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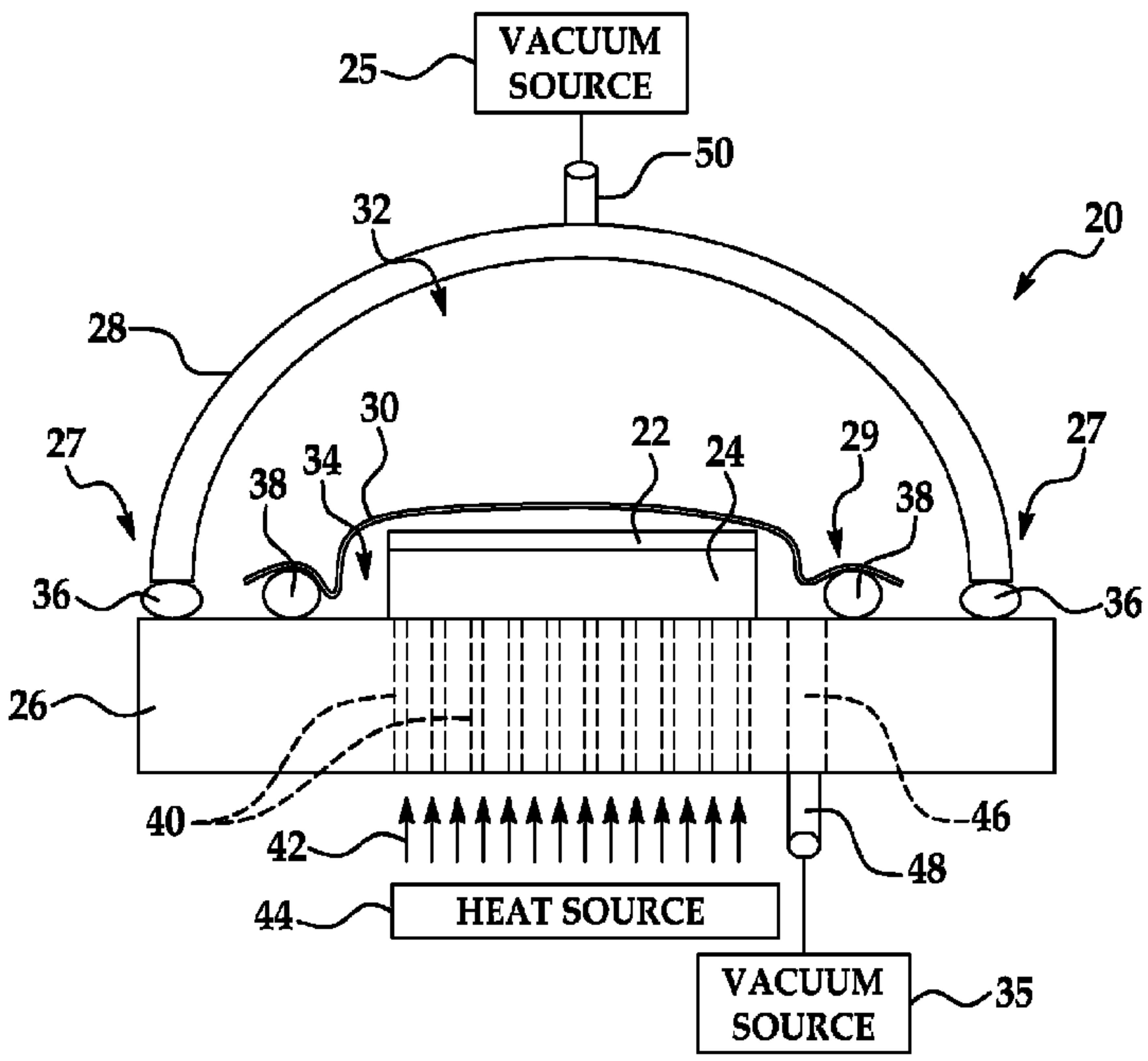

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Out-of-autoclave curing of a composite part is performed using a double vacuum chamber assembly comprising integrated inner and outer vacuum chambers.

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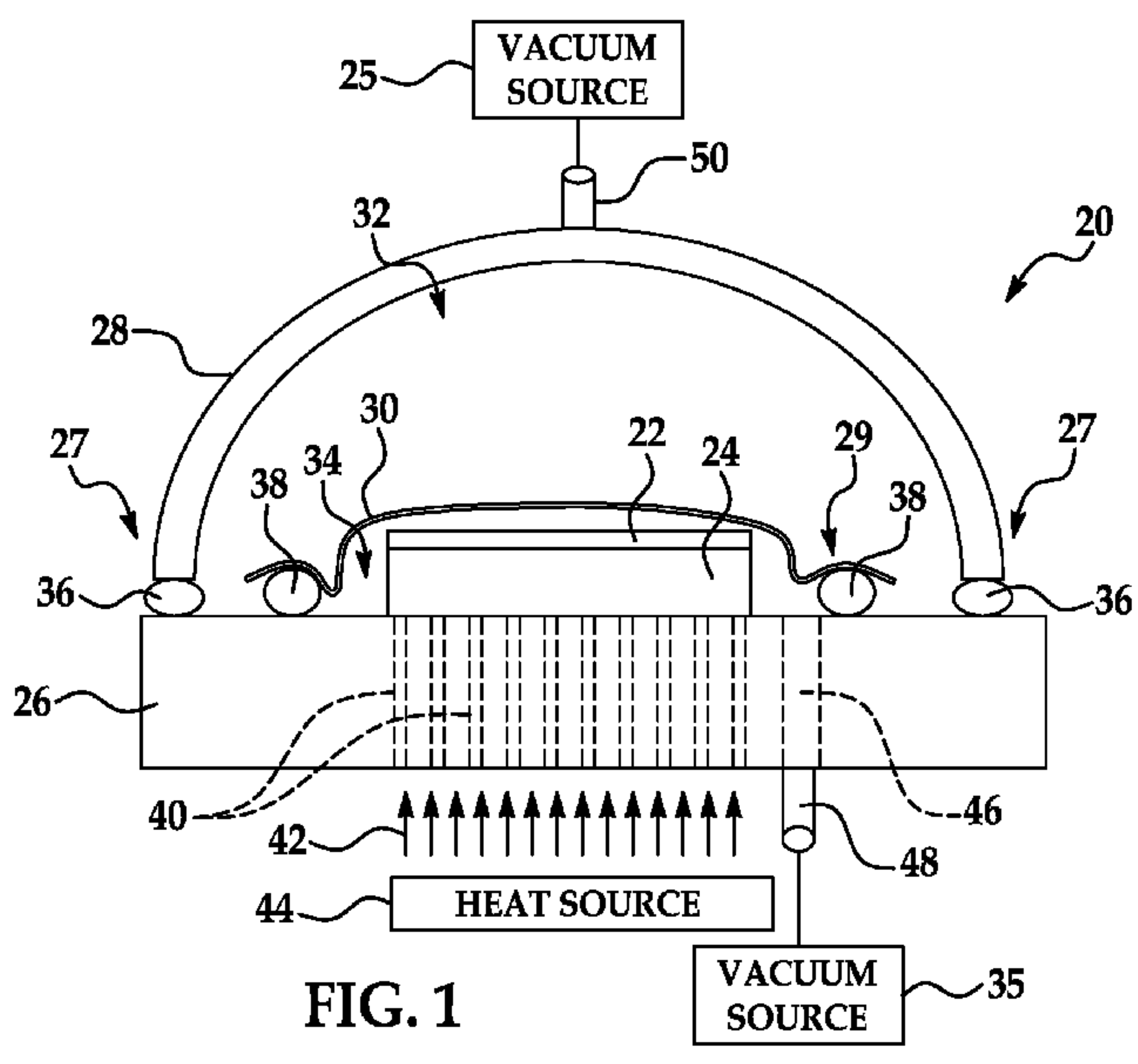

FIG. 1

(57) **Abstract**: Out-of-autoclave curing of a composite part is performed using a double vacuum chamber assembly comprising integrated inner and outer vacuum chambers.

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DOUBLE VACUUM CURE PROCESSING OF COMPOSITE PARTS

TECHNICAL FIELD

This disclosure generally relates to equipment and methods for making composite parts, and deals more particularly with double vacuum cure processing of composites.

BACKGROUND

Autoclaves are widely used to cure composite parts having higher performance specifications requiring tight dimensional tolerances and low porosity. Heating the composite within an autoclave results in a chemical reaction that both cures the resin and produces volatiles inside the composite that are driven out by pressure applied to the atmosphere within the autoclave. Similarly, pressclaves may be used to cure composites by applying heat and pressure to a heated part through an inflatable bladder. Autoclaves, pressclaves and similar equipment may be undesirable for use in some applications, however, due to their higher capital cost and the labor they require for setup and operation. Furthermore, autoclave and pressclave cure processing may be limited by the size of parts that can be processed.

Double vacuum bag (DVB) processing may also be employed to cure composite parts such as prepreg laminates. Unlike autoclave curing, DVB processing is not limited by the size of the part. The DVB process is also less capital equipment intensive than autoclave processing, and may provide tighter dimensional control and higher mechanical performance in the cured part compared to autoclave processing or single vacuum bag (SVB) processing.

Prior DVB equipment and processing methods can be relatively labor intensive and time consuming. DVB equipment comprises inner and outer vacuum bags that must be individually positioned and sealed to a tool base using hand labor. The bags must each be leak checked before processing begins. Additionally, the current DVB processing technique requires an intermediate low temperature hold step during the processing cycle in which the temperature of the part is held at a substantially constant level for a period of time as the part is ramped up to a desired cure temperature. This intermediate low temperature hold adds to the overall processing time of the part.

Accordingly, there is a need for a simplified double vacuum cure apparatus and related method for curing composite parts that both reduces labor costs and processing times.

SUMMARY

The disclosed embodiments provide apparatus and a related method for curing a prepreg laminate using double vacuum processing. The apparatus is effective in removing volatiles,

and may produce parts exhibiting reduced dimensional tolerance variations and improved mechanical properties. Time and labor needed to set up equipment and cure parts may be reduced through the use of an integrated double vacuum chamber assembly comprising a flexible inner bag that is permanently attached to a substantially rigid outer shroud. Use of the apparatus may allow reduction or elimination of an intermediate low temperature hold as the temperature of the part is being increased to the cure temperature, thereby further reducing processing time. The method and apparatus may be used to produce composite parts during an original manufacturing process or to rework parts using composite patches.

According to one disclosed embodiment, apparatus is provided for curing a composite part. The apparatus comprises a cure tool against which the part may be compressed during curing. A generally rigid shroud forms a first outer vacuum chamber over the composite part, and a vacuum bag covered by the shroud forms a second inner vacuum chamber over the composite part. Means may be provided for securing the bag to the shroud, which may include an adhesive. In one variation, the bag may include magnetic means for attaching the periphery of the bag to the tool.

According to another embodiment, apparatus is provided for out-of-autoclave curing of an uncured composite part, comprising a tool on which the uncured part may be placed, and a double vacuum chamber assembly. The double vacuum chamber assembly includes a generally rigid portion forming the first outer vacuum chamber and a generally flexible portion forming an inner vacuum chamber. The flexible portion of the vacuum chamber assembly is substantially disposed within and attached to the first portion. Each of the flexible and rigid portions of the vacuum chamber assembly may include a vacuum port for allowing a vacuum to be drawn in the chamber. The tool may include at least one opening therein through which warm air may be received for directly heating the tool. The apparatus may further comprise a thermal mass attached to the tool for improving heat transfer through the tool to the part.

According to a disclosed method embodiment, curing a composite part comprises placing the part on a tool and drawing first and second vacuums over the part. The temperature of the part is increased substantially continuously and at a substantially constant rate to a preselected cure temperature. The first vacuum is reduced as the temperature of the part is being increased to the cure temperature. The method further comprises maintaining the temperature of the part substantially at the cure temperature for a preselected period, and reducing the temperature of the part after the cure temperature has been maintained for the preselected period. The vacuum in the inner chamber is held substantially constant as the temperature is increased continuously to the cure temperature as well as during the period that the temperature is being maintained at the cure temperature. Drawing the first and second vacuums may be performed by placing a flexible bag over the part, forming a substantially vacuum type seal between the bag and the tool, drawing air from the bag through a vacuum port in the tool, placing a substantially rigid shroud over the bag and the part, and drawing air from the shroud through a vacuum port in the shroud.

According to a further embodiment, a method is provided of curing a composite part comprising placing the part against a tool and drawing first and second vacuums over the part. The method further comprises increasing the temperature of the part substantially continuously to a preselected cure temperature, including changing the rate of temperature increase at least once as the temperature is continuously increased. The method also includes reducing the amount of the first vacuum as the temperature of the part is being continuously increased to the cure temperature. The temperature of the part is maintained substantially at the cure temperature for a preselected period. The temperature of the part is reduced after the cure temperature has been maintained for the preselected period.

According to another embodiment, a method is provided of curing and removing volatiles from a composite patch used to rework an area of a structure. The method comprises forming a double vacuum chamber assembly and placing the double vacuum chamber assembly over the patch. The double vacuum chamber assembly is sealed to the structure around the patch, and is used to draw first and second vacuums over the patch. The method further comprises increasing the temperature of the patch substantially continuously to a preselected cure temperature, and reducing the amount of the first vacuum as the temperature of the patch is being increased to the cure temperature. The temperature of the patch is maintained substantially at the cure temperature for a preselected period and is then reduced after the cure temperature has been maintained for the preselected period.

According to an aspect, there is provided a method of curing a composite part, the method comprising: placing the composite part against a tool having at least a first side and a second side opposite the first side, the composite part placed against the first side of the tool; drawing a second vacuum and a first vacuum over the composite part in, correspondingly, a second vacuum area in which the composite part is located and a first vacuum area outside the second vacuum area, wherein the second vacuum area is formed by a flexible bag covering the composite part and the first vacuum area is formed by a substantially rigid shroud covering both the bag and the composite part, and wherein the vacuum pressure of the second vacuum is above the vacuum pressure of the first vacuum such that the bag only applies partial compaction pressure to the composite part; increasing the temperature of the composite part to a preselected cure temperature; before the temperature of the composite part reaches the preselected cure temperature, reducing the vacuum pressure of the first vacuum such that the bag applies substantially full compaction pressure to the composite part; maintaining the temperature of the composite part substantially at the preselected cure temperature for a preselected period while maintaining the vacuum pressure of the second vacuum substantially constant during the entire process cycle; and reducing the temperature of the composite part after the preselected cure temperature has been maintained for the preselected period.

According to another aspect, there is provided a method of curing a composite part, the method comprising: placing the composite part against a tool having at least a first side and a second side opposite the first side, the composite part placed against the first side of the tool; placing a flexible bag over the composite part to form a second vacuum area in which the composite part is located; forming a substantially vacuum tight seal between the bag and the tool; drawing air from the bag through a second vacuum port in the tool to thereby draw a second vacuum in the second vacuum area; placing a substantially rigid shroud over the bag and the composite part to form a first vacuum area outside of the second vacuum area; forming a substantially vacuum tight seal between the bag and the shroud; drawing air from the shroud through a first vacuum port in the shroud to thereby draw a first vacuum in the first vacuum area, wherein the vacuum pressure of the second vacuum is above the vacuum pressure of the first vacuum such that the bag covering the composite part only applies partial compaction pressure to the composite part; increasing the temperature of the composite part by heating the tool and the composite part substantially continuously until the tool and the composite part reach a preselected temperature; before the temperature of the composite part reaches a cure temperature of the composite part, reducing the vacuum pressure of the first vacuum such that the bag applies substantially full compaction pressure to the composite part; maintaining the temperature of the composite part substantially at the cure temperature for a preselected period while maintaining the vacuum pressure of the second vacuum substantially constant during the entire process cycle; reducing the temperature of the composite part after the cure temperature has been maintained for the preselected period; and terminating the vacuums in the second and first vacuum areas.

According to yet another aspect, there is provided a method of curing a composite part, the method comprising: placing the composite part against a tool having at least a first side and a second side opposite the first side, the composite part placed against the first side of the tool; placing a flexible bag over the composite part to form a second vacuum chamber in which the composite part is located; forming a substantially vacuum tight seal between the bag and the tool; drawing air from the second vacuum chamber through a second vacuum port located in the tool to thereby draw a second vacuum in the second vacuum chamber; placing a substantially rigid shroud over the bag and the composite part to form a first vacuum chamber outside of the second vacuum chamber; forming a substantially vacuum tight seal between the bag and the shroud; and drawing air from the first vacuum chamber through a first vacuum port located in the shroud to thereby draw a first vacuum in the first vacuum chamber, wherein the vacuum pressure of the first vacuum is below the vacuum pressure of the second vacuum such that the bag covering the composite part only applies partial compaction pressure to the composite part; increasing the temperature of the composite part by heating the tool and the composite part substantially continuously until the tool and the composite part reach a preselected cure temperature; before the temperature of the composite part reaches the preselected cure temperature, reducing the vacuum pressure of the first vacuum such that the bag applies substantially full compaction pressure to the composite part; maintaining the temperature of the composite part substantially at the preselected cure temperature for a preselected period, while maintaining the vacuum pressure of the second vacuum substantially constant; reducing the temperature of the composite part after the preselected cure temperature has been maintained for the preselected period; and terminating the vacuums in the first vacuum chamber and the second vacuum chamber.

According to yet another aspect, there is provided a method of curing a composite part, the method comprising: placing the composite part against a tool having a first side and a second side opposite the first side; forming on the first side, a first vacuum chamber over the composite part by placing a substantially rigid shroud over the composite part; forming, on the first side, a second vacuum chamber over the composite part by placing a flexible bag over the composite part inside the shroud; forming a first substantially vacuum tight seal between the shroud and the tool; forming a second substantially vacuum tight seal between the bag and the tool; drawing a first vacuum having a first vacuum pressure in the first vacuum chamber; drawing a second vacuum having a second vacuum pressure in the second vacuum chamber, the first vacuum pressure being below the second vacuum pressure such that the bag only applies partial compaction pressure to the composite part; heating the tool and the composite part; before the temperature reaches a cure temperature of the composite part, reducing the first vacuum pressure while maintaining the second vacuum pressure at about a constant level throughout curing such that the bag applies substantially full compaction pressure to the composite part; thereafter increasing the temperature to the cure temperature; maintaining the cure temperature for a preselected time period; reducing a temperature of the tool and the composite part after the cure temperature has been maintained for the preselected time period; and after reducing the temperature, terminating the first vacuum and the second vacuum.

According to yet another aspect, there is provided a method of curing a composite part, the method comprising: placing the composite part against a tool having a first side and a second side opposite the first side; forming, on the first side, a first vacuum chamber over the composite part by placing a substantially rigid shroud over the composite part; forming, on the first side, a second vacuum chamber over the part by placing a flexible bag over the composite part inside the shroud; forming a first substantially vacuum tight seal between the shroud and the tool; forming a second substantially vacuum tight seal between the bag and the tool; drawing a first vacuum having a first vacuum pressure in the first vacuum chamber; drawing a second vacuum having a second vacuum pressure in the second vacuum chamber, the first vacuum pressure being about equal to the second vacuum pressure; heating the tool and the composite part, wherein heating is performed at a first rate; thereafter, before the temperature reaches a cure temperature of the composite part, heating the tool and the composite part at a second rate, the second rate being less than the first rate; thereafter, before the temperature reaches the cure temperature, heating the tool and the composite part at a third rate, the third rate being greater than the second rate; at a time when the second rate is being increased to the third rate, reducing the first vacuum pressure while maintaining the second vacuum pressure at about a constant level throughout curing; thereafter increasing the temperature at the third rate to the cure temperature; maintaining the cure temperature for a preselected time period; reducing a temperature of the tool and the composite part after the cure temperature has been maintained for the preselected time period; and after reducing the temperature, terminating the first vacuum and the second vacuum.

The disclosed embodiments provide apparatus and a related method for double vacuum curing of composite laminates which obviate the need for autoclave processing, and may produce parts exhibiting reduced part-to-part dimensional variations and improved mechanical properties.

BRIEF DESCRIPTION OF THE ILLUSTRATIONS

FIG. 1 is an illustration of a sectional view of apparatus for double vacuum curing of composite laminates according to one embodiment.

FIG. 2 is an illustration of a sectional view of an alternate form of the apparatus in which magnetic means are employed to attach the flexible inner bag to a tool.

FIG. 3 is an illustration of a sectional view of another embodiment of the apparatus in which the flexible inner bag and outer rigid shroud are integrated into a single assembly.

FIG. 4 is an illustration of a sectional view of another embodiment of the apparatus in which an opening is provided in the tool for improving heating of the tool.

FIG. 5 is an illustration of a further embodiment of the apparatus employing thermocouples and the use of a heating source integrated into the tool.

FIG. 6 is an illustration of another embodiment of the apparatus in which a thermal mass has been added to the tool to improve heat transfer to the part.

FIG. 7 is an illustration of a perspective view of another embodiment of the apparatus in which a heating conduit is integrated into the tool.

FIG. 8 is an illustration of a flow diagram showing the steps of a method of double vacuum curing a composite laminate.

FIG. 9 is an illustration of a graph showing the relationship between temperature and vacuum pressure over time according to one process embodiment.

FIG. 10 is an illustration of a graph similar to FIG. 9, for an alternate process embodiment.

FIG. 11 is an illustration of a flow diagram of aircraft production and service methodology.

FIG. 12 is an illustration of a block diagram of an aircraft.

DETAILED DESCRIPTION

Referring first to FIG. 1, a double vacuum chamber apparatus 20 is used to perform out-of-autoclave curing of a composite part 22. As used herein, “part” and “composite part” are used in their broadest sense and include but are not limited to various forms of structures, such as, without limitation, beams, supports, panels, structural and non-structural members, elements and subassemblies, to name only a few. The part 22 may comprise a multi-ply prepreg laminate which is placed on or against a tool 24 supported on a metallic tool base 26. A substantially rigid outer shroud 28 is sealed around its outer periphery 27 to the tool base 26 by a seal 36, thereby forming a first, outer vacuum chamber 32 over the composite part 22. In one embodiment, the seal 36 may comprise a reusable elastomeric seal that is permanently affixed to the periphery 27 of the outer shroud 28. The outer shroud 28 may comprise any suitable material such as a metal or a composite that possesses sufficient rigidity to allow the shroud 28 to be substantially self-supporting and retain its shape. The shroud 28 may possess any of various shapes both in footprint and cross section, that is suitable for covering the particular part 22 to be cured. The outer shroud 28 includes a vacuum port 50 connected with a suitable vacuum source 25 which is operable to draw a desired vacuum in the outer vacuum chamber 32.

A flexible, inner vacuum bag 30 contained inside the outer shroud 28 also covers the part 22 and is sealed around its periphery 29 to the tool base 26, thereby forming a second, inner vacuum chamber 34 over the part 22. The bag 30 may comprise, for example and without limitation, a conventional one-time-use nylon bag and the seal 38 may be a conventional, non-reusable sealant. Alternatively, the bag 30 may be a reusable type made of, for example and without limitation, an elastomeric material, and the seal 38 may comprise a reusable elastomeric seal. Although not shown in FIG. 1 for purposes of clarity, additional layers of material may be placed on the part 22, beneath the flexible bag 30, including but not limited to separator films, breathers and caul plates.

The tool base 26 may include a passageway 46 therein which communicates with the inner vacuum chamber 34. The passageway 46 is coupled through a vacuum port 48 to a vacuum source 35 which is used to draw a desired level of vacuum within the inner vacuum chamber 34 during cure processing. The tool base 26 may also include one or more vent openings 40 therein to allow heat indicated by the arrows 42 from a heat source 44 to be vented directly against the tool 24. Alternatively, cure processing using the apparatus 20 may be performed within an oven (not shown) which is used to heat the composite part 22 to the required cure temperature.

FIG. 2 illustrates an alternate embodiment of the apparatus 20 in which a reusable type elastomeric inner vacuum bag 30 covers the composite part 20. The bag 30 includes a magnetic strip 52 integrated into and surrounding the periphery of the bag 30 for holding the bag 30 against the metallic tool base 26. The bag 30 further includes a reusable vacuum seal 54 permanently bonded to the bag 30 for creating a vacuum tight seal outside of the magnetic strip 52 and surrounding the part 22. Integration of the bag 30, the magnetic strip 52 and the reusable seal 54 into a single assembly allow the bag 30 to be quickly deployed over the part 22 and sealed to the tool base 26.

Attention is now directed to FIG. 3 which illustrates another embodiment of the apparatus 20 in which the inner, flexible bag 30 is permanently attached to the periphery 27 of the outer shroud 28 so that the outer shroud 28 and inner bag 30 form a single double vacuum chamber assembly 37 that may be easily and quickly placed on and sealed to the tool base 26, covering the part 22. The integration of the outer shroud 28, inner bag 30 and seal 36 into a single assembly 37 permits checking the outer shroud 28 and inner bag 30 for leaks before they are installed over the part 22, thus reducing processing time. In this example, a reusable seal 36 is attached to the periphery 27 of the shroud 28, with the inner bag 30 sandwiched therebetween so that the seal 36 functions to seal both the outer and inner vacuum chambers 32, 34 respectively on the tool base 26.

It should be noted here that while the various embodiments are described in connection with producing original composite parts as part of a manufacturing process, various components of the apparatus including the double vacuum chamber assembly 37, and well as the disclosed method may be employed to rework parts or structures. For example the embodiments may be employed to cure a composite patch (not shown) and remove volatiles therefrom that is used to rework a portion of a structure such as an aircraft skin (not shown), either to improve the structure or to restore the structure to original specifications. In a rework application of the embodiments, the double vacuum chamber assembly 37 may be placed on and sealed to the structure, rather than to a tool base 26 as shown in the Figures.

Attention is now directed to FIG. 4 which illustrates another embodiment of the apparatus 20 in which a tool 24 mounted on a tool base 26 includes a generally U-shaped cross section forming an opening 56 on the backside 57 of the tool 24. The opening 56 allows warm air shown by the arrow 58 from a suitable heat source (not shown) to circulate evenly around and directly contact the backside 57 of the tool 24, thereby improving the transfer of heat to the composite part 22. In this particular example, the tool 24 includes a pair of tool surfaces 24a, 24b for heating and maintaining the shape of the part 22. The outer shroud 28 is provided with a peripheral flange 28a which forms a surface 39 against which the seal 36 may conform to create a vacuum tight seal around the outer vacuum chamber 32.

Referring now to FIG. 5, a further form of the apparatus 20 includes a substantially rigid outer shroud 28 to which the inner flexible bag 30 and the reusable seal 36 are permanently attached so that the shroud 28, bag 30 and seal 36 may be installed and removed over the part 22 as a single assembly 37. In this example, thermocouples 60 may be provided in the shroud 28 and/or in the tool 24 in order to measure the temperature of the part 22. Suitable displays 62 may be provided to display the temperature sensed by the thermocouples 60. In this embodiment, a radiant or other form of heat source 65 may be placed within the opening 56 so as to be in close proximity to and direct heat along the back side

57 of the tool 24 in order to increase the efficiency and reduce the time required for heat transfer to the part 22.

FIG. 6 illustrates still another embodiment of the apparatus 20 in which a thermal mass 64 comprising a thermally conductive material such as, without limitation, copper or aluminum, is attached to the backside 57 of the tool 24 in order to further maximize the speed and efficiency of heat transfer to the part 22, as well as to heat the part 22 more uniformly. The embodiment of the apparatus 20 shown in FIG. 6 utilizes an integrated double vacuum chamber configuration, similar to that shown in FIGS. 3 and 5. The outer periphery 29 of the bag 30 is bonded to the flange 28a on the shroud 28 by a layer of adhesive 66. The seal 36 is in turn bonded to the periphery 29 of the bag 30 by a second layer of adhesive 68.

FIG. 7 illustrates an embodiment of the apparatus 20 in which an opening 56 in the backside 57 of the tool 24 is closed by a cover 70 to form a conduit 72 through the tool 24. A suitable source of warm air 74 may direct warm air through the conduit 72 as shown by the arrows 76 in order to directly warm the backside 57 of the tool 24 and thus the part 22. The outer shroud 28 and the inner bag 30 are not shown in FIG. 7 for purposes of clarity.

FIG. 8 illustrates the steps of a method for double vacuum curing of a composite part 22 which may employ the apparatus 20 shown in FIGS. 1-7. Beginning at step 78, an uncured composite part 22 is placed on or against a suitable cure tool 24. As shown at 80, first and second vacuums are then drawn over the part 22 using the vacuum chambers 32, 34 respectively formed by the outer shroud 28 and the inner bag 30. As will be discussed below in more detail, initially the level of the first vacuum may be nearly equal to that of the second vacuum. At step 82, with the first and second vacuums having been drawn, the temperature of the part 22 is continuously increased through heating until the part temperature reaches a preselected cure temperature. As will be explained below, the part temperature may or may not be increased at a constant rate, however, it is increased substantially continuously. As the temperature of the part 22 is being increased to the cure temperature, the first vacuum is reduced to some preselected level, as shown at step 84 so that the level of the second vacuum is greater than the level of the first vacuum. Once the part 22 reaches the cure temperature, the cure temperature is maintained, as shown at step 86 for a preselected period during which the part 22 cures. After the part 22 is cured, the temperature of the part 22 is reduced as shown at step 88, and the first and second vacuums are terminated as shown at step 90.

FIGS. 9 and 10 respectively illustrate vacuum pressure and temperature profiles according to two differing processing schedules suitable for double vacuum curing of the composite part 22. As previously noted however, the disclosed method utilizing the processing schedules shown in FIGS. 9 and 10 may also be used to remove volatiles and cure composite patches (not shown) used to rework an area of a part or structure. Referring particularly to FIG. 9, the temperature of the part 22 indicated by plot 92 is continuously increased at a substantially constant rate from time t_0 to t_2 until the preselected cure temperature has been reached at t_2. Beginning at t_0, the vacuum pressures in the outer and inner vacuum chambers 32, 34, respectively represented by plots 94 and 96 are drawn to preselected levels, which may be nearly equal. In some cases, the first vacuum pressure 94 in the outer vacuum chamber 32 may be slightly below, at or slightly above the vacuum pressure 96 in the inner chamber 34.

In this embodiment, the vacuum pressure 96 in the inner chamber 34 is maintained substantially constant during the entire process cycle. However, at some point, t_1 between t_0 and t_2, the vacuum pressure 94 in the outer vacuum chamber 32 is reduced to a level that is materially less than the vacuum pressure 96 in the inner vacuum chamber 34. During the period between t_0 and t_1, because the two pressures 94, 96 are nearly equal, the vacuum pressure 94 in the outer vacuum chamber 32 prevents the inner bag 30 from applying full compaction pressure on the part 22, thereby allowing volatiles in the part 22 to escape more readily as the temperature 92 is being ramped up to the cure temperature. At time t_1, however, the reduction of the vacuum pressure 94 allows the vacuum pressure 96 in the inner chamber 34 to apply nearly full pressure to the part 22 in order to compact the part 22 and force out air pockets in the laminate part 22 to avoid porosities. The period between t_2 and t_3 represents the preselected period during which the temperature 92 is maintained at a constant cure temperature. Beginning at t_3, the temperature 92 is ramped down during a cooling cycle to an ambient temperature at t_4, at which point the vacuum pressures 94, 96 may be terminated.

FIG. 10 illustrates a cure processing schedule which is generally similar to FIG. 9 however ramping of the temperature 92 to the cure temperature, though continuous, is not constant, but rather includes one or more changes in the rate of temperature increase. In the illustrated example, the temperature 92 is increased between t_0 and t_1 at a rate that is greater than that shown in the schedule of FIG. 9. However, at t_1, the rate of temperature increase is reduced until t_2 at which point the temperature ramp rate is resumed until the cure temperature is reached at t_3.

Embodiments of the disclosure may find use in a variety of potential applications, particularly in the transportation industry, including for example, aerospace, marine and automotive applications. Thus, referring now to FIGS. 11 and 12, embodiments of the disclosure may be used in the context of an aircraft manufacturing and service method 98 as shown in Figure 11 and an aircraft 100 as shown in Figure 12. During pre-production, exemplary method 98 may include specification and design 102 of the aircraft 100 and material procurement 104. During production, component and subassembly manufacturing 106 and system integration 108 of the aircraft 100 takes place. The disclosed methods and apparatus may be used to cure composite parts manufactured during step 106 and integrated in step 108. Thereafter, the aircraft 100 may go through certification and delivery 110 in order to be placed in service 112. While in service by a customer, the aircraft 100 is scheduled for routine maintenance and service 114 (which may also include modification, reconfiguration, refurbishment, and so on). The disclosed methods and apparatus may be used to cure composite parts that are installed on the aircraft 100 during the maintenance and service 114.

Each of the processes of method 98 may be performed or carried out by a system integrator, a third party, and/or an operator (e.g., a customer). For the purposes of this description, a system integrator may include without limitation any number of aircraft manufacturers and major-system subcontractors; a third party may include without limitation any number of vendors, subcontractors, and suppliers; and an operator may be an airline, leasing company, military entity, service organization, and so on.

As shown in FIG. 12, the aircraft 100 produced by exemplary method 98 may include an airframe 116 with a plurality of systems 118 and an interior 120. Examples of high-level systems 118 include one or more of a propulsion system 122, an electrical system 124, a hydraulic system 126, and an environmental system 128. Any number of other systems may be included. Although an aerospace example is shown, the principles of the disclosure may be applied to other industries, such as the marine, automotive and construction industries.

The apparatus and methods embodied herein may be employed during any one or more of the stages of the production and service method 98. For example, components or subassemblies corresponding to production process 98 may be fabricated or manufactured in a manner similar to components or subassemblies produced while the aircraft 100 is in service. Also, one or more apparatus embodiments, method embodiments, or a combination thereof may be utilized during the production stages 106 and 108, for example, by substantially expediting assembly of or reducing the cost of an aircraft 100. Similarly, one or more of apparatus embodiments, method embodiments, or a combination thereof may be utilized while the aircraft 100 is in service, for example and without limitation, to maintenance and service 114.

Although the embodiments of this disclosure have been described with respect to certain exemplary embodiments, it is to be understood that the specific embodiments are for purposes of illustration and not limitation, as other variations will occur to those of skill in the art.

What is claimed is:

1. A method of curing a composite part, the method comprising:

placing the composite part against a tool having at least a first side and a second side opposite the first side, the composite part placed against the first side of the tool;

drawing a second vacuum and a first vacuum over the composite part in, correspondingly, a second vacuum area in which the composite part is located and a first vacuum area outside the second vacuum area, wherein the second vacuum area is formed by a flexible bag covering the composite part and the first vacuum area is formed by a substantially rigid shroud covering both the bag and the composite part, and wherein the vacuum pressure of the second vacuum is above the vacuum pressure of the first vacuum such that the bag only applies partial compaction pressure to the composite part;

increasing the temperature of the composite part to a preselected cure temperature;

before the temperature of the composite part reaches the preselected cure temperature, reducing the vacuum pressure of the first vacuum such that the bag applies substantially full compaction pressure to the composite part;

maintaining the temperature of the composite part substantially at the preselected cure temperature for a preselected period while maintaining the vacuum pressure of the second vacuum substantially constant during the entire process cycle; and

reducing the temperature of the composite part after the preselected cure temperature has been maintained for the preselected period.

2. The method of claim 1, wherein drawing the second vacuum and the first vacuum includes:

placing the bag over the composite part to form the second vacuum area;

forming a substantially vacuum tight seal between the bag and the tool;

drawing air from the bag through a second vacuum port in the tool;

placing the shroud over the bag and the composite part to form the first vacuum area; and

drawing air from the shroud through a first vacuum port in the shroud.

3. The method of claim 2, further comprising:

forming a substantially vacuum tight seal between the bag and the shroud.

4. The method of claim 2 or 3, further comprising:

holding a periphery of the bag against the tool using a magnet.

5. The method of any one of claims 1 to 4, wherein increasing the temperature of the composite part comprises increasing the temperature substantially continuously until the composite part reaches the preselected cure temperature.

6. The method of claim 5, wherein increasing the temperature of the composite part comprises increasing the temperature substantially continuously and at a substantially constant rate until the composite part reaches the preselected cure temperature.

7. The method of claim 5, wherein increasing the temperature of the composite part comprises changing the rate of temperature increase at least once as the temperature is substantially continuously increased.

8. The method of claim 7, wherein increasing the temperature substantially continuously and changing the rate of temperature increase comprises:

increasing the temperature at a first rate during a first time interval;

increasing the temperature at a second rate less than the first rate during a second time interval; and

increasing the temperature at a third rate greater than the second rate during a third time interval.

9. The method of any one of claims 1 to 8, further comprising attaching a thermal mass to the second side of the tool.

10. A method of curing a composite part, the method comprising:

placing the composite part against a tool having at least a first side and a second side opposite the first side, the composite part placed against the first side of the tool;

placing a flexible bag over the composite part to form a second vacuum area in which the composite part is located;

forming a substantially vacuum tight seal between the bag and the tool;

drawing air from the bag through a second vacuum port in the tool to thereby draw a second vacuum in the second vacuum area;

placing a substantially rigid shroud over the bag and the composite part to form a first vacuum area outside of the second vacuum area;

forming a substantially vacuum tight seal between the bag and the shroud;

drawing air from the shroud through a first vacuum port in the shroud to thereby draw a first vacuum in the first vacuum area, wherein the vacuum pressure of the second vacuum is above the vacuum pressure of the first vacuum such that the bag covering the composite part only applies partial compaction pressure to the composite part;

increasing the temperature of the composite part by heating the tool and the composite part substantially continuously until the tool and the composite part reach a preselected temperature;

before the temperature of the composite part reaches a cure temperature of the composite part, reducing the vacuum pressure of the first vacuum such that the bag applies substantially full compaction pressure to the composite part;

maintaining the temperature of the composite part substantially at the cure temperature for a preselected period while maintaining the vacuum pressure of the second vacuum substantially constant during the entire process cycle;

reducing the temperature of the composite part after the cure temperature has been maintained for the preselected period; and

terminating the vacuums in the second and first vacuum areas.

11. The method of claim 10, further comprising:

holding a periphery of the bag against the tool using a magnet.

12. The method of claim 10 or 11, wherein increasing the temperature of the composite part comprises increasing the temperature substantially continuously and at a substantially constant rate.

13. The method of claim 10 or 11, wherein increasing the temperature of the composite part comprises changing the rate of temperature increase at least once as the temperature is substantially continuously increased.

14. The method of claim 13, wherein increasing the temperature substantially continuously and changing the rate of temperature increase comprises:

increasing the temperature at a first rate during a first time interval;

increasing the temperature at a second rate less than the first rate during a second time interval; and

increasing the temperature at a third rate greater than the second rate during a third time interval.

15. The method of any one of claims 10 to 14, further comprising attaching a thermal mass to the second side of the tool.

16. A method of curing a composite part, the method comprising:

placing the composite part against a tool having at least a first side and a second side opposite the first side, the composite part placed against the first side of the tool;

placing a flexible bag over the composite part to form a second vacuum chamber in which the composite part is located;

forming a substantially vacuum tight seal between the bag and the tool;

drawing air from the second vacuum chamber through a second vacuum port located in the tool to thereby draw a second vacuum in the second vacuum chamber;

placing a substantially rigid shroud over the bag and the composite part to form a first vacuum chamber outside of the second vacuum chamber;

forming a substantially vacuum tight seal between the bag and the shroud; and

drawing air from the first vacuum chamber through a first vacuum port located in the shroud to thereby draw a first vacuum in the first vacuum chamber, wherein the vacuum pressure of the first vacuum is below the vacuum pressure of the second vacuum such that the bag covering the composite part only applies partial compaction pressure to the composite part;

increasing the temperature of the composite part by heating the tool and the composite part substantially continuously until the tool and the composite part reach a preselected cure temperature;

before the temperature of the composite part reaches the preselected cure temperature, reducing the vacuum pressure of the first vacuum such that the bag applies substantially full compaction pressure to the composite part;

maintaining the temperature of the composite part substantially at the preselected cure temperature for a preselected period, while maintaining the vacuum pressure of the second vacuum substantially constant;

reducing the temperature of the composite part after the preselected cure temperature has been maintained for the preselected period; and

terminating the vacuums in the first vacuum chamber and the second vacuum chamber.

17. The method of claim 16, further comprising holding a periphery of the bag against the tool using a magnet.

18. The method of claim 16 or 17, wherein increasing the temperature of the composite part comprises increasing the temperature substantially continuously and at a substantially constant rate.

19. The method of claim 16 or 17, wherein increasing the temperature of the composite part comprises changing the rate of temperature increase at least once as the temperature is substantially continuously increased.

20. The method of claim 19, wherein increasing the temperature substantially continuously and changing the rate of temperature increase comprises:

increasing the temperature at a first rate during a first time interval;

increasing the temperature at a second rate less than the first rate during a second time interval; and

increasing the temperature at a third rate greater than the second rate during a third time interval.

21. The method of any one of claims 16 to 20, further comprising attaching a thermal mass to the second side of the tool.

22. A method of curing a composite part, the method comprising:

placing the composite part against a tool having a first side and a second side opposite the first side;

forming on the first side, a first vacuum chamber over the composite part by placing a substantially rigid shroud over the composite part;

forming, on the first side, a second vacuum chamber over the composite part by placing a flexible bag over the composite part inside the shroud;

forming a first substantially vacuum tight seal between the shroud and the tool;

forming a second substantially vacuum tight seal between the bag and the tool;

drawing a first vacuum having a first vacuum pressure in the first vacuum chamber;

drawing a second vacuum having a second vacuum pressure in the second vacuum chamber, the first vacuum pressure being below the second vacuum pressure such that the bag only applies partial compaction pressure to the composite part;

heating the tool and the composite part;

before the temperature reaches a cure temperature of the composite part, reducing the first vacuum pressure while maintaining the second vacuum pressure at about a constant level throughout curing such that the bag applies substantially full compaction pressure to the composite part;

thereafter increasing the temperature to the cure temperature;

maintaining the cure temperature for a preselected time period;

reducing a temperature of the tool and the composite part after the cure temperature has been maintained for the preselected time period; and

after reducing the temperature, terminating the first vacuum and the second vacuum.

23. The method of claim 22, wherein heating further comprises:

heating substantially continuously at a substantially constant rate to the cure temperature.

24. The method of claim 22 or 23, wherein heating comprises heating the tool and the composite part only from the second side of the tool, the second side excluded from the first vacuum chamber and the second vacuum chamber.

25. A method of curing a composite part, the method comprising:

placing the composite part against a tool having a first side and a second side opposite the first side;

forming, on the first side, a first vacuum chamber over the composite part by placing a substantially rigid shroud over the composite part;

forming, on the first side, a second vacuum chamber over the part by placing a flexible bag over the composite part inside the shroud;

forming a first substantially vacuum tight seal between the shroud and the tool;

forming a second substantially vacuum tight seal between the bag and the tool;

drawing a first vacuum having a first vacuum pressure in the first vacuum chamber;

drawing a second vacuum having a second vacuum pressure in the second vacuum chamber, the first vacuum pressure being about equal to the second vacuum pressure;

heating the tool and the composite part, wherein heating is performed at a first rate;

thereafter, before the temperature reaches a cure temperature of the composite part, heating the tool and the composite part at a second rate, the second rate being less than the first rate;

thereafter, before the temperature reaches the cure temperature, heating the tool and the composite part at a third rate, the third rate being greater than the second rate;

at a time when the second rate is being increased to the third rate, reducing the first vacuum pressure while maintaining the second vacuum pressure at about a constant level throughout curing;

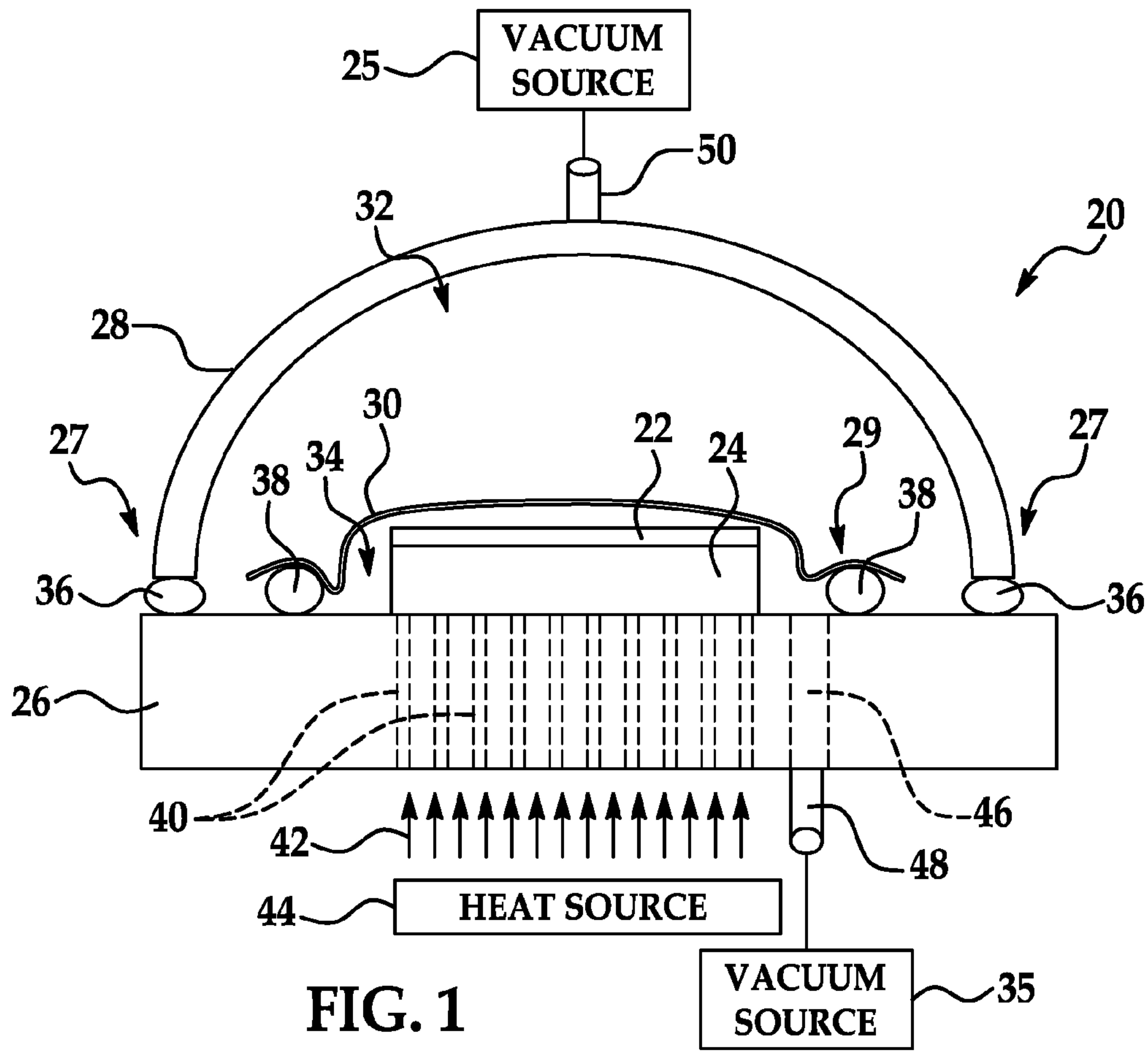
thereafter increasing the temperature at the third rate to the cure temperature;

maintaining the cure temperature for a preselected time period;

reducing a temperature of the tool and the composite part after the cure temperature has been maintained for the preselected time period; and

after reducing the temperature, terminating the first vacuum and the second vacuum.

26. The method of claim 25, wherein increasing the temperature at the first rate, the second rate, and the third rate is performed by heating the composite part using a heat source configured to apply heat directly to only the second side of the tool, the second side of the tool excluded from the first vacuum chamber and the second vacuum chamber.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50
32
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28
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22
24
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38
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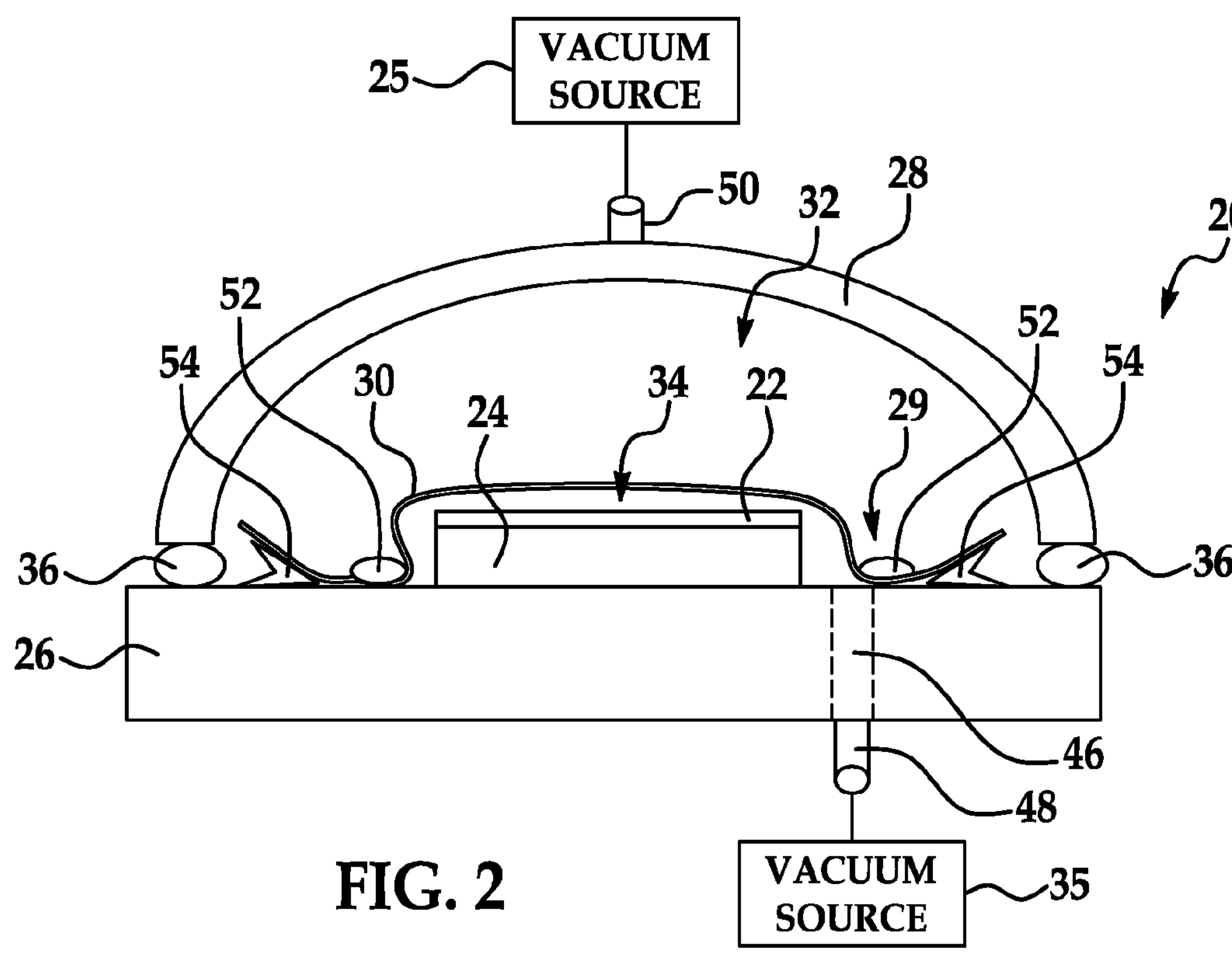
38
36
36
26
40
46
42
48
HEAT SOURCE
44
VACUUM SOURCE
35

FIG. 1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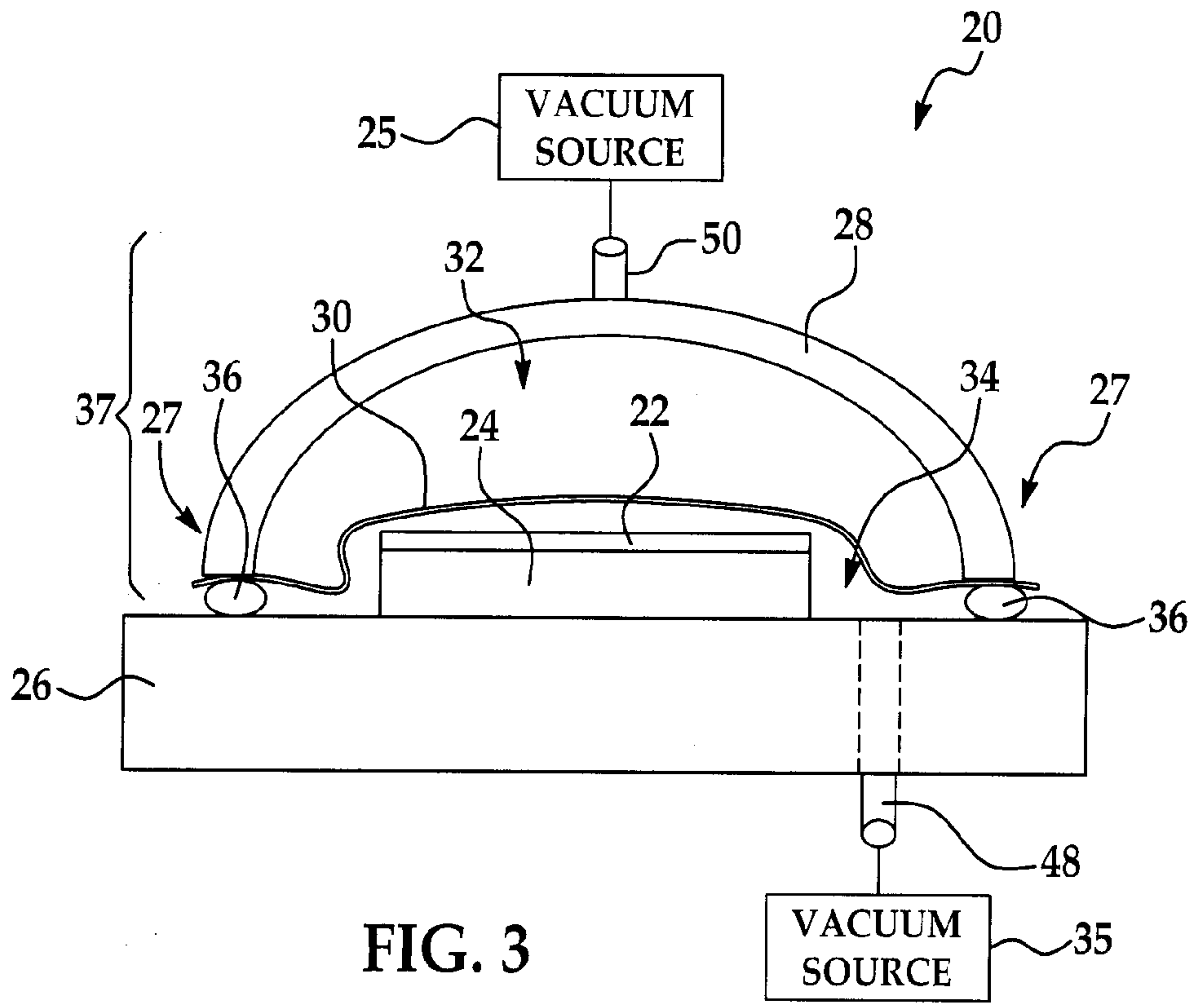
26
46
48
VACUUM SOURCE
35

FIG. 2


20
VACUUM SOURCE
25
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36
37
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24
22
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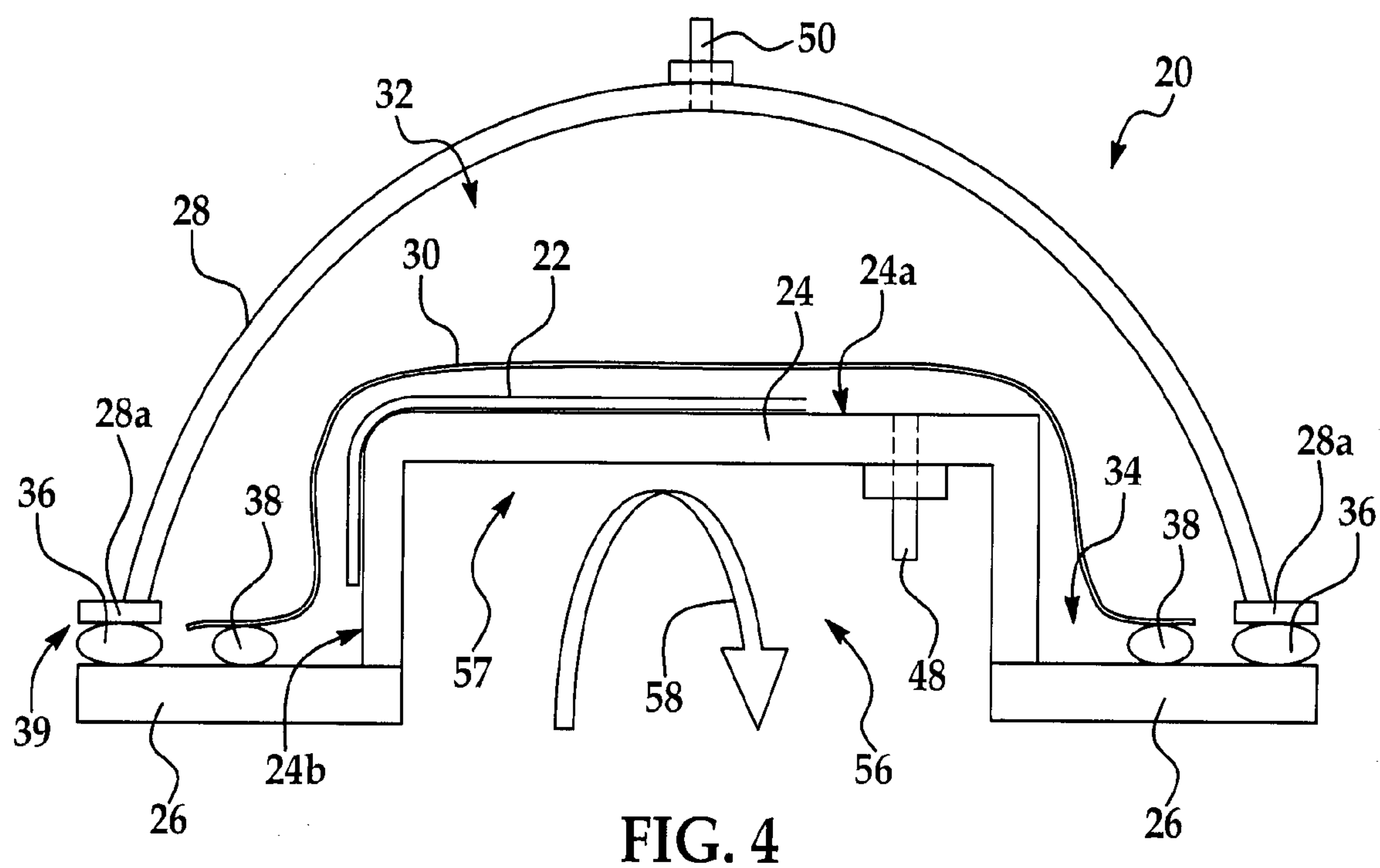
26
48
VACUUM SOURCE
35

FIG. 3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28
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22
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24a
28a
36
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34
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28a
36
39
24b
57
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FIG. 4

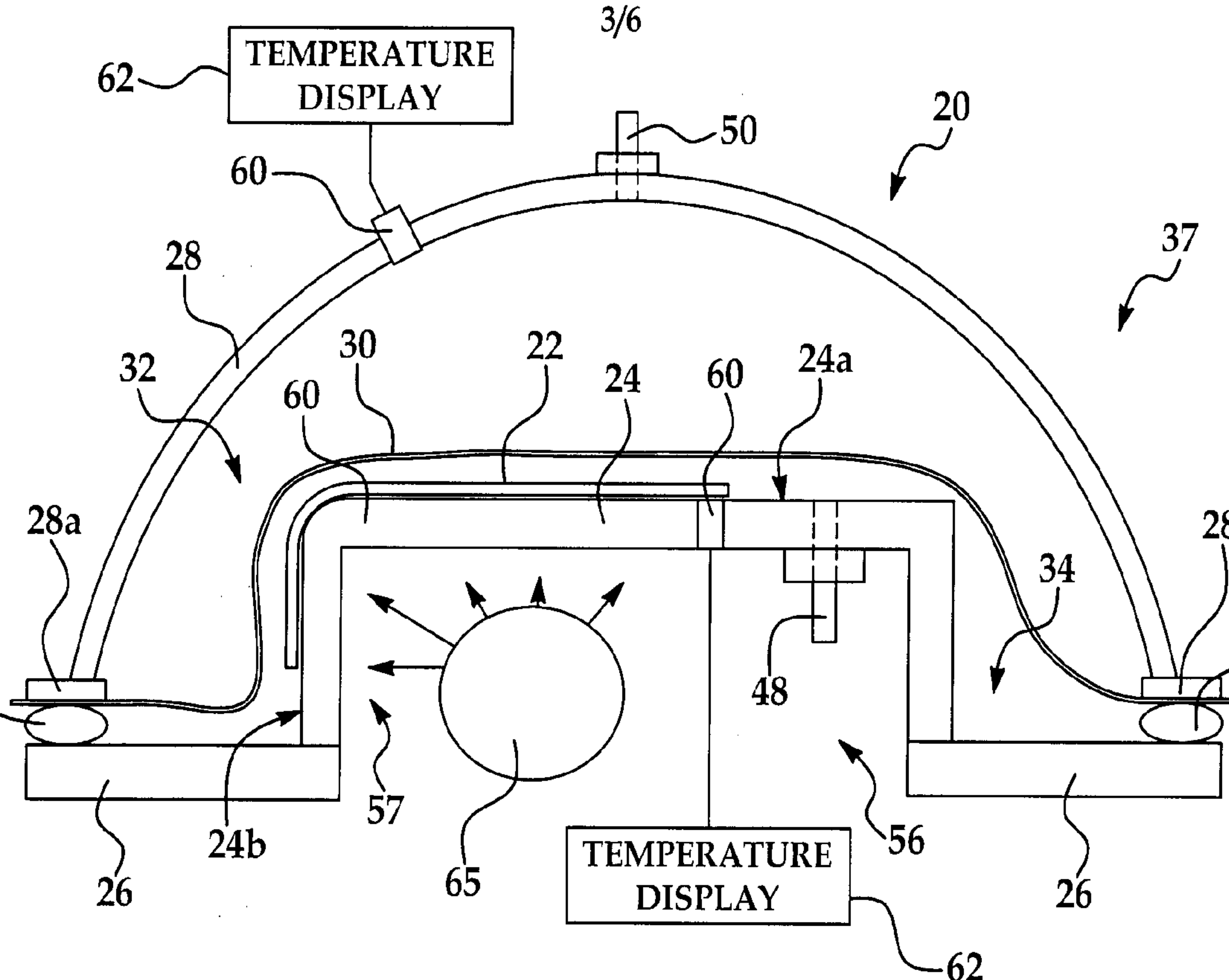
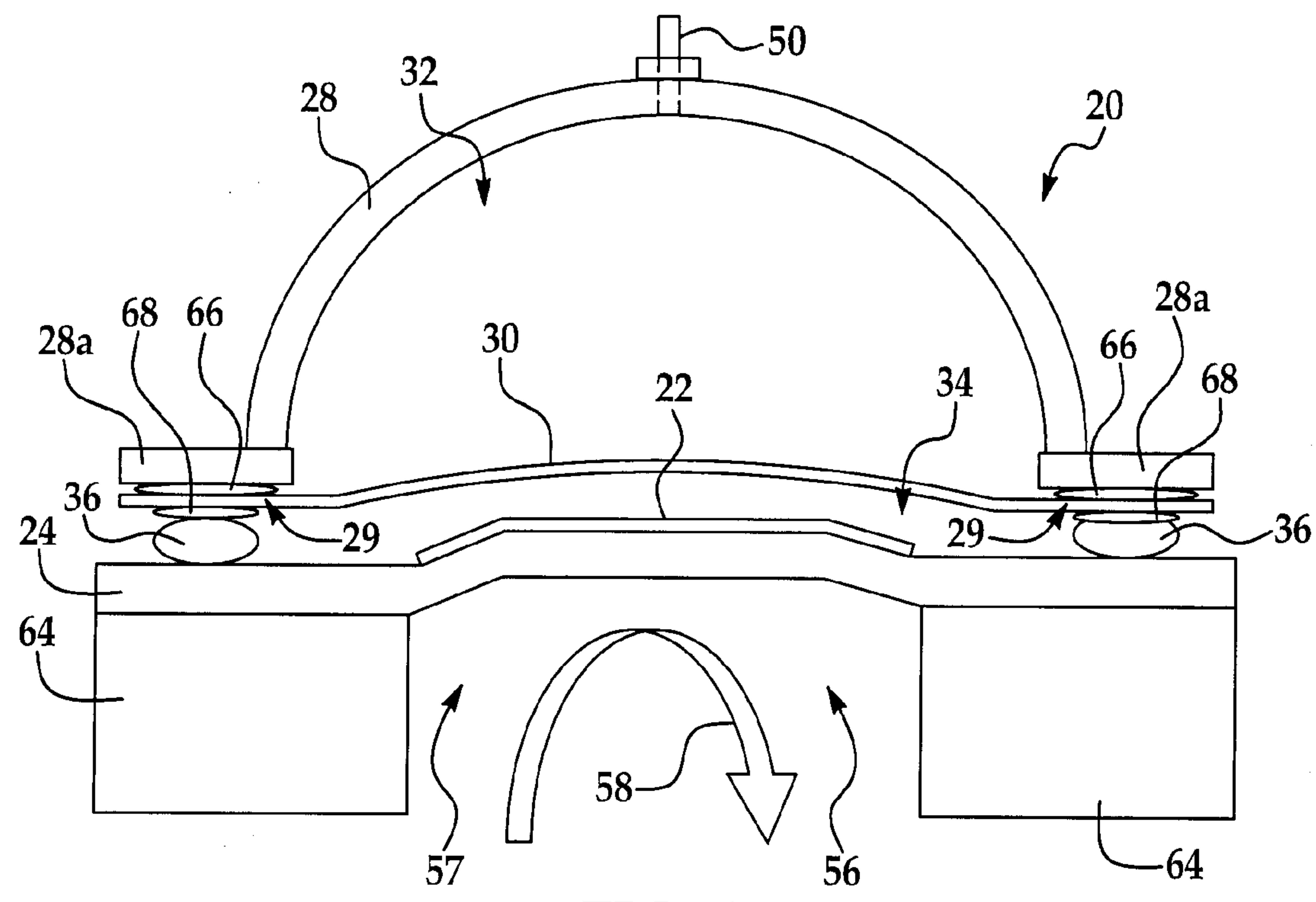

TEMPERATURE DISPLAY
62
60
50
20
37
28
32
30
22
24
60
24a
28a
34
36
48
24b
57
65
56
26
TEMPERATURE DISPLAY
62

FIG. 5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28a
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66
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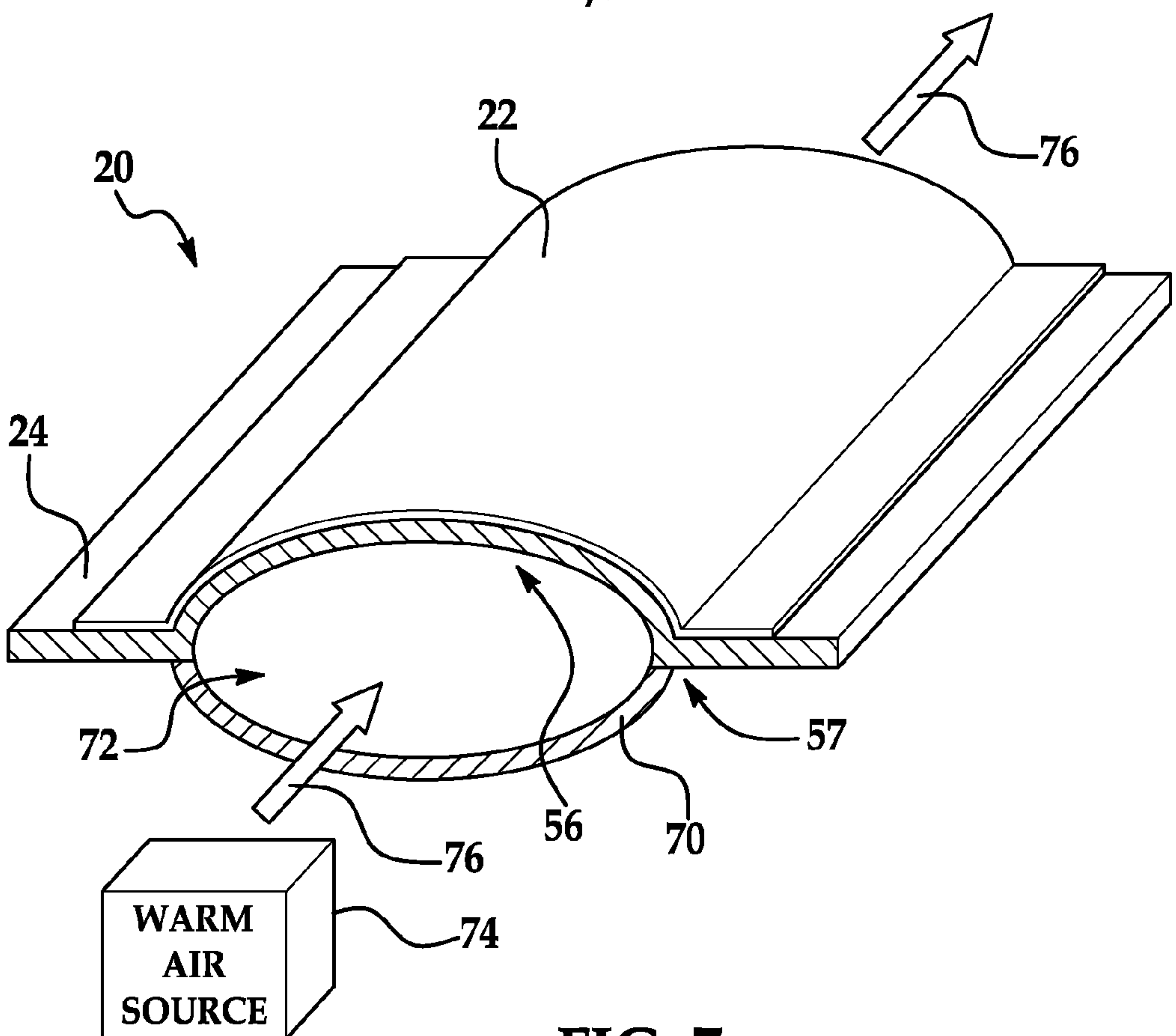
24
64
58
57
56

FIG. 6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22
76
24
72
76
56
70
57
WARM AIR SOURCE
74

FIG. 7

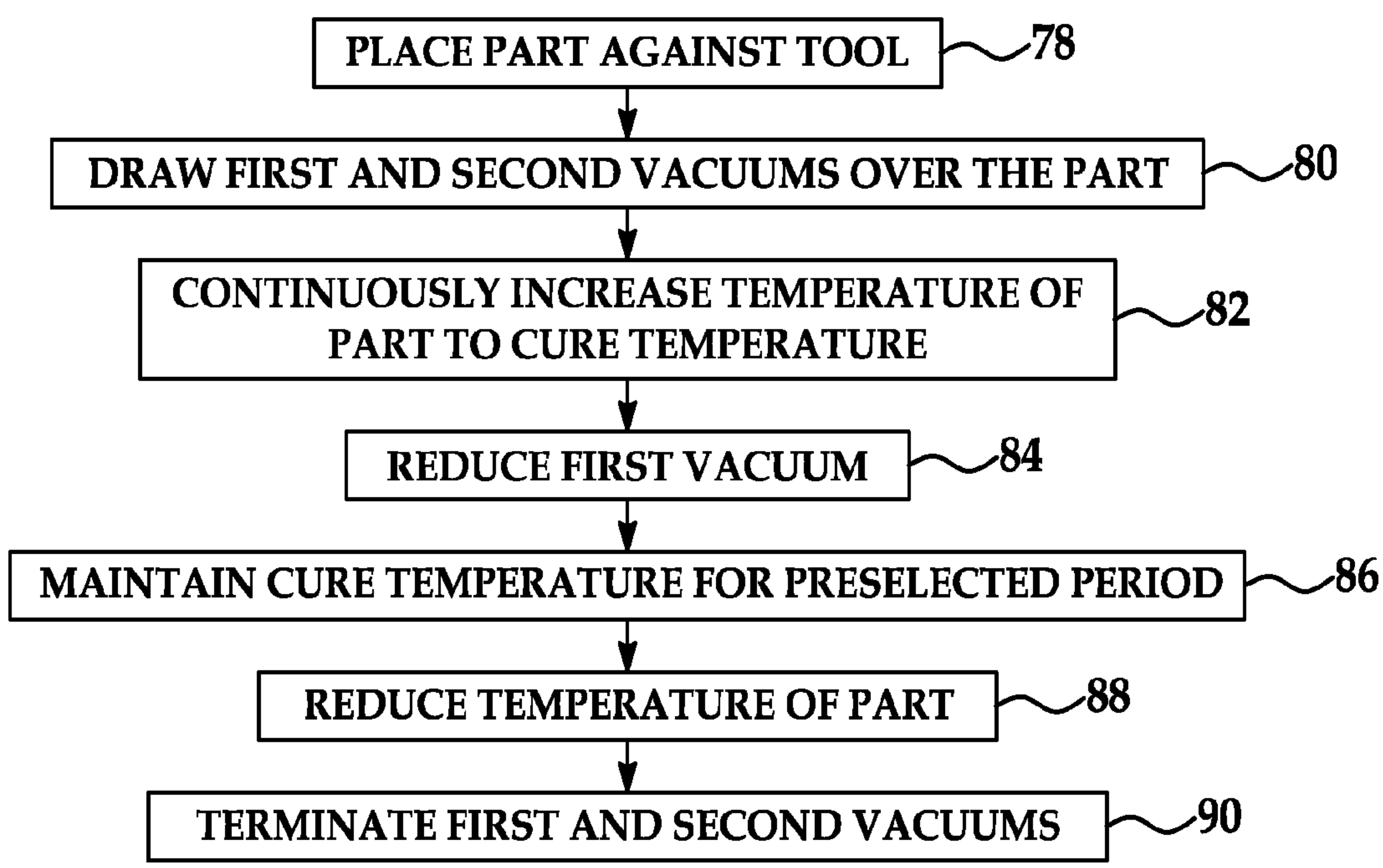

PLACE PART AGAINST TOOL
78
DRAW FIRST AND SECOND VACUUMS OVER THE PART
80
CONTINUOUSLY INCREASE TEMPERATURE OF PART TO CURE TEMPERATURE
82
REDUCE FIRST VACUUM
84
MAINTAIN CURE TEMPERATURE FOR PRESELECTED PERIOD
86
REDUCE TEMPERATURE OF PART
88
TERMINATE FIRST AND SECOND VACUUMS
90

FIG. 8

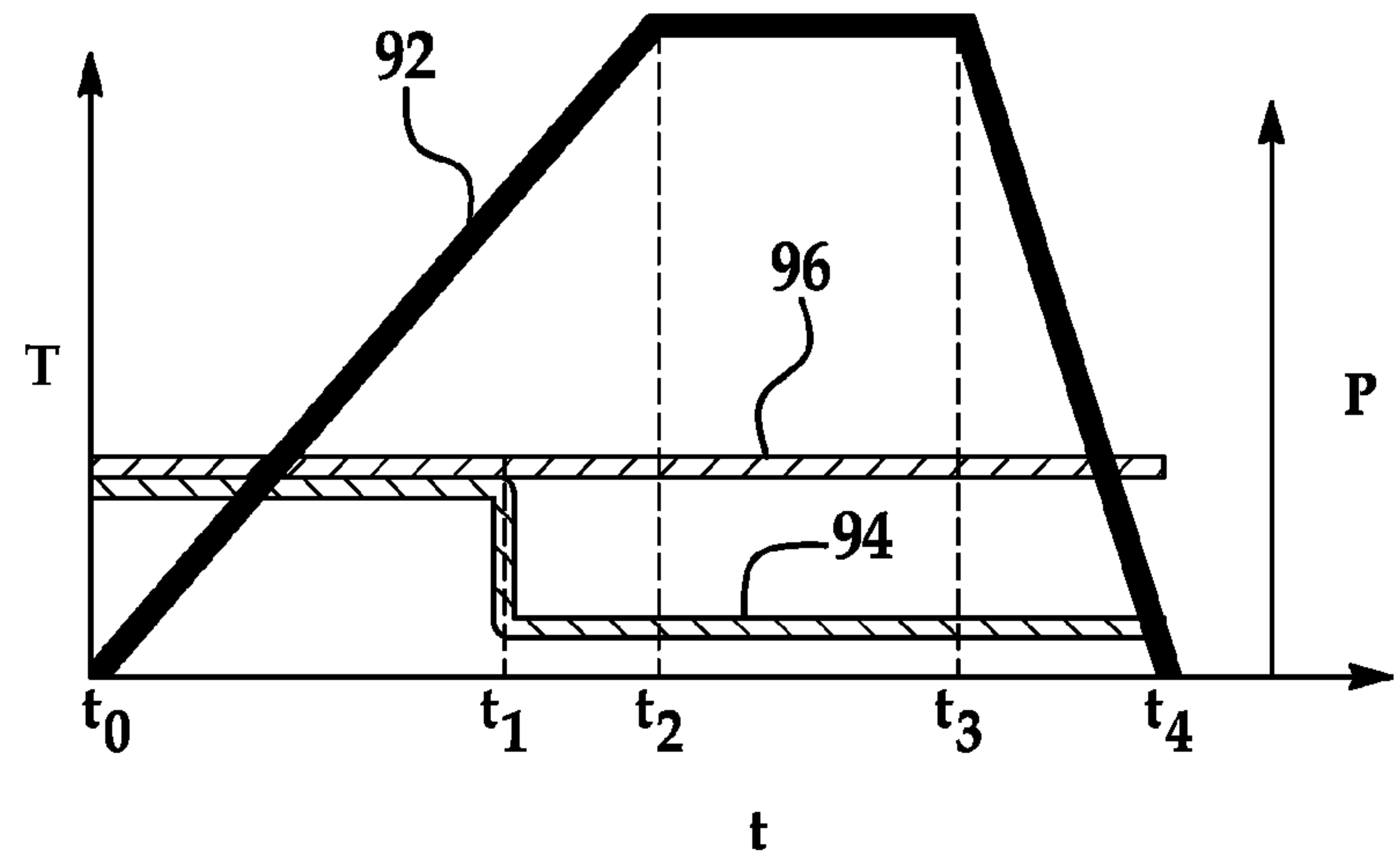


FIG. 9

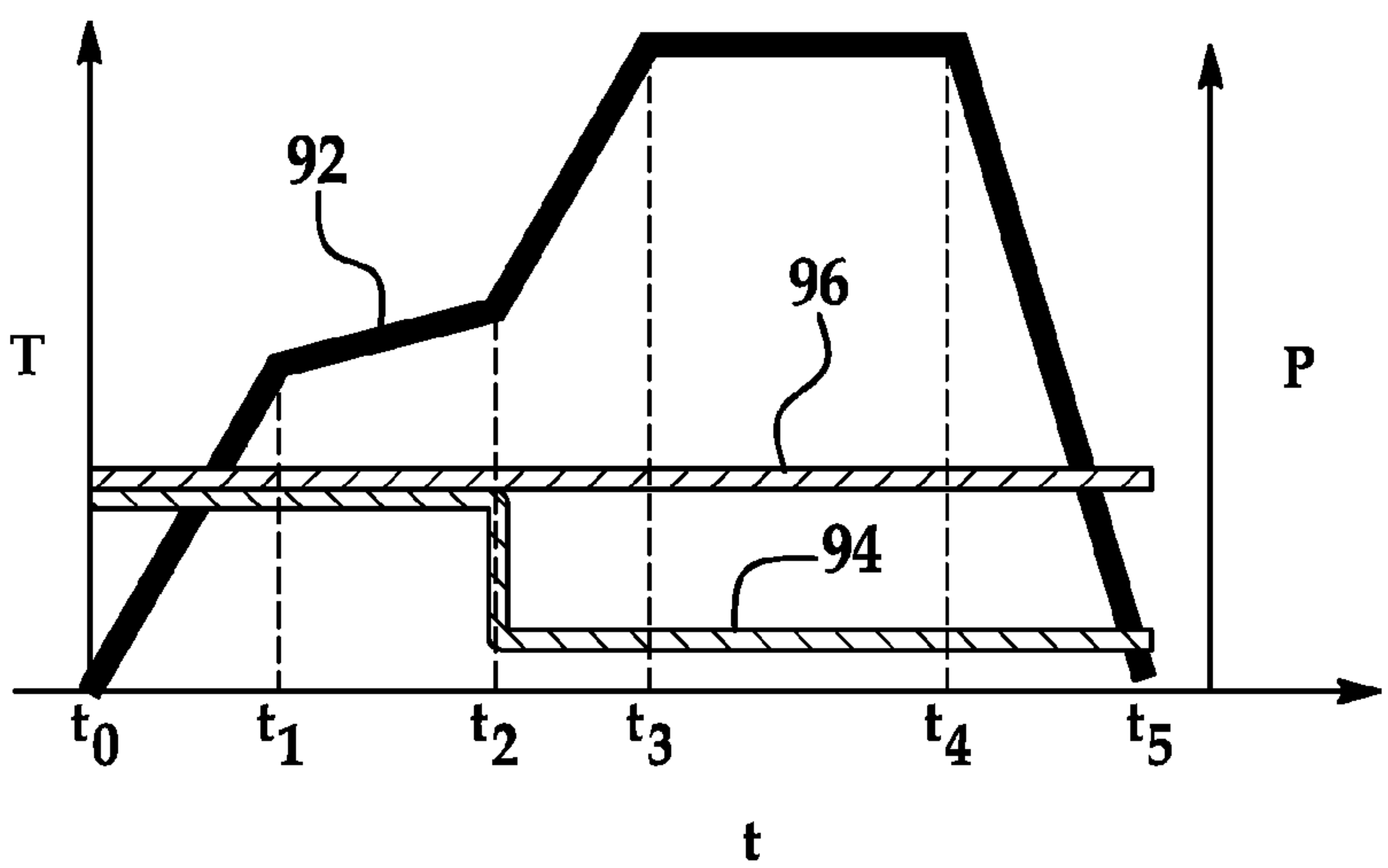


FIG. 10

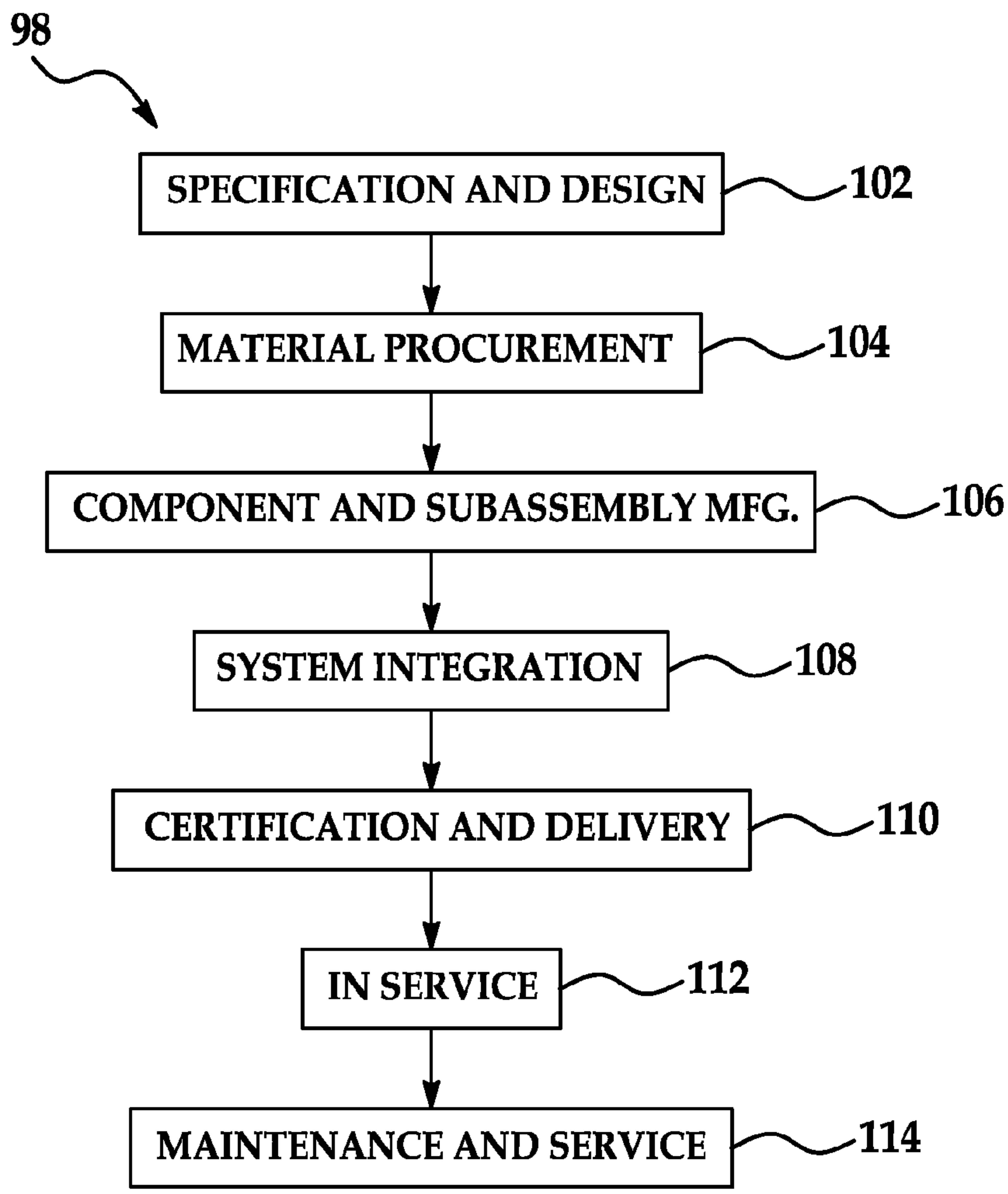

98
SPECIFICATION AND DESIGN
102
MATERIAL PROCUREMENT
104
COMPONENT AND SUBASSEMBLY MFG.
106
SYSTEM INTEGRATION
108
CERTIFICATION AND DELIVERY
110
IN SERVICE
112
MAINTENANCE AND SERVICE
114

FIG. 11

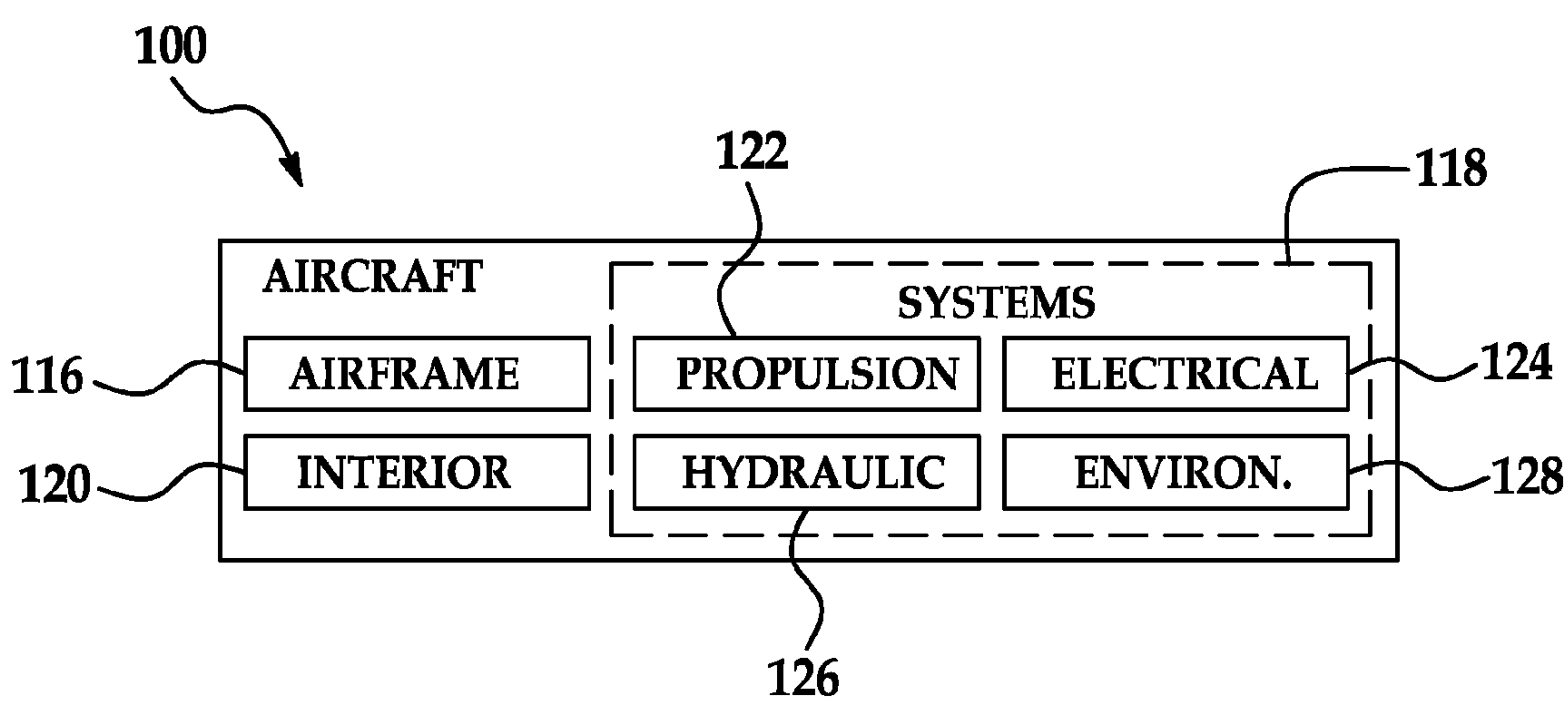
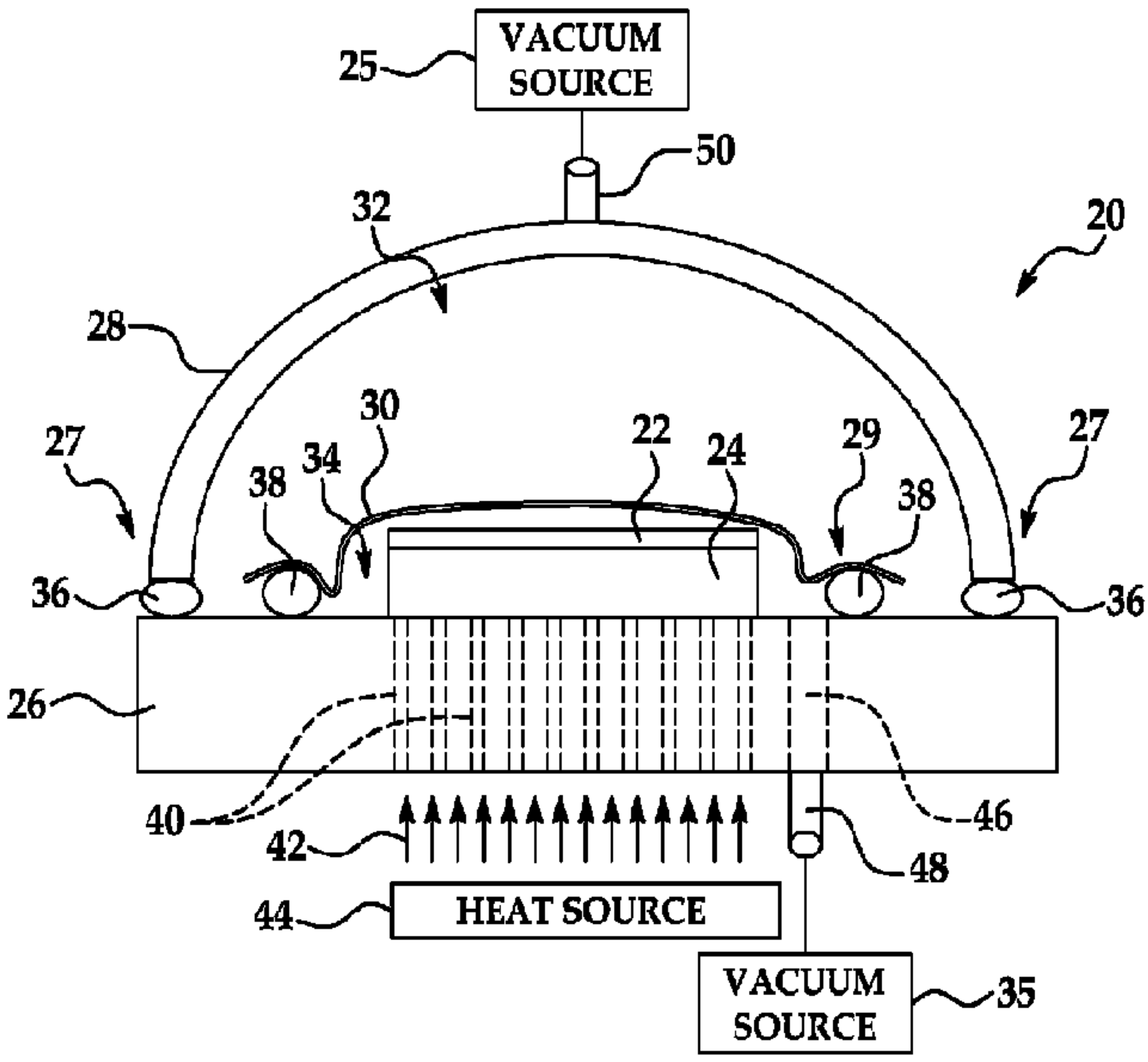

100
122
118
AIRCRAFT
SYSTEMS
116
AIRFRAME
PROPULSION
ELECTRICAL
124
120
INTERIOR
HYDRAULIC
ENVIRON.
128
126

FIG. 12



VACUUM SOURCE
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42
48
44
HEAT SOURCE
VACUUM SOURCE
35