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(54) THERMAL ENERGY STORAGE VESSEL, SYSTEMS, AND METHODS

(75) Inventors: **John P. Bell**, Bloomfield, NY (US); **Joseph M. Bell**, Victor, NY (US); **Michael S. Bower**, Fillmore, NY (US); **Gerard C. Walter**, Penfield, NY (US)

Correspondence Address:
JOHN M. HAMMOND
PATENT INNOVATIONS LLC
150 LUCIUS GORDON DRIVE, SUITE 205
WEST HENRIETTA, NY 14586 (US)

(73) Assignee: **BELL INDEPENDENT POWER CORPORATION**, Pittsford, NY (US)

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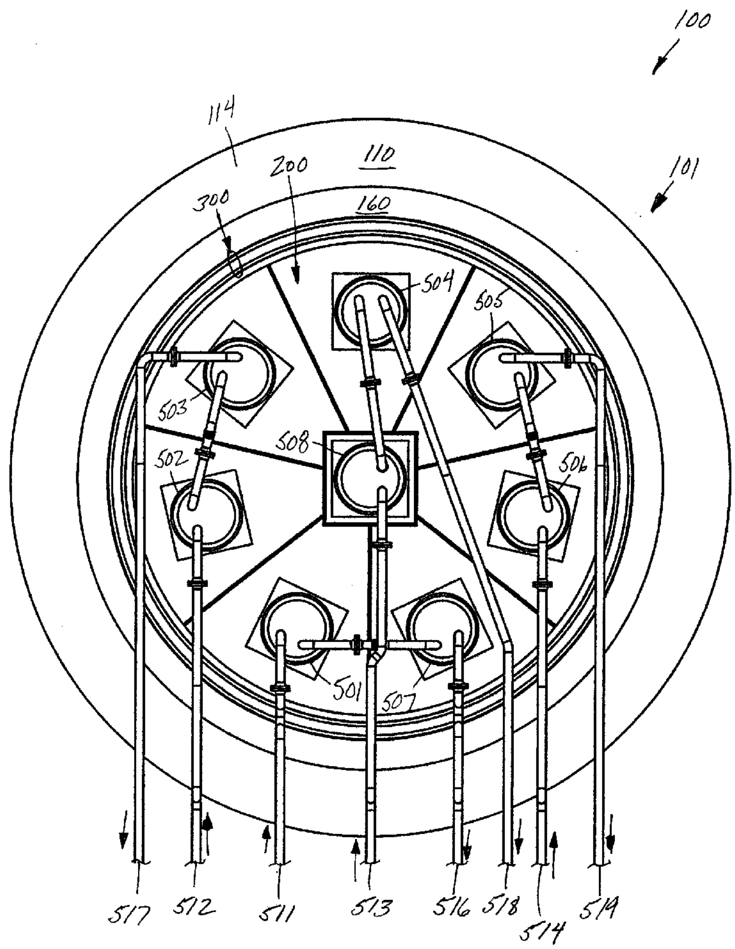
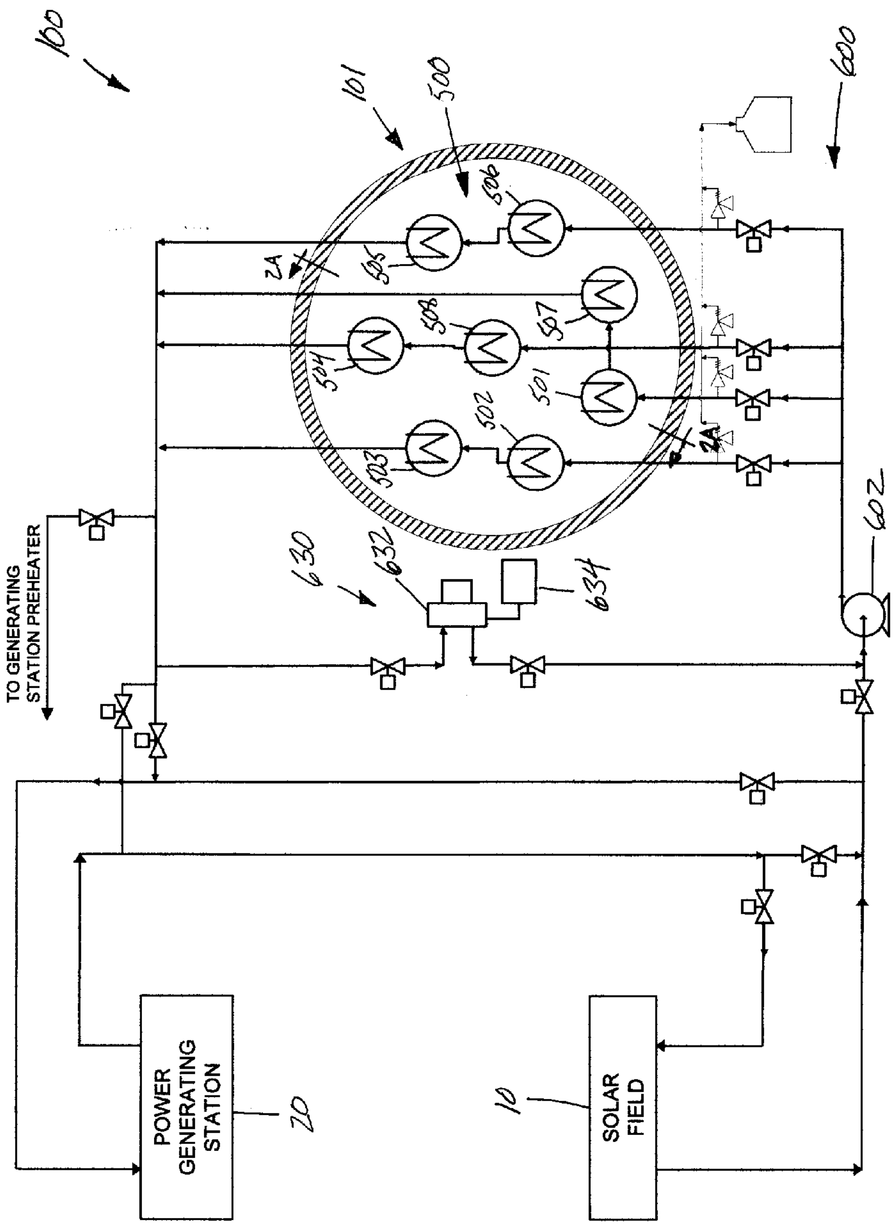
(57) **ABSTRACT**

A containment vessel for a thermal energy storage system comprising a bottom wall joined to a surrounding containment side wall, and a liner comprising a liner bottom disposed upon the bottom wall of the vessel, the liner bottom having an outer perimeter and comprising an array of plates, each of the plates joined at a portion of its perimeter to a portion of the perimeter of an adjacent plate by a flexible joint; and a liner side wall joined to the outer perimeter of the liner bottom and disposed within the containment side wall. A thermal energy storage system comprising the containment vessel and an array of heat exchangers is also disclosed. The heat exchangers are disposed in the vessel, and are each supported by a support frame joined to one of the plates of the array of plates of the liner.

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TO GENERATING STATION PREHEATER
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POWER GENERATING STATION
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SOLAR FIELD
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FIG. 1

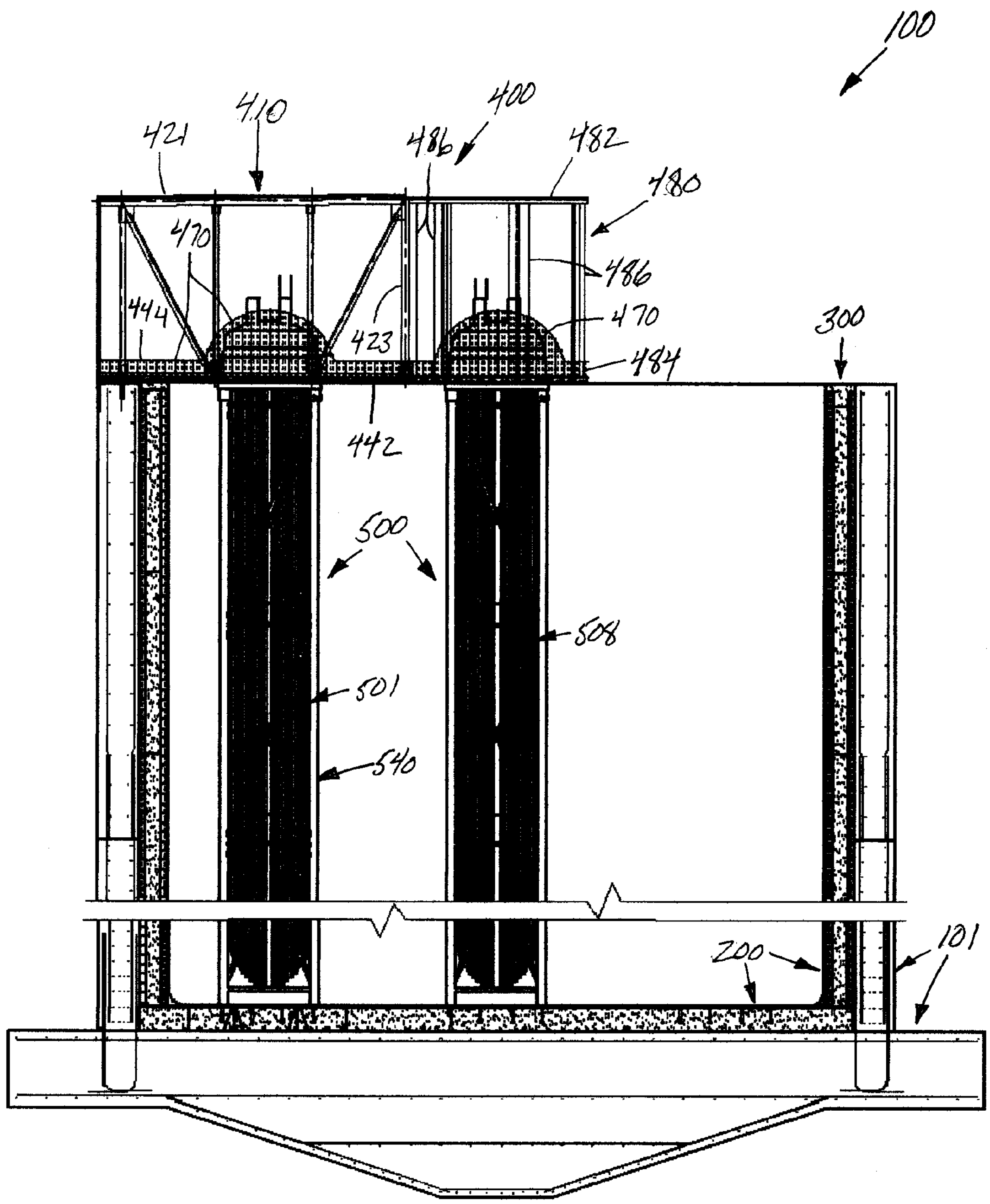
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FIG. 2A

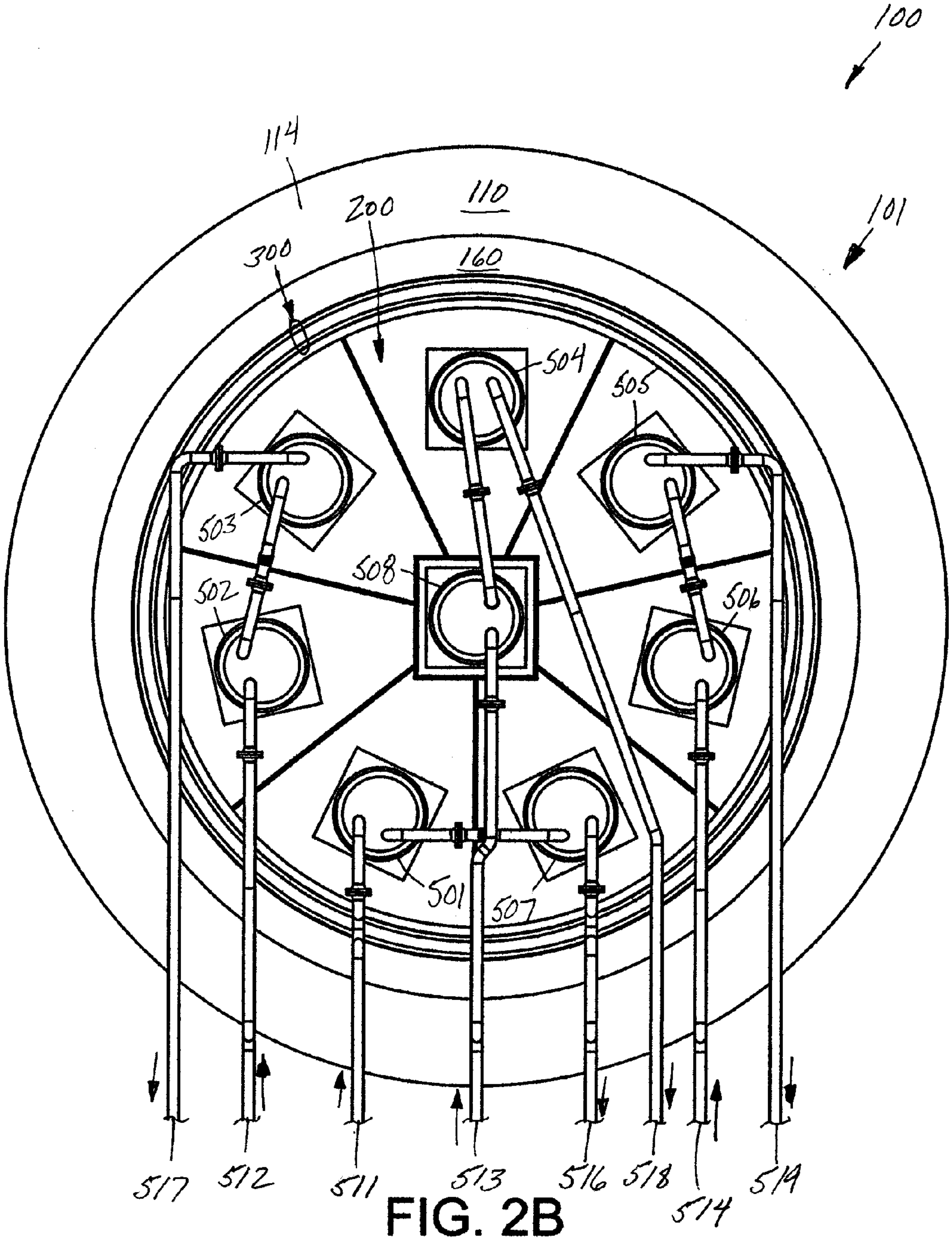
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FIG. 2B

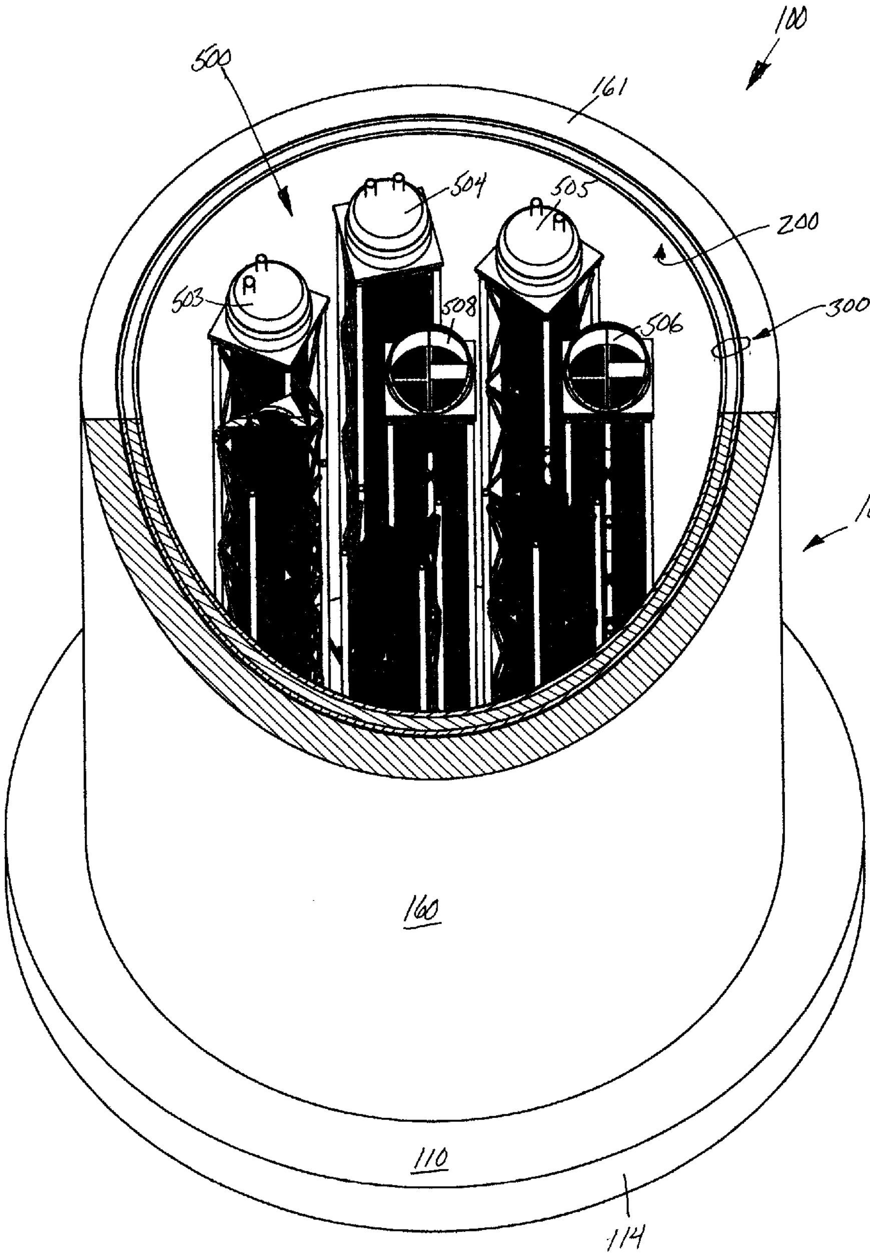

FIG. 2C

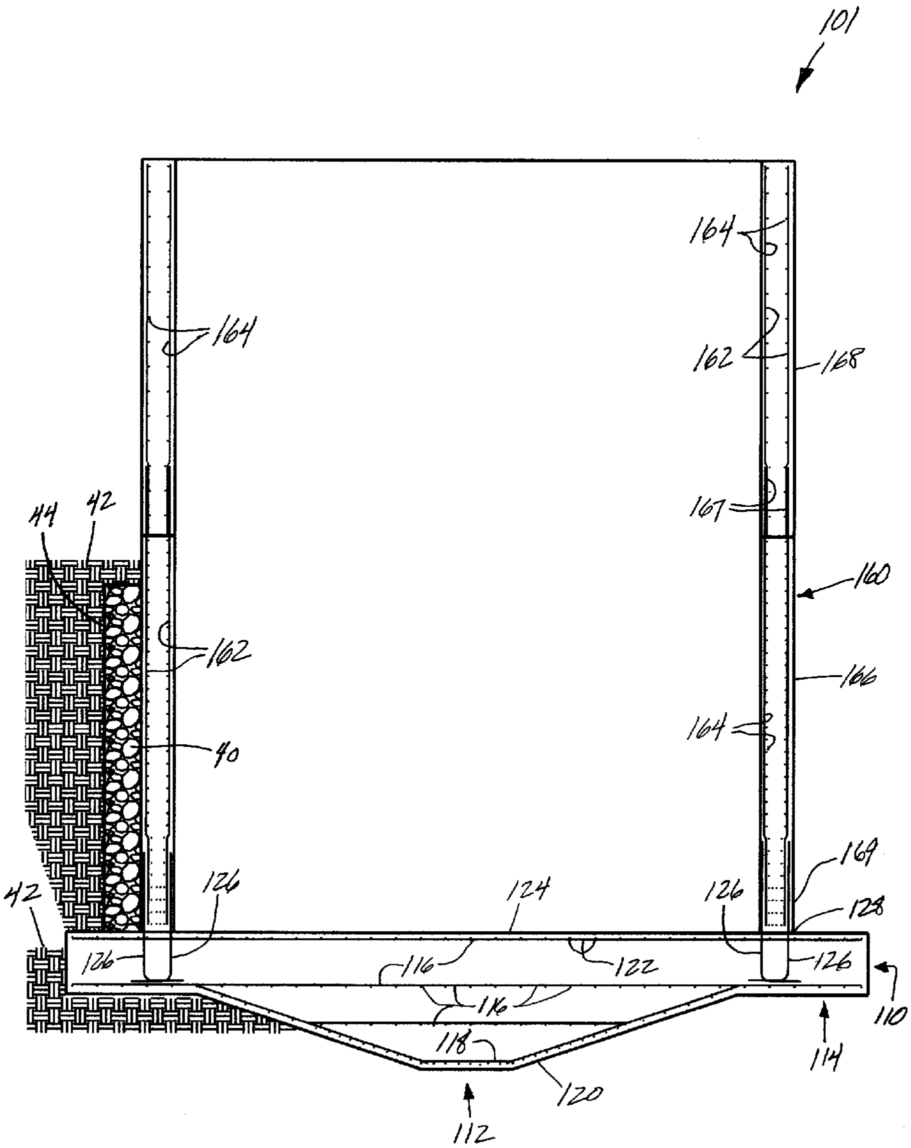
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FIG. 3

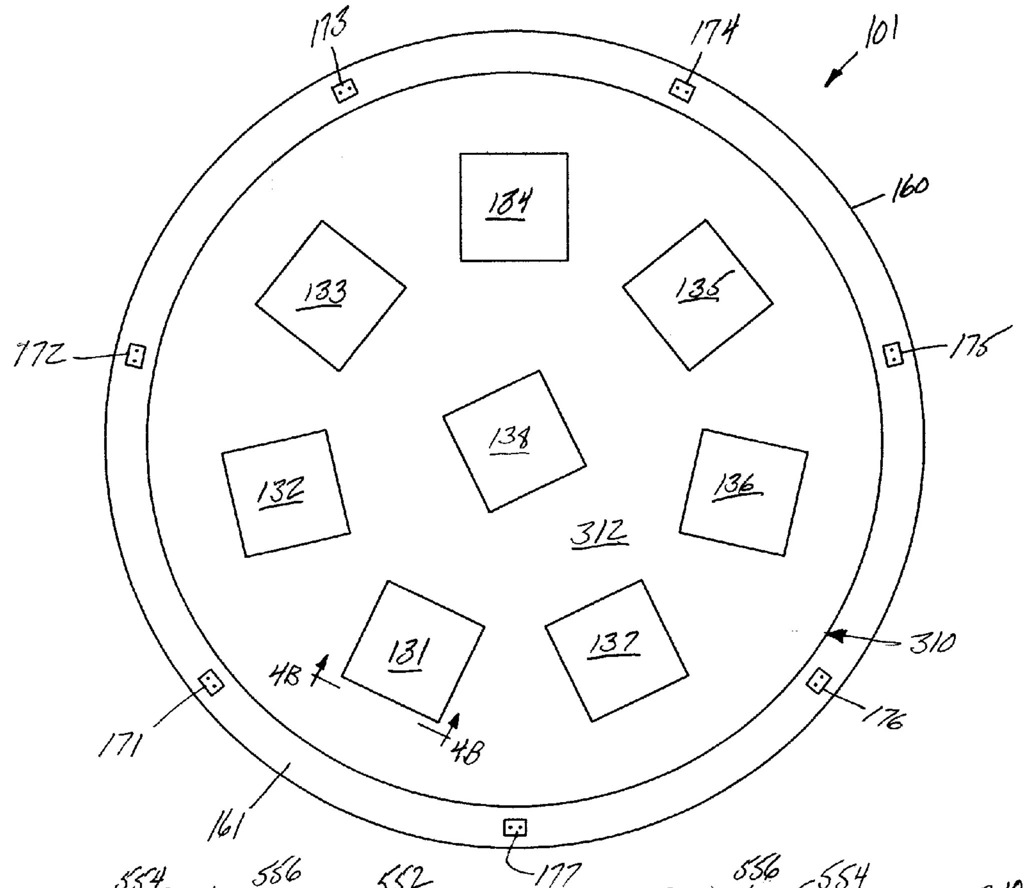
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FIG. 4A

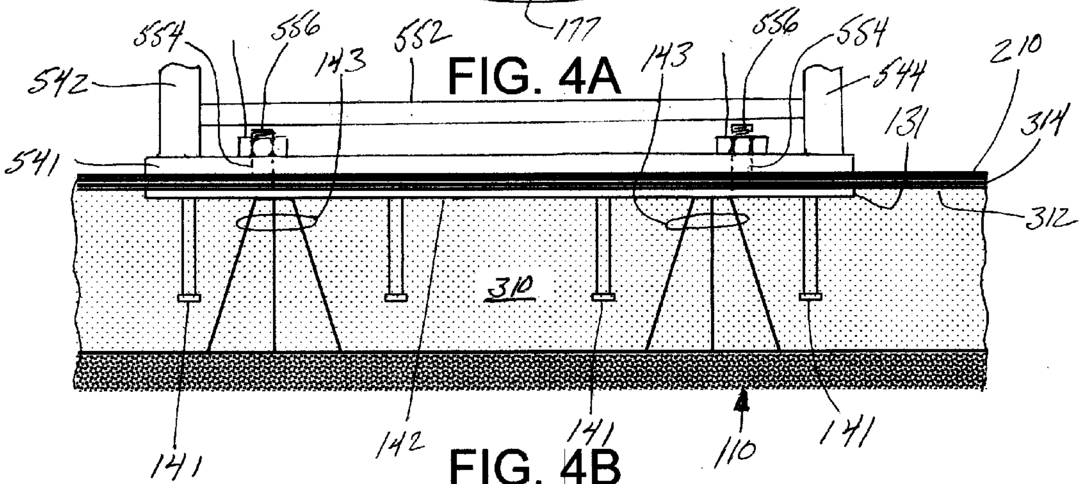
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FIG. 4B

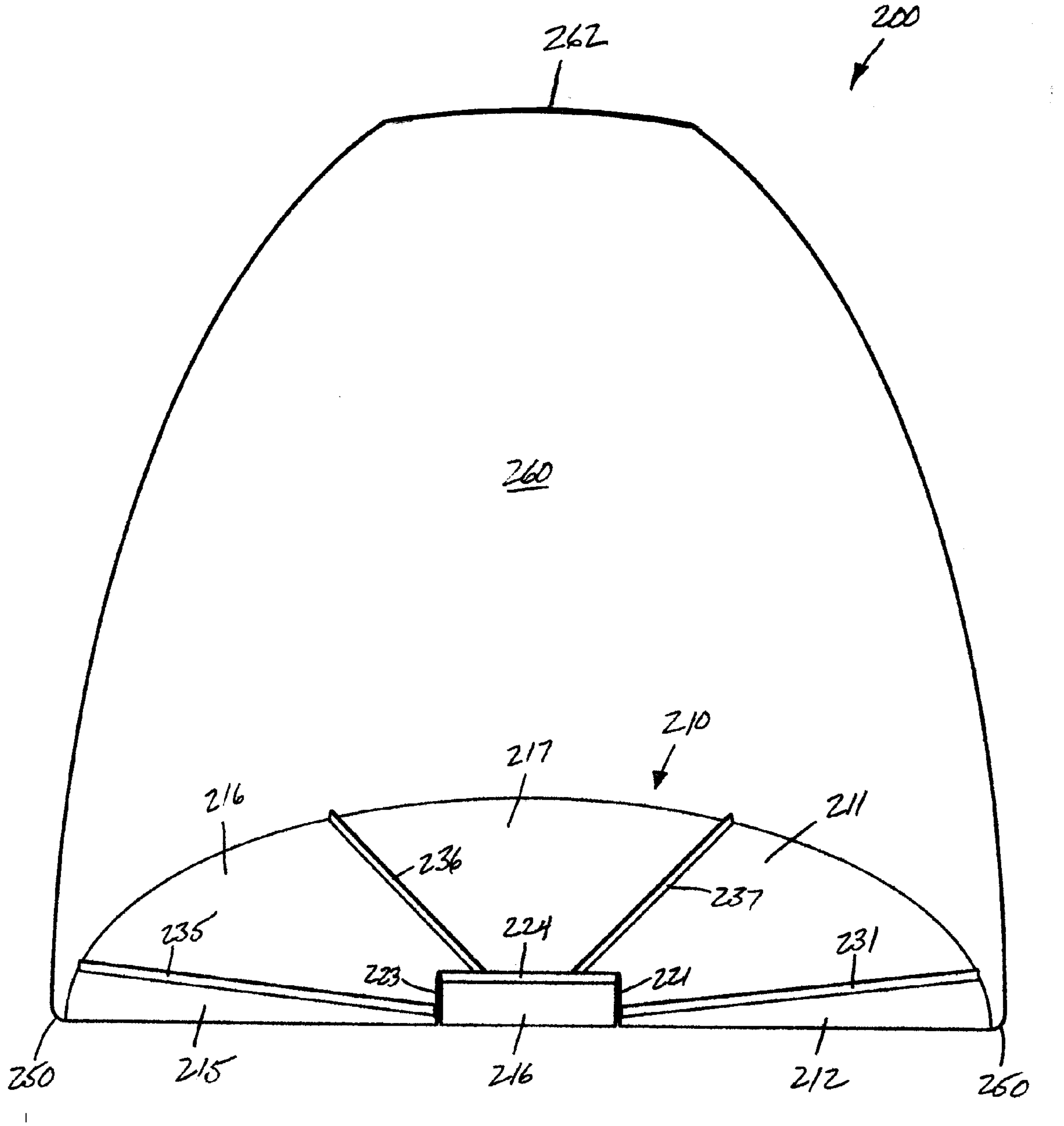
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FIG. 5A

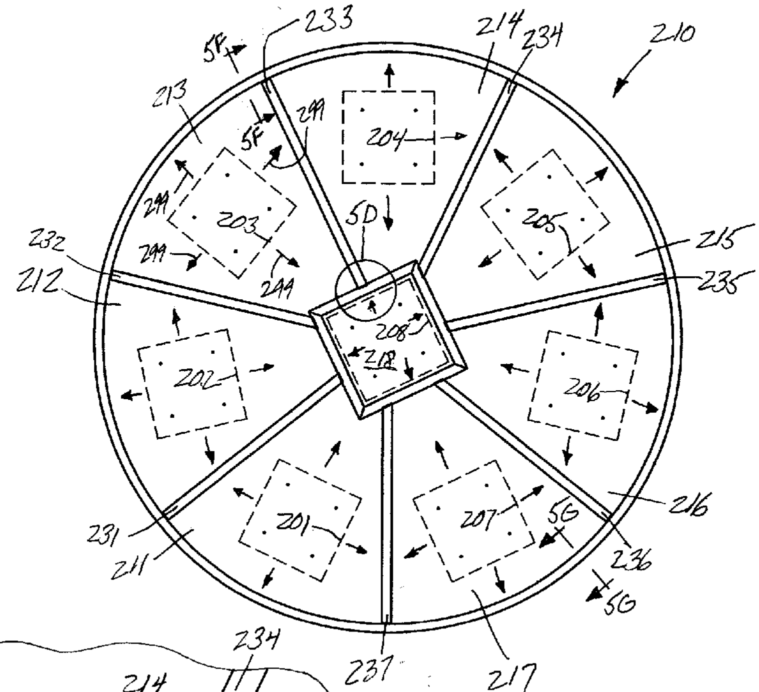
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FIG. 5B

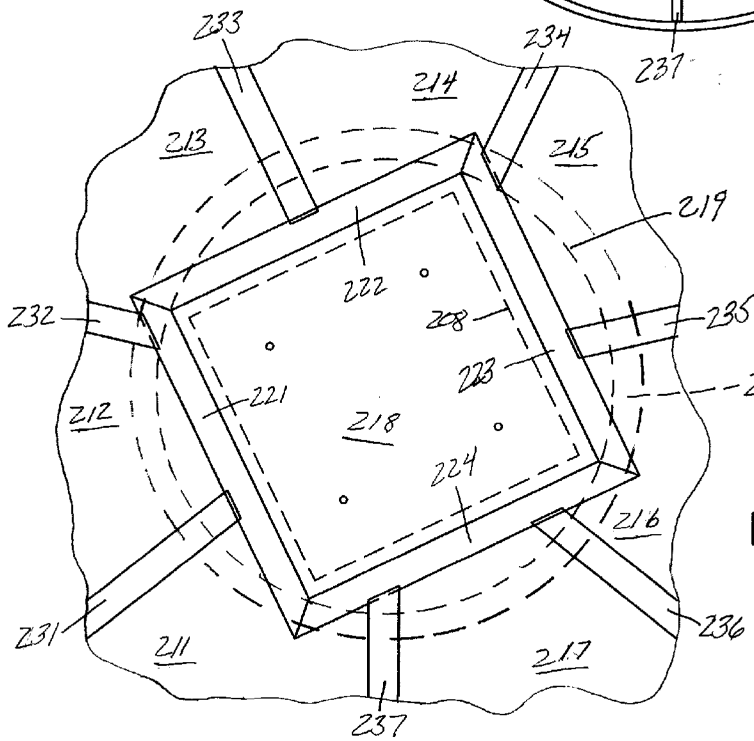
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FIG. 5C

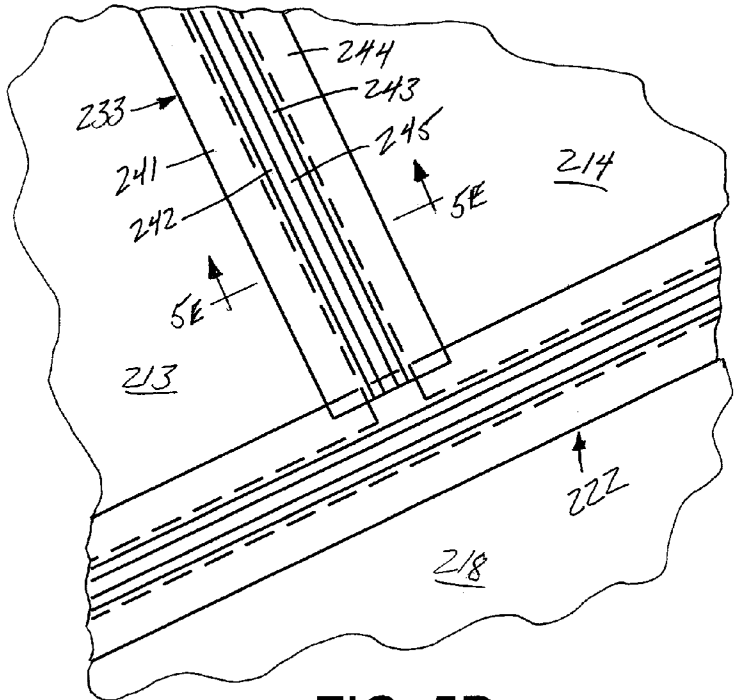
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FIG. 5D

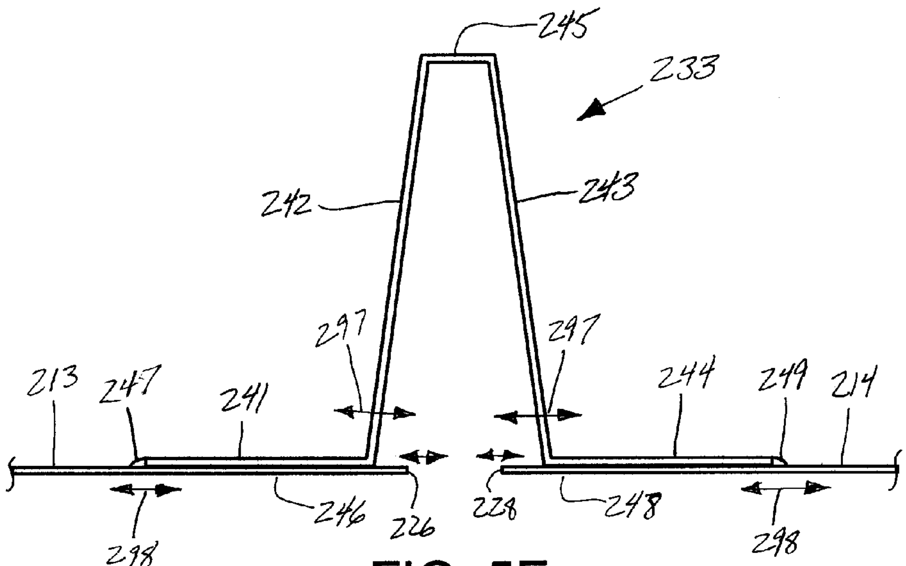
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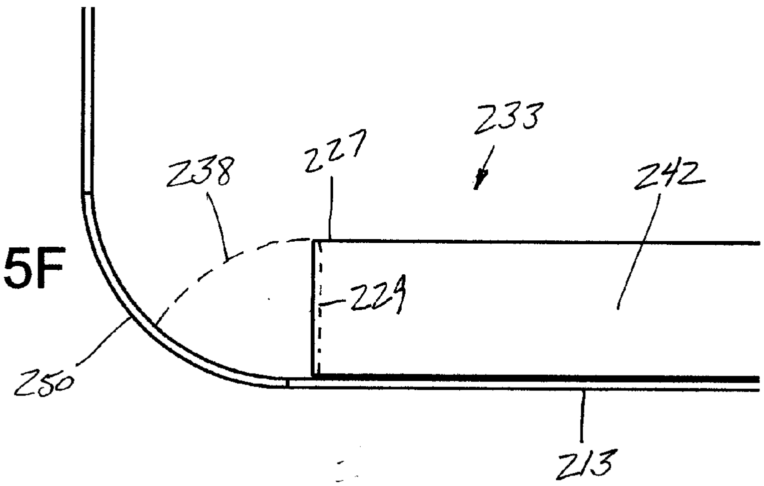
FIG. 5E

FIG. 5F



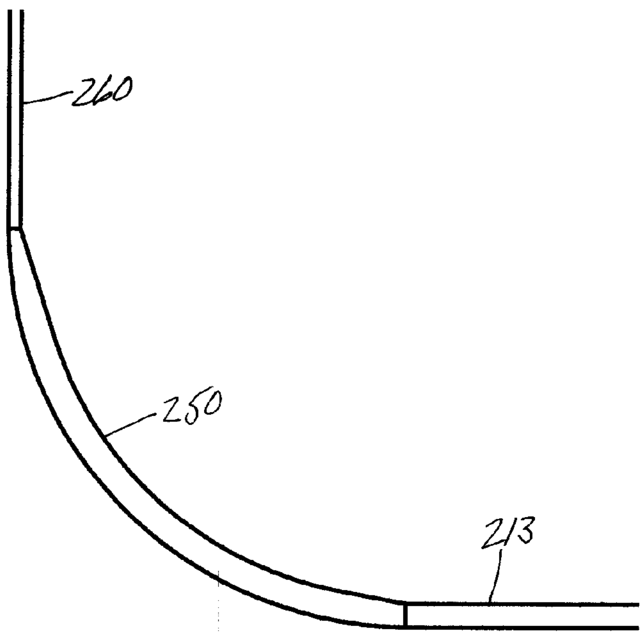


FIG. 5G

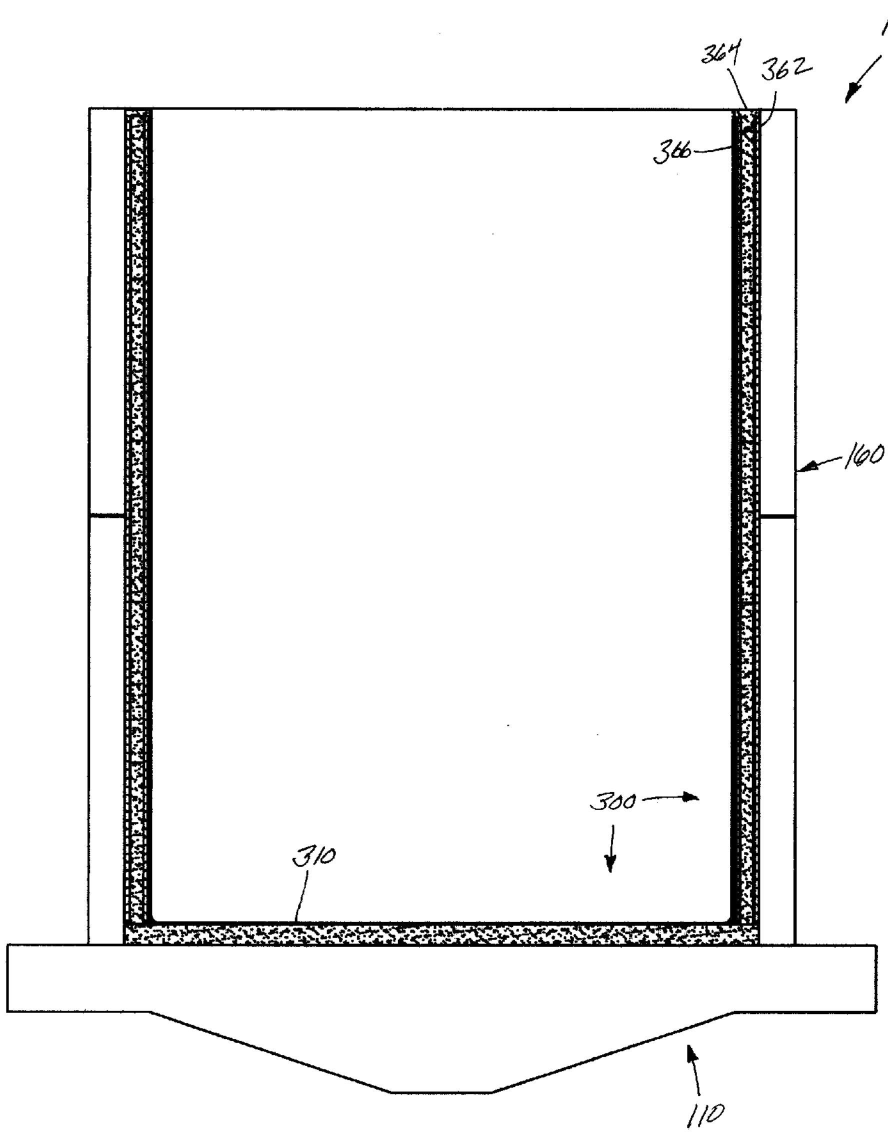


FIG. 6A

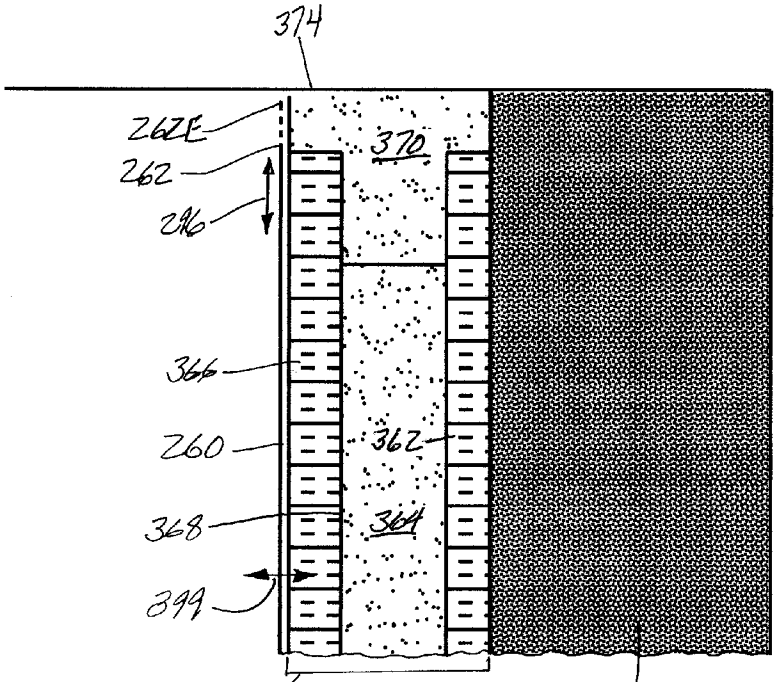

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FIG. 6B

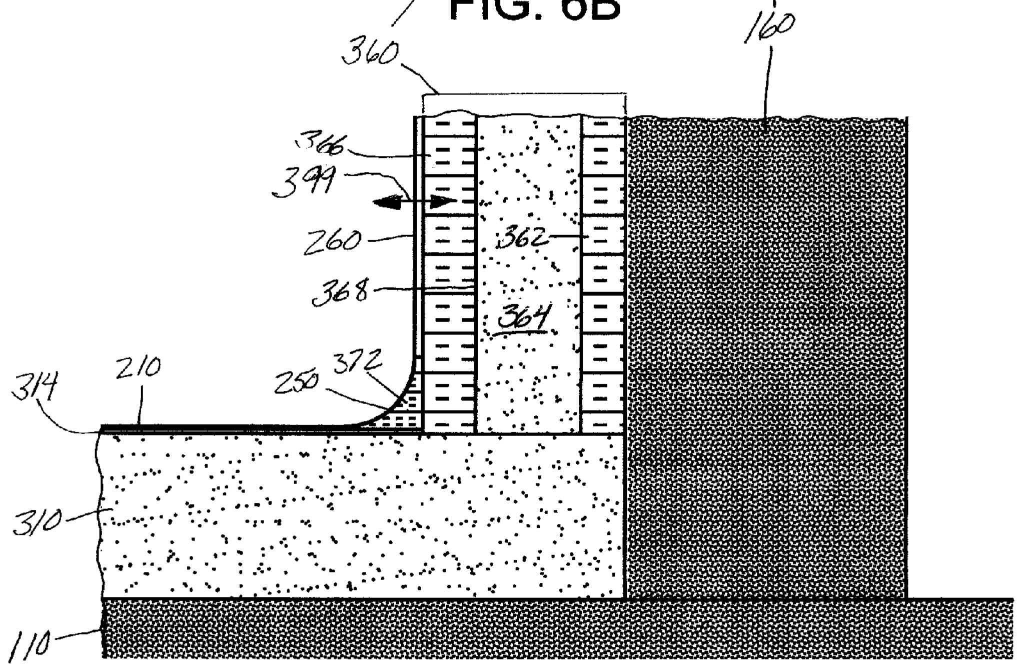
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FIG. 6C

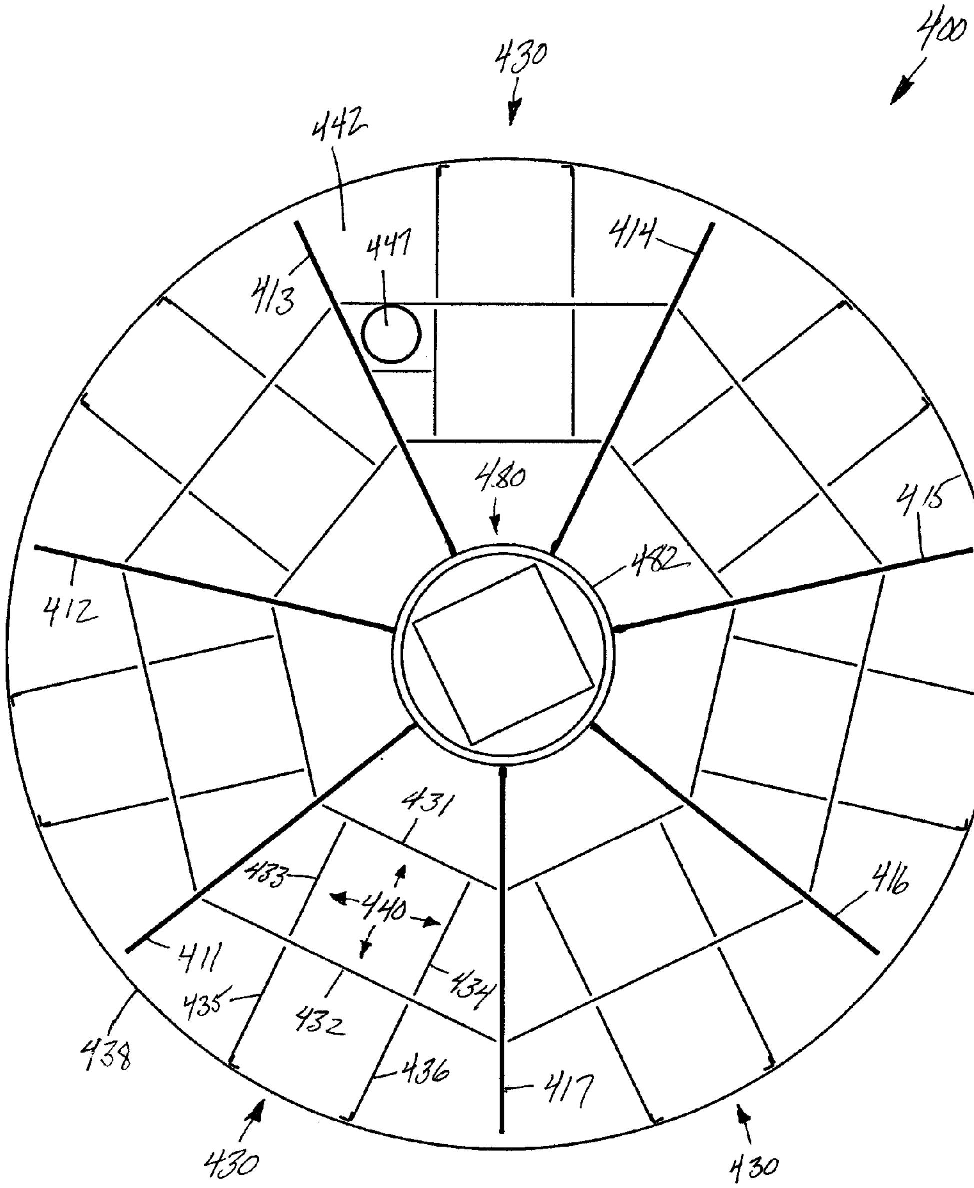
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FIG. 7A

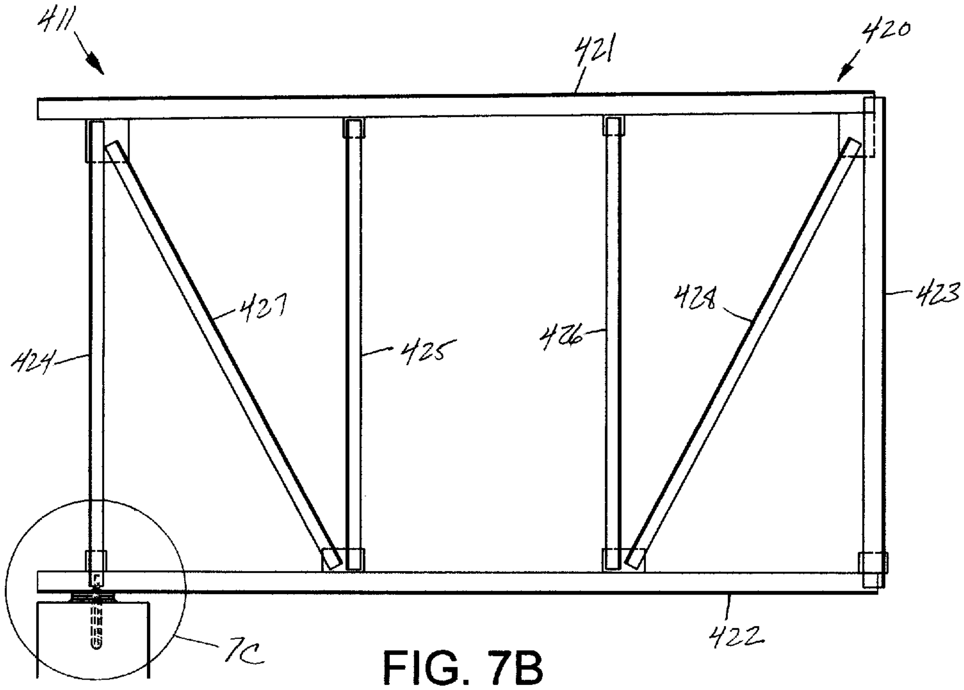

FIG. 7B

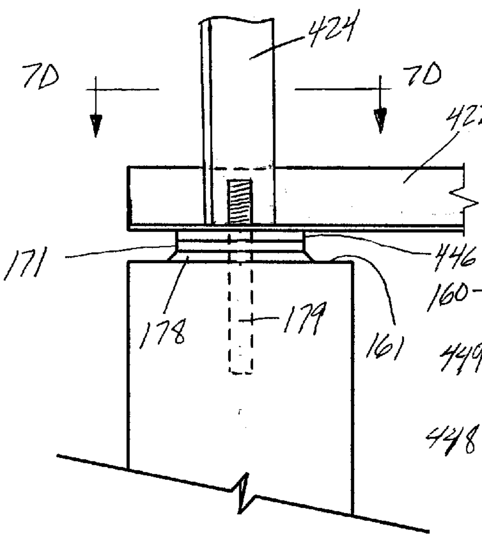

FIG. 7C

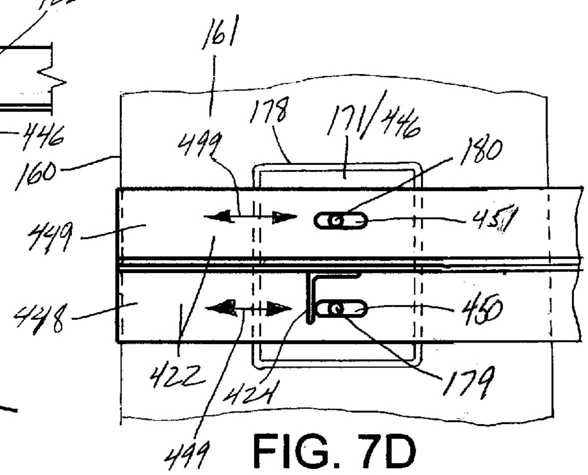

FIG. 7D

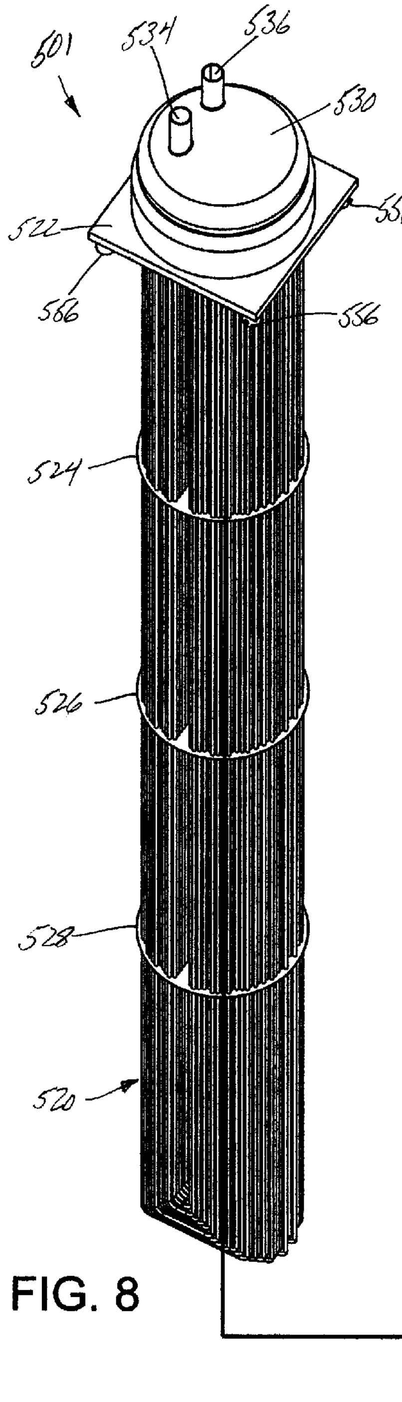
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FIG. 8

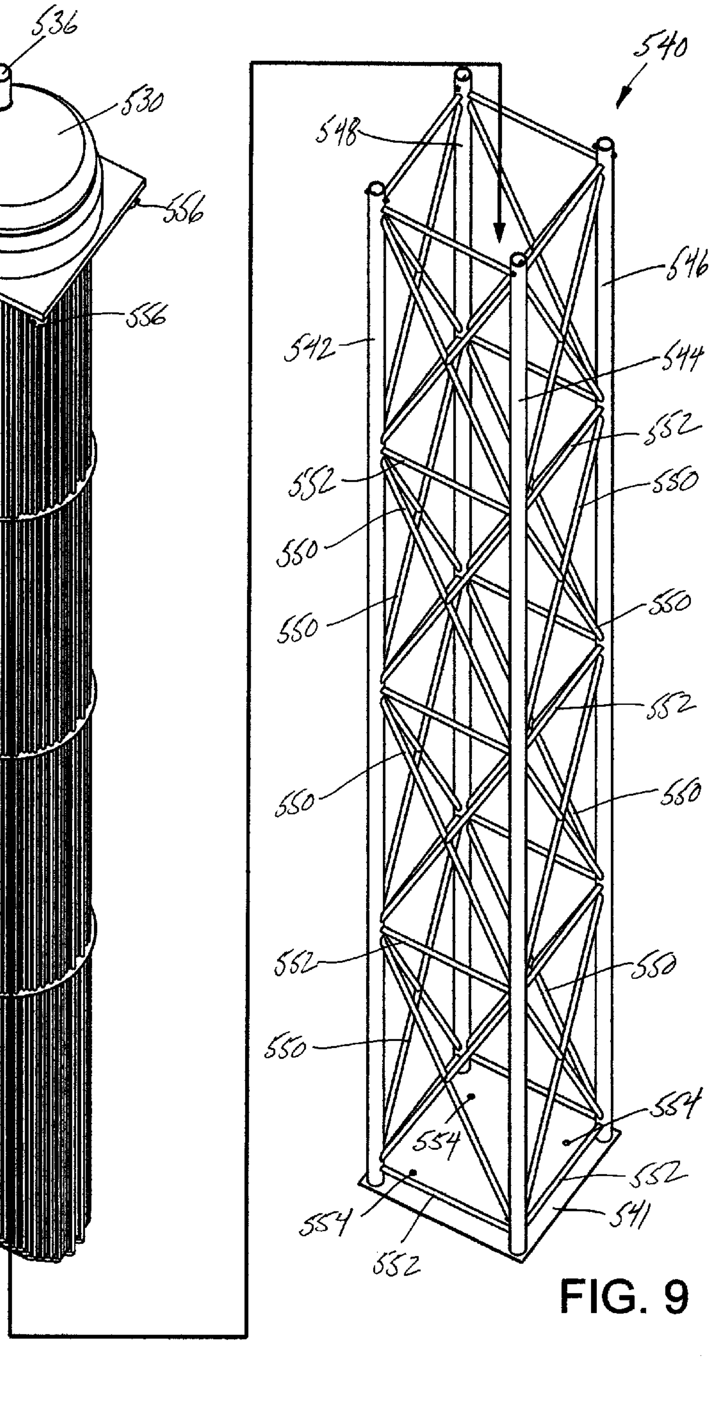
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FIG. 9

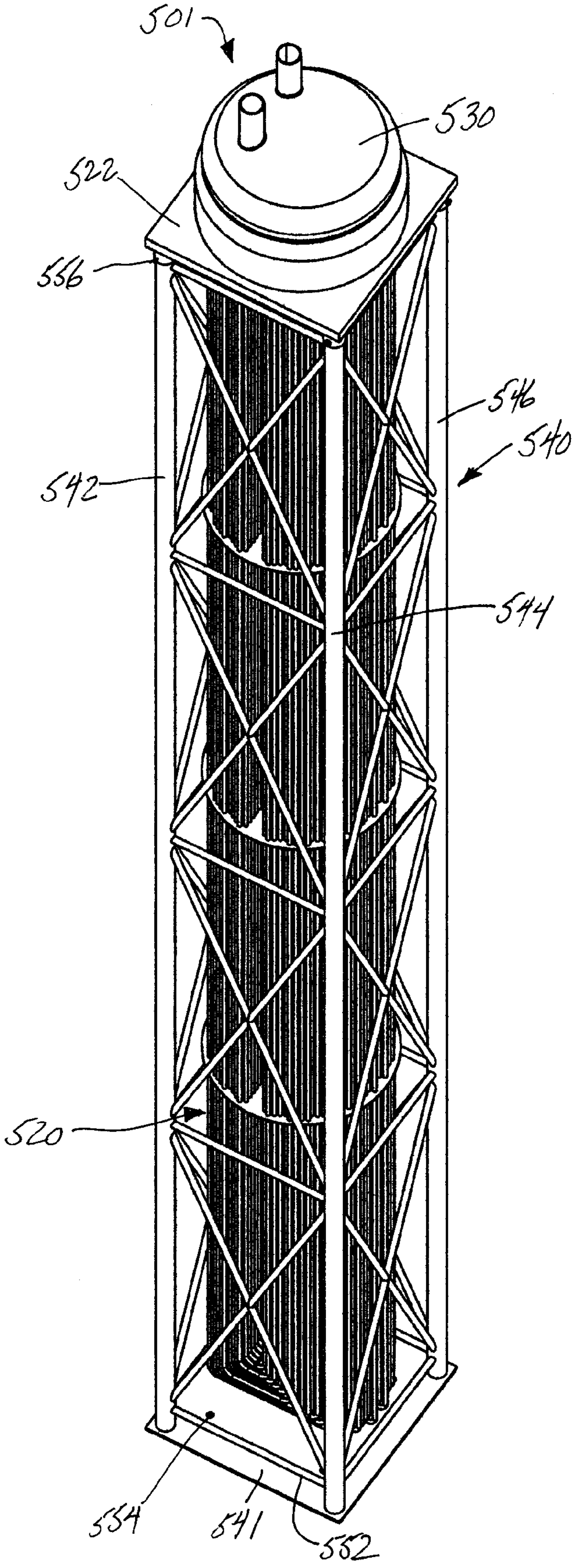

FIG. 10

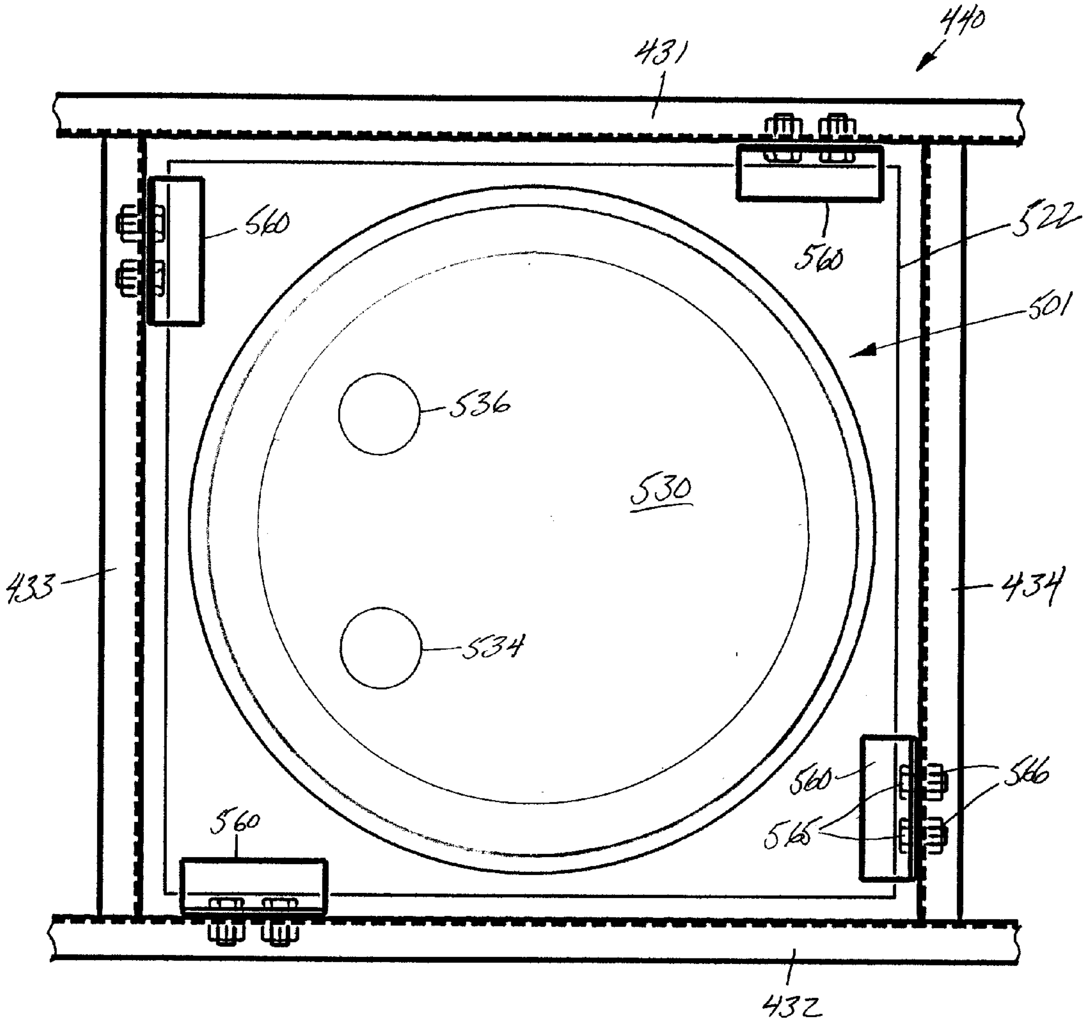

FIG. 11A

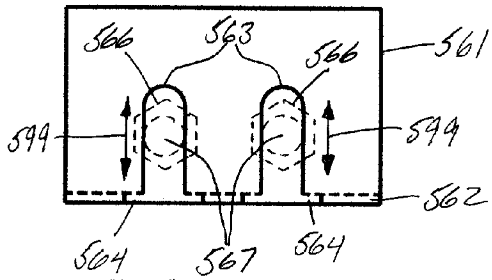

FIG. 11B

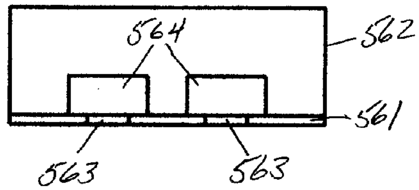

FIG. 11C

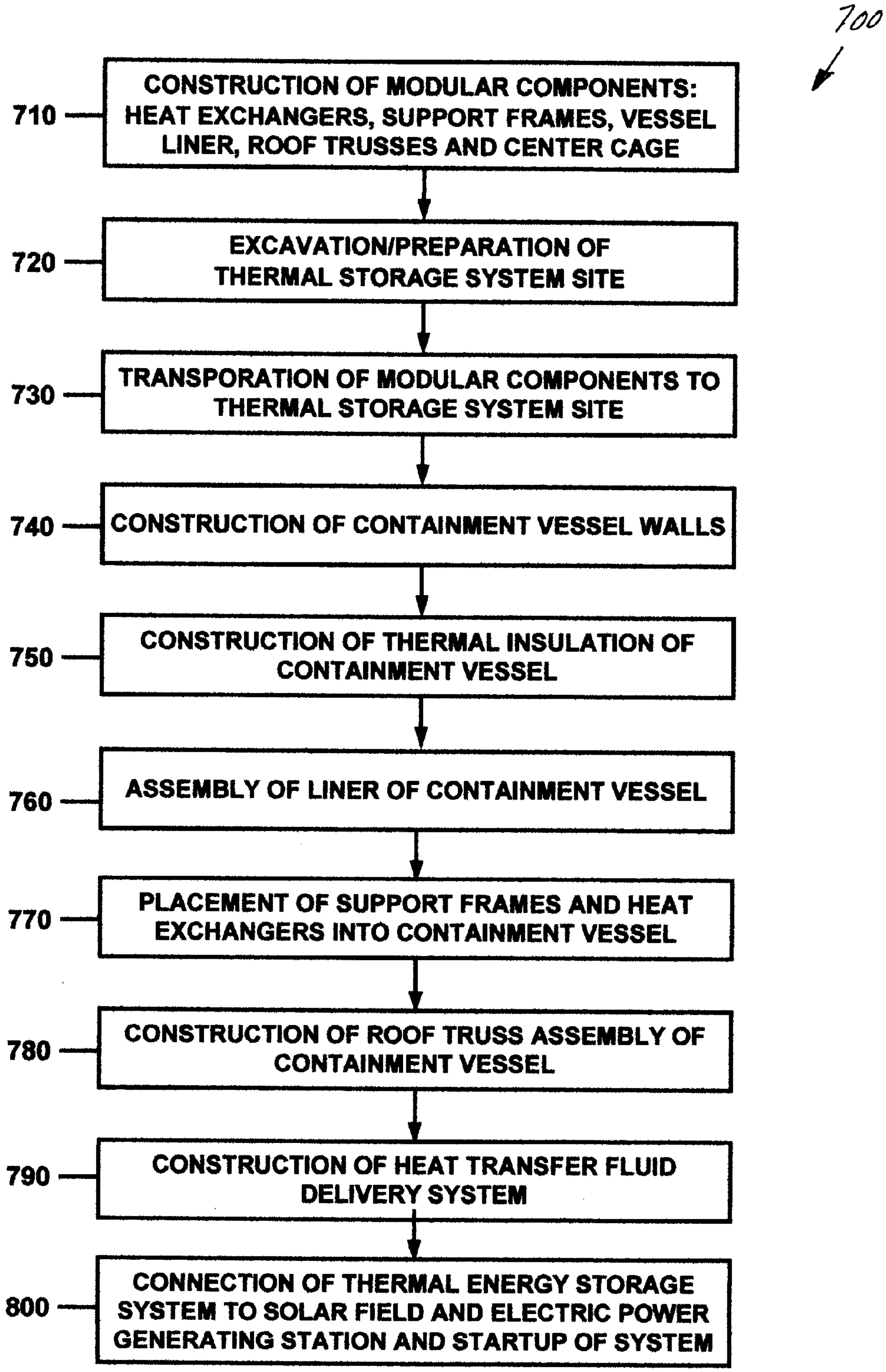
700
710
CONSTRUCTION OF MODULAR COMPONENTS: HEAT EXCHANGERS, SUPPORT FRAMES, VESSEL LINER, ROOF TRUSSES AND CENTER CAGE
720
EXCAVATION/PREPARATION OF THERMAL STORAGE SYSTEM SITE
730
TRANSPORATION OF MODULAR COMPONENTS TO THERMAL STORAGE SYSTEM SITE
740
CONSTRUCTION OF CONTAINMENT VESSEL WALLS
750
CONSTRUCTION OF THERMAL INSULATION OF CONTAINMENT VESSEL
760
ASSEMBLY OF LINER OF CONTAINMENT VESSEL
770
PLACEMENT OF SUPPORT FRAMES AND HEAT EXCHANGERS INTO CONTAINMENT VESSEL
780
CONSTRUCTION OF ROOF TRUSS ASSEMBLY OF CONTAINMENT VESSEL
790
CONSTRUCTION OF HEAT TRANSFER FLUID DELIVERY SYSTEM
800
CONNECTION OF THERMAL ENERGY STORAGE SYSTEM TO SOLAR FIELD AND ELECTRIC POWER GENERATING STATION AND STARTUP OF SYSTEM

FIG. 12

THERMAL ENERGY STORAGE VESSEL, SYSTEMS, AND METHODS

CROSS-REFERENCE TO RELATED PATENT APPLICATIONS

[0001] This application claims priority from U.S. provisional patent application Ser. No. 61/228,351, filed Jul. 24, 2009, the disclosure of which is incorporated herein by reference. This application is also related to copending commonly owned U.S. patent application Ser. No. 12/033,604 of Geiken et al., filed Feb. 19, 2008; and to U.S. patent application Ser. No. 12/172,673 of Flynn et al., filed Jul. 14, 2008. The disclosures of these United States patent applications are incorporated herein by reference.

BACKGROUND

[0002] 1. Field of the Invention

[0003] The inventions disclosed herein relate generally to energy storage and, more particularly, to thermal energy storage systems and methods thereof.

[0004] 2. Description of Related Art

[0005] Worldwide, there are ever-growing demands for electricity due to increasing populations, technology advancements requiring the use of electricity, and the proliferation of such technology to more and more countries around the world. At the same time, there is an increasing push to harness reusable sources of energy to help meet these increasing electricity demands and offset and/or replace traditional carbon-based generators which continue to deplete natural resources around the world.

[0006] Many solutions have been developed to collect and take advantage of reusable sources of energy, such as solar cells, solar mirror arrays, and wind turbines. Solar cells produce direct current energy from sunlight using semiconductor technology. Solar mirror arrays focus sunlight on a receiver pipe containing a heat transfer fluid which absorbs the sun's radiant heat energy. This heated transfer fluid is then pumped to a turbine which heats water to produce steam, thereby driving the turbine and generating electricity. Wind turbines use one or more airfoils to transfer wind energy into rotational energy which spins a rotor coupled to an electric generator, thereby producing electricity when the wind is blowing. All three solutions produce electricity when their associated reusable power source (sun or wind) is available, and many communities have benefited from these clean and reusable forms of power.

[0007] Unfortunately, when the sun or wind is not available, such solutions are not producing any power. In the case of solar solutions, non-reusable energy solutions are often employed during nighttime hours. Similar issues arise for wind turbines during calm weather. Therefore, some form of energy storage is needed to store excess energy from the reusable power sources during power generation times to support energy demands when the renewable power source is unavailable or unable to meet peak demands for energy.

[0008] Solar mirror arrays generate and transfer heat as an inherent part of their operation. Solar cells and wind turbines which typically generate electricity can also selectively be used to drive heaters to generate heat and/or transfer heat from windings to a heat transfer fluid. Several solutions have been developed to store heat from these renewable energy sources for use in non-energy-generating times. In particular, one or more large vessels of a liquid may be used to temporarily contain the sensible heat contained by oil heated in a solar field, and delivered to the liquid in the vessels by heat exchangers disposed therein. Hot oil is delivered to heat exchangers in a vessel containing relatively cold liquid, and the liquid in contact with the heat exchangers is heated up. The liquid may initially be in solid form, with some portion of the energy transfer being in the latent heat of fusion in the solid liquid transition.

[0009] During nighttime, or on overcast days when the solar field is down, the flow through the heat exchangers in the thermal energy storage vessel is directed to a steam generator which drives a turbine, which in turn is connected to an electrical generator. Heat is transferred from the heated liquid back into the oil in the heat exchangers, which is pumped to the steam turbine, to drive the turbine and generate electrical power.

[0010] One suitable energy storage medium is a molten inorganic salt, with a liquid phase temperature range from about 400 to 750 degrees Fahrenheit (° F.). This temperature range is effective for providing high pressure steam to drive large scale steam turbines for electrical power generation. Additionally, inorganic salts typically have a substantially higher specific gravity than water or organic heat transfer oils, in the range of about two to about four times that of water. On a volumetric basis, a molten inorganic salt can contain more sensible heat than an equal volume of a typical organic heat transfer oil, and is thus preferred in this regard.

[0011] Thermal energy storage systems which use molten salt are known, such as the "Solar Two" system which was built near Barstow, Calif., and was operational from about 1994 to 1999. This system used molten salt comprised of a combination of about 60% sodium nitrate and about 40% potassium nitrate as an energy storage medium, which was circulated from a cold storage tank, through the solar field where it was heated, to a hot storage tank. A summary of a similar system is described and shown in FIG. **2** of the aforementioned copending U.S. patent application Ser. No. 12/033,604 of Geiken et al.

[0012] Another known thermal energy storage system is the single-tank thermocline energy storage system, which is also described in the aforementioned patent application Ser. No. 12/033,604 of Geiken et al., and shown in FIG. **3** thereof. The thermocline tank of this system contains a hot molten salt in the top portion thereof and a relatively cool molten salt in the bottom portion thereof. When the solar field **52** is active, a hot heat transfer fluid is pumped from the solar field to a heat exchanger. The relatively cool molten salt is pumped from the bottom of the thermocline tank out to the heat exchanger where it is heated by proximity to the hot heat transfer fluid from the solar field. The heated molten salt is then returned to the top of the thermocline tank. When the solar field is not active, the flow to and from the thermocline tank is reversed. Heated molten salt is pumped out of the top of the thermocline tank to the heat exchanger, where it transfers its heat to the heat transfer fluid. The heat transfer fluid is pumped to a steam turbine system for generating electricity. The molten salt which gave up some of its heat in the heat exchanger is then returned to the bottom of the thermocline tank. While this system takes advantage of a vertical temperature gradient within the thermocline tank to enable simplification to a single tank, challenges with respect to the pumping, valving, and delivery of molten salt through a complex network of piping to the solar field, and to the power generator remain present.

[0013] It is therefore preferable to have a thermal energy storage system in which the molten salt is simply contained within a vessel as the thermal storage medium, and not pumped throughout the overall system. Instead, the thermal energy is transferred from the solar field to the vessel of molten salt by the circulation of a heat transfer fluid, such as an organic heat transfer oil, from the solar field through one or more heat exchangers immersed in the molten salt in the vessel. In like manner, during nighttime or overcast days, the thermal energy is transferred from the vessel of molten salt to the power generator by the circulation of the heat transfer fluid therebetween. The handling of heat transfer fluid by standard pumps, valves and piping is much simpler than the equivalent handling of a molten inorganic salt, which is corrosive, and which is abrasive if some portion of solid phase salt (crystals) is present, and which can solidify in the pumps, valves, and piping at temperatures lower than 400° F., thus requiring a disruptive thawing process step to restart the system.

[0014] By using a heat transfer fluid to perform the energy transfer from the solar field to the thermal storage vessel, and from the vessel to the power generator, the problems to be addressed are simplified to those relating to containment of the molten salt, and heat transfer to and from the molten salt. This simplification notwithstanding, the problems of containing the molten salt, and transferring thermal energy to and from it are significant, particularly at the scale needed by a public utility for an economically viable thermal energy storage process. The main problems are summarized briefly as follows:

[0015] 1. The containment vessel is of economic necessity quite large, and the molten salt contained therein is quite dense, on the order of two to four times the density (or specific gravity) of water. Consequently, the structural loads on the vessel bottom and side wall are very high.

[0016] 2. The molten salt within the vessel may reach temperatures of up to about 750° F. Therefore, the containment vessel bottom and side walls must retain the required structural strength to contain the molten salt at temperatures much higher than the ambient environment.

[0017] 3. The containment vessel will undergo repeated thermal expansion and contraction, and must be able to accommodate such extreme thermal cycling. During system fabrication, the vessel is constructed at substantially ambient temperature, and is then cycled up to as high as 750° F. during startup and operation. The vessel is then cycled between its minimum operating temperature (about 400° F. to about 500° F.) to its maximum operating temperature of about 750° F. on a daily basis when in operation. The vessel may also be occasionally cycled back down to ambient temperature of between about 0° F. and about 90° F. during process shutdowns. Given the requisite size of the containment vessel (on the order of 25 feet in diameter by 30 feet high in one embodiment), the dimensional changes of the vessel (and any insulation contained therein or applied thereto) over the full temperature range is significant, and must be accommodated. Accordingly, the repeated cycles of thermal expansion and contraction must occur without any structural failures of the vessel, which could result in leaks of the molten salt therefrom and/or collapse of the vessel.

[0018] 4. The heat exchangers contained within the vessel must also be able to withstand the above-described thermal cycling, and must remain securely fixed within the vessel during such cycling.

[0019] 5. Many environments where a thermal energy storage system may be located are seismically active. Accordingly, the containment vessel and heat exchangers must be able to withstand seismic events such as earthquakes without significant damage, and without any leakage of the molten salt.

[0020] 6. A high degree of serviceability is preferred in operation of the system. For example, it is desirable that if a single heat exchanger develops a problem, such as a leak, that the heat exchanger can be removed and replaced without shutting down the overall system, thus incurring costly downtime.

[0021] 7. Modularity of the system is preferred. In construction of the vessel and overall thermal energy storage system, a system that is of a modular design is more cost effective. In a modular system, a major portion of the system components can be fabricated in a shop environment, which is better equipped and controlled, and then shipped to the job site. Final construction and assembly can then be done on the job site.

[0022] It is further noted that at minimum, for any thermal energy storage system that comprises a molten inorganic salt as a thermal storage medium, the above problems 1-4 must be simultaneously addressed or otherwise rendered inconsequential by the features and capabilities of the system. A system that further addresses problems 5, 6, and/or 7 will be further advantageous.

SUMMARY

[0023] In accordance with the present disclosure, the problem of containing a large mass of molten salt, which undergoes repeated extreme thermal cycling in a thermal energy storage system is solved by providing a containment vessel comprising a bottom wall joined to a surrounding containment side wall, and a liner comprising a liner bottom disposed upon the bottom wall of the vessel, the liner bottom having an outer perimeter and comprising an array of plates, each of the plates joined at a portion of its perimeter to a portion of the perimeter of an adjacent plate by a flexible joint; and a liner side wall joined to the outer perimeter of the liner bottom and disposed within the containment side wall. The vessel may be cylindrical, with the bottom wall of the vessel correspondingly being circular.

[0024] The liner contained within the vessel is constructed so as to be able to expand and contract under the loading thereof with the molten salt, and in particular, due to the thermal expansion and contraction caused by contact with the molten salt at temperatures up to about 750° F. In one embodiment, the array of plates of the liner bottom is comprised of a plurality of radially arranged sector-shaped plates. Such an array of plates may be further comprised of a central plate, bounded by a portion of each of the radially arranged sector-shaped plates. The central plate may be circular, or the central plate may be a polygon. The central plate may be square. The number of radially arranged sector-shaped plates may be between three and eleven, or more, depending upon the number and size of the heat exchangers of the thermal energy storage system to be disposed within the vessel and supported by the plates. In some embodiments, the number of sides of the polygon of the central plate may be equal to the number of

radially arranged sector-shaped plates. In one embodiment, the number of radially arranged sector-shaped plates is seven; along with a central plate, the resulting eight total plates support eight heat exchangers. Each of the plates of the liner bottom may be joined to the bottom wall of the vessel.

[0025] A flexible joint which joins a plate at a portion of its perimeter to a portion of the perimeter of an adjacent plate may be comprised of a first riser joined to the portion of perimeter of the first adjacent plate, and a second riser joined to the portion of perimeter of the second adjacent plate, the first riser also being joined to the second riser. The flexible joint may be further comprised of an intermediate plate disposed between and joined to the first riser and the second riser.

[0026] Depending upon the particular molten salt, the liner may be made of a material selected from, but not limited to, plain carbon steels; steels alloyed with copper, manganese, molybdenum, nickel, silicon, tungsten, titanium, vanadium and chromium, individually or in any combination thereof such as chromium-molybdenum, or nickel-chromium-molybdenum; and stainless steels. In one embodiment, the liner is made of 316 stainless steel.

[0027] The bottom wall and containment side wall of the vessel may be made of concrete, and preferably, steel-reinforced concrete. The bottom wall of the vessel may be formed so as to decrease in thickness from the central region thereof to the perimeter region thereof. The vessel may be further comprised of bottom thermal insulation disposed between the bottom wall of the vessel and the liner bottom, and side wall insulation disposed between the containment side wall of the vessel and the liner side wall. The side wall insulation may compressible and expandable, so as to accommodate the radial thermal expansion and contraction of the liner over the range of operating temperatures of the salt contained in the vessel.

[0028] A thermal energy storage system may include the instant containment vessel comprising a bottom wall joined to a surrounding containment side wall, and a liner comprising a liner bottom disposed upon the bottom wall of the vessel, the liner bottom having an outer perimeter and comprising an array of plates, each of the plates joined at a portion of its perimeter to a portion of the perimeter of an adjacent plate by a flexible joint; and a liner side wall joined to the outer perimeter of the liner bottom and disposed within the containment side wall; and an array of heat exchangers disposed in the vessel, each of the heat exchangers supported by a support frame joined to one of the plates of the array of plates of the liner. The heat exchangers may operate in parallel, or pairs of heat exchangers of the array of heat exchangers may be connected in series.

[0029] The roof truss assembly may be disposed on a top surface of the containment side wall. Each of the support frames of the heat exchangers may be joined to the roof truss assembly. For seismic stability, each of the heat exchangers and frames may be constrained to prevent movement in the horizontal direction; simultaneously, the heat exchangers and frames must be permitted to expand and contract in the vertical direction due to their exposure to the range of operating temperatures of the salt contained in the vessel. The problem of constraining a heat exchanger and its support frame in the horizontal direction while permitting it to move in the vertical direction is solved by providing a fastening arrangement at the upper portion of the frame which joins the heat exchanger frame to the roof truss assembly in a manner that fixes the horizontal location of the upper portion of the frame with respect to the truss assembly, while permitting the upper portion of the frame to translate vertically up and down with respect to the truss assembly.

[0030] The roof truss assembly may be comprised of a plurality of radially disposed roof trusses. The roof truss assembly may further include a central cage joined to each of the roof trusses. The roof truss assembly may be radially expandable with respect to the containment side wall of the vessel.

[0031] In accordance with the invention, a method for making a thermal energy storage system is also provided. One aspect of the method is that because the system is of a modular design, a large share of the system components may be fabricated in a shop of factory environment in a better equipped and controlled environment and then shipped to the thermal system construction site. The modular components include the heat exchangers, heat exchanger support frames, vessel liner, heat transfer fluid delivery system, and roof trusses and center cage of the roof truss assembly. This may be done in parallel while the excavation and grading of the site is performed. If the containment vessel is to be partially below grade, a containment pit may be dug. The containment vessel bottom wall and side wall may then be constructed while the modular components are shipped to the construction site. The thermal insulation may then be applied to the vessel bottom and/or vessel side wall. The liner may then be fabricated from modular components. The pre-fabricated modular heat exchanger support frames and heat exchangers may then be placed in the containment vessel, and the roof truss assembly may be assembled from pre-fabricated trusses and a central cage. The heat transfer fluid delivery system may then be constructed and connected to the heat exchangers, the solar field, and the electrical generation station. The thermal energy storage system may then be started up, and used for storing and releasing thermal energy.

BRIEF DESCRIPTION OF THE DRAWINGS

[0032] The present disclosure will be provided with reference to the following drawings, in which like numerals refer to like elements, and in which:

[0033] FIG. **1** is a schematic illustration of a thermal storage system and method in accordance with the present disclosure;

[0034] FIG. **2**A is a side elevation cross-sectional of a containment vessel and heat exchangers of the thermal storage system;

[0035] FIG. **2**B is a plan view of the containment vessel, and heat exchangers of the thermal storage system;

[0036] FIG. **2**C is a perspective cutaway view of the containment vessel and heat exchangers of the thermal storage system;

[0037] FIG. **3** is a cross-sectional view of the containment vessel of the thermal storage system;

[0038] FIG. **4**A is a plan view of the containment vessel of FIG. **3**, depicting one arrangement of an array of heat exchangers contained therein;

[0039] FIG. **4**B is a detailed cross sectional view of a plate for supporting a heat exchanger on the bottom of the containment vessel;

[0040] FIG. **5**A is a perspective cutaway view of a liner of the containment vessel of FIG. **3**;

[0041] FIG. **5**B is a plan view of the bottom of the liner of FIG. **5**A;

[0042] FIG. **5**C is a detailed plan view of a central plate of the liner bottom of FIG. **5**B;

[0043] FIG. **5**D is a detailed plan view of a radial flexible joint at its intersection with the central plate of the liner bottom of FIG. **5**B;

[0044] FIG. **5**E is a detailed cross-sectional view of a flexible joint of the liner bottom, taken along the line **5**E-**5**E of FIG. **5**D;

[0045] FIG. **5**F is a detailed cross-sectional view of an outer end of a flexible joint of the liner bottom, taken along the line **5**E-**5**E of FIG. **5**B;

[0046] FIG. **5**G is a detailed cross-sectional view of a joining of the liner bottom to the liner side wall, taken along the line **5**G-**5**G of FIG. **5**B;

[0047] FIG. **6**A is a cross-sectional view of the containment vessel of the thermal storage system, showing the thermal insulation contained therein;

[0048] FIG. **6**B is a detailed cross-sectional view of the thermal insulation at the upper side wall of the containment vessel;

[0049] FIG. **6**C is a detailed cross-sectional view of the thermal insulation at the bottom and lower side wall of the containment vessel;

[0050] FIG. **7**A is a plan view of a roof truss assembly disposed on the top of the containment vessel;

[0051] FIG. **7**B is a side elevation view of a portion of the roof truss assembly of FIG. **7**A;

[0052] FIG. **7**C is a detailed side elevation view of a bearing support plate for supporting the roof truss assembly at the top of the side wall of the containment vessel;

[0053] FIG. **7**D is a top view of the bearing support plate of FIG. **7**C, taken along line **7**D-**7**D of FIG. **7**C and shown supporting a roof truss;

[0054] FIG. **8** is a perspective view of a heat exchanger of the thermal energy storage system;

[0055] FIG. **9** is a perspective view of a support frame for a heat exchanger of FIG. **8**;

[0056] FIG. **10** is a perspective view of the support frame of FIG. **9** assembled with the heat exchanger of FIG. **8**;

[0057] FIG. **11**A is a plan view of a locating frame of the roof truss assembly that is used to support the heat exchanger assembly of FIG. **10**;

[0058] FIG. **11**B and FIG. **11**C are orthogonal views of a joint of the locating frame of FIG. **11**A; and

[0059] FIG. **12** is a flow chart depicting a method of making the applicants' thermal energy storage system.

[0060] The present invention will be described in connection with a preferred embodiment, however, it will be understood that there is no intent to limit the invention to the embodiment described. On the contrary, the intent is to cover all alternatives, modifications, and equivalents as may be included within the spirit and scope of the invention as defined by the appended claims.

DETAILED DESCRIPTION

[0061] For a general understanding of the present invention, reference is made to the drawings. In the drawings, like reference numerals have been used throughout to designate identical elements.

[0062] FIG. **1** is a schematic illustration of a thermal storage system and method in accordance with the present disclosure. The thermal energy storage system **100** is comprised of a containment vessel **101**, which contains a heat exchanger or an array **500** of heat exchangers immersed in a molten salt. The system **100** is further comprised of a liquid transfer unit **600** (that may be of a modular design), which circulates a heat transfer fluid through the heat exchangers during operation of the system **100**. The liquid transfer unit **600** is comprised of liquid piping, various switching and control valves, a pump **602**, and a pressure relief tank **604**. The liquid transfer unit **600** may further include a heater loop **630** comprising an oil heater **632** and an expansion tank **634** for heating and circulating heat transfer fluid through the heat exchanger array **500** when the system **100** is not online.

[0063] In daytime operation of the system **100**, the control valves of the liquid transfer unit **600** are positioned such that heat transfer oil is recirculated by the pump **602** from the solar field **10**, through the heat exchanger array **500** in the vessel **101**, and back out to the solar field **10**. In the solar field **10**, the heat transfer fluid passes through piping in the solar collectors, which collect and concentrate the solar radiation by suitable means such as mirrors and/or lenses onto the piping. The heat transfer fluid passing therethrough is heated to a high temperature of as much as 800° F. This hot heat transfer fluid is then pumped through the heat exchanger array **500** in the containment vessel **101**. Heat from the hot heat transfer fluid is transferred into the molten salt contained in the vessel **101**, and the heat transfer oil is cooled. The relatively cold heat transfer oil is recirculated back to the solar field for reheating. During a startup condition, the solid salt in the vessel is heated and melted into a liquid (molten) state, and is then further heated up beyond its melting point. The molten salt thus contains energy in the form of the latent heat of fusion of the salt, as well as the sensible heat of the heated liquid. It is also noted that during the delivery of hot oil from the solar field **10** to the system **100**, some portion of the hot oil may be routed directly to a power generating station **20** by pumps, piping, and valving (not shown) for driving the power generating station **20**.

[0064] On overcast days and during nighttime, this sensible and latent heat is available to be transferred back into the heat transfer oil, and delivered to an electrical power generating station or "power block" **20**. During this portion of the operation, the control valves of the liquid transfer unit **600** are positioned such that heat transfer oil is recirculated by the pump **602** from the power block **20**, through the heat exchanger array **500** in the vessel **101**, and back out to the power block **20**. In the power block **20**, the heat transfer fluid passes through a steam generator, which produces high pressure steam that is used to drive a turbine, which drives an electrical generator. The heat transfer fluid passing therethrough is cooled substantially as its thermal energy is transferred to produce steam. This relatively cold heat transfer fluid is then pumped through the heat exchanger array **500** in the containment vessel **101**, where it is reheated and delivered back to the power block **20**. This cycle may continue, with the thermal energy contained in the molten salt that was transferred from the solar field being used to generate electrical power during nighttime or overcast days, for as long as the molten salt contains enough thermal energy to heat the heat transfer fluid to a temperature suitable for producing steam in the steam turbines of the power block **20**.

[0065] The salt used for thermal energy storage may be a salt mixture, or a eutectic salt mixture. Suitable salts include, without limitation, lithium nitrate, potassium nitrate, sodium nitrate, sodium nitrite, calcium nitrate, lithium carbonate, potassium carbonate, sodium carbonate, rubidium carbonate, magnesium carbonate, lithium hydroxide, lithium fluoride, beryllium fluoride, potassium fluoride, sodium fluoride, calcium sulfate, barium sulfate, lithium sulfate, lithium chloride, potassium chloride, sodium chloride, iron chloride, tin chloride, and zinc chloride, and mixtures and solutions thereof.

[0066] A thermal energy storage system containing a molten salt will be particularly useful in the commercial generation of electrical power if it can contain a minimum of 3,400 MMBTU (million British Thermal Units) for transfer to the power block **20** during nighttime or overcast days. Such a system would have the capacity to maintain generating operation of a 50 megawatt power block for about 6 hours.

[0067] This need for large thermal capacity in a thermal energy storage system results in the previously recited problems of vessel size, related structural loads, high operating temperatures, and repeated thermal cycling. These problems are solved in the thermal energy storage system, containment vessel, heat exchanger array, and related support frames. The containment vessel is comprised of a bottom wall joined to a surrounding containment side wall, and an expandable liner. The expandable liner includes a liner bottom disposed upon the bottom wall of the vessel, the liner bottom having an array of plates. Each of the plates is joined at a portion of its perimeter to a portion of the perimeter of an adjacent plate by a flexible joint. The side wall of the liner is joined to the outer perimeter of the liner bottom and disposed within the containment side wall. An array of heat exchangers is contained within the vessel. The heat exchangers are held within support frames, which are joined to the bottom wall of the vessel, and to a roof truss assembly disposed upon the top of the vessel. In the following disclosure, the containment vessel of the thermal energy storage system **100** will be described first, followed by descriptions of the expandable liner, the thermal insulation of the vessel, the roof truss assembly, and the heat exchanger array. The respective relationships between these components and sub-assemblies to form the overall thermal storage system **100**, and methods for making and assembling the system **100**, vessel, liner, and heat exchanger will also be provided.

[0068] Turning first to FIGS. **2**A-2C, a portion of the thermal energy system **100** is shown. The system **100** is comprised of a containment vessel **101** including a liner **200** and thermal insulation **300**, a roof truss assembly **400**, a heat exchanger array **500**, and a liquid transfer unit **600** (FIG. **1**). For the sake of simplicity of illustration in the cross-sectional view of FIG. **2**A, only two heat exchangers of the heat exchanger array **500**, and only a portion of the roof truss assembly **400** are shown. The system **100** is also shown with a vertical portion having been cut away; the height of the vessel **101**, liner **200**, insulation **300**, and heat exchanger array **500** may be greater relative to the diameter of the vessel **101** than shown in FIG. **2**A.

[0069] Referring to FIGS. **3** and **4**A, in one embodiment, the containment vessel **101** is cylindrical, with the bottom wall of the vessel correspondingly being circular, although other vessel shapes may be employed. The vessel **101** is comprised of a bottom wall **110** joined to a surrounding containment side wall **160**. The bottom wall **110** and containment side wall **160** of the vessel may be made of concrete, and preferably, steel-reinforced concrete comprised of steel rebar embedded in the concrete. The bottom wall **110** of the vessel **101** may be formed so as to decrease in thickness from the central region **112** thereof to the perimeter region **114** thereof. The steel rebar **116** in the bottom wall **110** may be arranged in a layered crossed pattern, with some portion of the rebar **118** positioned proximate to the lower surface **120** of the bottom wall **110**, and some portion of the rebar **122** positioned proximate to the upper surface **124** of the bottom wall **110**.

[0070] The containment side wall **160** may be comprised of vertical rebar **162** and horizontal rebar **164**. In construction of the containment vessel **101**, the bottom wall **110** is constructed first, followed by the side wall **160**. The side wall **160** is joined to the bottom wall **110**. In one embodiment, this may be accomplished by embedding a circular ring of L-shaped rebar **126**, which protrudes upwardly from the upper surface **124** of the bottom wall **110**. When the side wall **160** is poured, the exposed portion of the L-shaped rebar **126** becomes embedded in the side wall **160**, thereby joining the side wall **160** to the bottom wall **110**. In one embodiment, the side wall **160** may be comprised of an lower section **166** and an upper section **168**, with the concrete of the lower section **166** being poured first, followed by the pouring of concrete of the upper section **168**. Some vertical rebar **167** may extend from the lower section **166** upwardly, and become embedded in the upper section **168** when it is poured, thereby joining the lower section **166** to the upper section **168**. In order to withstand the higher fluid pressure from the molten salt at the bottom of the vessel **110**, the distribution of rebar in the lower section **166** may be "denser" than in the upper section **168**, with the lowest portion **169** of the lower section **166** being of greatest density, as shown in FIG. **3**.

[0071] To further provide strength to the vessel **110** to withstand the higher fluid pressure from the molten salt at the bottom thereof, the vessel **110** may be constructed such that the bottom wall **110** and the lower section **166** of the sidewall **160** are "below grade," i.e., buried in the surrounding ground. To construct the vessel in this manner, a pit may be dug in the ground, and the bottom wall **110** and lower section **166** of the side wall **160** constructed as described above. Referring again to FIG. **3**, the bottom wall **110** and lower section **166** of the side wall **160** are then buried with backfill. In one embodiment, a layer of "engineered fill" **40** may be filled in along most of the lower section **166** of the side wall **110** of the vessel **101**. The engineered fill **40** may be uniformly packed such that it exerts a more uniform pressure against the lower section **166** of the side wall **110**. The remaining portion of backfilling is accomplished with the local soil **42** that is available on site. In one embodiment, a layer of geotextile **44** may be disposed between the outer limit of the engineered fill **40** and the backfilled soil **42**. To seal the bottom wall **110** to the sidewall **160**, thereby preventing water vapor or liquid from entering the containment vessel **101**, a seal **128** between them may be made by applying a suitable sealing material around the entire perimeter of the vessel **101** at the outer junction of the bottom wall **110** and side wall **160**. In one embodiment, the seal **128** may be made of rods of bentonite clay formed to the junction.

[0072] Details of one exemplary design of the applicants' thermal energy storage system and containment vessel will now be provided. These details are to be considered as exemplary only, and not limiting. May other designs of the system and vessel are possible, and are within the scope of the present invention. In this embodiment, the side wall **160** of the vessel may be about 26 feet in diameter and about 31 feet high, with a wall thickness of about 1.5 feet. The bottom wall of the vessel has a central region **112** of about 3.5 feet in diameter and 5 feet thick, tapering proportionately in the radial direction as shown in FIG. **3** to a thickness of about 2.5 feet in the outer region **114**. The bottom wall **110** and side wall **160** may be reinforced with #6 rebar ASTM A 615 Grade 60 distributed substantially as shown in FIG. **3**. The concrete used in the bottom wall **110** may be 5000 psi (pounds per square inch) concrete, and the concrete used in the side wall **160** may be 4000 psi (pounds per square inch) concrete. The geotextile may be MIRAFI® 500× sold by the TenCate Geosynthetics Corporation of Pendergrass, Ga., USA. The engineered fill may be naturally occurring material or crushed stone with a gradation of 100% less than 6 inches in size, 70-100% less than 3 inches, 50-100% less than number 4 sieve, and 50% less than number 200 sieve, compacted to 95% per ASTM standard D698.

[0073] The liner **200** of the containment vessel **101** will now be described. The liner is characterized as being able to expand and contract under the loading thereof with molten salt, and in particular, due to the thermal expansion and contraction caused by contact with the molten salt at temperatures up to about 750° F., during the repeated high-temperature thermal cycling of the vessel **101** as previously described herein. The construction and structure of the liner **200** is best understood with reference to FIGS. **5**A-**5**G. The liner **200** is comprised of a liner bottom **210** disposed upon the bottom wall **110** of the vessel, and a liner side wall **260** joined to the outer perimeter of the liner bottom **210**. The liner **200** is disposed within the containment vessel side wall **160**, and covers substantially the entire inner surface of the side wall **160** and the vessel bottom wall **110**. The liner **200** is separated from the containment vessel walls **110** and **160** by thermal insulation, as will be explained subsequently herein.

[0074] The liner bottom **210** is comprised of an array of plates. Each of the plates serves to support the bottom of a heat exchanger frame, which in turn supports a heat exchanger disposed within the containment vessel **101**, as will be described subsequently herein. In the exemplary embodiment described and shown in the drawings herein, the heat exchanger support frames have a square-shaped bottom, and hence the respective "footprints" **201**-**208** of the heat exchanger support frame bottoms are shown in dotted line in FIG. **5**B.

[0075] The plates of the liner bottom **210** and the side wall **260** of the liner **200** are preferably made of metal, which provides sufficient structural strength at high temperatures, and which is joinable at the job site by suitable means such as welding. The particular metal must also be resistant to corrosion by the molten salt. Suitable metals include stainless steel, titanium, and other metals and metal alloys previously cited herein with regard to the liner. In one embodiment, the liner **200** may be made of 316 stainless steel.

[0076] In an embodiment in which the containment vessel **101** and the liner **200** are cylindrical in shape, as depicted in FIGS. **2**A, **3**A, and **5**A, the liner bottom **210** is substantially circular. In such an embodiment, the array of plates of the liner bottom **210** may be comprised of a plurality of radially arranged sector-shaped plates **201**-**217**. Such an array of plates **211**-**217** may be further comprised of a central plate **218**, which is bounded by a portion of each of the radially arranged sector-shaped plates **211**-**217**. In the embodiment depicted in FIGS. **5**A-**5**C, the central plate **218** is square, dimensioned to substantially match the footprint **208** of the central heat exchanger support frame bottom. Alternatively, the central plate **218** may be a polygon. For example, in the embodiment depicted in FIGS. **5**B and **5**C, the central plate may be a heptagon, with the sides of the heptagon being adjacent to a corresponding portion of the perimeter of each of the respective radially-arranged sector plates **211**-**217**. In another embodiment, the central plate **218** may be circular, as indicated by the inner dotted line circle **219** of FIG. **5**C.

[0077] The number of radially arranged sector-shaped plates may be between three and eleven, or more, depending upon the number and size of the heat exchangers of the thermal energy storage system to be disposed within the vessel and supported by the plates. In some embodiments, the number of sides of the polygon of the central plate **218** may be equal to the number of radially arranged sector-shaped plates. In the embodiment depicted in FIGS. **5**A-**5**C, the number of radially arranged sector-shaped plates is seven; along with the central plate **218**, the resulting eight total plates support an array of eight heat exchangers **501**-**508**, as depicted in FIG. **1**.

[0078] It is preferable for the heat exchangers to be firmly supported and located within the containment vessel **101**, particularly if a seismic event such as an earthquake occurs. To achieve this, the bottoms of each of the support stands of the heat exchangers is firmly joined to the bottom wall **110** of the containment vessel **101**. Since this joining is made through the liner bottom **210**, each of the plates **211**-**218** of the liner bottom **210** is also joined to the bottom wall **110** of the containment vessel at the location of its respective heat exchanger **501**-**508** that it supports. With each of the plates **211**-**218** thus fixed in location in the bottom of the containment vessel **101**, when the salt contained therein is heated from ambient temperature to a molten state at up to about 750° F., each of the plates **211**-**218** undergoes a substantial thermal expansion radially outwardly from its respective heat exchanger footprint, as indicated by arrows **299** for plate **213**. If the liner bottom **210** does not have provisions to accommodate this thermal expansion, a problem arises in that the expansion puts the liner bottom under very high stresses, which can cause the liner bottom to warp and/or buckle. With repeated thermal cycling, the liner **200** is prone to cracking and failure.

[0079] This problem is solved by providing a liner bottom **210** wherein each of the plates **211**-**218** is joined at a portion of its perimeter to a portion of the perimeter of an adjacent plate by a flexible joint. Referring again to FIGS. **5**B and **5**C, sectoral plates **211** and **212** are joined at a radial flexible joint **231**. In like manner, successive pairs of sector plates from plates **212**-**217** are joined by radial flexible joints **232**-**237**. The perimeter of the central plate **218** is joined to the respective inner ends of the sector plates **211**-**217** at flexible joints **221**-**224** disposed around such perimeter. In another embodiment (not shown) the central plate **218** may have a heptagonal perimeter, which is joined to the respective inner ends of the sector plates **211**-**217** at seven flexible joints. In another embodiment, the central plate **218** may have a circular perimeter **219**, with the respective inner ends of the sector plates **211**-**217** joined thereto at a circular flexible joint **220**.

[0080] FIG. **5**D is a detailed plan view of an exemplary radial flexible joint **233** between sector plates **213** and **214**, at its intersection with the flexible joint **222** along the perimeter of the central plate **218** of the liner bottom **210**. FIG. **5**E is a detailed cross-sectional view of one embodiment of a flexible joint of the liner bottom, taken along the line **5**E-**5**E of FIG. **5**D. Referring FIGS. **5**D and **5**E, and in one embodiment depicted therein, a flexible radial joint such as joint **233** (or a plate perimeter joint such as joint **222**) may be made by pre-forming a sheet of metal into a first flange **241**, a first riser **242**, a second riser **243**, and a second flange **244**. The first flange **241** is joined to the perimeter region **246** of sector plate

213 by weld 247, and the second flange 244 is joined to the perimeter region 248 of sector plate 214 by weld 249.

[0081] When the plates 213 and 214 expand and contract due to the contact with the cyclically heated and cooled molten salt as indicated by bidirectional arrows 298, the first and second risers 242 and 243 of the flexible joint 233 move correspondingly as indicated by bidirectional arrows 297. The respective perimeter edges 226 and 228 of the sector plates 213 and 214 are sufficiently separated such that they do not contact each other when the thermal cycling occurs. In that manner, the respective plates are free to expand and contract relative to adjacent plates, without introducing high stresses into the liner bottom 210.

[0082] Referring again to FIG. 5E, and in one embodiment, the exemplary flexible joint 233 may be further comprised of an intermediate plate 245 that is formed between the first and second risers 242 and 243. In another embodiment (not shown), an upwardly directed arched transition region may be provided between the first and second risers 242 and 243. Referring again to FIG. 5D, at the intersection of a radial flexible joint such as joint 233, and a center plate perimeter flexible joint such as joint 222, the two joints are joined and sealed to each other by welding.

[0083] The flexible joints may be made by suitable forming means such as a sheet metal brake, or by stamping with a die. The flexible joints may be made of the same material as the sector plates 211-217 and the central plate 218.

[0084] FIG. 5F is a detailed cross-sectional view of an outer end of an exemplary flexible joint 233 of the liner bottom 210, taken along the line 5E-5E of FIG. 5B.

[0085] The outer end 227 of the flexible joint 233 may be sealed with an end cap or plug 229 that is welded in place. In another embodiment, the outer end 227 of the flexible joint 233 may include a curvilinear transition region 238 that is formed to intersect and be welded and sealed to the arcuate corner 250 of the liner bottom. In another embodiment (not shown) a flat beveled corner may be provided instead of an arcuate corner. In another embodiment (not shown), a perimeter flexible joint may be provided around the outer perimeter edges of the sector plates 211-217.

[0086] One aspect of the liner 200 of the containment vessel 101 is that it may be designed in a modular manner, i.e. such that the various pieces of the liner bottom 210 and liner side wall 260 may be cut and formed in a workshop or factory, and then transported to the job site to be assembled. The side wall 260 may be formed from upper and lower arcuate panels that are pre-formed in a shop and welded together at the job site. In one embodiment, the lower panels may be thicker than the upper panels to contain the higher fluid pressures near the bottom of the containment vessel 101. The respective sector plates 211-217, center plate 218, radial flexible joints 231-237, and center plate perimeter joints 221-224 may also all be pre-cut and formed in a shop. The arcuate corner 250 may be made in pieces by forming a suitable length of tubing into a circle of the diameter of the liner, and cutting it axially into quarters, and then into shorter sections. The side wall 260 may be formed in chords for welding into the cylindrical side wall shape at the job site.

[0087] Other configurations of the sectoral portions of the liner bottom 210 are also possible. In one embodiment, the sectoral portions may be formed by suitable means such as by stamping, with a radial flexible joint running through the middle region thereof. In such an instance, the welded seams between them may intersect the heat exchanger support plate locations. In another embodiment, each sectoral section could be provided with a flexible joint formed along one radial edge, with the other radial edge being a simple straight edge. In that manner, when the sectoral plates are joined together, a flexible joint is provided between each of them. Additionally, the center plate 218 could be formed with its perimeter flexible joints integrally formed therein. Many other configurations are possible, with the operative requirement being that the respective adjacent plates are separated by flexible joints to accommodate the expansion and contraction during thermal cycling.

[0088] Details of one exemplary design of the applicants' liner 200 for a containment vessel 101 will now be provided. These details are to be considered as exemplary only, and not limiting. May other designs of the liner 200 are possible, and are within the scope of the present invention. In this embodiment, the liner 200 is dimensioned to match the previously described exemplary design of the containment vessel 101. The side wall 260 of the liner 200 may be about 22.5 feet in diameter and about 31 feet high. All panels of the exemplary liner are of 316 stainless steel. Lower panels of the liner preferably may have a minimum wall thickness of about ¼ inch, and upper panels of the wall have a minimum thickness of about ⅛ inch. The seven sectoral plates 211-217 and center plate 218 of the liner 200 have a minimum thickness of about ⅛ inch.

[0089] The flexible joints of the liner are formed from 14 gauge 316 stainless steel, with a flange ½ inches wide, a riser height of 2¼ inches, and an intermediate plate width of ½ inch. The radial flexible joints are made about 10% to 11 feet long as needed to match the lengths of the radial edges of the sector plates 211-217. The center plate 218 is a square of about 4 feet on a side, with the center plate flexible joints of corresponding length; although as noted previously, the center plate may be circular or polygonal, so long as it is large enough to place a heat exchanger frame thereupon. The radius of the edge transition 250 between the liner bottom 210 and the liner side wall 260 is about 4 inches, and may be made from a circularly formed 8-inch diameter stainless steel pipe that is cut into shorter lengths and sectioned lengthwise in quarters. In fabrication, all exposed intersections and/or overlaps between adjacent components are fully welded, in order to provide a maximum structural strength and leak-free liner 200 within the containment vessel 101.

[0090] It is further noted that the liner of the instant containment vessel is not limited to a use in which each of the bottom plates is fixed to a supporting surface beneath them. In other applications, the liner bottom may be supported by a supporting surface without the plates being joined to the surface, or the liner itself may serve as a vessel in which the expandable bottom serves to reduce stresses from thermal expansion and contraction, and/or mechanical loading from the liquid contained therein.

[0091] The thermal insulation 300 of the containment vessel 101 will now be described. The insulation 300 is characterized in that the inner portion of the side wall insulation is compressible and expandable, so as to accommodate the radial thermal expansion and contraction of the liner over the range of operating temperatures of the salt contained in the vessel as previously described herein. The construction and structure of the thermal insulation 300 is best understood with reference to FIGS. 6A-6C, and FIGS. 4A-4B.

[0092] Referring first to FIG. 6A, the vessel 101 may be provided with a layer of bottom thermal insulation 310. The bottom insulation **310** may be a castable refractory insulation that is poured and leveled on the bottom slab **110** of the vessel **101**. Suitable castable refractory insulations include, without limitation, materials containing a combination of titanium oxide, magnesium oxide, calcium oxide, iron (III) oxide, (cristobalite) silica dioxide, aluminum dioxide, and (tridymite) silicon dioxide. Referring also to FIG. **4**A, when the refractory insulation is poured, a set of support plates **131-138** may be embedded in the upper surface **312** of the cast insulation. FIG. **4**B is a detailed cross sectional view of one exemplary support plate **131** for supporting a heat exchanger on the bottom of the containment vessel **101**, taken along line **4**B-**4**B of FIG. **4**A. The support plate **131** may be further comprised of an array of anchor studs **141** which extend downwardly from the lower surface **142** thereof. The anchor studs **141** may be arranged in rows and columns. In fabrication of the vessel **101**, before the bottom refractory insulation **310** is poured, the various support plates **131-138** may be placed in the desired locations to receive and support the array of heat exchangers. Each of the support plates **131-138** may be placed upon sets of support stands **143**, which temporarily hold the support plates **131-138** in place until the bottom insulation **310** is poured and cured. The support stands **143** may be made of metal sheet or wire. After the insulation **310** is cured, the anchor studs **141** are embedded in the insulation **310**, and the top surfaces of the support plates **131-138** and the top surface **312** of the insulation are substantially flush, i.e. coplanar. The anchor studs **133** serve to firmly secure the support plates **131-138** in place in the bottom insulation **310**, which in turn secure the lower portion of the respective heat exchangers and support frames in place. This aspect is beneficial in preventing the heat exchangers from moving substantially during a seismic event. In the event that a layer of bottom insulation **310** is not provided, the heat exchanger support plates **131-138** may be embedded directly into the vessel bottom **110** in a similar manner.

[0093] In the embodiment depicted in FIG. **4**B, the liner bottom **210** is also shown being disposed on the layer of bottom insulation **310**. One or more layers of thermal cloth insulation may also be provided between the liner bottom **210** and the bottom insulation **310**. These layer(s) of thermal cloth provide a reduced-friction surface for the liner bottom **210** to expand and contract along during thermal cycling.

[0094] Referring now to FIGS. **6**B and **6**C, the thermal insulation **300** of the vessel **101** is further comprised of side wall insulation **360**. In one embodiment, the side wall insulation may be comprised of a first, outer layer of batt insulation **362** disposed on the side wall **160** of the vessel **101**. In construction, the batt insulation **362** is temporarily adhered to the side wall **160**. Alternatively, a temporary form may be constructed and a layer of side wall refractory insulation **364** may be cast. Following the pouring and curing of the side wall refractory insulation **364**, a second, inner layer **366** of batt insulation may be applied to the inner surface **368** of the side wall refractory insulation **364**. To complete the side wall refractory insulation **364**, a cap **370** may be poured at the top portion thereof.

[0095] The liner **200** may then be constructed within the vessel **101** as previously described herein. The liner bottom **210** is substantially contiguous with the bottom insulation **310**, with a thermal cloth **314** optionally disposed therebetween. The liner side wall **260** is substantially contiguous with the side wall insulation **360**. During construction of the liner, additional batt insulation **372** may be disposed in the corner formed between the bottom insulation **310**, the side wall insulation **360**, and the liner wall transition **250**.

[0096] One aspect of the combination of the liner **200** and the vessel insulation **300** is that the inner side wall insulation **366** is compressible and expandable, so as to accommodate the radial thermal expansion and contraction of the liner **200**, and the resulting motion of the liner side wall **260** over the range of operating temperatures of the salt contained in the vessel **101**. Referring to FIGS. **6**B and **6**C, it can be seen that the liner side wall **260** moves radially inwardly and outwardly during repeated thermal cycling, and is followed by the side wall insulation **366**, as indicated by bidirectional arrows **399**. Another aspect of the liner **200** is that the upper edge **262** of the liner side wall **260** moves vertically as indicated by bidirectional arrow **296** of FIG. **6**B as the liner side wall **260** expands and contracts during the thermal cycling.

[0097] To accommodate this movement, during construction of the liner **200** at ambient temperature, the upper edge **262** of the liner side wall **260** is terminated at a distance below the upper edge **374** of the insulation cap **370**. In that manner, the upper edge **262** of the liner side wall **260** can be displaced to the extent indicated at **262**E, without contacting and binding against any objects disposed at the top of the vessel **101**.

[0098] Details of one exemplary design of the applicants' thermal insulation **300** for a containment vessel **101** will now be provided. These details are to be considered as exemplary only, and not limiting. May other designs of the thermal insulation **300** are possible, and are within the scope of the present invention. In this embodiment, the thermal insulation **300** is dimensioned to match the previously described exemplary design of the containment vessel **101**. In this embodiment, the bottom insulation **310** may be an aluminum-silicate cement bonded castable refractory insulation, such as, for example, "RESCOCAST 6," manufactured and sold by Resco Products Inc., of Pittsburgh Pa., USA. The bottom insulation **310** may be about 9% inches thick. The castable side wall insulation **364** may be of the same material at a thickness of about 6 inches. In construction, the side wall insulation **260** may be built up vertically in several sequences of application of outer batt insulation **362**, poured cast insulation **364**, and inner batt insulation **366**. The side wall batt insulation **262** and **266** may be made of alumina, zirconia, and silica spun ceramic fibers formed into a blanket, such as, for example, DURABLANKET® S insulation manufactured and sold by Unifrax LLC of Niagara Falls, N.Y., USA. The layers **362** and **366** of side wall batt insulation may be about 1 inch thick as applied, with it being understood that the outer batt insulation layer **362** may be compressed to some extent by the poured side wall insulation **364**, and the inner batt insulation layer is compressed during thermal expansion of the liner **200**. The thermal cloth **314** may be a refractory silica cloth, such as, for example, REFRASIL® C-Series cloth manufactured and sold by Hitco Carbon Composites, Inc. of Gardena, Calif., USA.

[0099] The roof truss assembly **400** of the thermal storage system **100** and containment vessel **101** will now be described. One aspect of the roof truss assembly **400** is that it provides a structure for covering the containment vessel **101**, thereby retaining the heat energy therein, and protecting the contents thereof from exposure to weather and/or to unauthorized access. Another aspect of the roof truss assembly **400** is that it provides lateral support to the heat exchanger support frames, while permitting such frames to expand vertically due to thermal expansion. The roof truss assembly **400** is best understood with reference to FIG. 2A, and FIGS. 7A-7D. Referring first to FIG. 2A, which depicts a portion of the assembly, the roof truss assembly **400** is comprised of a plurality of radially disposed roof trusses **410**. The roof truss assembly may further include a central cage **480** joined to each of the roof trusses **410**.

[0100] Referring now to FIG. 7A, and in the embodiment depicted therein, the roof truss assembly **400** may be comprised of radially disposed roof trusses **411-417**.

[0101] In one embodiment, the roof truss assembly may include seven roof trusses, and seven linkages provided therebetween, for providing support to the seven heat exchangers **501-507** (see FIG. **1**). Referring also to FIG. **7**B, an exemplary roof truss **411** is comprised of a framework **420** of members, including an upper member **421**, a lower member **422**, a proximal upright member **423**, a distal upright member **424**, upright support struts **425** and **426**, and diagonal support struts **427** and **428**. The various members may be made of tubing, angle (L), channel, I-beam or other structural shapes. The members may be made of a metal, such as steel or aluminum. The members are joined to each other by suitable means such as by brackets and fasteners, or by welding.

[0102] Referring to FIGS. **2** and **7**A, the central cage **480** of the roof truss assembly **400** is comprised of an upper ring **482**, a lower ring **484**, and a plurality of vertical struts **486** joined to the upper ring **482** and the lower ring **484**. Each of the proximal upright members **423** of the roof trusses **411-417** is joined to the upper ring **482** and the lower ring **484** of the central cage **480**.

[0103] A network of structural members is provided between each of the respective pairs of roof trusses. For example, referring again to FIG. **7**A, a network **430** of structural members is provided between roof trusses **411** and **417**. The network **430** is comprised of an inner tangential member **431**, an outer tangential member **432**, and first, second, third, and fourth radial members **433-436**. The network **430** of structural members serves to join the respective pairs of roof trusses to each other, and to an outer circumferential ring **438**. Additionally, the inner and outer tangential members **431** and **432**, and the first and second radial members **433** and **434** are dimensioned and positioned so as to form a structural frame **440** for supporting a heat exchanger. Details of this structural frame **440** will be provided subsequently herein with reference to FIGS. **11**A-**11**C.

[0104] The third and fourth radial members **435** and **436** of network **430** are joined to the outer circumferential ring **438**. The ends of the inner and outer tangential members **431** and **432** may be joined to the respective lower members **422** of the roof trusses **411** and **417**. Additionally, second upper networks (not shown) of structural members that are similar to the first network **430**, and comprise inner and outer tangential members, radial members, and an outer ring member may be provided, wherein each of the upper networks are joined to the respective upper members **421** of adjacent pairs of roof trusses. The various members of the networks **430** may be made of tubing, angle (L), channel, I-beam or other structural shapes. The members may be made of a metal, such as steel or aluminum. The members are joined to each other by suitable means such as by brackets and fasteners, or by welding.

[0105] The roof truss assembly **400** may also be provided with a top sheet covering (not shown) disposed upon the upper members **421** of the roof trusses, and extending out to overhang the outer ring **438**; and a side covering (not shown) around the outer ends of the roof trusses. In that manner, the components of the thermal storage system **100** contained therein are protected from exposure to weather and/or to unauthorized access. The top sheet covering and side coverings may be provided in multiple pieces, which are joined and sealed to each other, and to the roof truss assembly at the job site. Referring again to FIG. **2**A, the roof truss assembly may also be provided with a bottom sheet covering **442** which is joined to the lower members **422** of the roof trusses. The bottom sheet **442** provides a protective barrier to prevent personnel from falling into the containment vessel during inspection and service, and also provides a structural support, upon which thermal insulation can be disposed, to further conserve the heat energy contained within the vessel **101**. Referring again to FIG. **7**A, the roof truss assembly **400** may be further provided with a salt fill port **447**, which extends downwardly through the bottom sheet **442**. The salt fill port **442** may be provided with a removable cap (not shown). In that manner, the vessel **101** can be filled with granular solid salt through the fill port **442** at the time of startup of the thermal storage system **100**.

[0106] The roof truss assembly **400** is supported by the upper edge of the vessel side wall **160**. The roof truss assembly may be configured and supported so as to be radially expandable with respect to the containment side wall of the vessel. Referring again to FIG. **4**A, the vessel side wall **160** is provided with a plurality of truss bearing plates joined to the top surface **161** thereof. In the embodiment of the thermal storage system **100** depicted in FIGS. **4**A and **7**A-**7**D, the upper surface **161** is provided with seven bearing plates **171-177** positioned to receive and support corresponding bearing plates provided on each of the roof trusses **411-417**.

[0107] FIG. **7**C is a detailed side elevation view of an exemplary bearing support plate **171** for supporting a roof truss at the top surface **161** of the side wall **160** of the containment vessel **101**; and FIG. **7**D is a top view of the bearing support plate **171** of FIG. **7**C, taken along line **7**D-**7**D of FIG. **7**C, and shown supporting a roof truss **411**. The bearing support plate **171** may be bonded to the upper surface **161** of the side wall **160** by grout **178**. A threaded rod **179** may be embedded in the side wall **160** and extend upwardly through the support plate **171**, to which it may be joined, and beyond above the support plate **171**. Two threaded rods **179** and **180** may be so provided. The lower member **422** of the roof truss **411** is provided with a corresponding bearing support plate **446** that rests upon bearing support plate **171**.

[0108] In the embodiment depicted in FIGS. **7**C and **7**D, the lower member **422** is comprised of first and second back-to-back angle L pieces **448** and **449**, which are provided with slots **450** and **451** formed therein. Threaded rods **179** and **180** extend upwardly through respective slots **450** and **451**. When the thermal energy system **100** is in operation and contains hot molten salt, the roof truss assembly **400** is heated due to its proximity to the molten salt. The roof truss assembly **400** undergoes thermal expansion and contraction during the thermal cycling, with each of the roof trusses such as roof truss **420** expanding and contracting. The lower member **422** is free to expand and contract as indicated by bidirectional arrows **499**, with the slots **450** and **451** permitting such motion with respect to the respective threaded rods **179** and **180** which are embedded in the vessel side wall **160**. The mated bearing support plates **171** and **446** may be provided with a suitable lubricant to facilitate the sliding action between them. In one embodiment, the bearing plates are provided with a fluoropolymer coating such as TEFLON®. Other anti-friction coatings may be used. The threaded rods **179** and **180** may also be provided with retaining nuts (not shown), which are loosely disposed above the respective angle L pieces **448** and **449**.

[0109] One aspect of the roof truss assembly **400** is that it may be of modular construction. The roof trusses **411-417**, the central cage **480**, the various pieces of the networks between the roof trusses, and the top, bottom, and side protective sheets may all be fabricated in a shop or factory and shipped to the job site for simple and quick assembly.

[0110] The heat exchanger array **500** of the thermal storage system will now be described. The heat exchanger array **500** is shown schematically in FIG. **1**, and in elevation, plan and cutaway perspective views in FIGS. **2**A, **2**B, and **2**C. For the sake of simplicity of illustration, only two heat exchangers are shown in FIG. **2**A; and the roof truss assembly **400** is not shown in FIGS. **2**B and **2**C. The heat exchanger array **500** is comprised of a plurality of heat exchangers disposed in the containment vessel **101**, and a plurality of heat transfer fluid delivery and exit pipes, which are connected to the heat transfer fluid supply unit **600**. In the embodiment depicted in FIGS. **1-2**C, the heat transfer array is comprised of eight heat exchangers disposed in a circular arrangement of seven heat exchangers **501-507**, with the eighth heat exchanger **508** being disposed in the center of the arrangement. Pairs of the heat exchangers may be connected in series, such as exchangers **501** and **507**, **502** and **503**, **508** and **504**, and **506** and **505**. Heat transfer fluid is supplied to the pairs of heat exchangers through respective delivery pipes **511-514** and withdrawn from the pairs of heat exchangers through respective exit pipes **516-519**. Other arrangements of more or fewer heat exchangers, and other connection arrangements with or without connections in series may be suitable.

[0111] Each of the heat exchangers **501-508** may be supported by a support frame, which may be joined at the bottom thereof to the liner bottom **210**, and at the top thereof to the roof truss assembly **400**. FIGS. **8** and **9** are perspective views of an exemplary heat exchanger **501** and support frame **540**. The heat exchanger **501** is comprised of a plurality of heat exchanger tubes **520**, which are sealed by welding, for example, to a header plate **522**. The tubes **520** may be U-tubes, i.e., formed into U-shapes, and joined at their respective ends to the header plate **522**. The tubes may be supported and aligned along their lengths by several tube alignment sheets **524**, **526**, and **528**. A cap **530** is joined to the header plate **522**, and is provided with an inlet port **532**, and outlet port **534**, and internal passageways to direct the heat transfer fluid into and out of the U-tubes **520**. In operation, heat transfer fluid is delivered into inlet port **532**, through the inlets of the respective U-tubes **520** that are jointed to the header plate **522**, through the outlets of the U-tubes **520**, and out the outlet port **534**.

[0112] The heat exchangers **501-508** may be constructed of a variety of materials, for example, but not limited to plain carbon steels; steels alloyed with copper, manganese, molybdenum, nickel, silicon, tungsten, titanium, vanadium and chromium, individually or in any combination thereof such as chromium-molybdenum, or nickel-chromium-molybdenum; and stainless steels.

[0113] Referring now to FIG. **9**, a support frame **540** is provided for receiving and supporting the heat exchanger **501**. The support frame **540** is comprised of a base plate **541**, and a plurality of upright support columns **542-548**, which are joined to each other by a network of diagonal cross struts **550** and horizontal cross struts **552**. In the embodiment depicted in FIG. **9**, the support plate **541** is square, and four upright support columns **542-548** are provided. Other shapes of base plate **541** and arrangements of support columns **542** et seq. and cross struts **550**/**552** are possible.

[0114] Referring also to FIG. **4**B, the base plate **541** is provided with a plurality of mounting holes **554**, through which mounting studs **556** extend. The mounting studs **556** are joined to the heat exchanger support plate **131**, and to the liner bottom **210**. When the heat exchanger **501** and heat exchanger support frame **540** are placed in operating position in the containment vessel **101**, nuts **558** are used to secure them in place. FIG. **10** is a perspective view of the heat exchanger **501** assembled to the support frame **551**. The heat exchanger **501** and the support frame **540** are modular in that they can be separately fabricated and then joined to each other. The heat exchanger **501** and the support frame **540** can be fabricated in a shop and then joined to each other to be shipped to the job site. The entire assembly can then be placed in the containment vessel; or they can be separated, and the support frame **540** first installed in the containment vessel, followed by the placement of the heat exchanger **501** into the support frame **540**. The cap **530** of the heat exchanger **501** may be provided with a lug (not shown) for engagement with a lifting hook for such placement purposes.

[0115] In the embodiment depicted in FIGS. **8-10**, the heat exchanger is provided with engagement sleeves **556** which are joined to the underside of the header plate **522** proximate to the corners thereof. When the heat exchanger **501** is lowered into the support frame **540**, the upper ends of the support columns **542-548** are received in the engagement sleeves **556**. The support columns **542-548** may be further secured therein by bolts (not shown) which pass through the engagement sleeves **556** and upper ends of the support columns **542-548**.

[0116] One aspect of the combination of the heat exchangers **501-508**, heat exchanger support frames **540** and the roof truss assembly **400** is that for seismic stability, each of the heat exchangers frames may be constrained to prevent movement in the horizontal direction by the roof truss assembly **400**, while simultaneously being permitted to expand and contract in the vertical direction due to their exposure to the range of operating temperatures of the salt contained in the vessel **101**. The constraining of a heat exchanger and its support frame in the horizontal direction while permitting it to move in the vertical direction is enabled by providing a fastening arrangement at the heat exchanger header plate which joins the heat exchanger and support frame to the roof truss assembly in a manner that fixes the horizontal location of the upper portion of the heat exchanger and frame with respect to the truss assembly, while permitting the heat exchanger header plate and upper portion of the frame to translate vertically up and down with respect to the truss assembly.

[0117] This is best understood with reference to FIGS. **7**A, **10**, and **11**A-**11**C. As was described previously with reference to FIG. **7**A, a network **430** of structural members is provided between adjacent roof trusses, such as network **430** between roof trusses **411** and **417**. A frame **440** is formed by and within network **430** and dimensioned to substantially match the perimeter of the heat exchanger header plate **522**.

[0118] Referring in particular to FIGS. **11**A-**11**C, the heat exchanger header plate **522** is provided with a plurality of brackets **560** joined proximate to the perimeter thereof by suitable means such as welding. The brackets **560** may be

L-shaped, with a vertical leg **561** and a horizontal leg **562**. The vertical legs **561** of the brackets **560** are provided with elongated slots **563**, which transition into relief slots **564** that are formed in the horizontal legs **562**. The brackets **560** are joined to the four members **431-434** of the frame **440** that is formed in the network **430** of structural members by bolts **565** and nuts **566**. The shanks **567** of the bolts **565** (both shown in dotted line in FIG. **11**B) are disposed in the elongated slots **563** of the brackets **560**. When the salt in the thermal energy storage system is heated to a molten state from ambient temperature, the support frame **540** of the heat exchanger expands upwardly, which raises the header plate **522** of the heat exchanger **501**; and subsequently, during thermal cycling, the header plate **522** rises and falls with the vertical expansion and contraction of the support frame **540**. This rising and falling of the header plate **522** of the heat exchanger **501** is permitted by the sliding motion of the bolts **565** in the vertical slots **563** of the brackets **560**, as indicated by bidirectional arrow **599**. Simultaneously, the heat exchanger **501** and its support frame **540** are prevented from horizontal motion in the event of a seismic disturbance. It is to be understood that the heat exchangers **502-507** are supported in substantially the same manner; and that a frame similar to frame **440** is provided within the central cage **480** to support the central heat exchanger **508** in substantially the same manner.

[0119] Details of one exemplary design of a suitable heat exchanger and support frame of the applicants' thermal energy storage system and containment vessel will now be provided. These details are to be considered as exemplary only, and not limiting. Many other designs of the system and heat exchangers are possible, and are within the scope of the present invention. This exemplary embodiment is designed to match the previously described exemplary designs of the containment vessel **101**, liner **200**, insulation **300**, and roof truss assembly **400**. The U-tubes **520** and tube alignment sheets **524/526/528** of the heat exchanger **501**, and the columns **542-548**, cross struts **550/552**, and base plate **541** of the support frame **540** are made of "2¼ Cr-1 Mo alloy," (also known as ASME SA-213-T22 tubing), a steel alloy containing molybdenum and chromium, which is particularly suitable for high temperature pressure vessels in corrosive environment. The heat exchanger cap **530**, header plate **532**, and engagement sleeves **556** are made of SA 516 GR 70 carbon steel.

[0120] The heat exchanger **501** is about 32 feet long from the top of the cap **530** to the distal ends of the U-tubes **520**. The U-tubes are made of 2¼ Cr-1 Mo alloy tubing having an outside diameter of ¾ inch and a wall thickness of 0.083 inch and have lengths between about 28 to about 30 feet. The header plate **522** is a square having a side of about 41 inches long and a thickness of about 2⅜ inches. The heat exchanger comprises about 336 U-tubes having a total combined length of about 20,000 feet. The heat exchanger is designed per the ASME Boiler and Pressure Vessel Code, Section VIII, Division 1, 2007 Edition, to operate at a maximum allowed working pressure of 250 pounds per square inch. Following fabrication of a heat exchanger or various components thereof, such as the cap **530** and header plate **522**, the heat exchanger or components may be heat treated to relieve residual stresses at various welds, tube bends, and other locations. In one embodiment, the heat exchanger cap and header plate are heat treated at 1100° F. for about one hour per inch of thickness of the header plate (i.e. about 2 hours and 22 minutes for the above exemplary heat exchanger cap **530** and header plate **522**). In one embodiment, the heat exchanger tubes are heat treated at about 1250° F. for about one hour per inch of diameter of the tubes (i.e. about ¾ hour for the above exemplary heat exchanger tubes).

[0121] The support frame base plate **541** is a square having a side of about 36 inches long and a thickness of about ¾ inch. The columns **542-548** are of ANSI 3 inch NPS (nominal pipe size) pipe having a wall thickness of about 0.300 inches, and the cross struts **550** and **552** are of ANSI 1 inch NPS pipe having a wall thickness of about 0.179 inches.

[0122] Referring to FIG. **2**A, when the placement and assembly of the heat exchangers **501-508** and support frames, and the assembly of the roof truss assembly **400** are complete, a layer of batt insulation **470** is applied to the upper surface of the bottom sheet of the roof truss assembly **400**, and the caps **530** of the heat exchangers **501-508**.

[0123] FIG. **12** is a flow chart depicting a method of making the applicants' thermal energy storage system. It is to be understood that although the steps of the method **700** of FIG. **12** are illustrated in a serial order, the method is not limited to being done in the order depicted in FIG. **12**. Certain steps of the method **700** may be performed in parallel, and/or in orders other than depicted in FIG. **12**.

[0124] One aspect of the method is that because the system is of a modular design, a large share of the system components may be fabricated in a shop of factory environment. In step **710**, the modular components including the heat exchangers **501-508**, heat exchanger support frames **540**, vessel liner **200**, and roof trusses **411-418**, networks **430** and center cage **480** of the roof truss assembly **400**, and the heat transfer fluid delivery system **600** are fabricated. This may be done in parallel while the excavation and grading **720** of the site is performed. If the containment vessel **101** is to be partially below grade, a containment pit may be dug. The containment vessel bottom wall **110** and side wall **160** may then be constructed in step **740** while the modular components are shipped to the construction site in step **730**. The thermal insulation **300** may then be applied to the vessel bottom **110** and/or vessel side wall **160** in step **750**. The liner **200** may then be fabricated from the pre-fabricated bottom plates, flexible joints, and side wall sections in step **760**. The pre-fabricated modular heat exchanger support frames **540** and heat exchangers **501-508** may then be placed in the containment vessel in step **770**, and the roof truss assembly may be assembled from pre-fabricated trusses and a central cage in step **780**. The heat transfer fluid delivery system may then be constructed and connected to the heat exchangers in step **790**. The thermal energy storage system **100** may then be connected to the solar field **10** and the electrical generation station **20**, and started up in step **800**. The system **100** may be used to store thermal energy from the solar field **10**, and release thermal energy to the electrical generation station **20**.

[0125] It is, therefore, apparent that there has been provided, in accordance with the present invention, a vessel for containing a thermal energy storage liquid, a thermal energy storage system comprising such vessel, and methods for making and using the vessel and thermal energy storage system. Having thus described the basic concept of the invention, it will be rather apparent to those skilled in the art that the foregoing detailed disclosure is intended to be presented by way of example only, and is not limiting. Various alterations, improvements, and modifications will occur and are intended to those skilled in the art, though not expressly stated herein. These alterations, improvements, and modifications are intended to be suggested hereby, and are within the spirit and scope of the invention. Additionally, the recited order of processing elements or sequences, or the use of numbers, letters, or other designations therefore, is not intended to limit the claimed processes to any order except as may be specified in the claims.

We claim:

1. A vessel comprising a bottom wall joined to a surrounding containment side wall, and a liner comprising:

a. a liner bottom disposed upon the bottom wall of the vessel, the liner bottom having an outer perimeter and comprising an array of plates, each of the plates joined at a portion of its perimeter to a portion of the perimeter of an adjacent plate by a flexible joint; and

b. a liner side wall joined to the outer perimeter of the liner bottom and disposed within the containment side wall.

2. The vessel of claim **1** wherein the vessel is cylindrical, the vessel bottom wall is circular, and the array of plates of the liner bottom is comprised of a plurality of radially arranged sector-shaped plates.

3. The vessel of claim **2**, wherein the array of plates is further comprised of a central plate bounded by a portion of each of the radially arranged sector-shaped plates.

4. The vessel of claim **3**, wherein the central plate is circular.

5. The vessel of claim **3**, wherein the central plate is a polygon.

6. The vessel of claim **5**, wherein the number of radially arranged sector-shaped plates is between three and eleven inclusive.

7. The vessel of claim **6**, wherein the number of radially arranged sector-shaped plates is seven.

8. The vessel of claim **5**, wherein the number of sides of the polygon is equal to the number of radially arranged sector-shaped plates.

9. The vessel of claim **1**, wherein each of the flexible joints is comprised of a first riser joined to the portion of perimeter of a first plate, and a second riser joined to the portion of perimeter of a second plate adjacent to the first plate, and wherein the first riser also joined to the second riser.

10. The vessel of claim **9**, wherein the flexible joints are further comprised of intermediate plates disposed between and joined to the respective first risers and the second risers.

11. The vessel of claim **1**, wherein the liner is made of a material selected from the group consisting of plain carbon steels; steels alloyed with copper, manganese, molybdenum, nickel, silicon, tungsten, titanium, vanadium and chromium chromium-molybdenum alloy steel, nickel-chromium-molybdenum alloy steel, and stainless steels.

12. The vessel of claim **1**, wherein the liner is made of stainless steel.

13. The vessel of claim **1**, wherein each of the plates of the liner bottom is joined to the bottom wall of the vessel.

14. The vessel of claim **1**, further comprising bottom insulation disposed between the bottom wall of the vessel and the liner bottom, and side wall insulation disposed between the containment side wall of the vessel and the liner side wall.

15. The vessel of claim **14**, wherein the side wall insulation is compressible and expandable.

16. The vessel of claim **1**, further comprising an array of heat exchangers disposed in the vessel, each of the heat exchangers supported by a support frame joined to one of the plates of the array of plates of the liner.

17. The vessel of claim **16**, wherein pairs of heat exchangers of the array of heat exchangers are connected in series.

18. A method for making a vessel at a vessel construction site, the method comprising:

a. pre-fabricating modular components of the vessel at a site other than the construction site, wherein the modular components include vessel liner components;

b. preparing ground of the construction site to receive the vessel;

c. constructing a bottom wall and a side wall of the vessel;

d. transporting the modular components to the construction site; and

e. assembling the vessel liner components to form a vessel liner within the vessel, the vessel liner comprising a liner bottom disposed upon the bottom wall of the vessel, wherein the liner bottom has an outer perimeter and comprises an array of plates, each of the plates joined at a portion of its perimeter to a portion of the perimeter of an adjacent plate by a flexible joint, and a liner side wall joined to the outer perimeter of the liner bottom and disposed within the containment side wall.

19. The method of claim **18**, further comprising placing heat exchangers supported by support frames into the vessel.

20. A method for storing thermal energy comprising:

a. providing a vessel comprised of:

i. a bottom wall joined to a surrounding containment side wall;

ii. a liner comprising a liner bottom disposed upon the bottom wall, the liner bottom having an outer perimeter and comprising an array of plates, each of the plates joined at a portion of its perimeter to a portion of the perimeter of an adjacent plate by a flexible joint; and a liner side wall joined to the outer perimeter of the liner bottom and disposed within the containment side wall; and

iii. an array of heat exchangers disposed in the vessel;

b. filling a portion of the open volume around the heat exchangers with a thermal storage medium;

c. connecting a heat transfer fluid delivery system to the heat exchangers; and

d. connecting the heat transfer fluid delivery system to a thermal energy source, thereby transferring thermal energy into the thermal storage medium.

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