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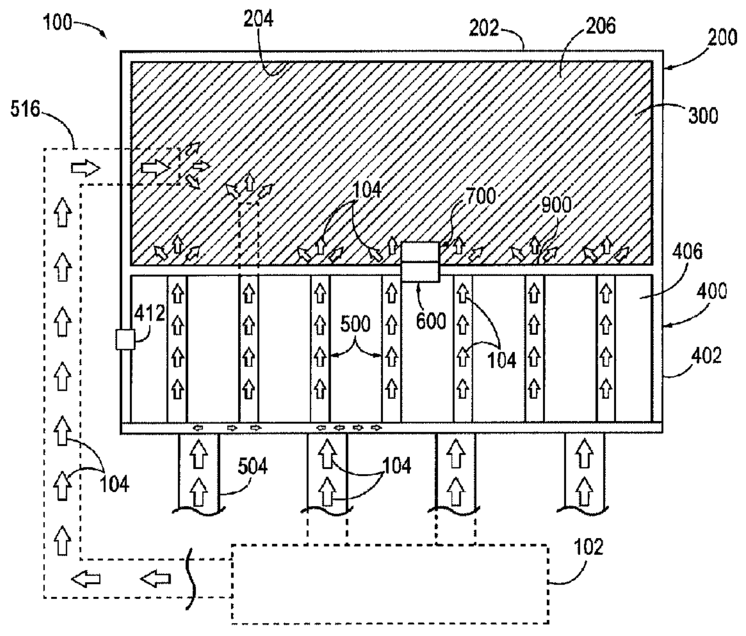

(57) **Abrégé/Abstract:**

A heat transfer device includes a storage chamber, a coolant housed within the storage chamber, a cooling chamber, one or more heat transfer components, a fluid passage between the storage chamber and the cooling chamber, and a barrier element. The one or more heat transfer components facilitate heat transfer from a heat source outside of the cooling chamber to the cooling chamber. The barrier element may have (i) a closed configuration, and (ii) an open configuration in which the barrier element is configured to allow the coolant in the storage chamber to flow from the storage chamber into the cooling chamber. The barrier element may reconfigure from the closed configuration to the open configuration in response to a trigger condition, such as the coolant housed within the storage chamber reaching a trigger temperature; and/or the initial pressure of the coolant housed within the storage chamber reaching a trigger pressure.

ABSTRACT

A heat transfer device includes a storage chamber, a coolant housed within the storage chamber, a cooling chamber, one or more heat transfer components, a fluid passage between the storage chamber and the cooling chamber, and a barrier element. The one or more heat transfer components facilitate heat transfer from a heat source outside of the cooling chamber to the cooling chamber. The barrier element may have (i) a closed configuration, and (ii) an open configuration in which the barrier element is configured to allow the coolant in the storage chamber to flow from the storage chamber into the cooling chamber. The barrier element may reconfigure from the closed configuration to the open configuration in response to a trigger condition, such as the coolant housed within the storage chamber reaching a trigger temperature; and/or the initial pressure of the coolant housed within the storage chamber reaching a trigger pressure.

HEAT TRANSFER DEVICES AND METHODS OF COOLING HEAT SOURCES

FIELD

The present disclosure relates to heat transfer devices.

BACKGROUND

Some devices, especially electronic devices, generate extensive amounts of waste heat. This heat must be controlled and dissipated properly to prevent reduced performance and/or premature failures. Therefore, the thermal interaction of any device with its environment is a critical design feature to assure its proper functionality.

There are many commercial and military applications that may require reliable thermal control systems for components that have short transient heat dissipation bursts. In addition, designing heat transfer devices for components that are inactive for long periods of time creates additional challenges. These devices must perform and/or be stored in a variety of environmental conditions, including a gradient and/or flux of ambient temperatures, pressures, vibrations, radiation dosages, magnetic fields, and/or induced currents.

SUMMARY

In one embodiment, there is provided a heat transfer device, comprising a storage chamber, a coolant housed within the storage chamber at an initial pressure, a cooling chamber adjacent to the storage chamber, one or more heat transfer components positioned and configured to facilitate heat transfer from a heat source to the cooling chamber, wherein the heat source is distinct from the cooling chamber, a

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fluid passage between the storage chamber and the cooling chamber; and a barrier element. The barrier element has (i) a closed configuration in which the barrier element is configured to restrict the coolant from flowing from the storage chamber through the fluid passage and into the cooling chamber; and (ii) an open configuration in which the barrier element is configured to permit the coolant in the storage chamber to flow from the storage chamber through the fluid passage and into the cooling chamber, wherein the barrier element is configured to passively reconfigure from the closed configuration to the open configuration in response to a trigger condition, in which the coolant housed within the storage chamber reaches a trigger temperature or a trigger pressure. The coolant housed within the storage chamber is in a liquid state, and the fluid passage is configured to cause the coolant to transition from the liquid state to a gaseous state.

The fluid passage may be configured to expand the coolant from the initial pressure to an expanded pressure as the coolant flows from the storage chamber through the fluid passage and to the cooling chamber responsive to the barrier element reconfiguring from the closed configuration to the open configuration.

The fluid passage may include an expansion valve coupled to the storage chamber and the cooling chamber such that the coolant flows from the storage chamber and into the expansion valve at the initial pressure and flows out of the expansion valve toward the cooling chamber at the expanded pressure, wherein the initial pressure is greater than the expanded pressure.

The expansion valve may define the fluid passage.

The storage chamber is an enclosed storage volume.

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The heat transfer device may include a storage housing, and the storage housing may define the enclosed storage volume.

The enclosed storage volume may be cylindrical.

The enclosed storage volume may be a rectangular prism.

The cooling chamber may include a first side that is proximate to the heat source and a second side that is opposite the first side, and the storage chamber may be located proximate to the second side.

The coolant may have a boiling point temperature that is greater than a range of operating temperatures of the heat transfer device.

The coolant may have a freezing point temperature that is less than a/the range of operating temperatures of the heat transfer device.

The coolant may have a phase change temperature that is within a range of operating temperatures of the heat transfer device.

The coolant may include, and may optionally be or consist of, methane.

The coolant may include a fire retardant.

The coolant housed within the storage chamber may be in a liquid state.

The coolant flowing through the fluid passage may cause the coolant to transition from the liquid state to a gaseous state.

The heat transfer device may include a heat distribution element located within the storage chamber and configured to distribute the heat across the coolant.

The heat distribution element may be an aluminum foam.

The storage chamber may be configured to store the coolant for a long period of time and/or through regimes/varieties of environmental conditions.

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The coolant may remain stable in storage for a long period of time and/or through regimes/varieties of environmental conditions.

The heat transfer device may include an additional storage chamber, additional coolant housed within the additional storage chamber, and an additional fluid passage between the additional storage chamber and the cooling chamber; and an additional barrier element having (i) a closed configuration in which the additional barrier element is configured to restrict the additional coolant from flowing from the additional storage chamber through the additional fluid passage and into the cooling chamber, and (ii) an open configuration in which the additional barrier element is configured to allow the additional coolant in the additional storage chamber to flow from the additional storage chamber through the additional fluid passage and into the cooling chamber.

The heat transfer device may involve an additional storage chamber and additional coolant housed within the additional storage chamber, and the fluid passage may be further configured to allow coolant to flow between the additional storage chamber and the cooling chamber. The heat transfer device may further include an additional barrier element having (i) a closed configuration in which the additional barrier element is configured to restrict the additional coolant from flowing from the storage chamber through the fluid passage and into the cooling chamber, and (ii) an open configuration in which the additional barrier element is configured to allow the additional coolant in the additional storage chamber to flow from the additional storage chamber through the fluid passage and into the cooling chamber.

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The additional barrier element may be configured to reconfigure from the closed configuration to the open configuration in response to an additional trigger condition.

The additional trigger condition may include at least one of: the additional coolant housed within the additional storage chamber reaching an additional trigger temperature; and the initial pressure of the additional coolant housed within the additional storage chamber reaching an additional trigger pressure.

The additional trigger condition may be different from the trigger condition.

The additional fluid passage may be configured to expand the additional coolant from the initial pressure to an expanded pressure as the additional coolant flows from the additional storage chamber through the additional fluid passage and to the cooling chamber responsive to the additional barrier element reconfiguring from the closed configuration to the open configuration.

Heat may be transferred from the heat source and to the coolant stored within the storage chamber.

At least one of the one or more heat transfer components may be configured to allow heat to transfer between the heat source, the cooling chamber, and the coolant in the storage chamber.

The heat transfer device may involve a storage heat transfer component configured to allow heat to transfer between the heat source and the coolant in the storage chamber.

As the heat is transferred from the heat source and to the coolant, the pressure of the coolant in the storage chamber increases.

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The pressure of the coolant in the storage chamber may be a driving pressure that forces the coolant in the storage chamber to flow through the fluid passage and into the cooling chamber.

Heat continues to flow from the heat source to the coolant housed within the storage chamber when the barrier element is in the open configuration, and wherein the heat continuing to flow to the coolant generates additional driving pressure that forces the coolant in the storage chamber to flow through the fluid passage and into the cooling chamber.

The barrier element may be configured to passively transition from the closed configuration to the open configuration in response to the trigger condition.

The barrier element may involve a closed circuit that is configured to cause the barrier element to transition from the closed configuration to the open configuration in response to the trigger condition.

The closed circuit may include one or more of a temperature sensor and/or a pressure sensor.

The temperature sensor and/or the pressure sensor may involve a thermocouple, a strain gauge, and/or a strain gauge with mesoscribe printed on it.

The barrier element may involve a burst disc that is configured to rupture when the coolant reaches the trigger temperature and/or the pressure of the coolant in the storage chamber reaches the trigger pressure.

The barrier element may involve a plunger that is configured to, when the trigger condition occurs, create a passage that the coolant can flow through.

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The barrier element may involve a burst disc, and creating the passage that the coolant can flow through may comprise the plunger rupturing the burst disc.

The plunger may include a pressure tab that is configured to burst when the coolant reaches the trigger temperature and/or the pressure of the coolant in the storage chamber reaches the trigger pressure, and the pressure tab bursting may cause the plunger to create the passage.

The plunger may include a restraining element that prevents the plunger from creating the passage, and the restraining element may be configured to melt when the coolant reaches the trigger temperature.

The melting of the restraining element may cause the plunger to rupture the burst disc and/or puncture a barrier (e.g., thin wall and/or wall with counter-sink).

The plunger may be further configured to plug the passage when a close condition occurs.

The close condition may correspond to one of a closing pressure and a closing temperature.

The barrier element may include a membrane configured to: restrict the coolant from flowing across the membrane when the pressure of the coolant in the storage chamber is below a threshold pressure; and allow the coolant to flow across the membrane when the pressure of the coolant in the storage chamber is greater than or equal to the threshold pressure.

The barrier element may include one or more of a release valve, a pressure release valve, and a check valve.

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After the occurrence of the trigger condition, the coolant flowing from the storage chamber through the fluid passage and into the cooling chamber may cause the pressure of the coolant in the storage chamber to decrease.

As the pressure of the coolant in the storage chamber decreases, a mass flow rate of the coolant out of the storage chamber may decrease correspondingly.

After the occurrence of the trigger condition, heat from the heat source may continue to warm the coolant within the storage chamber.

After the occurrence of the trigger condition, a continued warming of the coolant within the storage chamber may cause the pressure of the coolant in the storage chamber to increase.

The fluid passage may be a Joule Thompson device that is configured to bring the coolant from a high pressure to a low pressure when the coolant flows from the storage chamber to the cooling chamber via the fluid passage.

The fluid passage may include an expansion valve configured to cause the coolant to be converted from a liquid to a gas when the coolant flows from the storage chamber to the cooling chamber via the expansion valve.

The coolant may be a low-quality gas after the coolant flows from the storage chamber to the cooling chamber via the expansion valve.

The coolant may flow from the storage chamber and into the fluid passage at an initial temperature and may flow out of the fluid passage toward the cooling chamber at a final temperature, wherein the initial temperature is greater than the final temperature.

The cooling chamber may be an enclosed cooling volume.

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The heat transfer device may include a storage housing may define the enclosed cooling volume.

The enclosed cooling volume may be cylindrical.

The enclosed cooling volume may be a rectangular prism.

The one or more heat transfer components may include at least one of pins, vanes, rods, fins, or other structures configured to allow heat to transfer between a heat source and the cooling chamber.

As the coolant flows through the enclosed cooling volume, heat may be transferred from the one or more heat transfer components to the coolant.

The coolant gaining heat from the one or more heat transfer components may correspond to heat being drawn away from the heat source.

The one or more heat transfer components may include a plurality of sponge rods distributed within the enclosed cooling volume.

The one or more heat transfer components may be further configured to direct the flow of coolant within the enclosed cooling volume.

The fluid passage may include a through hole defined by the storage housing, wherein the through hole is configured to allow coolant to flow into the cooling chamber.

The one or more heat transfer components may include an inner heat transfer component that is located near the through hole, and an outer heat transfer component that is located further from the through hole than the inner heat transfer component, and wherein a size of the outer heat transfer component is greater than a size of the inner heat transfer component.

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The heat transfer device may include one or more vanes configured to direct the flow of coolant within the enclosed cooling volume.

The vanes may be further configured to allow heat to transfer between a heat source and the cooling chamber.

The vanes may include cutouts that are configured to allow the coolant to flow through the vanes.

The pins and vanes may be positioned within the enclosed cooling volume to ensure that the coolant is able to flow through the enclosed cooling volume.

The one or more heat transfer components may define a path for the coolant to flow within the enclosed cooling volume.

The path may include one or more switchbacks.

The one or more heat transfer components may define a plurality of paths for the coolant to flow within the enclosed cooling volume.

Individual paths of the plurality of paths may lead radially and/or symmetrically-radially outward from the expansion valve.

When the coolant in the enclosed cooling volume reaches the end of the path, the coolant may be exhausted from the enclosed cooling volume.

The heat transfer device may include one or more exit interfaces that enable coolant to flow from the enclosed cooling volume to an exhaustion, diffusion, and/or effusion region, and wherein exhausting the coolant from the enclosed cooling volume comprises the coolant flowing through the one or more exit interfaces and to the exhaustion, diffusion, and/or effusion region.

The exhaustion region may be the environment of the heat transfer device.

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The heat transfer device may include a chimney through which coolant is able to flow from the enclosed cooling volume to an exhaustion, diffusion, and/or effusion region, and exhausting the coolant from the enclosed cooling volume may comprise the coolant flowing through the chimney and to the exhaustion, diffusion, and/or effusion region.

The one or more heat transfer components may be added to the enclosed cooling volume using additive manufacturing.

The one or more heat transfer components may include functionally gradient materials.

A thermal expansion of the one or more heat transfer components may decrease the volume of a/the enclosed storage volume.

The coolant may flow into the cooling chamber from the storage chamber at a central location of the enclosed cooling volume.

A compression of the enclosed volume may contribute to and/or is the sole source of an increase in internal pressure of the enclosed volume.

The compression of the enclosed volume contributes to and/or may be the sole activating force that causes the barrier element reconfiguring from the closed configuration to the open configuration in response to a trigger condition.

The compression of the enclosed volume may contribute to and/or is the sole drive of the coolant through the cooling chamber.

The heat source may be one of an electronic device and an electronic component.

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There is further described a combination of any of the above-described heat transfer devices and an electronic device.

The electronic device may include an electronic component; and any of the heat transfer devices described above operationally coupled to the electronic component.

Any of the heat transfer devices described above may be used to cool a heat source.

In another embodiment, there is provided a heat transfer device The heat transfer device comprises a storage chamber, a coolant housed within the storage chamber at an initial pressure, a cooling chamber adjacent to the storage chamber, one or more heat transfer components positioned and configured to facilitate heat transfer from a heat source to the cooling chamber, wherein the heat source is distinct from the cooling chamber, a fluid passage between the storage chamber and the cooling chamber and a barrier element. The barrier element has (i) a closed configuration in which the barrier element is configured to restrict the coolant from flowing from the storage chamber through the fluid passage and into the cooling chamber; and (ii) an open configuration in which the barrier element is configured to permit the coolant in the storage chamber to flow from the storage chamber through the fluid passage and into the cooling chamber, wherein the barrier element is configured to passively reconfigure from the closed configuration to the open configuration in response to a trigger condition, in which the coolant housed within the storage chamber reaches a trigger temperature or a trigger pressure. The fluid passage is configured to expand the coolant from the initial pressure to an expanded

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pressure as the coolant flows from the storage chamber through the fluid passage and to the cooling chamber responsive to the barrier element reconfiguring from the closed configuration to the open configuration. The fluid passage comprises an expansion valve coupled to the storage chamber and the cooling chamber such that the coolant flows from the storage chamber and into the expansion valve at the initial pressure and flows out of the expansion valve toward the cooling chamber at the expanded pressure, wherein the initial pressure is greater than the expanded pressure.

In another embodiment, there is provided a heat transfer device. The heat transfer device comprises a storage chamber, a coolant housed within the storage chamber at an initial pressure, a cooling chamber adjacent to the storage chamber, and one or more heat transfer components positioned and configured to facilitate heat transfer from a heat source to the cooling chamber, wherein the heat source is distinct from the cooling chamber, a fluid passage between the storage chamber and the cooling chamber. The device further includes a barrier element having (i) a closed configuration in which the barrier element is configured to restrict the coolant from flowing from the storage chamber through the fluid passage and into the cooling chamber; and (ii) an open configuration in which the barrier element is configured to permit the coolant in the storage chamber to flow from the storage chamber through the fluid passage and into the cooling chamber, wherein the barrier element is configured to passively reconfigure from the closed configuration to the open configuration in response to a trigger condition, in which the coolant housed within the storage chamber reaches a trigger temperature or a trigger pressure. The barrier element comprises a burst disc that is configured to rupture in response to at least

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one of, at least one of the coolant, the barrier element, and the burst disc reaching the trigger temperature, and a current pressure of the coolant in the storage chamber reaching the trigger pressure.

In another embodiment, there is provided a heat transfer device comprising a storage chamber, a coolant housed within the storage chamber at an initial pressure, a cooling chamber adjacent to the storage chamber, and one or more heat transfer components positioned and configured to facilitate heat transfer from a heat source to the cooling chamber, wherein the heat source is distinct from the cooling chamber. The device further incudes a fluid passage between the storage chamber and the cooling chamber and a barrier element having (i) a closed configuration in which the barrier element is configured to restrict the coolant from flowing from the storage chamber through the fluid passage and into the cooling chamber; and (ii) an open configuration in which the barrier element is configured to permit the coolant in the storage chamber to flow from the storage chamber through the fluid passage and into the cooling chamber, wherein the barrier element is configured to passively reconfigure from the closed configuration to the open configuration in response to a trigger condition, in which the coolant housed within the storage chamber reaches a trigger temperature or a trigger pressure. The barrier element comprises a plunger that is configured to, when the trigger condition occurs, create a passage that the coolant can flow through.

In another embodiment, there is provided a heat transfer device comprising a storage chamber, a coolant housed within the storage chamber at an initial pressure, a cooling chamber adjacent to the storage chamber and one or more heat transfer

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components positioned and configured to facilitate heat transfer from a heat source to the cooling chamber, wherein the heat source is distinct from the cooling chamber. The device further includes a fluid passage between the storage chamber and the cooling chamber and a barrier element having (i) a closed configuration in which the barrier element is configured to restrict the coolant from flowing from the storage chamber through the fluid passage and into the cooling chamber; and (ii) an open configuration in which the barrier element is configured to permit the coolant in the storage chamber to flow from the storage chamber through the fluid passage and into the cooling chamber, wherein the barrier element is configured to passively reconfigure from the closed configuration to the open configuration in response to a trigger condition, in which the coolant housed within the storage chamber reaches a trigger temperature or a trigger pressure. The barrier element comprises a membrane configured to restrict the coolant from flowing across the membrane when a current pressure of the coolant in the storage chamber is below a threshold pressure and allow the coolant to flow across the membrane when the current pressure of the coolant in the storage chamber is greater than or equal to the threshold pressure.

In another embodiment, there is provided a heat transfer device, comprising a storage chamber, a coolant housed within the storage chamber at an initial pressure, a cooling chamber adjacent to the storage chamber and one or more heat transfer components positioned and configured to facilitate heat transfer from a heat source to the cooling chamber, wherein the heat source is distinct from the cooling chamber. The device further includes a fluid passage between the storage chamber and the cooling chamber and a barrier element having (i) a closed configuration in which the

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barrier element is configured to restrict the coolant from flowing from the storage chamber through the fluid passage and into the cooling chamber; and (ii) an open configuration in which the barrier element is configured to permit the coolant in the storage chamber to flow from the storage chamber through the fluid passage and into the cooling chamber, wherein the barrier element is configured to passively reconfigure from the closed configuration to the open configuration in response to a trigger condition, in which the coolant housed within the storage chamber reaches a trigger temperature or a trigger pressure. The cooling chamber further comprises multiple curved vanes that define multiple curved coolant flow paths extending radially outward from the fluid passage, and wherein the cooling chamber further comprises multiple exit interfaces through which the coolant is permitted to exit the multiple curved coolant flow paths.

In another embodiment, there is provided a method of cooling a heat source. The method involves storing a coolant in a liquid state at an initial temperature in a storage chamber and based upon an occurrence of a trigger condition in which the coolant within the storage chamber reaches at least one of a trigger temperature and a trigger pressure, passively reconfiguring a barrier element from (i) a closed configuration in which the barrier element is configured to restrict the coolant from flowing from the storage chamber through a fluid passage, and to (ii) an open configuration in which the barrier element is configured to allow the coolant in the storage chamber to flow from the storage chamber through the fluid passage. The method further involves causing the coolant to transition from the liquid state to a gaseous state in the fluid passage and allowing the coolant to flow from the fluid

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passage and into a cooling chamber, wherein while the coolant flows through the cooling chamber, heat is transferred from the heat source and to the coolant via one or more heat transfer components.

The coolant may flow from the storage chamber and into the fluid passage at an initial pressure and may flow out of the fluid passage toward a cooling chamber at a final pressure, wherein the initial pressure is greater than the final pressure.

The fluid passage may include an expansion valve and causing the coolant to flow through the fluid passage may comprise causing the coolant to flow into the expansion valve.

The method may involve allowing heat to transfer from the heat source to the coolant in the storage chamber.

The storage chamber may be an enclosed volume, and the trigger condition may include at least one of the coolant, barrier element, and/or one or more sensor(s) reaching a trigger temperature, and/or the coolant, barrier element, and/or one or more sensor(s) reaching a trigger pressure.

A detection of the trigger condition may be based at least in part on a Boussinesq approximation.

Reconfiguring the barrier element may include a burst disc passively rupturing when the coolant reaches a/the trigger temperature and/or the pressure of the coolant in the storage chamber reaches a/the trigger pressure.

Reconfiguring the barrier element may include a plunger passively rupturing a barrier when the coolant reaches the trigger temperature and/or the pressure of the coolant in the storage chamber reaches the trigger pressure.

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The method may involve exhausting the coolant and the heat from the heat source absorbed by the coolant from a cooling chamber.

The cooling chamber may include at least one exit interface, and exhausting the coolant may include allowing the coolant, as well as any heat absorbed by the coolant during its traversal of a coolant flow path, to flow out of the heat transfer device.

Any of the methods described above may be performed by any of the heat transfer devices described above.

In another embodiment, there is provided a heat transfer device for cooling a heat source. The heat transfer device includes a storage chamber, a coolant housed within the storage chamber at an initial pressure, a cooling chamber adjacent to the storage chamber and one or more heat transfer components positioned and configured to facilitate heat transfer from a heat source to the coolant in the cooling chamber, wherein the heat source is distinct from the cooling chamber. The device further includes a fluid passage between the storage chamber and the cooling chamber and a barrier element having (i) a closed configuration in which the barrier element is configured to restrict the coolant from flowing from the storage chamber through the fluid passage and into the cooling chamber; wherein in the closed configuration heat flows away from the heat source to the coolant causing an increase in the temperature and in the pressure of the coolant; and (ii) an open configuration in which the barrier element is configured to permit the coolant in the storage chamber to flow from the storage chamber through the fluid passage and into the cooling chamber, thereby reducing the temperature of the coolant as the coolant expands into

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at least one of the cooling chamber and the fluid passage. The barrier element is configured to reconfigure from the closed configuration to the open configuration in response to a trigger condition, wherein the trigger condition includes at least one of at least one of the coolant housed within the storage chamber, the barrier element, and a sensor reaching a trigger temperature, and at least one of the pressure of the coolant housed within the storage chamber, the barrier element, and the sensor reaching a trigger pressure.

In another embodiment, there is provided a method of cooling a heat source using the heat transfer device described above, the method comprising storing the coolant in the storage chamber, and based upon an occurrence of the trigger condition, reconfiguring the barrier element from (i) the closed configuration in which the barrier element is configured to restrict the coolant from flowing from the storage chamber through a fluid passage, to (ii) the open configuration in which the barrier element is configured to allow the coolant in the storage chamber to flow from the storage chamber through the fluid passage to the cooling chamber, wherein while the coolant flows through the cooling chamber, heat is transferred from the heat source to the coolant via the one or more heat transfer components.

The features, functions, and advantages that have been discussed can be achieved independently in various embodiments or may be combined in yet other embodiments further details of which can be seen with reference to the following description and drawings.

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BRIEF DESCRIPTION OF THE DRAWINGS

Fig. **1** is a schematic diagram representing heat transfer devices according to the present disclosure.

Fig. **2** is a schematic diagram representing example heat transfer devices in which the barrier element is in the closed configuration.

Fig.**3** is a schematic diagram representing example heat transfer devices in which the barrier element is in the open configuration.

Fig. **4** is a diagram of an example cylindrical storage chamber in which the barrier device is a burst disc or membrane centrally located within the storage chamber.

Fig. **5** is a diagram of an example storage chamber having a polygonal prism shape, and in which the barrier device is a burst disc or membrane that is not centrally located within the storage chamber.

Fig. **6** is a diagram of an example apparatus that includes a storage chamber and multiple additional storage chambers.

Fig. **7** is a diagram of an example cylindrical storage chamber in which the barrier device includes a plunger device.

Fig. **8** is a diagram of an example storage chamber in which the barrier device includes a plunger device and including a chimney.

Fig. **9** is a diagram of an example apparatus that includes a storage chamber and an additional storage chamber.

Fig.**10** is a diagram of an example cylindrical cooling chamber with a single coolant flow path and multiple switchbacks.

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Fig. **11** is a diagram of an example cooling chamber with multiple coolant flow paths extending radially outward from a through hole.

Fig. **12** is a diagram of an example cylindrical cooling chamber with multiple coolant flow paths having switchbacks.

Fig. **13** is a diagram of an example cylindrical cooling chamber with two coolant flow paths and an opening.

Fig. **14** is a diagram of an example cooling chamber with multiple curved coolant flow paths extending radially outward from a through hole.

Fig. **15** an exploded view of an example heat transfer device according to the present disclosure.

Fig. **16** is a flowchart schematically representing methods for cooling a heat source using a heat transfer device according to the present disclosure.

DESCRIPTION

Heat transfer devices, electronic devices, and methods for cooling a heat source are disclosed. Generally, in the figures, elements that are likely to be included in a given example are illustrated in solid lines, while elements that are optional to a given example are illustrated in broken lines. However, elements that are illustrated in solid lines are not essential to all examples of the present disclosure, and an element shown in solid lines may be omitted from a particular example without departing from the scope of the present disclosure.

The heat transfer devices described herein can be used to passively cool a heat source, such as electronics that m ay generate heat. As heat transfers from the

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heat source and to the heat transfer device, the pressure and/or temperature of a coolant stored in a chamber of the heat transfer device increases. Once the pressure and/or temperature of the coolant reaches a threshold pressure and/or temperature a passive event allows the coolant to flow out of the chamber. The coolant then cools the heat source by absorbing additional heat via one or more heat transfer components.

Fig. **1** is a schematic diagram representing heat transfer devices **100** according to the present disclosure. In some embodiments, heat transfer devices **100** may be referred to as a Thermal Exchange Wafer (TEW). As illustrated in Fig. **1**, a heat transfer device **100** may be configured to draw heat away (i.e., cool) a heat source **102**. A heat source **102** may include an active component that generates heat, such as an engine, electronic component, etc. Alternatively, or in addition, heat source **102** may include a component that passively acquires heat from another source, such as a heat shield, a heat sink, etc. In such embodiments, the heat transfer device **100** may be configured to draw heat away from the heat source **102**.

As schematically illustrated in Fig. **1**, heat transfer devices **100** include at least a storage chamber **200**, a coolant **300** housed within the storage chamber **200**, a cooling chamber **400**, one or more heat transfer components **500**, a fluid passage **600** between the storage chamber **200** and the cooling chamber **400**, and a barrier element **700**. The barrier element **700** is configured to have a closed configuration in which the barrier element **700** restricts the coolant **300** from flowing from the storage chamber **200**, and an open configuration in which the barrier element **700** allows the

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coolant **300** in the storage chamber **200** to flow through the fluid passage **600** and into the cooling chamber **400**.

Fig. **2** illustrates example heat transfer devices **100** in which the barrier element **700** is in the closed configuration. Fig. **2** illustrates heat **104** flowing from heat source **102** to the coolant **300** during operation of the heat transfer devices **100**. Heat **104** may flow from the heat source **102** and through the heat transfer components **500**, a storage housing **202**, a cooling housing **402**, a storage heat transfer component **516**, another heat transfer means (such as a radiation and/or other environmental conductors located proximate to the heat transfer devices **100** and/or heat source **102**), or a combination thereof. Fig. **2** further shows the heat **104** flowing into the coolant **300**. In this way, when the barrier element **700** is in the closed configuration, the heat transfer device **100** draws heat **104** away from the heat source **102** and stores heat **104** in the coolant **300**. Such heat transfer may (or may not) be described as Forced convection, where buoyancy force is $g\alpha\Theta L$, where L is a length scale, and Θ is a temperature scale, as described by DJT's Physical Fluid Dynamics **2**nd edition Ch. **14**, Convection.

Additionally, when the barrier element **700** is in the closed configuration, the transfer of heat **104** into the coolant **300** causes the temperature of the coolant **300** to increase. Because the volume enclosed by the storage chamber **200** is a fixed volume, the pressure of the coolant **300** increases in correspondence with the temperature increase and according to the properties of thermal expansion of the coolant **300**. In some embodiments, the heat transfer devices **100** also include a heat distribution element **302** located within the enclosed storage volume **206**, and which is

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configured to distribute heat **104** across the coolant **300**. For example, the heat distribution element **302** may include an aluminum foam, or other conductive mesh through which heat **104** can be distributed across and into the coolant **300**.

Fig. **3** illustrates example heat transfer devices **100** in which the barrier element **700** is in the open configuration. Fig. **3** shows a coolant path **304** along which the coolant **300** flows from the enclosed storage volume **206**, through the fluid passage **600**, and into cooling chamber **400**. The pressure of the coolant **300** in the storage chamber **200** may drive the flow of coolant **300** through the fluid passage **600** and into the cooling chamber **400**. That is, because the pressure of the coolant **300** in the storage chamber **200** is greater than the pressure in the cooling chamber **400**, the coolant **300** may passively flow from the storage chamber **200** to the cooling chamber **400**. According to the thermodynamic properties of the coolant the temperature of the coolant **300** will drop as the coolant **300** expands into the cooling chamber **400**. Alternatively, or in addition, the temperature of the coolant **300** also may be reduced by an expansion device (e.g., a thermal expansion valve, an expansion valve, an expansion element, capillary tube, etc.) in the fluid passage **600**.

Once the coolant **300** enters the cooling chamber **400**, Fig. **3** illustrates the coolant flowing along one or more coolant flow paths **520** and to an exit interface **412**. Fig. **3** also shows heat **104** flowing from the heat transfer components **500** and into the coolant **300**. Once the coolant **300** reaches the exit interface **412**, both the coolant **300** and the heat **104** which the coolant **300** has absorbed is exhausted into an exhaustion region, such as the environment, an overflow tank **108**, or other location outside of the cooling chamber **400**. In this way, when the barrier element

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700 is in the open configuration, the passive flow of the coolant **300** causes the heat transfer device **100** to both draw heat **104** away from the heat source **102** and exhaust the heat **104** into an exhaustion region. In some embodiments, the cooling chamber **400** includes one or more test ports. Such test ports may be used for functions including but not limited to Non-Destructive Testing (NDT) and/or Non-Destructive Inspection (NDI), a leak test, a flow test, testing of safety/reliability/mission-reliability/repeatability, injection of fluid or some other substance into the cooling chamber, drawing of a vacuum and/or altering the pressure in the cooling chamber, cleaning of the chamber including removal of grit/FOD and/or unsintered AM powder, and/or an additional exhaust port during operation of the device; though other methods and/or devices may achieve these functions including the single exhaust port in contribution with or disjoint from the test ports; and such test ports may be permanently or temporarily sealed.

The coolant **300** will continue to passively flow out of the storage chamber **200** until the pressure of the coolant **300** in the storage chamber **200** and the pressure in the cooling chamber **400** reaches equilibrium. Additionally, the mass flow rate of the coolant **300** out of the storage chamber **200** will be relationally dependent upon the pressure difference between the pressure of the coolant **300** in the enclosed storage volume and the pressure in the cooling chamber **400**. This will cause the mass flow rate of the coolant **300** to reduce as the storage chamber **200** and the pressure in the cooling chamber **400** equilibrates.

Moreover, while not specifically illustrated in Fig. **3**, according to the present disclosure the transfer of heat **104** from the heat source **102** to the coolant **300**

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depicted in Fig. **2** continues to occur while the barrier element **700** is in the open configuration. In this way, while the barrier element **700** is in the open configuration, the heat **104** which continues to flow into the coolant **300** in the storage chamber **200** increases the pressure of the coolant **300** in the storage chamber **200**, thus driving a continued flow of coolant **300** into the cooling chamber **400**.

As illustrated in Figs. **1–3**, the storage chamber **200** may include a storage housing **202**. An internal surface **204** of the storage housing **202** defines an enclosed storage volume **206**. The storage housing **202** and the enclosed storage volume **206** may take various suitable shapes depending on application and/or volumetric requirements for specific applications. As illustrative examples, the storage housing **202** and/or the enclosed storage volume may be cylindrical, a rectangular prism, or any other shape. As illustrated in Figs. **1–3**, a coolant **300** is stored within the enclosed storage volume **206**. The coolant **300** may include any substance capable of efficiently absorbing heat. Within normal operating conditions for which a particular heat transfer device is designed, the coolant **300** is able to flow from the storage chamber **200** to the cooling chamber **400** through the fluid passage **600** when the barrier element **700** is in a fully and/or partially open configuration, as schematically represented in Fig. **3**. The coolant **300** may be a liquid at normal operating conditions of the heat transfer devices **100**. Normal operating conditions of the heat transfer devices **100** include a range of potential conditions (e.g., temperature, pressure, humidity, etc.) that are likely to exist during the course of an undertaking for which a particular heat transfer device **100** is designed. In this way, depending on the purposes of individual heat transfer devices, different coolants **300** may be selected

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that have characteristics that align with the normal operating conditions of the corresponding heat transfer device **100**.

In some embodiments, the coolant **300** may be selected for its ability to remain in a stable condition for long periods of time. Examples of such periods of time include **10^-18**, **10^-15**, **10^-9**, **10^0**, **10^1**, **10^2**, **10^3**, **10^4**, **10^5**, **10^6**, **10^7**, **10^8**, at least **10^-18**, at least **10^-15**, at least **10^-9**, at least **10^0**, at least **10^1**, at least **10^5**, at least **10^10**, less than **10^-18**, less than **10^-15**, less than **10^-9**, less than **10^0**, less than **10^1**, less than **10^5**, and/or less than **10^10**, seconds, minutes, hours days, weeks, months, years, decades, or other units of time. However, others may be used without departing from the scope of the present disclosure. For example, where a heat transfer device **100** is designed to cool an electronic component of a spacecraft, the coolant may need to remain stable in the storage chamber for years before the electronic component is activated and/or otherwise generates heat. To achieve this level of stability, the coolant **300** may be such that a boiling point temperature is greater than a range of operating temperatures of the heat transfer device, and/or a freezing point temperature is less than a range of operating temperatures of the heat transfer device. This may allow the heat transfer device **100** to remain dormant for long periods of time without the coolant breaking down, losing/altering its functional properties, or damaging the heat transfer device **100**. For example, the coolant **300** may partially and/or entirely comprise methane. In some embodiments, the coolant **300** may include component elements that improve the stability of the coolant **300**. For example, the coolant may include a component element that is itself a fire retardant, or which, when combined with other components

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of the coolant **300** prevent the coolant **300** from igniting. Alternatively, or in addition, the coolant **300** may include component elements that improve and or provide a voltage-carrying capability of the coolant **300**. For example, the coolant may optionally include a mixture of water and manganese sulfate. In some embodiments, the heat transfer devices **100** may include storage heat transfer component **516**. The storage heat transfer component **516** may be a component distinct from the heat transfer components **500**, and which is configured to permit heat to transfer between the heat source **102** without passing through the cooling chamber **400**.

The fluid passage **600** is configured to allow coolant **300** to flow from the storage chamber **200** to the cooling chamber **400**. In some embodiments, the fluid passage **600** is configured to expand the coolant **300** as it flows through the fluid passage. For example, coolant **300** may flow into the fluid passage **600** at an initial pressure and may flow out of the fluid passage **600** at an expanded pressure that is lower than the initial pressure. The reduction of the pressure of the coolant **300** may be a result of the coolant **300** moving from the enclosed storage volume **206** such that it is housed within an increased volume (i.e., from the enclosed storage volume **206** to an area including both the enclosed storage volume **206** and the enclosed cooling volume **406**), may be a result of the coolant **300** passing through an expansion device (e.g., a thermal expansion valve, an expansion valve, an expansion element, capillary tube, etc.) as the coolant **300** moves through the fluid passage **600**, or a combination thereof. For example, the fluid passage **600** may include an expansion valve **602** coupled to the storage chamber **200** and/or the cooling chamber **400**. In such embodiments, the coolant **300** flows from the storage chamber and into such an

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expansion valve **602** at an initial pressure and flows out of the expansion valve **602** and toward the cooling chamber **400** at an expanded pressure that is less than the initial pressure. Alternatively, or in addition, the expansion valve **602** and/or another component of the fluid passage **600** may cause the coolant **300** to transition from a liquid state to a gaseous state. For example, in some embodiments, coolant **300** is stored in the enclosed storage volume **206** in a liquid state but is a gas when the coolant **300** flows into the cooling chamber **400** via the fluid passage **600**.

The fluid passage **600** may include a fluid chamber **640**. The fluid chamber **640** may be an enclosed volume that coolant enters via the barrier element **700** when the barrier element **700** is in an open configuration. Coolant **300** may exit the fluid chamber **640** and enter the enclosed cooling volume **406**. Additionally, in some embodiments, the fluid passage **600** may be a shared fluid passage **660** into which coolant **300** flows when any individual barrier element **700** of a set of more than one barrier element **700** are in an open configuration.

As illustrated in Figs. **1–3**, heat transfer device **100** also includes a cooling chamber **400** that is located adjacent to the storage chamber **200**. Cooling chamber **400** includes a cooling housing **402** that has an internal surface **404** which defines an enclosed cooling volume **406**. One or more of the cooling housing **402** and/or the enclosed cooling volume **406** may be cylindrical, a rectangular prism, or any other shape. The shape of the enclosed cooling volume **406** may be the same shape as the enclosed storage volume **206** or may be a different shape.

The heat transfer device **100** may further include a through hole **408** that is located at an interface between the fluid passage **600** and the enclosed cooling

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volume **406**. The through hole **408** is defined by the storage housing **202** and/or cooling housing **402** and is configured to allow coolant **300** to flow from the fluid passage **600** to the enclosed cooling volume **406**. The through hole **408** may be located at a central region of the cooling chamber **400**. Alternatively, the through hole **408** may be positioned at any other location of the cooling chamber **400**, such as along a side region of the cooling chamber **400**. Moreover, according to the present disclosure the heat transfer device **100** may include two or more through holes **408** through which coolant can pass from the fluid passage **600** to the enclosed cooling volume **406**. In such embodiments, the two or more through-holes can be radially symmetric or radially asymmetric. For example, where the heat transfer device **100** includes three or more through holes, all may be symmetric, asymmetric, or a sub-set may be symmetric. Additionally, individual through holes do not have to be circular, and they may take on any shape, including a square, a trapezoid, etc. In some embodiments, the heat transfer device **100** also includes an adapter **410** positioned in or adjacent to a through hole **408** that is configured to convert the shape of the corresponding through hole **408**. For example, an adapter **410** may be placed in a circular through hole **408** to convert it to a trapezoidal through hole **408**.

The cooling chamber **400** also may include one or more exit interfaces **412** configured to allow the coolant **300** to flow out of the enclosed cooling volume **406**. An exit interface **412** may correspond to a hole defined by the cooling housing **402**. The coolant may flow out of the enclosed cooling volume **406** and into an exhaustion region, such as the environment **106**, an overflow tank **108**, or another location outside of the enclosed cooling volume **406**. In some embodiments, the exit

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interface **412** may allow coolant **300** to flow from the enclosed cooling volume **406** to a chimney **414** that allows the coolant to flow through or adjacent to the enclosed storage volume **206**, and/or one or more other components of the heat transfer device **100**. Alternatively, or in addition, the cooling chamber **400** may include a sewer structure configured to direct the flow of coolant **300** toward and/or through the enclosed cooling volume **406**. In some embodiments, the sewer structure may also direct the flow of coolant **300** out of the enclosed cooling volume **406**, and/or the heat transfer device **100**.

Heat transfer device **100** also includes one or more heat transfer components **500** that are configured to allow heat to transfer between the heat source **102** and the enclosed cooling volume **406**. Individual heat transfer components **500** may include a heating end **501** located proximate to the heat source **102** and a cooling end **503** located within the enclosed cooling volume **406**. The heating end **501** may be operatively coupled to the heat source **102** such that heat **104** generated by the heating source flows to the heating end **501**. In some embodiments, the heat transfer components **500** may include a conductive portion **518** that extends into the enclosed storage volume **206**. Alternatively, or in addition, a barrier **900** between the enclosed cooling volume **406** and the enclosed storage volume **206** may correspond to and/or optionally include a heat transfer component **500**, such as a conductive film, coating, layer and/or other barrier structure that partially or completely separates the enclosed cooling volume **406** from the enclosed storage volume **206**. For example, such a barrier **900** may include one or more of a braze foil **902**, a parting sheet with fin array,

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and/or other conductive components that are configured to allow heat to transfer into the enclosed storage volume **206** and/or evenly distribute the heat across the barrier.

According to the present disclosure, the one or more heat transfer components **500** may include pins **506**, vanes **508**, rods **510**, fins, and/or other structures that are configured to allow heat to transfer between the heat source **102** and the enclosed cooling volume **406**. For example, the heat transfer components **500** may include a plurality of sponge rods distributed within the enclosed cooling volume. Heat transfer device **100** may include a number of pins **506**, rods **510**, or a combination thereof arranged within the enclosed cooling volume **406** in a matrix array, an off-set matrix array, a spiral array, or any other distributed pattern. The size of individual pins **506**, vanes **508**, rods **510**, fins, and/or other heat transfer components may be constant or may vary in size. For example, in some embodiments, heat transfer components **500** located near through hole **408** may be smaller (i.e., have a smaller radius, surface area, height, etc.) than heat transfer components **500** located further from the through hole **408**. The cross-sectional shape of pins **506** and/or rods **510** may be circular, ovoid, polygonal, Vesica Piscis, or another shape.

In some embodiments, some, or all of the cooling housing **402** may comprise a conductive material that distributes heat from the heat source **102** to the enclosed cooling volume **406**. For example, a side and/or portion **416** of the cooling housing **402** may comprise a conductive material that distributes heat from the heat source **102** to the enclosed cooling volume **406**, the internal surface **404**, and or one or more pins **506**, vanes **508**, rods **510**, fins, and/or other structural components of the heat transfer components **500**. The side and/or portion **416** of the cooling housing **402**

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may be a flat side/portion, or may have raised, curved, or other irregularities **418** that increase the surface area for heat transfer between the side and/or portion **416** and the enclosed cooling volume **406**.

The heat transfer device **100** may further include one or more vanes or other structures configured to guide the flow of coolant **300** through the enclosed cooling volume **406** from the through hole **408** to the exit interface **412**. The vanes or other structures may optionally include cutouts **514** that are configured to allow the coolant to flow through the vanes. The cutouts **514** also may be described as voids, holes, openings, passages, passageways, etc. The cutouts **514** may be circular, ovoid, polygonal, diamond, or another shape. The cutouts may alter the wall shear τ_w, as defined by Shapiro's *The Dynamics and Thermodynamics of Compressible Fluid Flow* Ch. **27**, Volume **2**. Such diamond through holes may fully penetrate walls of the structure; including vanes mentioned above, where such walls may have constant or varying thickness, with flat or non-flat surfaces, crescent shaped in this instantiation. In some embodiments, the one or more vanes or other structures may be heat transfer components **500** configured to allow heat to transfer from the heat source **102** to the enclosed cooling volume **406**. For example, the heat transfer components **500** may include vanes **508**, fins, or other structures that are positioned to guide the flow of coolant **300** along a coolant flow path **520**. In various embodiments, individual vanes **508**, fins, or other structures may have a constant width, a varying width, a constant height, a varying height, be perpendicular to an associated surface of the cooling housing **402**, have a camber angle between the individual vane **508** and the associated surface of the cooling housing **402**, or a combination thereof.

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The coolant flow path **520** may include one or more switchbacks **522**. In some embodiments, there may be two or more coolant flow paths **520** through which coolant **300** can flow from a through hole **408** to an exit interface **412**. For example, where the through hole **408** is centrally located in the enclosed cooling volume **406**, the vanes or other structures may define a plurality of coolant flow paths **520** that lead radially outward from the through hole **408**.

According to the present disclosure, the heat transfer device **100** also includes a barrier element **700** that is configured to control the flow of coolant **300** from the storage chamber **200** to the cooling chamber **400**. The barrier element **700** is configured to have a closed configuration in which the barrier element **700** restricts the coolant **300** from flowing from the storage chamber **200**, and an open configuration in which the barrier element **700** allows the coolant **300** in the storage chamber **200** to flow through the fluid passage **600** and into the cooling chamber **400**. Example barrier elements **700** may include, but are not limited to, any combinations of burst discs, permeable membranes, plungers, release valves, pressure release valves, check valves, pyrotechnic valves, solenoid valves, ball, and spring valves, etc.

According to the present disclosure, the barrier element **700** is configured to reconfigure from the closed configuration to the open configuration in response to a trigger condition. For example, the trigger condition may correspond to the coolant **300** housed in the enclosed storage volume **206** reaching a certain temperature, the current pressure (i.e., the pressure at a corresponding time, a present time, or current time) of the coolant **300** housed in the enclosed storage volume **206** reaching a certain pressure level, or a combination thereof.

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In some embodiments, the barrier element **700** is configured to passively transition from the closed configuration to the open configuration. That is, the barrier element **700** may not require a signal or other stimulus from outside of the heat transfer device **100** to transition from the closed configuration to the open configuration. For example, the barrier element **700** may be configured to passively transition from the closed configuration to the open configuration in response to operating conditions of the heat transfer device **100** (e.g., conditions of the coolant **300** in the enclosed storage volume **206**, etc.).

For example, the barrier element **700** may include a burst disc **702** that forms a barrier that restricts the coolant **300** from flowing from the enclosed storage volume **206**, and which is configured to rupture when a pressure that the coolant **300** applies to the burst disc **702** exceeds a certain pressure level. In various embodiments, one or more of the characteristics of the burst disc **702** (e.g., size, thickness, component materials, elasticity, etc.), the characteristics of the coolant **300** (e.g., the type of coolant, the component ingredients of the coolant, etc.), and the initial conditions of the heat transfer device **100** (e.g., a size of the enclosed storage volume **206**, an amount of the coolant **300**, an initial pressure of the coolant **300**, etc.) may be designed so that the burst disc **702** ruptures when the coolant **300** reaches a set temperature. That is, when characteristics of the heat transfer device **100** are so designed, when the coolant **300** reaches the set temperature the coolant **300** will exert an amount of pressure on the burst disc **702** that is sufficient to rupture the burst disc **702**.

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Alternatively, or in addition, the barrier element **700** may include a membrane **704** through which coolant **300** can only pass through when certain conditions are met. For example, the membrane **704** may be configured to restrict the coolant **300** from flowing from the enclosed storage volume **206** when the pressure exerted by the coolant **300** onto the membrane **704** is below a threshold pressure and may be configured to allow the coolant **300** to flow across the membrane **704** when the pressure that the coolant **300** applies to the membrane **704** exceeds the pressure threshold.

Moreover, the barrier element **700** may include at least one plunger device **706** that is configured to create a passage through which the coolant **300** is able to flow from the enclosed storage volume **206** to the fluid passage **600**. The plunger device **706** may include a puncturing needle **708** having a puncturing end **710**, such as a needle tip and/or a hollow tip. In some embodiments, the plunger device **706** includes a driving mechanism that causes the puncturing end **710** to rupture a barrier or burst disc **702** or other barrier responsive to the trigger condition. For example, the plunger device **706** may include a pressure tab that is configured to burst when a pressure exerted on the pressure tab exceeds a threshold value, or when the temperature of the pressure tab exceeds a threshold value. In another example, as illustrated in Fig. **7**, the plunger device **706** may optionally include a restraining element **740** that prevents the plunger device **706** from moving to a neutral position, wherein the plunger device **706** moving to the neutral position includes creating the passage through which the coolant **300** is able to flow from the enclosed storage volume **206** to the fluid passage **600**. In such embodiments, the plunger device **706** may include a

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spring, piston, or other dynamic mechanism that biases the plunger device **706** to the neutral position. The restraining element **740** may be configured to restrain the plunger device **706** in a non-neutral position until the occurrence of a trigger event. For example, the restraining element **740** may comprise a material (e.g., wax, lead, etc.) that melts at a threshold temperature, where once melted, the plunger device **706** is allowed to move to the neutral position. In some embodiments, the plunger device **706** also may be configured to plug the passage in response to a close condition, such as a closing pressure being applied to the plunger device, the plunger device **706** reaching a closing temperature, etc.

As illustrated in Fig. **7**, in some embodiments, the heat transfer device **100** also may include a closed circuit **742** that is configured to control and/or initiate the transition of the barrier element **700** from the closed configuration to the open configuration. The closed circuit **742** may include a sensor **744**, such as pressure sensor (e.g., strain gauge), temperature sensor (e.g., thermocouple), or other sensor that is configured to detect the occurrence of a trigger condition. For example, the closed circuit **742** may include a thermocouple that is configured to produce a voltage sufficient to cause the barrier element **700** to transition between the closed configuration and the open configuration.

Additionally, as schematically illustrated in dashed lines in Fig. **1**, heat transfer device **100** also may optionally include one or more additional storage chambers **250**, additional coolants **350** housed within the additional storage chambers **250**, additional fluid passages **650** between the additional storage chambers **250** and the cooling chamber **400**, and additional barrier elements **750**. In some embodiments, the heat

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transfer device **100** may include a plurality of additional storage chambers **250**, where each individual additional storage chamber **250** stores additional coolant **350**. Similar to barrier element **700**, individual additional barrier elements **750** may be configured to have a closed configuration in which the additional barrier element **750** restricts the additional coolant **350** from flowing from the additional storage chamber **250**, and an open configuration in which the additional barrier element **750** allows the additional coolant **350** in the additional storage chamber **250** to flow through the additional fluid passage **650** and into the cooling chamber **400**.

In some embodiments, individual additional barrier elements **750** are configured to reconfigure from the closed configuration to the open configuration in response to an additional trigger condition(s) that are different from the trigger conditions for barrier element **700**. For example, the additional trigger condition for an additional barrier element **750** may correspond to one or both of (i) the additional coolant **350** housed within the additional storage chamber **250** reaching an additional trigger temperature, and (ii) the initial pressure of the additional coolant **350** housed within the additional storage chamber **250** reaching an additional trigger pressure. The additional fluid passage **650** may be configured to expand the additional coolant **350** from an initial pressure to an expanded pressure as the additional coolant **350** flows from the additional storage chamber **250** through the additional fluid passage **650** and to the cooling chamber **400** responsive to the additional barrier element **750** reconfiguring from the closed configuration to the open configuration. Alternatively, or in addition, the fluid passage **600** may be a shared fluid passage **660**, and the

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additional barrier element **750** may be configured to allow the additional coolant **350** to flow into the shared fluid passage **660**.

According to the present disclosure, at least one of the component elements of the heat transfer device **100** may be constructed using additive manufacturing. For example, one or more heat transfer components **500** may be partially or completely constructed and/or otherwise added to the enclosed cooling volume **406** using additive manufacturing. Example additive manufacturing methods and printers include, but are not limited to, VAT photopolymerization, powder bed fusion, binder jetting, material jetting, sheet lamination, material extrusion, directed energy deposition, directed metal laser sintering, direct metal printing, electron beam additive manufacturing, electron beam melting, electron beam powder bed, fused deposition modeling, indirect power bed, laser cladding technology, laser deposition technology, laser deposition welding, laser deposition welding with integrated milling, laser engineering net shape, laser freeform manufacturing technology, laser metal deposition-powder, laser metal deposition-wire, laser powder bed, laser puddle deposition, laser repair technology, powder directed energy deposition, stereolithography, selective laser melting, selective laser sintering, small puddle deposition, as well as hybrid processes thereof. For example, powder may be formed as collected waste powder or produced powder from Electrical Discharge Machining (EDM) machining processes.

Exemplary additive manufacturing materials include metals such as steel, stainless steel, titanium, copper, aluminum, nickel alloys, and alloys thereof, including but not limited to **IN625**, IN**718**, Ti-**6**Al-**4**V, Al-Si-**10**Mg, SS**316**, Monel, Monel K**500**,

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Copper, Ti-**5553**, Ti-**6**Al-**6**V-**2**Sn, Ti-**6242**, Maraging Steel MSI **18**, Mar **300**, **316**L, **17-4**, **15-4**, Cobalt Chrome SP**2**, Ti-**6**Al-**4**V ELI, Nickel Alloy HX, gold (au), silver (ag), as well as plastics/polymers/elastomers including Acrylonitile Butadiene Styrene (ABS), Polylactic acid (PLA), Polyvinyl alcohol, and Polycarbonate, and others including ULTEM, Kel-F, Kevlar, Nylon, and Carbon Composite, as well as thermoplastics such as Polyamide (PA), Polyphenylene Sulfide (PPS), Polyether Ether Ketone (PEEK), Poly-Ether-Ketone-Ketone (PEKK), Polyetherimide (PEI), Polyphenylsulfone (PPSU), Polyethersulfone (PES), Thermoplastic Polyimide (TPI), liquid crystalline polymer (LCP), polyamide-imide (PAI), or the like.

Alternatively, or in addition, the heat transfer device disclosed herein may be partially or completely formed of or may otherwise include Functionally Gradient Material (FGM). For example, a component element of the fluid passage **600**, such as an expansion valve or other type of valve, may be formed of a FGM that comprises a blend from Ti-**6**Al-**4**V to Al-Si-**10**Mg. In one example, the structure disclosed herein may be formed by altering the blending of deposited additively manufactured material such that Functionally Gradient Material (FGM) properties may be achieved, including varying the Coefficient of Thermal Expansion (CTE). Such varying may be useful for passive actuation of puncturing devices.

Further, in the construction of the heat transfer devices disclosed herein, support materials may be used, such as support materials for plastics like PVA or support materials for metallic elements, including water-soluble crystals and other melt-aways, including, but not limited to Cu, Ag, Al, Sb, Zn and Sn, as well as other alloys such as solder and low melting point Ag alloy solder (Ag-Sn-Pb, Ag-Pb, Ag-Sn,

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Ag-Sn-Cu, Ag-Cd-Zn, Ag-Cd); polyethylene, polyamide, polyimide, polypropylene, PMMA, polyether sulfone, thermoplastic polyester, copolymer or polyhexafluroropropylene and polytetrafluoroethylene, polyfluorovinylidene, and other organic composite photoresist materials, including but not limited to dry film type resists such as those discussed in U.S. Patent No. **5,805,971**. The device also may be constructed with non-thermoplastic materials, including epoxies, including high-temp resistant epoxies.

One or more parts of the structure also may be formed from plastics, including but not limited to Nylon, acrylonitrile butadiene styrene, polyactic acid, polyetherimide (ULTEM®), Carbon fiber, para-aramid synthetic fibers (KEVLAR®), polychlorotrifluoroethylene, polytetrafluoroethylene (TEFLON™), and polyethylene terephthalate. In some embodiments, the structure may be constructed of flexible material for purposes of resiliency to high-vibration regimes, flexure in aeroelastic applications.

Turning now to Figs. **4–14**, illustrative non-exclusive examples of storage chambers **200** and cooling chambers **400** according to the present disclosure are illustrated. Where appropriate, the reference numerals from the schematic illustrations of Figs. **1–3** are used to designate corresponding parts of the examples of Figs. **4–14**; however, the examples of Figs. **4–14** are non-exclusive and do not limit heat transfer devices **100** to the illustrated embodiments of Figs. **4–14**. That is, heat transfer devices **100** according to the present disclosure are not limited to the specific embodiments of the example storage chambers **200** and cooling chambers **400** illustrated in Figs. **4–14**, and heat transfer devices **100** may incorporate any number of

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the various aspects, configurations, characteristics, properties, etc. of heat transfer devices **100** that are illustrated in and discussed with reference to the schematic representations of Figs. **4–14** and/or the embodiments of Figs. **4–14**, as well as variations thereof, without requiring the inclusion of all such aspects, configurations, characteristics, properties, etc. For the purpose of brevity, each previously discussed component, part, portion, aspect, region, etc. or variants thereof may not be discussed, illustrated, and/or labeled again with respect to the examples of Figs. **4–14**; however, it is within the scope of the present disclosure that the previously discussed features, variants, etc. may be utilized with the examples of Figs. **4–14** in various embodiments.

Figs. **4–6** illustrate example storage chambers for a heat transfer device **100** according to the present disclosure, in which the barrier device comprises a burst disc or membrane. For example, Fig. **4** illustrates an example cylindrical storage chamber **200** in which the barrier element **700** is a burst disc or membrane centrally located within the storage chamber **200**. According to the present disclosure, when at least one of (i) the temperature of the coolant **300** reaches a trigger temperature, and (ii) the pressure of the coolant **300** stored in the storage chamber **200** reaches a threshold pressure, the barrier element **700** ruptures and/or otherwise allows the coolant **300** to flow into an associated enclosed cooling volume via a fluid passage **600**.

Fig. **5** illustrates an example storage chamber **200** having a polygonal prism shape, and in which the barrier element **700** is a burst disc or membrane that is not centrally located within the storage chamber **200**. When in the open configuration,

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coolant **300** stored in the enclosed storage volume **206** flows into the fluid passage **600**. The coolant **300** may then flow into an associated enclosed cooling volume **406** by passing through a through hole **408**. Fig. **5** further illustrates fluid chamber **640** as including a catch **642** that is configured to physically prevent debris from traveling through the through hole **408** with the flow of coolant **300**.

Fig. **6** illustrates an example apparatus that includes a storage chamber **200** and multiple additional storage chambers **250**. For example, Fig. **6** illustrates an apparatus that includes an enclosed storage volume **206** that stores coolant **300**, and multiple additional storage chambers **250** that store additional coolant **350**. Fig. **6** also shows the apparatus including a barrier element **700** and multiple additional barrier elements **750**. Fig. **6** also shows multiple barrier elements **760** that, when in an open configuration, each allow additional coolant to flow into a shared fluid passage **660** that comprises a fluid chamber **640**.

Figs. **7–9** illustrate example storage chambers for a heat transfer device **100** according to the present disclosure, in which the barrier device comprises a plunger device. For example, Fig. **7** illustrates an example cylindrical storage chamber **200** in which the barrier element **700** includes a plunger device **706**. According to the present disclosure, when at least one of (i) the temperature of the coolant **300** reaches a trigger temperature, and (ii) the pressure of the coolant **300** stored in the storage chamber **200** reaches a threshold pressure, the plunger device **706** actuates the puncturing needle **708** so that the puncturing end **710** creates a rupture in a burst disc **702** or other barrier. Coolant **300** is then able to flow through the rupture and into the

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fluid passage **600**. The coolant **300** may then pass into the enclosed cooling volume **406** via the through hole **408**.

As schematically illustrated in Fig. **7**, the plunger device **706** optionally may include a pressure tab that is configured to burst when a pressure exerted on the pressure tab exceeds a threshold value, or when the temperature of the pressure tab exceeds a threshold value. In another example, the plunger device **706** may include a restraining element **740** that prevents the plunger device **706** from moving to a neutral position, wherein the plunger device **706** moving to the neutral position includes creating the passage through which the coolant **300** is able to flow from the enclosed storage volume **206** to the fluid passage **600**.

Fig. **8** illustrates an example storage chamber **200** in which the barrier element **700** includes a plunger device **706** and including a chimney **414**. The example storage chamber **200** shown in Fig. **8** also includes an opening **920** defined by the storage housing **202**. The opening **920** may allow a line of sight through the storage chamber **200**. In some embodiments, the storage chamber **200** and the cooling chamber **400** may include opening **920** so that a line of sight exists through the storage chamber **200** and cooling chamber **400** such that at least a portion of the heat source **102** and/or other surface to which the heat transfer device **100** is attached is made visible. Fig. **8** also illustrates fluid passage **600** including multiple through holes **408**, and a chimney **414** that allows the coolant **300** to flow from the enclosed cooling volume and through the enclosed storage volume **206** and/or one or more other components of the heat transfer device **100**.

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Fig. **9** illustrates an example apparatus that includes a storage chamber **200** and additional storage chambers **250**. Specifically, Fig. **9** illustrates an apparatus that includes multiple barrier elements **700** (i.e., plunger devices **706**) that each, when in an open configuration, allow coolant **300** or **350** to flow into a shared fluid passage **660** and through hole **408**. Fig. **9** also illustrates a chimney **414** that allows the coolant **300** or **350** to flow from the enclosed cooling volume and through the enclosed storage volume **206** and/or one or more other components of the heat transfer device **100**.

Figs. **10–14** illustrate example cooling chambers for a heat transfer device **100** according to the present disclosure. For example, Fig. **10** illustrates an example cylindrical cooling chamber **400** with a single coolant flow path **520** and multiple switchbacks **522**. Coolant **300** may enter the enclosed cooling volume **406** via the through hole **408** and may be directed by vanes **508** to flow along the coolant flow path **520**. Fig. **10** also illustrates an offset matrix array of pins **506**. In various embodiments, individual vanes **508** may have a constant width, a varying width, a constant height, a varying height, may be perpendicular to an associated surface of the cooling housing **402**, may have a camber angle between the individual vane **508** and the associated surface of the cooling housing **402**, or a combination thereof. One or more of the vanes **508** and pins **506** may be configured to allow heat to transfer from a heat source **102** and into the coolant **300** as the coolant **300** flows along the coolant flow path **520**. Fig. **10** also illustrates an exit interface **412** through which the coolant **300**, as well as any heat absorbed by the coolant during its traversal of the coolant flow path **520**, may flow out of the enclosed cooling volume **406**.

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Fig. **11** illustrates an example cooling chamber **400** with multiple coolant flow paths extending radially outward from a through hole. Coolant may enter the enclosed cooling volume via the through hole **408** and may flow radially outward along one of the coolant flow paths **520** defined by vanes **508**. Fig. **11** also illustrates a plurality of heat transfer components **500** arranged in a matrix array, configured to allow heat to transfer from a heat source **102** and into the coolant **300** as the coolant **300** flows along the coolant flow paths **520**. Fig. **11** also illustrates multiple exit interfaces **412** through which the coolant **300**, as well as any heat absorbed by the coolant during its traversal of the coolant flow path **520**, may flow out of the enclosed cooling volume **406**.

Fig. **12** illustrates an example cylindrical cooling chamber **400** with multiple coolant flow paths **520** having switchbacks **522**. Coolant may enter the enclosed cooling volume via the multiple through holes **408** and may flow along one of the coolant flow paths **520** defined by the vanes **508**. Fig. **12** further shows a portion **416** of the cooling housing **402** as comprising a conductive material that distributes heat from the heat source **102** to the coolant **300** as it flows along the coolant flow paths **520**. Fig. **12** also illustrates multiple exit interfaces **412** through which the coolant **300**, as well as any heat absorbed by the coolant during its traversal of the coolant flow path **520**, may flow out of the enclosed cooling volume **406**.

Fig. **13** illustrates an example cylindrical cooling chamber **400** with two coolant flow paths **520** and an opening **920**. Coolant may enter the enclosed cooling volume via the multiple through holes **408** and may flow along one of the two coolant flow paths **520** to chimney **414**. Fig. **13** also illustrates a plurality of heat transfer

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components **500** arranged in a matrix array. Fig. **13** also shows heat transfer components that are located proximate to the through holes **408** are smaller than (e.g., have a reduced radius, height, surface area, etc.) the heat transfer components that are proximate the chimney **414**. The example cooling chamber **400** shown in Fig. **13** also includes an opening **920** defined in by the cooling housing **402** that allows a line of sight through the cooling chamber **400**.

Fig. **14** illustrates an example cooling chamber **400** with multiple curved coolant flow paths extending radially outward from a through hole. Coolant **300** may enter the enclosed cooling volume via the through hole **408** and may flow radially outward along one of the curved coolant flow paths **520** defined by curved vanes **508**. In Fig. **14** the coolant **300** enters the enclosed cooling volume at a central distribution location that is designed to allow the coolant **300** to flow through each of the multiple curved coolant flow paths. Thus, as the coolant **300** flows into the central distribution location, the coolant **300** is pushed outward from the central distribution location and into each of the multiple curved coolant flow paths. As shown in Fig. **14**, the coolant flow paths **520** defined by the vanes **508** may expand the farther they are from the through hole **408**. Fig. **14** also illustrates a plurality of heat transfer components **500** (i.e., pins **506**) arranged in a matrix array, configured to allow heat to transfer from a heat source **102** and into the coolant **300** as the coolant **300** flows along the coolant flow paths **520**. Fig. **14** also illustrates multiple exit interfaces **412** through which the coolant **300**, as well as any heat absorbed by the coolant during its traversal of the coolant flow path **520**, may flow out of the enclosed cooling volume **406**.

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Additionally, Fig. 14 illustrates cutouts **514** in vanes **508**. In this way, the coolant **300** is allowed to flow between different coolant flow paths **520** through cutouts **514**, and thus the temperatures of the coolant **300** and heat transfer components **500** can be uniform across the cooling chamber **400**. The cut outs **514** are illustrated as circular cutouts **514** that are configured to allow the coolant **300** to flow through the vanes **508**. However, according to the present disclosure, the cutouts **514** may be otherwise distributed, sized, and/or shaped including diamond, Vesica Pisces and/or other shapes. For example, in some embodiments, the cutouts **514** may be distributed, sized, and/or shaped within the vanes **508** so that the flow rate of coolant **300** through each cutout **514** is constant for all cutouts **514**. Additionally, in some embodiments, one or more of vanes **508** may be hollow and/or include internal pathways. In this way, the coolant **300** may travel internally within the hollow vanes **508**, internal pathways, and/or through the cutouts **514** as the coolant **300** travels outwardly from the center of the cooling chamber **400**.

Fig. **15** is an exploded view of an example heat transfer device according to the present disclosure. Specifically, Fig. **15** illustrates component elements of a storage chamber **200** partially defined by storage housing **202** and configured to store a coolant and a heat distribution element **302** configured to distribute heat across the coolant **300**. Fig. **15** also illustrates a barrier **900** between the storage chamber **200** and the cooling chamber **400** that comprises a heat transfer component **500**, such as a conductive film, coating, layer and/or other barrier structure that partially or completely separates the enclosed cooling volume **406** from the enclosed storage volume. For example, in the example depicted in Fig. **15**, barrier **900** includes one or

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more of a braze foil **902**, a parting sheet with fin array, and/or other conductive components that are configured to allow heat to transfer into the cooling chamber **400** and/or evenly distribute the heat across the barrier **900**. In some embodiments, the storage housing **202** and/or barrier **900** may include one or more seals, such as a Gibbous O-ring Layering seal that prevents the coolant from leaking from the enclosed storage chamber **200**. Fig. **15** also shows the example heat transfer device as including a barrier element **700** and fluid passage **600**. In its exploded view, Fig. **15** also shows the example heat transfer device as including the example cooling chamber **400** depicted in Fig. **14**.

Fig. **16** schematically provides a flowchart that represents illustrative, non-exclusive examples of methods according to the present disclosure. In Fig. **16**, some steps are illustrated in dashed boxes indicating that such steps may be optional or may correspond to an optional version of a method according to the present disclosure. That said, not all methods according to the present disclosure are required to include the steps illustrated in solid boxes. The methods and steps illustrated in Fig. **16** are not limiting and other methods and steps are within the scope of the present disclosure, including methods having greater than or fewer than the number of steps illustrated, as understood from the discussions herein.

Fig. **16** is a flowchart depicting methods **1600**, according to the present disclosure, for cooling a heat source using a heat transfer device **100**. Methods **1600** include storing a coolant (e.g., coolant **300**) in a storage chamber (e.g., storage chamber **200**) at **1602**. For example, the storage chamber may include an enclosed volume (e.g., enclosed storage volume **206**) that is defined by a housing of the

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storage chamber. The coolant may include any substance capable of efficiently absorbing heat, and which within normal operating conditions is able to flow from the storage chamber to the cooling chamber through the fluid passage. The coolant **300** may be a liquid at normal operating conditions of the heat transfer device **100**.

Methods **1600** optionally may include allowing heat to transfer from the heat source (e.g., heat source **102**) to the coolant stored in the storage chamber at **1604**. For example, heat may transfer from the heat source to the coolant through components configured to facilitate heat transfer (e.g., the heat transfer components **500**, the storage housing **202**, the cooling housing **402**, the storage heat transfer component **516**, etc.) another heat transfer means, such as a radiation and/or other environmental conductors located proximate to the heat transfer device **100** and/or heat source, or a combination thereof.

At **1606**, a barrier element reconfigures from (i) a closed configuration in which the barrier element is configured to restrict the coolant from flowing from the storage chamber through the fluid passage, and to (ii) an open configuration in which the barrier element is configured to allow the coolant in the storage chamber to flow from the storage chamber through the fluid passage. In some embodiments, the barrier element may reconfigure from the closed configuration to an open configuration based upon an occurrence of a trigger condition. The trigger condition may include at least one of the coolant reaching a trigger temperature, and/or the coolant reaching a trigger pressure. In some embodiments, the barrier element may passively reconfigure from the closed configuration to an open configuration in response to the trigger condition. For example, the barrier element may include one or more of a burst

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disc, a membrane, a plunger device, a release valve, a pressure release valve, a check valve, a pyrotechnic valve, a solenoid valve, a ball, and spring valve, etc., that passively transition from the closed configuration to the open configuration responsive to the trigger condition.

At **1608**, the coolant is allowed to flow from the fluid passage and through the cooling chamber, wherein while the coolant flows through the cooling chamber heat is transferred from the heat source and to the coolant via one or more heat transfer components. For example, responsive to the barrier element being in an open configuration, the coolant may flow into the cooling chamber via the fluid chamber. In some embodiments, the coolant flows from the storage chamber and into the fluid passage at an initial pressure and flows out of the fluid passage toward a cooling chamber at a final pressure that is less than the initial pressure. In some embodiments, the fluid passage includes an expansion valve through which the coolant flows when it passes through the fluid passage. As the coolant flows through the cooling chamber along one or more coolant flow paths, heat from the heat source flows into the coolant. For example, the cooling chamber may include one or more heat transfer components configured to allow heat to transfer between a heat source and the coolant, such as conductive pins, vanes, rods, fins, or other structures. In some embodiments, some or all of the conductive elements define the coolant flow path(s).

At **1610**, the coolant and the heat from the heat source absorbed by the coolant are exhausted from the heat transfer device. For example, the cooling chamber may include at least one exit interface through which the coolant, as well as any heat

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absorbed by the coolant during its traversal of the coolant flow path, may flow out of the enclosed cooling volume.

As used herein, the terms “adapted” and “configured” mean that the element, component, or other subject matter is designed and/or intended to perform and/or support one or more given function(s). It is also within the scope of the present disclosure that elements, components, and/or other recited subject matter that is recited as being adapted to perform a particular function may additionally or alternatively be described as being configured to perform that function, and vice versa. Similarly, subject matter that is recited as being configured to perform a particular function may additionally or alternatively be described as being operative to perform that function.

As used herein, the term “and/or” placed between a first entity and a second entity means one of (**1**) the first entity, (**2**) the second entity, and (**3**) the first entity and the second entity. Multiple entries listed with “and/or” should be construed in the same manner, i.e., “one or more” of the entities so conjoined. Other entities optionally may be present other than the entities specifically identified by the “and/or” clause, whether related or unrelated to those entities specifically identified. Thus, as a non-limiting example, a reference to “A and/or B,” when used in conjunction with open-ended language such as “comprising,” may refer, in one example, to A only (optionally including entities other than B); in another example, to B only (optionally including entities other than A); in yet another example, to both A and B (optionally including other entities). These entities may refer to elements, actions, structures, steps, operations, values, and the like.

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The various disclosed elements of apparatuses and steps of methods disclosed herein are not required to all apparatuses and methods according to the present disclosure, and the present disclosure includes all novel and non-obvious combinations and subcombinations of the various elements and steps disclosed herein. Moreover, one or more of the various elements and steps disclosed herein may define independent inventive subject matter that is separate and apart from the whole of a disclosed apparatus or method. Accordingly, such inventive subject matter is not required to be associated with the specific apparatuses and methods that are expressly disclosed herein, and such inventive subject matter may find utility in apparatuses and/or methods that are not expressly disclosed herein.

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EMBODIMENTS IN WHICH AN EXCLUSIVE PROPERTY OR PRIVILEGE IS CLAIMED ARE DEFINED AS FOLLOWS:

1. A heat transfer device, comprising:

a storage chamber;

a coolant housed within the storage chamber at an initial pressure;

a cooling chamber adjacent to the storage chamber;

one or more heat transfer components positioned and configured to facilitate heat transfer from a heat source to the cooling chamber, wherein the heat source is distinct from the cooling chamber;

a fluid passage between the storage chamber and the cooling chamber; and

a barrier element having:

(i) a closed configuration in which the barrier element is configured to restrict the coolant from flowing from the storage chamber through the fluid passage and into the cooling chamber; and

(ii) an open configuration in which the barrier element is configured to permit the coolant in the storage chamber to flow from the storage chamber through the fluid passage and into the cooling chamber, wherein the barrier element is configured to passively reconfigure

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from the closed configuration to the open configuration in response to a trigger condition, in which the coolant housed within the storage chamber reaches a trigger temperature or a trigger pressure;

wherein the coolant housed within the storage chamber is in a liquid state, and the fluid passage is configured to cause the coolant to transition from the liquid state to a gaseous state.

2. The heat transfer device of claim **1**, wherein the fluid passage is configured to expand the coolant from the initial pressure to an expanded pressure as the coolant flows from the storage chamber through the fluid passage and to the cooling chamber responsive to the barrier element reconfiguring from the closed configuration to the open configuration.

3. The heat transfer device of claim **1** or **2**, wherein the fluid passage comprises an expansion valve coupled to the storage chamber and the cooling chamber such that the coolant flows from the storage chamber and into the expansion valve at the initial pressure and flows out of the expansion valve toward the cooling chamber at the expanded pressure, wherein the initial pressure is greater than the expanded pressure.

4. The heat transfer device of any one of claims **1**-**3**, further comprising:

an additional storage chamber;

additional coolant housed within the additional storage chamber;

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an additional fluid passage between the additional storage chamber and the cooling chamber; and

an additional barrier element having (i) a closed configuration in which the additional barrier element is configured to restrict the additional coolant from flowing from the additional storage chamber through the additional fluid passage and into the cooling chamber, and (ii) an open configuration in which the additional barrier element is configured to allow the additional coolant in the additional storage chamber to flow from the additional storage chamber through the additional fluid passage and into the cooling chamber.

5. The heat transfer device of claim **4**, wherein the additional barrier element is configured to reconfigure from the closed configuration to the open configuration in response to an additional trigger condition, and wherein the additional trigger condition is different from the trigger condition.

6. The heat transfer device of any one of claims **1**-**5**, further comprising:

an additional storage chamber;

additional coolant housed within the additional storage chamber, wherein the fluid passage is further configured to allow coolant to flow between the additional storage chamber and the cooling chamber; and

an additional barrier element having (i) a closed configuration in which the additional barrier element is configured to restrict the additional coolant

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from flowing from the storage chamber through the fluid passage and into the cooling chamber, and (ii) an open configuration in which the additional barrier element is configured to allow the additional coolant in the additional storage chamber to flow from the additional storage chamber through the fluid passage and into the cooling chamber.

7. The heat transfer device of any one of claims **1-6**, wherein a current pressure of the coolant in the storage chamber is a driving pressure that forces the coolant in the storage chamber to flow through the fluid passage and into the cooling chamber.

8. The heat transfer device of any one of claims **1-7**, wherein the barrier element comprises a burst disc that is configured to rupture in response to at least one of:

at least one of the coolant, the barrier element, and the burst disc reaching the trigger temperature, and

a current pressure of the coolant in the storage chamber reaching the trigger pressure.

9. The heat transfer device of any one of claims **1-8**, wherein the barrier element comprises a plunger that is configured to, when the trigger condition occurs, create a passage that the coolant can flow through.

10. The heat transfer device of claim **9**, wherein the barrier element comprises a burst disc, and creating the passage that the coolant can flow through comprises the plunger rupturing the burst disc to create the passage.

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11. The heat transfer device of claim **10**, wherein the barrier element further comprises a restraining element configured to restrain the plunger to maintain the barrier element in the closed configuration until occurrence of the trigger condition, and wherein the restraining element is configured to permit the plunger to rupture the burst disc responsive to the trigger condition.

12. The heat transfer device of claim **11**, wherein the restraining element comprises a material that melts at the trigger temperature.

13. The heat transfer device of claim **10**, wherein the barrier element further comprises an electrical circuit that has a sensor that is configured to detect the trigger condition, and wherein the electrical circuit is configured to cause the plunger to rupture the burst disc upon the sensor detecting the trigger condition.

14. The heat transfer device of any one of claims **1**-**13**, wherein the barrier element comprises a membrane configured to: restrict the coolant from flowing across the membrane when a current pressure of the coolant in the storage chamber is below a threshold pressure; and allow the coolant to flow across the membrane when the current pressure of the coolant in the storage chamber is greater than or equal to the threshold pressure.

15. The heat transfer device of any one of claims **1-14**, wherein the one or more heat transfer components define at least one coolant path for the coolant to flow within the cooling chamber.

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16. The heat transfer device of claim **1**, wherein the cooling chamber further comprises multiple curved vanes that define multiple curved coolant flow paths extending radially outward from the fluid passage, and wherein the cooling chamber further comprises multiple exit interfaces through which the coolant is permitted to exit the multiple curved coolant flow paths.

17. The heat transfer device of claim **16**, wherein the cooling chamber further comprises a plurality of heat transfer components positioned within the multiple curved coolant flow paths.

18. The heat transfer device of claim **16**, wherein the multiple curved vanes comprise cutouts to allow the coolant to flow between the multiple curved coolant flow paths.

19. The heat transfer device of claim **16**, wherein the cooling chamber comprises a central distribution location, through which the coolant enters the multiple curved coolant flow paths, and wherein the multiple curved vanes extend radially outward from the central distribution location.

20. A heat transfer device, comprising:

a storage chamber;

a coolant housed within the storage chamber at an initial pressure;

a cooling chamber adjacent to the storage chamber;

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one or more heat transfer components positioned and configured to facilitate heat transfer from a heat source to the cooling chamber, wherein the heat source is distinct from the cooling chamber;

a fluid passage between the storage chamber and the cooling chamber; and

a barrier element having:

(i) a closed configuration in which the barrier element is configured to restrict the coolant from flowing from the storage chamber through the fluid passage and into the cooling chamber; and

(ii) an open configuration in which the barrier element is configured to permit the coolant in the storage chamber to flow from the storage chamber through the fluid passage and into the cooling chamber, wherein the barrier element is configured to passively reconfigure from the closed configuration to the open configuration in response to a trigger condition, in which the coolant housed within the storage chamber reaches a trigger temperature or a trigger pressure;

wherein the fluid passage is configured to expand the coolant from the initial pressure to an expanded pressure as the coolant flows from the storage chamber through the fluid passage and to the cooling chamber responsive to the barrier element reconfiguring from the closed configuration to the open configuration; and

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wherein the fluid passage comprises an expansion valve coupled to the storage chamber and the cooling chamber such that the coolant flows from the storage chamber and into the expansion valve at the initial pressure and flows out of the expansion valve toward the cooling chamber at the expanded pressure, wherein the initial pressure is greater than the expanded pressure.

21. A heat transfer device, comprising:

a storage chamber;

a coolant housed within the storage chamber at an initial pressure;

a cooling chamber adjacent to the storage chamber;

one or more heat transfer components positioned and configured to facilitate heat transfer from a heat source to the cooling chamber, wherein the heat source is distinct from the cooling chamber;

a fluid passage between the storage chamber and the cooling chamber; and

a barrier element having:

(i) a closed configuration in which the barrier element is configured to restrict the coolant from flowing from the storage chamber through the fluid passage and into the cooling chamber; and

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(ii) an open configuration in which the barrier element is configured to permit the coolant in the storage chamber to flow from the storage chamber through the fluid passage and into the cooling chamber, wherein the barrier element is configured to passively reconfigure from the closed configuration to the open configuration in response to a trigger condition, in which the coolant housed within the storage chamber reaches a trigger temperature or a trigger pressure;

wherein the barrier element comprises a burst disc that is configured to rupture in response to at least one of:

at least one of the coolant, the barrier element, and the burst disc reaching the trigger temperature, and

a current pressure of the coolant in the storage chamber reaching the trigger pressure.

22. A heat transfer device, comprising:

a storage chamber;

a coolant housed within the storage chamber at an initial pressure;

a cooling chamber adjacent to the storage chamber;

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one or more heat transfer components positioned and configured to facilitate heat transfer from a heat source to the cooling chamber, wherein the heat source is distinct from the cooling chamber;

a fluid passage between the storage chamber and the cooling chamber; and

a barrier element having:

(i) a closed configuration in which the barrier element is configured to restrict the coolant from flowing from the storage chamber through the fluid passage and into the cooling chamber; and

(ii) an open configuration in which the barrier element is configured to permit the coolant in the storage chamber to flow from the storage chamber through the fluid passage and into the cooling chamber, wherein the barrier element is configured to passively reconfigure from the closed configuration to the open configuration in response to a trigger condition, in which the coolant housed within the storage chamber reaches a trigger temperature or a trigger pressure;

wherein the barrier element comprises a plunger that is configured to, when the trigger condition occurs, create a passage that the coolant can flow through.

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23. The heat transfer device of claim **22**, wherein the barrier element comprises a burst disc, and wherein the plunger is configured to rupture the burst disc to create the passage.

24. The heat transfer device of claim **23**, wherein the barrier element further comprises a restraining element configured to restrain the plunger to maintain the barrier element in the closed configuration until occurrence of the trigger condition, and wherein the restraining element is configured to permit the plunger to rupture the burst disc responsive to the trigger condition.

25. The heat transfer device of claim **24**, wherein the restraining element comprises a material that melts at the trigger temperature.

26. The heat transfer device of claim **23**, wherein the barrier element further comprises an electrical circuit that has a sensor that is configured to detect the trigger condition, and wherein the electrical circuit is configured to cause the plunger to rupture the burst disc upon the sensor detecting the trigger condition.

27. A heat transfer device, comprising:

a storage chamber;

a coolant housed within the storage chamber at an initial pressure;

a cooling chamber adjacent to the storage chamber;

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one or more heat transfer components positioned and configured to facilitate heat transfer from a heat source to the cooling chamber, wherein the heat source is distinct from the cooling chamber;

a fluid passage between the storage chamber and the cooling chamber; and

a barrier element having:

(i) a closed configuration in which the barrier element is configured to restrict the coolant from flowing from the storage chamber through the fluid passage and into the cooling chamber; and

(ii) an open configuration in which the barrier element is configured to permit the coolant in the storage chamber to flow from the storage chamber through the fluid passage and into the cooling chamber, wherein the barrier element is configured to passively reconfigure from the closed configuration to the open configuration in response to a trigger condition, in which the coolant housed within the storage chamber reaches a trigger temperature or a trigger pressure;

wherein the barrier element comprises a membrane configured to: restrict the coolant from flowing across the membrane when a current pressure of the coolant in the storage chamber is below a threshold pressure; and allow the coolant to flow across the membrane when the current pressure of the

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coolant in the storage chamber is greater than or equal to the threshold pressure.

28. A heat transfer device, comprising:

a storage chamber;

a coolant housed within the storage chamber at an initial pressure;

a cooling chamber adjacent to the storage chamber;

one or more heat transfer components positioned and configured to facilitate heat transfer from a heat source to the cooling chamber, wherein the heat source is distinct from the cooling chamber;

a fluid passage between the storage chamber and the cooling chamber; and

a barrier element having:

(i) a closed configuration in which the barrier element is configured to restrict the coolant from flowing from the storage chamber through the fluid passage and into the cooling chamber; and

(ii) an open configuration in which the barrier element is configured to permit the coolant in the storage chamber to flow from the storage chamber through the fluid passage and into the cooling chamber, wherein the barrier element is configured to passively reconfigure

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from the closed configuration to the open configuration in response to a trigger condition, in which the coolant housed within the storage chamber reaches a trigger temperature or a trigger pressure;

wherein the cooling chamber further comprises multiple curved vanes that define multiple curved coolant flow paths extending radially outward from the fluid passage, and wherein the cooling chamber further comprises multiple exit interfaces through which the coolant is permitted to exit the multiple curved coolant flow paths.

29. The heat transfer device of claim **28**, wherein the cooling chamber further comprises a plurality of heat transfer components positioned within the multiple curved coolant flow paths.

30. The heat transfer device of claim **28**, wherein the multiple curved vanes comprise cutouts to allow the coolant to flow between the multiple curved coolant flow paths.

31. The heat transfer device of claim **28**, wherein the cooling chamber comprises a central distribution location, through which the coolant enters the multiple curved coolant flow paths, and wherein the multiple curved vanes extend radially outward from the central distribution location.

32. A method of cooling a heat source, the method comprising:

storing a coolant in a liquid state at an initial temperature in a storage chamber;

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based upon an occurrence of a trigger condition in which the coolant within the storage chamber reaches at least one of a trigger temperature and a trigger pressure, passively reconfiguring a barrier element from (i) a closed configuration in which the barrier element is configured to restrict the coolant from flowing from the storage chamber through a fluid passage, and to (ii) an open configuration in which the barrier element is configured to allow the coolant in the storage chamber to flow from the storage chamber through the fluid passage;

causing the coolant to transition from the liquid state to a gaseous state in the fluid passage; and

allowing the coolant to flow from the fluid passage and into a cooling chamber, wherein while the coolant flows through the cooling chamber, heat is transferred from the heat source and to the coolant via one or more heat transfer components.

33. The method of claim **32**, wherein the coolant flows from the storage chamber and into the fluid passage at an initial pressure and flows out of the fluid passage toward the cooling chamber at a final pressure, wherein the initial pressure is greater than the final pressure.

34. The method of claim **32** or **33**, wherein the fluid passage includes an expansion valve, and causing the coolant to flow through the fluid passage comprises causing the coolant to flow into the expansion valve.

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35. The method of any one of claims **32-34**, further comprising allowing heat to transfer from the heat source to the coolant in the storage chamber.

36. The method of any one of claims **32-35**, wherein the storage chamber is an enclosed volume, and wherein the trigger condition includes at least one of:

at least one of the coolant, barrier element, and a sensor reaching the trigger temperature, and

at least one of the coolant, barrier element, and sensor reaching the trigger pressure.

37. The method of claim **32** wherein passively reconfiguring the barrier element comprises causing a burst disk to rupture in response to at least one of:

(i) at least one of the coolant, the barrier element and the burst disk reaching the trigger temperature; and

(ii) a current pressure of the coolant in the storage chamber reaching the trigger pressure.

38. The method of claim **32** wherein passively reconfiguring the barrier element comprises causing a plunger to create a passage for the coolant can flow through the fluid passage when the trigger condition occurs.

39. The method of claim **32** wherein passively reconfiguring the barrier element comprises causing a membrane to restrict a flow of coolant therethrough and through the fluid passage when a current pressure of the coolant in the storage

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chamber is below a threshold and causing the membrane to allow the flow of coolant therethrough and through the fluid passage when the current pressure of the coolant in the storage chamber is greater than or equal to the threshold pressure.

40. The method of any one of claims **32**-**39** wherein transferring heat from the heat source while the coolant flows through the cooling chamber comprises causing the cooling fluid to flow through multiple curved coolant flow paths extending radially outwardly from the fluid passage in the cooling chamber and permitting the coolant to exit the multiple curved coolant flow paths through multiple exit interfaces.

41. A heat transfer device for cooling a heat source, comprising:

a storage chamber;

a coolant housed within the storage chamber at an initial pressure;

a cooling chamber adjacent to the storage chamber;

one or more heat transfer components positioned and configured to facilitate heat transfer from a heat source to the coolant in the cooling chamber, wherein the heat source is distinct from the cooling chamber;

a fluid passage between the storage chamber and the cooling chamber; and

a barrier element having:

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(i) a closed configuration in which the barrier element is configured to restrict the coolant from flowing from the storage chamber through the fluid passage and into the cooling chamber; wherein in the closed configuration heat flows away from the heat source to the coolant causing an increase in the temperature and in the pressure of the coolant; and

(ii) an open configuration in which the barrier element is configured to permit the coolant in the storage chamber to flow from the storage chamber through the fluid passage and into the cooling chamber, thereby reducing the temperature of the coolant as the coolant expands into at least one of the cooling chamber and the fluid passage, wherein the barrier element is configured to reconfigure from the closed configuration to the open configuration in response to a trigger condition, wherein the trigger condition includes at least one of:

> at least one of the coolant housed within the storage chamber, the barrier element, and a sensor reaching a trigger temperature, and
>
> at least one of the pressure of the coolant housed within the storage chamber, the barrier element, and the sensor reaching a trigger pressure.

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42. The heat transfer device of claim **41**, wherein the fluid passage is configured to expand the coolant from the initial pressure to an expanded pressure as the coolant flows from the storage chamber through the fluid passage and to the cooling chamber responsive to the barrier element reconfiguring from the closed configuration to the open configuration.

43. The heat transfer device of claim **41** or **42**, wherein the coolant housed within the storage chamber is in a liquid state, and the fluid passage is configured to cause the coolant to transition from a liquid state to a gaseous state.

44. The heat transfer device of any one of claims **41**-**43**, further comprising:

an additional storage chamber;

additional coolant housed within the additional storage chamber;

an additional fluid passage between the additional storage chamber and the cooling chamber; and

an additional barrier element having:

(i) a closed configuration in which the additional barrier element is configured to restrict the additional coolant from flowing from the additional storage chamber through the additional fluid passage and into the cooling chamber, and

(ii) an open configuration in which the additional barrier element is configured to allow the additional coolant in the additional storage

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chamber to flow from the additional storage chamber through the additional fluid passage and into the cooling chamber;

wherein the additional barrier element is configured to reconfigure from the closed configuration to the open configuration in response to an additional trigger condition.

45. The heat transfer device of claim **44**, wherein the additional trigger condition is different from the trigger condition.

46. The heat transfer device of any one of claims **41**-**45**, further comprising:

an additional storage chamber;

additional coolant housed within the additional storage chamber, wherein the fluid passage is further configured to allow coolant to flow between the additional storage chamber and the cooling chamber; and

an additional barrier element having:

(i) a closed configuration in which the additional barrier element is configured to restrict the additional coolant from flowing from the storage chamber through the fluid passage and into the cooling chamber, and

(ii) an open configuration in which the additional barrier element is configured to allow the additional coolant in the additional storage

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chamber to flow from the additional storage chamber through the fluid passage and into the cooling chamber.

47. The heat transfer device of any one of claims **41**-**46**, wherein the barrier element is configured to passively transition from the closed configuration to the open configuration in response to the trigger condition.

48. The heat transfer device of any one of claims **41**-**47**, wherein the barrier element comprises a burst disc that is configured to rupture in response to at least one of:

at least one of the coolant, the barrier element, and the burst disc reaching the trigger temperature, and

a current pressure of the coolant in the storage chamber reaching the trigger pressure.

49. The heat transfer device of any one of claims **41**-**47**, wherein the barrier element comprises a plunger that is configured to, when the trigger condition occurs, create a passage that the coolant can flow through.

50. The heat transfer device of any one of claims **41**-**47**, wherein the barrier element comprises a membrane configured to:

restrict the coolant from flowing through the membrane when a current pressure of the coolant in the storage chamber is below a threshold pressure; and

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allow the coolant to flow through the membrane when the current pressure of the coolant in the storage chamber is greater than or equal to the threshold pressure.

51. The heat transfer device of any one of claims **41**-**50**, wherein the one or more heat transfer components define at least one coolant path for the coolant to flow within the cooling chamber.

52. A method of cooling a heat source using a heat transfer device of any one of claims **41**-**51**, the method comprising:

storing the coolant in the storage chamber;

based upon an occurrence of the trigger condition, reconfiguring the barrier element from:

(i) the closed configuration in which the barrier element is configured to restrict the coolant from flowing from the storage chamber through a fluid passage, to

(ii) the open configuration in which the barrier element is configured to allow the coolant in the storage chamber to flow from the storage chamber through the fluid passage to the cooling chamber, wherein while the coolant flows through the cooling chamber, heat is transferred from the heat source to the coolant via the one or more heat transfer components.

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53. The method of claim **52**, wherein the coolant flows from the storage chamber and into the fluid passage at an initial pressure and flows out of the fluid passage toward the cooling chamber at a final pressure, wherein the initial pressure is greater than the final pressure.

54. The method of claim **52** or **53**, wherein the cooling chamber includes at least one exit interface, and wherein the method further includes exhausting, diffusing, and effusing the coolant by allowing the coolant, to flow out of the cooling chamber.

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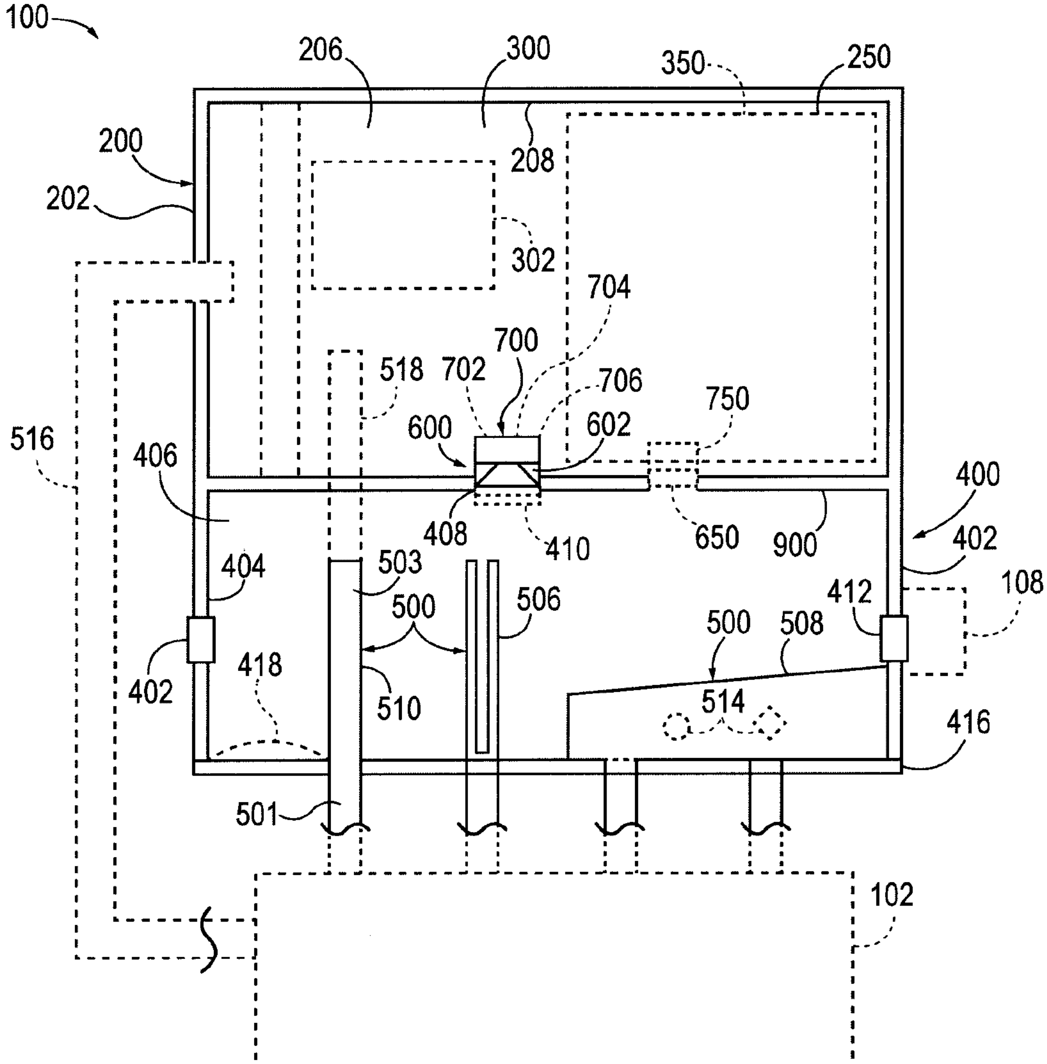
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FIG. 1

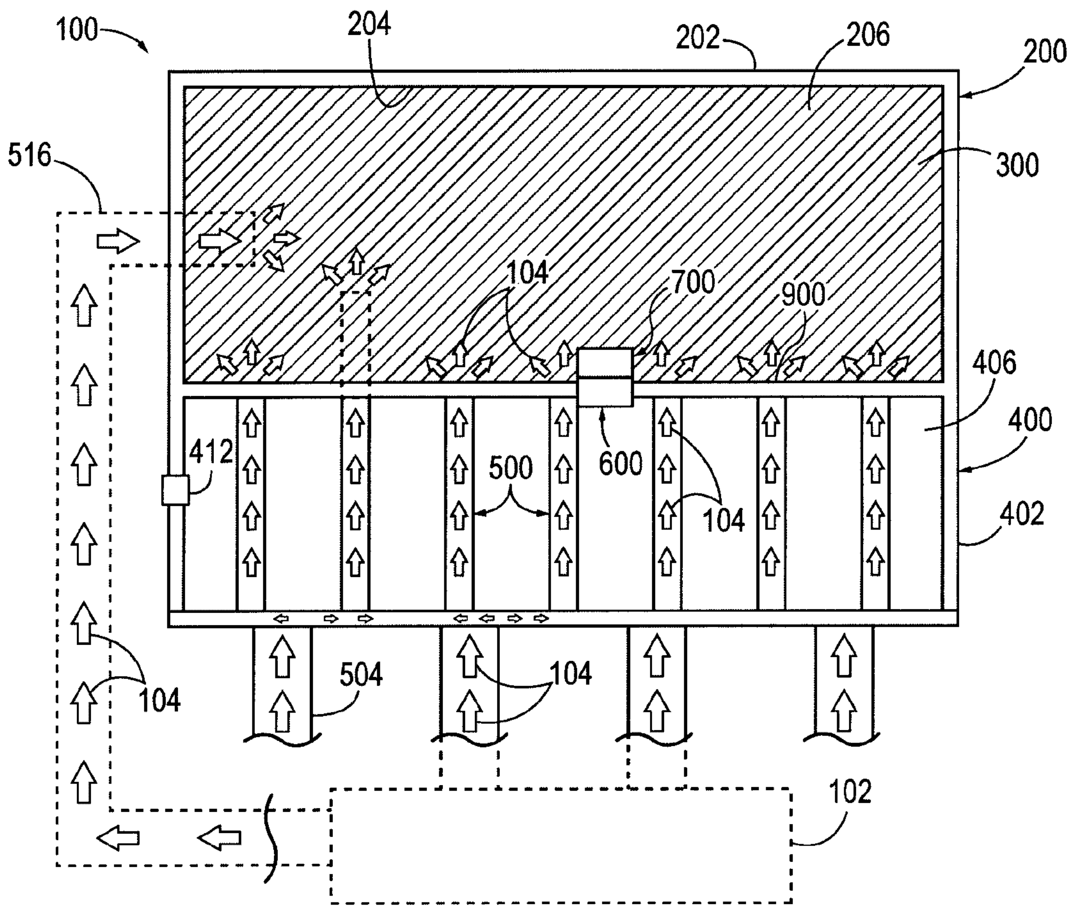
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FIG. 2

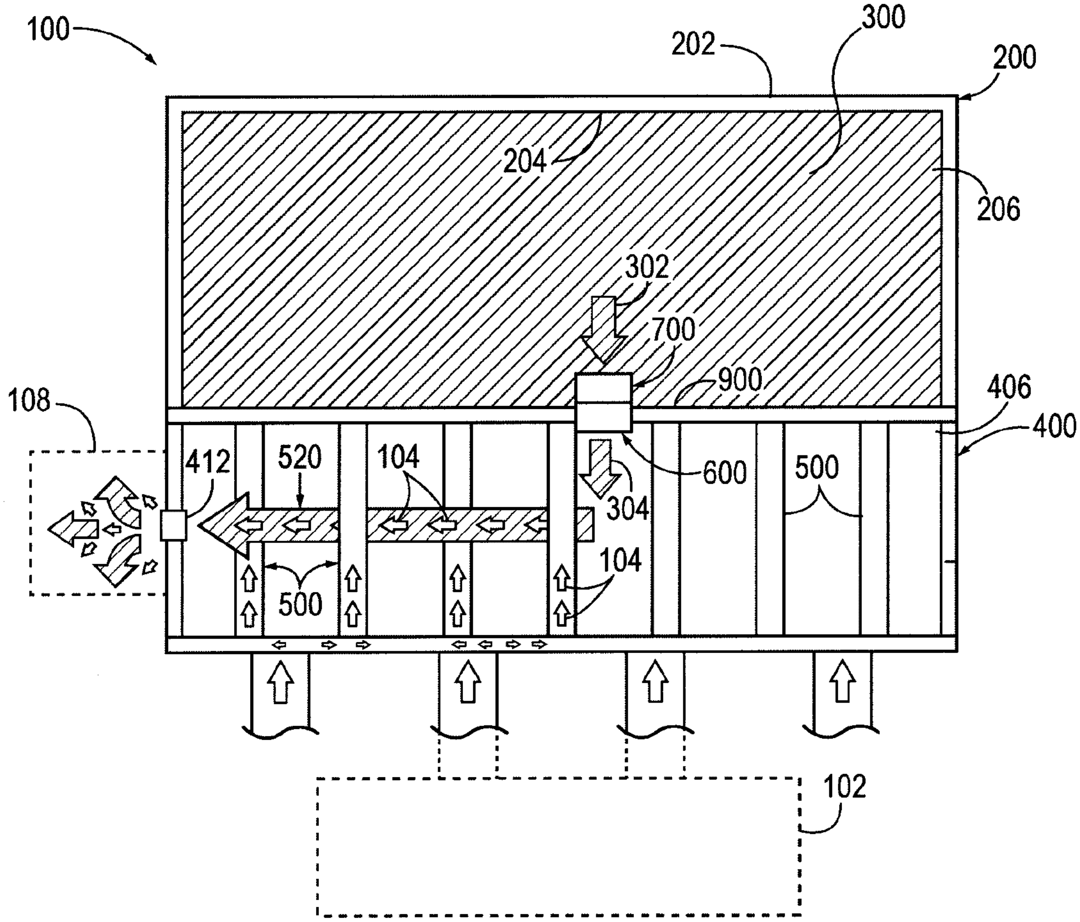
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FIG. 3

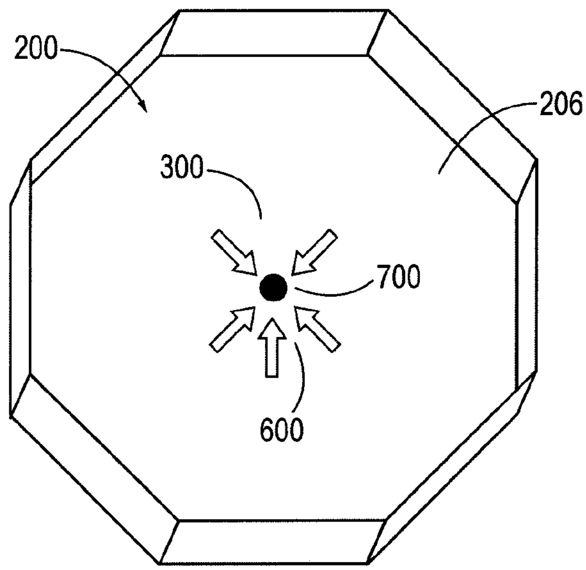

FIG. 4

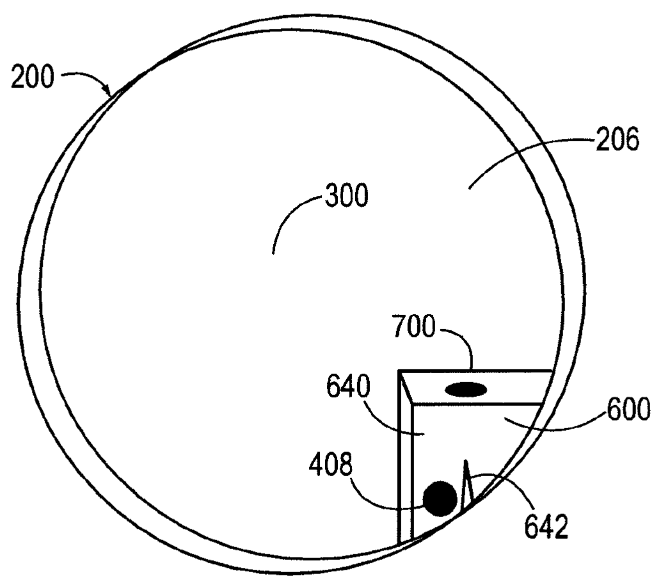

FIG. 5

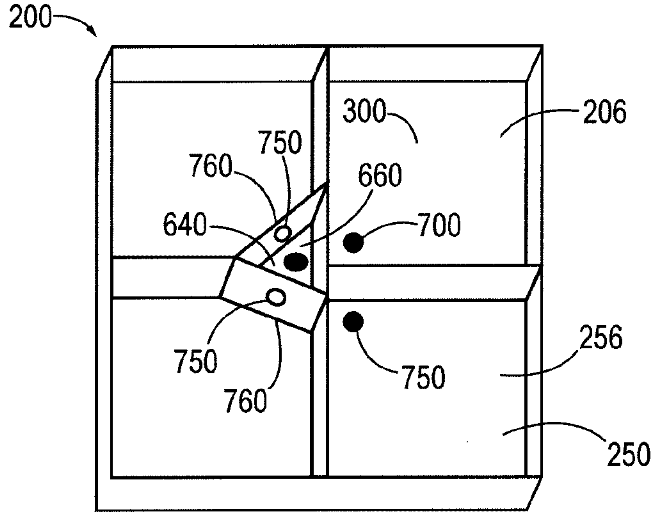
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FIG. 6

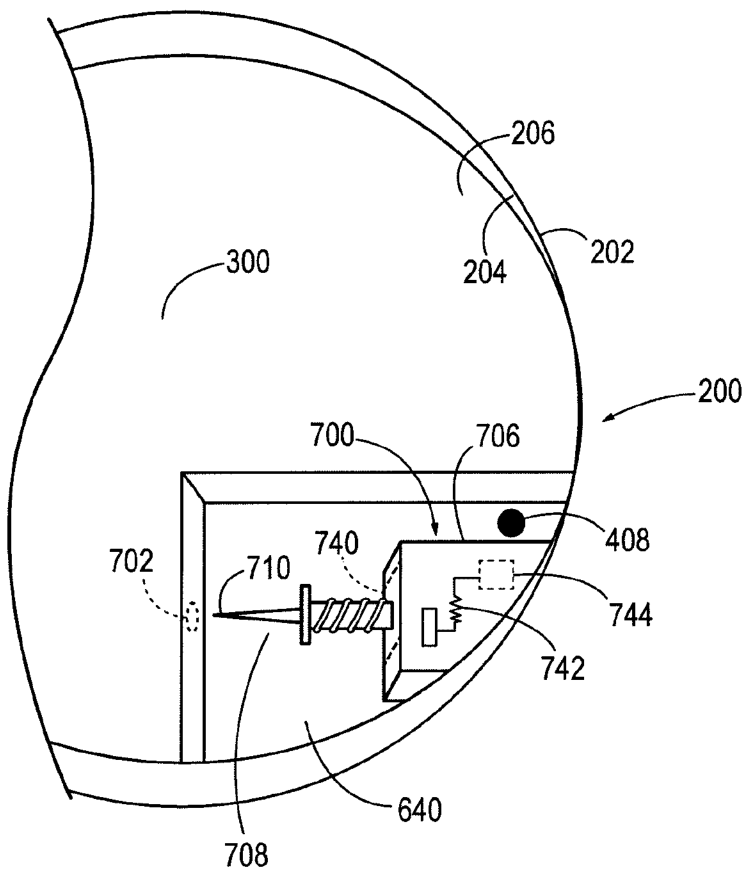
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FIG. 7

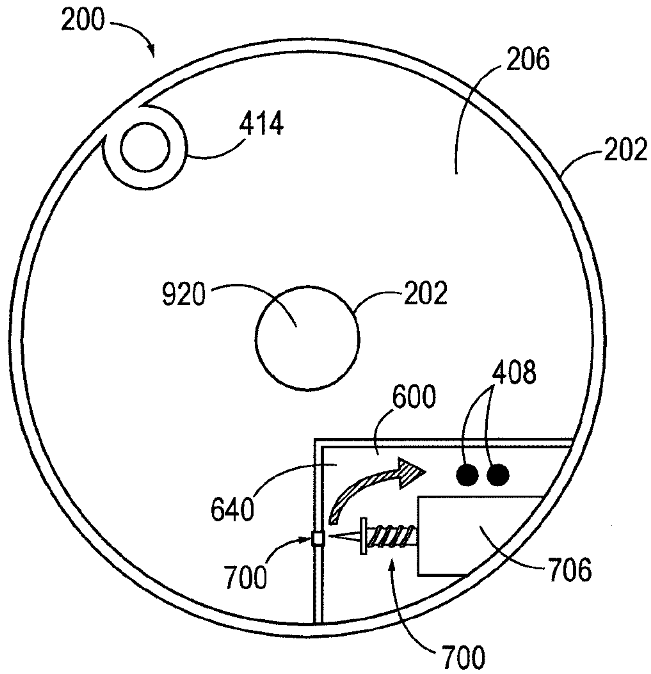
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FIG. 8

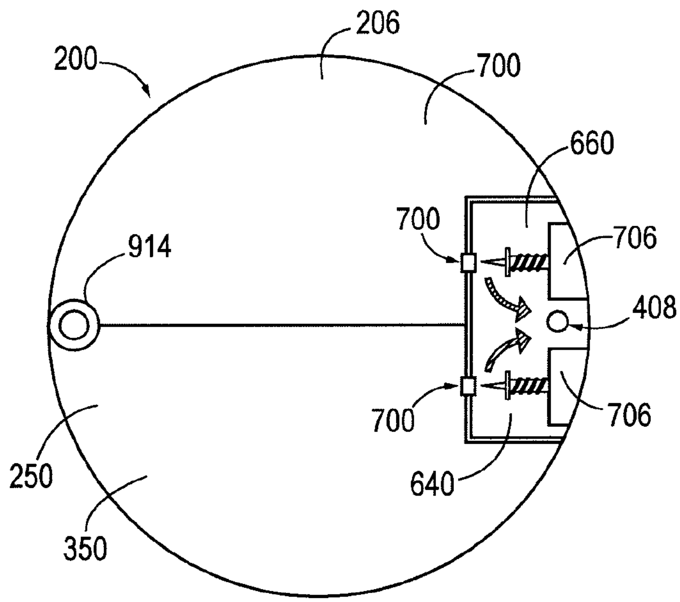
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FIG. 9

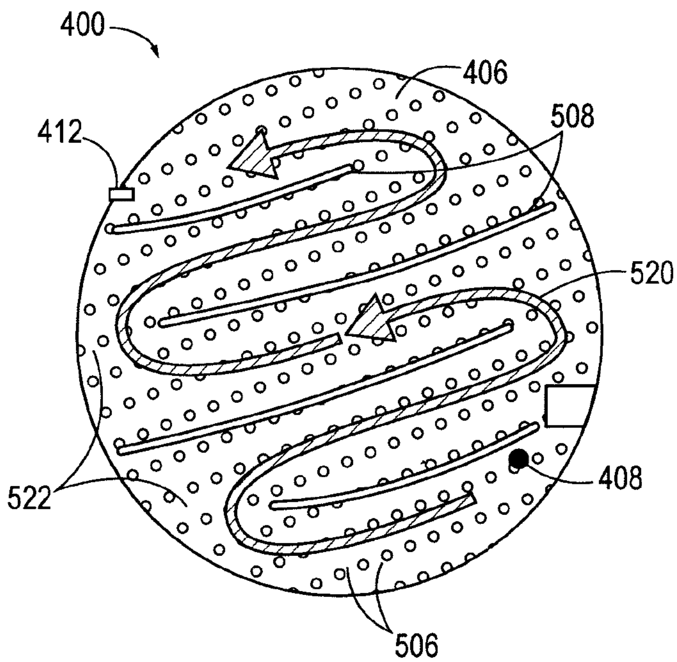
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FIG. 10

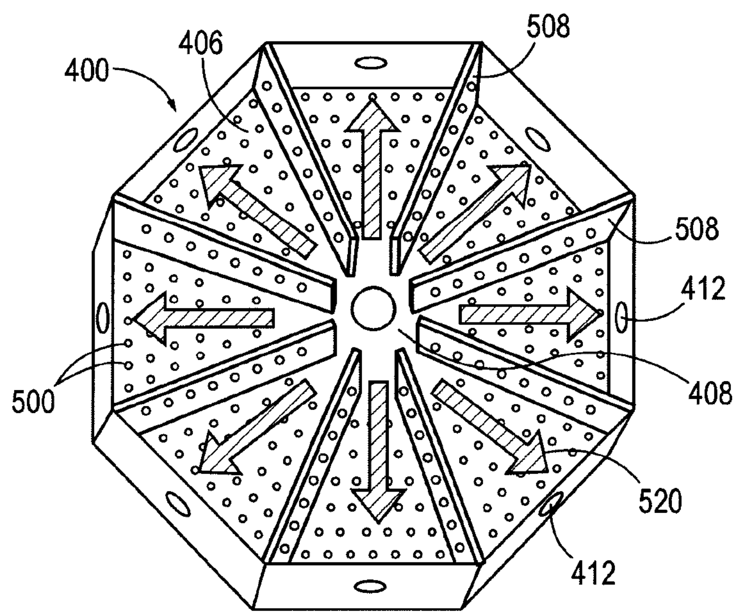
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FIG. 11

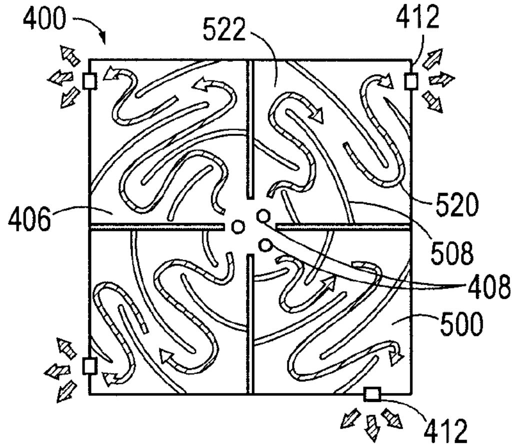

FIG. 12

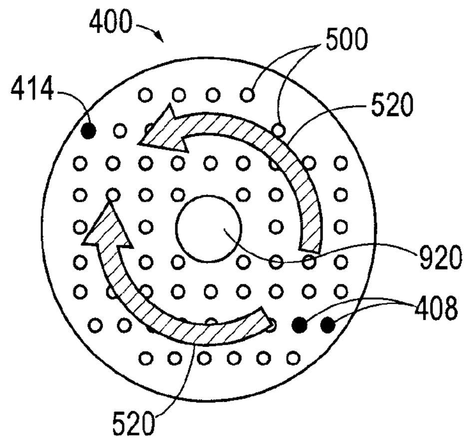

FIG. 13

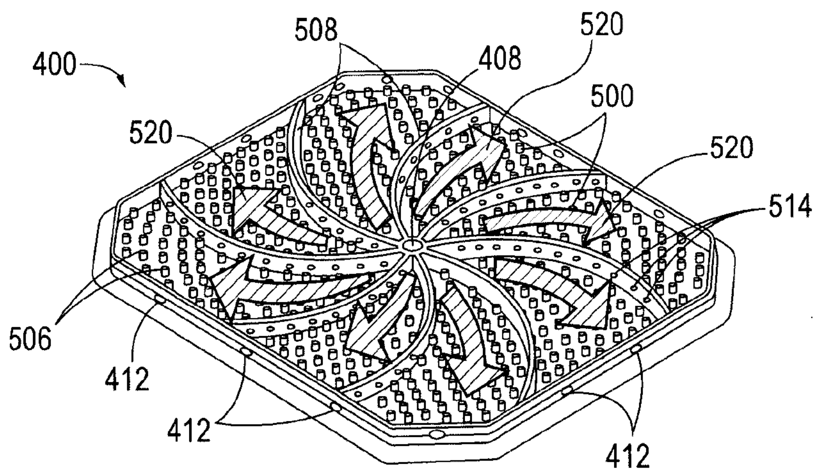

FIG. 14

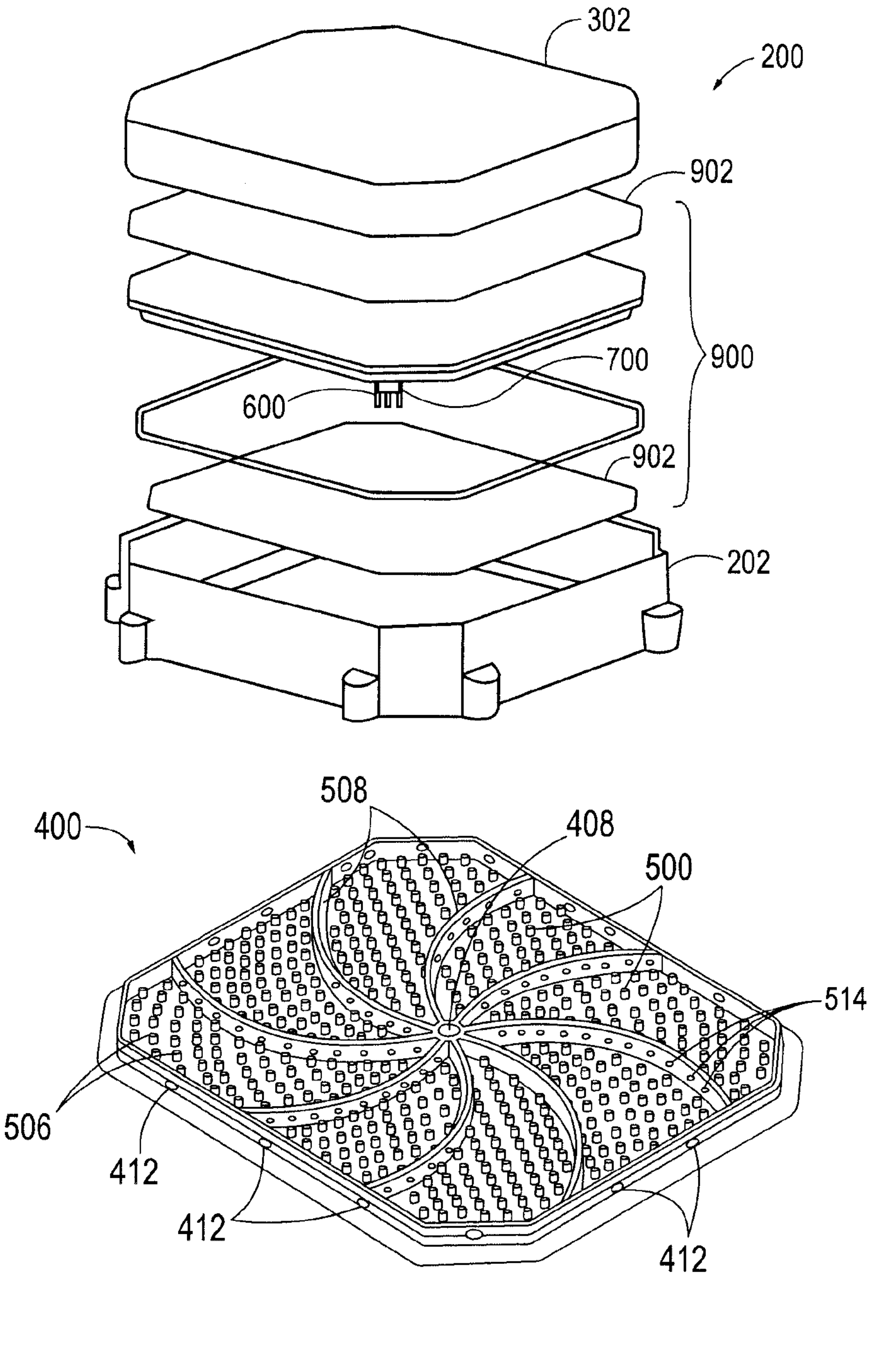
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FIG. 15

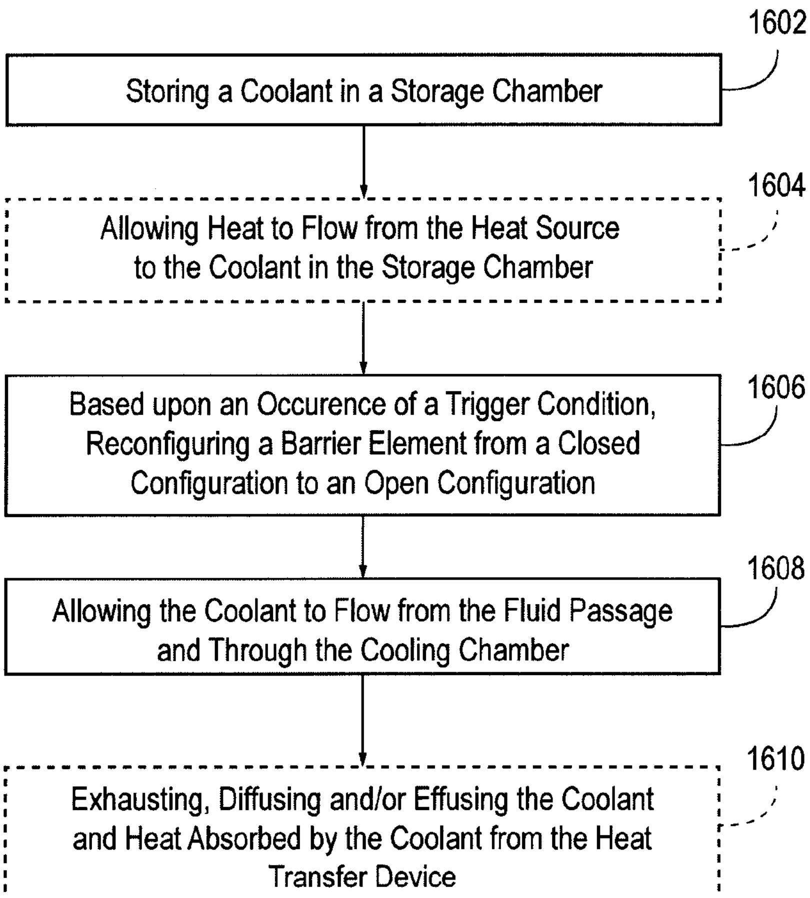
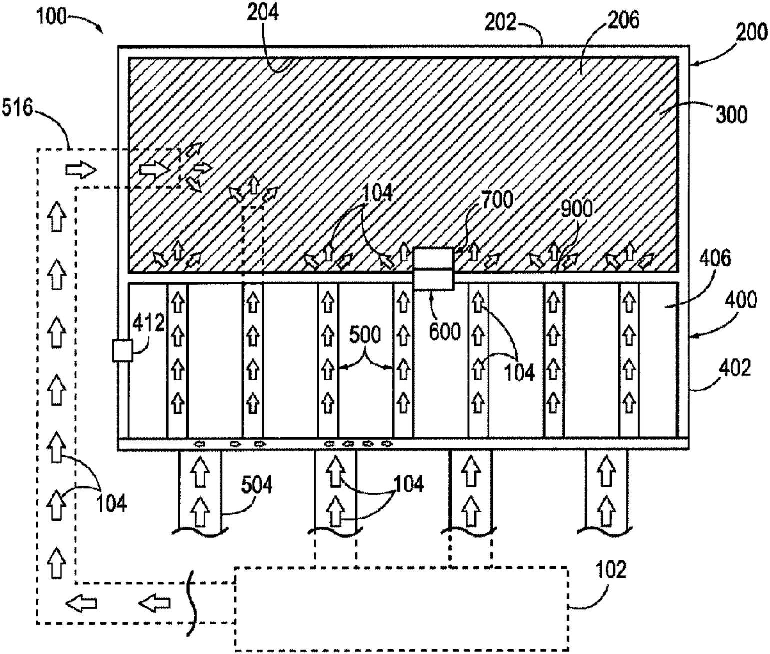

1602
Storing a Coolant in a Storage Chamber
1604
Allowing Heat to Flow from the Heat Source to the Coolant in the Storage Chamber
1606
Based upon an Occurence of a Trigger Condition, Reconfiguring a Barrier Element from a Closed Configuration to an Open Configuration
1608
Allowing the Coolant to Flow from the Fluid Passage and Through the Cooling Chamber
1610
Exhausting, Diffusing and/or Effusing the Coolant and Heat Absorbed by the Coolant from the Heat Transfer Device

FIG. 16



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