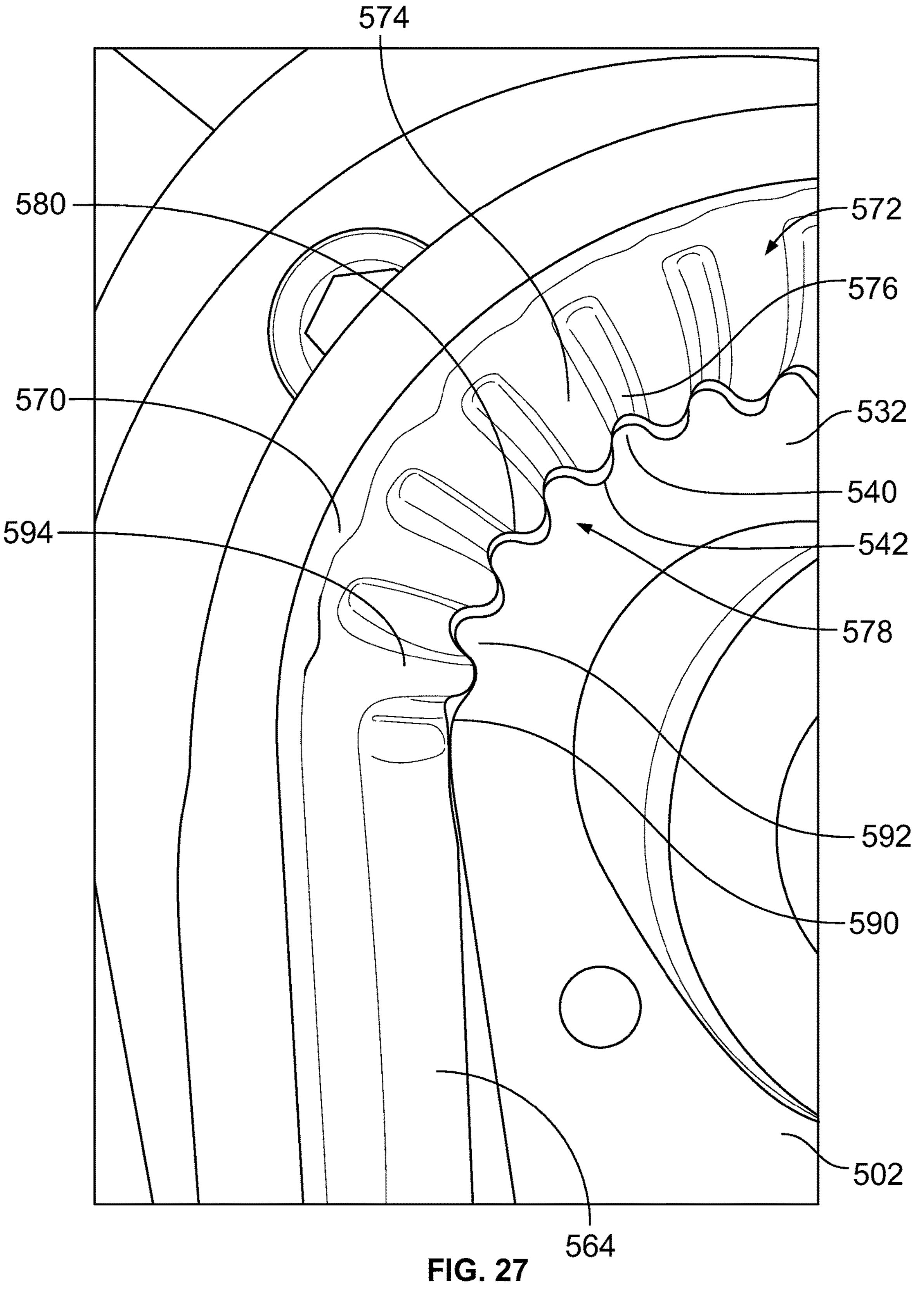

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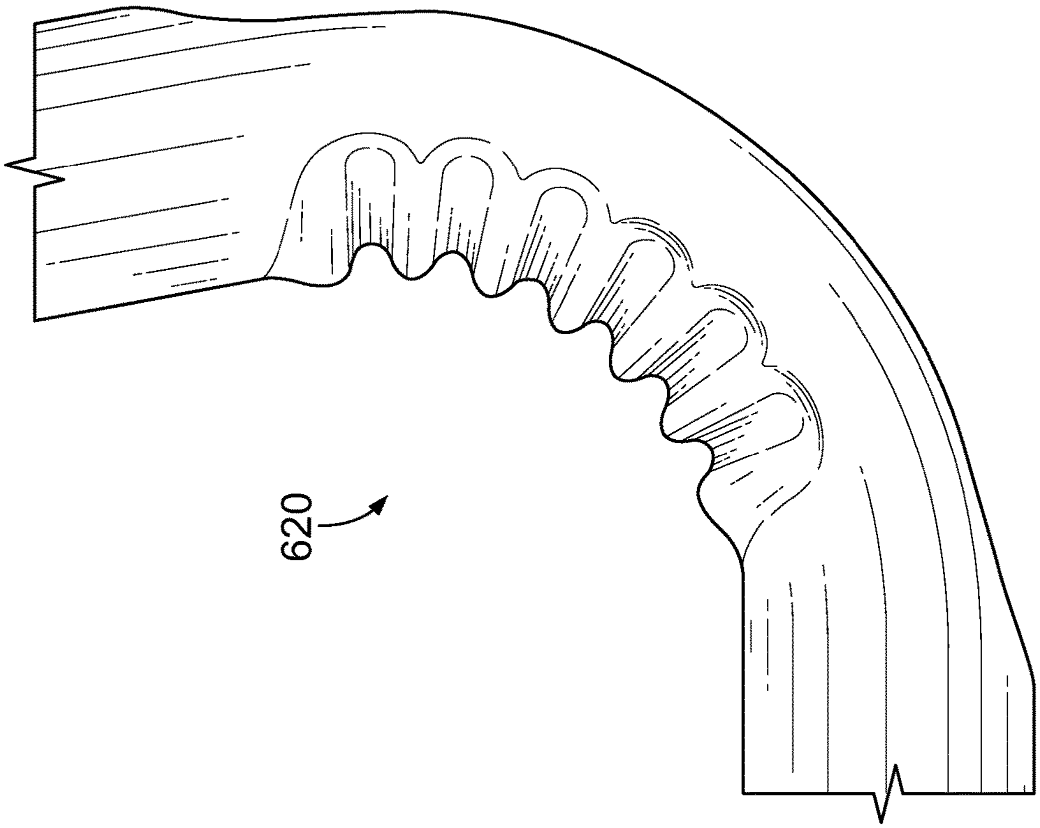

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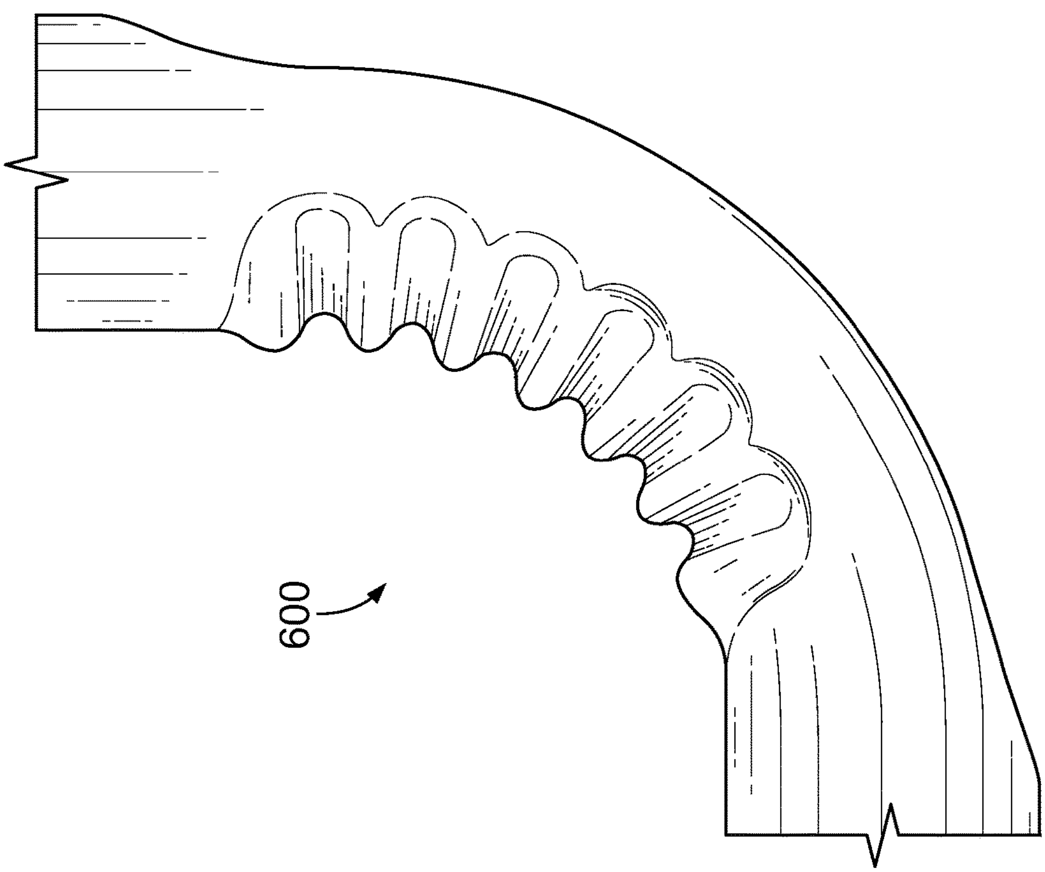


FIG. 28

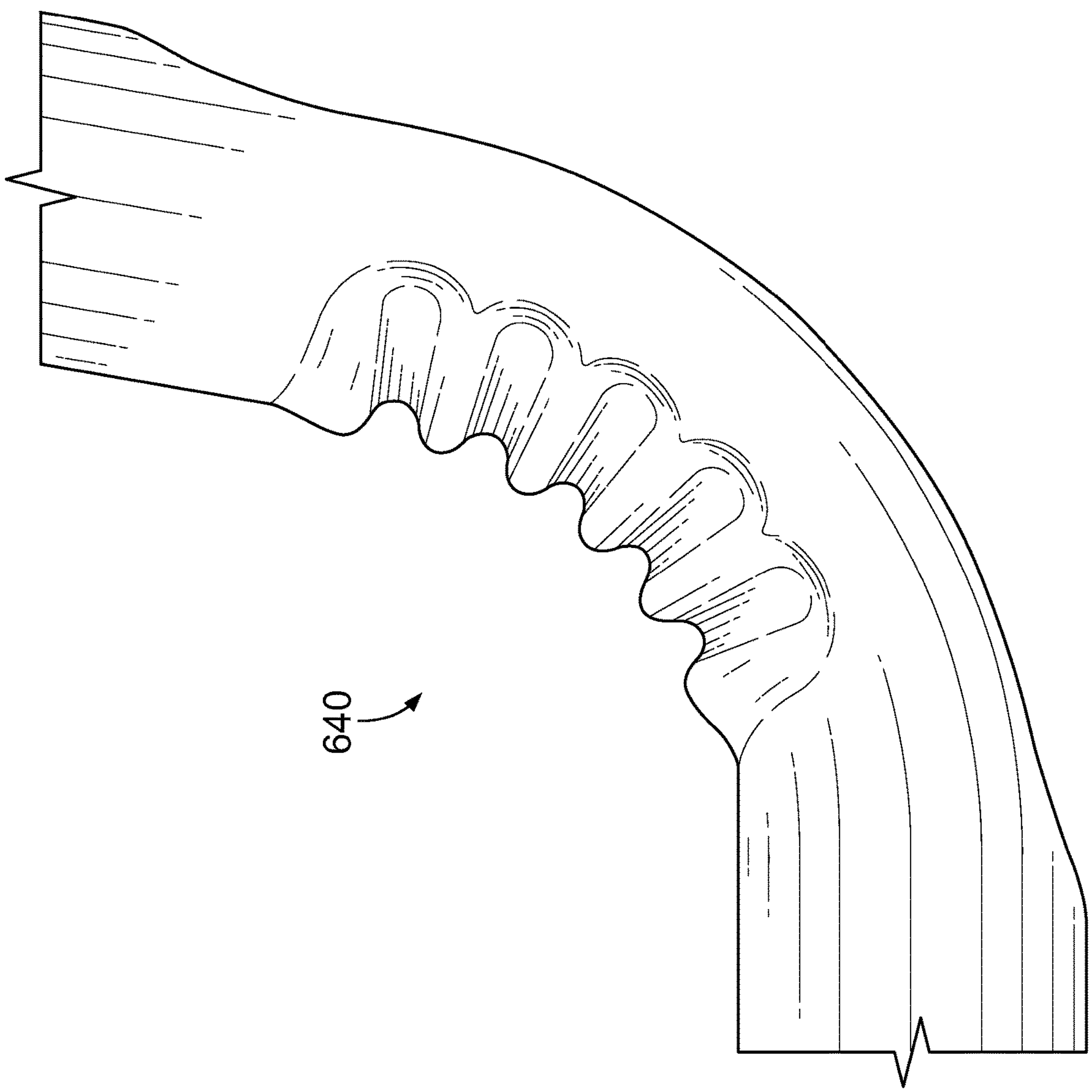
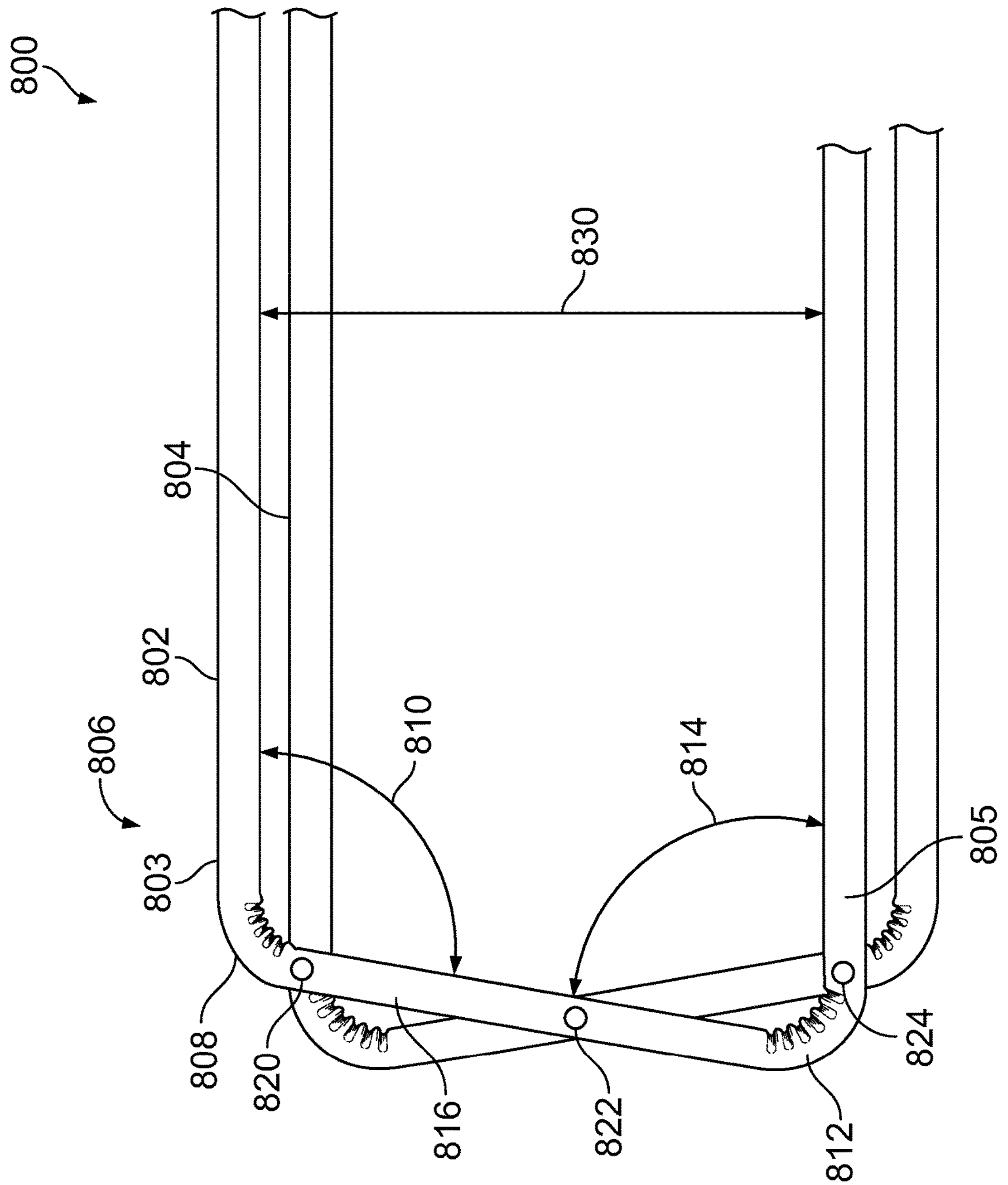


FIG. 30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812
824

FIG. 32

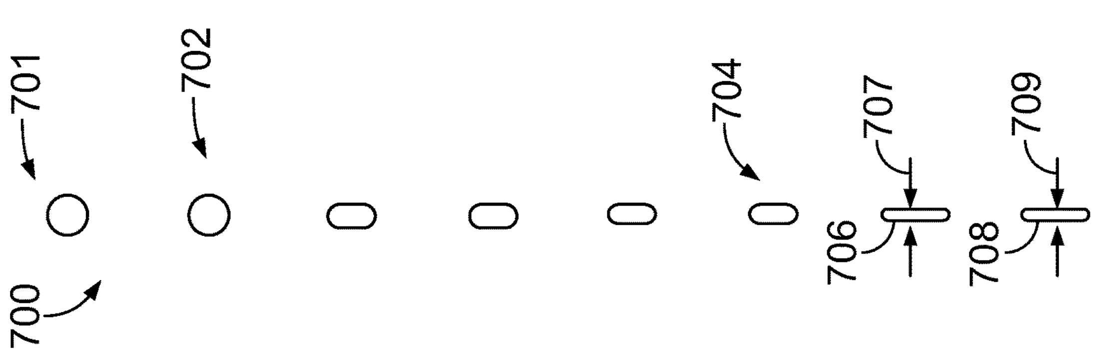
700
701
702
704
707
706
709
708

FIG. 31

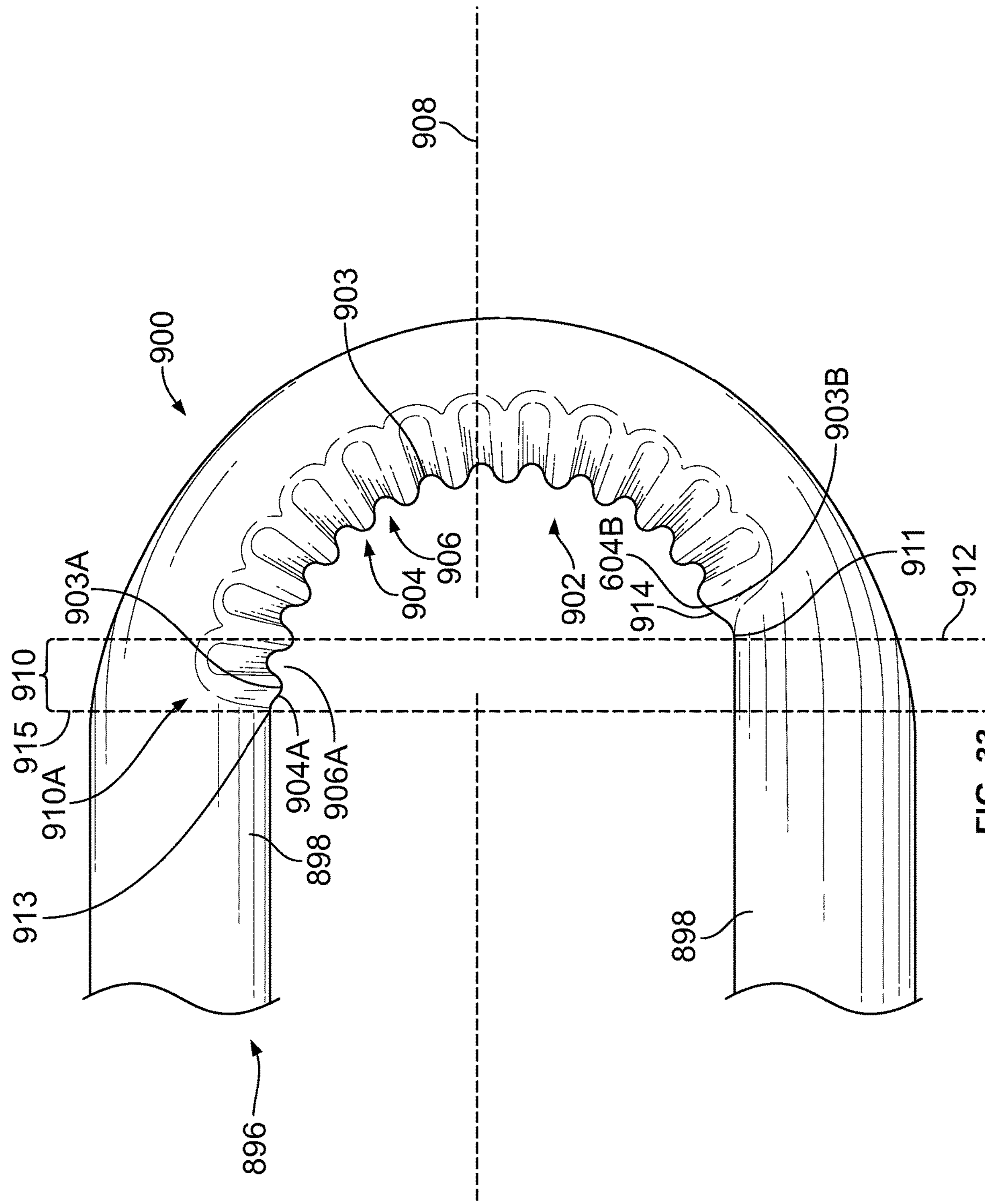
908
900
903
903B
906
904
902
604B
914
911
912
903A
910
915
910A
904A
906A
898
913
898
896

FIG. 33

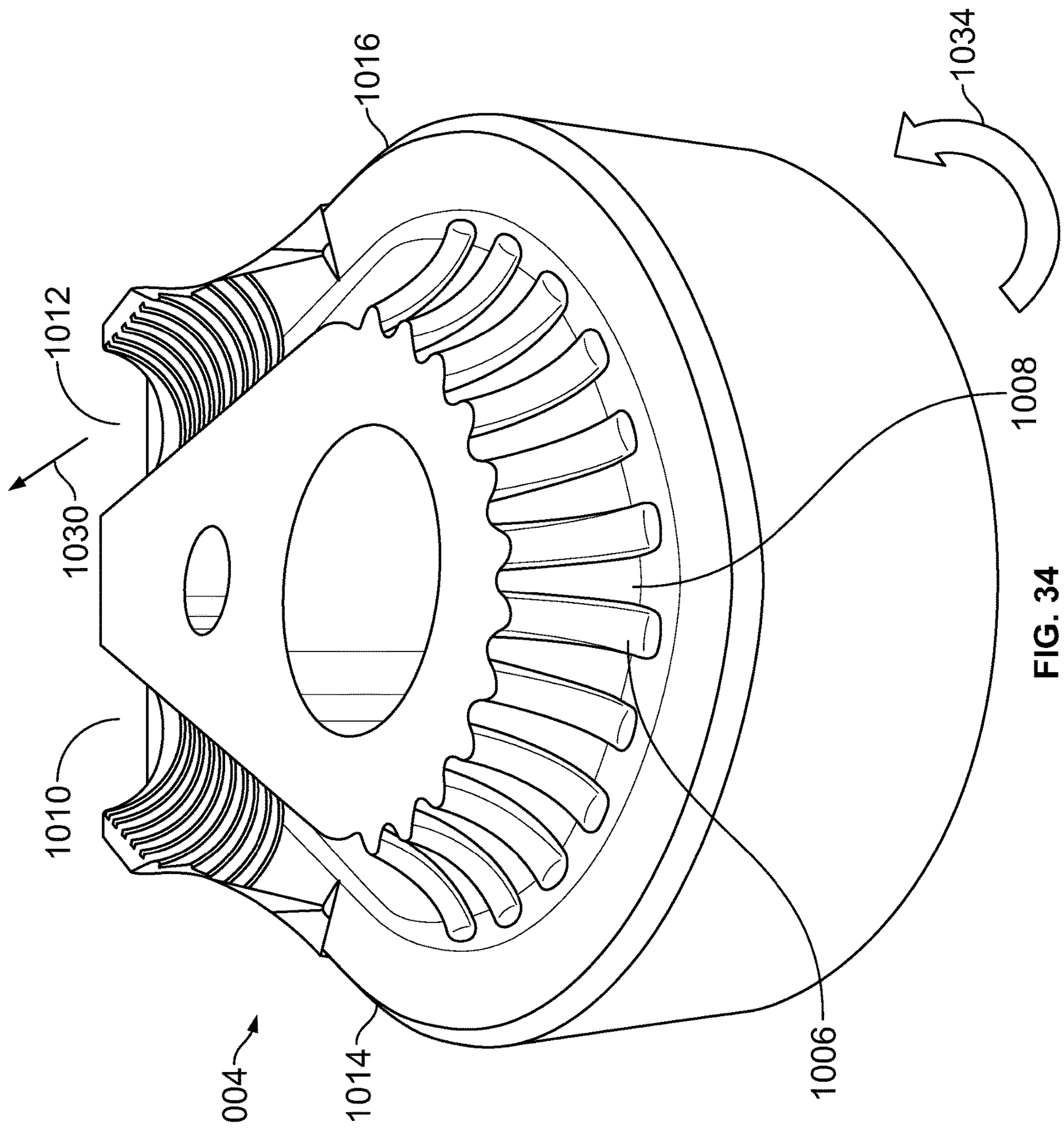

FIG. 34

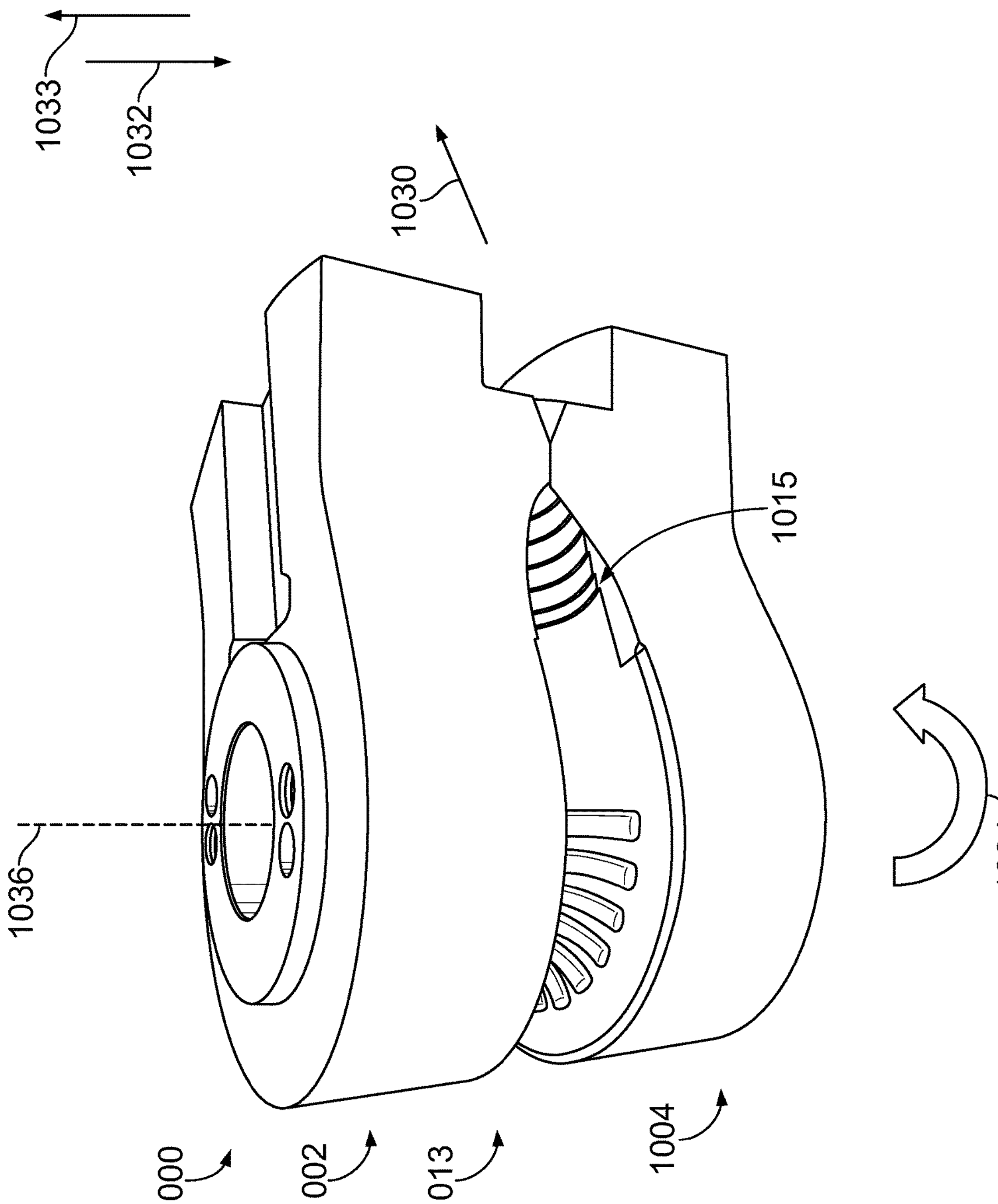

FIG. 35

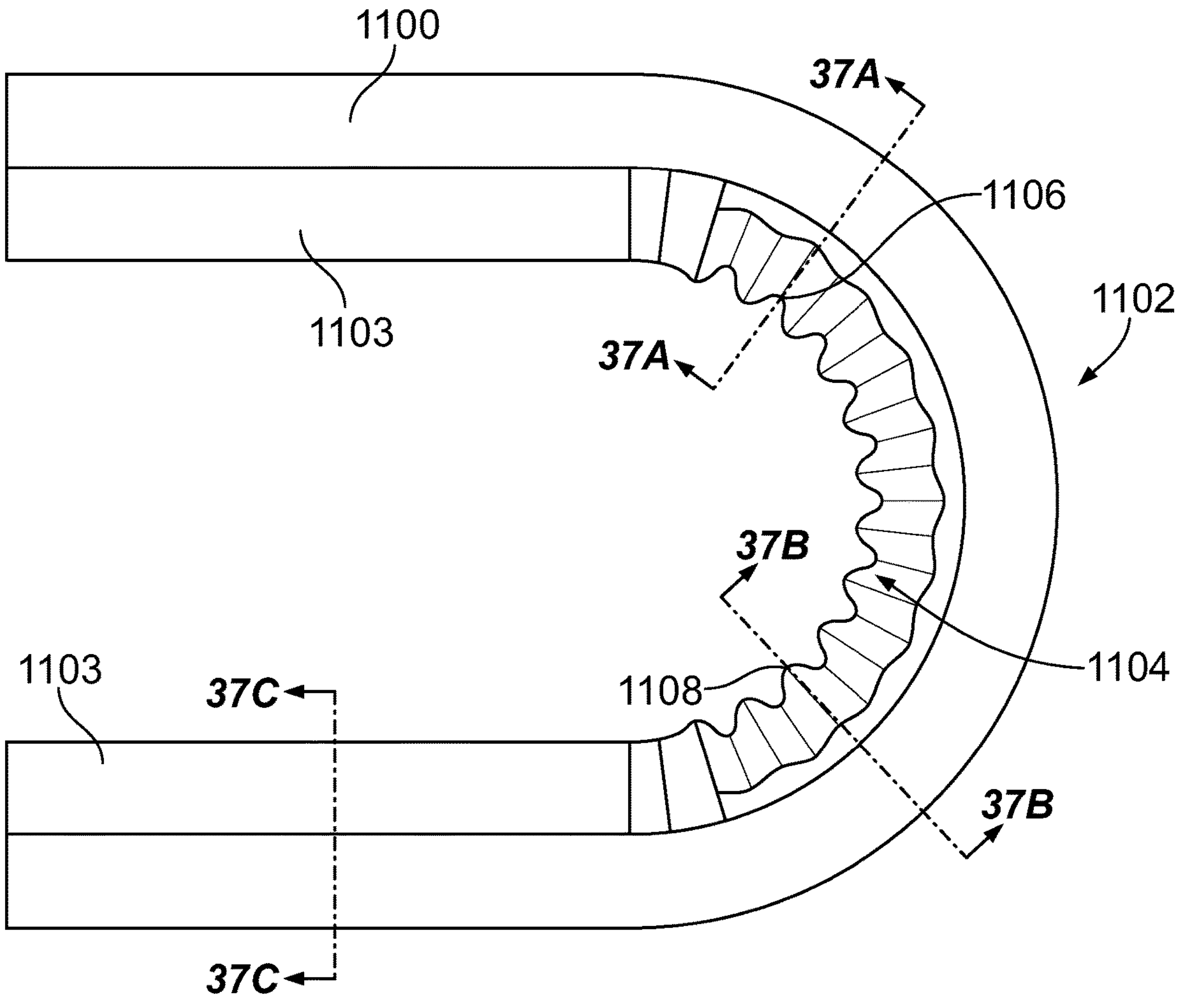

FIG. 36

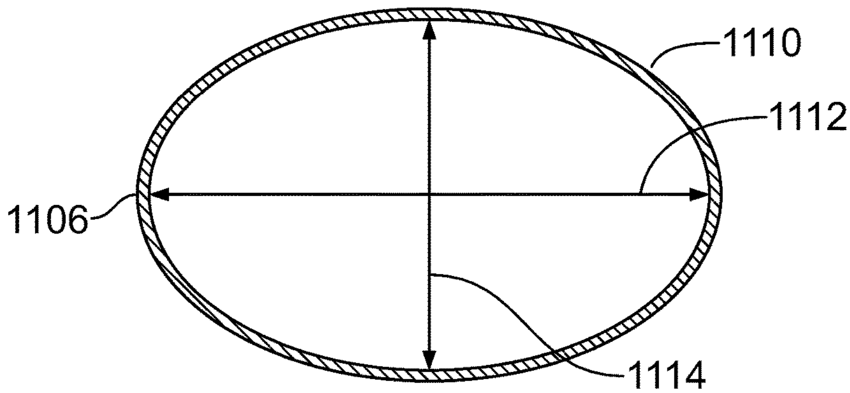

FIG. 37A

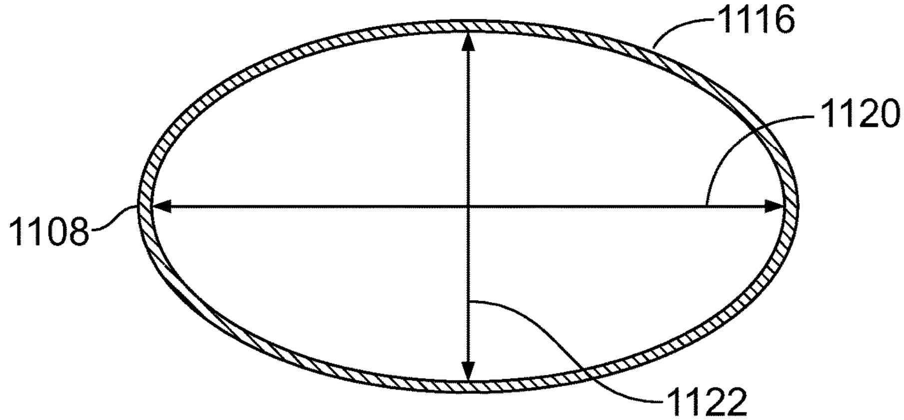

FIG. 37B

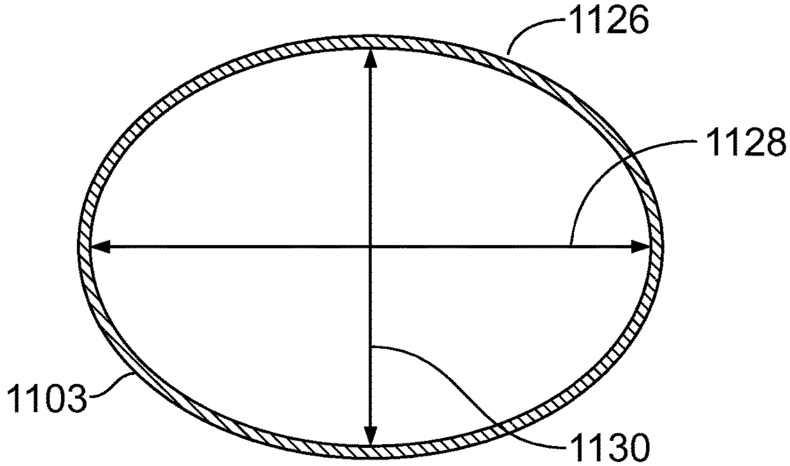

FIG. 37C

INDIRECT HEAT EXCHANGER PRESSURE VESSEL WITH CONTROLLED WRINKLE BENDS

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Patent Application No. 63/138,655, filed Jan. 18, 2021, and U.S. Provisional Patent Application No. 63/270,953 filed, Oct. 22, 2021, which are hereby incorporated herein by reference in their entireties.

FIELD

This disclosure relates to indirect heat exchangers and, more particularly, to indirect heat exchangers having serpentine circuit tubes with multiple formed bends that convey a pressurized working fluid through the serpentine circuit tube and permit heat transfer between the working fluid inside of the serpentine circuit tube and a fluid external to the serpentine circuit tube. The working fluid and the external fluid may each be gas, liquid or a mixture of gas and liquid.

BACKGROUND

Heat exchangers are known that include direct heat exchangers and indirect heat exchangers. A direct heat exchanger transfers heat between a working fluid and another fluid via contact between the fluids. An indirect heat exchanger transfers heat between a working fluid and another fluid indirectly through a medium separating the fluids.

Various types of heat exchange apparatuses are known that include direct heat exchangers, indirect heat exchangers, or both. Known heat exchange apparatuses include open circuit heat exchange apparatuses such as open circuit cooling towers and closed circuit heat exchange apparatuses such as closed circuit cooling towers. Open circuit cooling towers may exchange heat between a working fluid, such as water, and an external fluid such as ambient air by distributing the working fluid onto fill. The working fluid is directly cooled by ambient air as the working fluid travels along the fill. Closed circuit cooling towers, by contrast, keep the working fluid separated from the external fluid.

Closed circuit heat exchanger apparatuses include closed circuit cooling towers for fluids, evaporative condensers for refrigerants, dry coolers, air cooled condensers, and ice thermal storage systems. These heat exchange apparatuses utilize one or more heat exchangers to transfer heat between a pressurized working fluid and an external fluid such as ambient air, an evaporative liquid, or a combination thereof.

For example, a heat exchanger apparatus may include a closed circuit cooling tower having an indirect heat exchanger pressure vessel including an inlet header that receives a pressurized working fluid, an outlet header, and an indirect heat exchange coil connecting the inlet and outlet headers. The indirect heat exchange coil may include one or more serpentine circuit tubes configured to transfer heat between the pressurized working fluid inside the indirect heat exchange coil and a fluid, such as an evaporative liquid, external to the indirect heat exchange coil. The inlet header receives the internal working fluid from an upstream component of the heat exchange apparatus and the outlet header collects the pressurized working fluid before the working fluid is directed to a downstream component of the heat exchange apparatus.

Indirect heat exchanger pressure vessels, which includes the inlet header, outlet header, and one or more serpentine circuit tubes, are required to withstand high pressures appropriate for the specific application and satisfy domestic and international engineering standards such as ASME Standard B31.5. For example, an indirect heat exchanger pressure vessel of a closed circuit cooling tower may be rated to withstand an internal pressure of 150 psig for fluids such as water, glycols and brines. As another example, the indirect heat exchanger pressure vessel of an evaporative condenser may be able to withstand an internal pressure of up to 410 psig or higher for typical refrigerants such as ammonia or R-407C. As yet another example, some evaporative condensers have indirect heat exchanger pressure vessels with internal pressure ratings of 1200 psig or greater for refrigerants such as CO_2.

Serpentine circuit tubes of indirect heat exchanger pressure vessels typically include straight lengths and bends connecting the straight lengths. The straight lengths of the serpentine circuit tubes are typically joined with bends of approximately 180 degrees or by compound bends having multiple bends, such as two 90 degree bends joined by a tube length.

The serpentine circuit tubes may be stacked together during assembly of the heat exchange apparatus with the serpentine circuit tubes contacting one another, typically in the area of the return bends, and with the serpentine circuit tubes having a vertically staggered positioning.

Serpentine circuit tubes are often made by first forming an elongated tube from a long, flat strip of metal such as mild steel or stainless steel. The flat strip of metal is roll formed into a generally circular cross section and the longitudinal edges are welded together with a continuous, longitudinal weld to form a straight tube. In another approach, a seamless tube forming process is used to form the straight tube. The resulting straight tube may then be bent at spaced locations along the tube to form the tube into a serpentine shape with straight runs connected by bends. Tube bending is a complicated process and often utilizes a hydraulically, electrically, or manually-powered tube bender having a bend die, a clamp die, a pressure die, and optionally a mandrel and wiper die. The tube bender may be setup to form bends with any desired angle up to and including 180 degree bends, such as 80 degrees, 90 degrees, 100 degrees, or 180 degrees. As noted above, the return bends of a serpentine circuit tube may include compound bends each having two or more bends, such as an 80 degree bend and a 100 degree bend, connected by a length of straight tube.

To form a bend in a tube, the tube is fed into the tube bender and a portion of the tube is nestled in a recess of the bend die. The pressure die and clamp die, with recesses for the tube, are moved against the opposite side of the tube such that the pressure die is positioned to support the tube and the clamp die clamps the tube portion between the clamp die and the bend die. The tube bender then rotates or pivots the bend die and the clamp die through the desired bend angle. The pressure die moves forward as the bend die and clamp die pivot to support the tube and ensure the tube follows the profile of the bend die. Once the bend has been formed in the tube, the clamp die and pressure die retract from their clamped positions, the tube is fed forward until the next bend location of the tube is positioned in the tube bender, and the bend die, clamp die, and pressure die all move back to their initial positions. The bending process is repeated for each bend to be formed in the serpentine circuit tube. Some tubes are bent only once to form single-bend tubes, which commonly are referred to as hairpin or candy-cane tubes, that can be subsequently butt welded together.

The bending of a tube that is to receive a pressurized working fluid is a process that balances various considerations including performance, safety, and packaging criteria for a particular application. Further, unintended deformations in the tube wall during the bending process may lead to tube failures due to the pressure of the working fluid within the tube, corrosion of the tube, and/or a higher pressure drop of the working fluid through the tube. In some tube bending processes, an internal mandrel is advanced into the interior of the tube to support the tube wall during bending and a wiper die may be used to stiffen the tube wall at a trailing end of the inside of the bend to prevent unintended deformations in the tube. The internal mandrel may be a plug mandrel or may have one or more balls or rings, in which case the internal mandrel is referred to as a ball mandrel.

Tube bending generally involves the following parameters:

OD=Outside diameter of the tube

WT=Wall thickness of the tube

CLR=Centerline radius of the bend

The dimensions are measured using a common measurement scale, such as inches or millimeters. These parameters are used to calculate the following two characteristic ratios:

$$\text{Wall Factor} = W = \frac{OD}{WT}$$

$$D \text{ of Bend} = D = \frac{CLR}{OD}$$

Two other parameters that are featured in the bending process are the Outside Radius (OSR) of the bend, usually referred to as the extrados, and the Inside Radius (ISR) of the bend, usually referred to as the intrados.

The W and D ratios are further consolidated into a single factor that is indicative of the complexity of the bend. This factor is calculated as:

$$\text{Bend Complexity} = C_B = \frac{W}{D} = \frac{OD^2}{CLR \times WT}$$

The values of W, D, and/or CB may be used to determine whether a bend can be formed without an internal mandrel, called empty bending, or if an internal mandrel will be required, in which case the process is called mandrel bending. For mandrel bending, these ratios help determine whether the internal mandrel required should be a multiple ball, single ball or a simpler plug mandrel. Finally, these ratios help determine whether a wiper die will be required in combination with the internal mandrel. As an example, process recommendations for various bend complexities are shown in the table below:

TABLE 1

Table of Bend Complexity Values and Recommended Bending Process

C_B value	Recommended Bending Process
Less than 5	Empty Bending
5-10	Internal Mandrel recommended; Wiper Die not required
10-20	Internal Mandrel either Plug or Ball required; Wiper Die optional
20-50	Internal Mandrel with multiple balls required; Wiper Die required
Greater than 50	High Pressure Internal Mandrel and Wiper Die required

It is typical to look up the W, D, and/or C_B ratios on industry standard tube bending charts to decide the type of bending process required. For example, to determine the process parameters to bend a tube with outside diameter of 1" and a wall thickness of 0.05" with a centerline radius of 2", then the ratios W and D are:

$$W = \frac{1}{0.05} = 20$$

$$D = \frac{2}{1} = 2$$

An industry standard tube bending chart may recommend, in view of the W ratio of 20 and the D ratio of 2, that a regular pitch internal mandrel with 1 ball, supplemented with a wiper die, should be used.

Alternately, the C_B for the example bend above is:

$$C_B = \frac{20}{2} = 10$$

Referring to the table above, this C_B value also indicates that an internal mandrel is recommended, although a wiper die could be optional. The small differences in recommendations on mandrels and wipers are indicative of a certain amount of flexibility in bend configurations where tool design and tube material choices can sometimes compensate for the absence of an internal mandrel and/or wiper die.

The conventional bending charts used in industry and the bend complexity value (C_B) ranges discussed above are based on the assumption that the profile of the tooling groove formed by the bending and clamp dies, where the tube is seated during the bending process, is circular, complementing the shape of the round tube. However, bending tool design has made several advances in recent years and it is possible to design bend tooling with a composite radius in the tooling groove to compress and support the tube during the bending process and extend the range of empty bending up from a C_B value of approximately 5 to approximately 12.

Beyond this, especially as C_B approaches and exceeds 20, it becomes progressively more necessary to use internal mandrels and wiper dies to successfully bend the tube. The internal mandrel bending process has several disadvantages including that using a mandrel requires additional tooling which adds cost, may increase scrap if mandrels are not used correctly, may add to cycle time, and requires the use of lubricants which adds time and cost for the lubricant and subsequent environmental mitigation.

One issue as C_B approaches and exceeds 20 is that the associated mandrel bending imposes a limit on the continuous length of the tube. Serpentine circuit tubes can be very long, up to 400 feet long for some applications. The physical limits on the length of the mandrel rod and setup mean that internal mandrels cannot be used to bend long, continuous serpentine circuit tubes with several bends. This forces a manufacturer to form one or two bends in short segments of tube, sometimes called candy canes, and then butt weld the tube segments together to create larger circuits. Not only does this involve additional labor and cost, but additional butt welds increase the possibility of leaks and may not be permitted in many applications due to the high operating pressure the serpentine circuit tube will experience.

Another issue that may arise as C_B approaches and exceeds 20 is that the associated internal mandrel bending moves the neutral axis of the bend closer to the inside of the bend and may cause excessive thinning of the outside wall portion of the bend. Thinning of the outside wall portion of the bend may weaken the serpentine circuit tube such that the serpentine circuit tube cannot withstand the pressure of the working fluid for a particular application. Excessive thinning of the outside bend wall also creates variability in the process when forming the bends causing reduced quality in the bend areas.

The above issues make it desirable for a manufacturer to avoid the use of internal mandrels for tube bending. One way to avoid using internal mandrels for a tube with a given OD is to increase WT or increase CLR to a suitable value to bring the bend within the range of empty bending. Increasing the wall thickness (WT) may not be an option for manufacturers whose products do not require such relatively thick walls from an operational perspective. In certain cases, the thicker walls may increase the fluid side pressure drop, may make the products less thermally efficient, increase the weight of the assembly, and may increase the material cost of the serpentine circuit tube. Further, increasing CLR may not be an option where the serpentine circuit tube needs to fit in a given space for other operational considerations. Increasing CLR can also have negative impact on overall coil thermal and hydraulic efficiency in some cases.

SUMMARY

In one aspect of the present disclosure, an indirect heat exchanger pressure vessel is provided that includes an inlet header to receive a pressurized working fluid, an outlet header to collect the pressurized working fluid, and a serpentine circuit tube connecting the inlet and outlet headers and permitting the pressurized working fluid to flow from the inlet header to the outlet header. The pressurized fluid may be, for example, water, glycol, a glycol mixture, ammonia, or CO_2 as some examples. The pressurized fluid may be a liquid such as water or a liquid/gas combination such as refrigerant liquid and refrigerant vapor. The serpentine circuit tube includes runs and a return bend connecting the runs. The return bend includes a controlled wrinkled portion including alternating ridges and grooves. The controlled wrinkled portion of the return bend provides a rigid structure that resists internal pressure during operation of the indirect heat exchanger pressure vessel. Further, the controlled wrinkled portion provides a constructive bend centerline radius that is larger than an actual bend centerline radius of the return bend. The larger constructive bend centerline radius reduces the bend complexity factor for the return bend compared to a return bend of a conventional serpentine circuit tube having the same outer diameter and wall thickness. Due to the reduced bend complexity factor, the return bend having controlled wrinkled portions may be bent without the use of an internal mandrel which simplifies the manufacturing process of the serpentine circuit tube.

The present disclosure also provides an indirect heat exchanger pressure vessel including an inlet header to receive a pressurized working fluid, an outlet header to collect the pressurized working fluid, and a serpentine circuit tube connecting the inlet and outlet headers to permit flow of pressurized working fluid from the inlet header to the outlet header. The serpentine circuit tube includes runs, a return bend connecting the runs, and tangent points at junctures between the return bend and the runs. The return bend includes a bend angle and a controlled wrinkled portion. The controlled wrinkled portion is spaced from the tangent points along the serpentine circuit tube and has an angular extent about an inside of the return bend that is less than the bend angle. In this manner, the controlled wrinkled portion may be formed using a bend die having corresponding controlled wrinkle-forming features for less than the entire intrados of the return bend to permit the serpentine circuit tube to be slid out lengthwise from the bend die and increases the rapidity at which return bends may be formed in the serpentine circuit tube. In one embodiment, the controlled wrinkled portion includes ridges having amplitudes that are smaller adjacent the tangents points and increase as the wrinkled portion extends away from the tangent points to reduce resistance to fluid flow through the return bend and reduce the internal fluid pressure drop at the return bend relative to a non-tapered or non-eased configuration of the wrinkle ridges.

In another aspect, an indirect heat exchanger pressure vessel is provided that includes an inlet header to receive a pressurized working fluid, an outlet header, and a serpentine circuit tube connecting the inlet header and the outlet header to facilitate flow of the pressurized working fluid from the inlet header to the outlet header. The serpentine circuit tube includes a pair of runs and a return bend connecting the runs. The return bend includes an inner portion having a sinusoidal wave pattern at an intrados of the return bend, the sinusoidal wave pattern including peaks and valleys. The inner portion of the bend includes an arc pattern intersecting the sinusoidal wave pattern, the arc pattern comprising peak arcs intersecting the peaks and valley arcs intersecting the valleys. The intersecting sinusoidal wave pattern and arc pattern provide a smooth, continuously curving side wall of the serpentine circuit tube which strengthens the return bend against internal pressure. In one embodiment, the sinusoidal wave pattern has one or more end portions with shallower peaks and valleys and an intermediate portion with deeper peaks and valleys to reduce the internal fluid pressure drop across the return bend compared to a sinusoidal wave pattern having a constant peak and valley size.

The present disclosure also provides a closed circuit cooling tower including an indirect heat exchanger comprising a plurality of serpentine circuit tubes having runs and return bends connecting the runs. The return bends include wrinkled bends having controlled wrinkled portions. The closed circuit cooling tower comprises a fan operable to generate airflow relative to the serpentine circuit tubes and an evaporative liquid distribution assembly configured to distribute evaporative liquid onto the serpentine circuit tubes. The closed circuit cooling tower further comprises a sump to receive falling evaporative liquid from the serpentine circuit tubes and a pump operable to pump evaporative fluid from the sump back to the evaporative liquid distribution assembly. The controlled wrinkled bends strengthen the serpentine circuit tubes to withstand internal pressure from the working fluid within the serpentine circuit tubes during operation of the cooling tower. The controlled wrinkled bends also provide a constructive centerline radius of the

wrinkled bends that is larger than the actual centerline radius of the controlled wrinkled bends and provides a reduced bend complexity factor compared to a return bend of a conventional serpentine circuit tube having the same outer diameter and wall thickness. The reduced bend complexity factor permits the controlled wrinkled bend to be bent without the use of an internal mandrel which simplifies the manufacturing process of the serpentine circuit tube.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a perspective view of an indirect heat exchange apparatus having serpentine circuit tubes with runs connected by bends of the serpentine circuit tubes;

FIG. **2** is a schematic view of a heat exchange apparatus including serpentine circuit tubes;

FIG. **3** is a side elevational view of a serpentine circuit tube having runs connected by 180 degree bends;

FIG. **4** is an enlarged view of the bend shown in a dashed circle of FIG. **3** showing a controlled wrinkled portion of an inside of the bend;

FIG. **5** is a cross-sectional view taken across line **5-5** in FIG. **4** showing a cross-section of the bend at a groove of the wrinkled portion;

FIG. **6** is a cross-sectional view taken across line **6-6** in FIG. **4** showing the cross-section of the bend at a ridge of the wrinkled portion;

FIG. **7** is a cross-sectional view taken across line **7-7** in FIG. **4** showing the cross-section of one of the runs of the circuit tube;

FIG. **8** is a perspective view of the bend of FIG. **4** showing the wrinkled portion of the inside of the bend and a smooth outer wall portion of the outside of the bend;

FIG. **9**A is a cross-sectional view taken across line **9**A-**9**A in FIG. **8** showing a sinusoidal pattern of the wrinkled portion that is spaced from tangent points of the bend and the runs so that the wrinkled portion has an angular extent that is less than the 180 degree bend angle of the bend;

FIG. **9**B is a cross-sectional view similar to FIG. **9**A of another embodiment of the bend having a wrinkled portion with a varying amplitude of ridges and valleys of the sinusoidal pattern;

FIG. **9**C is a cross-sectional view similar to FIG. **9**A of another embodiment of the bend having a wrinkled portion with a varying period and a varying amplitude of ridges and valleys of the sinusoidal pattern;

FIGS. **10**, **11**, **12**, **13**A, and **13**B show a process of determining the sinusoidal pattern of the bend;

FIG. **14** is a graphical representation of a portion of the sinusoidal pattern of the wrinkled portion of the return bend showing peaks and valleys of the sinusoidal pattern;

FIG. **15** is a graphical representation of a portion of the sinusoidal pattern of the return bend intersecting with an arc pattern of the return bend, the arc pattern including a peak arc that intersects a peak of the sinusoidal pattern and a valley arc that intersects a valley of the sinusoidal pattern;

FIG. **16**A is a graphical representation of the peak arc of FIG. **15** showing the peak arc having a radius of curvature, an angular extent, and a center, wherein the center is radially inward of a center line of the serpentine circuit tube;

FIG. **16**B is a graphical representation similar to FIG. **16**A of a peak arc having a composite radius of curvature;

FIG. **16**C is a graphical representation similar to FIG. **16**A of a peak arc having a shape defined by a portion of an ellipse;

FIG. **17**A is a graphical representation of the valley arc of FIG. **15** showing the valley arc having substantially the same radius of curvature as the peak arc, a shorter angular extent than the peak arc, and a center, wherein the center is radially outward from a center line of the tube;

FIG. **17**B is a graphical representation similar to FIG. **17**A of a valley arc having a composite radius of curvature;

FIG. **17**C is a graphical representation similar to FIG. **17**B of a valley arc having a shape defined by a portion of an ellipse;

FIG. **18** is a perspective view showing a portion of the sinusoidal pattern, the peak arc, and the valley arc of FIG. **15** and a continuous, curved wrinkled surface portion connecting the peak arc and the valley arc;

FIG. **19** is a perspective view of a tube bender showing a bend die, a pressure die, and a clamp die of the tube bender;

FIG. **20** is a side elevational view of the bending die of FIG. **19** showing ridges and grooves that form corresponding ridges and grooves of the wrinkled portion of the tube;

FIGS. **21**, **22**, **23**, **24**, **25**, and **26** show a process of forming a bend of a serpentine circuit tube using the tube bender of FIG. **19**;

FIG. **27** is a top plan view of the tube bent using the tube bender of FIG. **19** and the lower part of the bending die that shows the meshed engagement between the ridges of the bend wrinkled portion and the ridges of the bend die; and

FIGS. **28**, **29**, and **30** are elevational views of bends having, respectively, ninety degree, eighty degree, and one-hundred degree bend angles;

FIG. **31** is a cross-sectional view of a serpentine circuit coil having runs with progressively flattening cross-sections;

FIG. **32** is an elevational view of compound bends of a pair of serpentine circuit tubes with three points of contact therebetween, each compound bend including a bend of 80 degrees and a bend of 100 degrees;

FIG. **33** is an elevational view of a bend having an asymmetrical wrinkle pattern;

FIG. **34** is a perspective view of a lower portion of a bend die used to form the bend of FIG. **33**;

FIG. **35** is a perspective view of the bend die lower portion of FIG. **34** and a corresponding bend die upper portion;

FIG. **36** is a plan view of a tube having a flattened cross-section, the tube including straights and a return bend with a wrinkled portion;

FIG. **37**A is a cross-sectional view taken across line **37**A-**37**A in FIG. **36** showing an elliptical cross-section of the tube at a valley of the wrinkled portion;

FIG. **37**B is a cross-sectional view taken across line **37**B-**37**B in FIG. **36** showing an elliptical cross-section of the tube at a peak of the wrinkled portion; and

FIG. **37**C is a cross-sectional view taken across line **37**C-**37**C in FIG. **36** showing an elliptical cross-section of the tube at one of the straights of the tube.

DETAILED DESCRIPTION

Regarding FIG. **1**, an indirect heat exchanger pressure vessel such as a coil assembly **10** is provided that may be used in a heat exchange apparatus, such as an evaporative condenser, closed circuit fluid cooler, or an ice thermal storage system. The coil assembly **10** includes an inlet header **12**, outlet header **14**, and serpentine circuit tubes **16**. The serpentine circuit tubes **16** each include runs **18** that are connected with 180 degree bends **20** or compound bends **21** including two 90 degree bends **23**, **25** separated by a straight length **27**. The serpentine circuit tubes **16** permit working fluid to flow from the inlet header **12**, through the serpentine circuit tubes **16**, and to the outlet header **14**.

Regarding FIG. **2**, a heat exchange apparatus such as a cooling tower **24** is provided that includes an outer structure **26**, one or more fans **28** including fan blades **30** and motor(s) **32**, a direct heat exchanger such as fill **34**, and an indirect heat exchanger pressure vessel **36**. The cooling tower **24** may be an evaporative condenser, closed circuit cooing tower, or dry cooler heat exchanger as some examples. The indirect heat exchanger pressure vessel **36** includes inlet header **38**, one or more serpentine circuit tubes **37** with circuit runs **39** and bends **40** and outlet header **42**. The inlet and outlet headers **38**, **42** may be reversed depending on the application. In some embodiments, the fill **34** is above the indirect heat exchanger pressure vessel **36** and/or the fill **34** is located between runs of the serpentine circuit tubes **37**.

Regarding FIG. **2**, the cooling tower **24** includes an evaporative liquid distribution system **43** including a spray assembly **44** having spray nozzles or orifices **46** that distribute an evaporative fluid, such as water, onto the serpentine circuit tubes **37** and the fill **34**. The evaporative liquid distribution system **43** includes a sump **50** for collecting evaporative fluid from the fill **34** and the coil **36** and a pump **52** that pumps the collected evaporative fluid through a pipe **54** to the spray assembly **44**. The cooling tower **24** further includes one or more air inlets **35**, inlet louvers **58** which keep the evaporative liquid from leaving cooling tower **24**, an air outlet **59**, and an eliminator **56** to collect water mist from the air before the air leaves the air outlet **59**. The fan **28** is operable to generate or induce air flow upwards relative to the serpentine circuit tubes **37** and the fill **34**. In other embodiments, the cooling tower **24** may have one or more fans configured to induce airflow in upflow, downflow, or crossflow directions relative to the indirect heat exchanger and/or direct heat exchanger of the cooling tower **24**.

Regarding FIG. **3**, a serpentine circuit tube **70** is provided that may be utilized with a heat exchange apparatus, such as the coil assembly **10** in FIG. **1**, or the cooling tower **24** discussed above with respect to FIG. **2**. The serpentine circuit tube **70** includes an internal passageway **72** and a tubular side wall **74** extending thereabout. The serpentine circuit tube includes an end portion **76** that may be connected to an inlet header and an end portion **78** that may be connected to an outlet header. Depending on the application, the end portion **76** may alternatively be connected to an outlet header and the end portion **78** may be connected to an inlet header. The serpentine circuit tube **70** includes runs **79**, such as runs **80**, **82**, and bends **84**. In one embodiment, the runs **79** may be parallel. In other embodiments, one or more of the runs **80** extend transversely, e.g., sloped, relative to one another to allow for internal fluid draining. The serpentine circuit tube **70** may be self-draining such that any liquid in the internal passageway **72** travels down toward the end portion **78** under the effect of gravity. The material of the serpentine circuit tube **70**, outer diameter of the serpentine circuit tube **70**, wall thickness of the side wall **74**, number of runs **79**, length of runs **79**, number of bends **84**, angular extent of bends **84**, centerline radius of the bends **84**, and intrados/extrados of the bends **84** may be selected for a particular heat exchange apparatus. As another example in this regard, instead of a single angle bend **84** connecting a pair of runs **79**, the serpentine circuit tube may have one or more bends **84** that each include a pair of bends, such as 90 degrees, connected by a straight segment similar to the compound bend **21** shown in FIG. **1**. The runs **80** may have circular cross-sections throughout the runs **80**. In other embodiments, the serpentine circuit tube **70** includes one or more runs **80** with non-circular cross-sections such as cross sections that are elliptical or obround.

The serpentine circuit tube **70** may be formed from a single straight tube that is bent at spaced locations along the tube to form the bends **84**. The serpentine circuit tube **70** may be formed by progressively roll forming an elongated strip of material into a tubular shape and welding longitudinal edges of the elongate strip together to form a single weld running along the length of the serpentine circuit tube **70**. In another approach, the serpentine circuit tube **70** may be made from a plurality of separately formed components. For example, the runs **79** may be separate components that are welded to the bends **84**. Alternately the serpentine circuit tube **70** may be formed by welding separate lengths of tube together and then bending the longer welded tube. The serpentine circuit tube **70** may be made of a metallic material, such as carbon steel or stainless steel.

Regarding FIG. **4**, each bend **84** includes an intrados **90**, an extrados **92**, and a controlled wrinkled portion **94** of an inside **96** of the bend **84** and a smooth outer surface **98** at an outside **100** of the bend **84**. The controlled wrinkled portion **94** includes a continuously curving and controlled wrinkled surface **134** of the ridges **114** and the grooves **116**. The continuously curving controlled wrinkled surface **134** is uninterrupted by edges, corners, or flats to avoid localized areas of stress. The continuously curving and controlled wrinkled surface **134** is shaped by ridges **114** and grooves **116** of the bend **84** that are, in turn, defined at least in part by an intersecting sinusoidal wave pattern **110** and an arc pattern **150** as discussed in greater detail below with respect to FIG. **15**. The bend **84** shown in FIG. **4** has a 180 degree bend angle. When the subject disclosure refers to a particular bend angle of a bend, it is intended that the bend angle is an approximate value, such as +/−5 degrees. In some embodiments, all of the bends **84** of the serpentine circuit tube **70** have controlled wrinkled portions **94**. In other embodiments, fewer than all of the bends **84** have controlled wrinkled portions **94**.

The serpentine circuit tube **70** has a tube center line **102** extending through the runs **80**, **82** and in the bend **84**. The controlled wrinkled portion **94** is radially inward from the tube center line **102** and separated therefrom by a side surface portion **104**. The smooth outer surface portion **98** and the side surface portion **104** permits the bend **84** to be stacked with bends of other serpentine circuit tubes in conventional arrangements as would a prior art tube having a smooth inner bend.

Referring to FIG. **4** at the intrados **90** of the bend **84**, the controlled wrinkled portion **94** has a sinusoidal wave pattern **110** at the intrados **90** of the bend **84** as discussed below with respect to FIGS. **8** and **9**A. The wrinkled portion **94** includes an alternating series of ridges **114** and grooves **116**. In one embodiment, the bend **84** has relief portions **222**, **224** intermediate the sinusoidal wave pattern **110** and tangent points **122**, **124** between the runs **80**, **82** and the bend **84**. The relief portions **222**, **224** facilitate provision of a controlled wrinkled portion angle **240** that is less than a bend angle **220** as discussed in greater detail below. The relief portions **222**, **224** extend from the tangent points **122**, **124** to points **216**, **218**. The wrinkled portion **94** further includes tapered lead-in portions **140**, **142** extending between points **216**, **218** and points **400** (see FIG. **4**) wherein the sinusoidal wave pattern **110** begins and ends. In one embodiment, the relief portions **222**, **224** each have a first radius and the tapered lead-in portions **140**, **142** each have a smaller, second radius. The sinusoidal wave pattern **110** starts at one point **400**, extends through a peak **130** of the end ridge **118**, undulates through the ridges **114** and grooves **116**, extends through a peak **132** of the end ridge **120**, until reaching the other point **400**.

The ridges **114** include end ridges **118**, **120** that optionally have tapered lead-in portions **140**, **142**. The tapered lead-in portions **140**, **142** provide a smooth transition between the relief portions **222**, **224** and the sinusoidal wave pattern **110**. The tapered lead-in portions **140**, **142** smooth flow of the working fluid through the bend **84** and assists the material of the bend **84** to flow during bending. The tapered lead-in portions **140**, **142**, ridges **114**, and grooves **116** reduce the internal fluid pressure drop caused by the working fluid flowing through the bend **84**. Further, the tapered lead-end portion **140** facilitates better draining of the serpentine circuit tube **70**. The bend **84** may have both tapered lead-in portions **140**, **142** if the working fluid may flow through the bend **84** in either direction **143**, **145**. If the working fluid will only be flowing through the bend **84** in one direction **143**, **145**, the bend **84** may have only one tapered lead-in portion **140**, **142**.

Regarding FIG. **9**B, a cross-sectional view of a bend **84'** is provided that is similar to the bend **84** and has a sinusoidal wave pattern **110'** at a midline of the bend **84'**. The bend **84'** has ridges **114'** and grooves **116'** that vary in amplitude around the bend **84'**. Specifically, the ridges **114'** and grooves **116'** closer to runs **80'**, **82'** have small amplitudes and the ridges **114'** and grooves **116'** near a middle of the bend **84'** have larger amplitudes. For example, ridges **114**A', **114**B' have larger amplitudes than ridges **114**C', **114**D'. The more gradual increase in the amplitude of the ridges **114'** and grooves **116'** provide a reduced resistance to fluid flow through the bend **84'** such that the bend **84'** has a reduced pressure drop across the bend **84'** compared to the bend **84** in some applications. The more gradual increase in the amplitude of ridges **114'** and grooves **116'** may also reduce stress in the material of the bend **84'** during the bending operation compared to the bend **84** in some applications. In other embodiments, the amplitude of the sinusoidal wave pattern of the bend **84'** may increase from adjacent one run connected to the bend **84'** to adjacent the other run connected to the bend **84'**.

Regarding FIG. **9**C, a cross-sectional view of a bend **84"** is provided that is similar to the bend **84** and has a controlled wrinkled portion **94"** with a sinusoidal wave pattern **110"** at an intrados of the bend **84"**. The controlled wrinkled portion **94"** includes ridges **114"** and grooves **116"**. The controlled wrinkled portion **94"** includes a first portion **115"** having ridges **114"**A, B and grooves **116"**A, B with a first amplitude and a first period **117"**. The controlled wrinkled portion **94"** includes a second portion **119"** having ridges **114"**C, D and grooves **116"**C, D with a second amplitude greater than the first amplitude. The ridges **114"**C, D and grooves **116"** C, D have a second period **121"** that is less than the first period **117"**. The controlled wrinkled portion **94"** further includes a third portion **123"** having ridges **114"**E, F and grooves **116"**E, F with a third amplitude that is substantially the same as the second amplitude of the second portion **119"** and a third period **125"** that is less than the second period **121"**. The bend **84"** receives fluid in direction **127"** and the ridge **114"**A includes a tapered lead-in portion **129"** to smooth fluid flow through the bend **84"**. The tapered lead-in portion **129"** reduces pressure drop across the bend **84"** and improves draining of fluid in the bend **84"**.

The characteristics of the sinusoidal wave pattern **110** utilized for a given return bend may be selected for a particular application. For example, the number of ridges/grooves, amplitude, period, and/or one or more tapered lead-in portions may be selected for a particular application. The characteristics of the return bend may vary throughout the return bend, such as the amplitude and period varying throughout the return bend. The shape of the controlled wrinkled portion **94** as formed at least in part by two different intersecting cross-sectional profiles. Regarding FIGS. **4** and **15**, the controlled wrinkled portion **94** includes a sinusoidal wave portion **110** at the intrados **90** of the bend **84**. The other pattern is an arc pattern **150** that includes alternating peak arcs **152** and valley arcs **154**. Referencing FIGS. **16**A and **17**A, the peak arc **152** has a peak arc radius **152'** and a center **182** and the valley arc **154** has a valley arc radius **158** and a center **172**. In this embodiment, the peak arc **152** and valley arc **154** are substantially the same. As used herein, the term substantially the same refers to dimensions that are effectively the same when taking manufacturing variation into account, such as within +/−10% of one another. The peak arc **152** extends through an angle **160** that is greater than an angle **162** through which the valley arc **154** extends.

Returning to FIGS. **5** and **15**, the valley arc **154** forms a valley semicircular inner wall portion **170** having the valley arc radius **158** and the center **172**. Opposite the valley semicircular inner wall portion **170**, the bend **84** includes an outer wall portion **174** that may be semicircular. In some embodiments, the outer wall portion **174** may be curved with a flattened portion due to extrados **92** (see FIG. **4**) of the bend **84** being tensioned during the bending process. The bend **84** includes connecting wall portions **176**, **178** that connect the valley semicircular inner wall portion **170** to the outer wall portion **174**. The connecting wall portions **176**, **178** have a curvature that may be dissimilar from the inner and outer wall portions **170**, **174**. The connecting wall portions **176**, **178** provide a smooth transition between the geometries of the inner and outer wall portions **170**, **174** to minimize stress concentration at the junctures between the geometries of the inner and outer wall portions **170**, **174**. By reducing stress concentration at the juncture between the geometries of the inner and outer wall portions **170**, **174**, the connecting wall portions **176**, **178** assist in the bend **84** being able to withstand high internal operating pressure.

Regarding FIGS. **6** and **15**, the peak arc **152** defines a peak semicircular inner wall portion **180** having the peak arc radius **156** with the center **182**. The bend **84** has an outer wall portion **184** opposite the peak semicircular inner wall portion **180**. Like the outer wall portion **174** (see FIG. **5**), the outer wall portion may be semicircular. In some embodiments, the outer wall portion **184** may be curved with a flattened portion due to the extrados **92** (see FIG. **4**) of the bend **84** being tensioned during the bending process. The bend **84** further includes connecting wall portions **186**, **188** connecting the peak semicircular inner wall portion **180** and the outer wall portion **184**. Like the outer wall portion **174**, the outer wall portion **184** may have a semicircular shape or generally curved shape in some embodiments. Further, the connecting wall portions **186**, **188** provide a smooth transition between the geometries of the inner and outer wall portions **180**, **184** to minimize stress concentration at the junctures between the geometries of the inner and outer wall portions **180**, **184**. The connecting wall portions **186**, **188** contribute to the ability of the bend **84** to withstand high internal operating pressure. The peak arc **152** and valley arc **154** may each have a respective single radius as shown in FIGS. **16**A and **17**A. In another embodiment, the peak arc **152** and/or the valley arc **154** has a compound or composite radius. For example, and with reference to FIG. **16**B, the peak arc **152'** has different radii **156**A', **156**B'. Each radius of the peak arc **152**' is tangent at the point where the radius joins an adjacent radius. Likewise in FIG. **17**B, the valley arc **154**' has different radii **158**A', **158**B'.

In another embodiment, the peak arc **152** and/or the valley arc **154** has a shape that is a portion of an ellipse. For example, the peak arc **152**" of FIG. **16**C is an arc defined by an angle of **160**", such as 160 degrees, between points **426**", **430**" of an ellipse **439** having a major dimension **441** and a minor dimension **443**. Similarly, the valley arc **154**" in FIG. **17**C has a shape that is defined by an angle **162**", such as 142 degrees, between points **445**, **447** of an ellipse **449** having a major axis **451** and a minor axis **453**.

Regarding FIG. **7**, the run **82** is shown with the side wall **74** having a circular cross-section with a center at the tube center line **102**. Side wall **74** may also have a non-circular cross section such as elliptical or oblong cross-section. The side wall **74** of the serpentine circuit tube **70** has a wall thickness **190** that extends about the inner passageway **72**.

Regarding FIG. **8**, the sections of the runs **80**, **82** and the bend **84** are shown in a perspective view. As noted above, the controlled wrinkled portion **94** has a continuously curving controlled wrinkled surface **134** including curved ridge surface portions **200** on opposite sides of each ridge **114** and curved groove surface portions **202** on opposite sides of each groove **116** connecting the curved ridge surface portions of adjacent ridges **114**. The ridge surface portions **200** and groove surface portions **202** form the continuous, undulating appearance of the controlled wrinkled portion **94**.

Regarding FIG. **9**A, the serpentine circuit tube **70** has an outer diameter **210** and the wall thickness **190**. The tube center line **102** extends through the runs **80**, **82** and the bend **84**. The serpentine circuit tube has junctures **214**, **215** between the runs **80**, **82** and the bend **84**. At the junctures **214**, **215**, the tube **70** includes the tangent points **122**, **124** between the runs **80**, **82** and the bend **84**. The bend **84** includes the reliefs **222**, **224** extending away from the tangent points **122**, **124** and the tapered lead-in portions **140**, **142** ramp radially inward toward the peaks **130**, **132** of the end ridges **118**, **120**. The bend **84** has a center **230** and a center line radius **232** extending from the center **230** to the tube center line **102**. In the embodiment shown, the bend **84** has a bend angle **220** of 180 degrees and the controlled wrinkled portion **94** extends about the center **230** through a controlled wrinkled portion angle **240** that is less than the bend angle **220**. For example, the controlled wrinkled portion angle **240** may be 5° or less, 10° or less, or 15° or less than the bend angle **220**. In one embodiment, the bend angle is 180 degrees and the wrinkled portion angle **240** is approximately 166 degrees.

Referring again to FIG. **9**A, the controlled wrinkled portion **94** positions peaks **250** of the ridges **114** at the intrados **90** (see FIG. **4**) of the bend **84** and positions valleys **252** of the grooves **116** radially outward from the peaks **250**. By positioning the valleys **252** outward of the intrados **90** of the bend **84**, the wrinkled portion **94** creates a constructive bend center line **254**. The constructive bend center line **254** has a constructive bend center line radius **256** that is greater than the center line radius **232** of the tube centerline **102**. Because the constructive bend center line radius **256** is larger than the bend center line radius **232**, the bend complexity ratio of the bend **84** for a given bend intrados and extrados is less than the bend complexity ratio of a conventional bend having the same intrados, extrados, outer diameter, and wall thickness. The bend **84** has a lower bend complexity ratio because of the larger constructive bend center radius **256**.

For example, a tube bend for a particular application may be provided with the following characteristic ratios:

$$\text{Wall Factor} = W_1 = \frac{OD_1}{WT_1}$$

$$D \text{ of Bend} = D_1 = \frac{CLR_1}{OD_1}$$

$$\text{Bend Complexity} = C_{B1} = \frac{W_1}{D_1}$$

Wherein OD refers to tube outer diameter, WT refers to wall thickness, and CLR refers to the bend centerline radius. Assuming that the values of these ratios for the tube bend are:

$W_1=20$ and $D_1=2$ therefore $C_{B1}=10$

Referring to Table 1 above, these values indicate that internal mandrel bending may be required if a conventional tube bender is used.

Now certain parameters of the bend are changed to show improved serpentine tube characteristics such as tighter bend radius for the same wall thickness, reduced coil weight, reduced internal fluid side pressure drop, reduced bend wall stresses, increased tube strength, increased tube stiffness, and/or increased heat transfer efficiency. These changes affect the characteristic ratios. For example, the new characteristic ratios may be selected as:

$W_2=30$ and $D_1=2$ therefore $C_{B2}=15$

The Bend Complexity characteristic ratio is now in the range where conventional tube benders can no longer compensate, and an internal mandrel is conventionally used to make this bend.

Internal mandrel bending is often undesirable for a variety of reasons as discussed above, making internal mandrel bending impractical for manufacturers that utilize long continuous lengths of tube to fabricate heat exchanger coils.

Referring again to FIG. **9**A, one way to overcome the internal mandrel requirement is to lower the Bend Complexity by increasing the Bend CLR. In our example, if we can increase the CLR of the bend while the tube outer diameter and wall thickness remains the same, we can increase the D of the bend from two to three and obtain the following bend complexity (C_B) ratio:

$W_2=30$ and $D_2=3$ therefore $C_{B2}=10$

Because the C_{B2} ratio is in the range of five to ten, the bend may be formed without an internal mandrel. However, simply increasing the bend CLR for a given application may not be acceptable because the new bend would be larger and occupy more space than the original bend. For example, the center-to-center distance between tube runs would be greater which means fewer tube runs could be fit into a certain envelop or coil height. Further, because each bend of the serpentine circuit tube would be taller, the serpentine circuit tube would have fewer runs for a given coil envelope or height which would reduce heat exchange capacity of the serpentine circuit tube. Reducing the number of runs of a serpentine circuit coil to increase the bend CLR is not an acceptable solution for many applications.

Referring again to FIG. **9**A, the controlled wrinkled portion **94** of the bend **84** provides the constructive bend center line radius **256** that is larger than the actual bend center line radius **232** without increasing the distance between the runs **80**, **82**. The larger constructive bend center line radius **256** increases the CLR of the bend **84**, which increases the D of the bend for a given OD and permits the C_B to be in a range such that mandrel bending is not required.

More specifically, the controlled wrinkled portion **94** provides a constructive bend center line **254** in the available space of the bend **84** thereby allowing for sufficient length along the inside of the bend **84** for the material to form the ridges **114** and grooves **116** in a controlled manner without buckling. The wrinkled portion **94** also maintains or improves other coil characteristics such as internal fluid pressure drop and heat transfer efficiency. Other characteristics of the bend **84** such as a reduction of the thinning of the wall on the extrados and overall stiffness of the bend **84** are also improved.

Referring to FIG. **4**, the alternating ridges **114** and grooves **116** of the controlled wrinkled portion **94** provide space for the material of the tube **70** to fold itself into the smaller available arc length during bending of the tube **70**. The material of the tube **70** is folded in the sinusoidal wave pattern **110** along the intrados of the bend **84**. The specific variables of the sinusoidal wave pattern **110**, e.g., number of peaks/valleys, depth of the valleys (amplitude of the sinusoidal wave), span of arc, etc. are calculated for a particular application as discussed below. This method can be used to calculate the variables for various combinations of material, OD, WT and CLR, and to optimize for various characteristics such as pressure drop and thermal efficiency.

The controlled wrinkled portion **94** provides advantages over conventional tube bends. For example, compared to other bends having wrinkles, the sinusoidal wave pattern **110** minimizes the stresses developed in the material of the tube **70** which allow for much higher internal fluid pressures. The ridges **114** and grooves **116**, including the tapered lead-in portions **140**, **142** may be sized to limit obstruction to the flow of fluid within the bend **84** and minimize internal fluid pressure drop through the bend **84**. The sinusoidal wave pattern **110** increases the length of the material along the intrados **90** compared to a conventional bend having the same bend center line radius which increases the total surface area of the bend **84** and improves heat transfer efficiency by increasing fluid turbulence within the bend area. Further, the ridges **114** and grooves **116** operate as corrugated structure that stiffens the bend **84** as compared to a smooth, non-wrinkled bend. Still further, the controlled wrinkled portion **94** pushes the neutral axis of the bend **84** outward toward the extrados **92** of the bend **84** thereby reducing thinning of the material of the bend **84** along the extrados compared to a smooth, non-wrinkled bend.

Regarding FIGS. **10**-**13**B, a process is provided for determining the geometry of the bend **84** of the serpentine circuit tube **70** to replace a bend **306** of a conventional serpentine circuit tube **300** while, at the same time, fitting within the coil envelope of the conventional serpentine circuit tube **300** and utilizing a tighter bend radius for a given wall thickness.

Regarding FIG. **10**, the conventional serpentine circuit tube **300** has runs **302**, **304**, a bend **306**, an outer diameter **308**, a wall thickness **310**. The bend **306** is a 180° bend and the bend **306** has an intrados **312** with an arc length **314** and an extrados **315**. Initially and with respect to FIG. **11**, the serpentine circuit tube **70** is provided with the outer diameter **210** that is the same as outer diameter **308** and a wall thickness **190** that is less than the wall thickness **310**. For example, the outer diameter **308** and the outer diameter **210** may both be 1.05 inches, the wall thickness **310** may be in the range of approximately 0.04 inches to approximately 0.07 inches, such as 0.048 inches, and the wall thickness **190** may be in the range of approximately 0.02 inches to approximately 0.05 inches, such as approximately 0.03 inches to approximately 0.04 inches. The outer diameter **210** is selected to be the same as the outer diameter **308** so that the bend **84** stacks with adjacent bends **84** as would the bend **306** when stacked with adjacent bends **306**. The tighter bend radius for a given thickness **190** may improve the efficiency of heat transfer between the working fluid inside of the serpentine circuit tube **70** and the fluid outside of the serpentine circuit tube **70**. Further, the tighter bend radius for a given wall thickness **190** may reduce the internal fluid pressure drop in the serpentine circuit tube **70** since the inner diameter of the tube run increases.

Referencing FIG. **11**, the process of determining the geometry of the bend **84** includes initially setting the serpentine circuit tube **70** to have an initial bend **316** connecting the runs **80**, **82**. The initial bend **316** has a 180° bend angle and a center line radius **317** that is larger than a center line radius **313** of the bend **306** shown in FIG. **10**. Referencing FIGS. **10** and **11**, the initial bend **316** has an intrados **320** with an arc length **318** that is larger than the arc length **314** due to the center line radius **317** being greater than the center line radius **313**.

Regarding FIG. **12**, in order for the bend **84** to fit within the same coil envelope as the conventional bend **306** of FIG. **10**, meaning the center-to-center distance between the tube runs is equivalent, the bend **84** has the extrados **92** that matches the extrados **315** of the bend **306** and the tube **70** has the outer diameter **210** that matches the outer diameter **308**. To provide the matching extrados **92**, **315**, the process of determining the geometry of the bend **84** includes moving the tangent points **122**, **124** of the runs **70**, **82** toward one another in directions **330**, **332** (FIG. **11**) until: 1) the bend **84** has the actual center line radius **232** equal to the center line radius **313** of the bend **306**; and 2) an arc length of the intrados **90** of the bend **84** equals the intrados **312** of the bend **306**.

To compensate for the reduced vertical distance between the tangent points **122**, **124**, the material of the serpentine circuit tube **70** at the inside of the bend **84** is shaped to have the sinusoidal wave pattern **110**. The sinusoidal wave pattern **110** has variables that define the shape of the sinusoidal wave pattern **110**, such as the length of the sinusoidal wave pattern **110**, number of peaks/valleys, period, and/or amplitude.

Referring now to FIG. **13**A, the process of determining the geometry of the bend **84** next includes providing a line **339** having an intrados arc length **340** that matches the arc length **336** of the intrados **90** from FIG. **12**. The arc length **336** of the intrados **90** extends between the transition points **122**, **124** in FIG. **12**.

The sinusoidal wave pattern **110** is offset from the tangent points **122**, **124** of the bend **84** by two portions of the serpentine circuit tube **70**. The first portion is the relief portions **222**, **224** corresponding to the offset angle, such as 7° on either side of the sinusoidal wave pattern **110**, and measured between angles **220**, **240** (see FIG. **4**). The second portion is the tapered lead-in portions **140**, **142**. The sinusoidal wave pattern **110** starts and ends at points **400** (see FIG. **4**). To create the offset of the sinusoidal wave pattern **110** from the tangent points **122**, **124**, the process of determining the geometry of the bend **84** includes removing lengths **342**, **344** from the length **340** to give a sinusoidal pattern length **346** that is less than the intrados arc length **340** as shown in FIG. **13**A. Thus, the lengths **342**, **344** each include two length portions: 1) a length portion corresponding to one of the relief portions **222**, **224**; and 2) a length portion corresponding one of the tapered lead-in portions

140, 142. The lengths 342, 344 are determined, for example, by solving for the length portions using the intrados radius and the angular offset.

The difference between the length 340 of the line 339 (see FIG. 13A) and the arc length 318 (see FIG. 11) is taken up by the total arc length 346 of the sinusoidal wave pattern 110. Referencing FIG. 13A, the total arc length 346 of the sinusoidal wave pattern 110 may be expressed as:

$$\text{Total arc length of sinusoidal pattern}_{346}=\text{Intrados arc length}_{340}-\text{Lengths}_{342,344} \quad \text{[Equation 1.1]}$$

Once the total arc length 346 of the sinusoidal wave pattern 110 is known, the total arc length 346 is divided by the number of peak portions 250A and valley portions 252A, such as in the range of 6 to 18 peaks and valleys, such as 8 to 12 peaks and valleys, to determine the arc length 350 for each peak portion 250A and valley portion 252A. Each peak portion 250A and valley portion 252A has a radius 349 and an arc length 350 given by:

$$\text{Arc Length}_{350}=\text{Radius}_{349}\times\theta \quad \text{[Equation 1.2]}$$

Wherein θ is the angular extent of the peak portion 250A and valley portion 252A. The radius of each peak portion 250A and valley portion 252A may be determined using the following operations.

Referencing FIG. 13B, a geometric shape 351 is provided having an arcuate line AD and triangles formed by ABCD. Because the triangle ABC is a right triangle, the following equation may be recognized:

$$\sin\left(\frac{\theta}{2}\right)=\frac{AB}{CA} \quad \text{[Equation 1.3]}$$

The equation may be rearranged to be:

$$\sin\left(\frac{\theta}{2}\right)=\frac{c}{2r} \quad \text{[Equation 1.4]}$$

The relationship of a=r×θ may be substituted into equation 1.4 to result in:

$$\sin\left(\frac{\theta}{2}\right)=\frac{c\theta}{2a} \quad \text{[Equation 1.5]}$$

At this point, the "a" value is known, i.e., the total arc length 346 of the sinusoidal wave pattern 110 divided by the number of peak portions 250 and valley portions 252 (FIG. 13A). The "c" value is known (see c/2 in FIG. 13B), i.e., the length 346 divided by the number of peak portions 250 and valley portions 252 selected.

The foregoing equation may then be solved for theta using a numerical method such as Newton-Raphson iteration. Once theta has been determined, the radius of the peak portions 250A and valley portions 252A may be determined by solving for radius 349 in equation 1.2.

The radius 349 and theta permits the amplitude of the sinusoidal wave pattern 110 to be determined using the following equation:

$$\text{Amplitude}_{352}=\text{Radius}_{349}-(\text{Radius}_{349}\times\cos\,\theta)$$

It will be appreciated that ad-hoc adjustment to the sinusoidal wave pattern 110 may be utilized to tailor the sinusoidal wave pattern 110 for a particular application.

Regarding FIG. 12, the tapered lead-in portions 140, 142 to smooth the bending of the material of the serpentine circuit tube 70 to reduce stress risers at the transition between the reliefs 222, 224 (see FIG. 4) and the sinusoidal wave pattern 110.

Regarding FIGS. 14-18, the intersecting sinusoidal wave pattern 110 and arc pattern 150 of the controlled wrinkled portion 94 will be discussed in greater detail. The intersecting sinusoidal wave pattern 110 and arc pattern 150 provide a three-dimensional profile of the inner bend. The three-dimensional profile of the inner bend provides a corrugated structure that has a high strength to resist internal fluid pressure within the serpentine circuit tube 70. The intersecting sinusoidal wave pattern 110 and arc pattern 150 cause the bend 84 to experience low stress even when the bend 84 is under a high internal pressure.

Referencing FIG. 14, one half of the sinusoidal wave pattern 110 will be discussed, with the other half of the sinusoidal wave pattern 110 being identical in the embodiment of FIG. 9A. The sinusoidal wave pattern 110 begins at point 400 and is spaced from the tangent point 122 by the relief 222 and the tapered lead-in portion 140. The tapered lead-in portion 140 ramps gradually upward toward the point 400 proximate a peak 250 of the end ridge 118. The sinusoidal wave pattern 110 oscillates about the center line 406, which intersects the sinusoidal wave pattern 110 at transitions 410 between concave portions 412 and convex portions 414 (when viewed from the center 230). In the embodiment of FIG. 14, the centerline 406 of the sinusoidal wave pattern 110 is located on the intrados 90 of the bend 84 (see FIG. 12). In another embodiment, the valleys 252 of the sinusoidal wave pattern 110 are on the intrados 90 of the bend 84 such that the intrados 90 is tangent to the grooves 116. In yet another embodiment, the peaks 250 of the sinusoidal wave pattern 110 are on the intrados 90 of the bend 84 such that the intrados 90 is tangent to the ridges 114.

In reference to FIG. 14, the centerline 406 of the sinusoidal wave pattern 110 has a radius 416. In one embodiment, the bend 84 has a centerline radius 232 (see FIG. 12) in the range of approximately 1.5 inches to approximately 2 inches, such as in the range of 1.7 inches to approximately 2 inches, such as 1.875 inches. The centerline 406 may have a radius in the range of approximately 1 inch to approximately 1.5 inches, such as in the range of approximately 1.3 inches to approximately 1.4 inches, such as 1.35 inches.

Regarding FIG. 15, the arc pattern 150 includes the peak arc 152 that intersects the sinusoidal wave pattern 110 at each peak 250, and a valley arc 154 that intersects the sinusoidal wave pattern 110 at each valley 252. The peak arc 152 and valley arc 154 are separated about the bend 84 by an angle 420 that may be in the range of, for example, approximately 4° to approximately 14°.

Regarding FIG. 16A, the peak arc 152 has the center 182 of the peak arc 152 radially inward from the tube center line 102 of the bend 84. The center 182 is positioned along a midline plane 424 of the serpentine circuit tube 70. The peak arc 152 extends through an angle 160 that may be in the range of, for example, 150° to approximately 170°, such as 160°. The peak arc 152 has an arc length 427 that extends from end point 426 to end point 430 of the peak arc 152.

Regarding FIG. 17A, the valley arc 154 has the center 172 thereof radially outward from the center line 102 of the serpentine circuit tube 70. The valley arc 154 extends through an angle 162 that is less than the angle 160 in FIG. 16A. In one embodiment, the angle 162 is in the range of approximately 100° to approximately 150°, such as 140°.

The valley arc **154** has an arc length **432** between end points **434**, **436** of the valley arc **154** that is less than the arc length **427** of the peak arc **152**.

Regarding FIG. **18**, the continuously curving controlled wrinkled surface **134** (as shown in FIG. **8**) of the controlled wrinkled portion **94** may be formed at least a part by connecting the peak arc **152** and the valley arc **154** with a surface portion **440** having a convex surface portion **442**, a concave surface portion **444**, and a transition **446** that transitions between the convex and concave surface portions **442**, **444**. The surface portion **440** may be mirrored across a vertical plane that contains peak arc **152** to the opposite side of the ridge **114**.

In one embodiment, the continuously curving wrinkled surface **134** is perpendicular to a vertical plane that contains the peak arc **152**, as well as a vertical plane that contains the valley arc **154**. Referencing FIG. **15**, the vertical plane that contains peak arc **152** is defined as being perpendicular to the horizontal plane **424** (see FIG. **8**), and contains the origin or center **230** and peak point **250**. The vertical plane that contains valley arc **154** is defined as being perpendicular to the horizontal plane **424** and contains the center **230** and valley **252**. The vertical planes that contain the peak and valley arcs **152**, **154** are separated by angle **420**. Regarding FIG. **18**, the concave surface portions **442** and convex surface portions **444** connect the peak and valley arcs **152**, **154** and provide the undulating three-dimensional profile of the continuously curving controlled wrinkled surface **134** (FIG. **8**). Each concave and convex surface portion **442**, **444** terminates at two, four pole splines, one of which starts at peak arc end point **426** (FIG. **16**A) and ends at valley arc end point **434** (FIG. **17**A), while the other four pole spline starts at peak arc end point **430** (FIG. **16**A) and ends at valley arc end point **436** (FIG. **17**A).

Regarding FIGS. **19** and **20**, a tube bender **500** is provided to bend a segment of the serpentine circuit tube **70** into the bend **84** discussed above. The tube bender **500** includes a bend die **502** and a clamp die **504** that is pivotal about an axis **506**. The tube bender **500** includes a pressure die **508** for supporting an outside of the bend **84** and a trailing portion of the serpentine circuit tube **70**. The bend die **502** and the clamp die **504** include recesses **512**, **514** with surfaces **516**, **518** extending thereabout that clamp onto a tube once the tube has been advanced in direction **520** onto a gap **522** between the bend die **502** and the clamp die **504**. The clamp die **504** and the pressure die **508** may be actuated in direction **524** to secure a portion of the tube between the clamp die **504** and the bend die **502**. The pressure die **508** includes a recess that receives a portion of the tube and may be shifted in direction **526** along with movement of the tube upon the bend die **502** and clamp die **504** being pivoted about the axis **506** in direction **528** to support the outside of the tube during the bending operation.

Regarding FIGS. **19** and **20**, the bend die **502** includes an upper part **530**, a lower part **532**, and a recess **534** that receives a portion of the tube therein as the bend die **502** and clamp die **504** are pivoted in direction **528**. The bend die **502** has a wrinkled portion **536** that is the mirror image of the wrinkled portion **94** of the tube so that the bend die **502** imparts the wrinkled pattern **94** into the tube. For example, the wrinkled portion **536** includes ridges **540** that form the grooves **116** (FIG. **8**) and grooves **542** that form the ridges **114** (FIG. **8**).

Referencing FIG. **20**, the ridges **540** each have an intermediate portion **544** and opposite end portions **546**. The intermediate portion **544** may have a first width about the bend die **502** and the ends **546**, **548** have widths around the bend die **502** that are larger than the width of the intermediate portion **544** such that the ridges **540** flare outwardly as they extend away from a midline **550** of the bend die **502**. The grooves **542** may correspondingly have an intermediate portion **552** and opposite end portions **554**, **556** that are narrower around the bend die **502** than the intermediate portion **552** due to the increasing width of the ridges **540** as the ridges **540** extend away from the midline **550**. The ridges **540** and the grooves **542** have undulating and continuous curved surfaces **560** such that the wrinkled portion **536** forms the continuous wrinkled surface **134** of the tube.

Regarding FIGS. **21**-**25**, a method of forming the bend **84** using the tube bender **500** is provided. The tube bender **500** shown in FIGS. **21**-**25** has similar components as the tube bend **500** shown in FIG. **19** but with a different orientation of the components. Similar reference numbers will be used to describe the tube benders of FIGS. **20** and **21**-**25** for ease of discussion.

Regarding FIGS. **21** and **22**, a tube **564** is advanced into the tube bender **500** so that the pressure die **508** supports an outer surface of the tube **564**. In FIG. **22**, the bend die **502** and clamp die **504** engage a portion **505** the tube **564** and begin to pivot in direction **565** into the page of FIG. **22**.

Regarding FIGS. **23** and **24**, the bend die **502** and clamp die **504** are pivoted in direction **565** to begin forming the bend **570** in the tube **564**. The pressure die **508** continues to support the outside of the tube **506** and is shifted in direction **526** to move with the tube **564** during the bending operation.

Regarding FIG. **25**, the tube bender **500** has formed the bend **570** by bending the tube **564** 180 degrees.

FIG. **26** shows the upper part **530** of the bend die **502** shifted upward in direction **569** from the lower part **532**, the clamp die **504** shifted away from the tube **564** (into the page), and the pressure die **508** is retracted from the tube **564**. The tube **564** is then shifted in direction **571** to position the next bend location along the tube **564** in the tube bender **500**.

Regarding FIG. **27**, the bend **570** is shown having the wrinkled portion **572** including ridges **574** and grooves **576** formed in the inside of the bend **570**. FIG. **27** also shows how the lower part **532** have a sinusoidal pattern **578** at the midline **550** (see FIG. **20**) of bend die **502** that imparts a sinusoidal wave pattern **580** to the inside of the bend **570**. More specifically, the lower part **532** has the lower portions of the ridges **540** that form the grooves **576** in the bend **570** and the lower part **532** has the lower portions of the grooves **542** that receive the ridges **574** of the bend **570**. In this manner, the ridges **574** of the tube **564** and the ridges **540** of the bend die **502** form a tightly meshed configuration. Further, the ridges **540** and grooves **542** with the undulating, continuous surface thereon supports the inside of the tube. The upper part **530** (FIG. **26**) of the bend die **502** forms a corresponding meshed engagement with the upper portion of the bend **570**.

Regarding FIG. **20**, the wrinkled portion **536** of the bend die **502** includes, now referring to FIG. **27**, a tapered transition portion **590** and an end ridge **592** that cooperate to form an end ridge **594** of the bend **570**. The tapered transition portion **590** provides a smooth lead-in to a peak of the end ridge **594** as discussed above with respect to FIG. **9**A.

Various types of bends may be provided in accordance with the disclosure here. For example, FIG. **28** shows a 90 degree bend **600**, FIG. **29** shows an eighty degree bend **620**, and FIG. **30** shows a one-hundred degree bend **640**.

Regarding FIG. **31**, a cross-sectional view of a serpentine circuit tube **700** is provided that is taken normal to the length of the serpentine circuit tube **700**. The serpentine circuit tube **700** similar to serpentine circuit tube **70** and includes runs **701**. The runs **701** include runs **702** having a circular cross-section and runs **704** having a non-circular cross-section, such as elliptical or obround. The runs **701** have cross-sections that progressively flatten with the run **706** having a width **707** that is wider than a width **709** of the run **708**.

Regarding FIG. **32**, a coil **800** including assembled serpentine circuit tubes **802**, **804** is provided. Each serpentine circuit tube **802**, **804** includes runs **803**, **805**, a compound bend **806** including first bend **808** having an first bend angle **810** of 80 degrees, a second bend **812** having a second bend angle **814** of 100 degrees, and a connecting portion **816** connecting the first and second bends **808**, **812**. The first and second bends **808**, **812** have inner controlled wrinkled portions that are similar to the controlled wrinkled portions of the bends discussed above. The serpentine circuit tubes **802**, **804** have three contact points **820**, **822**, **824**. Each serpentine circuit tube **802**, **804** has a height or distance **830** between the runs **803**, **805**. The serpentine circuit tubes **802** of coil **800** contact one another. In other embodiments, the coil may include serpentine circuit tubes that do not contact one another.

With reference to FIG. **33**, a portion of a tube **896** is shown that includes straights **898** and a bend **900**. The bend **900** is provided that is similar in many respects to the bends discussed above. The bend **900** includes a wrinkled portion **902** having ridges **904** and grooves **906**. The wrinkled portion **902** includes a sinusoidal pattern **903** along an intrados of the bend **900** that starts and ends at points **903**A, **903**B. The tube **896** has tangent points **911**, **913** at transitions between the straights **898** and the bend **900**.

The wrinkled portion **902** is asymmetrical about a plane **908** that bisects the bend **900**. Axes **915**, **912** extend perpendicular to the plane **908** and intersect, respectively, the tangent points **913**, **911**. The tangent points **911**, **913** are offset along the plane **908** a distance **910** such that the wrinkled portion **902** extends farther along the tube **896** on one side of the plane **908** than the other. The portion of the wrinkled portion **902** on the one side of the plane **908** (the upper portion in FIG. **33**) has an offset portion **910**A including at least one ridge **904** and/or at least one groove **906** more than the portion of the wrinkled portion **902** on the other side of the plane **908**.

The wrinkled portion **910** has an end groove **906**A and an end ridge **904**A. In one implementation, the end ridge **904**A lacks a tapered lead-in portion. The offset portion **910**A may provide a transition for flow in the tube **896** between the nearby straight **898** and the bend **900**. Further, the end ridge **904**B has a tapered lead-in portion **914** similar to various end ridges discussed above.

Regarding FIGS. **34** and **35**, a bend die **1000** is provided that is similar to the bend die **502** discussed above such that differences will be highlighted. The bend die **1000** is used to form the bend **900** and includes an upper portion **1002** and a lower portion **1004**. The upper and lower portions **1002**, **1004** have ridges **1006** and grooves **1008** that cooperate to form the ridges **904** and grooves **906** in the bend **900**. The upper and lower portions **1002**, **1004** each have a pair of channels **1010**, **1012**. The channels **1010** of the upper and lower portions **1002**, **1004** form an opening **1013** at one side **1014** of the bend die **1000** and the channels **1012** of the upper and lower portions **1002**, **1004** form another opening **1015** at the second side **1016**.

The openings **1013**, **1015** permit the bend die **1000** to have a tube fed into either opening **1013**, **1015** of the bend die **1000** and allow the bend die **100** to be turned in the corresponding direction to form the bend **900** in the tube. For example and with reference to FIG. **35**, a first portion of a tube may be advanced in direction **1030** into channel **1012** of the bend die lower portion **1004**. The upper portion **1002** is shifted downward in direction **1032** into engagement with the bend die lower portion **1004** to form the opening **1015** around the tube.

The bend die **1000** is then turned in direction **1034** about axis **1036** while a trailing portion of the tube is supported by a pressure die. The bend die **1000** is turned in direction **1034** to impart the desired angular extent to the bend **900**. Once the bend **900** has been formed, the bend die upper portion **1002** is shifted upward in direction **1033** and the tube is shifted relative to the bend die **1000** to position another portion of the tube in the bend die **1000** for bending. Continuing with the example, the tube is repositioned to advance a second portion of the tube into opening **1013**, the bend die **1000** is closed, and the bend die **1000** is turned in a direction opposite direction **1034**. The process of advancing and bending the tube is repeated until the desired number of bends have been imparted to the tube.

Regarding FIG. **36**, a tube **1100** is provided having a return bend **1102** and straights **1103**. The return bend **1102** has a wrinkled portion **1104** that is similar to the wrinkled portions discussed above. The wrinkled portion **1104** has valleys **1106** and peaks **1108**. The tube **1100** has a flattened cross-section at the valleys **1106**, the peaks **1108**, and/or the straights **1103**. The flattened cross-section of the tube **1100** may enable the tube **1100** to be tightly packed with adjacent tubes, such as in a coil assembly of a cooling tower. The flattened cross-section of the tube **1100** may also improve thermal performance of the tube **1100**.

The flattened cross-section of the tube **1100** may be, for example, an elliptical cross section. Regarding FIG. **37**A, the return bend **1102** includes a valley elliptical wall portion **1110** at the valley **1106**. The valley elliptical wall portion **1110** has a major dimension **1112** and a minor dimension **1114**.

Regarding FIG. **37**B, the return bend **1102** has a peak elliptical wall portion **1116** at the peak **1108**, the peak elliptical wall portion **1116** having a major dimension **1120** and a minor dimension **1122**. The major dimension **1120** of the peak **1108** is larger than the major dimension **1112** of the valley **1106**. In one embodiment, the minor dimension **1122** of the peak **1108** is smaller than the minor dimension **1114** of the valley **1106**.

Regarding FIG. **37**C, the return bend **1102** has a straight elliptical wall portion **1126** at the straight **1103**, the straight elliptical wall portion **1126** having a major dimension **1128** and a minor dimension **1130**. In one embodiment, the major dimension **1128** of the straight **1103** is smaller than the major dimensions **1112**, **1120** and the minor dimension **1130** is larger than the minor dimensions **1114**, **1122**.

The flattened cross-section of the portions of the tube **1100** may be provided in a number of different approaches. For example, the tube bender used to bend the tube and impart the wrinkled portion **1104** may flatten the bend **1102** during the bending procedure. In another approach, the tube initially has an elliptical cross-section and the bending procedure imparts the wrinkled portion **1104** to the bend **1102** without further flattening of the tube. In yet another approach, a tube bender is used to form one or more bends of a tube and a press is used to flatten the tube after the bending procedure.

Uses of singular terms such as "a," "an," are intended to cover both the singular and the plural, unless otherwise indicated herein or clearly contradicted by context. The terms "comprising," "having," "including," and "containing" are to be construed as open-ended terms. It is intended that the phrase "at least one of" as used herein be interpreted in the disjunctive sense. For example, the phrase "at least one of A and B" is intended to encompass A, B, or both A and B.

While there have been illustrated and described particular embodiments of the present invention, it will be appreciated that numerous changes and modifications will occur to those skilled in the art, and it is intended for the present invention to cover all those changes and modifications which fall within the scope of the appended claims. For example, the bends disclosed herein may be utilized in in various heat exchange apparatuses, such as an evaporative condenser, air cooled condenser, closed circuit fluid cooler, closed circuit cooling tower, open circuit cooling tower, dry cooler, ice thermal storage system, thermal storage coils, and/or a hydro-cooling coil, as some examples.

What is claimed is:

1. An indirect heat exchanger pressure vessel comprising:

an inlet header to receive a pressurized working fluid;

an outlet header to collect the pressurized working fluid;

a serpentine circuit tube connecting the inlet and outlet headers and permitting the pressurized working fluid to flow from the inlet header to the outlet header;

the serpentine circuit tube comprising runs and a return bend connecting the runs;

wherein the return bend has an intrados and an extrados;

the return bend having side surface portions intermediate the intrados and the extrados, the return bend having a controlled wrinkled portion between the side surface portions;

the controlled wrinkled portion including alternating ridges and grooves;

wherein the controlled wrinkled portion of the return bend includes a sinusoidal pattern at the intrados of the return bend, the sinusoidal pattern including peaks at the ridges and valleys at the grooves of the return bend;

wherein each ridge extends from the intrados of the return bend toward the side surface portions of the return bend; and

wherein each ridge widens as the ridge extends from the intrados toward the side surface portions of the return bend, each ridge having a first width at the intrados that is less than a second width at either of the side surface portions.

2. The indirect heat exchanger pressure vessel of claim **1** wherein the inlet header, the outlet header, and the serpentine circuit tube are configured to operate at an internal pressure of at least 150 psig.

3. The indirect heat exchanger pressure vessel of claim **1** wherein the inlet header, the outlet header, and the serpentine circuit tube are configured to operate at an internal pressure of at least 410 psig.

4. The indirect heat exchanger pressure vessel of claim **1** wherein the inlet header, the outlet header, and the serpentine circuit tube are configured to operate at an internal pressure of at least 1200 psig.

5. The indirect heat exchanger pressure vessel of claim **1** wherein the serpentine circuit tube includes a pair of tangent points at junctures between the return bend and the runs of the serpentine circuit tube;

the return bend having a bend angle;

the controlled wrinkled portion of the return bend spaced from the tangent points along the serpentine circuit tube; and

wherein the controlled wrinkled portion of the return bend has an angular extent about an inside of the return bend that is less than the bend angle.

6. The indirect heat exchanger pressure vessel of claim **1** wherein the controlled wrinkled portion of the return bend includes an arc pattern intersecting the sinusoidal pattern of the bend, the arc pattern comprising:

peak arcs intersecting the peaks; and

valley arcs intersecting the valleys.

7. The indirect heat exchanger pressure vessel of claim **6** wherein at least one of the peak arcs has a first radius of curvature and at least one of the valley arcs has a second radius of curvature, wherein the first radius of curvature and the second radius of curvature are substantially the same.

8. The indirect heat exchanger pressure vessel of claim **1** wherein the ridges include end ridges adjacent the runs of the serpentine circuit tube; and

wherein at least one of the end ridges includes a tapered lead-in portion to smooth the flow of pressurized working fluid about the ridges and grooves.

9. An indirect heat exchanger pressure vessel comprising:

an inlet header to receive a pressurized working fluid;

an outlet header to collect the pressurized working fluid;

a serpentine circuit tube connecting the inlet and outlet headers and permitting the pressurized working fluid to flow from the inlet header to the outlet header;

the serpentine circuit tube comprising runs and a return bend connecting the runs;

the return bend having a controlled wrinkled portion;

the controlled wrinkled portion including alternating ridges and grooves;

wherein the return bend has a bend radius and includes a tubular side wall extending about an interior of the return bend;

wherein the tubular side wall includes:

a first semicircular inner wall portion at each ridge of the return bend, a first outer wall portion, and a pair of first connecting wall portions on opposite sides of the return bend interior connecting the first semicircular inner wall portion and the outer wall portion, wherein the first semicircular inner wall portion, outer wall portion, and the first connecting wall portions are radially aligned; and

a second semicircular inner wall portion at each groove of the return bend, a second outer wall portion, and a pair of connecting wall portions on opposite sides of the return bend interior connecting the second semicircular inner wall portion and the second outer wall portion, wherein the second semicircular inner wall portion, second outer wall portion, and the second connecting wall portions are radially aligned.

10. The indirect heat exchanger pressure vessel of claim **9** wherein the first semicircular inner wall portion has a first radius of curvature and the second semicircular wall portion has a second radius of curvature that is substantially the same as the first radius of curvature.

11. The indirect heat exchanger pressure vessel of claim **9** wherein the first semicircular inner wall portion has a first angular extent and the second semicircular inner wall portion has a second angular extent, wherein the first angular extent and the second angular extent are each greater than 90 degrees.

12. The indirect heat exchanger pressure vessel of claim **11** wherein the first angular extent is greater than the second angular extent.

13. The indirect heat exchanger pressure vessel of claim **1** wherein the runs of the serpentine circuit tube comprise a plurality of pairs of runs; and

wherein the return bend comprises a plurality of return bends connecting the pairs of runs.

14. The indirect heat exchanger pressure vessel of claim **1** wherein the return bend comprises:

a first bend including a first controlled wrinkled portion of the controlled wrinkled portion;

a second bend including a second controlled wrinkled portion of the controlled wrinkled portion; and

a straight portion of the serpentine circuit tube connecting the first and second bends.

15. The indirect heat exchanger pressure vessel of claim **14** wherein the first bend has a first bend angle greater than or equal to 90 degrees and the second bend has a second bend angle less than or equal to 90 degrees.

16. The indirect heat exchanger pressure vessel of claim **1** wherein the return bend comprises a plurality of return bends; and

wherein the return bends of the serpentine circuit tube have centerlines that are all coplanar.

17. The indirect heat exchanger pressure vessel of claim **1** wherein the return bend has a bend angle of **180** degrees and the controlled wrinkled portion of the bend has an arc length of less than or equal to 180 degrees.

18. The indirect heat exchanger pressure vessel of claim **1** wherein the runs of the serpentine circuit tube include runs having a non-circular cross-sectional shape.

19. The indirect heat exchanger pressure vessel of claim **1** wherein the controlled wrinkle portion includes at least one tapered lead-in portion.

20. The indirect heat exchanger pressure vessel of claim **1** wherein the serpentine circuit tube has an outer diameter (OD), the serpentine circuit tube has a wall thickness (WT), and the return bend has a centerline radius (CLR);

wherein the return bend has a bend complexity factor (CB) given by the following equation:

$$C_B = \frac{OD^2}{CLR \times WT^2}$$

wherein the bend complexity factor is greater than or equal to 10.

21. The indirect heat exchanger pressure vessel of claim **20** wherein the bend complexity factor is less than or equal to 20.

22. The indirect heat exchanger pressure vessel of claim **1** wherein the serpentine circuit tube includes a plurality of serpentine circuit tubes; and

wherein the serpentine circuit tubes contact one another.

23. The indirect heat exchanger pressure vessel of claim **1** wherein the serpentine circuit tube includes a plurality of serpentine circuit tubes; and

wherein the serpentine circuit tube return bends do not contact one another.

24. The indirect heat exchanger pressure vessel of claim **1** wherein the return bend of the serpentine circuit tube has a non-circular cross-sectional shape.

25. The indirect heat exchanger pressure vessel of claim **1** wherein the return bend of the serpentine circuit tube has an elliptical cross-sectional shape.

26. The indirect heat exchanger pressure vessel of claim **1** wherein the controlled wrinkled portion is asymmetrical about a plane bisecting the return bend.

27. The indirect heat exchanger pressure vessel of claim **1** wherein the return bend has a bend angle of 180 degrees; and

wherein the controlled wrinkled portion is asymmetrical about a plane bisecting the return bend.

28. An indirect heat exchanger pressure vessel comprising:

an inlet header to receive a pressurized working fluid;

an outlet header to collect the pressurized working fluid;

a serpentine circuit tube connecting the inlet header and the outlet header to permit flow of the pressurized working fluid from the inlet header to the outlet header, the serpentine circuit tube including runs and a return bend connecting the runs, the return bend comprising:

an inner portion having a sinusoidal wave pattern at an intrados of the return bend, the sinusoidal wave pattern including peaks and valleys;

wherein the inner portion of the return bend includes an arc pattern intersecting the sinusoidal wave pattern, the arc pattern comprising peak arcs intersecting the peaks and valley arcs intersecting the valleys;

wherein the peak arcs each include a first radius of curvature and a second radius of curvature; and

wherein the valley arcs each include a third radius of curvature and a fourth radius of curvature; and

wherein the first radius of curvature and the third radius of curvature are substantially the same and the second radius of curvature and the fourth radius of curvature are substantially the same.

29. The indirect heat exchanger pressure vessel of claim **28** wherein the peak arcs have an angular extent that is greater than an angular extent of the valley arcs.

30. The indirect heat exchanger pressure vessel of claim **28** wherein the serpentine circuit tube has a centerline;

wherein the peak arcs each have a center radially inward of the centerline; and

wherein the valley arcs each have a center radially outward of the centerline.

31. The indirect heat exchanger pressure vessel of claim **28** wherein the return bend has a midline plane, the sinusoidal pattern being in the midline plane;

wherein the peak arcs are normal to the midline plane; and

wherein the valley arcs are normal to the midline plane.

32. The indirect heat exchanger pressure vessel of claim **28** wherein the sinusoidal pattern includes end peak portions adjacent the runs; and

wherein at least one of the end peak portions includes a tapered lead-in segment.

33. The indirect heat exchanger pressure vessel of claim **28** wherein the sinusoidal pattern has a period and an amplitude; and

wherein at least one of the period and the amplitude varies about the return bend.

34. The indirect heat exchanger pressure vessel of claim **33** wherein the sinusoidal pattern includes a first minimum amplitude adjacent one of the runs, a second minimum amplitude adjacent another one of the runs, and a maximum amplitude intermediate the first and second minimum amplitudes along the intrados of the bend.

35. The indirect heat exchanger pressure vessel of claim **28** wherein the peak and valley arcs each have an angular extent of at least 100 degrees.

36. The indirect heat exchanger pressure vessel of claim **28** wherein the peak arcs have a shape defined by a portion of a first ellipse; and

wherein the valley arcs have a shape defined by a portion of a second ellipse.

37. An indirect heat exchanger pressure vessel comprising:

an inlet header to receive a pressurized working fluid;

an outlet header to collect the pressurized working fluid;

a serpentine circuit tube connecting the inlet header and the outlet header to permit flow of the pressurized working fluid from the inlet header to the outlet header, the serpentine circuit tube including runs and a return bend connecting the runs, the return bend comprising:

an inner portion having a sinusoidal wave pattern at an intrados of the return bend, the sinusoidal wave pattern including peaks and valleys;

wherein the inner portion of the return bend includes an arc pattern intersecting the sinusoidal wave pattern, the arc pattern comprising peak arcs intersecting the peaks and valley arcs intersecting the valleys;

wherein the peak arcs have a shape defined by a portion of a first ellipse;

wherein the valley arcs have a shape defined by a portion of a second ellipse;

wherein the first ellipse has a first major dimension and a first minor dimension;

wherein the second ellipse has a second major dimension and a second minor dimension; and

wherein the first major dimension is substantially the same as the second major dimension and wherein the first minor dimension is substantially the same as the second minor dimension.

38. A closed circuit cooling tower comprising:

an indirect heat exchanger comprising a plurality of serpentine circuit tubes comprising runs and return bends connecting the runs;

the return bends of at least one of the serpentine circuit tubes including a wrinkled bend having a controlled wrinkled portion;

wherein the wrinkled bend includes:

an intrados;

an extrados;

side surface portions intermediate the intrados and the extrados;

wherein the controlled wrinkled portion is between the side surface portions;

wherein the controlled wrinkled portion includes alternating ridges and grooves;

wherein the controlled wrinkled portion includes a sinusoidal pattern at the intrados of the wrinkled bend, the sinusoidal pattern including peaks at the ridges and valleys at the grooves of the wrinkled bend;

wherein each ridge extends from the intrados of the return bend toward the side surface portions of the wrinkled bend; and

wherein each ridge widens as the ridge extends from the intrados toward the side surface portions of the return bend, each ridge having a first width at the intrados that is less than a second width at either of the side surface portions;

a fan operable to generate airflow relative to the serpentine circuit tubes;

an evaporative liquid distribution assembly configured to distribute evaporative liquid onto the serpentine circuit tubes;

a sump to receive evaporative liquid from the serpentine circuit tubes; and

a pump operable to pump evaporative fluid from the sump to the evaporative liquid distribution assembly.

39. The closed circuit cooling tower of claim 38 wherein the indirect heat exchanger includes an inlet header to receive pressurized working fluid and an outlet manifold to collect the pressurized working fluid;

wherein the serpentine circuit tubes connect the inlet header and outlet header, the serpentine circuit tubes permitting flow of pressurized working fluid from the inlet header to the outlet header; and

wherein the inlet header, the outlet header, and the serpentine circuit tubes are configured to operate at an internal pressure of at least 150 psig.

40. The closed circuit cooling tower of claim 38 wherein the at least one of the serpentine circuit tubes include tangent points at junctures between the wrinkled bend and adjacent runs of the serpentine circuit tube;

the wrinkled bend having a bend angle;

the controlled wrinkled portion of the wrinkled bend spaced from the tangent points along the serpentine circuit tube; and

wherein the controlled wrinkled portion of the wrinkled bend has an angular extent about an inside of the first wrinkled return bend that is less than the bend angle.

41. The closed circuit cooling tower of claim 38

wherein the controlled wrinkled portion further include an arc pattern intersecting the sinusoidal pattern, the arc pattern comprising peak arcs intersecting the peaks and valley arcs intersecting the valleys.

42. The closed circuit cooling tower of claim 41 wherein the at least one of serpentine circuit tubes has a centerline;

wherein the peak arcs have centers radially inward of the centerline; and

wherein the valley arcs have centers radially outward of the centerline.

43. The closed circuit cooling tower of claim 38 further comprising a direct heat exchanger, the evaporative liquid distribution assembly configured to distribute evaporative liquid onto the direct heat exchanger.

44. The indirect heat exchanger pressure vessel of claim 1 wherein a majority of the ridges are identical; and

wherein a majority of the grooves are identical.

45. The indirect heat exchanger pressure vessel of claim 9 wherein the inlet header, the outlet header, and the serpentine circuit tube are configured to operate at an internal pressure of at least 150 psig.

46. The indirect heat exchanger pressure vessel of claim 9 wherein the controlled wrinkled portion of the return bend includes a sinusoidal pattern at an intrados of the return bend, the sinusoidal pattern including peaks at the ridges and valleys at the grooves of the bend;

wherein the controlled wrinkled portion of the return bend includes an arc pattern intersecting the sinusoidal pattern of the bend, the arc pattern comprising:

peak arcs intersecting the peaks; and

valley arcs intersecting the valleys.

47. The indirect heat exchanger pressure vessel of claim 46 wherein at least one of the peak arcs has a first radius of curvature and at least one of the valley arcs has a second radius of curvature, wherein the first radius of curvature and the second radius of curvature are substantially the same.

48. The indirect heat exchanger pressure vessel of claim 9 wherein the ridges include end ridges adjacent the runs of the serpentine circuit tube; and

wherein at least one of the end ridges includes a tapered lead-in portion to smooth the flow of pressurized working fluid about the ridges and grooves.

49. The indirect heat exchanger pressure vessel of claim 9 wherein the serpentine circuit tube has an outer diameter

(OD), the serpentine circuit tube has a wall thickness (WT), and the return bend has a centerline radius (CLR);

wherein the return bend has a bend complexity factor (C_B) given by the following equation:

$$C_B = \frac{OD^2}{CLR \times WT}$$

wherein the bend complexity factor is greater than or equal to 10.

50. The indirect heat exchanger pressure vessel of claim **49** wherein the bend complexity factor is less than or equal to 20.

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