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(54) **Methods and systems for heating thermal storage units**

(57) Methods and systems for heating a thermal storage unit (TSU) are provided. A thermal storage system is provided that includes a system of heaters removably disposed at least partially within the TSU, a control system for adjusting power provided to the heaters, and a removal tool for removing one or more of the heaters from the TSU when the TSU is still hot. The thermal storage system may be used in a thermal and compressed air storage system for backup power applications.

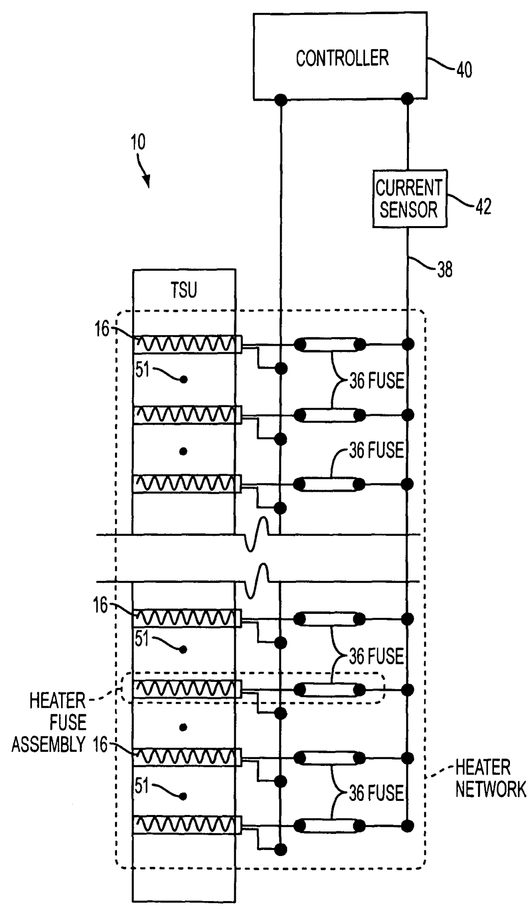

FIG. 3

EP 1 544 554 A2

Description

[0001] This application is a continuation-in-part of U.S. patent application Serial No. 10/738,825 (hereinafter "the '825 patent application"), (Attorney Docket No. AP-46), filed December 16, 2003, entitled "Thermal Storage Unit and Methods for Using the Same to Heat a Fluid," the entirety of which is incorporated herein by reference.

[0002] The present invention relates to methods and systems for heating thermal storage units (TSUs) and managing a system of heaters in a manner that increases the operational life of the heaters and maintains the TSUs at desired operating conditions with less interruption.

[0003] TSUs are well-known and often used in power delivery systems, such as compressed air storage (CAS) systems and thermal and compressed air storage (TACAS) systems. Such systems, often used to provide an available source of electrical power, often use compressed air to drive a turbine that powers an electrical generator.

[0004] In TACAS systems, it is desirable to heat the compressed air prior to reaching the inlet port of the turbine. It is known that heated air, as opposed to ambient or cool air, enables the turbine to operate more efficiently. Therefore, a mechanism or system is needed to heat the air before providing it to the turbine. One approach is to use a TSU.

[0005] TSUs provide thermal mass for energy storage. Once a TSU is heated to a desired temperature, fluid, such as compressed air, may be heated by routing the fluid through the TSU. Convection transfers heat from the TSU's thermal mass to the fluid, raising the temperature of the fluid as it passes through the TSU. Illustrative TSUs are described, e.g., in the '825 patent application.

[0006] A TSU in a TACAS system for backup power applications, such as that described in the '825 patent application and in U.S. Patent Application No. 10/361,728, (Attorney Docket No. AP-44), filed February 5, 2003, entitled "Systems and Methods for Providing Backup Energy to a Load," the entirety of which is incorporated herein by reference, preferably is maintained at its operating temperature continuously during a standby mode of operation for the system to deliver the rated power. The criteria for selecting a heating system, including the heater controller, is based on reliability and cost over the product life, which typically is 20 years. The following considerations are taken into account:

(1) operational life of the heater;
(2) the nature of heater failure and the impact on the operation of the heating system;
(3) difficulty of heater replacement and the impact of replacement on the ability of the backup power system to protect the load;
(4) integration and packaging of the heaters with the insulation system and the impact on the overall size of the TSU assembly;
(5) impact on standby losses the TSU assembly experiences when it is not delivering backup energy; and
(6) product availability - that is, whether the heating system is standard or custom.

[0007] In the past, TSUs largely have been heated with radiant heaters, which are disposed external to the TSUs. Disadvantageously, radiant heaters may waste a lot of energy by emanating heat to the ambient environment outside the TSUs, resulting in high standby losses. To reduce this type of standby loss, the radiant heater may be encased in thick insulation. This, however, occupies valuable space in a TACAS system, in which space is at a premium. Radiant heaters also are difficult to repair, requiring removal of the thick insulation surrounding the radiant heater and requiring additional personnel and/or special tools to maneuver the nearly half ton TSU out of the TACAS cabinet. When a radiant heater malfunctions, there often is significant loss in the overall uniformity of the temperature in the TSU, thereby requiring the TACAS system to be shutdown immediately for repair. This typically requires several days for a well-insulated TSU system to cool down to a safe handling temperature. During this time period, the TACAS system is offline and unable to provide backup power.

[0008] In view of the foregoing, it would be desirable to be able to provide methods and systems for heating a TSU with compact size and reduced standby losses.

[0009] It further would be desirable to be able to provide methods and systems for easily replacing and repairing the heating system of a TSU assembly without requiring additional personnel and/or special tools.

[0010] It even further would be desirable to be able to provide methods and systems for continuously heating a TSU without significant loss in the overall uniformity of the temperature of the TSU even when the heating system malfunctions.

[0011] It also would be desirable to be able to provide methods and systems for reducing the amount of time that the TACAS system is offline when repairing and/or replacing the heating system.

[0012] In view of the foregoing, it is an object of the present invention to provide methods and systems for heating a TSU with compact size and reduced standby losses.

[0013] It further is an object of the present invention to provide methods and systems for easily replacing and repairing the heating system of a TSU assembly without requiring additional personnel and/or special tools.

[0014] It even further is an object of the present invention to provide methods and systems for continuously heating a TSU without significant loss in the overall uniformity of the temperature of the TSU even when the heating system malfunctions.

[0015] It also is an object of the present invention to provide methods and systems for reducing the amount of time that the TACAS system is offline when repairing and/or replacing the heating system.

[0016] These and other objects of the present invention are accomplished by a TSU heating system preferably comprising a plurality of resistive cartridge heaters removably disposed in bores that are uniformly distributed throughout the thermal storage mass of the TSU. This reduces standby losses since the heat from the resistive cartridge heaters flows directly into and through the thermal storage mass of the TSU before passing through the insulation of the TSU and into the ambient environment.

[0017] In one embodiment, the heating system of the present invention comprises one or more redundant heaters, which are heaters in excess of a minimum number of heaters needed to heat/reheat the TSU within specification. More specifically, the minimum number of heaters is that quantity needed to raise a characteristic temperature of the TSU to a predetermined value in a predetermined amount of time when the minimum number of heaters are operated at the maximum power permitted by a heater control program. The redundant heaters shortens the time needed to reheat the TSU after a discharge event in which the temperature of the TSU is reduced and enables the heating system to operate within specification even with the failure of one or more heaters. That is, the redundant heaters allow the system to operate continuously without significant loss in the overall uniformity of the temperature of the TSU, even when one or more of the heaters have failed. Furthermore, when more than the minimum number of heaters are operational, the load on each individual heater is reduced, thereby extending its operational life. The use of redundant heaters also permits replacement of failed heaters to be deferred to routine TACAS maintenance intervals, rather than requiring immediate repair or replacement when an individual heater malfunctions.

[0018] The heaters may be configured so that a heater that experiences failure automatically disconnects from the heater network without affecting the other individual heaters, thereby permitting uninterrupted operation of the TSU system. A sensor coupled to the heaters detects when failure of any individual heater or heaters occur, thereby permitting a controller to adjust control parameters for uninterrupted operation and to generate warnings and alarms for maintenance.

[0019] In one embodiment, the present invention also utilizes a control system that requires no more than a single temperature input signal to reliably control the operation of the heater system. Preferably, the single temperature input signal to the heater control system comprises an average temperature signal derived from a plurality of temperature sensors positioned at numerous thermally equivalent locations over the TSU.

[0020] In one embodiment, the TSU assembly is disposed in the TACAS cabinet for easy access to the cartridge heaters. Systems and methods are provided to remove one or more cartridge heaters from the TSU assembly while the TSU assembly is still hot. This reduces the amount of time the TACAS unit is offline and the backup power system is unable to provide backup power.

[0021] Further features of the present invention, its nature and various advantages will be more apparent from the accompanying drawings and the following detailed description, in which:

[0022] FIG. 1 illustrates one embodiment of a TSU assembly of the present invention comprising a plurality of heaters removably disposed within a TSU;

[0023] FIG. 2 illustrates a typical construction of an electrical resistance cartridge heater;

[0024] FIG. 3 illustrates the TSU system of the present invention comprising the TSU assembly of FIG. 1 coupled to a controller;

[0025] FIG. 4A is a simplified block diagram of a backup power system, which is one application that can use the TSU system of the present invention;

[0026] FIG. 4B illustrates a system cabinet having the TSU system of the present invention;

[0027] FIG. 5A illustrates an example of characteristic heating curves of a TSU assembly of the present invention;

[0028] FIG. 5B illustrates the power provided to a heating system of the present invention to heat a TSU assembly in accordance with the characteristic heating curves of FIG. 5A;

[0029] FIG. 6 illustrates a removal tool and storage/transport container for removing and storing/transporting cartridge heaters; and

[0030] FIGS. 7A-G illustrates various embodiments of couplers incorporated in the removal tool of FIG. 6.

[0031] Referring to FIG. 1, an illustrative TSU assembly of the present invention is described. TSU assembly 10 comprises TSU 12 within which are disposed flow channels 14a-d and a plurality of heaters 16, e.g., a plurality of cartridge heaters. Insulation (not shown) can be disposed around TSU 12 to increase the efficiency of TSU assembly 10. In one embodiment, flow channels 14a-d are coupled together in fluidic communication. Fluid, such as compressed air, enters TSU 12 via inlet port 18, flows through flow channels 14a-d, and exits TSU 12 via outlet port 20. Fluid may flow sequentially through each flow channel, in parallel through two or more flow channels, or any other combination of flow channels. Alternatively, fluid may enter TSU i2 via port 20 and exit via port 18. Alternatively, TSU 12 may comprise one or more independent flow channels that are not coupled in fluidic communication e.g., fluid entering each flow channel 14a-d exits that flow channel without flowing through any of the other flow channels. A more detailed description of TSU 12 may be found in commonly-assigned U.S. Patent Application No. 10/943,293 (Attorney Docket No. AP-46 CIP), entitled "Thermal Storage Unit and Methods for Using the Same to Heat a Fluid," filed on September 17, 2004, the entirety of which is incorporated herein by reference.

[0032] TSU 12 may be constructed from solid material(s) that have adequate thermal conductivity and other desirable thermal properties such as high volumetric heat capacity to provide thermal mass for energy storage. TSU 12 also may be constructed from material(s) capable of withstanding high pressure, in addition to possessing desirable thermal properties. For example, TSU 12 may be constructed from iron, steel, aluminum, any alloys thereof, ceramic, fluid-filled rigid structure, or any other suitable material(s). TSU 12 also may be constructed of a material from which energy may be extracted as the material transitions from a liquid to a solid. For example, TSU 12 may be filled with molten aluminum that is normally maintained at approximately 670°C, e.g., by heaters 16. When power is needed to be extracted from, e.g., a TACAS system employing TSU assembly 10, the molten aluminum cools and starts to solidify, thus releasing heat at a substantially constant temperature that is then used to heat fluid flowing through flow channels 14a-d.

[0033] Cartridge heaters 16 preferably are disposed in bores uniformly distributed throughout TSU 12 such that the heaters provide uniform heating and allow for loss of an individual heater without significant loss in overall uniformity of temperature in TSU 12. This configuration also reduces standby losses since most of the heat emanating from the cartridge heaters flows directly into and through the thermal storage mass of TSU 12 before passing through the insulation to the ambient environment.

[0034] The bores are sized such that there is a small air gap (preferably, less than 1 mm) between each heater and the perimeter of the bore. Because the air gap is so small, the primary modes of heat transfer between the heaters and the TSU are conduction and radiation. Advantageously, the air gap permits the heaters to be easily removed from the bores. If the nominal dimensions of the bores were approximately equal to that of the heaters, it may be difficult to remove the heaters from the bores for replacement or repair if oxidation of the heater and bore surfaces causes the two structures to oxidize together. A small percentage of the heat emanating from the heaters may be lost to the ambient environment without flowing through the thermal storage mass of TSU 12 by (1) escaping through the gap between the heaters and TSU 12 and/or (2) being conducted down the sheath of heater 16 and lost through the end of heater 16 that is adjacent to the insulation.

[0035] Preferably, heaters 16 are disposed within TSU 12 so that (1) the proximal ends of the heaters protrude out of the TSU and the insulation (not shown) surrounding the TSU and (2) the heater wiring may be connected to a control system (e.g., control system 40 shown in FIG. 3) located external to the TSU. Preferably, heaters 16 are disposed in TSU 12 so that each heater is independently removable from the TSU. That is, each heater may be physically detached from the TSU without having to detach any of the remaining heaters. Advantageously, this facilitates repair and replacement of failed heaters. Preferably, each cartridge heater 16 is releasably coupled to a metal skin that covers the insulation surrounding TSU 12 using fasteners 22, e.g., clips that screw into studs that are affixed to the metal skin. In the embodiment of FIG. 1, cartridge heaters 16 are disposed between flow channels 14a,c and 14b,d and have longitudinal centerlines disposed orthogonal to the longitudinal axis of TSU 12 such that the longitudinal centerlines of the heaters form a plane. Alternatively, cartridge heaters 16 may be distributed throughout TSU 12 in an alternative configuration.

[0036] FIG. 2 illustrates a typical construction of an electric resistance cartridge heater 16 (as described in Integrating Electrical Heating Elements in Appliance Design; Hegbom, Thor, 1997 (page 306)). Cartridge heater 16 comprises outer tube 24 made from a good thermal conductor such as metal. Inside outer tube 24 are two layers of insulators: cylindrical insulator 26 made from, e.g., ceramic, and insulation powder 28 made from, e.g., magnesium oxide powder, disposed between ceramic insulator 26 and outer tube 24. Insulators 26 and 28 may be made from any electrically non-conducting materials having good heat transfer properties. Helically wound around the outer perimeter of insulator 26 is resistive wire 30, which provides heat from cartridge heater 16 to the TSU when current is run through the wire. The proximal end of resistive wire 30 is coupled to terminal 32a, which may be disposed through the longitudinal length of insulator 26. The distal end of resistive wire 30 is coupled to terminal 32b, which is disposed in electrical isolation from terminal 32a.

Terminals 32a-b protrude from the distal end of cartridge heater 16 through end plug 34. End plug 34 prevents contaminants and moisture from entering outer tube 24. End plug 34 may be made from any electrically non-conducting material. Electrical cartridge heaters are readily available from a number of manufacturers. Examples include the CIR Cartridge Heaters marketed by Chromalox®, Inc. of Pittsburgh, Pennsylvania, the Mighty Watt Cartridge Heaters marketed by Ogden Manufacturing Co. of Arlington Heights, Illinois, and the FIREROD® Cartridge Heaters marketed by Watlow Electric Manufacturing Company of St. Louis, Missouri.

[0037] Advantageously, cartridge heaters are low cost, readily available, and well characterized for performance and reliability. Cartridge heaters are available in a variety of lengths, diameters, powers and voltages. As opposed to radiant heaters, the use of cartridge heaters reduces the cost of the TSU assembly because it allows a manufacturer to take advantage of volume discounts. That is, a TSU system uses more cartridge heaters per system than radiant heaters. This allows a manufacturer to qualify for volume discounts even when manufacturing fewer TSU systems. Furthermore, because cartridge heaters are compact heaters, the cartridge heaters may be installed through the insulation surrounding the TSU so that the heaters substantially share the same volume occupied by the TSU. This reduces the overall size of the TSU assembly, as compared to radiant heaters that are installed external to the TSU and requires additional insulation to reduce flow of energy to the ambient environment. The compact size of cartridge heaters also allows an operator to easily remove and replace a heater without requiring additional manpower and/or special tools.

[0038] Pursuant to one aspect of the present invention, TSU assembly 10 comprises one or more redundant heaters, which are heaters in excess of a minimum number of heaters needed to heat/reheat TSU 12 within specification. More specifically, the minimum number of heaters is that quantity needed to raise a characteristic temperature of TSU 12 (e.g., the average temperature of TSU 12) to a predetermined value in a predetermined amount of time when the minimum number of heaters are operated at the maximum power permitted by a heater control program, e.g., controller 40 of FIG. 3. The redundant heaters shorten the time needed to reheat the TSU after a discharge event in which the temperature of the TSU is reduced and enables the heating system to operate within specification even with failure of one or more heaters. That is, the redundant heaters allow the system to operate continuously without significant loss in the overall uniformity of the temperature of the TSU, even when one or more of the redundant heaters have failed. Furthermore, when more than the minimum number of heaters are operational, the load on each individual heater is reduced, extending its operational life.

[0039] The use of redundant heaters also permits replacement or repair of failed heaters to be deferred to routine TACAS maintenance intervals, rather than requiring immediate repair or replacement when an individual heater malfunctions. For example, if the TSU assembly incorporates five redundant heaters in addition to the minimum number of heaters needed to heat/reheat the TSU, the TSU system operates within specification until more than five of the total number of cartridge heaters fail. Accordingly, even when one or more of the heaters fail, TSU assembly 10 continues to heat TSU 12 within specification, e.g., by heating TSU 12 to and maintaining TSU 12 at a steady state temperature. Replacement of failed heaters during routine maintenance permits continuous operation between maintenance intervals and potentially extends the operational life of the remaining heaters.

[0040] Heaters 16 may fail in one of two modes. First, heater 16 may experience a short-to-ground type of failure, e.g., a failure that occurs when the insulation within the heater fails. In a short-to-ground type of failure, the failed heater draws excessive amounts of current. Second, heater 16 may experience element failure by one of several causes, including fracture/breakage of resistive wire 30 at one or more locations along its length. This may result from oxidation of the wire surface and the associated loss of material as the wire elongates and contracts during thermal cycling. Additionally, element failure can occur when wire 30 breaks at a junction (weld joints, etc.) used to connect adjacent sections of wire or when solder connections connecting terminals 32a and/or 32b to resistive wire 30 fail. In element failure, the failed heater acts as an open-circuit and stops drawing current.

[0041] In one embodiment of the present invention shown in FIG. 3, the network of cartridge heaters 16 are configured to allow any individual heater 16 to be removed automatically from the electrical circuit after the heater fails, either by a short-to-ground or element failure, without affecting operation of the remaining heaters, thereby permitting uninterrupted operation of the TSU system. In one embodiment, each cartridge heater 16 is coupled in series to fuse 36 that is sized to rapidly disconnect its associated cartridge heater in the event of a short-to-ground type of failure. All heater-fuse assemblies are connected in parallel to form a heater network, which is coupled to single electrical supply line 38 that is controlled by heater controller 40. When an element failure occurs, the failed heater automatically is removed from the heater network because the failed heater stops drawing current from electrical supply line 38, acting as an open circuit. Similarly, when a short-to-ground failure occurs, the fuse coupled in series to the failed heater blows, rapidly disconnecting the failed cartridge heater from the heater network.

[0042] This configuration allows any individual heater 16 to be removed automatically from the electrical circuit after the heater fails without affecting operation of the remaining heaters, thereby permitting uninterrupted operation of the TSU system. That is, this permits continued operation of the system within specification, e.g., heating TSU 12 to and maintaining TSU 12 at a steady state temperature. The ability to disconnect failed heaters automatically is particularly effective when used in conjunction with redundant heaters to provide uninterrupted operation of the TSU to both reheat TSU 12 to and maintain the temperature of TSU 12 at steady state conditions.

[0043] Current sensor 42, which is disposed in series with electrical power supply line 38 and coupled to controller 40, senses the current drawn by cartridge heaters 16. When a heater fails and automatically disconnects from the heater network, the current flowing through power supply line 38 reduces by a proportional amount. Current sensor 42 senses this current reduction, thereby detecting when a cartridge heater has failed. Controller 40, which may comprise a computer or application-specific integrated circuit (ASIC), responds to the signals output by current sensor 42 by adjusting control parameters, adjusting the power provided to the heaters, and generating warnings and/or alarms for maintenance.

Advantageously, this allows controller 40 to limit the maximum temperature to which heaters 16 are heated, extending the operational life of the heaters, reducing maintenance costs and improving reliability. Current sensor 42 may comprise an open loop Hall effect transducer, e.g., the HAL 50-S current transducer marketed by LEM Components of Switzerland, or another type of current sensor known to one of skill in the art or otherwise.

[0044] The present invention may be used in many applications. FIG. 4A illustrates one such application. More specifically, FIG. 4A shows a TACAS system 21 for providing output power utilizing TSU assembly 10 of FIGS. 1 and 3, described above. For example, FIG. 4A may represent a backup energy system that provides backup power to a load in the event of a disturbance in the supply of power from another power source (e.g., utility power failure.)

[0045] The following discussion of TACAS system 21 is not intended to be a thorough explanation of the components of a TACAS, but rather an illustration of how TSU assembly 10 can enhance the performance of a TACAS system. For a detailed description of a TACAS system, see commonly-assigned, co-pending U.S. patent application No. assembly 10/361,728, filed February 5, 2003, which is hereby incorporated by reference herein in its entirety.

[0046] As shown in FIG. 4A, TACAS system 21 includes storage or pressure tank 23, valve 25, TSU assembly 10, electrical input 27, turbine 29, generator 31 and electrical output 33. When electric power is needed from system 21, compressed air from pressure tank 23 may be routed through valve 25 to TSU assembly 10. TSU assembly 10 may heat the compressed air before it is provided to turbine 29.

[0047] The hot air emerging from TSU assembly 10 may flow against the turbine rotor (not shown) of turbine 29 and drive turbine 29, which may be any suitable type of turbine system (e.g., a radial-flow turbine). In turn, turbine 29 may drive electrical generator 31, which produces electric power and provides it to electrical output 33.

[0048] Also shown in FIG. 4A is turbine exhaust 35 (e.g., the exhaust gases emerging from turbine 29). Turbine exhaust 35 may be vented through an exhaust pipe (not shown), or simply released to recombine with atmospheric air.

[0049] Not only is system 21 advantageous because it uses a relatively inexpensive and efficient TSU, it is also non-polluting. That is because, unlike conventional systems that use fuel-combustion systems to provide hot air to the turbine, it does not require a fuel supply to heat the air that is being supplied to turbine 29. Instead, TSU assembly 10 may be powered by electrical input 27 during standby operation, which provides the energy needed to heat the compressed air, while providing effective pressure containment. System 21 therefore provides the benefits of heating compressed air from pressure tank 23 before it is supplied to turbine 29, without producing the harmful emissions associated with combustion systems.

[0050] TACAS system 21 may also include control circuitry 37 which may be coupled to both TSU assembly 10 and electrical input 27. Control circuitry 37 may include controller 40 of FIG. 3. Control circuitry 37, along with electrical input 27, may therefore be used to monitor and control the temperature of TSU assembly 10. As a result, the TSU assembly 10 may be heated to and maintained at a desired steady state temperature.

[0051] Moreover, valve 25 may be coupled to piping (not shown) that bypasses TSU assembly 10 and feeds into turbine 29 along with the output from TSU assembly 10. By controlling the portion of the total compressed air flow through the TSU, the ratio of heated to non-heated air provided to turbine 29 may be modified, thereby providing another means for controlling the temperature of the air being supplied to the turbine. A more detailed discussion of systems and methods for controlling the temperature and pressure of fluid being provided to turbine 29 can be found, for example, in U.S. Patent Application No. 10/943,294, filed September 17, 2004 (Attorney Docket No. AP-48), entitled "Systems and Methods for Controlling Temperature and Pressure of Fluids" and U.S. Patent Application No.10/943,328, filed September 17, 2004 (Attorney Docket No. AP-50), entitled "Systems and Methods for Controlling Pressure of Fluids", both of which are hereby incorporated by reference in their entireties.

[0052] Another advantage of utilizing TSU assembly 10 is that larger pressure tanks are not required as is the case with compressed air storage systems that do not utilize thermal storage units or combustion systems.

[0053] The present invention is presented in the context of industrial backup utility power. Alternatively, the present invention may be used in any application associated with generating power, such as in thermal and solar electric plants or continuously operating TACAS systems. Furthermore, the present invention may be used in any other application where thermal storage, fluid heating or heated fluid delivery may be desirable.

[0054] FIG. 4B illustrates TSU assembly 10 (absent insulation) disposed within system cabinet 46 for a backup generator 44. In a preferred embodiment, TSU assembly 10 is oriented for access to cartridge heaters 16 from the front of system cabinet 46. In the embodiment of FIG. 4B, backup generator 44 includes compressor 48 disposed between TSU assembly 10 and cabinet door 50. To permit ease of access to TSU assembly 10 and cartridge heaters 16, compressor 48 is designed to be easily detachable from backup, generator 44.

[0055] Referring now to FIGS. 5A-B, a preferred control algorithm for controlling cartridge heaters 16 is described. The control algorithm preferably requires no more than a single temperature input signal to control the electric power provided to heaters 16. Such a control algorithm is based, in part, on a single temperature input from the TSU and a characteristic heating curve. Preferably, the control algorithm accepts TSU sensor temperature of FIG. 5A and not the average heater temperature of FIG. 5A because temperature sensors for the heater may be more prone to failure than temperature sensors for the TSU due to the higher heater temperatures. Instead, the control algorithm preferably is programmed to infer the average heater temperature based on the TSU sensor temperature and a model that provides a relationship, which may be empirically determined or derived from thermal modeling, among the TSU sensor temperature, the average heater temperature, and optionally the average temperature of the TSU (i.e., the TSU average block temperature in FIG. 5A). Using the model, characteristic heating curve H of heaters 16, illustratively depicted in FIG. 5A, may be determined given the behavior of the TSU sensor temperature. The temperature of each cartridge heater 16 theoretically equals the average heater temperature shown in FIG. 5A.

[0056] As used herein, when controller 40 is programmed to require no more than a single temperature input to control the power provided to heaters 16, the controller is capable of controlling the heater power with one or more input data signals, only one of which represents temperature. Accordingly, the controller still may accept one or more input data signals in addition to a single input data signal that represents temperature. The controller may still receive input signals that are functions of other parameters, such as a signal indicative of the current from current sensor 42 of FIG. 3. Indeed, controller 40 also may accept additional input signals that represent temperature so long as the controller is capable of controlling the power delivered to the heaters using one or more data input signals, only one of which represents temperature. For example, the controller may accept additional data signals representing temperature to implement a backup algorithm to detect fault conditions (as described in greater detail hereinbelow).

[0057] In an alternative embodiment, the heater system of the present invention may be programmed to use a two temperature input control system that accesses both the heater temperature and the temperature of the TSU for proper operation. Such a two temperature input control system may be more complex to implement than a single temperature control system, such as that described below with respect to FIGS. 5A and 5B. That is, in a two temperature control system, the heater controller operates properly when both temperature signal inputs are accurate (within predetermined tolerance levels). If one malfunctioned, then the control system may become non-operational. Since a TSU assembly requires a high degree of reliability to service the TACAS system properly, the control system may be programmed so that redundant temperature readings and algorithms for checking the redundancies are implemented for each of the two temperature inputs. Thus, the complexity of a reliable control system increases with the number of inputs. Furthermore, since sensors fail more rapidly at higher temperatures and thus temperature sensors for the heater may be more prone to failure than temperature sensors for the TSU, the control algorithm may be programmed with additional control measures for the heater temperature sensors to provide an accurate control signal.

[0058] Accordingly, while there may be advantages to using a control system that requires no more than a single temperature input signal to reliably control the operation of the heater system, the heater system of the present invention alternatively may comprise a control algorithm that requires more than a single temperature input signal to reliably control the operation of the heater system. For example, two temperature input signals may be used with the variable time-base zero-crossing control algorithm discussed below with respect to CHART 1.

[0059] The TSU sensor temperature may be determined from a plurality of temperature sensors, e.g., thermocouples 51 of FIG. 3, that are distributed about the TSU preferably in thermally equivalent locations. The term "thermally equivalent locations" refers to isothermal locations in the TSU in which all the sensors report the same temperature within a specified tolerance. Preferably, controller 40 is programmed to use an average sensor temperature (which is designated as the TSU sensor temperature of FIG. 5A) to control the heating system of the present invention. This may be accomplished, for example, by coupling thermocouples in parallel so that the TSU sensor temperature represents the average of the individual temperature data collected from the temperature sensors. Indeed, when thermocouples disposed in thermally equivalent locations are coupled in parallel, the average of the temperature signals theoretically is equal to the temperature sensed by each thermocouple (not accounting for tolerances). This average sensor temperature may not, however, be the same value as the average temperature of the TSU (as discussed in greater detail below). Alternatively, controller 40 may be programmed to accept all the temperature sensor signals and use the average of two or more of the temperature sensor signals to control the heating system of the present invention. For example, the control algorithm may be programmed with a polling algorithm that determines and rejects data outliers. If a temperature sensor fails and disconnects from the sensor network, the system continues to operate normally.

[0060] The control algorithm illustrated in FIGS. 5A-B comprises several stages. Immediately following a discharge event, in which the TSU is reheated after a discharge of power from the TACAS, the control algorithm enters an equilibrate stage. In the equilibrate stage, cartridge heaters 16 are idle for a predetermined period of time to protect the heaters by permitting temperature gradients in the TSU and heaters to level out.

[0061] Thereafter, the control algorithm enters a ramp stage, in which power is provided to cartridge heaters 16. During the ramp stage, the level of power provided to cartridge heaters 16 ramps up to full power (that is, the maximum power permitted by the control algorithm) over a predetermined period of time to soft-start the heaters. The maximum power permitted by the control algorithm is selected, in part, based on a goal to heat the TSU to the TSU set point within a predetermined amount of time. Note that, depending on the locations in which the temperature sensors are disposed within the TSU, the actual average temperature of the TSU may lag the TSU sensor temperature when the TSU is being reheated. This is due to the fact that the temperature sensors may not be distributed at, and therefore not account for, the colder extremities of the TSU. However, as shown in FIG. 5A, the TSU sensor temperature and the average temperature of the TSU converges to the same TSU set point temperature at steady-state standby operation.

[0062] Once the cartridge heaters are ramped up to the maximum power permitted by the control algorithm, the heaters are maintained at full power until the average heater temperature reaches a maximum heater temperature, the selection of which is based, in part, on the following considerations: a desire for heaters that have long operational life, a desire for cheaper and smaller heaters, and metallurgical and other thermal instabilities that occur at higher temperatures. Because controller 40 preferably is programmed to control the power provided to the heaters based on the TSU sensor temperature, and not the average heater temperature, the control algorithm infers that the average heater temperature has reached the maximum heater temperature based on the TSU sensor temperature and the model described above. Accordingly, the heaters are maintained at full power until the TSU sensor temperature reaches a value corresponding to the maximum heater temperature. Advantageously, by limiting the TSU sensor and heater temperatures, controller 40 reduces the likelihood that the TSU may be damaged by excessive stress during pressurized operation.

[0063] If redundant heaters are used, the full power period is shorter than that experienced when only the minimum number of heaters is used to heat TSU 12. Advantageously, this reduces load on each heater and lengthens the operational life of all the heaters.

[0064] If the previous discharge event only partially discharged the energy stored in the TSU, the TSU sensor temperature may reach the value corresponding to the maximum heater temperature before the cartridge heaters are ramped up to the maximum power permitted by the control algorithm. In this situation, control algorithm begins to reduce the rate at which power is delivered to the cartridge heaters without ever maintaining the heaters at full power.

[0065] Once the TSU sensor temperature has reached the value corresponding to the maximum heater temperature, the power to the cartridge heaters is reduced at a rate that maintains the average heater temperature at the maximum heater temperature. The control algorithm calculates this rate based on the model described above.

[0066] When the TSU sensor temperature increases to a steady state temperature called the TSU set point in FIG. 5A, the control algorithm switches to steady state temperature control to power the heaters sufficiently to maintain the TSU sensor temperature approximately at the steady state TSU set point. This results in a reduction in the rate at which power is provided to the cartridge heaters as the heaters continue to deliver heat to the extremities of the TSU and to offset thermal losses to the ambient environment. The heater temperature is allowed to reduce towards the TSU set point. After a period of time determinable from the model, the TSU is fully charged and the TSU sensor temperature and the TSU average block temperature have converged to the steady-state TSU set point. Thereafter, the controller provides sufficient standby power to the heaters to maintain the heater and TSU sensor temperatures at the steady state TSU set point temperature. Advantageously, when redundant heaters are used, each heater is heated to a lower temperature than that required when only a minimum number of heaters are used to maintain TSU 12 in standby mode. This lengthens the operational life of all the heaters.

[0067] In preferred embodiments, the heater controller uses a control algorithm that reduces temperature excursions within the thermal storage mass of the TSU by adjusting the power provided to the heaters at a high frequency, e.g., 60 Hz. Such control algorithms may include a variable time-base zero-crossing algorithm for AC power or a DC voltage control algorithm for DC power. For example, in a variable time-base zero-crossing control algorithm, a silicon controlled rectifier (SCR) may be switched on to permit conduction of power to the heaters when the AC voltage signal crosses zero volts. The variable time base controls the proportion of time in which conduction is permitted to the time in which conduction is not permitted. In variable-time based control, the controller changes the time base according to the power requirement. CHART 1 below provides an example of variable time based control over a variable period:

CHART 1	
No conduction	0 cycles conducting for a 1 cycle period
25% power	1 cycle conducting, 3 cycles non-conducting for the 4 cycle period
50% power	1 cycle conducting, 1 cycle non-conducting for the 2 cycle period
75% power	3 cycles conducting, 1 cycle non-conducting for the 4 cycle period
Continuous conduction	1 cycle conducting for the 1 cycle period

Advantageously, in variable time base control, the heaters are switched on and off much more frequently than in fixed time based control. Because the heaters are switched on and off more frequently, the heaters experience less temperature variations, thereby increasing operational life.

[0068] In a DC voltage control algorithm, the controller provides predetermined DC voltage levels depending on the percent power required. For example, with a 100V power supply, the controller may provide 86.6V for 75% power and 70.7V for 50% power. The heater controller of the present invention also may use other control algorithms known to persons of skill in the art or otherwise.

[0069] Heater controller 40 also may be programmed with an optional backup algorithm to detect fault conditions, in addition to its main control algorithm described above. The backup algorithm may be programmed to calculate acceptable power and temperature parameters based on measurements of the energy delivered from the TSU during a previous discharge event and an associated state temperature, such as the TSU sensor temperature at the end of the discharge state. For example, the energy delivered from the TSU during a discharge event may be estimated based on the mass of the thermal storage material of the TSU, the specific heat of the thermal storage material, and the TSU's change in temperature. Based on this estimation of the energy delivered during the last discharge event, the backup algorithm may be programmed to determine the desired state of the heating system from the model of the heating system, e.g., illustrated in FIGS. 5A and 5B. From the desired state of the heating system, the backup algorithm can determine acceptable temperature and power parameters, incorporating tolerance levels suitable for the application for which the system is used. If the real-time TSU sensor temperature or a secondary temperature input obtained from the TSU and/or the heaters deviates from the acceptable temperature parameters, and/or the real-time power deviates from the acceptable power parameters, controller 40 may activate a safe operation mode in which the controller reduces the amount of power delivered to the heaters to a predetermined level. The controller then may direct the TSU system to operate at the reduced level until maintenance can be performed to correct the fault condition. Similar to the main control algorithm described above, the backup algorithm also may employ variable time-base zero-crossing control for AC power, DC voltage control for DC power, or another control algorithm known to one of skill in the art or otherwise.

[0070] Pursuant to another aspect of the present invention, methods and systems are provided for retrieving cartridge heaters from the TSU assembly when the TSU assembly is still hot, e.g., at the TSU set point temperature. FIG. 6 illustrates one embodiment of a removal tool comprising heater puller 52 and protective housing 54. Protective housing 54 includes an insulated cylinder or other appropriate shape having sufficient length to completely surround cartridge heater 16. This reduces the chances that an operator accidentally contacts any of the hot surfaces of the cartridge heater when the heater is removed from the TSU assembly and transferred to storage and transport container 56.

[0071] Container 56 includes protective case 58 lined with insulation, plate 60 having one or more holes through which a plurality of cartridge heaters 16 may be stored, cover 62 and carrying handle 64. Preferably, protective housing 54 and container 56 are designed to handle heaters that have been heated to their operating temperature, e.g., approximately 760°C. If the protective housing and container are designed to handle heaters heated to a temperature less than their operating temperature, additional time is needed to cool down the TSU before removing the heaters therefrom. The holes in plate 60 are spaced apart sufficiently to permit placement of cartridge heaters 16 therein using heater puller 52 and protective housing 54. Preferably, plate 60 has a sufficient number of holes to accept a complete set of heaters 16. Plate 60 is mounted at a distance from the bottom of protective case 58 to allow cartridge heaters 16 to rest on the bottom. Alternatively, each cartridge heater 16 may incorporate a flange (see FIG. 7A) that is disposed on the heater such that the distal end of cartridge heater 16 clears the insulation liner on the bottom of protective case 58 when the flange is resting on plate 60.

[0072] Heater puller 52 includes a coupler (illustrative embodiments of which are described with respect to FIGS. 7A-G) disposed on the distal end of puller 52 and actuator 70 disposed on the proximal end of puller 52. The coupler is a mechanism for releasably engaging heater puller 52 to the proximal ends of heater cartridges 16. Actuator 70 may be mechanically coupled to coupler 68 and actuated to engage heater puller 52 to and disengage heater puller 52 from cartridge heater 16. The coupler also may comprise locking pliers, a locking ferrule, or a notched sleeve that rotates and locks to a complementary feature on the proximal end of cartridge heater 16. The coupler also may comprise other coupling mechanisms known to one of ordinary skill in the art or otherwise.

[0073] FIGS. 7A-G illustrate numerous embodiments of the heater puller of FIG. 6. FIG. 7A illustrates a first embodiment of a heater puller. Plier-type heater puller 80 comprises coupler 82 and actuator 83.
Coupler 82 includes two gripping surfaces 84 that conform to the shape of the proximal end of heater 16. Actuator 83 includes two handles 86a and 86b, each having a distal end that is coupled rigidly to one of the gripping surfaces, and pivot 88 about which the handles rotate. When the proximal ends of handles 86 are urged apart, handles 86 pivot about pivot 88 so that gripping surfaces 84 also move away from each other. Similarly, when the proximal ends of the handles are urged together, so too are the gripping surfaces. Thus, when a heater is placed between the gripping surfaces, heater puller 80 may be engaged securely to the heater by squeezing the handles together. While the heater puller is engaged to a heater, an operator can pull the heater from or push a heater into a TSU.

[0074] Optionally, heater puller 80 also may comprise latching mechanism 90 disposed on the proximal end of actuator 83 (see FIG. 7B). Latching mechanism 90 comprises hook 92 pivotally coupled to handle 86a, release lever 94 rigidly coupled to hook 92, spring 96 coupled to hook 92 (via release lever 94) and handle 86a, and anchor 98 coupled to handle 86b. Once gripping surfaces 84 are engaged to heater 16, latching mechanism 90 securely maintains that engagement without additional action on the part of the operator.

[0075] In operation, an operator squeezes handles 86a and 86b together to engage gripping surfaces 84 to heater 16. The operator then may engage hook 92 to anchor 98. Spring 96 imparts tension to hook 92 to keep the hook engaged to anchor 98, thereby preventing gripping surfaces 84 from releasing heater 16. When the operator is ready to release heater 16 from heater puller 80, the operator may actuate release lever 94 against the spring force of spring 94 and disengage hook 92 from anchor 98. This permits the operator to urge handles 86a and 86b apart, thereby urging gripping surfaces 84 apart and disengaging the gripping surfaces from heater 16.

[0076] FIGS. 7C and 7D illustrate a second embodiment of the heater puller. Ferrule-type heater puller 100 comprises sliding sleeve 102, ferrule 104 disposed at the distal end of sliding sleeve 102, center rod 106, and grips 108 that are mounted on compliant extensions 109 of center rod 104. Center rod 106 and grips 108 may be advanced into and out of center bore 110, which extends from the proximal end of sliding sleeve 102 to the distal end of ferrule 104, to respectively close and open grips 108. To open grips 108 (as shown in FIG. 7D), center rod 106 is advanced towards the distal end of sliding sleeve 102. The compliance of extensions 109 allows a heater to be inserted between grips 108. Sliding sleeve 102 and ferrule 104 then may be actuated in the distal direction towards heater 16 to close grips 108. Ferrule 104 engages compliant extensions 109, contracting the extensions (and thus grips 108) around heater 16 and thereby securely engaging the heater to heater puller 100. While the heater puller is engaged to the heater, an operator can pull the heater from or push a heater into a TSU.

[0077] Optionally, heater puller 100 also may comprise locking clip 112 which is configured to engage center rod 110. Once grips 108 are engaged to heater 16 by actuating sliding sleeve 102 in the distal direction so that ferrule 104 engages extensions 109, locking clip 112 may be attached to the proximal end of center rod 106 protruding out of sliding sleeve 102. This prevents the center rod from sliding back into the sliding sleeve and thereby prevents grips 108 from disengaging heater 16.

[0078] FIGS. 7E-F illustrates a third embodiment of a heater puller. Notch-type heater puller 120 comprises actuator 122 and coupler 124 having one or more L-shaped slots 126. Each slot 126 incorporates detent 128 to slide past associated pin 130 disposed on the proximal end of heater 16. This permits pin(s) 130 to engage coupler 124 with reduced rotation. While the heater puller is engaged to the heater, an operator can pull the heater from or push a heater into a TSU. FIG. 7F provides an end view of heater 16 with two pins 130.

[0079] FIG. G illustrates a fourth embodiment of a heater puller. Hook-style heater puller 140 comprises actuator 142 and hook coupler 144 disposed on the distal end of actuator 142. Hook coupler 144 is designed to be engaged to loop 146 disposed on the proximal end of heater 16. While the heater puller is engaged to the heater, an operator can pull the heater from or push a heater into a TSU.

[0080] Heater puller 142 also may comprise locking rod 148 that is rotatably and slidably disposed through retainers 150, which in turn may be coupled to handle 152 of actuator 142. In operation, once hook 144 is engaged to loop 146, an operator can lock hook 144 to loop 146 be actuating locking rod 148. In particular, the operator may actuate locking rod 148 in the distal direction towards heater 16 until the distal end of locking rod 148 engages proximal face 154 of heater 16. Alternatively, locking rod 148 also may engage a complementary feature on proximal face 148 designed to receive the rod. The operator then may rotate locking rod 148 so that latch 156 integral thereto locks into receptor 158. Because the distal end of rod 148 is engaged to the proximal face of heater 16, hook 144 cannot accidentally disengage from loop 146. Advantageously, when the distal end of locking rod 148 is engaged to heater 16, the looking rod also may be used to push the heater back into the TSU.

[0081] In operation, an operator can switch the TACAS system containing the TSU system of the present invention to a maintenance mode, during which power to cartridge heaters 16 is turned off and the TACAS system is offline and unavailable to provide backup power.

The operator can disconnect the electrical connections of cartridge heaters 16 and displace any other hardware disposed in front of cartridge heaters 16 (e.g., compressor 48 of FIG. 4). Once the operator removes or loosens heater restraints 22, the operator can engage heater puller 52 to the proximal end of cartridge heater 16 that protrudes out from insulation 72 of TSU assembly 10. After a secure engagement is made, the operator can slide protective housing 54 over the proximal end of heater puller 52 and pull heater 16 from its bore in TSU 12 into protective housing 54. Thereafter, heater 16 is deposited into storage and transport container 56.

[0082] The operator then can slide a new heater 16 into the vacant bore preferably at a predetermined rate, secure the heater to TSU 12 using the associated heater restraint, and connect the heater to the electrical supply. After the operator completes removal and installation of the desired number of heaters, heater controller 40 preferably is restarted in a special restart mode similar to a reheat cycle described above with respect to FIGS. 5A-B. While the description herein describes shaft puller 52 as being detached from protective housing 54, it is within the scope of the invention to have a removal tool comprising an integral shaft puller and protective housing.

[0083] If heaters 16 and thermal storage mass 12 are designed so that the proximal ends of heaters 16 do not protrude out of insulation 72, heater puller 52 may be designed to engage an engagement feature on the proximal face of heater 16.

[0084] Advantageously, the removal tool and storage/transport container enables an operator to replace one or more heaters without having to wait the several days it typically takes for the TSU to cool to a temperature low enough to permit the operator to handle the heater without protective equipment. This reduces the duration of the maintenance interval when the TACAS unit is offline and the backup power system is unable to provide backup power.

[0085] Although illustrative embodiments of the present invention are described above, it will be apparent to one skilled in the art that various changes and modifications may be made without departing from the invention. For example, while the present specification describe use of resistive cartridge heaters, other electric resistance heaters suitable for insertion into a thermal storage unit or any other types of heaters appropriate for the present invention also may be used. Furthermore, the present invention also may be used with three-phase power. In that case, a set of heaters 16 may be provided for each phase or heaters 16 may comprise a plurality of three-phase heaters. If fuses 36 also are employed, a fuse may be provided for each heater or phase of a heater. It is intended in the appended claims to cover all such changes and modifications that fall within the true spirit and scope of the invention.

Claims

1. A thermal storage system for heating fluid flowing therethrough, the system comprising:

   a thermal storage unit (TSU) having a first longitudinal axis;

   insulation at least partially surrounding the TSU;

   at least one flow channel disposed within the TSU;

   an inlet in fluidic communication with the at least one flow channel, the inlet accepting the fluid to be heated;

   an outlet in fluidic communication with the at least one flow channel;

   a plurality of heaters, each of the plurality of heaters having a longitudinal centerline and a length, wherein the plurality of heaters are disposed at least partially within the TSU and each of the plurality of heaters are independently removable from the TSU; and

   a controller for controlling electric power provided to the plurality of heaters.

2. The system of claim 1, wherein the plurality of heaters comprises a plurality of resistive cartridge heaters.

3. The system of claim 1 or 2, wherein the longitudinal centerline of each of the plurality of heaters is not parallel to the first longitudinal axis.

4. The system of claim 3, wherein the longitudinal centerline of each of the plurality of heaters is orthogonal to the first longitudinal axis.

5. The system of claim 3 or 4, wherein the longitudinal centerlines of the plurality of heaters form a single plane that is parallel to the first longitudinal axis.

6. The system of claim 1, 2, 3, 4 or 5, wherein the at least one flow channel comprises at least two flow channels each having a channel centerline parallel to the first longitudinal axis, wherein the at least two flow channels are disposed next to each other and the plurality of heaters are disposed in between the at least two flow channels.

7. The system of any one of claims 1 to 6, wherein the plurality of heaters are disposed to protrude externally out of the insulation.

8. The system of any one of claims 1 to 7, wherein the plurality of heaters comprises one or more redundant heaters.

9. The system of any one of claims 1 to 8, wherein at least two of the plurality of heaters are coupled in parallel to form a heater network, wherein the heater network is coupled to an electric power source.

10. The system of any one of claims 1 to 9, further comprising a plurality of heater-fuse assemblies each having a fuse coupled in series with one of the plurality of heaters, wherein at least two of the plurality of heater-fuse assemblies are coupled in parallel to form a heater network.

11. The system of claim 9, further comprising a current sensor, wherein:

the current sensor is coupled to the heater network such that the current sensor detects current drawn by the heater network, and

the controller is programmed to adjust the electric power provided to the plurality of heaters responsive to signals from the current sensor.

12. The system of any one of claims 1 to 11, further comprising a plurality of temperature sensors disposed to sense the temperature of the TSU at a plurality of locations, wherein the controller is programmed to require no more than a single temperature input signal to control the electric power provided to the plurality of heaters, wherein the single temperature input signal is equal to the average value of two or more of the temperatures sensed by the plurality of temperature sensors.

13. The system of claim 12, wherein the plurality of locations are a plurality of thermally equivalent locations.

14. The system of claim 12 or 13, further comprising a current sensor, wherein:

the current sensor is coupled to the plurality of heaters such that the current sensor detects current drawn by the plurality of heaters, and

the controller is programmed to adjust the electric power provided to the plurality of heaters responsive to signals from the current sensor.

15. The system of any one of claims 1 to 14, further comprising:

a heater puller having proximal and distal ends, a coupler disposed on the distal end and an actuator disposed on the proximal end, wherein:

the coupler is configured to engage at least one of the plurality of heaters, and

the actuation of the actuator engages the coupler to at least one of the plurality of heaters.

16. The system of claim 15, further comprising a locking mechanism that prevents the coupler from disengaging from the at least one of the plurality of heaters.

17. The system of claim 15 or 16, wherein:

the coupler comprises a plurality of gripping surfaces to engage at least one of the plurality of heaters, and

the actuator comprises a plurality of handles and a pivot about which each one of the plurality of handles rotates, each one of the plurality of gripping surfaces coupled to one of the plurality of handles.

18. The system of claim 15, 16 or 17, wherein:

the actuator comprises a sliding sleeve and a center rod slidably disposed within the sliding sleeve, the sliding sleeve having a distal sleeve end and the center rod having a distal rod end, and

the coupler comprises a ferrule disposed on the distal sleeve end, a plurality of compliant extensions disposed on the distal rod end, and grips mounted on the plurality of compliant extensions, the ferrule engaging the plurality of compliant extensions when the sliding sleeve is actuated in a distal direction with respect to the center rod.

19. The system of claim 15, 16, 17 or 18, wherein:

at least one of the plurality of heaters comprises at least one pin, and

the coupler comprises at least one L-shaped slot, the L-shaped slot configured to engage the at least one pin.

20. The system of claim 15, 16, 17, 18 or 19 wherein:

at least one of the plurality of heaters comprises a loop, and

the coupler comprises a hook configured to engage the loop.

21. The system of any one of claims 15 to 20, further comprising a protective housing having insulation, the protective housing having a longitudinal length equal to at least the length of each of the plurality of heaters.

22. A backup energy system comprising:

the thermal storage system of any one of claims 1 to 21 for heating fluid;

a turbine coupled to the thermal storage system for receiving the heated fluid from the outlet, the heated fluid driving the turbine; and

an electrical generator for providing electric power when the turbine is driven by the heated fluid.

23. The backup energy system of claim 22, wherein the fluid is compressed gas, the backup energy system further comprising a compressed gas system to provide the compressed gas to the thermal storage system.

24. The backup energy system of claim 22 or 23, further comprising at least one temperature sensor to sense the temperature of at least one component of the thermal storage system, wherein the controller is configured to reduce the electric power provided to the plurality of heaters when the temperature of the at least one component of the thermal storage system deviates from at least one acceptable temperature parameter that is related to parameters measured during a previous discharge event.

25. A thermal storage system for heating fluid flowing therethrough, the system comprising:

a thermal storage unit (TSU) having a first longitudinal axis;

insulation at least partially surrounding the TSU;

at least one flow channel disposed within the TSU;

an inlet in fluidic communication with the at least one flow channel, the inlet accepting the fluid to be heated;

an outlet in fluidic communication with the at least one flow channel;

a plurality of heaters;

a controller for controlling electric power provided to the plurality of heaters; and

a plurality of heater-fuse assemblies each having a fuse coupled in series with one of the plurality of heaters, wherein at least two of the plurality of heater-fuse assemblies are coupled in parallel to form a heater network.

26. The system of claim 25, further comprising a current sensor, wherein:

the current sensor is coupled to the heater network such that the current sensor detects current drawn by the heater network, and

the controller is programmed to adjust the electric power provided to the plurality of heaters responsive to signals from the current sensor.

27. A thermal storage system for heating fluid flowing therethrough, the system comprising:

a thermal storage unit (TSU) having a first longitudinal axis;

insulation at least partially surrounding the TSU;

at least one flow channel disposed within the TSU;

an inlet in fluidic communication with the at least one flow channel, the inlet accepting the fluid to be heated;

an outlet in fluidic communication with the at least one flow channel;

a plurality of heaters; and

a controller for controlling electric power provided to the plurality of heaters, wherein the controller is programmed to require no more than a single temperature input signal to control the electric power provided to the plurality of heaters.

28. The system of claim 27, further comprising a plurality of temperature sensors disposed to sense the temperature of the TSU at a plurality of thermally equivalent locations, wherein the single temperature input signal is equal to the average value of two or more of the temperatures sensed by the plurality of temperature sensors.

29. The system of claim 27 or 28, further comprising a current sensor, wherein:

the current sensor is coupled to the plurality of heaters such that the current sensor detects current drawn by the plurality of heaters, and

the controller is programmed to adjust the electric power provided to the plurality of heaters responsive to signals from the current sensor.

30. A thermal storage system for heating fluid flowing therethrough, the system comprising:

a thermal storage unit (TSU) having a first longitudinal axis;

insulation at least partially surrounding the TSU;

at least one flow channel disposed within the TSU;

an inlet in fluidic communication with the at least one flow channel, the inlet accepting the fluid to be heated;

an outlet in fluidic communication with the at least one flow channel;

a plurality of heaters including at least one redundant heater; and

a controller for controlling electric power provided to the plurality of heaters.

31. A method for heating fluid flowing through a thermal storage system, the method comprising:

providing a thermal storage unit (TSU) having at least one flow channel disposed therein;

providing a plurality of heaters disposed at least partially within the TSU;

controlling electric power provided to the plurality of heaters;

transferring heat from the plurality of heaters to the TSU from a plurality of locations within the TSU;

heating the TSU to a steady state temperature within a predetermined amount of time;

maintaining the TSU at the steady state temperature;

transferring heat from the TSU to the fluid flowing in the at least one flow channel; and removing at least one of the plurality of heaters from the TSU without removing the remaining ones of the plurality of heaters from the TSU.

32. The method of claim 31, wherein providing a plurality of heaters comprises providing a plurality of resistive cartridge heaters.

33. The method of claim 31 or 32, wherein heating the TSU comprises heating the TSU to the steady state temperature within the predetermined amount of time even when one of the plurality of heaters fails.

34. The method of claim 31, 32, or 33, wherein controlling electric power further comprises requiring no more than a single temperature input signal to control the electric power provided to the plurality of heaters.

35. The method of claim 34, further comprising sensing current drawn by the plurality of heaters, wherein controlling electric power further comprises controlling electric power provided to the plurality of heaters responsive to the sensed current.

36. The method of any one of claims 31 to 35, further comprising removing at least one of the plurality of heaters from the TSU while the temperature of the TSU is substantially equal to the steady state temperature.

37. The method of any one of claims 31 to 36, wherein controlling electric power comprises controlling electric power provided to the plurality of heaters using a DC voltage control algorithm.

38. The method of any one of claims 31 to 37, wherein controlling electric power comprises controlling electric power provided to the plurality of heaters using a variable time-base zero-crossing control algorithm.

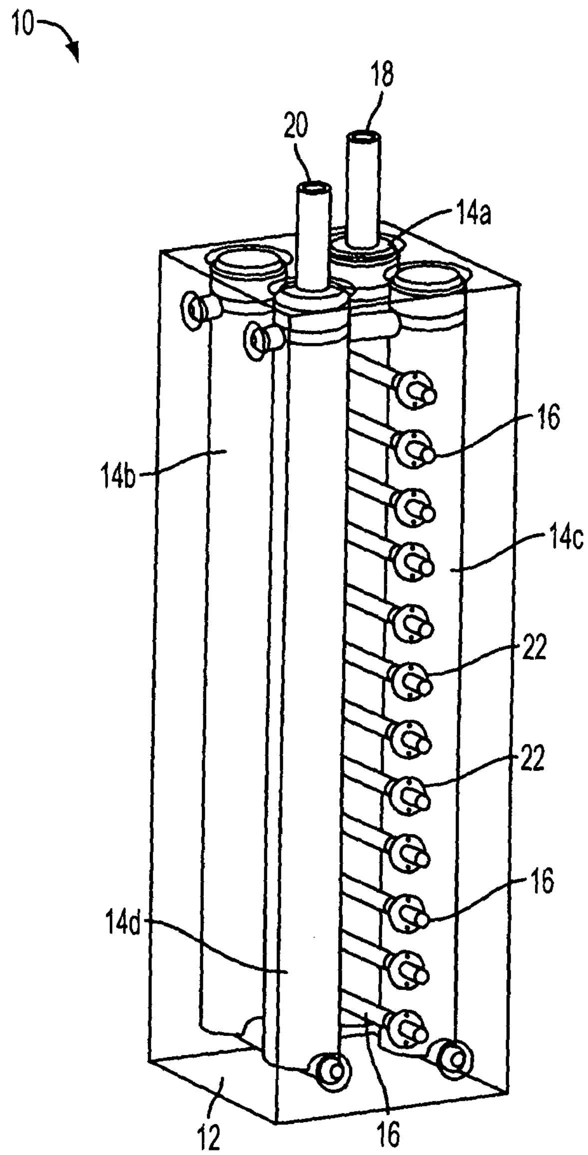

FIG. 1

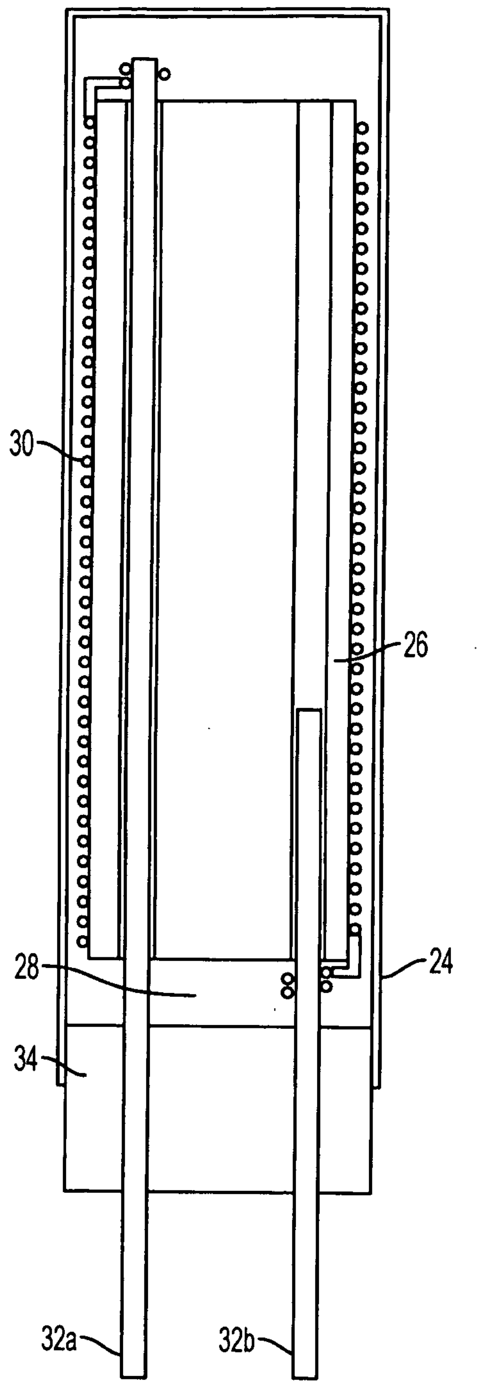

FIG. 2

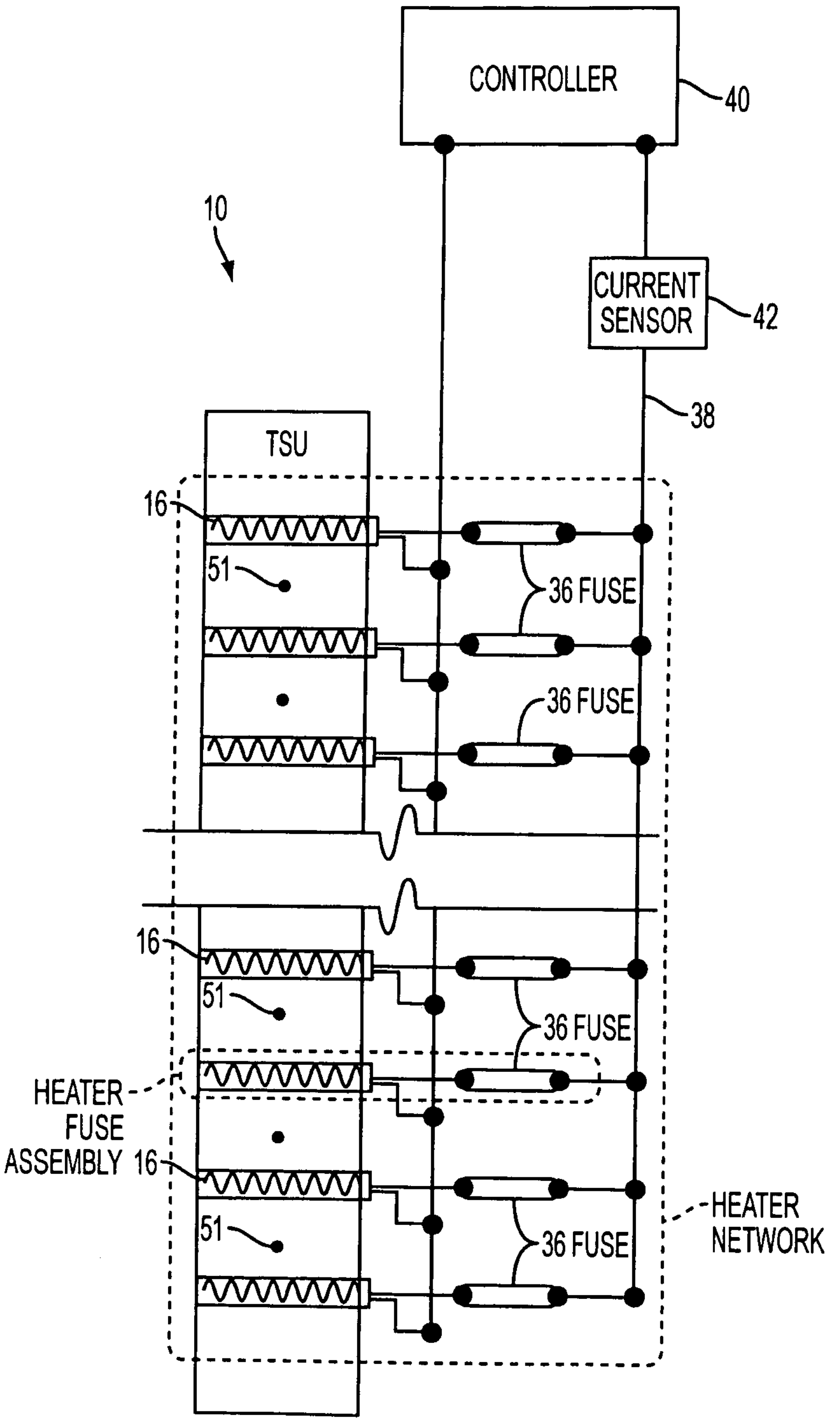
CONTROLLER
40
10
CURRENT SENSOR
42
38
TSU
16
51
36 FUSE
36 FUSE
16
51
36 FUSE
HEATER FUSE ASSEMBLY
16
51
36 FUSE
HEATER NETWORK

FIG. 3

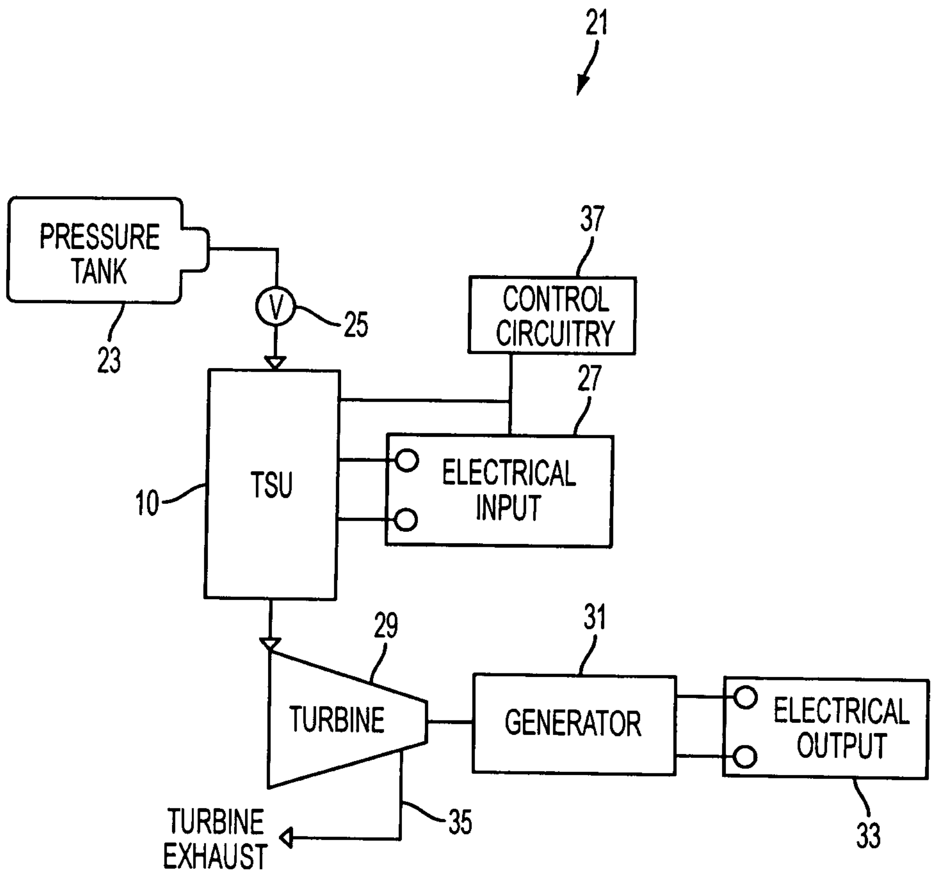
21
PRESSURE TANK
23
V
25
CONTROL CIRCUITRY
37
27
TSU
10
ELECTRICAL INPUT
29
31
TURBINE
GENERATOR
ELECTRICAL OUTPUT
TURBINE EXHAUST
35
33

FIG. 4A

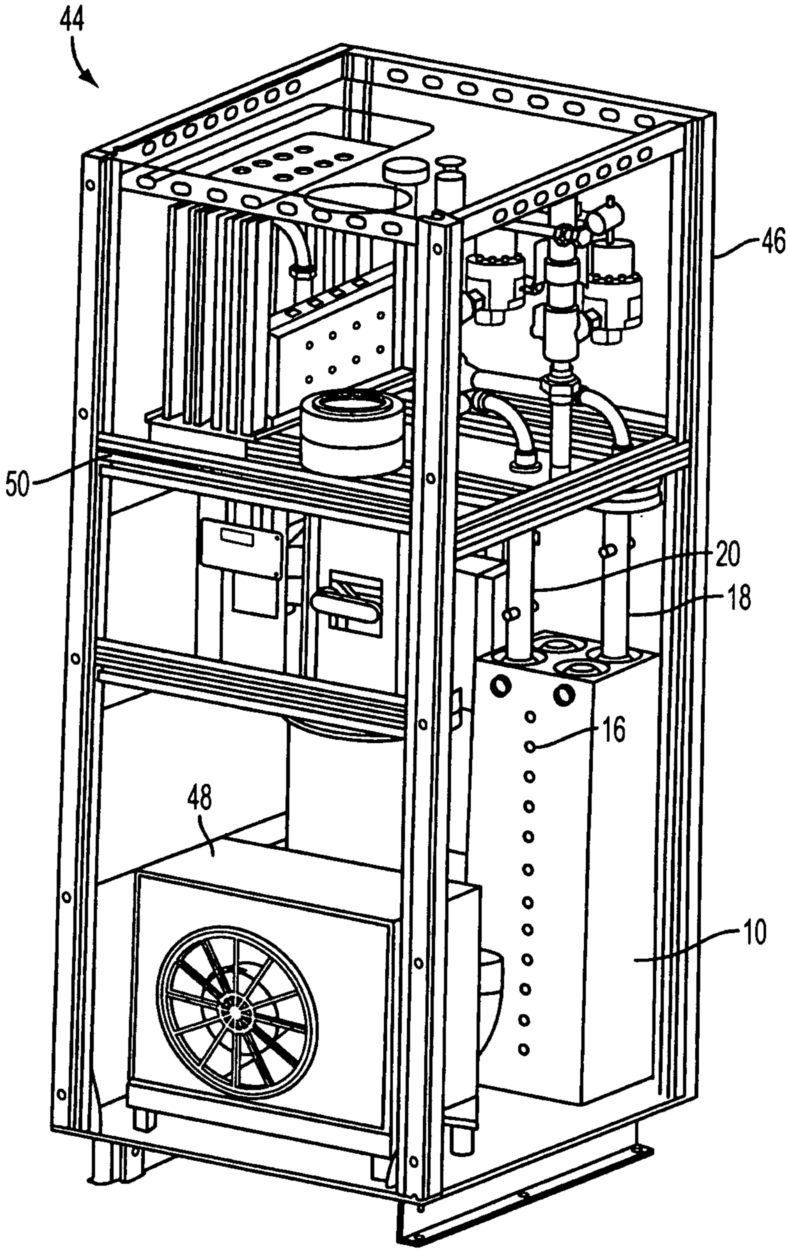

FIG. 4B

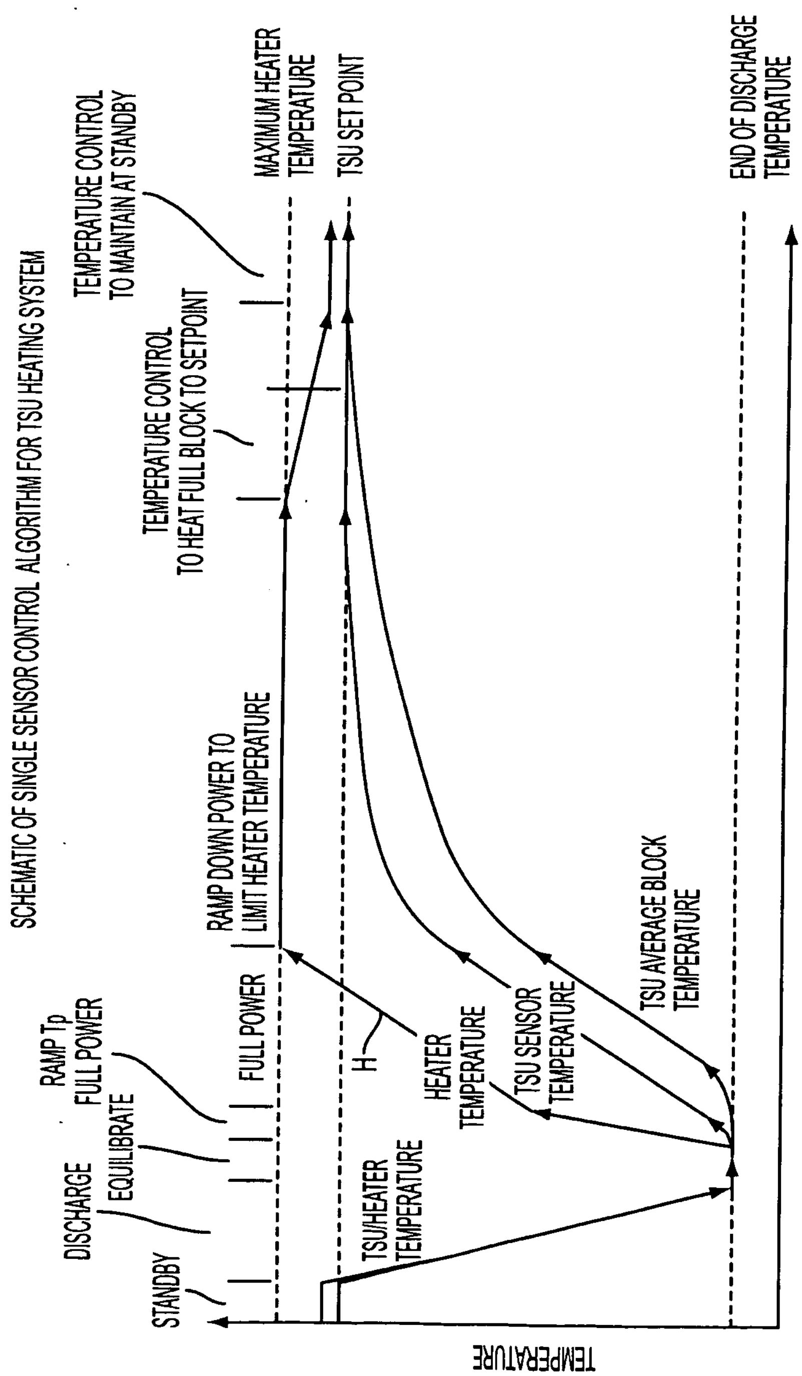
SCHEMATIC OF SINGLE SENSOR CONTROL ALGORITHM FOR TSU HEATING SYSTEM
STANDBY
DISCHARGE
EQUILIBRATE
RAMP Tp FULL POWER
FULL POWER
RAMP DOWN POWER TO LIMIT HEATER TEMPERATURE
TEMPERATURE CONTROL TO HEAT FULL BLOCK TO SETPOINT
TEMPERATURE CONTROL TO MAINTAIN AT STANDBY
MAXIMUM HEATER TEMPERATURE
TSU SET POINT
END OF DISCHARGE TEMPERATURE
TSU/HEATER TEMPERATURE
H
HEATER TEMPERATURE
TSU SENSOR TEMPERATURE
TSU AVERAGE BLOCK TEMPERATURE
TEMPERATURE

FIG. 5A

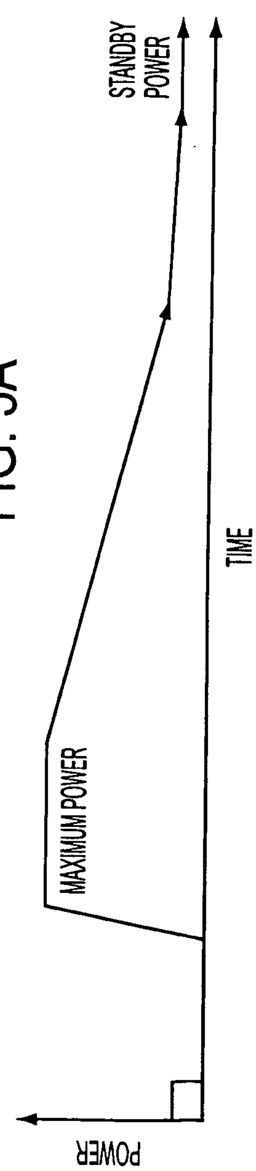
MAXIMUM POWER
STANDBY POWER
POWER
TIME

FIG. 5B

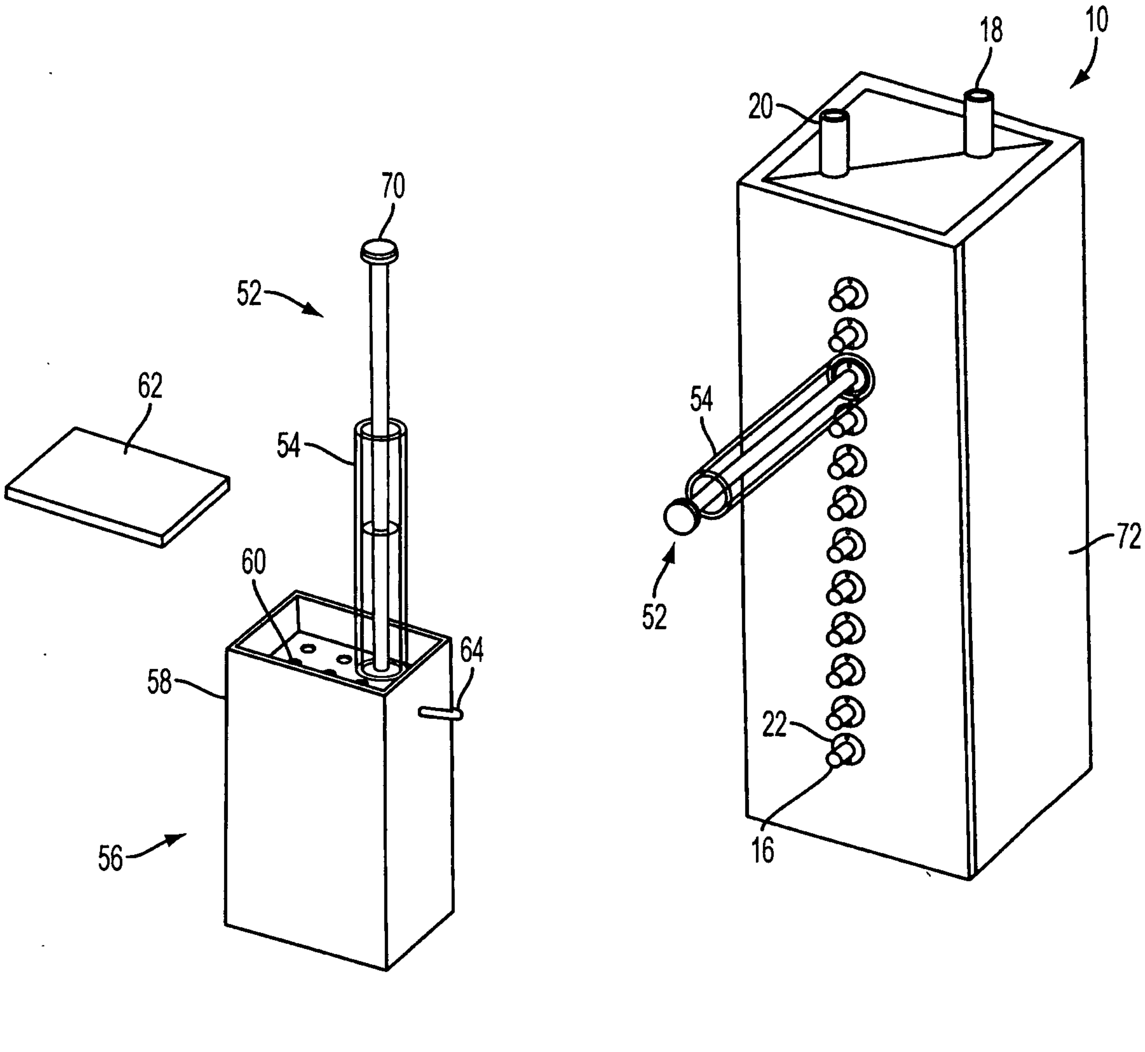

FIG. 6

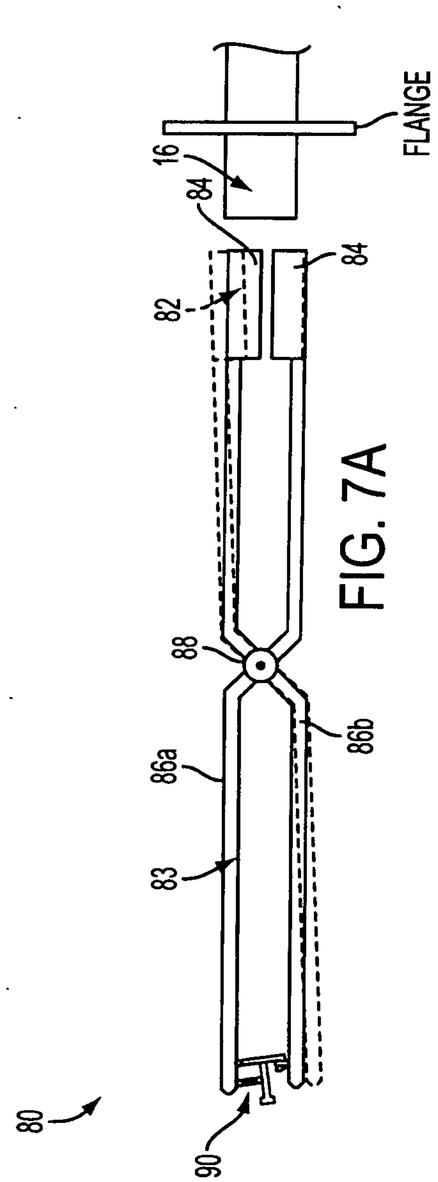

FIG. 7A

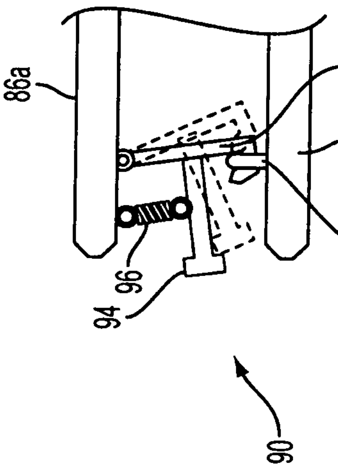

FIG. 7B

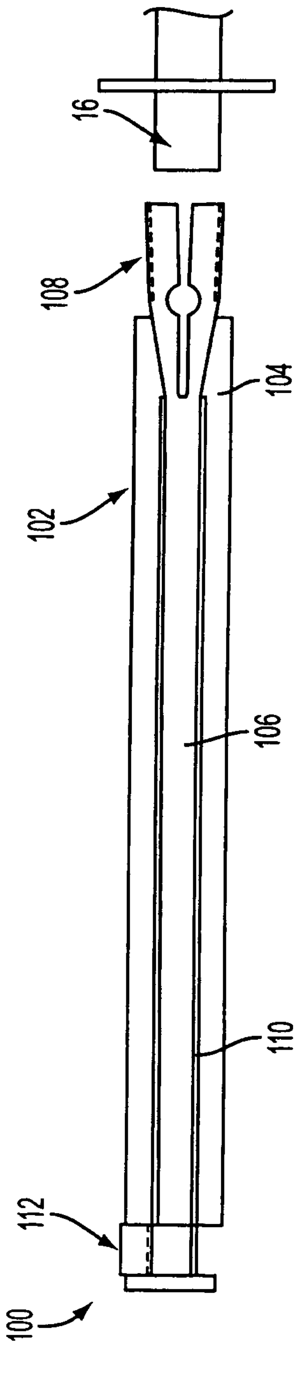
16
108
104
102
106
110
112
100

FIG. 7C

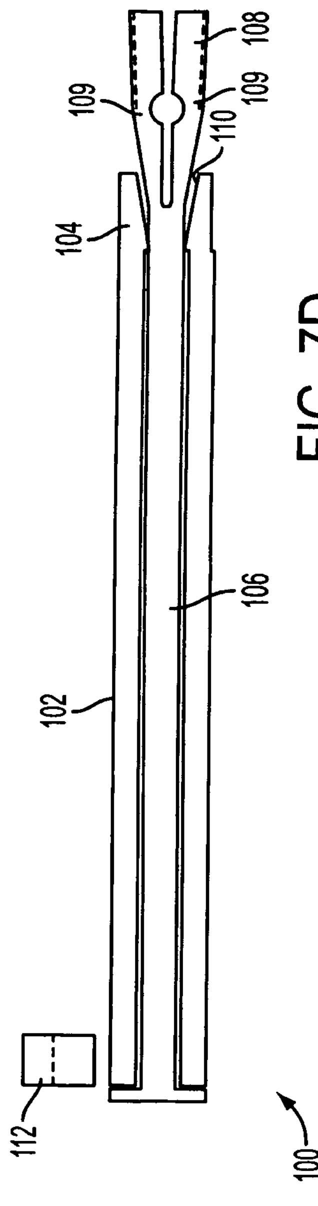
108
109
109
110
104
106
102
112
100

FIG. 7D

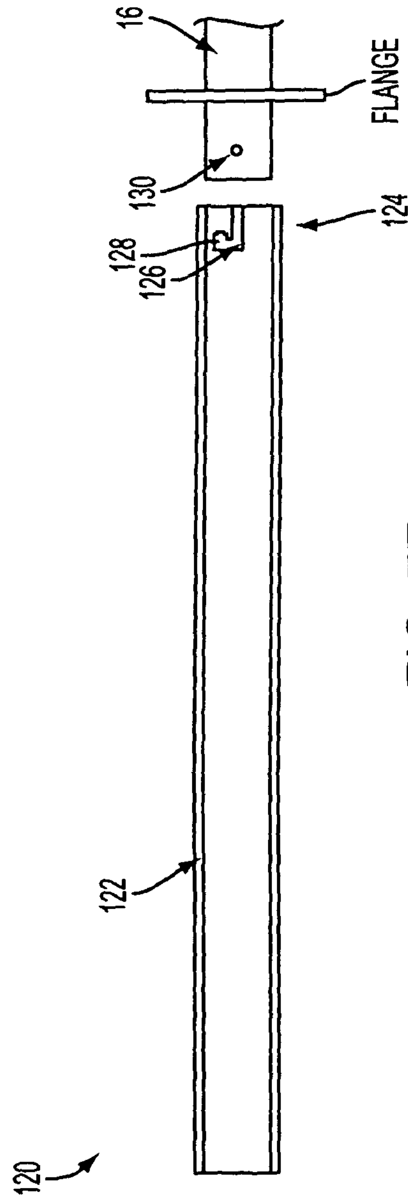

FIG. 7E

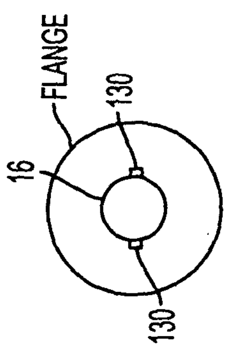

FIG. 7F

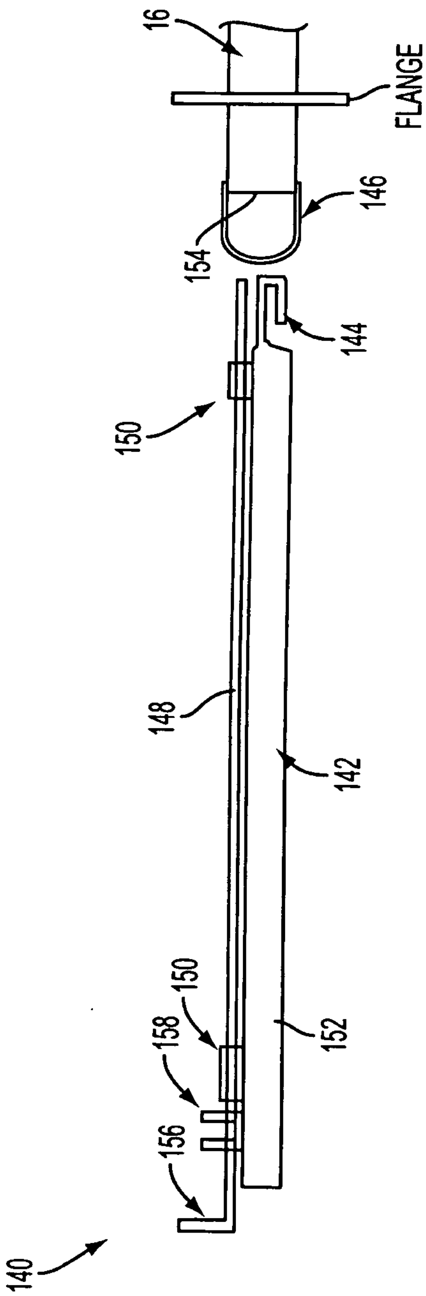

FIG. 7G