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(54) **HIGH-DENSITY, HIGH-TEMPERATURE  
THERMAL ENERGY STORAGE AND  
RETRIEVAL**

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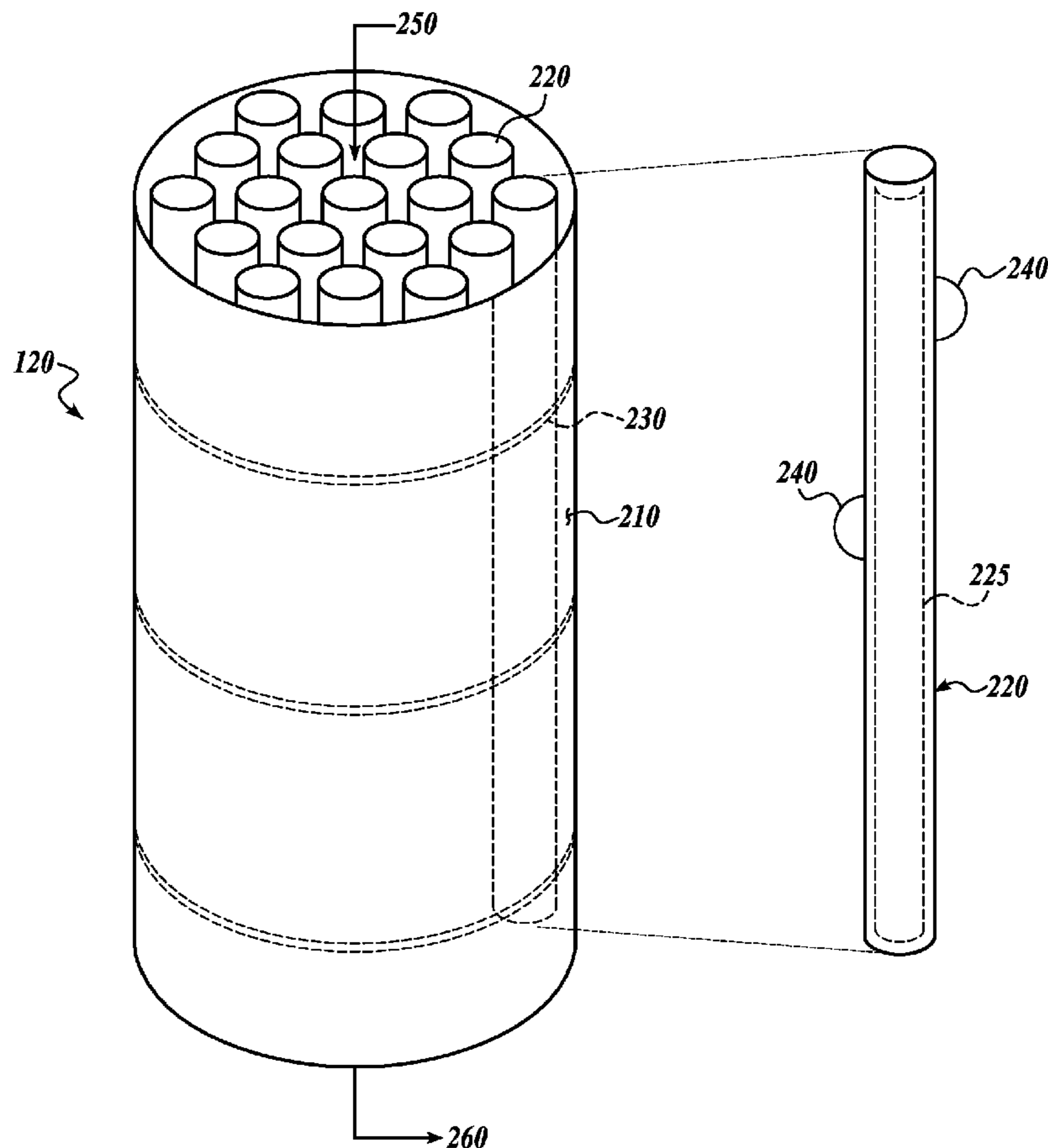
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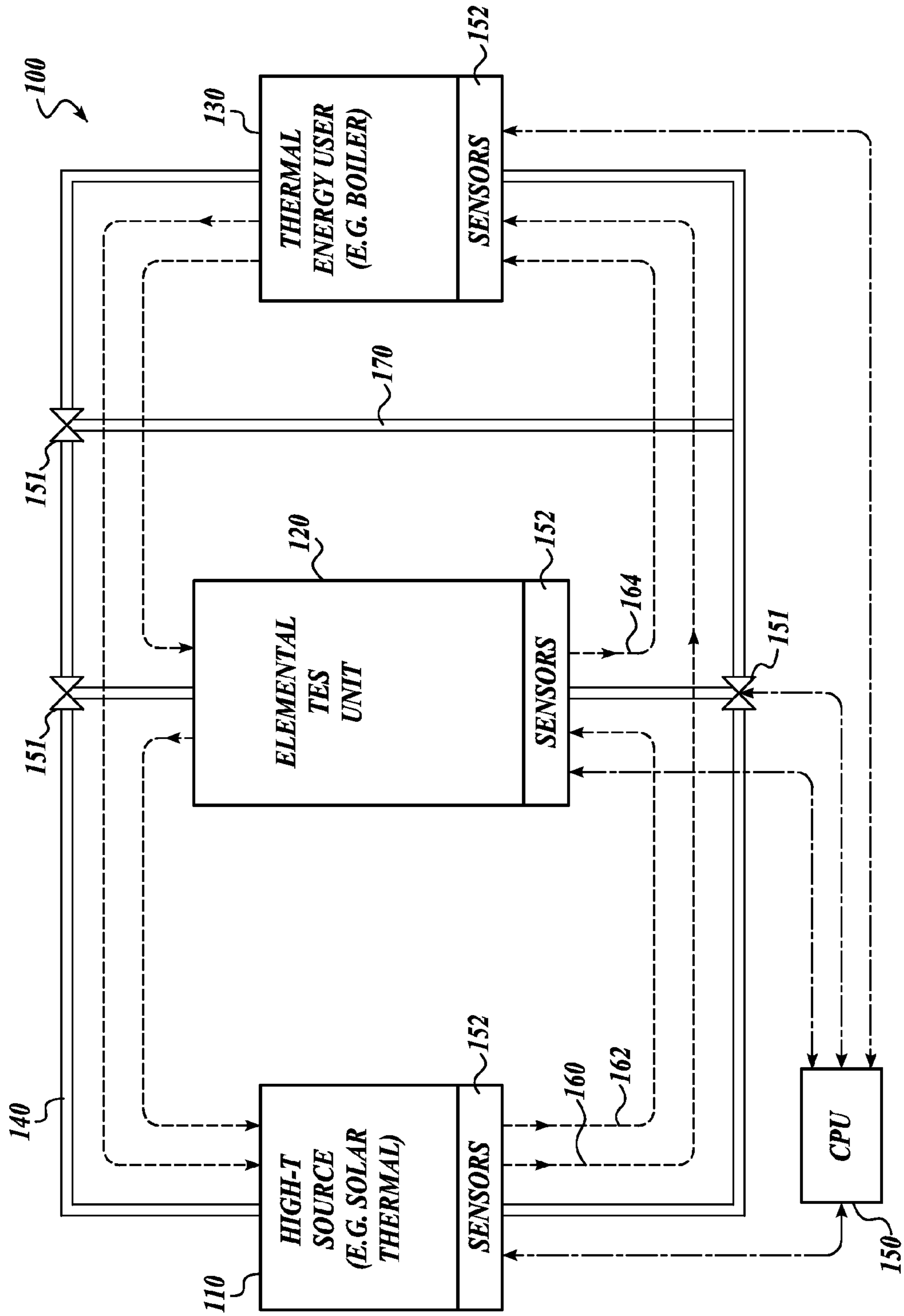
(57) **ABSTRACT**

A thermal energy storage (TES) system that uses an elemental material (e.g., elemental sulfur) as an energy storage material is disclosed. The energy storage material is separately stored from a heat transfer fluid. For example, the energy storage material can be sealed within one or more corrosion-resistant containers that are further contained within an outer shell. A heat transfer fluid flows through the shell via an inlet and an outlet, over and around the containers. A TES system may include an energy source that receives thermal energy intermittently, and a steam generator.

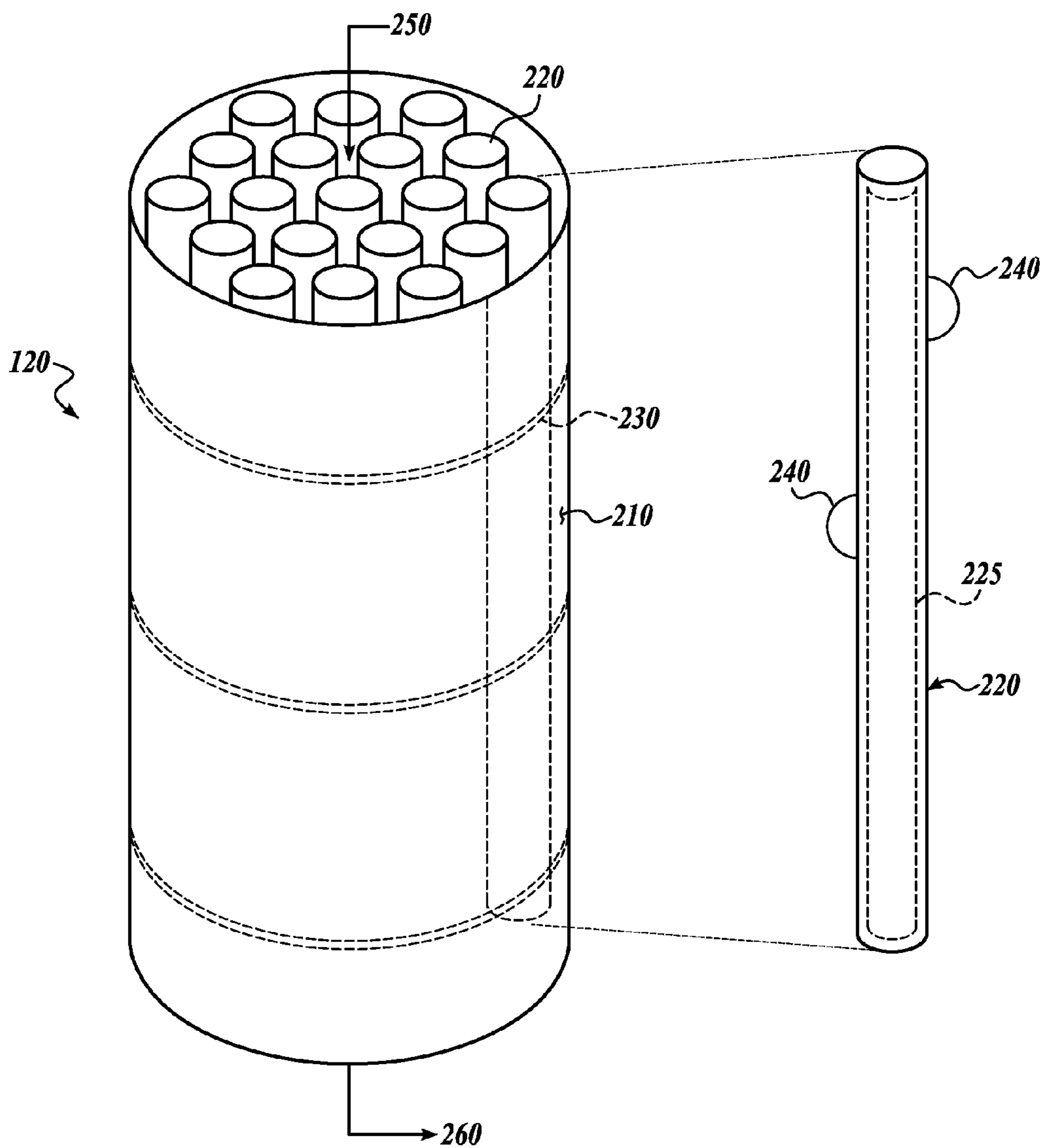
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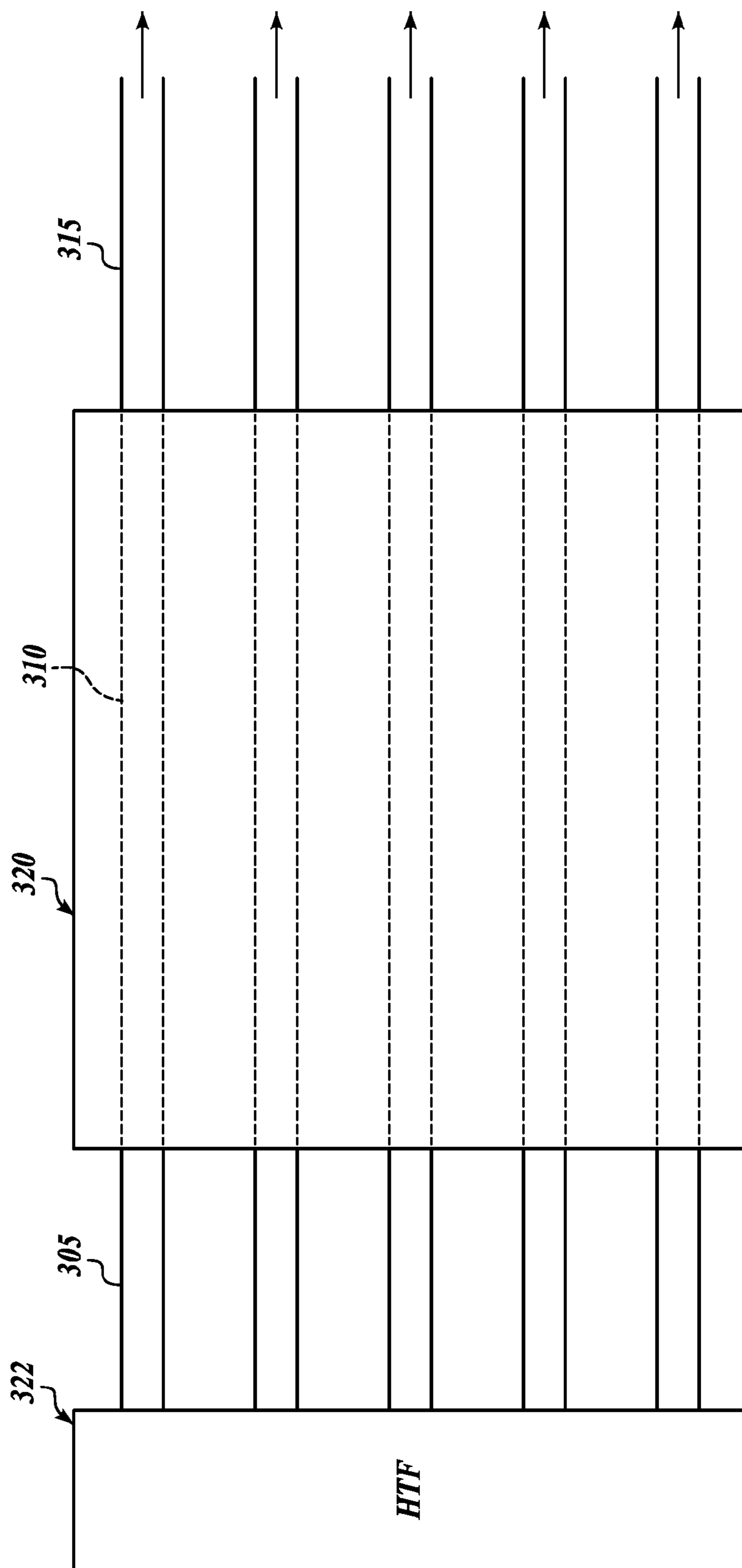




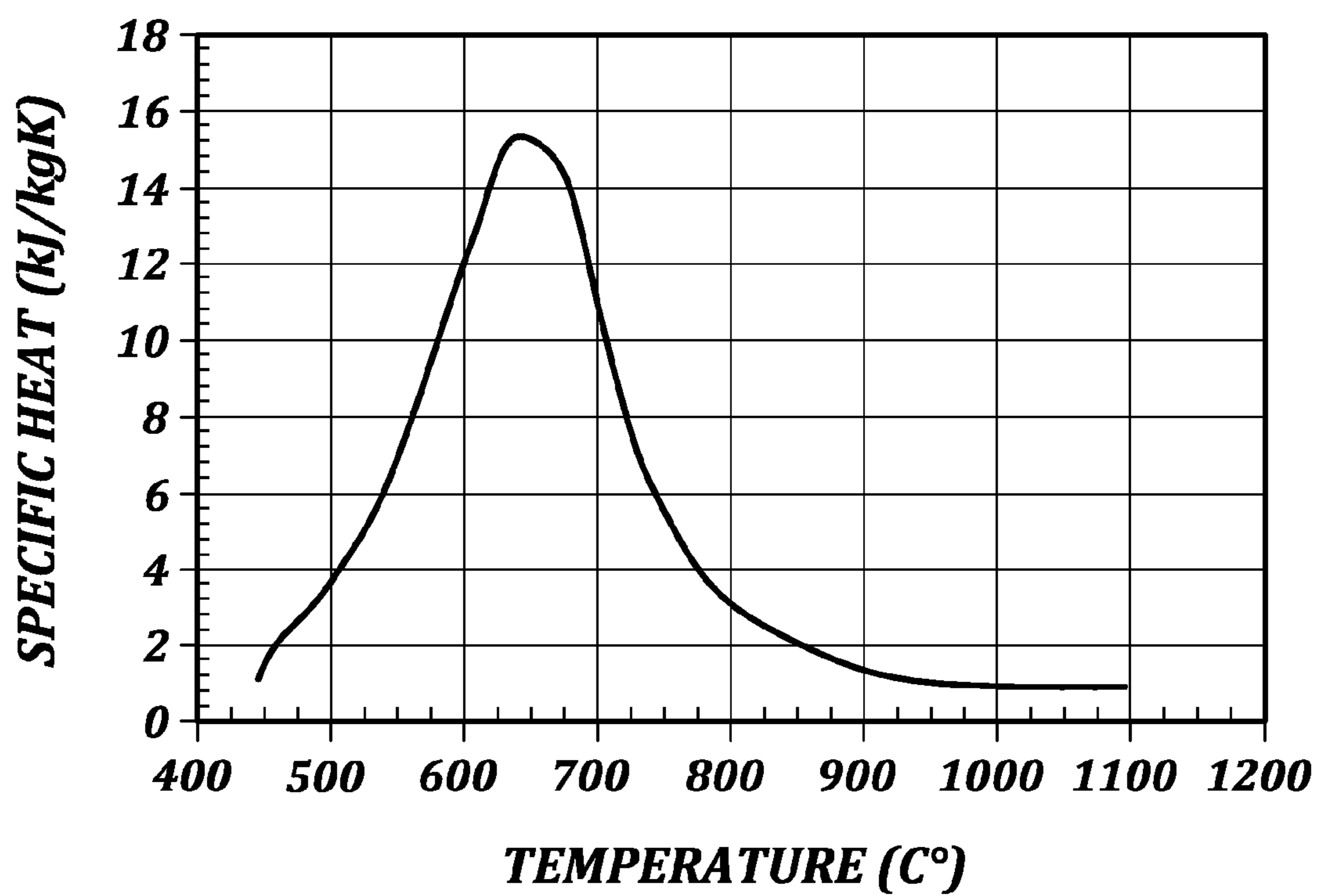
*Fig. 1.*



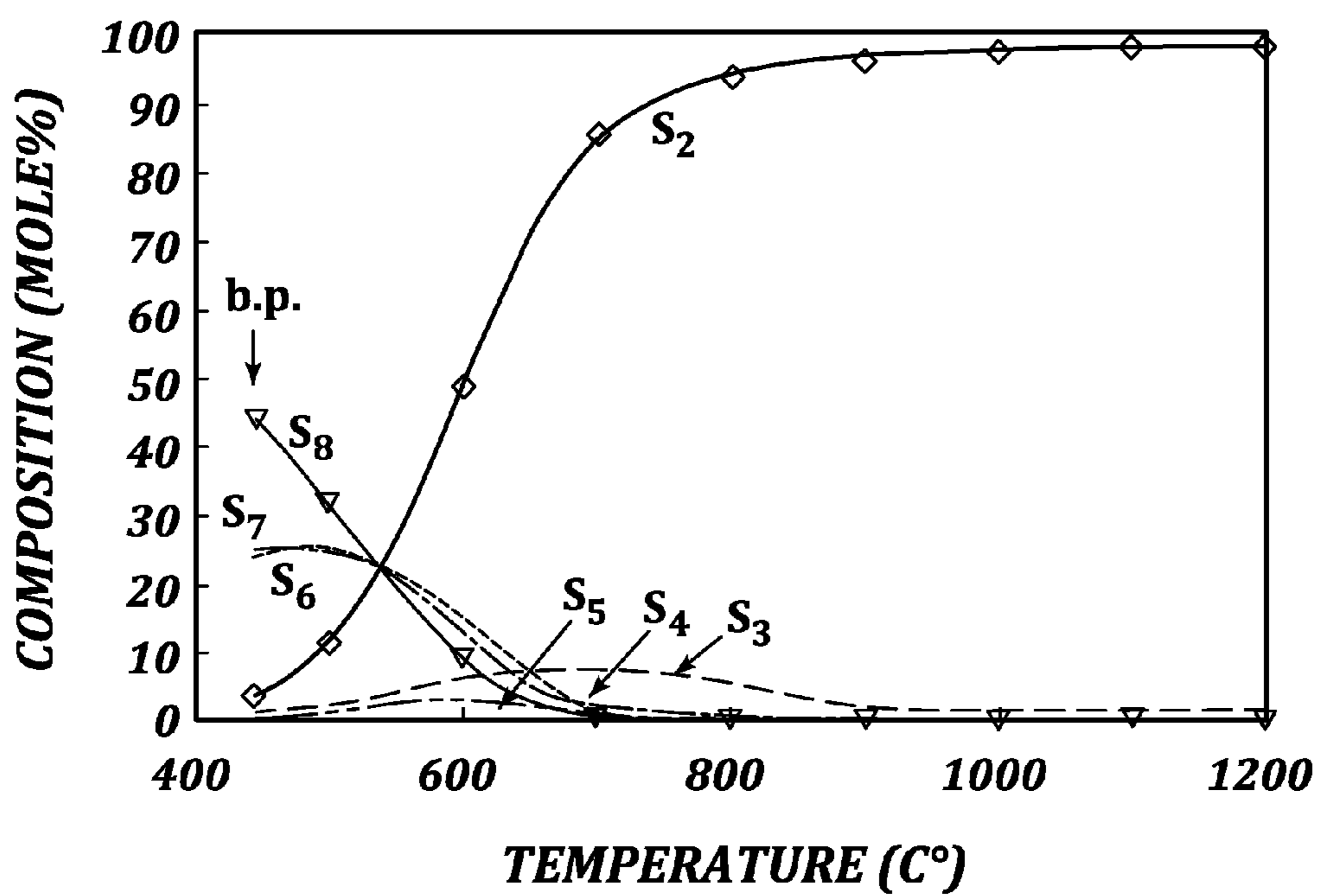
*Fig. 2.*



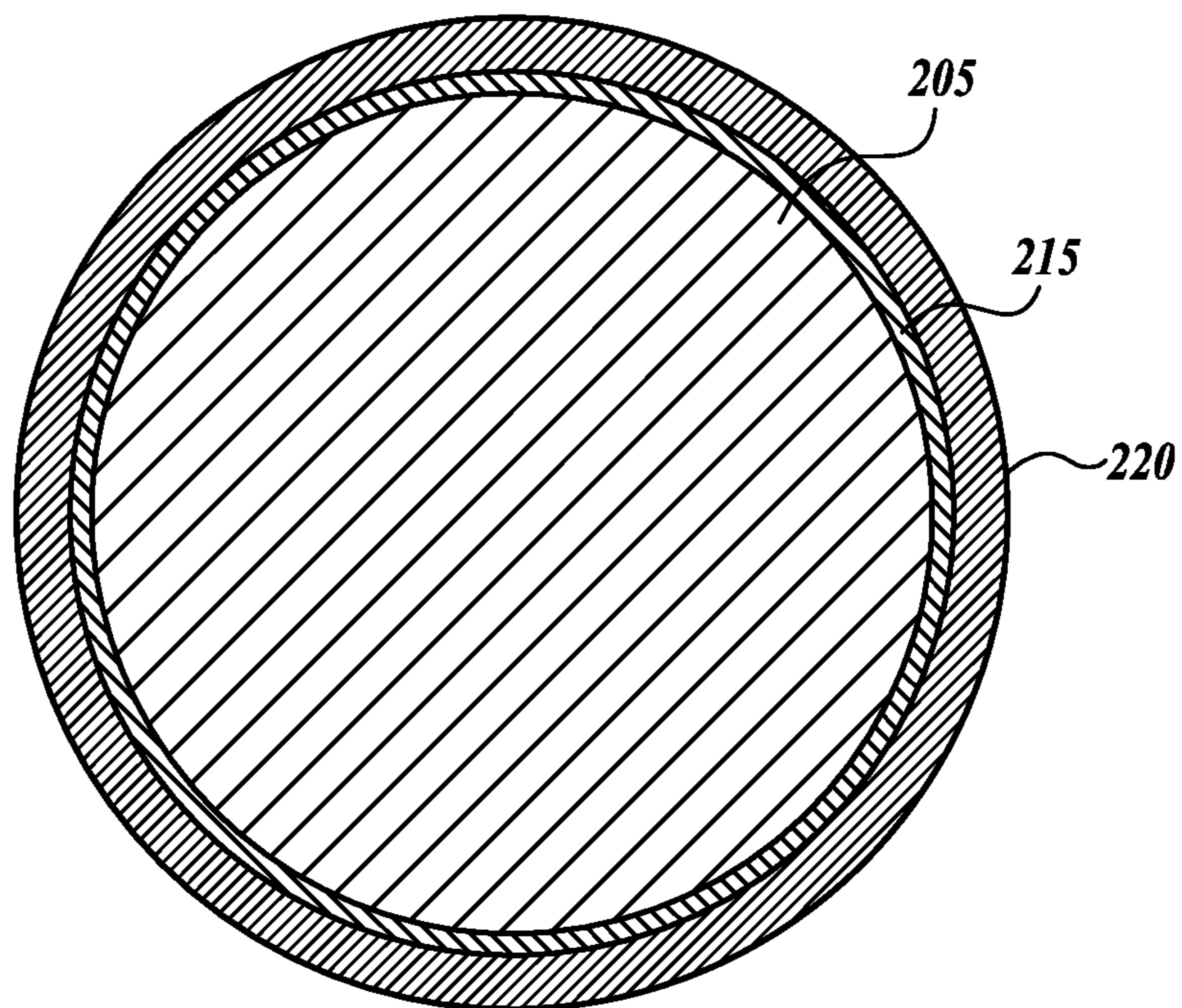
*Fig. 3.*



*Fig. 4.*



*Fig.5.*



*Fig. 6.*

**HIGH-DENSITY, HIGH-TEMPERATURE  
THERMAL ENERGY STORAGE AND  
RETRIEVAL**

CROSS-REFERENCE TO RELATED  
APPLICATION

**[0001]** This application claims the benefit of U.S. patent application Ser. No. 61/872,462, filed Aug. 30, 2013, the disclosure of which is hereby incorporated by reference in its entirety.

STATEMENT OF GOVERNMENT LICENSE  
RIGHTS

**[0002]** This invention was made with Government support under Contract DE-AR0000140, awarded by the United States Department of Energy, Advanced Research Projects Administration—Energy. The Government has certain rights in the invention.

BACKGROUND

**[0003]** Thermal energy storage (TES) is a process in which thermal energy is collected and stored for later use. TES is particularly useful where energy production fluctuates or is intermittent, such as is the case in certain alternative energy generation applications. For example, thermal energy storage can be used with solar power generation facilities to store energy collected in daylight hours for later use. Thermal energy storage can provide buffering against changing weather conditions, can evenly distribute electricity production, can time-shift energy use, and can increase the capacity and the efficiency of energy production.

**[0004]** Several criteria define an ideal energy storage system. Because a TES system stores large amounts of energy (e.g., MWh or GWh), it is typically a significant portion of the overall energy plant size. Therefore, it is important that the energy storage material be low cost to result in a system that is overall cost effective. Additional figures of merit include an energy storage material that has a high energy density; an energy storage material that is mechanically and chemically stable; an efficient heat transfer between a heat transfer fluid (HTF) and the energy storage material; compatibility between the HTF, heat exchanger, and/or the energy storage material; reversibility of the charge and discharge cycles in the energy storage system; and low thermal losses from the energy storage system.

**[0005]** Various classes of energy storage materials are used in TES systems, such as oils, molten salts, and phase change materials. However, to be technically and economically feasible, the energy storage material should have a combination of the following characteristics: low cost, long lifetime, high thermal stability, high specific heat and thermal conductivity, low vapor pressure, high availability, and low toxicity. Currently available energy storage materials are too costly to be economically feasible for large-scale TES.

**[0006]** As an example, molten salts have been used as an energy storage material because of their low vapor pressure and reasonable thermal stability at temperatures up to about 600° C. However, molten salts are too costly to be viable for large-scale TES. Molten salts also do not generally exhibit thermal stability at higher temperatures (e.g., >600 C), and available options for addressing this problem are expensive. Because such salts are also used in fertilizers they are subject to high market demand and associated cost volatility. Further-

more, molten salts can have high freezing points. For example, binary and ternary eutectic salt mixtures (e.g., solar salt, Hitec®-XL) freeze at approximately 220° C. and 120° C., respectively. The high freezing points can cause complications that require routine freeze protection of solar field piping, valves, and joints in an energy storage system. These complications ultimately result in an increase in operation and maintenance costs.

**[0007]** As another example, phase change materials, such as paraffin wax, have been used as a thermal energy storage material. Paraffin wax has a wide range of melting temperatures and is chemically inert.

**[0008]** However, conventional phase change materials have poor heat transfer performance since most forms attempt to exploit the solid-liquid transition. Other limitations include thermal decomposition after extended cycling, subcooling of the phase change materials, and density changes.

**[0009]** A significant limitation of conventional thermal energy storage materials is instability of the material over time. As the conventional TES material is repeatedly cycled through large temperature changes, and typically through one or more phase changes, the complex molecules that form the TES material gradually degrade or decompose, reducing the system performance.

**[0010]** Thermochemical energy storage, such as ammonia dissociation, metal hydride oxidation, and methanation, has also been investigated. However, thermochemical energy storage presents numerous challenges, such as adequate reaction kinetics, low-cost catalysts, and sufficient reaction yield at TES operating temperatures and pressures. Thermochemical energy storage must also be reversible.

**[0011]** Thus, there is a need for a thermal energy storage system that is simple, efficient, durable, low-cost, and easy to implement. The energy storage material should be readily available and capable of accommodating high temperatures for current and future TES application (i.e., temperatures up to 1000° C.). In addition, a thermal energy storage component that includes the energy storage material should be resistant to corrosion, thermal degradation, and mechanical fatigue. Furthermore, the thermal energy storage system should have adequate heat transfer characteristics and acceptable pressure losses. The present disclosure seeks to fulfill these needs and provides further related advantages.

SUMMARY

**[0012]** This summary is provided to introduce a selection of concepts in a simplified form that are further described below in the Detailed Description. This summary is not intended to identify key features of the claimed subject matter, nor is it intended to be used as an aid in determining the scope of the claimed subject matter.

**[0013]** A thermal energy storage (TES) component includes an outer shell with an inlet and an outlet, configured to accommodate flow of a heat transfer fluid therethrough. A plurality of containers are disposed in the shell, and each of the containers contain only an elemental material, for example, selected from sulfur, mercury, selenium, hydrogen, nitrogen, and oxygen. The TES component is configured to selectively (i) transfer thermal energy from the heat transfer fluid to the elemental material for thermal energy storage, and to transfer energy from the elemental material to the heat transfer fluid to recover stored thermal energy. The containers are thermally conductive to accommodate the design heat transfer requirements, structurally robust to accommodate



design pressures within the system, and compatible with the material contained therein, as well as the heat transfer fluids transporting thermal energy to and from the TES component.

**[0014]** In an embodiment, the elemental material transitions between two or more allotropic forms during the transfer of thermal energy between the heat transfer fluid and the elemental material.

**[0015]** In an embodiment the elemental material consists of sulfur. In an exemplary embodiment the elemental material comprises sulfur in its  $S_8$  and  $S_2$  allotropic forms. Depending on the available temperature range, this embodiment can be configured to transition between a gaseous, solid, liquid, and liquid-vapor states during the transfer of thermal energy between the elemental material and the heat transfer fluid.

**[0016]** In an embodiment the elemental material consists of sulfur, mercury, or selenium, and is present in the containers in liquid form and gaseous form during the transfer of thermal energy between the elemental material and the heat transfer fluid.

**[0017]** In an embodiment the elemental material consists of sulfur, mercury, or selenium, and is configured to remain in gaseous, solid, liquid, liquid-vapor, or allotropic form during the transfer of thermal energy between the elemental material and the heat transfer fluid.

**[0018]** In an embodiment the containers are sealed cylinders or spheres.

**[0019]** In an embodiment the elemental material consists of sulfur, mercury, or selenium, and is configured to remain in a gaseous, liquid, liquid-vapor, or allotropic form during the transfer of thermal energy between the elemental material and the heat transfer fluid.

**[0020]** In an embodiment the containers are formed from stainless steel, iron, carbon steel, carbon, aluminum, nickel, tantalum, molybdenum, platinum, Hastelloy®, or a combination thereof, and are lined with a liner that does not react with the elemental material.

**[0021]** An indirect thermal energy storage system configured for use with a thermal energy source, for example, an intermittent thermal energy source, and includes a thermal energy storage component comprising a shell with an inlet and an outlet, and containing a plurality of sealed containers that contain only an elemental material, wherein the elemental material consists of sulfur, mercury, selenium, hydrogen, nitrogen, or oxygen. A system further includes a thermal energy user, for example, a steam boiler, heat exchanger, or the like. A fluidic control system is operable to circulate a heat transfer fluid between the thermal energy source, the thermal energy storage component, and the thermal energy user to selectively (i) transport thermal energy from the thermal energy source to the thermal energy user, (ii) transport thermal energy from the thermal energy source to the thermal energy storage component, and (iii) transport thermal energy from the thermal energy storage component to the thermal energy user.

**[0022]** In an embodiment the plurality of sealed containers are sealed cylinders.

**[0023]** In an embodiment the elemental material consists of sulfur.

**[0024]** A method of operating an indirect thermal energy storage system includes cycling an energy storage system as described above between two temperatures, for example, a low temperature less than about 500° C. and a high temperature greater than about 700° C.

**[0025]** In an embodiment the thermal storage material is stored in the shell while the heat transfer fluid is passed through the tubes.

#### DESCRIPTION OF THE DRAWINGS

**[0026]** The foregoing aspects and many of the attendant advantages of this invention will become more readily appreciated as the same become better understood by reference to the following detailed description, when taken in conjunction with the accompanying drawings.

**[0027]** FIG. 1 is a schematic diagram of a thermal energy storage system in accordance with the present invention;

**[0028]** FIG. 2 is a schematic partially exploded view of an embodiment of a thermal energy storage component of the system shown in FIG. 1;

**[0029]** FIG. 3 illustrates diagrammatically an alternative embodiment wherein the elemental material is sealed in a shell, and the heat transfer fluid flows through tubes that extend through the shell;

**[0030]** FIG. 4 is a graph showing an effective specific heat of sulfur vapor as a function of temperature;

**[0031]** FIG. 5 is a graph showing equilibrium of species of sulfur vapor at a total pressure of 1 atmosphere; and

**[0032]** FIG. 6 is schematic cross-sectional view of a current embodiment of the thermally conductive container of the energy storage component shown in FIG. 2.

#### DETAILED DESCRIPTION

**[0033]** The present disclosure describes thermal energy storage (TES) systems that use an elemental material (e.g., elemental sulfur) as an energy storage material. The use of an elemental material offers many advantages compared to other material options, including thermal stability, availability, heat transfer characteristics, thermal storage capacity, and overall system cost. As discussed in more detail below, the elemental energy storage material in some embodiments is sealed within an array of corrosion-resistant containers or tubes that are disposed within an outer shell. A heat transfer fluid (HTF) flows through the shell via an inlet and an outlet to transport thermal energy to or from the energy storage material. In particular, the elemental thermal energy storage material does not serve as the heat transfer fluid, but rather serves solely as a repository and source for thermal energy.

**[0034]** The indirect TES system provides many advantages over a direct storage system by confining an energy storage material to the storage reservoir. The indirect TES system allows the thermal energy storage material to be optimized for cost and performance, while the HTF can be separately optimized for compatibility with the elements of the heat transfer loop, pumping requirements, and heat transfer capabilities.

**[0035]** By storing thermal energy in an energy storage material that is physically separated from a HTF (i.e., an indirect TES system), the TES system configuration can be optimized for both performance and cost. For example, a direct energy storage system, such as that described in U.S. Publication No. 2013/0037741, which is hereby incorporated by reference in its entirety, requires a mixture containing elemental sulfur and at least one additive (e.g., a halogenated hydrocarbon) to serve both as a heat transfer material and an energy storage material for reversible energy storage in a direct TES configuration (i.e., where the heat transfer material is also an energy storage material). The additive is required to reduce viscosity of the sulfur to allow for ease of

pumping. However, in contrast to a direct energy storage system, the energy storage material of the present disclosure is not pumped throughout the TES system, and therefore requires no additives to reduce viscosity of the energy storage material, nor special system accommodations for the energy storage material throughout the TES system. As discussed herein, an energy storage material consisting only of an elemental material allows for optimization of the thermal energy storage performance and cost.

[0036] Furthermore, compared to a conventional shell and tube heat exchanger system wherein a HTF typically flows through tubes in the heat exchanger, and the energy storage material flows through the shell around the tubes, the thermal energy storage component of the present disclosure has numerous advantages. For example, the TES component of the present disclosure can provide better protection of the encapsulated elemental material against undesirable exposure to the environment, as the shell can provide an additional barrier of protection for the energy storage material that is encapsulated in the containers. Encapsulation of elemental material in containers also provides ease of handling by allowing individual containers to be extracted, inspected, and replaced when needed. Moreover, the containers can maximize the exergetic efficiency during charging and discharging by optimizing hydrodynamic shape and heat transfer surface area to volume ratio.

[0037] FIG. 1 is a system diagram showing the components of a closed loop TES system 100 in accordance with the invention. The components include a thermal energy source 110, an elemental material TES component 120, and a boiler or steam generator 130. A HTF is circulated through a piping system 140 to transport the thermal energy between these components 110, 120, 130.

[0038] In particular, the HTF is controllable to selectively flow between the thermal energy source 110 and the TES component 120, between the TES component 120 and the steam generator 130, and between the thermal energy source 110 and the steam generator 130. The steam generator 130 may be of conventional construction, as are well-known in the art. The steam generator 130 may, for example, provide steam to a steam turbine (not shown) for generating electrical energy.

[0039] The closed loop TES system 100 will typically include a fluid control system comprising a central processing unit 150 that is in signal communication with sensors 152, for example, temperature and pressure sensors. The central processing unit 150 is operably connected to control valves 151, pumps (not shown), and the like, based at least in part on information received from sensors 152. The system 100 is configured to: (i) selectively circulate HTF directly between the thermal energy source 110 and the steam generator 130 for power generation, as indicated by direct generation loop 160; (ii) selectively circulate HTF between the thermal energy source 110 and the TES component 120 to store excess thermal energy in the elemental material (i.e., a charging process), as indicated by charging loop 162; and (iii) selectively circulate HTF between the TES component 120 and the steam generator 130 for power generation from stored thermal energy (i.e., a discharging process), as indicated by indirect generation loop 164. One or more controllable bypass flow paths 170 may also be provided.

[0040] Although separate flow loops are shown, it is contemplated that two or more of the flow loops may be operable at any given time. For example, if the energy generated by the

high temperature source 110 exceeds current energy needs, a portion of the HTF may flow along the direct generation loop 160 and another portion of the HTF may flow along the charging loop 162.

[0041] Referring still to FIG. 1, the energy source 110 may receive energy from an intermittent and/or fluctuating energy source. The energy source may comprise any heat source, for example, fossil fuel burners, electric heaters, a solar thermal energy system, a wind energy system configured convert energy to thermal energy for storage, and/or a geothermal energy system. In a particular embodiment, the energy source 100 is energized with a concentrating solar thermal energy system.

[0042] Examples of suitable HTFs include, for example, synthetic organic HTFs (e.g., Therminol®, DowTherm®), molten salts, liquid metals, etc.

[0043] Referring now to FIG. 2, a diagrammatic exploded view of the TES component 120 is presented, which shows an outer shell 210 with an array of containers 220 disposed in the outer shell 210. The TES component 120 may include baffles 230 to modify the flow field around the containers 220, for example, to increase turbulence and/or increase residence time, thereby improving the heat transfer characteristics, and to maintain the array of containers 220 in a desired spacing. The containers 220 may further be formed with surface features 240 such as ridges, recesses, channels, surface roughness or the like, to improve flow and heat transfer characteristics. The shell 210 has an inlet 250 and an outlet 260 that allow the HTF to flow through the TES component 120 and over and around the containers 220. (For simplicity and clarity corresponding nozzles are not illustrated.)

[0044] During the charging loop 162, thermal energy is transferred from the HTF to the energy storage material within the containers 220. During the indirect generation loop 164, thermal energy is transferred from the energy storage material within the containers 220 to the HTF to recover the stored thermal energy for power generation.

[0045] As shown in FIG. 2, in this embodiment the shell 210 is symmetric, such that the flow direction of the HTF can be easily reversed when changing from a thermal charging or discharging cycle. However, it is understood that the shell 210 and containers 220 may take any shape, so long as the shell can contain the containers 220 and permit flow of the HTF.

[0046] In the current embodiment, the containers 220 are in the form of circular cylinders. The cylinders contain and encapsulate an energy storage material comprising an elemental material 225, for example, elemental sulfur fluid. The container 220 is configured to provide sufficient surface area for heat transfer, while protecting the elemental material 225 from harmful interaction with the environment, and provides structural support and ease of handling. In other embodiments the container 220 comprises a cylinder having a circular, oval or polygonal cross section. In another embodiment the container 220 is a hollow pellet, for example, a spherical container, an oblate or prolate spheroidal container, or a similar irregular pellet-like container. The container 220 is sealed, such that the encapsulated elemental material 225 is protected from contamination from outside sources, and cannot escape from the container 220. The container 220 may preferably be sealed under vacuum or an inert atmosphere. It is contemplated that the cylindrical container may be non-circular, tapered, finned, or otherwise configured, for example, to optimize heat transfer performance.

[0047] In an alternative embodiment illustrated diagrammatically in FIG. 3, the elemental material is contained in a sealed shell 320 and the HTF 322 flows in inlets 305 through tubes 310 that pass through the sealed shell 320, and exits through outlets 315. This alternative configuration has certain advantages, because the maximum temperature for the elemental material is lower than the maximum temperature in the HTF 322, which makes the insulation easier, and can reduce overall costs.

[0048] As used herein, an elemental material refers to a gas, liquid, or solid that comprises a single element. The elemental material may comprise, for example, elemental sulfur, mercury, selenium, hydrogen, nitrogen, and/or oxygen. In a currently preferred embodiment, the elemental material is sulfur.

[0049] Although a system using a non-circulating TES material is currently preferred, a two-tank indirect TES system is also contemplated, as are known in the art. For example, a two-tank indirect TES system is disclosed in U.S. Pat. No. 7,971,437 to Flynn et al., which is hereby incorporated by reference in its entirety. In another alternative embodiment, a single-tank thermocline thermal energy storage configuration may be used, such as the thermocline system also disclosed in Flynn et al.

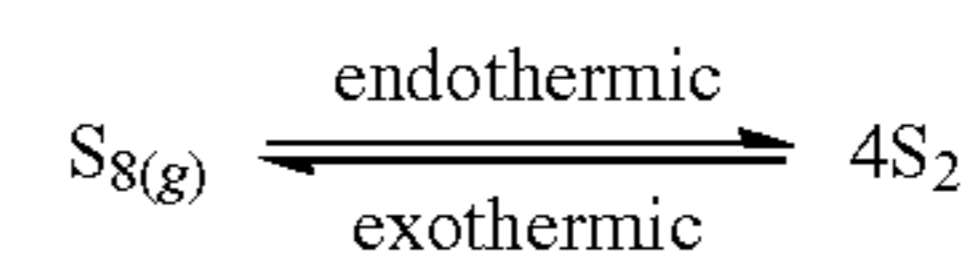
[0050] The element of the elemental material can be present in one or more allotropic forms. The element can be in liquid form and/or gaseous form. In some embodiments, when the element is sulfur, mercury, or selenium, the element is in a liquid form and a gaseous form, at TES system operating conditions. In some embodiments, when the element is sulfur, mercury, or selenium, the element is in a gaseous form, at TES system operating conditions.

[0051] The elemental material may be selected to operate within a prescribed temperature range (e.g., between 400 and 600° C., between 500 and 900° C.). By cycling the elemental material between a relatively low temperature state and a high-temperature state, a large excursion in internal energy, including both sensible heat and latent heats of fusion and vaporization, can be accessed.

[0052] Sulfur, for example, has numerous advantages compared to conventional TES materials such as oils or nitrates salts. First, sulfur in a relatively pure form is readily available at a low cost, for example, using the Frasch process from salt deposits. And while it has a lower effective specific heat than oils or nitrate salts and would thus require a larger mass to achieve comparable energy storage, the low cost and high availability of sulfur can easily offset these considerations. Second, an attractive feature of elemental sulfur in high-temperature energy storage applications is its high values of heat capacity in a desirable temperature range, as illustrated in FIG. 4. Third, elemental sulfur has high thermal stability across a wide range of temperatures, and can thus have a long lifetime, particularly when the energy storage material is cycled at different temperatures over the duration of a power generation system. Fourth, sulfur has a low vapor pressure compared to other low cost thermal energy storage fluids, e.g., water, for the temperatures of interest for thermal energy storage. Fifth, sulfur in a fluid state benefits from natural convection for the temperatures of interest for most thermal energy storage applications. The effect of natural convection in TES systems can significantly enhance the heat transfer characteristics of the system and enable the TES system to charge and discharge effectively. The induced buoyancy-driven flow can also have turbulent specifications that further

contribute to efficient exchange of thermal energy between elemental material and container.

[0053] Without wishing to be bound by theory, it is believed that in a TES component that uses elemental sulfur as an energy storage material, the endothermic bond-breaking and exothermic bond-making of a reversible chemical reaction between sulfur chains can cause concatenation to produce a variety of molecular forms. The equilibrium concentrations of the various sulfur species as a function of temperature is shown in FIG. 5, wherein S<sub>2</sub>-S<sub>8</sub> indicate allotropes of sulfur vapor at one atmosphere, and the boiling point b.p. is shown for reference. The various molecular forms of sulfur can be used in a high temperature storage system based upon thermochemical principles, in addition to sensible or latent storage. As an example, at elevated temperatures sulfur undergoes the following reversible reaction:



where the enthalpy of reaction is  $\Delta H=414 \text{ kJ}\cdot\text{kmol}^{-1}$ . And while the advantage of sulfur dissociation energy decreases at TES applications above 700° C., sulfur can still be advantageously used as TES material due to its strong thermal stability, adequate specific heat, and low cost.

[0054] As yet another example, an elemental material can be encapsulated in a large plurality of small containers, for example, spherical containers, and the containers can fill a shell to provide a fluidized bed or packed bed system. Packing of the containers can be designed to maximize a surface area to volume ratio, maximize heat transfer efficiency to a HTF, minimize pressure loss, and reduce cost associated with a large vessel shell. An exemplary packed bed thermal energy storage device is disclosed in U.S. Patent Publication No. 2013/0240171 to Morgan et al., which is hereby incorporated by reference in its entirety.

[0055] FIG. 6 is a cross-sectional view of a current embodiment for the containers 220, which may also be considered a cross-sectional view of a small spherical conductive container, as discussed above. The container 220 may be made of any suitable non-reactive and mechanically stable material that is compatible with the elemental material 205 and the HTF (not shown) under TES system operating conditions (e.g., temperatures and pressures). The container 220 is configured to sustain the maximum pressures exerted by an elemental material 205 contained within the container 220. For example, the containers can be made out of stainless steel, aluminum, nickel, tantalum, molybdenum, composite materials thereof, and/or alloys thereof. Other suitable container materials include iron, carbon steel, carbon, platinum, or combinations thereof.

[0056] In this embodiment, the container 220 includes a liner 215 on the inside of the container 220. The liner 215 material is selected to be chemically stable when in contact with the elemental material under TES system operating conditions. In some embodiments, instead of or in addition to a liner, the inside of container 220 may be preconditioned, modified, and/or smoothed. For example, the inside of container 220 may be irradiated, heat treated, electroplated, chemically etched or treated, mechanically work-hardened, or the like.

**[0057]** While a solar energy-based TES system is described above, it is understood that the TES component can be used in any thermodynamic system that can benefit from a TES component.

**[0058]** During operation, the HTF enters the TES component **120** and flows between and around the containers **220**. The HTF exchanges thermal energy with the elemental material.

**[0059]** As discussed above, in another contemplated embodiment the elemental fluid is sealed within the shell, and the HTF flows through tubes that extend through the shell.

**[0060]** The elemental material **205** is selected to operate in a particular temperature range. For example, if the elemental material **205** is sulfur and the system is configured to store thermal energy in the latent heat associated with the solid-liquid and liquid-vapor phase changes, the elemental fluid may be cycled between 100° C. and 1000° C. Contemplated exemplary operating temperature ranges include e.g., between 100° C. and 200° C., between 100° C. and 500° C., between 100° C. and 800° C., and between 500° C. and 1000° C.

**[0061]** The following examples are included for the purpose of illustrating, not limiting, the described embodiments.

#### EXAMPLES

##### Example 1

##### Energy Density of TES System Using Sulfur Elemental Fluid

**[0062]** Calculations have been conducted using a spatial and temporal TES model. The results are shown in Table 1.

TABLE 1

Effect of storage temperature on loading and energy density of a TES system using saturated sulfur vapor			
Storage temperature (° C.)	Saturated pressure (MPa)	Saturated vapor density (kg/m <sup>3</sup> )	Energy density (kWh/m <sup>3</sup> )
800	4.95	77.51	12.56
900	10.07	143.32	27.73
1000	17.99	262.78	58.97

**[0063]** From Table 1 it will be appreciated that the energy density of a sulfur TES system can reach a desirable value by deviating from saturation conditions and operating within the superheated vapor or supercritical regime.

**[0064]** While illustrative embodiments have been illustrated and described, it will be appreciated that various changes can be made therein without departing from the spirit and scope of the invention.

The embodiments of the invention in which an exclusive property or privilege is claimed are defined as follows:

1. A thermal energy storage component, comprising:
  - an outer shell having an inlet and an outlet to accommodate a flow of a heat transfer fluid from the inlet to the outlet; and
  - a plurality of thermally conductive containers disposed in the outer shell, wherein each container contains only an elemental material comprising an element selected from the group of elements consisting of sulfur, mercury, selenium, hydrogen, nitrogen, and oxygen;

wherein the thermal energy storage component is configured to selectively: (i) transfer thermal energy from the heat transfer fluid to the elemental material for thermal energy storage, and (ii) transfer thermal energy from the elemental material to the heat transfer fluid to recover stored thermal energy.

2. The thermal energy storage component of claim 1, wherein the elemental material transitions between two or more allotropic forms during the transfer of thermal energy between the heat transfer fluid and the elemental material.

3. The thermal energy storage component of claim 1, wherein the elemental material consists of sulfur.

4. The thermal energy storage component of claim 1, wherein the elemental material consists of sulfur, mercury, or selenium, and further wherein the elemental material is in a liquid form and a solid form during at least a portion of the transfer of thermal energy.

5. The thermal energy storage component of claim 1, wherein the elemental material consists of sulfur, mercury, or selenium, and further wherein the elemental material is in a liquid form and a gaseous form during at least a portion of the transfer of thermal energy.

6. The thermal energy storage component of claim 1, wherein the plurality of containers are sealed.

7. The thermal energy storage component of claim 1, wherein the plurality of containers are cylinders.

8. The thermal energy storage component of claim 1, wherein the plurality of containers are spheres.

9. The thermal energy storage component of claim 1, wherein the plurality of containers are formed of a material selected from the group consisting of stainless steel, iron, carbon steel, carbon, aluminum, nickel, tantalum, molybdenum, platinum, and any combination thereof.

10. The thermal energy storage component of claim 1, wherein the heat transfer fluid is selected from the group consisting of a molten salt, a liquid metal, and a synthetic organic heat transfer fluid.

11. An indirect thermal energy storage system configured for use with a thermal energy source comprising:

- (a) a thermal energy storage component comprising a shell having an inlet and an outlet, and a plurality of sealed thermally conductive containers disposed within the shell, wherein each sealed thermally conductive container contains only an elemental material comprising an element selected from the group of elements consisting of sulfur, mercury, selenium, hydrogen, nitrogen, and oxygen;

(b) a thermal energy user; and

- (c) a fluidic control system operable to selectively circulate a heat transfer fluid between the thermal energy source, the thermal energy storage component, and the thermal energy user to selectively: (i) transport thermal energy from the thermal energy source to the thermal energy user, (ii) transport thermal energy from the thermal energy source to the thermal energy storage component, and (iii) transport thermal energy from the thermal energy storage component to the thermal energy user.

12. The indirect thermal energy storage system of claim 11, wherein the plurality of containers are cylindrical.

13. The indirect thermal energy storage system of claim 11, wherein the plurality of containers are spherical.

14. The indirect thermal energy storage system of claim 11, wherein the thermal energy user comprises a steam boiler.

**15.** The indirect thermal energy storage system of claim **14**, wherein the elemental material consists of sulfur.

**16.** A thermal energy storage component, comprising:  
a sealed outer shell having containing an elemental fluid selected from the group of elements consisting of sulfur, mercury, selenium, hydrogen, nitrogen, and oxygen; and a plurality of tubes having an inlet and an outlet to accommodate a flow of a heat transfer fluid from the inlet to the outlet;

wherein the thermal energy storage component is configured to selectively: (i) transfer thermal energy from the heat transfer fluid to the elemental material for thermal energy storage, and (ii) transfer thermal energy from the elemental material to the heat transfer fluid to recover stored thermal energy.

**17.** The thermal energy storage component of claim **16**, wherein the elemental material consists of sulfur.

**18.** The thermal energy storage component of claim **16**, wherein the elemental material consists of sulfur, mercury, or

selenium, and further wherein the elemental material is in a liquid form and a solid form during at least a portion of the transfer of thermal energy.

**19.** The thermal energy storage component of claim **16**, wherein the elemental material consists of sulfur, mercury, or selenium, and further wherein the elemental material is in a liquid form and a gaseous form during at least a portion of the transfer of thermal energy.

**20.** The thermal energy storage component of claim **16**, wherein the plurality of containers are formed of a material selected from the group consisting of stainless steel, iron, carbon steel, carbon, aluminum, nickel, tantalum, molybdenum, and any combination thereof

**21.** The thermal energy storage component of claim **16**, wherein the heat transfer fluid is selected from the group consisting of a molten salt, a liquid metal, and a synthetic organic heat transfer fluid.

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